NATIONAL RADIO ASTRONOMY OBSERVATORY

Charlottesville, Virginia

May 5, 1975

VLA COMPUTER MEMORANDA #122

"A Descriptive Introduction To Optical Processors
Suitable for VLA Line Mapping"

L. E. Somers

I. INTRODUCTION

A conventional digital solution to the VLA spectral line map processing problem may not be the most cost effective. The problem is one of the cost and time required to process and display massive amounts of data. The time requirement is that of the observer's/analyst's needs and attention span as well as to keep up with the data rate. The processing requirement consists of sorting or formating, Fourier transforming, and data recording. Finally, the display requirement is to present the results in a convenient and understandable manner. The scope of our aspirations is summarized below.

Signal Bandwidth	$\simeq 0.5 - 50 \times 10^6$ Hz
Observing Time	$\simeq$ 0.1 to 12 hrs.
Number of Frequency Channels	$\simeq$ 100 - 250
Number of Resolution Cells in a Map	$\simeq 10^6 - 10^7$
Desired Processing Time	Significantly less than observation time
Display Time	$\leq$ 5 min.

Optical processors may offer attractive solutions to this problem. Their intrinsic Fourier transforming properties, combined with suitable electro-optic transducers, provide a solution which could be adequate in performance, cost effective, flexible and conveniently interactive. The current state-of-the-art in optical processing, e.g., electro-optic modulators, optics, light sources, detector arrays, digital interfaces, etc., can support the development of optical processors for the VLA line problem. The principal requirement at this early point in a design study is not to design an adequate processor. Rather, it is to identify possible configurations and the resultant performance characteristics, assess their compatibility with the observer's requirements, and then select the configuration of greatest merit. Three general configurations have been identified. The resulting processors have significantly different characteristics. The Analog Optical Processor leads to a total-power radio telescope. The Analog Optical Correlator results in a correlation telescope. The u-v Plane Processor (used in conjunction with digital correlators) also results in a correlation radio telescope. The first and second configurations are driven from the receiver i.f. and are relatively inflexible. The u-v Plane Processor is driven from the correlators and has great flexibility.

There are a number of basic requirements which must be satisfied by any optical processing approach. Cost effectiveness is one, including not only the capital investment (design, fabricate, test, debug, etc.) but also the operating cost at the site. A second is performance. One must be able to process pictures free of any significant distortion or degradation due to the image forming process. Timely processing of the data is also important. Timely in the sense of generating maps at the rate required by the observer/analyst as well as timely in keeping up with the data rate. And finally the overall development and operation of such an instrument must be achievable within the two to five year time span allotted this program.

In addition to these basic requirements it is desirable to have both on-line and off-line operating capabilities in the optical processor. By on-line we mean "during an observation". The observer should be able to monitor his data in all frequency channels while observing and thus be able to insert his judgement etc. during observation. In addition, if there is excess processing capacity in the optical processor, time shared off-line operation would be desirable. For example, an observer with some previous day's data might wish to use the optical processor on a time-shared basis to edit, analyze, sidelobe suppress, combine, display, etc. This we refer to as off-line processing. In addition to on-line and off-line operation, the processing of continuum data in the optical processor may also be desirable.

Map display is a problem of difficulty and importance comparable to the sort and processing problem. It is possible to build a number of photographic and other electro-optic encoding and display generating devices into the output of the optical processor. These facilities should be flexible with respect to polarization, color and spatial encoding schemes for the convenient synthesis of multi-channel and multi-dimensional radio sky maps. There is great opportunity in this area which has not been explored W.R.T. the VLA; the observer/analyst requirements must be explored and identified before further progress can be made.

In optical processors, implementing the "sort" and "weight" is entirely different than the equivalent operations for a FFT. No thought has been given to this implementation for either of the Analog Optical Processors. These operations can be performed in the u-v Plane Processor by a combination of algorithmic and position (in baseline-time) gain modulation during the modulator input operation. The details depend heavily on the modulator (oil, film, electron beam, laser beam, etc.).

These processes will be the subject of a future memo; after the most attractive optical processor has been selected.

The optical processor will be intimately integrated with other map processing computers. In a sense it will stand alone (and process whatever data is presented), but the selection, pre-processing and presentation of data to the optical processor will be done under the supervision of a general purpose digital computer. This applies with particular emphasis to the u-v Plane Processor.

Finally, flexibility of processing and approach to the use of the optical processor is important. By flexibility, we mean the ability to interact conveniently (within one's attention span) with the massive amounts of imagery available from a line observation. The observer/analyst should be able to add, subtract, delete, multiply, weigh, combine, edit, abstract, over-lay, contour, inject, etc., various data in the study and analysis of his observations.

II. OPTICAL PROCESSORS

By way of general introduction, Figure 1 characterizes the radio telescope as an image forming instrument. Shown is a "lens" forming an image of the radio sky. The plane u'v' containing the radio "lens" is also the plane of the entrance pupil of the radio telescope. The concept of an entrance or exit pupil (associated with a lens) is very useful. They are analogous to the input and output terminals of an electrical network.

In the diffraction theory of image formation, the entrance pupil contains the Fourier transform of the object complex field distribution. The exit pupil contains the entrance pupil distribution weighted by the (complex) lens aberration function. Finally, the image formed by such a system is the Fourier transform of the exit pupil complex field distribution. The energy distribution associated with this image is proportional to the usual brightness or intensity image. This description of image formation is the classical diffraction theory of image formation. It is also the basic concept behind the Analog Optical Processor shortly to be described.

There is another way of obtaining the same brightness image, i.e., by way of the van Cittert-Zernike relationship. Specifically, the complex degree of coherence μ_{12} is the Fourier transform of the object (sky) brightness distribution. This thoery forms the foundation of all imaging correlation telescopes. One simply records the complex degree of coherence (proportional to the complex visibility function) in the u-v plane and Fourier transforms to obtain the sky brightness map.

The same optical configuration can be used to implement both of the above image forming concepts, Figure 2. This configuration performs a Fourier transform on the complex optical field between the entrance pupil [input plane] and the image [output plane]. Thus it is linear in the complex optical field. The distinction between an output which is linear in the optical field or in the square of the optical field will be important in later paragraphs. The spatial Fourier transform relationship is valid for monochromatic and quasimonochromatic light.

III. THREE BASIC PROCESSORS

There are three general types of optical processors which can be applied to the VLA line problem. They are referred to as the Analog Optical Processor, the Analog Optical Correlator and the u-v Plane Processor. The first results in a total power radio telescope. The second results in a correlation radio telescope. It is implemented with an analog electro-optic correlator capable of performing an optical modulation proportional to the product of two i.f. signals. The third results in a conventional correlation radio telescope. It requires digital correlators. The three different concepts are shown in Figures 3, 4 and 5. Figure 6 shows how the u-v Plane Processor might be integrated into the overall VLA map processing and display system. Tables follow Figure 6 summarizing some of the more important characteristics of these processors. In the remainder of this memo some general observations on the nature, characteristics and problems associated with these approaches are offered.

Variations on the basic themes are possible. Most appear to be more in the form of subsets rather than fundamentally different. Additionall basic configurations, if recognized, are welcome.

A. The Analog Optical Processor

In this configuration (Figure 3) we form an optical analog of the r.f. wavefront incident on the entrance pupil of the radio telescope. That is if

$$U_{u'v't}\Big|_{z'=0} = A_{lm}\, e^{-i[\omega_r' t - k_r(l u' + m v')]}$$

represents a general monochromatic (or quasi-monochromatic) r.f. wave propagating in the l,m direction, an optical analog of that wave

$$U_{xyt}\Big|_{z=0} = G A_{lm}\, e^{-i[(\omega_0 + \omega_r)t - K k_r(l x + m y)]}$$

is formed in the entrance pupil of the optical system by a suitable spatial-temporal modulator. This optical wavefront is then spatially Fourier transfomred by the lens to form an image

$$\mu_{x''y''t} = G\, A_{lm}\, \delta\left(x'' - \frac{Kl}{\lambda r}\right) \delta\left(y'' - \frac{Km}{\lambda r}\right) e^{-i(\omega_0 + \omega_r)t}$$

in the output plane of the processor. Optical detectors [film, diode arrays, the eye, etc.] will perform a $\langle \mu \mu^* \rangle$ operation on $\mu_{x''y''t}$ thus generating a map proportional to the radio sky brightness. The title Analog Optical Processor is thus evident. We have generated an optical analog of the r.f. wavefront and formed an image with that wavefront.

The spectral line filtering (≈250 channels) must be performed prior to the squaring operation. This could be in the output plane of the processor [conceivable] but is more likely to be implemented prior to the input plane. Thus, for a 5 MHz bandwidth, this processor would work at a sampled data rate in excess of 10 MHz.

Implementing the modulation indicated to generate the optical wavefront can be done with membrane or Acousto-optic devices. Another approach would be to process the real and imaginary data separately and combine them in the output; no serious thought has been given to this possibility.

An area of unexplored technology, with respect to this processor, is the output image sensor. The size, integration time, dynamic range, uniformity, and data rate requirements on that sensor may be severe problems. The output from a conventional image sensor is directly proportional to sky brightness.

Both this and the Analog Optical Correlator accept i.f. signals at the processor input terminals. The noise smoothing integration is done in the output (image) plane of the processor. Since the time-bandwidth at i.f. is on the order of 10^7 times greater than that after integration, it is unlikely we will use either of these processing concpets in an off-line mode because of data storage limitations.

B. Analog Optical Correlator

Another approach to this problem would implement an array of analog multiplyers which are capable of modulating a coherent optical wavefront (Figure 4). In this processor the i.f. signals would be brought (in pairs) to the appropriate analog multiplyer element. It would generate an optical amplitude transmission proportional to the product of the two voltages. The modulated light would then be spatially Fourier transformed by means of the lens and the output image formed in the output plane of the processor. This results in a correlation telescope. This system could probably be implemented with membrane devices, acousto-optic devices and perhaps electron beam-on-film devices.

The principal advantage of this approach is the economy in not having to build a large number of digital correlators. It shares this advantage with the analog optical processing approach. Principal liabilities revolve about the integration being done in the output plane as well as the requirement for a linear output. Specifically, the output plane sensor would have to be capable of coherently integrating a time varying complex amplitude image for a number of seconds in each of 250 line images. The specific requirements and their realizability with current state-of-the-art technology must be studied further if this processing concept proves to be attractive.

C. u-v Plane Processor

In the u-v Plane Processor (Figure 5) we rely on the Fourier Transform* relationship between the complex visibility and the sky brightness. A Fourier transform is implemented by generating a complex optical field (propostional to the complex visibility function) in the input plane of the processor. This can be done by a sequential (real-imaginary) input operation or by modulating the amplitude and phase of a spatial carrier with the visibility function. The latter approach reduces the effective space-bandwidth product of the processor but certain electro-optic media require such a carrier and the reduction is usually worth the cost.

In this approach the conventional digital correlator would be used; the spectral lines being generated prior to/or in conjunction with the correlation process. The time average of the correlator outputs would also be performed by digital techniques. The resulting complex visibility would be delivered to a data store. There are at least two different stores available. One is a photographic or image storage media; actually storing the u-v points for each frequency channel as they are generated. Another is a magnetic disc store. Here the disc memory would be so constructed that the input format (frequency-baseline-time) would be accepted and an output format (time-baseline-frequency) would be generated. If a disc store is used, it would probably be used in conjunction with an electron beam-on-oil film input plane transducer.

The u-v Plane Processor has many advantages. It is a conservative approach. If implemented with current state-of-the-art technology, it can realize a partial (map size limited to $\simeq 10^6$ total points) VLA line processor. It is a straightforward engineering undertaking to improve existing technology to implement the final processor. 250 channels is no problem. It has a great deal of flexibility, i.e., it can display both the u-v plane and the corresponding map simultaneously and it can support both on-line and off-line processing on a time shared basis.

---

* van Cittert-Zernike

Editing, calibrating, adding, weighing, convolving, displaying, etc. can be performed under the control of a supervisory digital computer.

The principal liability of this processor is that the Fourier transform of the visibility function appears in the output plane of the processor as the complex optical field. This is undesirable because most optical detectors are sensitive to the field squared rather than to the field. This would result in radio maps which are the square root of the square of the brightness distribution. Thus, the negative and positive sidelobes would both appear as positive sidelobes, leading to interpretation ambiguities. There are a number of ways around this problem. Holographic techniques could be used. A time modulated coherent bias wave could be introduced to permit discrimination between the linear and the non-linear output terms. Alternatively, the all positive map could be accepted as an interim map which would (perhaps) be suitable for most astronomical applications; the proper processing being done only when required.

If it is necessary to provide a linear map, these schemes will be further evaluated and practical means of implementing them developed.

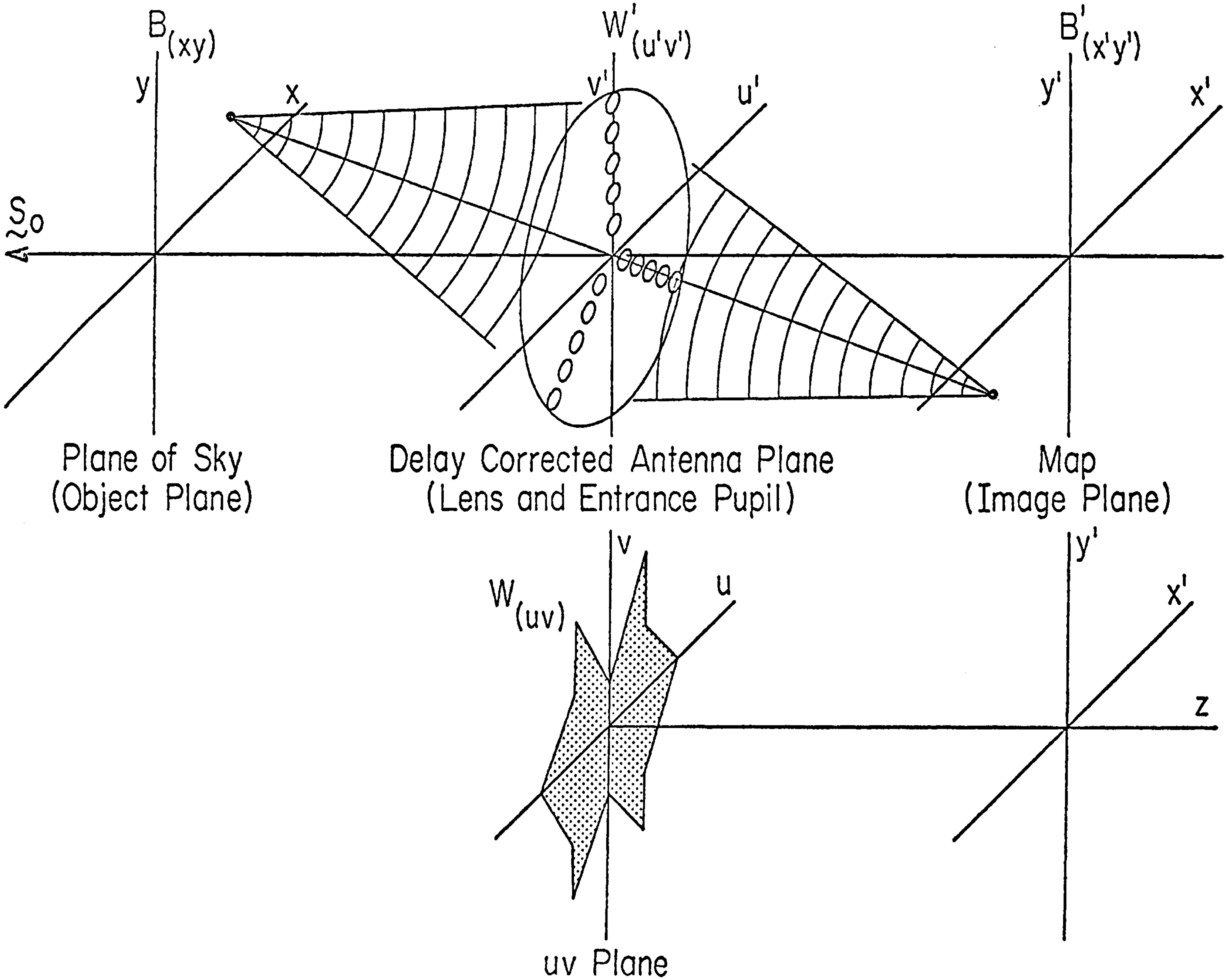


FIGURE 1

[redacted] [redacted]

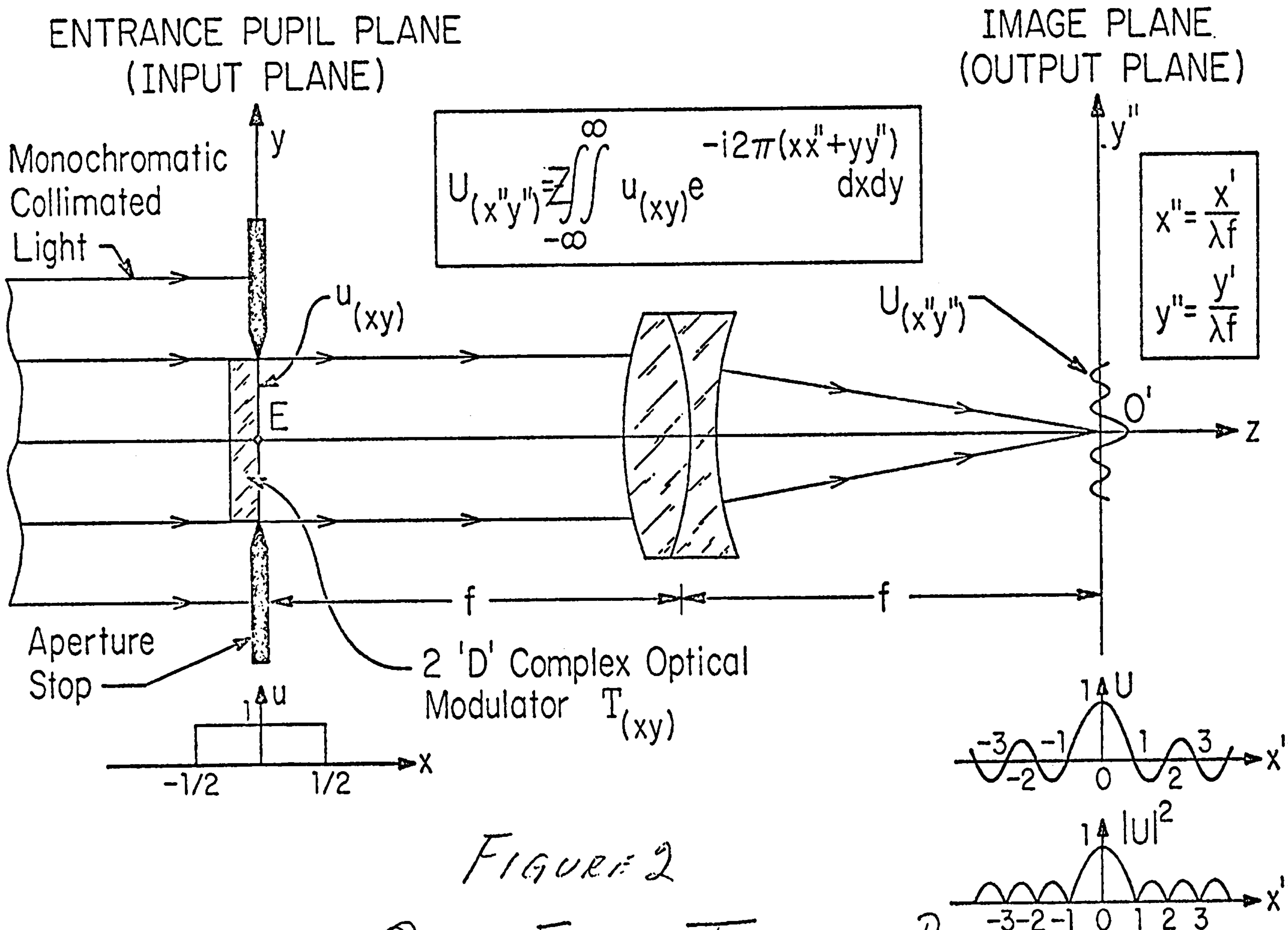


FIGURE 2

OPTICAL FOURIER TRANSFORM PROCESSOR

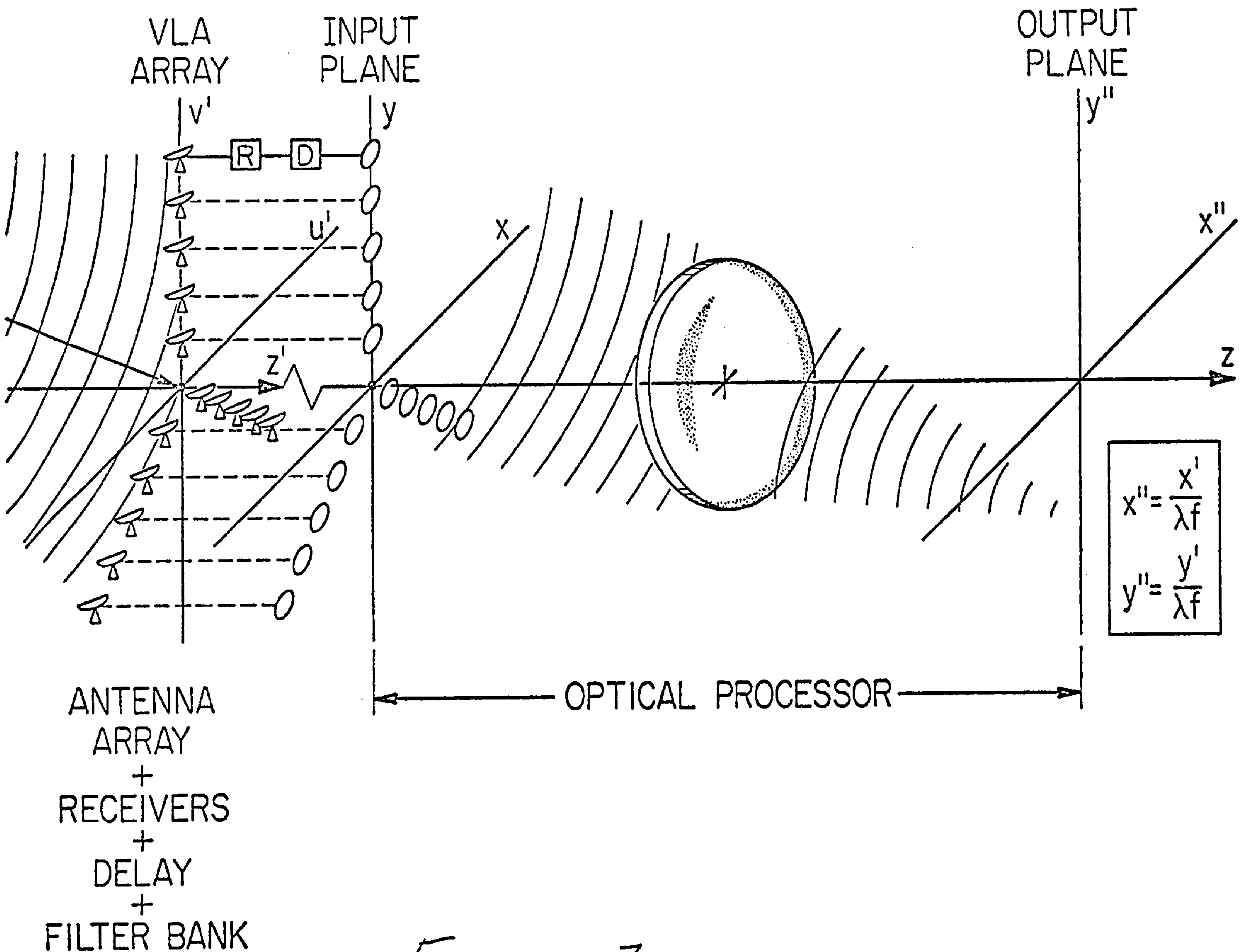


Figure 3

[redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted]

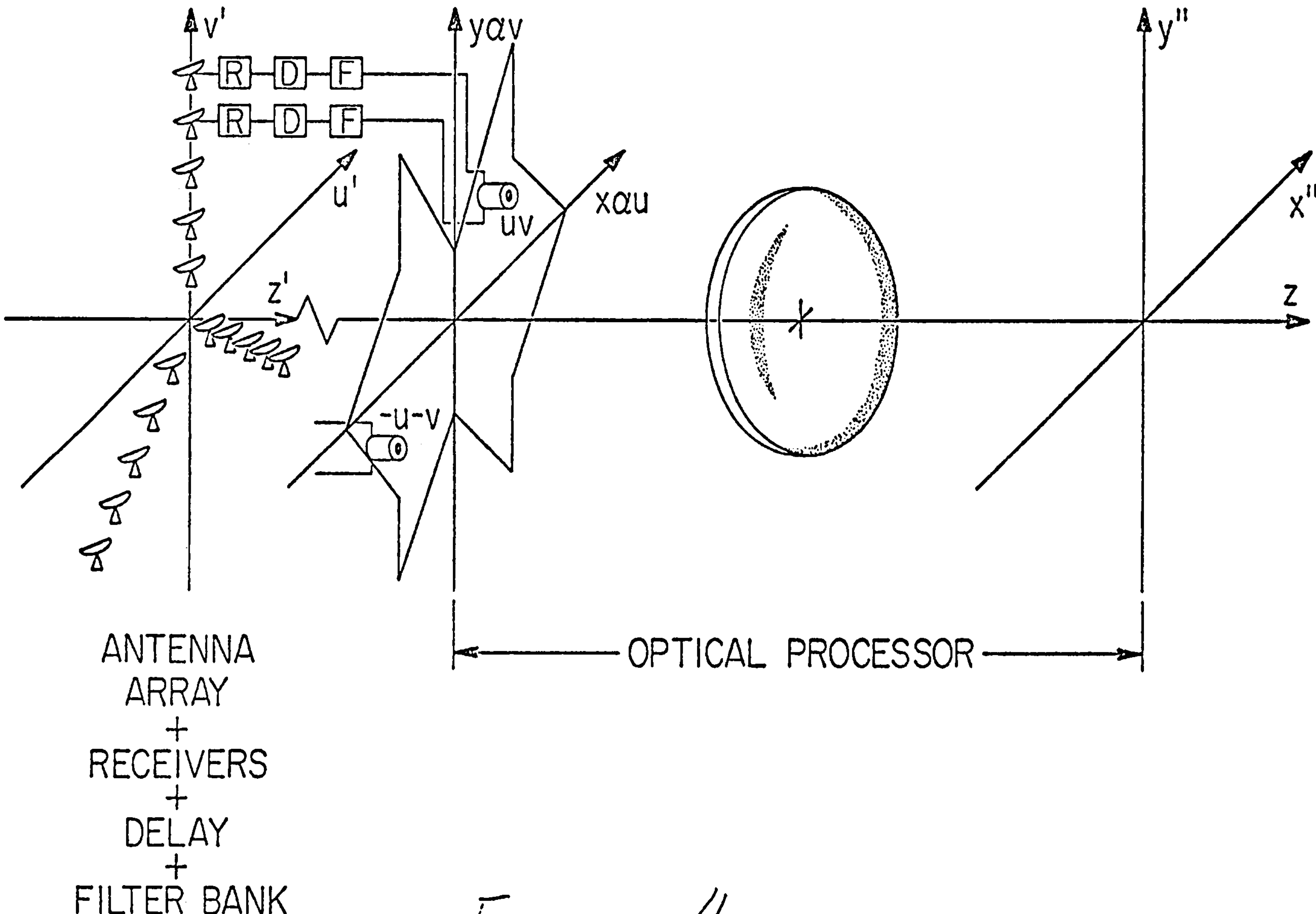


FIGURE 4

ANALOG OPTICAL CORRELATOR

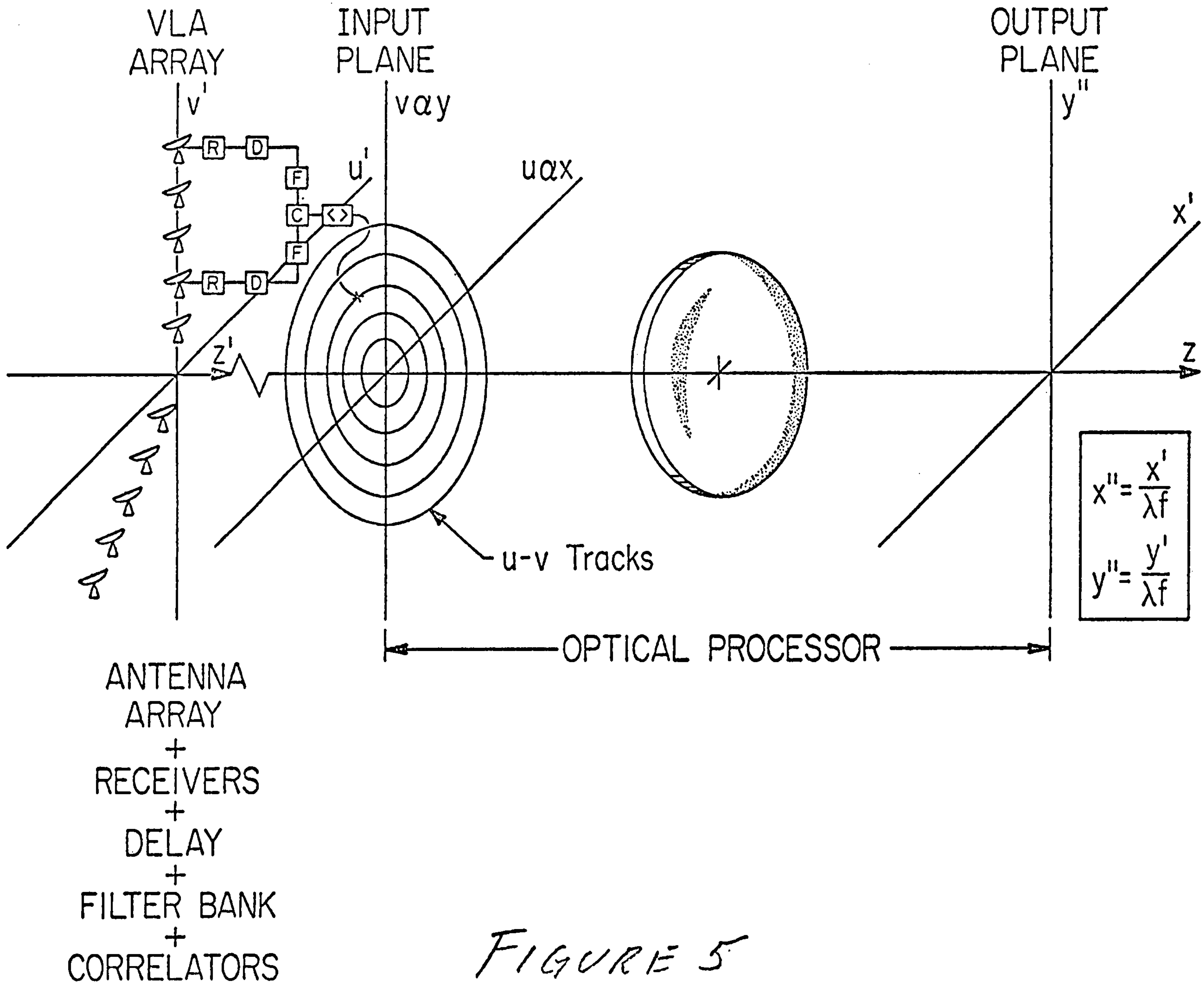


FIGURE 5

U-V PLANE PROCESSOR

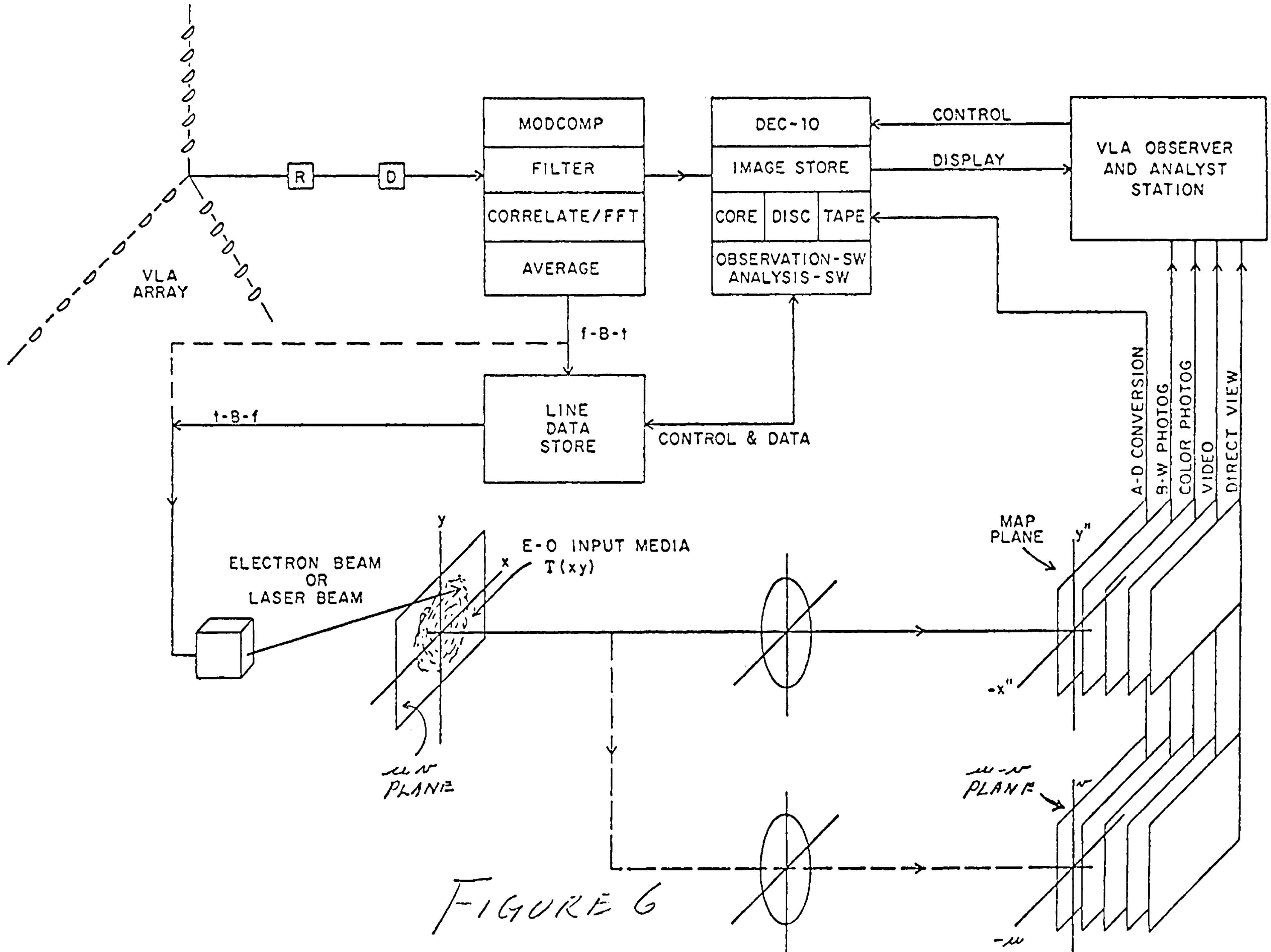
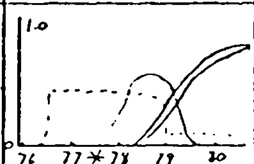
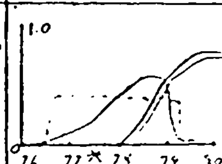
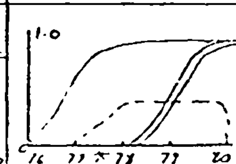

VLA ARRAY
R
D
MODCOMP
FILTER
CORRELATE/FFT
AVERAGE
DEC-10
IMAGE STORE
CORE
DISC
TAPE
OBSERVATION-SW
ANALYSIS-SW
CONTROL
DISPLAY
VLA OBSERVER AND ANALYST STATION
f-B-f
t-B-f
LINE DATA STORE
CONTROL & DATA
A-D CONVERSION
B-W PHOTOG
COLOR PHOTOG
VIDEO
DIRECT VIEW
ELECTRON BEAM OR LASER BEAM
E-O INPUT MEDIA
T(xy)
y
x
u-v PLANE
MAP PLANE
y"
-x"
u-v PLANE
-u

FIGURE 6

GENERAL CHARACTERISTICS	ANALOG OPTICAL PROCESSOR	OPTICAL CORRELATION PROCESSOR	u-v PLANE PROCESSOR	COMMENTS
Number of Frequency Channels	10^2 + Probably image sensor limited	10^2 + Probably image sensor limited	10^2 to 10^3 Storage limited	Space Multiplexed on film or time multiplexed on oil or PROM modulators.
Current Technology	Marginal - No commercial E-O device array available	Marginal - No commercial device array available	Probable - Commercial device array available	Optical Meeting Topic; Final SOA Answer 6/15
Cost ($)	Filters and 10^6 +	Filters and 10^6 +	Filters and Correlators and 10^6 $\pm$	Cost cannot be well estimated at this time. u-v plane processor may be least expensive. Cost estimate available by 9/75.
	Cost Bounds $(0.5\times10^6 <$	$\$<2.0\times10^6)$ for all 3	processors.	
Type Telescope	Total Power	Correlation	Correlation	
Probability of Success	0.5^+	0.5^+	0.8^+	Optical Meeting Topic. Final SOA Answer 6/15
Image Quality	Impossible to specify quantitatively at this time. All three processors should be capable of image quality in excess of fundamental data limit for VLA in line mapping mode of operation.			
Post i.f. "Electronics"	"None"	"None"	Filters and Correlators	"None" ≡ relative to banks of correlators
Interim System Compatibility	No/Partial	No/Partial	Yes/Complete	
Orthodox Approach	No	No	Yes	
Development Cycle $/yr				- - - Device Dev. ——— System Dev. (1st) ═══ System Dev. (Final) * Interim Line Availability
Usefulness in post observation map analysis	Little, Depends on E-O Input Device	Little, Depends on E-O Input Device	Great, e.g. Convolution, Weights, Taper, Element in an iterative loop	Post observation map analysis can be served well and flexibly by the u-v plane processor.
Useful multi-dimensional display device	Not likely	Not likely	Very convenient and flexible display device	
On-line/Off-line Capability	Not Practical	Not Practical	Yes	
Map Access Time Analysis Observation	Not Available 1 sec.	Not Available 1 sec.	1 sec. 1 sec.	
Display of u-v Plane	None	None	Convenient	
Expandable # Frequency Channels	Unknown	Unknown	Yes	To be discussed at Optical Meeting.
Feasibility Demonstration	Possible in 18-24 Months	Possible in 18-24 Months	Possible in 6 Months	Times may change pending Optical Meeting.
Contractor Dependence	High	High	Medium to low	In-house experience can be gained prior to final system design with v-p Plane Processor.
Operational Reliability Final Format Interim Format	+ 0	+ 0	+ +	Out of +, 0, -.