NATIONAL RADIO ASTRONOMY OBSERVATORY
Charlottesville, Virginia

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VLA COMPUTER MEMORANDUM #129

OPTICAL PROCESSOR PROPOSAL

by

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I. INTRODUCTION

I-A The Problem

Spectral-line map synthesis and production for the VLA is a major digital data processing problem. This problem can be greatly reduced by the use of a two dimensional electro-optic Fourier transform processor. As technology develops, such a processor should offer additional capabilities attractive for future VLA development.

I-B The Processor

The proposed processor reflects a middle of the road approach, selected after careful study of alternatives. Rather than relying on the most technologically advanced transducers for data input, it uses the well known and established photographic materials. Thus, the dependence on progress in materials research is eliminated and the program becomes, essentially, an engineering design and fabrication effort. The benefit of this approach is to reduce risk to a very low level; the price is the inconvenience and delay of film transports. The need for a linear output with the size and precision associated with the VLA makes even this conservative approach an ambitious engineering effort.

Our intent has been to offer a manufacturable and reliable instrument which:

1. can meet the initial VLA spectral line processing and map production requirements,
2. has a low operating cost, and
3. can be expanded in performance without major reinvestment.

The proposed map synthesis and production system (hereafter referred to as the VLA Optical Processor) consists of three parts; (1) a film recorder, (2) an optical system, and (3) an output digitizing system. The film recorder is also used as a hard-copy output device to produce maps on 35-mm film for astronomer use. The VLA optical processor is designed to accept digital input data in a (u-v-f), a (t-b-f), or a (b-t-f) format. The output for each observing frequency, is a 10 bit digital map and a 35 mm slide.

The processor will be under the control of a general purpose digital computer and thus has the potential for time-shared operation and for interactive analysis and interpretation. It can also be operated as a stand-alone, batch processor, accepting data from a mass-store and generating both digital and photographic maps. In operation, data are selected from the data base and delivered for whatever preprocessing may be desired, e.g., weighting and smoothing. From here they are delivered to the film recorder. If the data base is t-B the recorder will have an elliptical format. If the data have been gridded, the recorder format will be rectangular. Exposed film will be automatically developed and delivered to the modulator plane of the optical system. A simple film or plate transport is used. Once in the processor, the film is illuminated with a laser, automatically positioned on the optical axis of the processor, and the Fourier transform is read out by a scanning sensor array.

I-C The Program

A program for the development and operation of the VLA optical processor has been assembled. It is a 30-month program consisting of:

- Phase I: a 6-month component evaluation, processor design, and feasibility demonstration;
- Phase II: a 12-month hardware fabrication and assembly effort; and
- Phase III: 12 months of debugging, fine tuning, and integration. An operating system capable of going on-line when delivered is invisioned.

One employee (e.g., BS in electrical engineering) will be required to maintain and operate the processor. One engineer and one technician will be required for 18-20 months during fabrication and integration. The directed support of a "post-doc" for 2 to 3 years and the temporary (18-month) assignment of Dr. D'Addario complete the anticipated NRAO/VLA manpower requirements. Some programming support also will be required. However, since this processor greatly lightens the load on the VLA spectral-line computer facility, there could be a net savings in software effort.

A firm cost for the complete map synthesis and production facility will be known in September, 1976. It is not expected to exceed $1,000,000. Annual operating cost, including maintenance, operator salary, and consumables is estimated at $ 75,000. By having feasibility demonstrations of all critical components performed for our particular problem before leaving the design stage and before commiting a substantial amount of money, the phased approach outlined above will allow us to introduce a processing technology, which is new to radio astronomy, without unreasonable risk.

I-D Future Prospects

The VLA optical processor can be improved in many dimensions. It can be made faster, the internal noise can be reduced, larger uv planes can be processed, and it can be made fully interactive by the replacement of film. Many of these improvements will be obtained as the result of improved processor component technology.

There are major (DOD, etc.) investments currently being made in the input transducer area. These will lead to transducers of higher space-bandwidth product (numerical field of view) and lower noise. As these transducers develop, they should provide attractive substitutes for the film in the processor.

Superposition techniques in optical processing are well known and understood but have not yet been commonly used. Their development is of interest to VLA processing where source component subtraction is an important part of the desired computations. Additionally, superposition might be used with mosaicing to solve the three dimensional (uvw) problem and the large field of view problem. Some specific examples of possible improvements are:

a. to increase space-bandwidth product by a factor of 10,

b. to decrease total processing time from 30 sec/map to <10 sec/map, and

c. to reduce noise level from ~0.3% to ~.03%.

II. THE PROGRAM

II-A Overall Program

The main features of this program are shown in Figure 1. Here we summarize the current estimates of:

1. Permanent and temporary NRAO/VLA man-hours.
2. Dollar expenditures.
3. Major program activities.

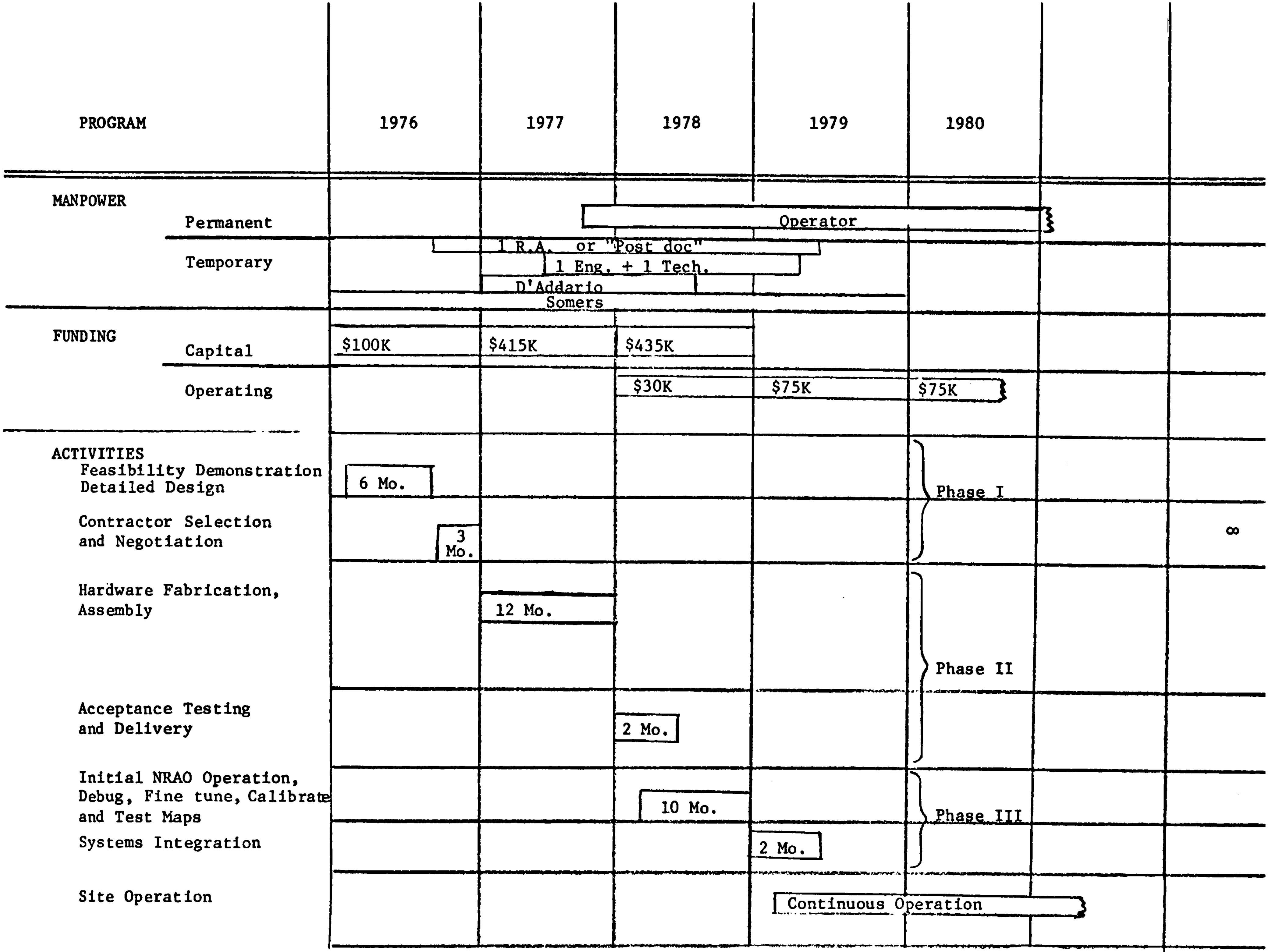


FIGURE 1: Optical Processor Development Program

II-B Phase 1

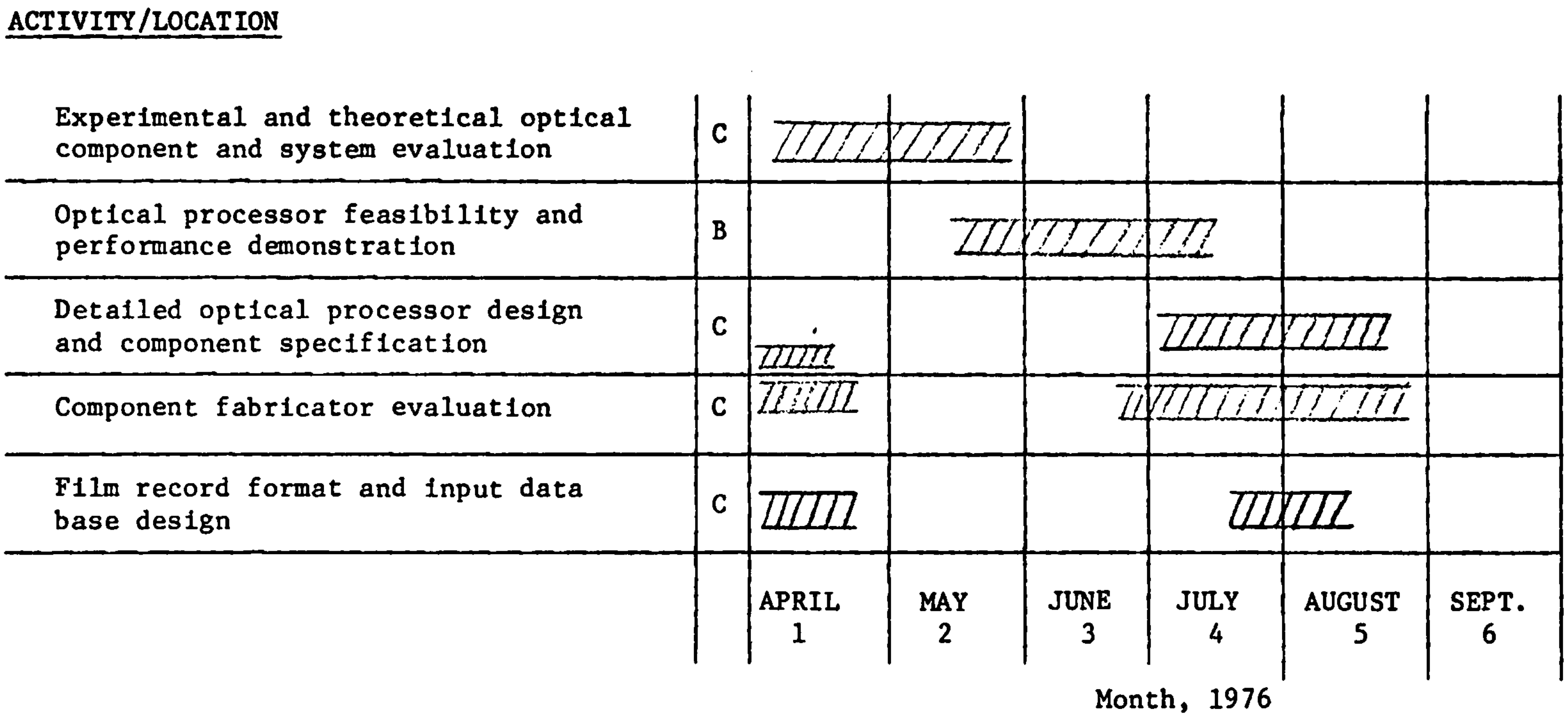
Phase 1 of the program, to which this proposal is largely directed, has a three fold objective:

1. component evaluation, processor performance prediction, and detailed processor design,
2. processor feasibility demonstration, and
3. component manufacturer evaluation.

A combined in-house and contractor effort is required to realize these objectives in a timely and effective way. We propose the Environmental Research Institute of Michigan (ERIM) as the Contractor for a six-month program. A possible work statement for ERIM is included in the Appendix. An activity summary chart is in Figure 2.

The plan calls for the experimental evaluation of optical components, film recorders and image sensors with the results used to predict VLA optical processor performance. This performance will then be demonstrated and measured experimentally. With these data we will be able to generate individual component specifications, to design optical processor operating modes (e.g., batch or interactive), and to establish I/O data formats and rates. Various tradeoff studies and component fabricator evaluation will also be performed. Bench marks for Phase 2 and 3 will be defined. The final result will be

1. demonstrated processor performance,
2. detailed processor design suitable for component procurement,
3. data (input and output) requirements, and



A - NRAO
B - ERIM
C - BOTH

FIGURE 2

4. detailed cost and delivery information from qualified component contractors.

Phase 1 will be completed with another Steering Committee review and decision.

In closing this section we note that the optical configuration and the input modulator are, respectively, the most fundamental and the most state-of-the-art elements in this processor. The best optical configuration from an aberration, stationarity, manufacturability and dynamic range point of view was designed by Bulabois and Somers during the summer of 1975. This design has been reviewed and confirmed by a number of outside experts.* The input modulator, consisting of film and a film recorder, requires particular attention. The reason for this is because high precision is required and because the film writing format has a fundamental impact on processing rates, data formats and map defects. It is for these reasons that there is a large amount of joint ERIM-NRAO activity in Phase 1. These activities are indicated by a "C" in Figure 2.

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* Bulabois - J. Goodman - Somers October 3 meeting
Bulabois - A. Kozma - Somers October 20 meeting
H. H. Hopkins - Somers Nov. 10 and 20 meeting

II-C Phase 2

During Phase 2 a processor will be fabricated, assembled, and tested. Phase 2 will begin after contractor selection and negotiation around January 1977. Fabrication and assembly will require about one year. After an additional few months of acceptance tests and demonstrations, the processor will be delivered to the NRAO. A detailed discussion of Phase 2 is not appropriate at this time. A complete program will be presented in late fall of '76 in conjunction with Phase 1 results and recommendations.

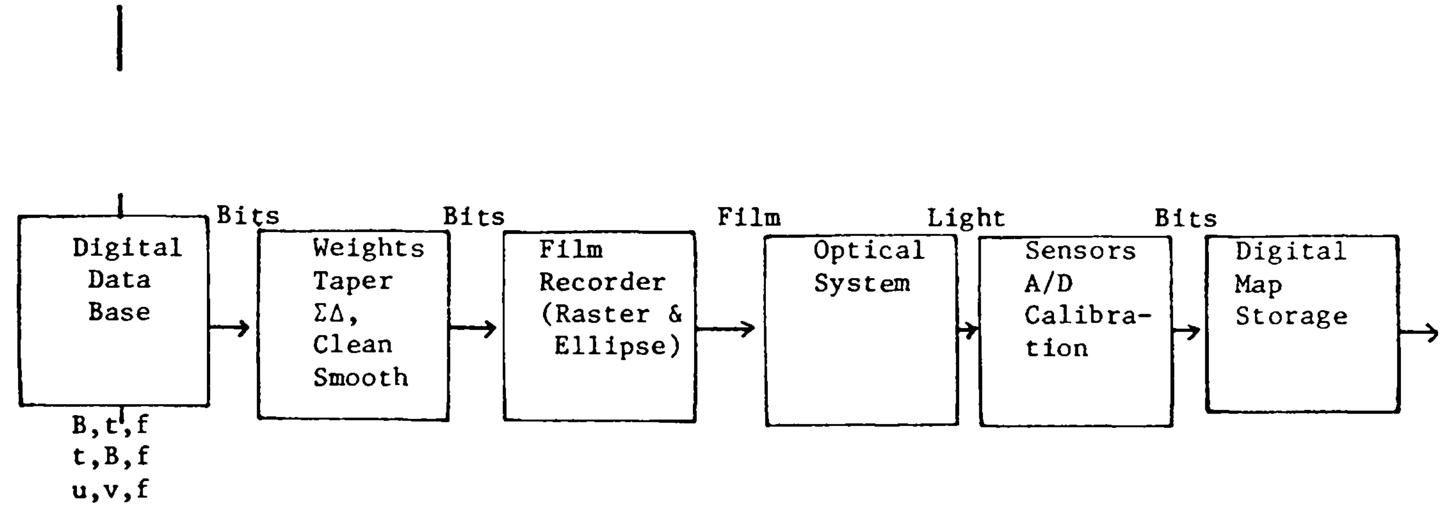
II-D Phase 3

Phase 3 will consist of in-house testing, calibration, programming, documentation, and development of operating procedures. It will also include operator training for maintenance and for spectral line and continuum map processing, production, and display.

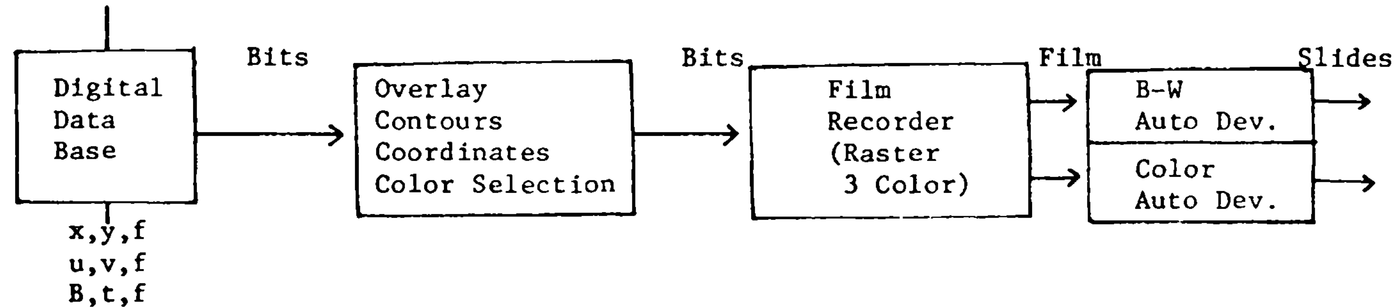
III. THE PROCESSOR

III-A Description

This discussion will present the processor in the following segments: data input, film recorder, optical system, and map output system. We propose to use the film recorder for both input to the optical system and for recording the final map output in slide form. Both concepts are shown in Figure 3 below.



Map Synthesis Operation



Map Slide Production Operation

FIGURE 3

III-A.1 Data Input

The film recorder receives the data to be processed optically. The input requirements on the recorder and the required data format define the data input specifications.

a) Input data rate

The film recorder has no unusual input data rate requirements, as was the case with some of the light modulators considered earlier. The input data rate is 10^5 complex words per second.

b) Format

The film format shall be defined in two modes: a uv raster scan and a baseline mode. The raster mode accepts sorted data of the same form as that used by the Fast Fourier Transform (FFT) processor. For this mode the processor requires an input sort device essentially identical to that required for conventional digital processing. In the baseline mode the recorder accepts and writes data along the track of each baseline in the uv plane, with no gridding. The recorder may accept data in either baseline-time or time-baseline order. If the baseline-time order is used, presorting is required only to the extent that frequency demultiplexing is performed.

The baseline-time mode greatly reduces the sort effort since one sorts the data only by frequency rather than into individual uv cells. Additionally cell averaging is not required. In a baseline mode, however, some preweighting must be done to de-emphasize the higher density of points in the shorter baselines. This can be done, digitally during the frequency sort, electronically during the film writing, or optically by the use of apodizing filters. There are three primary advantages in writing baselines directly. First, the frequency sort can be done in real or near real time and hence a several hour lag is eliminated. Second, as shall be discussed later, the problems of gridding are eliminated. Third, the frequency sort machine costs less than a full sort machine.

c) Sort Device

The sort device does not really perform a conventional sort, but the nomenclature seems too well adopted to change. The best existing treatment of the sort problem is VLA Computer memo #127 by B. Clark. Because the baseline-time format is favored, the sort machine proposed and priced in this report performs a frequency sort only.

III-A.2 The Film Recorder

The film recorder will be used to generate the optical processor input film. This is the film which carries the visibility data into the optical processor for Fourier transformation. The film recorder can also be used to generate a photographic (slide) record of the processed map. The film recorder scanning formats have not been determined and are one of the design study topics. It appears that both raster and elliptical scans would be desirable. The raster scan is compatible with gridded visibility data and with map data.* The elliptical scan is compatible with t-B data which has not been gridded. Thus, the data mass store format and the recorder scan format are closely related.

The general specifications for the film recorder are given in Table I. Final design specifications will result from the ERIM study. The specifications of an existing recorder of similar purpose are also tabulated. It is interesting to note that the Ampex recorder is a laser beam recorder which records a 6 MHz signal for up to 8 hours. This recorder is used in conjunction with an optical spectrum analyzer. That is, the film record is developed (automatically) and run through an optical spectrum analyzer to generate the power spectrum of the 6 MHz signal. The recorder-analyzer combination has a frequency resolution of 20 Hz or 1:300,000. A signal at -36db with respect to the peak signal can be detected. With manual intervention, -50db is possible.

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* The map data are obtained in a raster scan of the output plane with a linear diode array; described in a following section.

Recorder Parameters	Proposed VLA Film Recorder	Existing AMPEX LBR Film Recorder
Spot Size	8 μm	6 μm
Spot Positioning	1:100,000	1:100,000
Dynamic Range	>100:1 (Complex amplitude transmission)*	N.A.
u-v Plane Size	35mm x 35mm	10.6mm x 30mm (Actually 10.6mm wide record on 4500' tape)
Space-Bandwidth	2000 x 2000	N.A.
Complex Visibility Encoding	Carrier Frequency 32 c/mm	N.A.
Scan Lines/Sec	1000 scans/sec	$4\text{-}16\text{x}10^3$ lines/sec
Frame Write Time	<10 sec	≃0.1 sec
Input Word Rate (Two 8 Bit Words)	$>10^5$/sec	6 MHz (analog)

TABLE I

* This item depends on both recorder spot size and film granularity. Kodak date indicates that more than 100 can be obtained with 649-F films.

The point in mentioning this equipment is not to show that "all our problems are solved", for that is not the case. Rather, it is to make clear that there exists a very closely related problem (large time-bandwidth product Fourier analysis) which, for the past six years, has been solved by means similar to those proposed for the VLA.

III-A.3 Optical System

The optical system accepts the visibility data from the film recorder and performs a Fourier transform on the data. A mathematical statement for this operation is that the output map brightness is proportional to the integral

$$\iint_{-\infty}^{\infty} V_{uv}\, e^{i\phi_{uv}}\, e^{i2\pi(ux + vy)}\, dudv$$

where V_{uv} and ϕ_{uv} are respectively the amplitude and phase of the observed complex visibility.

The optical system, shown in Figure 4, performs the Fourier transform on the optical E field. We obtain a linear output, proportional to the sky brightness, by introducing a reference wave and recording only the cross product term from an optical square law detector. The equations which describe the signal wave (proportional to sky brightness), the reference wave (a constant) and the important terms in the detector output are also in the Figure.

The design philosophy aims for simplicity and a minimum number of components in order to minimize optical aberrations and noise due to scattered light. In this system there are just two optical elements (labeled L_1 and M_1) in the map channel and two (L_2 and m_1) in the reference wave channel. It is interesting to note that L_1 and m_1 can, in principal, be eliminated with proper use of the modulator M_1. A processor of this simplicity is manufacturable and will have good S/N (>35 db) and small aberration (3° to 6° rms). It will be very stable both temporarily and spatially, leading to the possibility of automated

OPTICAL PROCESSOR

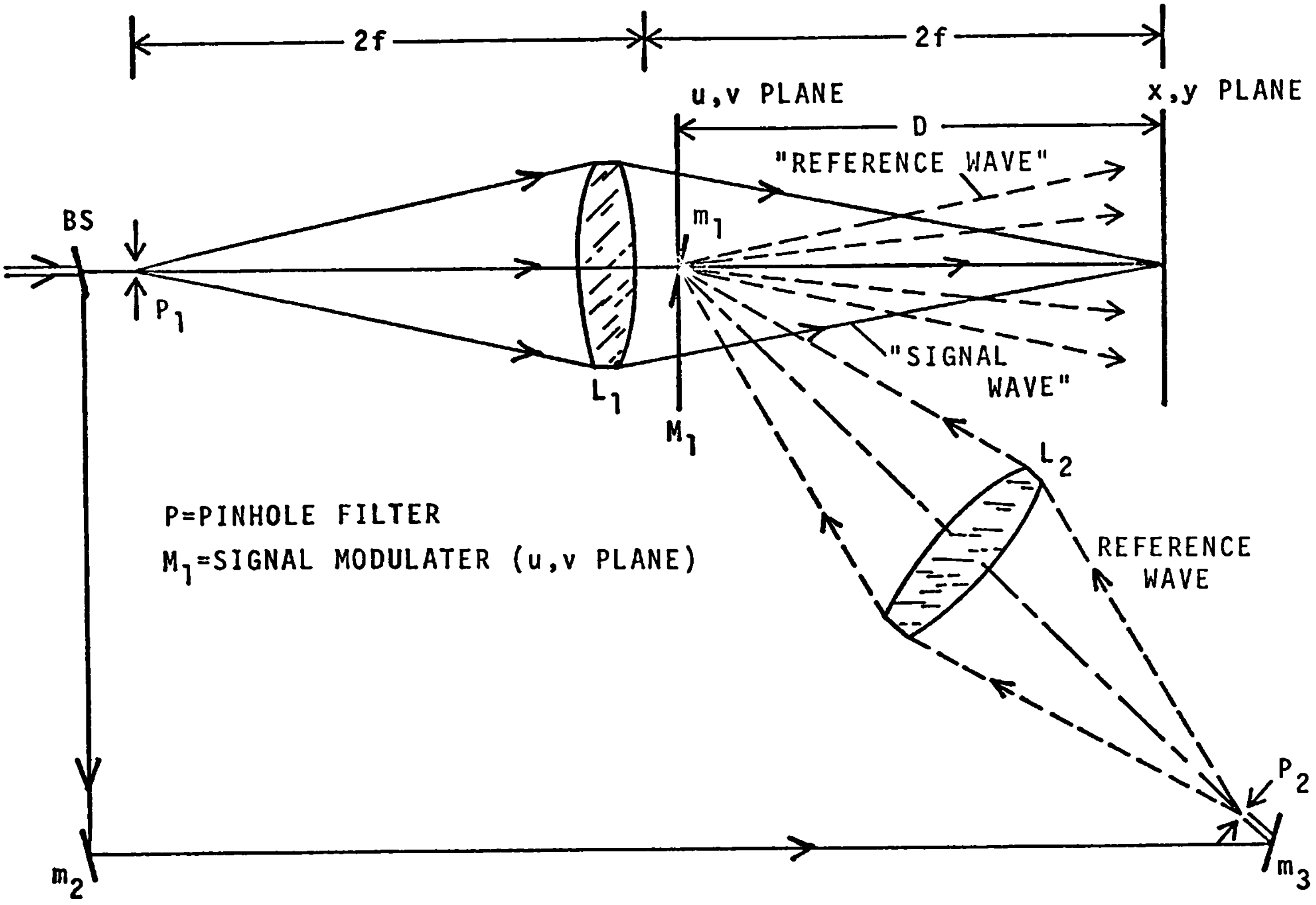

FIGURE 4

Reference Wave $R_\theta=A_o e^{-i(k\frac{(x^2+y^2)}{D} + \theta)}$; $\theta=0,\ \pi$

Signal Wave $S=A_1 e^{-ik\frac{(x^2+y^2)}{D}} \iint_A V_{uv} \mathrm{Cos}(2\pi f_c u + \phi_{uv})\ e^{i2\pi(ux+vy)}\ dudv$

Sensor Response Difference $\Big|_{\theta\,=\,0}^{\theta\,=\,\pi} = |R_o+S|^2 - |R\ +S|^2 = 2A_0A_1\ B_{x+x_c,y}$

Where $v_{uv}\ e^{i\phi_{uv}}$ and B_{xy} are the complex visibility and observed sky brightness respectively calibration and removal of aberrations. A net error of less than 3° rms is possible. It is expected that the processor will be so defect free that the principal source of error will be the accuracy of the input film record.

A schematic plan and isometric view of this processor is shown in Figure 5. In this configuration, which is suitable for batch operation, a film strip of 250, 500, or 750 uv input plane frames will be recorded, developed, and loaded into the film transport on the optical processor. They will be cycled through the processor, one map at a time, at about 10 seconds per map. The output will be digitized (see next section) and stored for subsequent astronomer use. The digital output will also be reentered into the film recorder for map slide generation.

Single-frame (interactive) processing is also possible. This requires the use of a film transport between the film recorder and optical processor. An electro-optic transducer, e.g., PROM, could also be used*. The feasibility of single-frame mapping will be considered in the proposed program.

There exist a number of commercially available products which exhibit the high levels of performance in the various areas required by a VLA spectral line optical processor. A partial list is summarized in Table II below:

Technique	Company	Specification Required/Available
Precision spot positioning	Ampex/Laser Beam Recorder	1:100,000/1:100,000
Calibration of stationary aberrations	Tropel-Telephone Labs/Digital Interferometer	$\lambda/100 < \lambda/100$ 3.6°/<3°
Data Encoding		
Complex	ERIM, GE, ITEK	Demonstrated
R + iI	ERIM, TROPEL	Demonstrated
Hologram	ESL, Stanford	Demonstrated

TABLE II

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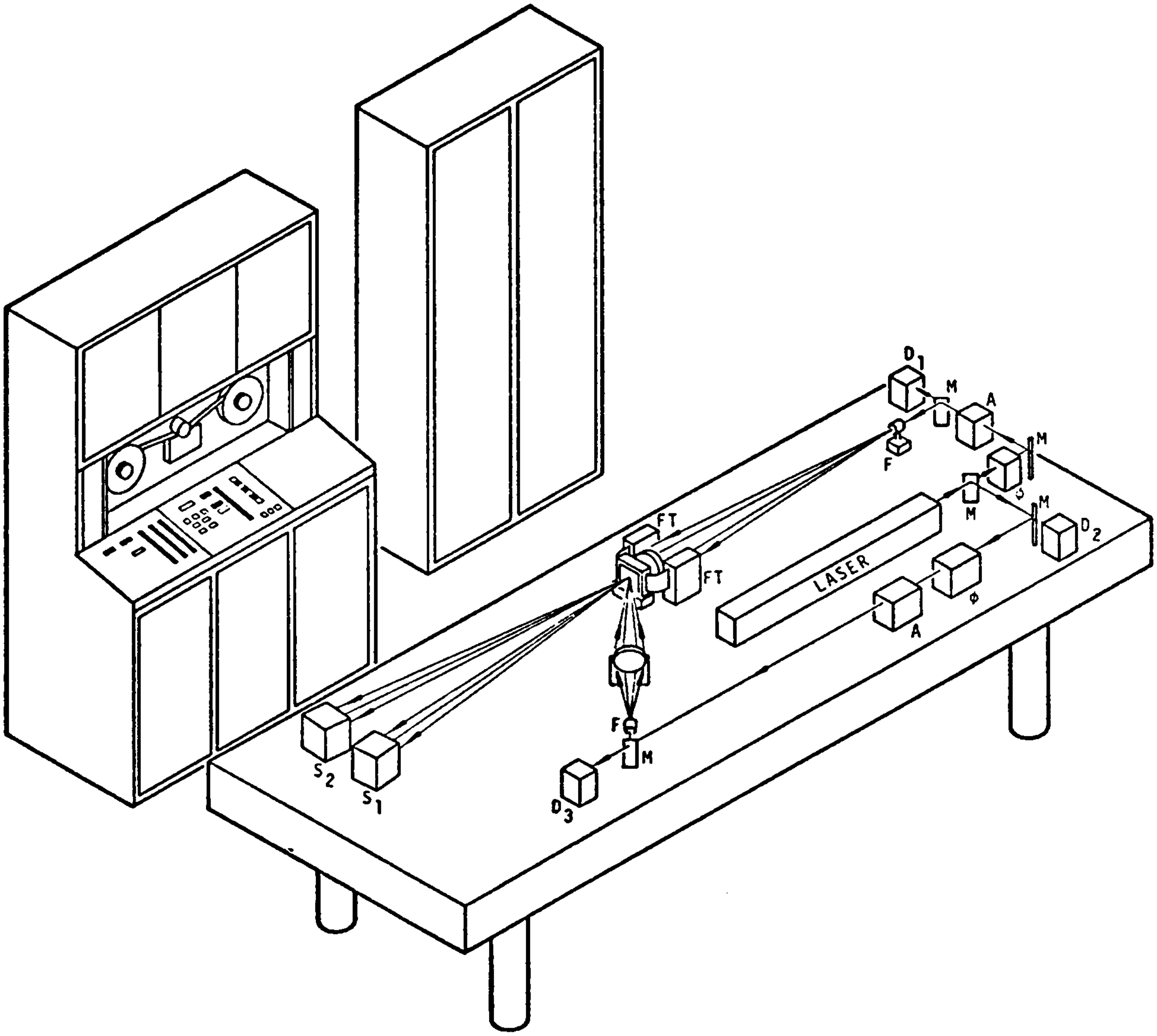
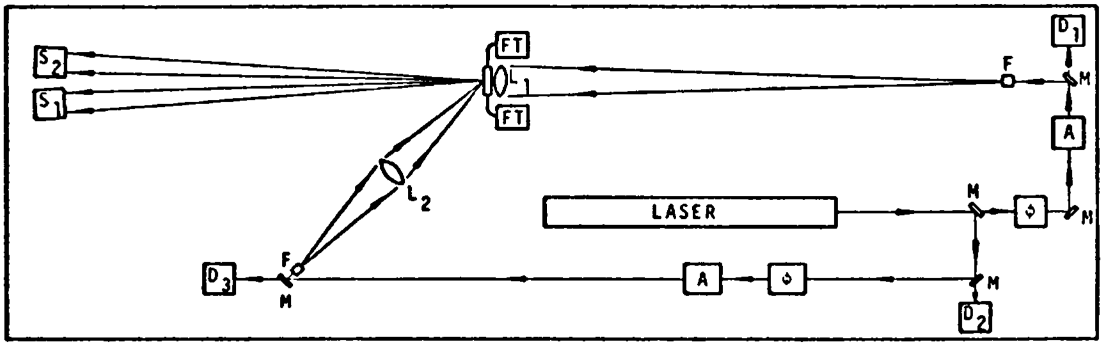
* Separate Memo



ISOMETRIC VIEW

SENSOR
ELECTRONICS
MINI/MICRO
MONITOR

FILM RECORDER
AND
PROCESSOR



SCHEMATIC PLAN VIEW

FIGURE 5

It is important to note that Tropel (a U.S. fabricator of excellent optical elements and systems) has a commercial product called the digital interferometer (DI). The DI uses (1) a reference wave, (2) an electro-optic image sensor to feed a digital computer and (3) self calibration (real and imaginary). These are all techniques which we plan to employ. The DI is used in lens fabrication to measure aberrations to $\lambda/100$ (a three sigma measurement). This is equivalent to an rms phase error of 1°.2. The present DI is currently limited to this precision only by the size of the digital memory associated with its PDP-8 computer.

Optical specifications for the proposed system are listed in Table III below:

Mirrors	First surface, low scatter, $<\lambda/100$
Laser	HeNe preferred-other if necessary
λ	0.6328 μm preferred - 1 μm if necessary
Phase Modulators	Piezo-electric driven mirrors
Amplitude Modulators	Acousto-optic or electro-optic
Liquid gate	$<\lambda/100$, low scatter
Lens L_1 and L_2	Strehl Ratio ≥ 0.995, finite conjugates on axis, single wave length, doublet. Focal length ≈ 1.5m, aperture $\gtrsim 100$mm
Film Transport	Automatic centering and positioning

(All aberration specifications are rms)

TABLE III - Optical Element Specifications

III-A.4 Some Special Considerations Relating Visibility Numerical Field Of View (NFOV) and the Number of Points in the Brightness Map

Until recently the number of points on a side in the brightness map has been assumed to be equal to the number of points on a side in the visibility plane (NFOV). The historic reason for this common assumption was the fact that the brightness map was derived from the visibility data by the use of the Fast Fourier Transform (FFT). The number of output points produced by the FFT is equal to the number of input points.

There are a class of problems where a very large number of output points are required (i.e., CLEAN for example) where heavy over sampling is necessary. If the FFT is not used, this large number of output points does not necessarily imply a large NFOV. In particular for the VLA, it seems that there is no case where a NFOV greater than approximately 2000 is required.

The optical processor lets one relate a large number of brightness points to a smaller number of visibility points, as does a classical ("direct") Fourier transform. This may be done by placing a large number of diodes (4000 is proposed) in the output plane while limiting the input NFOV to a smaller number (2000 is proposed). The important requirement is that the visibility points be placed with a positional precision corresponding to the larger number of points in the output plane. This appears possible with the processor/film record design under study. In operation, either the described baseline-time input mode would be used or a raster input mode where the data are not gridded. In this latter case the data on a raster line would be wriyten only as the beam crossed actual u-v curves. The result is that brightness maps are possible involving several thousand points on a side even though the film recorder itself has a beam spot size limiting the input NFOV to one or two thousand. A very large amount of computation would be required to produce brightness maps of comparable size using a conventional FFT approach.

III-A.5 Map Output System

The map output system consists of a diode array to sense the optical Fourier transform, associated amplifiers and switching electronics, A/D converters and fixed pattern noise removal circuits. It also includes the film recorder used to record output maps on film. An interface to a general purpose computer is also envisioned. As mentioned earlier, film record generation for output maps fits within the uv plane specifications for the film recorder and is not further discussed.

The sensor system consists of a linear silicon diode array which is electronically scanned in one direction and mechanically scanned in the other generating a square array. Each row of the array will be 4000 elements long. Individual diodes in this array are typically on 7.5 to 25 μm centers, resulting in a possible output plane size of 30 to 100 mm. The assumed (in previous discussions) dimension here is 15 μm and the corresponding output plane is about 60 mm square. These diodes are on monolithic silicone chips which will be mounted on a mechanical scanning bar. Eight chips of 500 diodes each is a representative configuration; four chips of 1024 diodes and 3 chips of 1872 diodes are also possible. The bar is an isothermal heat sink which is maintained at a cool (e.g. -50°C) temperature. This reduces the dark current (produced by generation - recombination processes) and stabilizes the response of the arrays such that it is possible to obtain better than a 1000:1 dynamic range.

It is reasonable to scan each array electronically at a 320 kHz rate. That is, one output datum is obtained every 3.1×10^{-6} sec. With eight arrays, all being scanned simultaneously, the scanner data rate is 2.56 MHz. The total array scan time is 6.25 sec. This scan time must be doubled however, because of the need to measure both the $/S + R/^2$ and the $/S - R/^2$ terms associated with the linearized output. The change of sign is obtained by introducing a π radian phase shift in the reference wave between scans. This phase modulation is a square wave with a period equal to twice the individual array scan time. The light associated with $/S + R/^2$ is first scanned, A/D converted and stored. 1.56×10^{-3} sec later the light associated with $/S - R/^2$ is scanned, A/D converted, subtracted from the previously stored scan and delivered to the output map storage memory. This technique automatically removes much of the fixed pattern noise present in diode arrays. The result is a 10 bit map. The total processor output rate is 1.28×10^6 words/sec, which comes from 8 separate arrays, each operating at 1.6×10^5 words/sec.

Custom designed diode array camera systems are available from the manufacturers of the diode arrays, and from others. The above description is based on Reticon's C-series arrays, but similar conclusions would be drawn from Fairchild data. A large dynamic range camera using Reticon arrays is in operation at Kitt Peak.

The salient parameters of the output sensor system are:

Scan	electronic and mechanical
Number of points	4000 x 4000
Configuration	8 chips, 500 diodes/chip
Dynamic range (max S/N_{rms})	1000:1 (10-bit precision)
Output rate	1.28×10^6 words/sec

TABLE IV

III-B Processor Performance

Using a fine-grain emulsion with the film recorder, optics, and sensor systems previously described leads to performance parameters for the overall processor which are summarized in Table V. Some parameters cannot be specified at this time because we need detailed component data which are not available without some laboratory measurement and because a detailed error analysis has not been performed.

An area for further study is the differences in map quality which result from cell averaging and gridding on the one hand and convolution of data with a finite writing spot on the other. The defects and the difference between defects seem to impact the size of the numerical field of view. Since the suggested optical system and sensor array are essentially diffraction limited and completely sampled, the principal differences will be due to the format and precision with which the complex visibility is written on the input film. It is this area which requires a specific mathematical model and further study.

PROCESSING SYSTEM PERFORMANCE

uv plane size (space-BW product)	2000 x 2000 cells
xy plane size	4000 x 4000 cells
Noise due to scattered light	<-20 db (below peak of a single point object)
Film record generation time	1-10 sec/frame
Processor read out time	12.5 sec/frame
Film chemical processing time	
Batch (250 frames)	10 min
Single	10-30 sec
Total Optical Processor time from request to map	
Batch (250 frames)	~1.5 hr
Single	22 + (1-30)* sec

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[*] Depends on film chosen. More than one film can be used. Some processing times are less than 1 sec.

TABLE V

III-C Cost Summary

The estimated processor development and construction costs are given in Table VI. Manpower costs are shown only for the efforts done outside NRAO, under contract.

	1976	1977	1978
EIRM/Ampex Study	100K		
Frequency Sort Machine			150K
Film Recorder		150K	
Automatic Developer			20K
Design & Assembly		125K	125K
Optical & Related Hardware		70K	
Digital Output		30K	30K
TV Monitor			20K
Control Computer			50K
Electronics		10K	10K
TOTAL BY YEAR	100K	385K	405K
Contingency		30K	30K
TOTAL			950K

TABLE IV

IV. COMPARISON OF OPTICAL/DIGITAL PROCESSORS

IV-A General*

It is difficult to make a good quantitative comparison between optical/digital (optical) and conventional digital (digital) processing. One may compare the optical system with a benchmark digital system of comparable speed. The system costs (Tables VI and VII) are both 10^6 dollar within the accuracy of the estimates. The cost of the optical processor includes design costs. Thus, if two processors were required, the cost comparison would favor the optical processor. These general statements are useful, but in fact the required comparison involves many more considerations than just the capital costs. In fact the processors offer different kinds of capabilities and would be used in different ways. A comparison of these must weigh heavily on a decision as to what processor to use.

The digital system we consider for comparison is based on the 10-second digital system described by Clark in VLA Computer Memo #127. Developments in solid state memory (for the transpose involved in the FFT) and in hardware FFT devices now make it appear that a 2048 x 2048 FFT can be done in about 4 seconds plus the I/O time for the data input and map output. The equivalent time for the optical processor is about 3 seconds per frame due to film development (in batch mode). The I/O times are determined by recovering the data from disk memory and storing the output map back on disk and thus are about the same for the two systems, and amount to about 15 seconds per map.

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* All comparisons are made based on two dimensional mapping. It is believed the 3D problems scale the same for both approaches.

Costs of Comparison Digital System

Sort Station	107K
Merge Station	147K
Comutation Station	144K
Transpace Station	250K
Fast FFT Station	150K
Hardcopy Output Device	100K
Film Developer	20K
System Integration	100K
	1018K

TABLE VII

IV-B Detailed Comparison

IV-B.1 Capital Investment

The capital investment is about the same for the two systems being compared - Digital - $1018K. Optical - $950K. Both numbers are uncertain by about 20% and thus there is no significant difference.

IV-B.2 Processing Time

The digital processor has rather different properties from the optical one; it produces no output during the completion of the u,v sort. This delays the first output about four hours beyond the end of the observation. For sorted data, the processing time is determined by the disk transfer times, giving a total frame time of about 20 seconds, going from u,v sorted data to a digital map on disk. The optical processor does not suffer from the pipeline delay and starts producing maps immediately. In a production mode, the per frame time is comparable to the digital system, about 20 seconds - probably a few percent faster than the digital system given the same interfacing equipment. However, the processing time of a single frame is also of interest. For this, the digital machine is rather faster, because the optical processor will take 30 seconds to process the film frame of the recorder data.

The optical processor also may be used in a mode not involving digital recording. In this "quick look" mode it is about twice as fast as when used to provide computer readable maps.

IV-B.3 Fourier Transform

The digital processor takes the gridded FFT of the data. This necessarily suffers from aliasing because of resampling the data with a uniform grid. That is, a source lying outside the synthesized field of view will appear within it, reduced in intensity by various factors including the sin x/x due to the convolution involved in gridding and the smearing by the 10 second integration time in the correlator (about $2/\pi$ and .8 respectively for a source just off the edge of the field of view). Except in configuration A, such sources are heavily attenuated by the antenna beam if full field maps are made.

Beam positioning errors in the film recorder produce errors in the image which increase with distance from the center of the image plane; the point source response is altered at the edge of the field. It can be shown that at a point in the image corresponding to the space-bandwidth product N of the recorder, the relative loss of peak point source response is $4\pi^2N^2\sigma^2$, where σ is the rms relative positioning error of the recorder. Thus, for our parameters of N=2000 and $\sigma = 1 \times 10^{-5}$, we have a 1.6% drop at the edge of the field. This non-systematic effect appears less important than the drop off at the edge of the field due to the finite recorder spot size and the resolution limit of film.

For the digital system, cell averaging and gridding produce similar errors; the corresponding loss is 1-sinc(0.5) = 36%, for points at the edge of the field. In addition, as mentioned above, the gridding causes outlying portions of the map to be aliased inward, unless very large arrays are used; the optical system is essentially free of this problem.

IV-B.4 Output

Digital - the digitized output is described by the mathematical model of the processor to a high precision, on the order of .02%. For hardcopy/picture output a Dicomed type device is priced which writes one frame in approximately three to eight minutes.

Optical - the digitized output is described by the mathematical model of the processor to an accuracy within 1%. The film writer used to write the data may also be used as a hardcopy/picture output device and produces a very high quality pictoral output in about 10 seconds per frame.

IV-B.5 Operation

The operational costs of the two systems are comparable. The digital system is probably slightly more expensive to maintain, but the optical system probably requires an operator with higher qualifications than the usual computer operator.

IV-C Additional Capabilities

Slight variations of the two processors could be used to solve various astronomical problems. Each processor has strong and weak points for a particular problem. Some of these are discussed below:

IV-C.1 Interpolated Output Points

As discussed earlier, as many as 4000 diodes can be used in the map readout, so that the optical processor can routinely produce nicely interpolated output maps of ~4000 on a side. To achieve the same number of output points using the digital processor, either a very large FFT must be used or the output must be numerically interpolated. Both of these take significant amounts of time.

IV-C.2 Further Development

The subject of further development enters under two headings - improvements to the system discussed here and the possible purchase of a second unit as part of a post-processing system.

The present optical processor is not truely interactive because of the use of film and the resulting 30-second development time. Light modulators have been developing steadily and it appears that they will replace film in optical processors in the near future. This development provides hope for a truly interactive system for the spectral-line problem.

It seems unlikely that a digital system constructed now would be so quickly passed in technology to justify altering it. Improvements in medium access-time memory will somewhat reduce the cost of a second system built a few years from now. However, this would probably not be as great a saving as the elimination of a very large part of the initial engineering costs of the optical processor in a second unit (perhaps as much as $300K). If a second film recorder were not required (as for example, if data would be carried on film from the site to the off site facility) the duplication cost would be reduced by an additional $150K.

PROPOSED 6-MONTH SYSTEM STUDY FOR VLA OPTICAL DATA PROCESSING

1. REVIEW VLA DATA-PROCESSING REQUIREMENTS

   RESOLUTION
   S/N RATIO
   PROCESSING ALGORITHMS
   IMAGE ANALYSIS PROCEDURES
   OPERATING SPEED

2. TRADEOFF STUDY OF AVAILABLE SUBSYSTEM TECHNOLOGY

   INPUT SIGNAL FORMAT AND RECORD
   PROCESSING OPTICS
   IMAGE READOUT DETECTOR
   POST PROCESSING AND DISPLAY
   IMAGE RECORDING
   FILM DEVELOPER

3. EXPERIMENTAL VERIFICATION OF PERFORMANCE OF KEY SUBSYSTEMS

   OPTICAL RECORDER
   RECORDING FILM
   OPTICAL PROCESSOR LENSES
   FILM DEVELOPER

4. SELECTION OF A PERFORMANCE AND COST-EFFECTIVE SYSTEM DESIGN CONCEPT

5. PREPARATION OF SYSTEM AND SUBSYSTEM DESIGN SPECIFICATIONS

6. DESCRIPTION AND PERFORMANCE ESTIMATES OF THE SUBSYSTEMS AND THE TOTAL SYSTEM