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STUDY OF A HYBRID MULTISPECTRAL PROCESSOR

by

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ENVIRONMENTAL
RESEARCH INSTITUTE
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FORMERLY WILLOW RUN LABORATORIES,
THE UNIVERSITY OF MICHIGAN

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Lyndon B. Johnson Space Center
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TECHNICAL REPORT

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Houston, Texas

FOREWORD

This report describes part of a comprehensive and continuing program of research into remote sensing of the environment from aircraft and satellites. The research is being carried out for NASA's L. B. Johnson Space Center, Houston, Texas, by the Environmental Research Institute of Michigan (formerly the Willow Run Laboratories, a unit of The University of Michigan's Institute of Science and Technology). The basic objective of this multidisciplinary program is to develop remote sensing as a practical tool to provide the planner and decision-maker with extensive information quickly and economically.

Timely information from remote sensing will be important to such people as the farmer, the city planner, the conservationist, and others concerned with a variety of problems, such as crop yield and disease, urban land studies and development, water pollution, and forest management. The scope of our program includes: (1) extending the understanding of basic processes; (2) developing new applications, advanced remote-sensing systems, and automatic data processing techniques to extract information in a useful form; and (3) assisting in data collection, processing, and analysis, including material spectra and ground-truth verification.

The research described here was performed under NASA Contract NAS 9-9784, Task B2.13, and covers the period from November 1, 1971 through January 31, 1973. Dr. A. Potter was Technical Monitor. The program was directed by R. R. Legault, Associate Director of the Environmental Research Institute of Michigan, and by J. D. Erickson, Principal Investigator and Head of the Multispectral Analysis Section. The ERIM number for this report is 31650-154-T.

ABSTRACT

This study sought to conceptualize a hybrid processor offering enough handling capacity and speed to process efficiently the large quantities of multispectral data that can be gathered by scanner systems such as MSDS, SKYLAB, ERTS, and ERIM M-7. Combinations of general-purpose and special-purpose hybrid computers were examined to include both analog and digital types as well as all-digital configurations. The current trend toward lower costs for medium-scale digital circuitry suggests that the all-digital approach may offer the better solution within the time frame of the next few years. The study recommends and defines such a hybrid digital computing system in which both special-purpose and general-purpose digital computers would be employed. The tasks of recognizing surface objects would be performed in a parallel, "pipeline" digital system while the tasks of control and monitoring were handled by a medium-scale minicomputer system. A program to design and construct a small, prototype, all-digital system has already been started at ERIM.

CONTENTS

STUDY OF A HYBRID MULTISPECTRAL PROCESSOR

1
SUMMARY OF PRESENT PROGRAM

This program was intended as a study of the feasibility and design of a hybrid computing system for use in parallel processing of multispectral data and also suitable as a prototype offering high data-throughput.

In pursuing this objective early in the program, the effort concentrated on configuring a general purpose hybrid computer to control the process and perform the operations of preprocessing. Evaluations were made both on paper and on-site of two systems which comprised the only apparent candidates: the EAI-690 (or PACER/680) system, and the Applied Dynamics AD-5 system. Both companies developed detailed configurations; these were costed against equivalent systems and critical components on these machines were tested at the respective plants. Technically both systems were adequate, but the AD-5 system was found to be less expensive. Evaluation of software indicated that EAI was clearly superior early in the program, but that Applied Dynamics could provide a reasonable system later in the program. Eventually, the AD-5 system emerged as the best choice on the basis of lower overall cost and the superiority of the DEC-built PDP-11/45 computer included.

At this point it was apparent that the technology of medium- and large-scale integrated digital circuitry was developing very quickly and that costs were beginning to decrease at a rate that made possible an altogether different approach. This new approach involved the use of a digital version of the analog portion of the hybrid, essentially replacing the functions defined for the analog computer with their digital equivalents. We projected the costs of the digital approach as being lower than those of the analog approach within less than a year—or certainly within less than the two years required to develop the system. With the recently announced ALUs (arithmetic logic units) in prospect, it now appears that the cost of the digital approach is equal to or less than that of the analog approach.

Given this conclusion, effort was devoted to defining the digital approach for both the classifier and preprocessor. With this purpose in mind, we held discussions with G. E. Space Systems Division, Valley Forge, and attended a symposium that reviewed and projected the state of the art in computer architecture. As a result, the design has emerged as a digital pipeline system operating under the control of a general-purpose, medium-scale, minicomputer system. The classifier is definitely feasible in this configuration; and for the preprocessor, reasonable flexibility appears obtainable.

The present plan, then, is to proceed with a pipeline, g.p. (general purpose) digital hybrid, meanwhile implementing the classifier and g.p. system with AAFE sponsorship, but delaying design and fabrication of the preprocessor until funds are available.

In short, we have found that the hybrid system concept is sound but that technological advances now make advisable a change from an analog to a digital implementation of the hybrid system. It is hardly surprising that a system conceived in 1969 should be differently implemented in 1973 — a technological gestation period of 4 years.

2
INTRODUCTION

Ongoing programs involving the application of a remote sensing, multispectral system as an aid in crop mapping, pollution detection, and location of ecological disturbances frequently overlook the problem that not only must the data be processed before they can be useful but also that the time allowable to produce the processed data is relatively short. This latter aspect of the problem must be solved before people who are trying to use remote sensing techniques become either hopelessly inundated by mountainous piles of data waiting to be processed, or abandon their efforts to use the techniques.

The magnitude of the discrepancy between the ability of a sensor to gather these data and the ability of a general purpose computer to process them, can perhaps best be appreciated by considering a brief numerical example. An airborne scanner, typically, covers a 20 to 30 mile flight line in about 15 minutes while recording scene data on one reel of magnetic tape. But it takes a general-purpose digital computer 1000 times as long to process these data. Thus, the data collected in 15 minutes will require 15,000 minutes of processing—or six 40-hour weeks. Given one computer to process this amount of data, the airborne scanner should only be used for eight 15-minute sorties per year. Clearly, such a discrepancy in relative capabilities is unacceptable. The data must be processed differently. But, then, just how should the data be processed?

In searching for an answer to this question, one must examine the problem more carefully. Actually the above discrepancy of 1000 to 1 is rather conservative, possibly by as much as a factor of 10. Also, while this form of processing yields a map containing the color-coded identification of each scene element at the time of the overflight, such maps will also contain errors in color-coding as well as geometrical errors resulting from motions of the airborne sensor. Moreover, the scene changes as one flies along: ground conditions vary, the atmosphere varies, sensor stability varies, and, in short, a time-related uncertainty characterizes the data. Therefore processing, as it becomes better understood, will require even more computation to remove errors and improve the results until they attain the quality the user requires.

The problem is indeed critical in making remote sensing a useful, cost-effective tool. Processing methods must be available or developed quickly enough to meet the demands of those who would use them. Timely solutions to the problems involved in this development require both lead time and continued effort.

In view of these considerations, the present program was undertaken to study the feasibility and design of a hybrid computing approach as a means of solving the data throughput problem which presently constrains the wider use of multispectral surveys. A further objective is to define a prototype system which could, given another generation of development, become the processor needed for operational use.

3
BACKGROUND

In the initial design of the multispectral scanner and processing equipment begun in 1964 for the U.S. Army Signal Corps (Ft. Monmouth), the objective established for processing the data prescribed that real-time processing be provided. Here, "real-time" was taken to mean at the same rate as employed in data collection. This requirement was important to provide data in a timely manner for tactical use. The design for this system was begun at the same time as the scanner. As a result, the data from the scanner were able to be processed shortly after they became available. This first system employed analog computer techniques implementing a statistical distance test for recognition.

After establishing the feasibility of the technique, a design was presented to the Air Force (WADC) in 1967 to provide a likelihood classifier. Using six spectral bands and eight signatures in the solution, this classifier operated in real time. With analog computing techniques, its operating rate was 10^5 decisions/sec. The system was enlarged in the following year to provide preprocessing, i.e., processing of the data to correct radiance variations prior to classification. In this form, the system (called SPARC, or Spectral Analyzer and Recognition Computer) was employed for several years to test the feasibility of the multispectral technique for a large variety of applications (see Appendix A).

As the members of the various sponsoring and collaborating agencies began to consider applications closer to operational use, it became clear that our original real-time requirement was of considerable importance. This truth became evident from two points of view. First, the operational demands (see Appendix A) require that substantial portions of the U.S. be surveyed periodically and that the results be provided quickly. Secondly, the available and planned sensors (ERIM-M7 scanner, MSDS scanner, ERTS, SKYLAB, and others) would far outstrip any capacity available to process the data gathered. One might also add another consideration: Experimentation with new applications for these sensor techniques could progress more quickly, and therefore more cheaply, if paced by a fast, inexpensive processor. As a corollary, many more tests could be run; and various experimenters having limited budgets could thus participate and pursue timely test and development of their ideas. The present cost of processing data for a typical research application is given in Appendix B.

In 1969 designs of a hybrid (digital-analog) computer were begun; NASA-MSC sponsorship dates from 1970. The general design was reported in March 1971; plans were then made to begin detailed design and fabrication of the system (SPARC/H). Although there appeared to be a great interest in the concept, no funds were forthcoming to pursue design and construction.

During the spring of 1971, a collaborative program called HYMPS (Hybrid Multispectral Processor System) was begun at MSC to test the concept on the EAI 8900 hybrid system at MSC/CAD. This program was essentially completed in the fall of 1971. It demonstrated the feasibility of the concept in a limited manner, using six channels, three distributions and a slowdown of 4 or 8: this required two of the three available 8800 analog consoles of the 8900 system. There was agreement that the classification function could be more efficiently handled on a special purpose hybrid computer but that preprocessing was well suited for a general-purpose hybrid computer.

In the summer of 1971, a study was undertaken with U.S. Department of Agriculture (USDA), Manned Spacecraft Center (MSC), and Purdue's Laboratory for Agricultural Remote Sensing (LARS) to examine the feasibility using remote sensing methods to perform a substantial portion of the ASCS (Agricultural Stabilization and Conservation Service) enforcement and crop survey operations. The requirements of this program were analyzed and, to meet the needs for processing the large volumes of data, a system was defined employing several hybrid computers of the SPARC/H (H for Hybrid) configuration. Review by members of Flight Operations Division (FOD),Computer Analysis Division (CAD), and Earth Observations Division (EOD) indicated the desirability of this approach and the inadequacy of the large-scale general-purpose digital computer (see Appendices C and D).

During the fall of 1971 we were informed that under the AAFE (Advanced Application Flight Experiments) Program and through NASA/Langley, funding was available to develop a small hybrid system for classifying multispectral data. In the interest of pursuing the development of a larger scale model of the system, agreements in principle to pursue the larger system under joint sponsorship were arrived at in meetings with both NASA/MSC and NASA/Langley. This plan is documented in Appendices D and E. Unfortunately, funds were not available from either sponsor at that time but support for continued effort was provided under the present contract with NASA/MSC.

In November 1972, funds became available from the AAFE program and development of the small system has since commenced. At present, although we have agreements in principle that the larger system be built, we are proceeding only with construction of the smaller system. It still appears desirable to proceed with the full system.

4
HYBRID CONFIGURATION

The general configuration derived for the SPARC hybrid classifier, SPARC/H, consists of a special-purpose analog computer (the classifier) controlled by a small general-purpose digital computer. The general and detailed configurations are given in Appendix A, Section 3; a block diagram of the system appears in Fig. 9 of the same appendix.

Two versions of this system were configured conceptually: (1) a large-scale system consisting of the classifier and two general-purpose hybrid consoles of which one is the preprocessor and the second a console to provide geometry correction of the map produced, and (2) a small system including the classifier with some preprocessing. These two versions are described and costed in Appendix E.

For these systems, we determined that the Applied Dynamics AD-5 system with a DEC PDP 11/45 computer was the best choice for the general purpose portion of the system—in comparison with the PACER/680 system of the only known competitor, EAI. Basically, the analog hardware of the AD-5 and EAI-680 are about equivalent in performance. In comparing the digital hardware, the PDP 11/45 computer was found superior in performance and lower in cost than the EAI-PACER. And while the EAI software system was superior to the AD software, the AD software nevertheless appeared adequate.

4.1. ANALOG CLASSIFIER

The classifier, using analog techniques, is basically identical to the present SPARC computer. The input data enter a set of parallel circuit groups, each of which is programmed to compute a likelihood value for each of the objects represented by that group. These likelihood values are compared and a maximum is then selected and supplied as an encoded output that identifies the object classified. The classifier is organized so that $\underline{n}$ objects measured in $\underline{k}$ spectral bands can be classified. The machine is described as an $\underline{n} \times \underline{k}$ classifier. Thus, the desired size of this classifier is 12×8—i.e., it can classify an input vector of 8 dimensions into one of 12 object classes. (The same machine could be used as a 24×4 classifier by properly partitioning the circuit groups.) The 12×8 classifier seems adequate for processing most scenes in the applications investigated thus far (see Appendix A). The detailed organization of such a classifier is given in Ref. [1] of Appendix A (see Ref. list, p. 40) and also in Appendix E.

The classifier exhibits an organization differing in several important particulars from that found in a general purpose hybrid computer: (1) it uses no integrators; (2) it requires that most of its circuitry be in a saturated state most of the time; (3) it requires several hundred multiplying digital-analog converters; and (4) it uses many nonlinear circuits.

This unusual configuration makes implemention of these functions in a special purpose analog system technically desirable and less costly. This approach was followed until the possibility arose that such a system might be obtainable at lower cost, using a digital mechanization.

4.2. DIGITAL CLASSIFIER

The analog techniques for classifying objects using multispectral data have been well developed over the past few years and, until very recently, appeared less costly and complex than digital techniques in which a special purpose mechanization would be used. The multiplier, one of the components of most significant cost, was previously estimated to cost on the order of several hundred dollars, and would be replicated, in the worst case, about 1000 times. Two significant changes have taken place: (1) the cost per 8-bit multiplier has declined to about \$160; and (2) the speed of such units has increased to a range of 70 to 200 nsec/product. As a result, the multiplier can be built to be multiplexed so that it can compute several products per input sample (5 μsec). Thus a factor of cost reduction ranging between 5 and 10 may be achieved. The estimated logic may now cost on the order of \$20K rather than as much as \$500K. Labor costs for wiring the medium-scale-integration ALUs (Arithmetic Logic Units) rather than the small-scale-integration dual in-line packages (DIPS) can be reduced by significant factors also.

The classifier in this configuration, then, will have the same organization as the SPARC but will have its functional components implemented in time-shared digital circuitry. Each component acts as a computing element in a hard-wired sequence, which may be thought of as a "pipeline" of computational circuits.

The statistical parameters of the objects to be classified are supplied to cyclic storage in the pipeline by an associated general-purpose digital computer, which may be a DEC PDP 11/45, or possibly an HP-2100. These parameters are computed from training sets made during an initial pass of the data —as is presently done on SPARC and in the operating systems used for the ERIM CDC-1604 and the IBM 7094.

The output of this classifier will be a maximum likelihood choice represented by a 4-bit code, which can either be directly stored digitally after word packing and buffering, or used to provide a map on a CRT film printer or on a color moving window display (described in Section 6).

5
PREPROCESSOR

5.1. ANALOG PREPROCESSOR

For most of this program period, considerable effort was devoted to choosing a system available as a general-purpose commercial hybrid to obtain the flexibility considered necessary to study the utility of various preprocessing techniques developed thus far. A particular area of concern was whether the bandwidth of the various components was sufficient to implement the required functions. To confirm the adequacy of the equipment in this respect, visits were made to EAI and Applied Dynamics and comparable systems were tested.

At EAI, the EAI 680 console was tested for frequency response and accuracy of various functions at the patch panel. Results are given in Table 1. The results indicate that the machine could be used for preprocessing operations with frequencies approaching 100 kHz. However, in view of the large number of limiters required and the speed of the squaring circuitry, standard circuits would need modification to perform classification at such rates. Furthermore, the large number of multiplying digital-to-analog converters (DACs) required necessitate special packaging; this might be worth considering except that the packaging cost appears much greater than if done at ERIM.

The software system seems excellent. It has been in operation for several years now and, since the new digital machine (PACER) is identical (except for one instruction), this software should operate on the new machine with no problem. The HOI (Hybrid Operation Interpreter) language, which is similar to BASIC with a subroutine call capability, should allow a briefly trained operator to control the recognition process with no difficulty.

At Applied Dynamics, tests of the same nature as at EAI were run on the AD-5 system; results are given in Table 2. These tests indicate that performance similar to the EAI 680 can be expected. One shortcoming in the AD-5 is that digitally controlled function generators (to mechanize angle functions in preprocessing) are not available.

Software was not available for demonstrations on the DEC PDP-11 system at the time of visit. A set of HCRs (Hybrid Communication Routines), is available for call from FORTRAN but not yet callable from a new system, HYBASIC (a version of DEC-BASIC), modified to allow call of HCR routines.

Cost comparison of the PACER/680 hybrid system from EAI and the PDP-11/AD-5 system from Applied Dynamics indicates a substantially lower cost for nearly equivalent hardware performance on the part of the Applied Dynamics equipment. Total costs for two full AD-5 consoles (AD-5/36) and a fully configured DEC PDP-11/20 system were about $460K. For the same

TABLE 1. TEST RESULTS FOR EAI-680

	CONDITION	INPUT	Frequency at 10^{o} Phase Shift	3 db Frequency	Comments
Inverters (10 K ohm input)	× 1 Gain × 10 Gain	±5 V Sine ±0.5 V Sine	150 kHz 75 kHz	500 kHz 200 kHz	
Inverters on Multipliers	× 1 Gain	±5 V Sine	--	500 kHz	
Integrator as Inverter	× 1 Gain	±5 V Sine	150 kHz	500 kHz	
Multipliers	Sine × Constant	a) +5 VDC b) 5 V peak	150 kHz	450 kHz	
Sine/Cos	--	±5 V Triangle	--	Sine function error greater than 10% above 10 kHz	
Multipliers	Sine × Sine	x = y = 5 V Sine	~50 kHz	Error above 10% greater than 50 kHz	

TABLE 2. TEST RESULTS FOR APPLIED DYNAMICS AD-5

	CONDITION	INPUT	Frequency at 10^{o} Phase Shift	3 db Frequency	Comments
Inverters	× 1 Gain × 10 Gain	±5 V Sine ±5 V Sine	400 kHz 25 kHz	1.8 MHz 80 kHz	2% overshoot 10% overshoot
Integrators	× 1 Gain × 10 Gain	±5 V Sine ±5 V Sine	170 kHz 37 kHz	1.1 MHz 135 kHz	20% overshoot 60% overshoot
Multipliers	a) Sine × Cos	a) +1 VDC	130 kHz	700 kHz	--
	b) Sine × Sine	b) 10 V peak Sine	~100 kHz	Error greater than 10% above 100 kHz	--
Sine/Cos		±10 V Triangle		2 kHz, or about 2% error	--
Front Panel Puts	10K Load	±10 V Sine	270 kHz	--	--

system based on a DEC PDP-11/45 system, costs were about $480K. The DEC PDP-11/45 system appears superior to the EAI PACER, and the DEC PDP-11/20 system about the same as the EAI PACER.

The equivalent system from EAI, using the PACER and 2-680 consoles, totaled about $720K.

Performance figures for the AD-5 circuitry were improved over those observed earlier in areas of bandwidth and saturation recovery. (The improved circuitry is now standard at no cost change.) As a result, instead of poorer performance by X10 amplifiers and squaring circuits, these units can operate reasonably at better than 100 kHz bandwidths.

The HYBASIC/PT for stand-alone, paper-tape-based hybrid operation was demonstrated at Applied Dynamics on 5 April 1972. Several representatives from ERIM operated the system and found it capable of exercising the functions of the AD-5—except for a few small bugs in the BASIC package, probably because of the tape reader. Although traditionally most of us had been skeptical about software development promises, we considered the modification of DEC-BASIC to control the AD-5 as being a demonstrated package. During June, the disk operating version of HYBASIC (the HYBASIC/DOS) was tested and completed, thus presenting us with a suitable software system.

From the foregoing, we concluded that for the present, the hybrid alone combines the speed, flexibility and sufficient accuracy at reasonable cost that is required to continue development toward an ultimate operational system. The techniques of highly parallel digital processing seemed well worth developing, but should not—for some time yet—be considered a substitute for the proposed hybrid techniques.

Table 3 summarizes some of these considerations and conclusions.

In brief, it appeared that the hybrid system was still superior as a function of its flexibility, present cost, and current availability.

5.2. DIGITAL PREPROCESSOR

A principal difficulty in defining the form of a digital preprocessor lies in the fact that there are several candidate techniques, of which several may be implementable and useful, but no one of which can be selected with certainty at this time. Since a digital preprocessor would probably have to be hard-wired, this fact was considered to be a sizable risk. Personnel at General Electric Space Division became interested and suggested collaborating on the overall SPARC/H problem.

As a result, we attended a briefing and demonstration of the 4-channel GEMS-A system on 15 June 1972, at the General Electric facility in Valley Forge, Pennsylvania. The present GEMS-A contains a good interactive capability for presenting color photos of scenes with zoom

TABLE 3. A COMPARISON OF HYBRID AND PARALLEL DIGITAL TECHNIQUES
(H. = Hybrid; P.D. = Parallel Digital)

Requirements	General	ERIM	ASCS/MSC
Accuracy	H. and P.D. both adequate	----	----
Speed	Comparable	----	----
Flexibility	H. Superior	Necessary at this time	Very desirable
Development required	P.D. requires considerable development to obtain flexibility; H. already satisfactory	Development delay time uncertain and not tolerable	Development should be sponsored but decision to adopt should be delayed
Cost	Ultimately comparable when configuration can be fixed—presently H. should be less	Since costs of H. and P.D. seem comparable, choose hybrid now to secure timely techniques availability	For ASCS, H. would be best choice now and for at least a year
Availability and Longevity for Research	H. is a useful tool now and should be so for duration of period to define operational system	Technique development slowed down due to lack of adequate, cheap processing	H. would be a good choice at this time

display, picking out training sets, and then rapidly displaying multidimensional-slicing recognition based on these training sets. When this recognition was extended to cover a 512 x 512 pixel photograph, the results appeared satisfactory; however, the system does not as yet allow processing of scanner data.

Following the initial presentation and demonstration, attention was focused on the area of preprocessing. Some discussion was held on current preprocessing techniques. Since this was and is a rather loosely defined area, the exact impact on the digital implementation of these techniques could not be assessed. It was agreed that continuing discussions between ERIM and G.E. personnel could prove useful in defining digital techniques for preprocessing with sufficient flexibility.

A rough quotation received from G.E. (Daytona Beach, Florida) for a classifier and preprocessor estimated a cost of $90K and a 9-month delivery. Since the cost range appeared reasonable, a more detailed specification was prepared (see Appendix F) and after some consultation, submitted to G.E.

A more detailed quote was then received indicating that a 12-channel 8-distribution system could be procured for about $90K. This would include portions of the preprocessor and the classifier.

From analyses by ERIM and G.E., it appears that the preprocessor could be economically implemented for a reasonable subset of desired functions. Because of funding limitations, however, it is not yet clear whether we can proceed with any substantial implementation of this item.

6
DISPLAY

In processing multispectral data at real-time rates, the results are generally displayed as a color recognition map on color film. The time required to prepare this map after the processing is completed is relatively long, i.e., on the order of several hours for a dedicated color film processing facility. To an investigator processing the data, this delay is quite unacceptable, especially in the preliminary processing stages. In these initial stages, it is desirable to preview the processing results on-line, especially if the data cover an extended area where gross errors may accumulate.

The processing of multispectral data usually results in the scene elements being classified as belonging to one of about 8 to 16 different scene materials. Since this number of classes cannot be adequately represented by a gray scale on a black and white monitor, color is necessary. The display output should be able to keep pace with the data-processing rate. If the data are processed solely by a conventional digital computer, the output rate is very slow (as described in the introduction to this report). For this case the display could be driven by the computer in a number of ways. However, if the display is to keep pace with the real time data-processing rate in a hybrid system, then the display must have high speed and be driven independently of the conventional digital computer's I/O channel so as not to completely tie up the computer and its I/O channel. These requirements rule out the possibility of using as the output device any electromechanical line printer or ink spray printer such as Data Corporation Digital Graphics Generator. At present, only a color CRT appears to meet these speed requirements.

For ease of viewing, the display should be of the refresh type. Since scanner data are processed on a line-by-line basis, with the number of lines per second roughly the same as conventional TV frame rates, it seems desirable to add a new line at each frame refresh while removing the oldest line. Since this is a previewing device, the display should need only a medium resolution of about 256 × 256 resolution elements. If processed data are coded as a 4-bit binary word, one processed scan line could be stored in a 1024-bit MOS shift register. The number of of scan lines stored depends upon the number of these registers used, but 256 lines are presently satisfactory since the display format could be easily changed. For example, the along-scan line resolution could be changed to 512 while the number of scan lines was lowered to 128. A block diagram of the basic display system is shown in Fig. 1. This semiconductor memory based system has an advantage over a video disk memory based system in the ease by which the synchronism of data input rate and video display rate may be achieved. A rotating disk would have to be modified to put its rotation in synchronism with the scan line rate. The reliability of such a technique is questionable. On the other hand, the shifting rate of the semi-

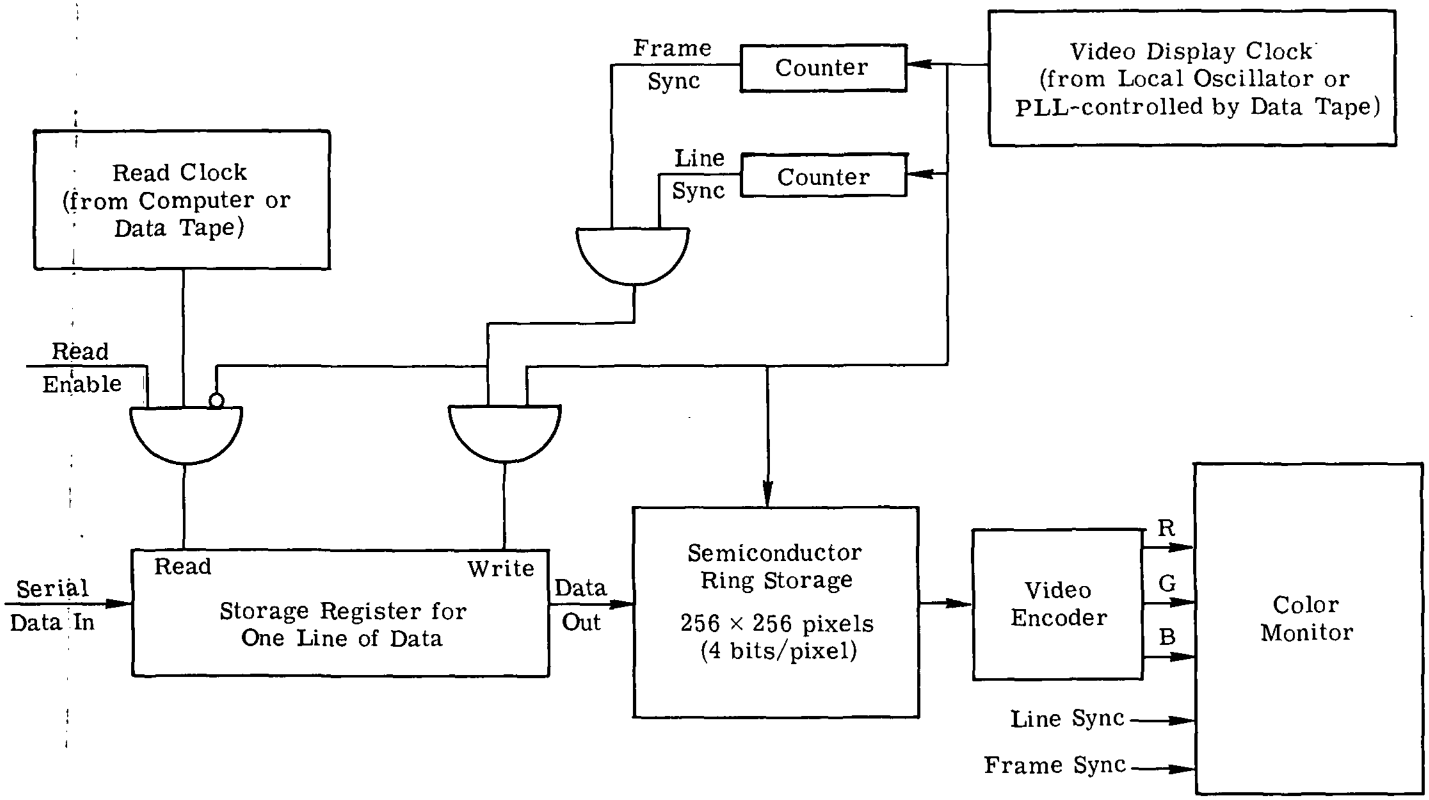

FIGURE 1. BLOCK DIAGRAM OF DISPLAY SYSTEM

conductor memory is easily accomplished and could even be locked to a varying data rate through a phase-locked loop (PLL).

The features that could be built into this basic system depend largely on the funding and effort available. The picture format change, zoom capability, and stop action, for example, are all desirable features which would allow the display to be more than just a previewer. These features permit an investigator to analyze accurately selected portions of the processed data, thereby allowing him to make on-the-spot decisions as to whether or not the recognition process should be modified.

7
CONCLUSIONS AND RECOMMENDATIONS

7.1. CONCLUSIONS

The all-digital parallel processor approach can provide a cost-effective alternative to the long-planned and discussed hybrid (digital-analog) system. This is primarily the result of recent developments leading to greater availability and lower cost of ALU's (Arithmetic Logic Units) suitable for high speed implementation of the classification algorithms now available.

Unfortunately, the hybrid system recommended over the past few years now seems to have succumbed to the march of time and technology. Although it would have been a valuable tool in advancing our research and realizing sooner the potential of multispectral sensing, development and use of such a system is probably obsolete.

The problems of providing timely processing to remotely sensed data are now more pressing than in previous years. The present development of the pipeline processor described can assist in the solution of these problems and is well worth pursuing.

7.2. RECOMMENDATIONS

As outlined in this report and in its appendices, a serious lack exists in the processing capabilities required to provide fast and useful output to people able to use data obtained by remote sensing with multispectral scanners. We would urge the support of a larger program to remedy this lack as quickly as possible. Specifically, development could proceed more quickly in the area of preprocessor study and implementation, as agreed previously. The choice of a digital implementation for this portion of the system, requiring more development than the analog approach, makes the problem in some ways more acute than it previously was.

Also, there is no color printing capability available for printing the results of the process with sufficient resolution, speed,and the control necessary to allow correction of scanner-aircraft distortions. This lack requires more concentrated attention before it becomes a formidable bottleneck.

Appendix A

An Operational Multispectral Surveys System *

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ABSTRACT

The evolution of multispectral survey techniques has entered a period in which the ability to collect data greatly exceeds the capability of processing facilities. At the same time these techniques have proven to have successful application in many areas, for which increasingly greater demands arise to collect and process such data.

These circumstances make it necessary to define and develop new processing techniques, better suited to the requirements of continued development toward operational applications. These requirements and a system to meet them are developed in this paper. The general and detailed design of a hybrid system are elaborated for this purpose and given the acronym SPARC/H (SPectral Analysis and Recognition Computer/Hybrid). This system is intended to accept and process multispectral data from existing and planned aircraft and spacecraft sensors.

Projected benefits, such as facilitation of research, savings in time and cost, and definition of future operational processing facilities are described. These benefits indicate that development and use of such a system should not be delayed.

1. INTRODUCTION

As multispectral sensing techniques develop from the stage of concept or research through large scale studies toward eventual operational use, the requirements placed on the techniques also begin to change. Whereas in the early stages of development, now several years ago, the questions were: can an object be detected, with what probability can it be detected? Now the questions are: can people with operational objectives use this data quickly and reliably; are the techniques cost effective?

Implicit in these latter questions is usually the assumption that processing techniques are available to meet these needs and that one has only to buy the right computer and begin using the processed data. This assumption is frequently made in planning scientific research programs and, as frequently, results in the collection of a great amount of data for which processing is essentially unavailable and is developed almost as an afterthought and after considerable delay and cost.

The risk of sizable delay and expense is more serious in multispectral surveys for three reasons: 1) the quantities of data involved are substantially larger than have been experienced in the past, 2) the anticipated data rates are such that no presently available processors can meet the demand and 3) the development of adequate processing capabilities is seriously lagging the ability to collect such data.

The objectives of this paper are then, 1) to assess the quantity of data and the cost of processing this data with present and projected equipment over the next few years, 2) to point out

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that the present lag in development is now creating serious penalties in cost and effectiveness of research, and 3) to describe techniques which can reduce the delays and costs in processing this data.

2. THE PRESENT SITUATION: AN ASSESSMENT OF DATA COLLECTION

The present status of a few representative applications of multispectral surveying are indicated in Figure 1. Each application shown represents a group of specific applications which range through the stages of development shown and which have, for the most part, progressed only to the early stages at present. Some specific applications are, however, being extended toward prototype operation, and an example of this may be found in the planned corn blight watch. It must be pointed out that this one application can overload all present processing facilities.

The capabilities of various sensing techniques meet the need of survey requirements, at least with regard to the quantity and, probably, the quality of data. The various processing techniques, however, are inadequate. This is simply indicated on the figure, but may be substantiated from present data collection capacity or projected needs for such data.

Figure 2 indicates the present and projected multispectral data capacity as various sensor programs begin to operate. These are the U of M 18 channel multi-aperture scanner, U of M Single Aperture 12 channel scanner, the MultiSpectral Data System of Bendix/NASA-Houston, the ERTS and SKYLAB scanners. These capacities are cumulative and are based on 4 hours of data/week from scanner and specified ERTS ground system output. The maximum planned rates are on the order of 15×10^9 data elements/week. Projected rates from an earlier study (1) are similar (about 5×10^9 elements per day, a coverage of the full United States twice a year) and tend to show a reasonable match between data generation capacity and data demand.

2.1. QUANTITY AND COST OF DATA PROCESSING

Data quantities of this rate are impressively large but the cost to process the data is not well known. Figure 3 gives some idea of the present rates and projected rates for costs of data processing per element and per square mile. The impact of these costs can be assessed if some typical problems are analyzed. Some are given in Figure 4. The practical impact of cost reduction by proceeding to prototype or operational equipment is easy to assess.

If, for example, the survey of the United States were to be done twice a year (an area of 8×10^6 mi^2), as the projected demand indicates, at a cost of \$420/mi^2 (the cost using research equipment) the total is about three billion dollars. If prototype equipment is used, the cost is forty million dollars and thirteen million dollars when operational. Thus a hypothetical savings of about three billions of dollars can be obtained eventually.

But we must consider the nearer future, and, so, taking projected data capacities and assuming that the data is processable, the cumulative cost picture is as shown for Figure 5 where the continued rise is the accumulated cost as various sensors are introduced and used. The two breaks shown in January 1972 and January 1973 indicate the introduction of a prototype processor at these two points in time, resulting in savings of about 100 million dollars per year over these next two years. If the prototype were ready in January of 1972, it would save almost seventy million dollars during that year but it is unlikely, however, that one can be made available in so short a time.

It should also be borne in mind that the rate of processing is costly as research and evaluation are delayed. If we can survey almost 8×10^6 square miles/year but can process only about 1/1000 of the data, a serious imbalance exists since much needed investigation is stopped. If more advanced techniques are used about 1/25 or 1/8 of the data can be processed.

It is thus apparent that high costs in time and money may be avoided by timely development and introduction of adequate processing equipment. Some of the benefits to be gained can be listed: 1) Facilitation of research and development; 2) Present costs can be reduced; 3) Projected data collection over the near future can be processed; 4) Projection of true operational costs can be made; 5) Operational needs for personnel and equipment can be defined.

2.2. GENERAL SYSTEM CONSIDERATIONS

The previous analysis presents generic conclusions about the quantity of data, and the rates with which such data must be processed. Another question must be answered also, what form of data processing is needed.

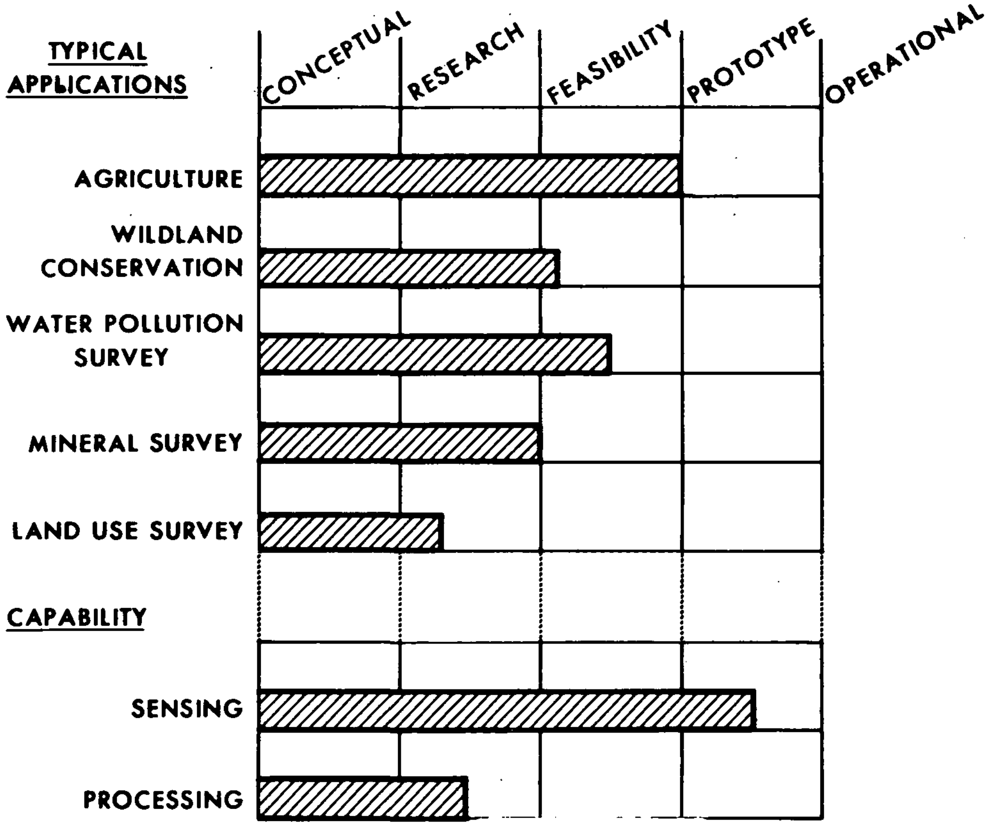


FIGURE 1. STATUS OF MULTISPECTRAL DEVELOPMENT

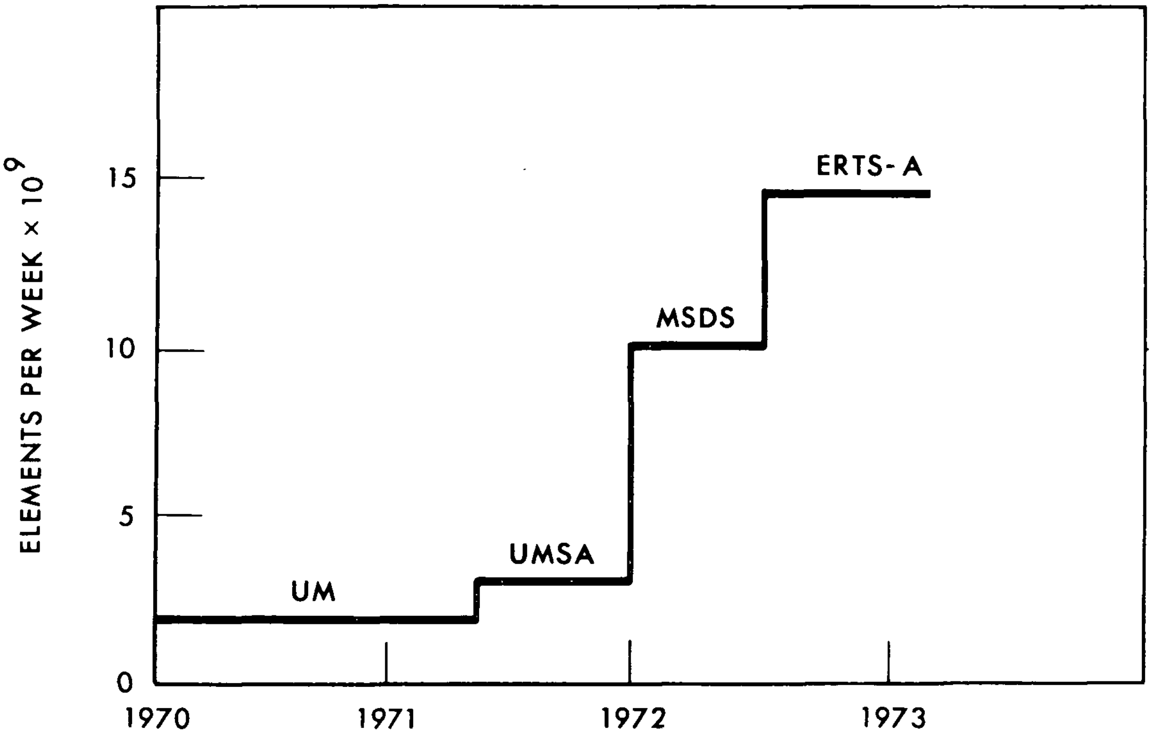


FIGURE 2. MULTISPECTRAL SCANNER DATA RATE CAPABILITIES

	\$/ELEMENT	\$/MI^2	HOURS/MI^2
RESEARCH	130×10^{-6}	420	2
FEASIBILITY	60×10^{-6}	195	1
PROTOTYPE	3×10^{-6}	10	0.05
OPERATIONAL	1×10^{-6}	3	0.02

FIGURE 3. OPERATING COST OF PROCESSING

JOB	AREA SIZE	RESEARCH PROCESSOR COST	PROTOTYPE PROCESSOR COST
SURVEY AGRICULTURAL COUNTY	36 sq. mi.	$15,000	$360
CORN BLIGHT SURVEY	100 sq. mi./wk.	$42,000/wk.	$1000/wk.
EVERGLADES SURVEY	4000 sq. mi./yr.	$1,680,000/yr.	$40,000/yr.
TYPICAL USER REQUEST	20 sq. mi./wk.	$8400/wk.	$200/wk.

FIGURE 4. PROCESSING COSTS FOR SOME TYPICAL OPERATIONS

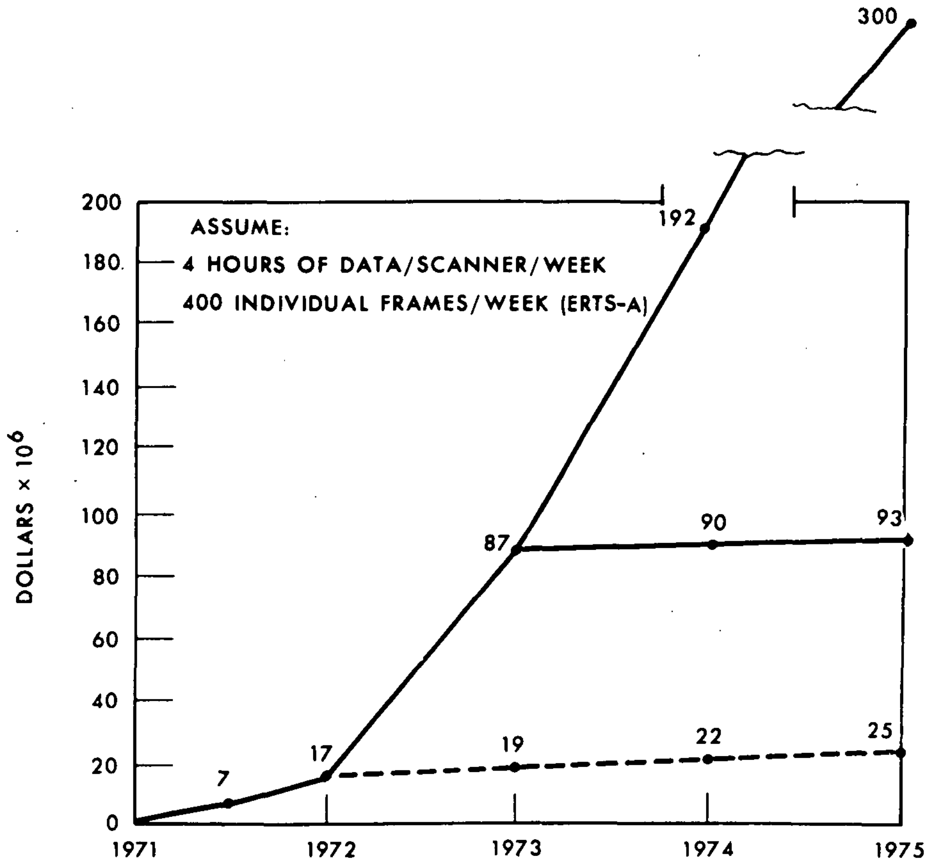


FIGURE 5. CUMULATIVE PROCESSING COST OF MULTISPECTRAL DATA

A particular point of view must be preserved, i.e., that of the problem-oriented user. The fact that the user of such data is not directly concerned with the techniques or physical parameters of sensing and processing but is, rather, interested in mapping, identifying and studying specific objects on the surface of the earth and the interrelationships of these objects, must be foremost in the conception and implementation of survey systems. The user would like to know, for example, how many bushels of wheat will come out of a county, how many ducks will be successfully raised in the prairies, how much water is needed to preserve the Everglades and where are the sources of pollution for Chesapeake Bay.

Data processing, it should be noted here, refers to the procedures, algorithms, and computations which are applied to the raw sensor output to provide useful data to the user. Data processing includes the combination of (1) data formatting, handling, editing, digitizing, or film printing with (2) data reduction and analysis consisting of image enhancement, spectral analysis, signature correlations, and recognition computations. Care in understanding the scope of data processing is required because the term can mean only (1) above, thereby leaving out data reduction, analysis and recognition (or classification) which are critical to the user.

This point of view must be preserved from the very beginning of survey, whether experimental or operational. The needs of the user must be reflected in planning the data collection, choice of scan platform, gathering "ground truth", processing the data and interpreting the results. This viewpoint, in fact, implicitly defines the "system" needed to serve the user since all these operations should be provided at one place by as many problem-oriented teams as are needed for the variety of applications.

From a more detailed point of view, this structure has many equipment implications as well. There may be several sensors, aircraft and spacecraft, involved in data collection for a specific survey. Processing functions are, however, much the same for many surveys and involve analysis, recognition, mapping and obtaining statistics of the objects of interest in the survey area. Equipment commonality is possible for processing data from the various sensors with some variations in the "front-end" equipment to obtain data in compatible form. As a result, the same people and the same equipment can be brought to bear on a great variety of kinds of surveys.

Within the concept of a survey center, then, an efficient operational center for providing fully processed data from several sources for many applications, can be defined. The role of the user/experimenter is to define the survey requirement and understand the relevance of the applicable sensing and processing techniques, with assistance as needed from interpreters/analysts at the center. The data collection personnel of the center can then, understanding the problem and the capabilities of the system, define the survey parameters related to data collection and ground truth. Finally, those people with the needed expertise in processing, recognition and interpretation of the data can, in collaboration with the user, provide the needed information in its most useful form, whether it be any or all of physical measurements, recognition maps or statistics.

These interacting roles, finally, define the man/machine interfaces, kinds of equipments, needed throughput rates, turn around times, kinds of people needed - - in short, the system which is the operational survey center.

2.3. PROCESSING REQUIREMENTS

Processing requirements which affect the system configuration are: 1) spatial resolution, 2) location accuracy, 3) data rate and quantity, 4) processing delay, 5) processing accuracy and 6) combination of various data sources.

The requirements for spatial resolution have been surveyed (1, 2, 3) and are distributed as shown in Figure 6. These high resolutions affect the quantity of data and the resolution of the output system.

Location accuracy desired (1) is given in Figure 7 and indicates that a general objective is that the system locate an object to within four resolution elements. This implies a need for very accurate information about sensor location, a consequent requirement to correct data in processing.

Data rate and quantity are very large and imply the need for processing data at rates of 5×10^9 elements per day. These rates make it necessary to develop new methods of data processing.

Processing times on the order of a few hours to a day are desirable to provide many investigators and operational offices the ability to react quickly to situations requiring immediate remedial action.

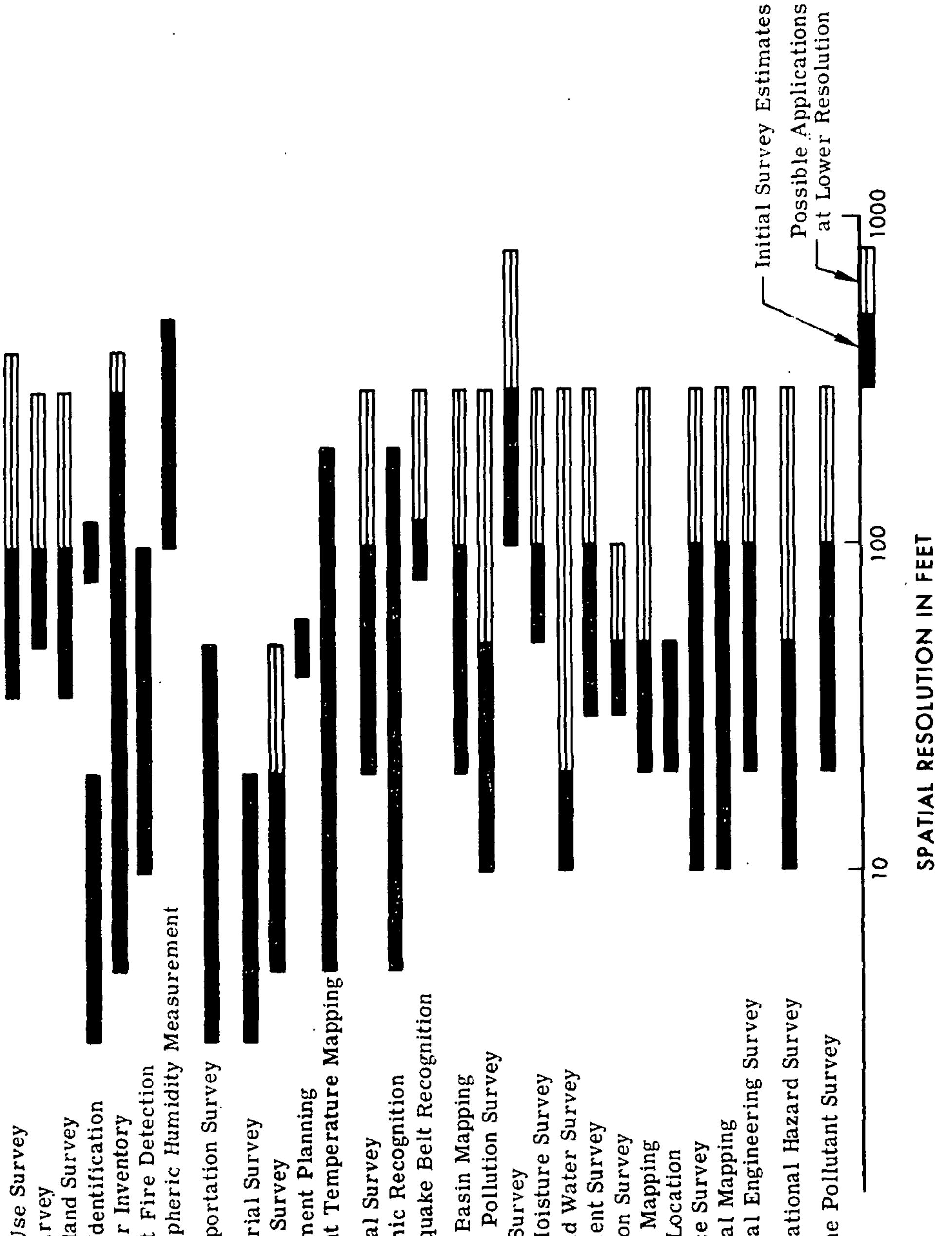


FIGURE 6. GRAPH OF RESOLUTION REQUIREMENTS

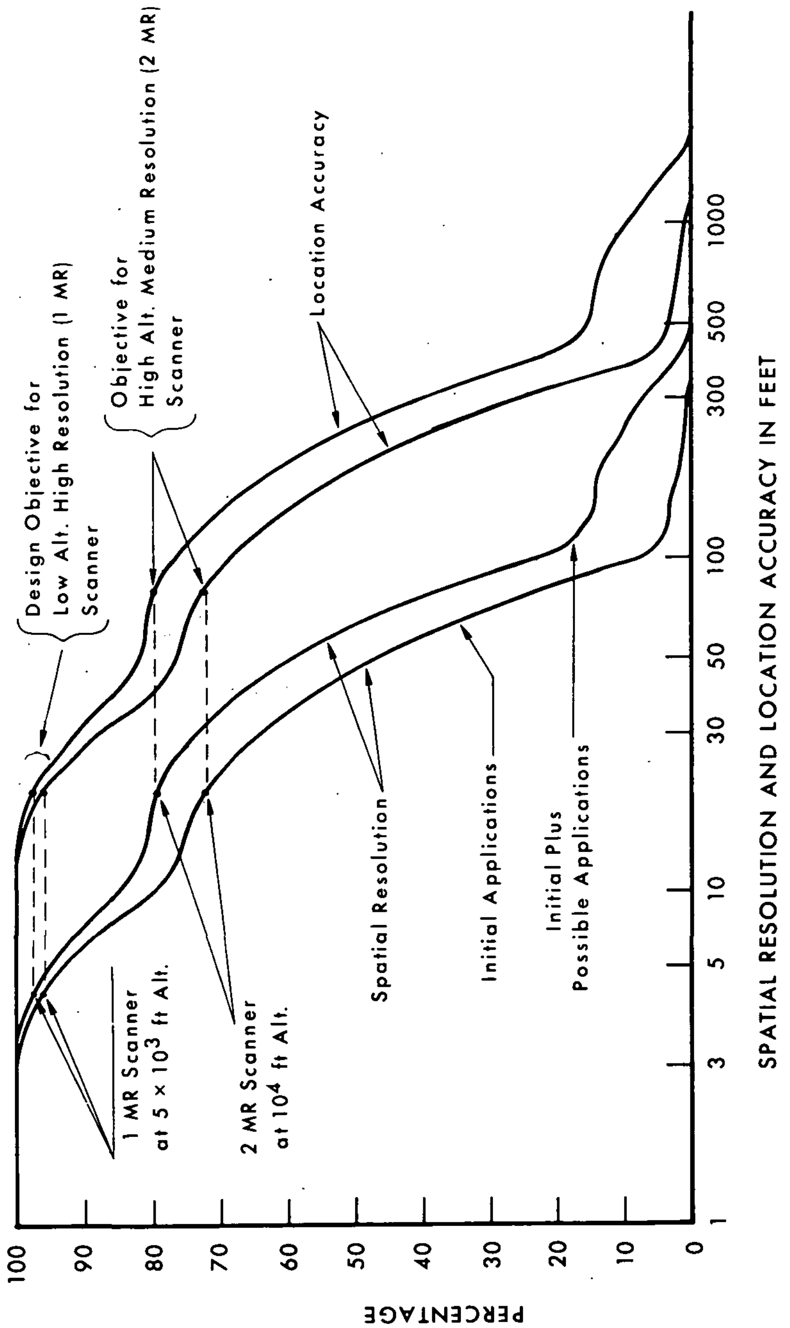


FIGURE 7. DISTRIBUTIONS OF REQUIRED SPATIAL RESOLUTION AND LOCATION ACCURACY FOR IDENTIFIABLE APPLICATIONS OF MULTISPECTRAL SURVEYS OF EARTH RESOURCES

Operational accuracy, or the ability to identify objects on the surface of the earth correctly, implies that techniques based on decision-theory have considerable statistical power to avoid degradation of the processed results. This has been determined after many experiments described in the references (see chronological references, pp 40-41). Some equipment implications of this requirement are also elaborated.*

The available data sources for multispectral surveys consist of various sensors in and above the atmosphere and will be used together for various applications. This implies that any processing system should provide both the equipment to accept all forms of relevant data and the people who can interpret and process these data. However, the determination of how such data may be used in conjunction is the subject of considerable future study, and can be investigated with such a system. Thus the result of this research can lead directly to a determination of the optimum form of the operational system.

2.4. EFFECTS OF REQUIREMENTS ON IMPLEMENTATION TECHNIQUE

Rates such as described above have serious implications on the techniques which can be employed for such processing. In particular, it appears that for this purpose conventional digital machines are poor choices. For example, suppose that 5×10^9 samples are processed per day to obtain a classification map. Then using a decision rule such as the maximum likelihood rule, about 10^3 multiplications per decision would be required, or 5×10^{12} multiplications per day. Using 1×10^5 sec per day, 5×10^7 multiplications per second are required.

This implies a cycle time of about 2×10^{-9} seconds for a general purpose machine and is beyond the state of the art for such machines for the foreseeable future. A special purpose machine is necessary or, conceivably, 10^3 general purpose machines could be used. The above analysis, of course, neglects input-output configurations and their limitations which will actually worsen the performance considerably. Even storage of such quantities of digital data in loosely packed form may be prohibitive.

Based upon the above considerations, a special-purpose high-speed analog computer was built and operated at The University of Michigan, Willow Run Laboratories. Its purpose is twofold: (a) statistical spectral analysis; and (b) target recognition by a likelihood-ratio discrimination method; hence the designation SPARC (SPectral Analysis and Recognition Computer). It can be programmed in accordance with any of several optimal decision criteria derived from statistical decision theories. These decision criteria take into account the statistical variability of the spectral properties of electromagnetic radiance from specific terrain features programmed into the computer. An analog machine, organized as is the SPARC, would operate on the 24-channel data as one composite sample, and for our example of 5×10^9 samples/day, it must accept about 5×10^4 composite samples/second. The present processor can classify about 10^5 composite samples/second.

It is thus clear that one analog system such as SPARC could handle the complete processing load by itself, operating only half the time and has a 10^3 to 10^4 speed advantage over conventionally organized digital computers, but has a cost comparable to a small computer.

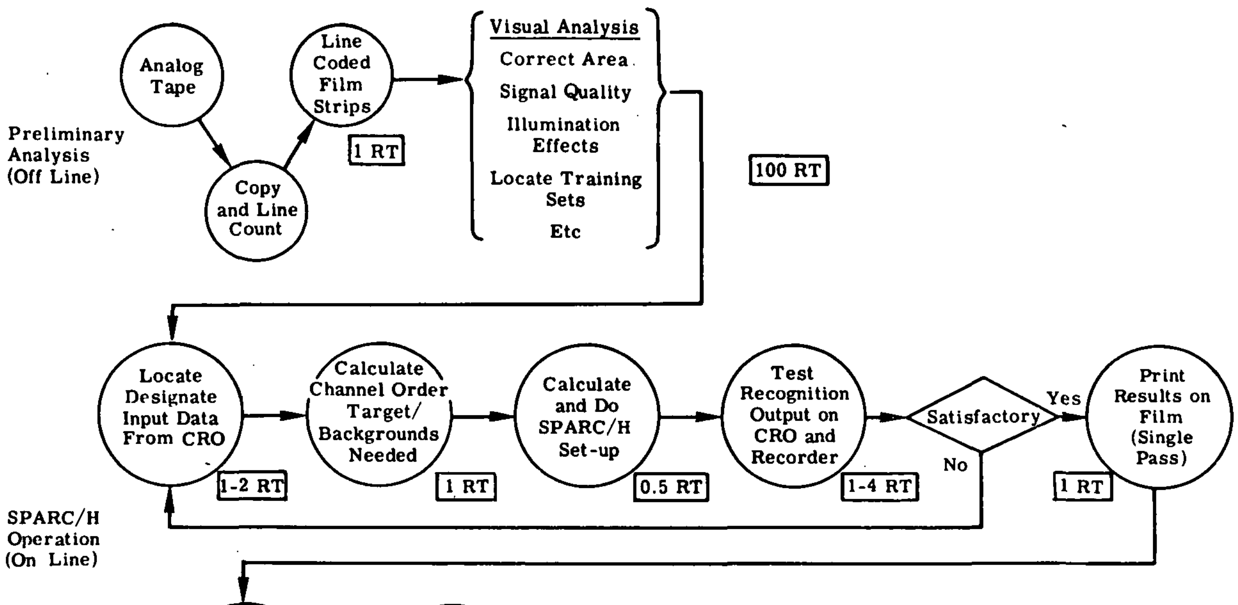
The specific need at this point is to obtain such throughput rates in practice. Present average throughput rates for SPARC are far below those discussed above because of the difficulty in setting up such a machine manually and because it is almost impossible to make an optimal setup without a digital machine as a part of the system. It is precisely here that development obtains the greatest benefit, an economical system able to keep up with the quantities of data involved.

3. CONFIGURATION OF THE PROTOTYPE SYSTEM (SPARC/H)

Facilitating the control of processing by an operator and obtaining high throughput, to a great extent specify the configuration of the system as a hybrid-digital for control and analog for video processing. However, before reaching this conclusion, it is necessary to consider the functions and techniques involved in some detail. It is also helpful to visualize the processing system as it may appear in the future, for example, in the form of an agricultural processing station operating in conjunction with a regional Agricultural Stabilization and Conservation Service (ASCS) Office. A flow diagram of such a station may be as shown in Figure 8.

As a part of such a station, one needs the ability to organize and use data from many sources besides scanners. These data can come from several instruments, micrometeorological sensors, local meteorological data, local surveys, measurements of local crop types and conditions, climatological history, atmospheric conditions, soil studies, and other miscellaneous sources. The operator must assimilate and organize these data for several purposes; to report these data insofar as they may affect crop yields and availabilities; to derive parameters needed for automatic crop recognition

*See Addendum, p.38.



Estimated Rates:	SPARC/H	Total
For 12 Channel, 6 Distribution:	4 RT (1 hr)	125 RT (32 hrs)
For 6 Channel, 12 Distribution:	4 RT (1 hr)	125 RT (32 hrs)

(Rates are in terms of Real Time-RT; Times given are per 15 minute Tape Reel)

FIGURE 8. SPARC/H PROCESSING FLOW AND TIMING CHART

and acreage computation; and to prepare analyses on merged data and recognition results. Computing capacity is required for these purposes, and it seems clear that a general purpose digital computer system is desirable to meet these requirements.

Control of the recognition process is a logical extension of the requirements for a digital machine since most of the parameters of the process are available in the machine as a result of the computations described above. The extent of this control is more difficult to define, however. Certainly, it extends to selecting the functions to be used in recognition, calculating the distributions needed for the process and specifying the spectral bands required to obtain some desired accuracy in the mapping or recognition operation. To some extent, the machine may also be required to monitor and obtain data from the mapping process.

The recognition or crop mapping process itself must, however, be considered as a different kind of problem. The above data comes from many sources, is rather poorly organized and is not a large amount of data. Scanner data is highly organized and is an extremely large amount of data. In order to achieve efficient and timely ASCS station operation, the required processing for the former is assimilation and organization; for the latter, the need is for very high throughput.

3.1. GENERAL SYSTEM CONFIGURATION

A configuration which can meet this need is shown in the form of a block diagram in Figure 9. The system is given the acronym SPARC/H, for SPectral Analysis and Recognition Computer/Hybrid. Analog data or digital data from the scanner is entered into the system from tape and is sampled at appropriate training sets by the digital machine. The hybrid machine determines the proper spectral bands and their number, defines an optimal decision rule involving the object-background signatures in the scene, and then commands a setup of the analog machine via an addressable interface system. The complete data is then processed by the analog system and results are tabulated in the digital machine and printed with a strip camera to obtain a map of the objects recognized.

The implementation of this system envisions it clearly as a prototype, able to obtain high throughput in the manner first described, but possessing flexibility and modularity. Investigations of improved decision modes and more complex processing may be tested against actual data in an environment similar to that which may be expected in stations devoted to earth resources applications. Both the analog and digital equipment mechanizations are configured with such flexibility and growth in mind.

3.2. DETAILED IMPLEMENTATION OF SPARC/H

The SPARC/H is a hybrid (digital-analog) and adaptive implementation of a recognition system for multispectral data now found in various separate systems used at Michigan for processing such data. At present, the functions of analyzing the target-background structure of a scene are performed on a Control Data Corporation CDC-1604 using programs developed over the past four years. The actual recognition of objects is normally accomplished on the SPARC system separately and without full access to the analyses performed on the digital machine. The first function implemented in the SPARC/H is the unification of these operations so that scene analysis and test of decision algorithms can be performed quickly and optimally.

Secondly, since data is available to both digital and analog systems simultaneously as recognitions are being made, it is possible not only to do sequential operations of analysis and recognition, but to perform these operations simultaneously, i.e., modify the decision algorithms in use by monitoring the results of the decision process and the data being supplied to the process. It becomes possible then to adapt or modify the signatures or the recognition algorithms during the data run to any rule definable on the digital machine and of such complexity that computation lags do not become intolerable. Such adaptations can be of several kinds; adaptation on signature parameters such as mean, variance, covariance; multiplicative modifications for corrections of gain and directional reflectance; changes in prior target probabilities; calibration updating, etc.

These functions are possible insofar as their mechanizations are feasible and are designed into the structure of the system. This implies that the SPARC/H analog system be addressable to the point at which it becomes a network of interconnectable computing elements enmeshed in an addressable interconnect system. It furthermore implies that the system be highly modularized to allow changes in the processing modules to modify their performance, number, configuration and accessibility to digital monitoring. At the same time, complexity must be controlled to assure successful and reliable operation.

The SPARC/H, then, can be described in detail and the areas in which design and development are necessary can be identified.

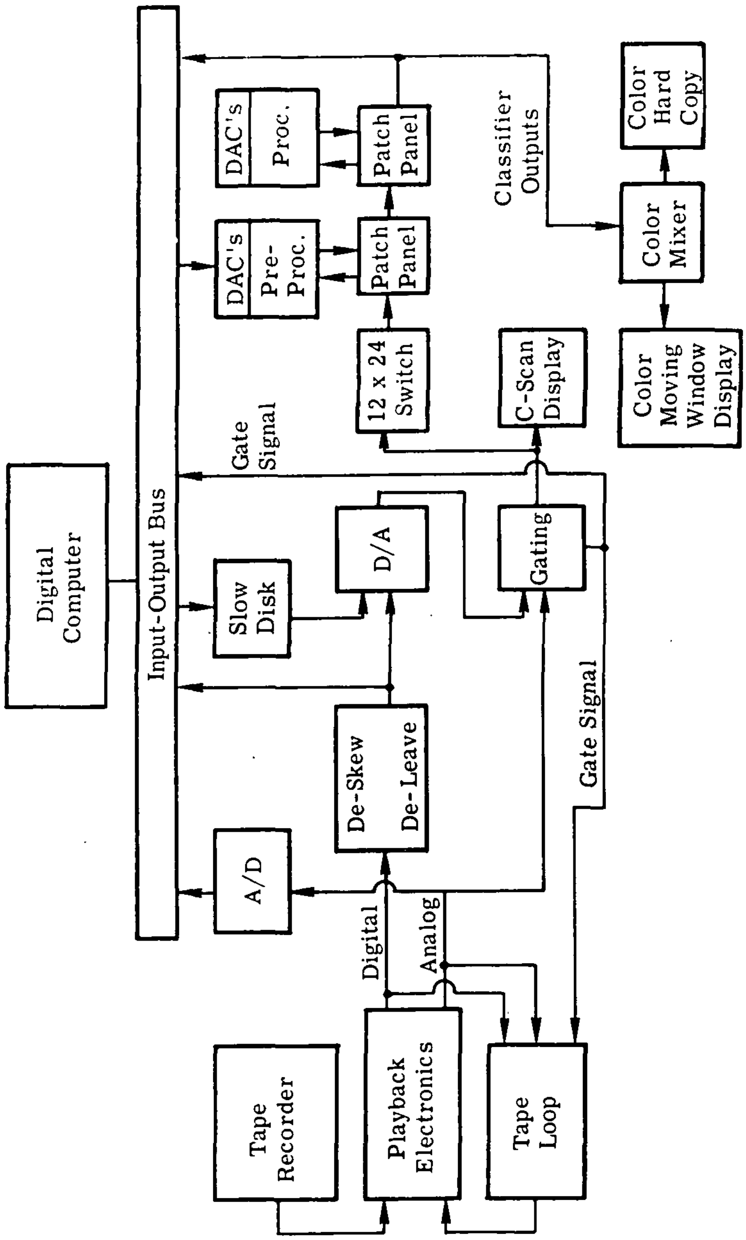


FIGURE 9. BLOCK DIAGRAM OF COMPLETE HYBRID PROCESSING SYSTEM

3.2.1. INPUT SUB-SYSTEM. The input sub-system comprises tape recorders configured for two operations; repetitive and continuous presentation of data from 12 to 24 analog or digital spectral channels in good registry. Digital data is deskewed and formatted with a tape-computer interface system presently designed and under construction.

Repetitive data is used in the gating system under operator control to obtain a display within which the operator can specify various fields for analysis by the digital system. The data is played through the same electronics which will then be used for recognition.

Continuous data is then supplied to the system after a setup has been made to allow the recognition operation to be performed as the tape is played, i.e., in real time.

3.2.2. DISPLAY AND CONTROL. This sub-system is the principal interface between the operator and the system. It presents data from any part of the system in pictorial form for the operator's use. It allows him to call analytic routines for signature analysis and to set up the recognition system for a specific problem.

3.2.3. INTERFACE AND GATING. This portion of the system is an automated switching and routing network. It accepts signals from tape and routes them in proper form with necessary identifications to either the digital computer or to the analog recognition system. It also routes command signals between the digital and analog sub-system. Decoding and generation of tape line numbers and identification data are also accomplished in this sub-system. Finally, necessary delays to adjust the system lags are incorporated here.

3.2.4. DIGITAL COMPUTER SUB-SYSTEM. This sub-system consists of a general purpose, small, fast, digital computer and a fast, multiplexed A-D converter. The output of the computer is supplied to the recognition system via a multiplexed address system to control and specify the recognition configuration.

The function of the machine is to analyze the input data from training sets and libraries and then configure the system for recognition. In the course of this process, the recognition system can be used for this computation to minimize error buildup. Once the system is configured, the analog multiplexer is used to monitor the recognition operation in the analog recognition processor.

An additional function of this sub-system is diagnostic monitoring of the analog system. Variability in this circuitry can be detected and compensated or flagged to the operator for attention if excessive.

The computer configuration includes 32×10^3 words of core memory and would also have tape and disc storage available. The class of machine considered could be termed "midi" in that expandability is possible to allow a greater portion of the adaptive processing load to be assumed as development of these techniques progresses.

3.2.5. PRE-PROCESSOR. The function of this sub-system is to transform data prior to processing to compensate for known effects on the data. Compensation may be made for illumination change, and scanner look angle effects, for example.

The pre-processor includes two or three banks of multipliers and adders to allow multiplicative and additive operations to be performed. It also includes function generators whose functions and parameters may be programmed.

The components of this sub-system are, to a great extent, the same as used in the present Michigan pre-processor except for addressable control.

3.2.6. RECOGNITION PROCESSOR. The processor is used in two ways in this system. During the analysis of the utility of spectral bands and the set of targets and background to be used in classification, the processor is used in conjunction with the slow disc to perform this analysis at a rate almost three orders of magnitude faster than with the digital machine alone. This provides a substantial improvement over previously used methods and makes the SPARC/H very attractive as a high-throughput prototype.

After this analysis and subsequent setup by the digital machine, the original data from the complete area overflown is supplied to the processor and classified at rates of about 10^5 decisions/second. The processor is organized in a manner similar to the present SPARC and can classify targets using several arrangements of the basic circuitry. It may be configured to classify three targets with up to 24 spectral bands, 6 targets with 12 spectral bands and 12 targets with 6 spectral bands. Analyses and tests performed so far indicate that the latter configuration will be the most useful.

(1) FACILITATE RESEARCH AND DEVELOPMENT

(2) MEETS THE NEEDS OF PROTOTYPE DATA PROCESSING DEMANDS

(3) ALLOWS PROJECTION OF OPERATIONAL COSTS

(4) DEFINES OPERATIONAL REQUIREMENTS FOR PERSONNEL AND EQUIPMENT

(5) REDUCES PRESENT COSTS

FIGURE 10. BENEFITS OF PROTOTYPE PROCESSOR

The processor then accepts compensated data from the pre-processor and, using one of several available likelihood decision rules, classifies the data into various targets and produces output decisions as video which can be viewed, accumulated or printed to obtain quantitative or pictorial output information.

The sub-system allows the use of various numbers of signatures with various spectral bands. The signature parameters and decision parameters are under program control and the outputs of various functional blocks are available to the digital system via the A-D sub-system for monitoring during setup or processing.

The components of this sub-system are based on those used in the present SPARC system used at Michigan and are such that decision rates on the order of 10^5 decisions/second can be obtained. The system is capable of multiple decisions (classification) and means for recording these should be provided.

3.3. RECOGNITION OUTPUT

This sub-system accepts the video decision output of the recognition processor and records it on film in black and white or color and provides data on the number of resolution elements recognized for the various classes recognized. The digital machine summarizes this data.

Color output should be provided for this sub-system, however some development appears necessary for this objective, particularly for data obtained with the NASA/Bendix system.

The printer system, however, is not determined only by the need to supply color output to avoid rerunning data up to 12 times; it is also strongly affected by the need to perform geometric corrections to the data as printed, thereby using location parameters of the scanner and correcting for changes due to motions of the aircraft as it gathers data.

In order for such a printer to meet the needs of processing and outputting data from scanners such as the Bendix/NASA 24 channel, 2 milliradian scanner, the ERTS scanner, the SKYLAB scanner and the present U of M scanner, certain requirements must be met. The principal requirements of the processed output is that it have sufficient resolution and spatial accuracy to allow maps to be made of large areas. The interests of users vary considerably for both these requirements ranging up to resolutions of 1 in 5000 (i.e., 5000 resolution elements per swath) and up to an average of about 4 resolution elements uncertainty in location (4 in 5000). Printing rates of about 10^5 elements per second are needed as well. Resolution and printing rates are not severe problems but registration (or spatial accuracy) is difficult.

The difficulty in obtaining good registration of output data arises from several sources in the data collection system among which are the distortion of the scanner itself, the axes of motion of the scanner platform and the uncertainty of location and altitude of the scanner. Any of these errors, if uncorrected, can cause unacceptable spatial error in a map. What is needed is a means of efficiently reducing or correcting such errors in the overall system. This will require modifications to reduce the errors in data collection or to measure these errors with sufficient accuracy and correct them during processing, or both.

To provide the greatest latitude for the scanner platform which is often subjected to uncontrollable problems in the field, it seems that the greatest portion of correction should be accomplished in the ground processing and printing operation. Assuming this ground rule, then, the errors which must be corrected may be estimated. For an aircraft, which encounters larger disturbing forces than a spacecraft and therefore generates the governing requirements, errors occur because of roll, pitch, yaw, velocity variations, altitude variations, course errors, scanner speed errors and scanner pattern nonlinearities.

A display such as a color strip-film printer, which can correct these errors must have considerable flexibility and, without elaborating other possible solutions, seems to be best met by a system including a cathode ray tube and variable speed printer. The cathode ray tube must be capable of writing a line with 0.1% accuracy (4 parts in 5000) anywhere within the area defined by the error values.

This area is bounded by the sum of errors due to pitch, yaw, and velocity in the flight direction and by the sum of course error, scanner distortion and scanner speed error and yaw in the direction normal to flight path. Several cross term errors are neglected in this allocation and it is assumed that only short term velocity errors are corrected in the CRT. Long term errors can be corrected with variable speed film drive. The most severe errors are pitch and yaw for flight line errors and course error for errors normal to flight line. These errors (for a scanner at 5000 ft., a path of 10 miles and a scan angle of 90°) are $\pm 35^{\circ}$ parallel to the flight line and about $\pm 35^{\circ}$ normal to flight line, respectively. The error area within which printing must take place is then defined, angularly, as a rectangle containing a 90° scan line increased along the scan line to 160° and having a side normal to this (along flight line) of 70°. Resolution required is almost doubled and the deflection accuracy required is severe.

If this printer were to print on 70mm color film, only about 35mm could be used across the film for the image and the image would have to be varied up and down along the length of the film by about $\pm$15mm.

The most promising technique for such printing seems to be a combination of CRT and rotating filter wheel with recognition color components presented during three sweeps of the CRT beam as each of 3 filters pass the face of the CRT. For the NASA/Bendix data, this requires a compression of the data after recognition and can be adequately done with a small core memory or with the digital machine either on-line or off-line.

4. TYPICAL OPERATING SEQUENCE

To summarize the description of the SPARC/H and its use, it is helpful to describe the steps which an operator or investigator would take to obtain a recognition map for a particular scene. This sequence is given in the following table:

Sequence of Operation	Time (min.)
Data Input	
Marked film supplied by analyst and line-angle numbers input to system	5
Tape (analog/digital) played into system and copied continuously on loop	20
When loop contains training area, tape stopped and data displayed and entered via A-D to digital computer for each target area and known backgrounds	
Multivariate distribution calculated in digital machine, all setup matrices calculated	5
Analysis	
Training sets packed onto slow disc for input to processor (sector/distribution)	-
Training sets played thru processor distributions sequenced channel by channel to determine channel order from probability of misclassification (Monte Carlo)	10
Target/background set calculated and input to processor	-
Recognition	
Tape data played thru processor, displayed on CRT (color), printed (up to 12 at a time) on 70mm color film or polaroid (for iteration analysis)	15
Printing and analysis (off-line)	-
Film developed, printed and map constructed	-
Results analyzed, iteration decided	-
	55

The investigator begins with a set of images on which he has identified the location coordinates (scan-line numbers and scanner angles) of the known objects which he would like to use as training sets, either as objects to be recognized or to be discriminated against.

Starting with an original or a copy tape of the data he proceeds to examine the area as the tape is played, viewing a display derived from some useful spectral band or bands. When the specified areas are reached on the tape, the data is automatically entered into the digital machine for derivation of signatures. At this point an analysis of effects which might interfere with processing may be done and appropriate functions for correction can be determined and entered into the pre-processor.

Once correction functions have been determined and have entered the pre-processor, data from the training set areas is written onto a disc in dense form. This data is then supplied, via the pre-processor, to the processor which then examines each channel and training set sequentially to determine the average frequencies of misclassification and thereby determine the spectral bands and distributions to employ in the classification process. When the calculation is complete, the operator places a patch-panel suited to the configuration into the processor and proceeds with classification.

The process in which the data is classified and mapped on film takes place by simply playing the data tape at normal speed into the processor and recording the classified outputs as specified colors using a color film strip camera. At the same time the operator may view the results of the process on a moving window display in color to allow on line evaluation of the performance of the multi-valued classification process. If results do not appear to be satisfactory the operator may immediately take steps to alter these decision results. He does this by changing any of a large number of parameters. Usually this would be done systematically by making additional analysis of areas (features) for which difficulties have been encountered. This data is on video tape and may be reviewed before development of the color film to allow still another iteration of the process, if desirable.

The exposed color film containing the recognition map is then developed and may be made into mosaics to obtain recognition maps of large areas. The operation of making these mosaics depends, however, on gathering accurate information about the attitude and location of the scanner and, subsequently, correcting the map with this information.

Thus, the system accomplishes a unification of processing steps in a form to allow facility of operation and high throughput, making it possible both to keep pace with the large quantities of data becoming available and to experiment with and define the forms of processing needed for operational use.

5. CONCLUSION

Multispectral sensing has progressed to the point where emphasis is beginning to be placed on operational applications rather than research studies. Under these circumstances, research processing techniques, previously useful, have now become uneconomical and seriously retard progress.

A serious imbalance exists and continues to develop between the ability to collect data and process it properly. To correct this, new techniques, designed with an operational viewpoint, are needed at the present time.

A system, such as SPARC/H, operated in a prototype environment offers many benefits important to the continued development of multispectral techniques. It will facilitate research and development. It will begin to match the capacity of data collection facilities. By using the system, realistic operational configurations may be defined in terms of equipment and personnel. And, finally, significant economic gains may be had in the course of future development.

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ADDENDUM

Implications of Operational Accuracy on System Configuration

The implications of requirements for operational accuracy are somewhat subtle and may be elicited by considering some simplified systems which embody approaches to large area survey processing. The many possible approaches are best typified by two - the a posteriori approach and the a priori approach.

(1) The a posteriori approach takes samples of data representing known objects and backgrounds and extrapolates this representative information over a large area. In this manner one obtains a spectral relationship between known imagery and the imagery to be analyzed. It may be argued that such an approach ignores the detailed "cause and effect" relationship between ground truth and imagery. (A little reflection will show that this is not necessarily true). As a result there is an inclination to work toward a system which incorporates signatures of a more absolute form.

(2) The a priori approach emphasizes use of an "absolute" signature rather than comparison of known samples from a local scene with large area data. The objective of this approach is to recognize and map targets based on specific pre-determined signatures which are fed into the system.

To use the a priori system we must obtain scanner radiance data from the scene with a given accuracy, record it, obtain information from a local source about the illumination at the target, the crops generally present, the atmospheric conditions prevailing, measure the reflectance standards at the scene to relate these data to the reflectance data bank. Then the radiance of the targets and backgrounds must be computed and used in a recognition system to map or analyze the scene. In this system several absolute measurements are needed to arrive at a decision. Scene illuminance, scanner radiance and reflectance standards, atmospheric conditions, ground conditions (cover, soil condition, crop/target and background relative frequencies) and aircraft geometry must all be measured absolutely. There probably will be difficulty in tracing standardization to primary sources in such a variety of measurements. In general, it appears safe to say that measurement of these parameters to absolute accuracies summing statistically to less than 2% (about 1% each) is not feasible and may not be feasible for years to come. If we accept present accuracies of standardization and measurement, we will probably find our final data accuracy ranging between 15% to 25% under good conditions. This simply will not allow results even comparable with those already obtained with the a posteriori system.

The a posteriori system, which is used at Michigan and also at Purdue, does a satisfactory classification operation with presently available scanner data. In doing this the system accepts targets and backgrounds from a small area, takes into account directional reflectance and, possibly, illumination variations, and usually works well for a data pass of some five to fifty miles. The information needed to operate the system is the identification of some "typical" samples (training sets) as seen under actual conditions of data collection, and the inclusion of statistical parameters from these samples in the machine. Effects of drift, gain, season, meteorological variations, atmospheric variations, spatial frequency, cover, soil effects, altitude, aircraft geometry, etc., are largely cancelled in this mode of operation.

What, then, is the role of accurate measurement, calibration and modeling of the scene and the system for the a posteriori approach. It may seem at first glance, that there is no role in such a system for these activities. This is not the case, however. The a posteriori approach does not actually exist in the pure form initially postulated. If it did, it would not be adequate to meet the requirements of recognizing objects in a real scene with real instruments. Calibration is necessary to correct the instrument. Accurate measurements are necessary to discover the functional relations among objects to be recognized in actual scenes. Models are necessary to describe and extend these relationships, and to predict functional associations of objects, to assess the importance of errors in the system and to posit improvements in operations.

It is evident that the organization of the processing system should facilitate the mechanization and use of a form of a posteriori processing. This is to say, the investigator using the system should be able to access some known "ground truth" areas in the large area quickly and accurately, to analyze the target-background distributions in a very short time and then to recognize and map the targets in which he is interested. The resulting map should be available immediately in a form suitable to allow him to decide whether he has satisfactory results or whether to iterate the processing sequence to improve the results.

It should also be apparent that such a system can also accomplish the _a priori_ approach, if it were found to be more practical. It should be appreciated also that a system built to mechanize the _a priori_ approach could not perform the processing required in the _a posteriori_ approach, principally because the requirement for rapid access to ground truth data sets and fast analysis of these sets is not necessary. Recognition requirements, however, are similar for each approach.

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Appendix B
A Derivation of Costs for Multispectral Processing

The results given in Appendix A for costs (see Figs. 3 and 4 therein) are not derived with sufficient detail to permit verification by the reader. This appendix presents the assumptions and experience employed to obtain the costs given.

The method used for computing the cost of research-type processing in which the analog SPARC is used is based on an average, or typical processing operation as defined from our experience in processing data for many users. For data gathered from an area 1 mile wide and 20 miles long by an aircraft flying at 5000 ft with a scanner having a 2-mrad (10 ft × 10 ft) resolution, the processing cost is about \$8400, excluding reports. To term this a "typical" operation many seem a little misleading when one considers the range of altitudes from low-flying aircraft through high-flying aircraft to spacecraft and the effect of altitude on resolution and area covered. However, from a research standpoint, the typical operation described above is quite representative.

In the above data-collection situation, the number of independent resolution cells viewed by the scanner in the 20-square mile area is about 5.5×10^6 cells. In order to give a more meaningful comparison of processing costs for data from various scanners, the number of data points (elements) a scanner collects must be considered. This is defined as the product of the number of resolution cells viewed times the number of spectral bands. Based on our experience with the 12-channel ERIM scanner, the number of elements for the typical job is 6.6×10^7; so for the given cost of \$8400, this results in a processing cost of 130×10^{-6} dollars/element. This number is the starting point for generating the two tables. It is also useful in computing processing costs for various scanners which have more or fewer spectral bands than the 12 assumed. The cost per square mile is easily computed from this dollar per element number (for the assumed typical case, it would also equal \$8400 divided by 20 sq mi). This processing operation takes one week (40 hours) or about 2-hr/sq mi, which explains how the research processing cost and time in Fig. 3 of Appendix A is obtained. These numbers were then projected to the more advanced stages of processing by scaling down costs in direct relation to the processing times involved. It was estimated that processing time could be reduced to 2 or 3 days (16 to 24 working hours) for the feasibility stage. As a case in point, the corn blight watch currently being carried out requires approximately 16 hr to process one data set on the SPARC.

The Hybrid SPARC prototype processing costs were projected by taking the research costs and times and scaling them down by a factor of 40. This number is obtained from the flow and timing chart, (Fig. 8 of Appendix A) where for one tape reel of data, which again is approximately 20 mi of flight data, the total processing time is 1 hr. Going from the prototype to the operational stage appears to be about the same as going from the research to the feasibility stage, yielding a reduction in processing time by about a factor of 2 in either case. So this, in brief, is how the cost figures were obtained; they do not include any ground truth operations or final report writing costs. The total cost for a "typical" operation including ground truth, some preanalysis, and final report runs about $12,000.

The cost of processing the data on a digital computer can best be found by considering the running times required. Because of the serial nature of a digital computer, the running times are strongly dependent on the number of data channels used. (This is not the case with the SPARC and SPARC/H which are organized in a parallel manner.) For purposes of comparison, it will be assumed that 12 data channels are used. Digitizing of the 12-channel data is accomplished at a slowdown of 32 to 1. The data-processing rate achieved with our CDC-1604 computer for likelihood ratio processing is given by the following formula:

$$\Delta t = 1.5 \times 10^{-4} \times (\text{N-chan})^2 \times \text{N-sig}$$

where Δt is the time required to process the data from one resolution cell, N-chan is the number of data channels, and N-sig is the number of signatures included in the recognition process. To process 12 channels for 4 signatures requires a processing time of 0.09 sec/resolution element, or 11 points/sec. The 2-mrad ERIM scanner collects data at an average rate of 10,000 points/sec for the typical job of flying at 5000 ft and making contiguous scans (here the instantaneous rate is actually about 180,000 points/sec). Thus, the processing slowdown is about 900 to 1. Adding in some other data handling operations that must be performed makes the total slowdown about 1000 to 1. For the typical job comprising 15 min of data, the computer time required would be 250 hr. At $100 per hr, the computer cost comes to $25,000 or about three times that of the analog research processor cost. But in practice only about 10% of the data are actually processed on the digital computer.* For this amount of data, the total cost for a typical job is comparable: about $10,000 versus the $12,000 for the research SPARC.

*Processing of only 10% of the data (by undersampling) is tolerable in a research stage of processing but would probably be unacceptable in the prototype or operational stages of processing.

Appendix C
ASCS Crop Survey System Requirements

As a result of study in the summer of 1971 to define an ASCS enforcement and crop surveys operation using remote sensing measurements, ERIM assisted NASA by defining a rough cut of system functions, specifications, and cost. Given some of the general requirements by USDA, it is possible to elaborate such a vehicle for the use of the committee.

<u>General Requirements</u>

Survey: 200×10^6 acres $\approx 300 \times 10^3$ mile^2

Rate: complete survey every 4 years

Reports: 3.6×10^6 determinations per year

Cost: less than present \$40 $\times 10^6$ (which includes administration)

Date: by 1 July each year (2 months data-collection time)

Accuracy of Crop Acreage Determination: 97% to 99-1/2%

Area Accuracy: 0.1 acre or 2% of areas less than 0.9 acre

Association with Tract: 99% accuracy

<u>System Requirements</u>

Resolution: 10 ft × 10 ft

Swath: 1.2 mile; 20% overlap (net 1 mile swath)

Speed: 100 mph

Aircraft Operation: 4 hrs/day; 20% efficiency (12 days/2 months)

Altitude: 5000 ft

Repeat Coverage: average of 2

Amortization: over 6 years

<u>Derived Requirements</u>

Flight Line Miles: $300 \times 10^3/4 = 75 \times 10^3$ mi

Repeated Coverage (2): $600 \times 10^3/4 = 150 \times 10^3$ mi

Aircraft Collection Rate: 12 days × 4 hrs/day = 48 hrs per A/C
100 mph × 48 hr = 4800 miles/season per A/C

Aircraft Required: 150/4.8 = 32

Processor Rate: $4 \times$ real time = 25 mph: $\frac{150 \times 10^3}{25}$

$= 6 \times 10^3$ hr processing time/processor (SPARC/H)

Processors Required: (2 mos = 1440 hr = $\frac{6 \times 10^3}{1440} \approx 4$ processors

Estimated Costs

Airborne

Aircraft: $\$0.500 \times 10^6$

Navigation System: $\$0.200 \times 10^6$

Scanner System: $\$0.400 \times 10^6$

General Electronics: $\$0.200 \times 10^6$

Total: $\$1.3 \times 10^6$/A/C $\times$ 32 airborne systems = $\$41.5 \times 10^6$

Ground

Processor: $\$1.0 \times 10^6 \times 4 = \$4 \times 10^6$

Total Capital $\$45.5 \times 10^6$

Support People (assuming full time)

Aircraft: 4 ea $\times 32 \times \$30 \times 10^3 = \$3.84 \times 10^6$/year

Ground: 10 ea $\times 4 \times \$30 \times 10^3 = \$1.2 \times 10^6$/year

Total: $\$5.04 \times 10^6$/year

Amortizing Capital Equipment over 6 Years: $\$7.6 \times 10^6$/year

Total: $\$12.64 \times 10^6$/year

Total cost is thus comparable to the present costs of operating the compliance program; so the system seems feasible from a cost-effective point of view. Further, these costs assume a two-month program duration although salaries are carried for 12 months—which implies system availability, at these cost levels, for other survey operations such as crop yield, damage assessment, or soil study.

In setting up this framework design the intent is not, of course, to freeze the system but rather to establish a reasonable estimate of the magnitude of the system in terms of equipment and cost, and at the same time to set forth and interrelate the significant parameters involved in system optimization. Although there are other parameters not considered herein—such as crop maturity variations with latitude—they appear to be second order parameters and may well prove cost-reducing.

Comments on Requirements and Costs

NOTE: These comments apply to corresponding sections of the above analysis.

General Requirements

These are all system requirements identified by the committee.

System Requirements

These constraints are those presently encountered in operating the Michigan system and obtaining results that are presently feasible. Aircraft operation of 4 hr/day provides coverage during usable illumination periods and time for preparation, transit, and data collection. Efficiency of aircraft operations involves the probability of satisfactory meteorological conditions over the duration of the Michigan flight program experience, i.e., one day in five is satisfactory for agricultural data collection. Repeated coverage is likely for many reasons: (1) to improve crop detection for specific crops; (2) to allow for unsatisfactory data collection; or (3) to improve crop classification accuracy by a second sampling. Amortization time is six years based on an estimate of aircraft and computer wearout and obsolescence rates.

Derived Requirements

These requirements are simply derived from the above, with the exception of the processor rate which is based on the hybrid (SPARC/H) design available now as a result of previous studies at Willow Run Laboratories.

Estimated Costs

These costs are based on presently available commercial aircraft costs, costs of commercial navigation systems, general-purpose scanner with 12-channel capability using 6 channels, and typical miscellaneous costs. Ground processor costs are based on a medium-scale SPARC/H system with additional general-purpose peripherals.

General Comments

A serious question must be considered with regard to the performance requirements desired for accuracy of crop identification, acreage assessment, and assignment of a crop acreage to a particular tract. Present crop identification accuracies average about 80 to 85% at best. Acreage assessments have geometric inaccuracies which can be corrected but cannot be related unambiguously to legal compliance requirements. And finally, geometric accuracy (i.e., knowing which tract should be associated with which element classified) may require extreme navigational accuracy or a very large number of "fixes" throughout a crop area, or both.

Present capabilities indicate that expected accuracies may be allocated as:

(1) classification accuracy — 85%

(2) multispectral class to legal class — 10% low ±5%

(3) geometric uncertainty — CEP of 0.5 mi/hr (relative) and (if corrected once per mile) gives CEP of 25 ft. For an average field size of 40 acres this becomes about 0.04%.

The RSS* of these capabilities is then basically limited by classification accuracy to about 85%. If a 15% to 20% error is allowable, whereas compliance is rejected at an acre-overage of 20%, then the system can be considered immediately feasible. The implications of this accuracy on compliance detection and enforcement must be assessed, however. It appears, then, that the stress of reducing component system errors should be placed first on classification, secondly on the relationship of classified acreage to legal acreage, and, lastly, on geometric uncertainty.

Conclusions

The above described requirements and system can be considered as both a rough system framework and a first-pass list of parameters affecting the system. We hope it will prove useful in continuing, refining, and detailing the system design.

Since the operational system discussed above appears to be feasible under the constraints described, then the prototype system — which we envisage as one aircraft and one processor — is also determined to be feasible under these same constraints.

*RSS = Root Sum Square.

Appendix D

Hybrid Multispectral Processor System - Status and Requirements as of 19 January 1972

Introduction and Summary

The present and anticipated demand for fully processed multispectral data exceeds the capabilities of available facilities by several orders of magnitude, thereby creating a need for processors adequate to this demand. This need is best met by a hybrid system in which preprocessing, classification and geometric correction can be done at real-time rates.

To proceed with development and use of such a system appears desirable at this time since its timeliness for use in present and anticipated programs at various divisions and centers is good and delay will be harmful. This is true for the efficient processing of data from the MSC airborne system, data from SKYLAB, data from the Michigan aircraft, the ERTS program and other survey programs.

A critical point has been reached in the projected performance of Michigan on the AAFE contract to design and build a hybrid under supervision of NASA/Langley. It is desirable that $450K but critical that at least $150K of additional funding be available by April, 1972 to initiate a system which can grow to a size adequate to meet the needs of the above-mentioned requirements for processed data. Agreement has been reached by NASA/Langley, /MSC and Michigan that such a system should be developed and used but funds have not yet been identified at /MSC for this purpose. This joint program is described in accompanying Appendix E: "A Plan For Development and Application of a Hybrid Spectral Analysis and Recognition Computer (SPARC/H)."

The purpose of this memo is to place the characteristics, timing, and need for this joint program in the context of the requirements of the Earth Resources Program of NASA and other agencies and to clarify the timeliness and utility of a program to provide a suitable processing system.

Status of Langley/MSC Collaboration

A proposal was made to the AAFE program in March 1971 to design and construct a hybrid processor for multispectral data. In October 1971 Michigan was informed that a contract for this purpose in the amount of $165K would be offered in early 1972. This was being informally negotiated when it became apparent that a more powerful, expandable system could be obtained by employing different equipment for this purpose. This possibility was discussed with Charles Husson and William Howle of NASA/Langley, John Overton and Ken Baker of NASA/MSC and, at various times, with members of the MSC staff including E. A. Davis, Milo Keathley, and John Frere of FOD, and M. R. Holter, and Robert MacDonald of EOD. There seems to be general agreement that the expandable system is desirable and should be developed.

A need for additional funds exists, however, to make it possible to provide an economically expandable system rather than the limited system originally proposed. This additional funding ranges from $150K for a minimal form of an expandable system capable of some stand-alone use in one year, to about $450K in the first year for a more powerful but needed system suitable as a pre-prototype and as a research tool. The AAFE program timing is such that purchase decisions must be made by March 1972 to take one of two courses, the limited system or the expandable system. For this reason, there is urgent need to have additional funds by that date.

Relevance to MSC Programs

The hybrid processor is relevant to MSC interests in two areas: as a prototype for operational large area survey systems, and as a tool for development of new processing techniques and the establishment of the feasibility of new applications for users of multispectral data. These areas have been defined in memos and papers over the last two years by various members of this Willow Run Laboratory. This relevance is briefly summarized here.

Survey Programs

The general need for fast processing has been elaborated on from two points of view and the two analyses agree rather well. In the first place, an analysis of the demand for multispectral data was done two years ago and indicated a need for processing rates of 6×10^4 samples/sec on the average. An analysis of available or planned data sources indicates that data would reach these rates in 1972. These rates are impossible to process economically with conventional equipment and a processor of the kind represented by the proposed hybrid is an economic and adequate solution.

This analysis was borne out in a striking manner during the MSC investigation of the ASCS program, wherein a cost savings of better than 10 to 1 was obtained by the substitution of the hybrid system for conventional machines. It was not at all clear, moreover, that the large, conventional system was even feasible. A preliminary estimate in the basis of information supplied by staff members of the Illiac-IV program indicated that even this machine was 5 to 10 times slower than the hybrid. The hybrid, moreover, would operate at a speed about one-tenth the rate obtainable at the state of the art and still be adequate.

It is reasonable to anticipate, at this time, that other survey programs will become desirable in the context of increasing interest in the environment. Programs studying preservation of parks, urban planning, pollution control, fisheries and others should prove feasible and will generate large quantities of data requiring processing. The evolution of such programs seems desirable and likely, and timely development of data processing systems to meet such needs should begin now. It is therefore important for NASA to have this technology available to meet these needs.

Preliminary and Supporting Research

The study of appropriate techniques for data handling and processing preliminary to their use in environmental surveys demonstrates in itself a need for faster and, therefore, cheaper means of analysis. These studies normally require processing large amounts of data. When the means are available to do this quickly and cheaply, the effectiveness of research is enhanced and, also, some research, impossible without such means, may then be done.

The interests of MSC and of Michigan in understanding and applying the techniques of remotely sensed data depend heavily on the degree of advancement in all areas of pertinent technology, but very heavily on advances in data processing. Progress in this area is, then, of great relevance to successful transference of this technology from research to application and has received inadequate attention and funding for several years.

The hybrid processor, furthermore, is useful in studying data from several sources. It is planned as a processor for data from the MSC scanner, the Michigan scanner, the SKYLAB system, ERTS and, in fact, from any analog or digital source of multispectral data. Since many scientists are interested in the use of data from several sources, a processing system compatible with all, or as many as possible, sources of data will be of greatest utility to a given research investigation. Since the needs for data in research programs cannot be specified completely, flexibility of this kind is very desirable, provides a capability useful to many people conducting research programs, and enables progress of these programs toward operational application.

It appears possible, furthermore, that the planned hybrid, when implemented at MSC, may be able to incorporate a good portion of equipment available in the present ground data stations to minimize the impact of cost in uprating these systems to recognition processors. Attention should be given to this possibility during development. It may be desirable to consider the use of an EAI-690 based processor for advanced development at MSC and the two ground data stations as potential production processors when modified later.

Conclusion, Recommendations

It appears that the relevance and utility of the proposed hybrid processor is well established. This is also true of the timeliness of the development plan proposed. If the development of the full system were to begin now, it would be available and valuable in defining processors for particular survey programs such as ASCS at a time and at a level of detailed understanding which would enhance the likelihood of these programs being well-conceived and successful.

That the value of such a processor is a function of its early availability seems safe to say, particularly at this time. The development of an expandable, rather than a limited, processor can also be recommended now in the light of applications foreseeable and not yet known. Accordingly, we recommend that the program for the design and use of the expandable hybrid processor begin now—and that supporting funds be sought to implement the full system, or at least, the minimal configuration of the expandable system. These funds must be available or certain by April 1972 to begin the design and fabrication of the system.

Appendix E
A Plan for Development of a
Hybrid Spectral Recognition Computer (SPARC/H) (December 1971)

Abstract

As a result of the interest in multispectral surveying and the expected large volumes of data resulting from such surveys, a configuration of equipment has been defined to meet the demand. This includes hybrid preprocessing and recognition equipment.

Since there is an interest and a need for such processing capability in several NASA programs, a system is proposed which can be supported by both NASA/Langley and NASA/MSC to obtain in a single, more capable processor, a system meeting the needs of each center and contributing to the advance of multispectral survey techniques.

The system includes a hybrid classifier and digital control now sponsored by NASA/ Langley under the AAFE program and constitutes, with available equipment, a preliminary recognition system. In addition to this, subsystems are defined which are required to complement the NASA/Langley classifier to produce a minimal stand-alone recognition system. Beyond this minimal system other subsystems are defined to accomplish preprocessing, geometrical data correction, and improved processing performance.

The complete system and plans for its implementation and use are described along with the specific areas of support relevant to the interests of both NASA centers. The program described extends over a period greater than two years.

Introduction

Over the past few years it has become increasingly apparent that the large volume and the demand for fast processing of multispectral data involved in any operational use of this data, would require processing equipment unlike computers now available. A hybrid (digital-analog) computing system capable of processing data at rates several orders of magnitude greater than can be obtained with conventional digital machines has been developed to meet this need. Its design is based on previous design and use of analog and digital systems for processing such data.

However, between the conceptual design and the operational use of such a system there is need for experimental and development evaluation and testing to verify the performance required and to develop the techniques of using such a system in operation. For this purpose, a flexible configuration of such a system has been developed to fill the need for a prototype enabling continued development of equipment, method, and algorithms to lead to specification of operational systems as the need for such systems is elaborated.

There has been interest and need for such a system in the various programs concerned with use, survey, or protection of earth resources. The AAFE (Advanced Application Flight Experiment) program has identified the need for such a system as critical for use of data in this program. The Earth Observations Division (EOD) of NASA/MSC has also established the importance of this need in their programs. Since the needs of both centers are similar but imply different emphases on different portions of a recognition processing system, a single coherent system has been developed to meet the requirements of both centers. The system is one in which both centers may obtain the benefits of having a complete system developed while individually sponsoring those parts of the system most closely aligned to the needs of each center. Thus a considerable duplication of equipment is avoided and, furthermore, use may be made of available equipment at Willow Run Laboratories to minimize the cost of the system. This plan, then, describes the system, the areas of sponsorship of NASA/Langley and NASA/MSC, the plan for developing the system, the use of available funds and equipment to accomplish this plan and, finally, the amount of additional funding to complete the system. The approach described appears to offer substantial benefit to the advancement of ongoing user data-processing for earth resource surveys at a reasonable cost and in a short time.

Complete System Description

The system is shown in Fig. E-1, a block diagram of SPARC/H. The complete system consists of all the blocks shown but is also expandable beyond the size shown. It is readily apparent that a large variety of subsystems could be derived from this complete system. However, in addition to the complete system, only two subsystems are of interest: (1) the AAFE Hybrid Classifier, and (2) the Minimal Operating System. These will be described in detail in a later section after reviewing the complete system. The minimal operating system is shown without cross-hatching in Fig. E-1 and is that portion which can be assembled with available equipment, anticipated first year MSC funds, and the AAFE contract. The full system will be assembled as shown when available funding will allow.

Data from either the NASA/Houston 24-channel scanner, or SKYLAB, or the Michigan scanner (analog) is entered into the system via the tape recorder and interface and is routed into the digital system (EAI-640 and EAI-693) for analysis of recognition parameters. Training sets are then assembled, as needed, into a cyclic storage for entry into the preprocessor and classifier to evaluate the selection of distributions or functions of spectral channels. Data is then played through the system to output printers and storage to print maps and tabulate the recognition results.

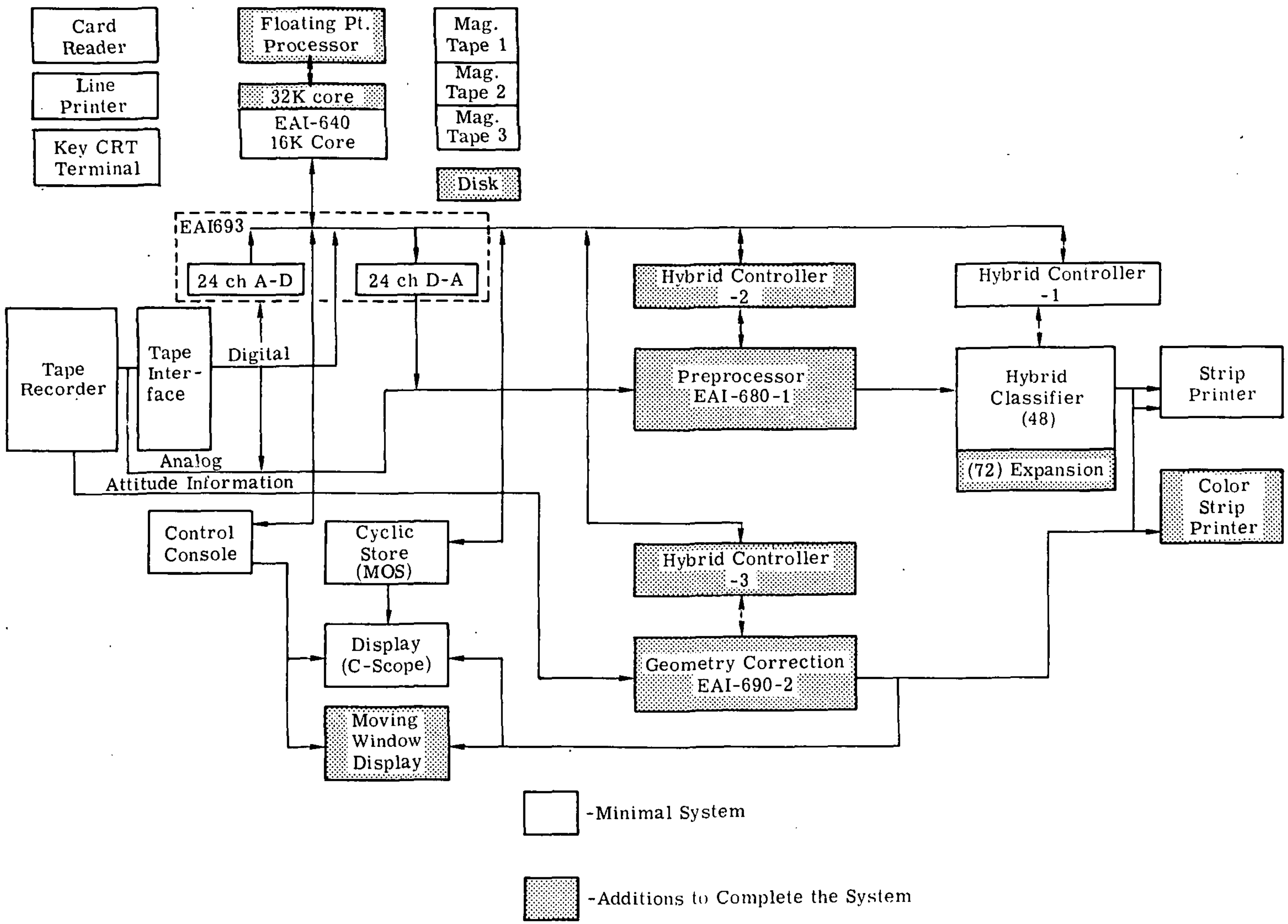

FIGURE E-1. BLOCK DIAGRAM OF HYBRID SPECTRAL ANALYSIS AND RECOGNITION COMPUTER (SPARC/H)

The strip printers are controlled by an EAI-680 hybrid console to allow the correction of data to obtain geometrically accurate maps of the results.

The digital machine (EAI-640) is used to calculate distribution parameters needed in the preprocessor and in the classifier. The minimal system would operate as a tape-oriented system but will be uprated to a disk-operated system as soon as possible.

Display of tape data and control of processing are accomplished on available and specially designed equipment.

AAFE Hybrid Classifier

The proposed AAFE Hybrid Classifier is intended to be the next step in the development of proven multispectral processing equipment and techniques which will lead to an eventual space-borne processor. The amount of funds available in the first year do not permit construction of a stand-alone minimal operating system. The proposed classifier would rely heavily on existing WRL equipment to function as a processing system. As a consequence of this, very little data would be processed on a noninterference basis using the existing multispectral input-output and control equipment. Most of this equipment would be obtained under second-year AAFE funding to provide a minimal operating system similar to the one shown in the block diagram of Fig. E-1.

Since the total expected funding under the AAFE program would not provide a complete operational prototype, a reduced system is being considered for the AAFE program. The digital computer portion of the system would be a mini-computer such as a Hewlett-Packard 2100. This computer has sufficient I/O capability and available software to produce a minimal hybrid processing system. However if the ultimate goal is a large flexible prototype for an operational system, then this computer would not be a desirable choice. For this goal the EAI-640 along with its hybrid interface, the EAI-693, and existing software provides a much better basis for constructing the larger system. In either case, the digital computers would be leased. The yearly lease cost for the HP-2100 is about 25K while the yearly lease cost is about 50K for the EAI-640 and -693. Leasing the EAI-640 under the AAFE contract would severely impair the possibility of meeting the contract objectives unless additional funding is obtained. On the other hand the objective of constructing an operation prototype will be impaired if the HP-2100 is used.

The AAFE program is divided into two 12-month phases. Phase I is to be funded at $165K and it is hoped that Phase II will be funded at about a level of $400K. The purpose of Phase I is to demonstrate the feasibility of the hybrid system with the minimum of hardware purchases. Provided that Phase I meets these requirements, Phase II continuation will be recommended for final implementation of the SPARC/H system.

TENTATIVE STATEMENT OF WORK FOR THE AAFE PROGRAM

Contractor Tasks — Phase I

1. Analog Processor — Evaluate, select, and purchase of components for fabrication of the analog processor. The initial processor will have a capability of six spectral channels and eight spectral signatures.

2. Interface — Implement control interface for the analog processor including addressing structure and digitally controlled attenuators.

3. Digital Computer — Evaluate digital computer best suited for use in SPARC/H. Specify, negotiate and contract for leasing (with purchase option, if possible) of digital computer and peripherals. Develop software necessary for signature extraction and setting up of the analog processor.

4. Phase II Design Studies — Investigate high-speed temporary storage techniques of selected video data for rapid analysis and improved CRT presentation. Evaluate available I/O hardware for improved system throughput.

5. Demonstration — Operate the system with existing multispectral processing peripherals. Using suitable multispectral data, obtain processed results. Compare with similar results obtained from the same data using present equipment. Comparison will be on the basis of processing time, cost, and accuracy.

6. Reports — Submit monthly letter reports of the program status. The final report should evaluate the work and the extent of Phase I accomplishments.

Contractor Tasks — Phase II

1. Analog Processor — Expand processor to handle up to 8 spectral channels or 12 spectral signatures and add preprocessing components.

2. Interface — Construct rapid-access training set data handler. Construct high-speed video data source. Expand interface for larger analog processor.

3. Digital Computer — Purchase digital computer system. Continue software development for control of additional peripherals and interfaces added during Phase II.

4. I/O — Purchase hard-copy film printer and complete the system configuration with the addition of available I/O data handlers.

5. Demonstrate — Demonstrate optimum channel-selection feature and the accuracy and time-saving improvements.

6. Report(s)—Submit monthly letter reports of the program status. The final report should include a complete system evaluation as outlined in the original task requirements.

Minimal Operating System

The minimal system shown in the block diagram is intended as the simplest system possible to obtain an operating hybrid recognition system within the constraint of minimum first-year funds. It is also configured in such a manner that it may be expanded to the full system with little loss of time and in a manner matched to the growth of the system power and software.

Software development is facilitated by the peripheral configuration, including a card reader, small line printer, magnetic tape, and a key-CRT terminal. Uprating to a larger (32K) core, disk and floating-point processor involves a minimal change. The magnitude of the cost to uprate this system is a function of the time before it takes place, involving change in tape-oriented software for the most part.

PROGRAM FOR SPARC/H AND RELATED PROGRAMS COVERING A TWO-YEAR DEVELOPMENT

	SPARC/H	RELATED PROGRAMS
Year 1		
	(1) Design and fabricate Hybrid Classifier, Control Console, Cyclic store	Develop preprocessing transforms, test on CDC 1604
	(2) Procure tape recorder, tape interface, display	Investigate Adaptive Recognition Techniques for effectiveness on CDC 1604
	(3) Lease EAI-640, -693 equipment	Develop Analysis, Setup and Monitor software for EAI-690 systems
	(4) Interface equipment using available SPARC equipment as possible	Define techniques for registration of geographic and scanner data
	(5) Test Recognition on SPARC/H	
Year 2		
	(1) Design and fabricate/procure moving window display, color strip printer	Begin processing of user data
	(2) Add preprocessor, geometry correction using EAI-680 systems	Begin User data processing
	(3) Increase size of classifier	Develop adaptive hybrid preprocessing and recognition and merge into user data processing
	(4) Add floating point processor, 16K of core, disk to EAI-640	Develop data registration techniques for hybrid

Year 3

(1) Procure leased EAI-690 equipment if satisfactory	Begin full user data processing at about 60 operations/year, processing studies at 30 operations/year for MSDS, SKYLAB, ERTS, U of M data
(2) Implement data registration techniques for mapping survey data	

For the full system, the procurements of Year 2 would take place in Year 1 and provide an operating system by the middle of Year 2 at which time user data processing could begin along with other experiments.

Costs (Full System in First Year)

	$
Year 1	
(1) Tape recorder, tape interface	95.K
(2) Lease complete EAI-690 system (728.5K purchase cost)	192.8K
(3) Design and fabricate hybrid classifier, control console, cyclic store	160.K
(4) Interface and test	25.K
(5) Design analysis, setup and monitor software	150.K
(6) Moving-window color display, color prints	60.K
Year 1 Total	682.8K
Year 2	
(1) Renewal of Year 1 lease	192.8K
(2) Software development	75.K
(3) System operation and maintenance	75.K
Year 2 Total	342.8K
Year 3	
(1) Procure leased EAI equipment	492.K
(2) System operation and maintenance	75.K
Year 3 Total	567.K
Total for the 3 Years	1,592.6K

Costs (Minimal System in First Year, Lease of Equipment)

			$
Year 1			
(1)	Tape recorder, tape interface, displays		115
(2)	Lease EAI-640, -693 equipment (200K)*		52.8K per yr
(3)	Design and fabricate scaled-down hybrid classifier, control console, cyclic store		125K
(4)	Interface and test		15K
(5)	Design analysis, setup and monitor software		100K
	Year 1 Total		407.8K

(NASA/Langley—$165K; NASA/MSC—242.8K)

Year 2			
(1)	Moving window display, color printer		60K
(2)	Preprocessor and geometry correction	($225K ea = 450K)*	
	Add floating pt. processor to EAI-640:		
	16K core	(24K)*	
	Disk	(54.5K)*	
	Total purchase cost	(528.5K)*	
	Lease cost		$140K per yr
(3)	Renewal of Year 1 lease		52.8K per yr
(4)	Increase size of classifier		65K
(5)	System operation and maintenance		75K
(6)	Software development		150K
	Year 2 Total		542.8K

Year 3		
(1)	Buy-out cost for leased EAI equipment	
	(a) Year 1 equipment—135.2K	
	(b) Year 2 equipment—442.5K	
		577.7K
(2)	System operation & maintenance	75K
	Year 3 Total	652.7K
	Total for the 3 years	$1,603.3K

If additional funds are available in Year 1, portions of the system may be purchased sooner.

*Costs in parentheses ($xxxK) are purchase costs.

The funding for this complete system, it appears, will come from a number of sources. These are: (1) NASA/Langley AAFE Program Phase I—165K and Phase II—400K, (2) NASA/MSC Proposed Hybrid Processor Construction, year 1—350K and year 2—350K, (3) a major portion of the funds for two closely related in-house tasks (Tape Interface—95K and Hybrid Studies—30K) sponsored by NASA/MSC, and (4) the ASCS program which requires geometry correction of the data, (this essentially uses one EAI-680 analog console and some computer programming which costs out to about 300K). Thus it is hoped that these sources will provide the funds (1,600K) necessary to construct a system which is mutually beneficial to all parties concerned.

Conclusion

It appears that a very powerful system may be had and be made available for user data processing in about 18 months if started as a full system. But if the minimal system approach is pursued, the full system is delayed by about a year. It would seem that the full system procurement in year 1 would be more closely phased with possible large-area survey applications.

The system as conceived under the AAFE program will eventually (in more than 2 years) have a reasonable processing capability. However it appears that the timeliness requirements for a prototype system to define a large-area surveys system will not be met unless an immediate coordinated effort is begun between NASA/Langley and NASA/MSC.

Appendix F
Specification: Parallel Digital Multispectral Processor

General

The processor described by this specification is a special-purpose highly parallel digital device dedicated mainly to the processing of digital multispectral data. The special-purpose nature of the machine is derived (1) from the desire to use maximum likelihood processing of the data and (2) from the assumption that Gaussian statistics can be used to represent the statistical nature of the data. These two constraints are sufficient to design a hardwired classifier for processing multispectral data. However, the size and speed of the machine must also be defined. It appears, at this time, that the size and speed of the processor will have to be defined for two phases of the overall program. Initially the classifier will be of smaller size and may be faster than is needed (due to its smaller size); later, when it is expanded to its full size, it should have the capability to process data at a rate commensurate with the data collection rate. The ERIM multispectral scanner collects data in 12 spectral bands for which the video bandwidth is 100 kHz, which in digital format is a bit rate of 19.2 megabits/sec. An appropriate external clock will be supplied to the classifier to process the data at this rate.

The classifier will be controlled by a digital computer. The computer selected for this purpose is a Digital Equipment Corporation (DEC) PDP-11/45. All statistical parameters characterizing the known classes of objects will be generated by the computer and these will be loaded into the appropriately addressed registers of the classifier by the computer. The output of the classifier will be monitored by the computer.

Performance

Data Input. The data input will consist of 8-bit data words transmitted over 8 parallel lines. The spectral bands (channels) will be multiplexed over these lines. For the first phase (smaller classifier) 6 channels of data will be processed. The word transfer rate will be 1.2 million words/sec. This is a data sampling rate of 200,000 samples per second. A sync signal and a clock frequency of M times 200,000 will be supplied, where M is some integer to be specified by the vendor. The expanded classifier of phase two must accept 12-channel data which corresponds to a word transfer rate of 2.4 million words/sec.

The data lines will be twisted pair in a single cable group with an Amphenol Blue Ribbon connector such as 26-4401-32P. The signals will be TTL logic levels. Line receiver is of the differential input type such as a Fairchild μA 9615 or equivalent.

Functions. The processor must classify a data vector (6 channels) into one of nine classes. Eight of these classes will be for scene materials and the ninth decision will be none of the programmed classes. They will be based on the maximum likelihood ratio for all pairwise ratios or, in effect, selection of the most probable class. Having made the decision as to the most probable class, the classifier must also check to see if the probability is not too low. If it is too low the no decision state will occur. The threshold for this decision should be variable and entered from the computer.

The expanded classifier of phase two should be capable of handling 12 channels of data for classification into 1 of 6 materials or use 6 spectral bands to classify into 1 of 16 materials at the data rate specified above. In addition, the expanded classifier must contain the two following preprocessing transformations:

(1) $P_j(\theta) = \pm a \pm b\theta \pm c\theta^2 \pm d\theta^3$

for $j \leq 4$, assignable to any adjacent set of bands, e.g., $\underbrace{12\ 11\ 10\ 9}_{P_1} \left| \begin{array}{c} 876 \\ P_2 \end{array} \right| \begin{array}{c} 54 \\ P_3 \end{array} \left| \begin{array}{c} 321 \\ P_2 \end{array} \right|$

(2) Rotation - 12×12 matrix operator

A separate costing on these preprocessing functions is requested in order to see if these could be included in the first phase of construction.

Computer Control. The classifier will be controlled by a DEC PDP-11/45 digital computer through its standard interface module, a DR-11B. This is a direct memory access (DMA) interface, thus a very high speed transfer of a data block can be performed. The coefficient for the statistical parameters will be transmitted through this interface. Since the computer has a 16-bit word length, it appears that each coefficient will be transferred using two computer words — one for address, the other for the numerical value.

The output of the classifier will also be transferred through this interface.

Outputs. There should be two outputs from the classifier: one is the result of the classification and the other is the value of the log of one of the computed probability density functions. The result of the classification can be represented by a 4-bit number which should be available as a direct output and as input to the computer. As input to the computer, these 4-bit words should be packed four to a word and loaded into a 6-word buffer register.

Similarly, the computed log of the probability function will be available as a direct output or as input to the PDP-11/45 computer. Only one value will be packed per computer word, and these also will be loaded into a 6-word buffer register. These registers will be connected to the DR-11B interface. The specific log function selected as output will be chosen by a manual switch. Any one of the probability functions could be selected so an additional switch position will allow the chosen (most probable) value to be the output.

Physical

The components shall be mounted on a chassis suitable for mounting in a standard rack 19 inches wide by 22 inches deep. The chassis should include chassis slides. The power supplies should also be rack-mountable and preferably on a separate chassis. Front panel finish, dark gray enamel or black anodized.

Environmental

Temperature: Operating, $10^{\circ}C$ to $50^{\circ}C$
Nonoperating, $-25^{\circ}C$ to $75^{\circ}C$
Altitude: Operating, sea level to 10,000 ft
Humidity: Operating, 0 to 95% relative humidity

Power Requirements

Voltage: 115V AC RMS ±10%
Frequency: 60 Hz ±5%

Manufacturing Technique

Good Commercial Quality

Acceptance Testing

Due to the very close tie of this device to a digital computer, it may not be feasible to perform acceptance testing at the Vendor's site. Therefore, two quotes are requested, one for on-site testing and one for testing performed at ERIM.

Warranty

90 days

Delivery

180 days A.R.O.

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