NATIONAL RADIO ASTRONOMY OBSERVATORY

Charlottesville, Virginia

May 10, 1977

MEMORANDUM

TO: Optical File and Review Committee

FROM: L. E. Somers

SUBJECT: Summary Memo on VLA Hybrid Processor

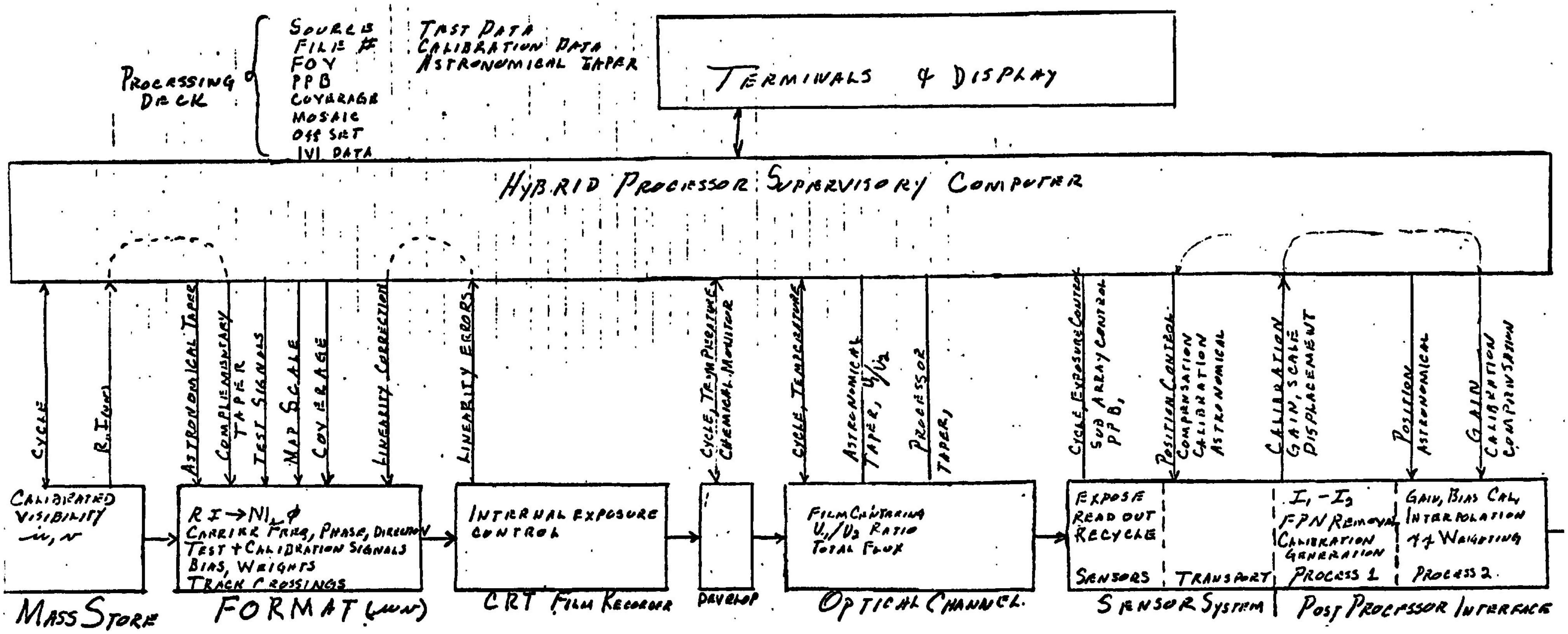
I. Processor Motivation and General Description

Map generation and reduction for the spectral line VLA is a very large data processing problem. When solved in an all digital processor there are a number of unattractive characteristics associated with the resulting processor or map. In contrast, a hybrid implementation consisting of digital input and output to an optical complex Fourier transform instrument results in a processor with fewer unattractive characteristics. For these reasons a hybrid processor for the VLA has been studied and the basic design established.

The complete VLA processing configuration is envisioned as a multi-processor complex with a completely integrated ("buried in the middle of") special purpose hybrid processor. In the remainder of this document we are concerned only with the hybrid processor.

The basic hybrid processor components are shown in figure 1. They consist of:

1. A sophisticated digital pre-processing interface called FORMAT,
2. A precision CRT film recorder with film developing station,
3. The Fourier transform optical channel,
4. A sensor system, and
5. A post processor interface.


PROCESSING DECK
SOURCE
FILE #
FOV
PPB
COVERAGE
MOSAIC
OFF SET
|V| DATA
TEST DATA
CALIBRATION DATA
ASTRONOMICAL TAPER
TERMINALS & DISPLAY
HYBRID PROCESSOR SUPERVISORY COMPUTER
CYCLE
R. I.
ASTRONOMICAL TAPER
COMPLEMENTARY TAPER
TEST SIGNALS
MAP SCALE
COVERAGE
LINEARITY CORRECTION
LINEARITY ERRORS
CYCLE, TEMPERATURE
CHEMICAL MONITOR
CYCLE, TEMPERATURE
ASTRONOMICAL TAPER, U_1/U_2
PROCESSOR TAPER,
CYCLE EXPOSURE CONTROL
SUB ARRAY CONTROL
PPB,
POSITION CONTROL
COMPENSATION
CALIBRATION
ASTRONOMICAL
CALIBRATION
GAIN, SCALE
DISPLACEMENT
POSITION
ASTRONOMICAL
GAIN
CALIBRATION
COMPARISON
CALIBRATED VISIBILITY
u, v
$RI \rightarrow NI, \phi$
CARRIER FREQ, PHASE, DIRECTION
TEST + CALIBRATION SIGNALS
BIAS, WEIGHTS
TRACK CROSSINGS
INTERNAL EXPOSURE CONTROL
FILM CENTERING
U_1/U_2 RATIO
TOTAL FLUX
EXPOSE
READ OUT
RECYCLE
SENSORS
TRANSPORT
$I_1 - I_2$
FPN REMOVAL
CALIBRATION GENERATION
PROCESS 1
GAIN, BIAS CAL
INTERPOLATION
& WEIGHTING
PROCESS 2
MASS STORE
FORMAT (u,v)
CRT FILM RECORDER
DEVELOP
OPTICAL CHANNEL
SENSOR SYSTEM
POST PROCESSOR INTERFACE

The processor is completely automated. It requires no observer intervention or adjustment, however, the observer must provide a "processing deck". Routine maintenance and consumable replacement is performed daily.

II. Processor Design and Performance

The hybrid processor has been designed to realize the best from the combined digital and analog technologies. The flexibility of digital processing has been preserved while avoiding the limited array sizes, aliasing and uv sort liabilities. The design philosophy and resulting processor performance are briefly presented; we start with aliasing and truncation.

If the full space-bandwidth associated with an A-array observation can be reproduced in the optical Fourier transform channel, the resulting map will be complete and uncorrupted by sampling or other truncation artifacts. An A-array observation which is to be mapped to the 3 db point of the primary beam has a space-bandwidth product of 3000. That is, there are ± 1500 rotations (2π) of the complex visibility function in 72 Km associated with a point source at the ± 3 db points of the primary beam. From primary beam pattern measurements we know

$$P \text{ (meters}/2\pi \text{ Rotation)} = \frac{\lambda}{L_{3db}} = \frac{2D}{1.04} = 48 \text{ (meters}/2\pi \text{ Rotation)}$$

$$\frac{72000}{48} = 1498 \text{ Rotations /A-array uv Coverage}$$

This space-bandwidth product has been provided in the optical processor. Thus the full 3db FOV space-bandwidth product of the A-array can be reproduced and there is no aliasing or truncation error in the resulting map.

The number of independent sample points in the processor output is limited by the sampling associated with the VLA or the number of samples made by the image sensor array. In this design we have chosen to use a 7200 element sensor array. This results in about 7 samples per processor beamwidth and a minimum of 10.5 samples per VLA beamwidth (both beams being measured to the first null or zero crossing). These sample densities are refered to as points per beam (ppb) in the remainder of this memo. Thus there are a relatively large number of ppb and subsequent map processing and reduction benefits with simple interpolation.

The uv sort and gridding requirements associated with the fast Fourier transform can be avoided in the hybrid processor because it is possible to generate the analog uv data with a "local" random access CRT film recorder. It is estimated that this can be done in about 20 seconds per map. In addition, with a CRT film recorder the two "natural" uv data formats [straight lines at an angle (t-b); elliptical tracks (b-t)] can be written directly. The recording time for the "natural" formats can be less than 20 seconds.

It should be noted that film recording time is proportional to the number of data. Thus, subarray operation of the VLA or less than full 12 hour coverage maps (snapshots) can be generated correspondingly faster in the film recorder.

In the following pages a summary of the hybrid processor performance and general characteristics is presented. As indicated, the peak map error is everywhere less than 1%. There are large regions of the map where the error is less than 0.5%.

VLA HYBRID PROCESSOR PERFORMANCE

A. GENERAL

-- Full A-array coverage mapped to 3db FOV at 10.5 ppb*
-- b-t, t-b or random input data
-- < 1% map error**
-- 3 maps/minute***
-- Gaussian taper
-- "Uniform" weighting
-- Redundant coverage compensated

B. INPUT (Optical Analog of Radio uv Space)

-- Frequency sorted calibrated visibility in t-b, b-t or random order
-- Internal test and calibration data
-- 10^6 16 bit words/second (address and data)
-- Space bandwidth product 3000 (full 72 Km A-array coverage to 3db FOV)
-- Weighting - "uniform"
-- Taper - Gaussian

C. OUTPUT (Optical Analog of Radio Sky)

C.1. Numerical

-- Observed radio sky brightness distribution (map)
-- 3 maps per minute***
-- Peak map error less than 1%**
-- 10.5 ppb (to first null of synthesized beam)*
-- FOV equal to 3db point in primary beam*
-- 7200 x 7200 map sample points (maximum)
-- 672 synthesized VLA beam per FOV (A-array)****
-- 7.2 ppb to first null of processor response
-- 1000 processor beam diameter FOV****
-- 13 bit brightness data
-- 16 bit coordinate data

C.2 Optical

The square of the observed radio sky brightness is presented on a projection screen with the full brightness range and spatial resolution of the map preserved.

* These are minimum values corresponding to A-array maps. Smaller array maps can have proportionally larger FOV and points per beam.

** The map of a point source located anywhere within the FOV will have an error of less than 1% of the peak source brightness at the center of the source and everywhere beyond the negative peak of the first sidelobe of the point source response.

*** D-array rates can be significantly faster with suitable preprocessing.

**** In the 3db FOV, complete circular uv coverage would produce 1000 synthesized beams. The VLA coverage however, produced only 672 synthesized beams in the 3db FOV.

III. Reflection on Various Array Applications

We wish to make the most cost and time effective use of the channel capacity in this processor; with particular emphasis on maximizing the number of maps generated per second for the smaller arrays. This is an important consideration and a real opportunity because the spectral line observations often use the smaller arrays and generate many more maps than do continuum observations.

We will concentrate on the D-array. But, before discussing it in detail there is an important A-array consideration. As designed, we obtain 10.5 ppb and a 3db FOV from the hybrid processor. If the coverage was truncated from 36 Km to 24 Km and the scale of the optical uv plane held constant, the shape of the synthesized beam would change somewhat but the principal effect would be to make it about 1.5 times larger in the output plane. This results in about 15 ppb; the FOV remains unchanged. On the other hand, if the coverage is truncated to 24 Km and the scale of the optical uv plane increased by a factor of 1.5, the principal effect would be to increase the processor FOV by 1.5 while maintaining the ppb at about 10.5. These are the salient map scaling opportunities associated with A-array mapping. They are somewhat different than those associated with the smaller arrays.

Table I is a tabulation of the number of synthesized beams to be found in the primary beam 3db FOV for the various arrays.

Array	Beams/FOV	Sample Points at 10/Beam
A	672	6720
B	205	2050
C	63	630
D	19	190

For various arrays, the number of points per synthesized beam are summarized below. A constant scale factor ($\$=1$) for the optical uv plane is assumed. This results in a constant FOV, namely the 3db FOV of the primary beam. The ppb are the number of samples made on a diameter of the approximately circular first null contour.

TABLE II

Array	ppb
A	10.7
B	35.1
C	115.3
D	379.2

A similar table for the FOV associated with each array can be made. Here we assume the optical uv plane scale is increased as the array size is reduced. This maintains ppb constant at about 10.5

TABLE III

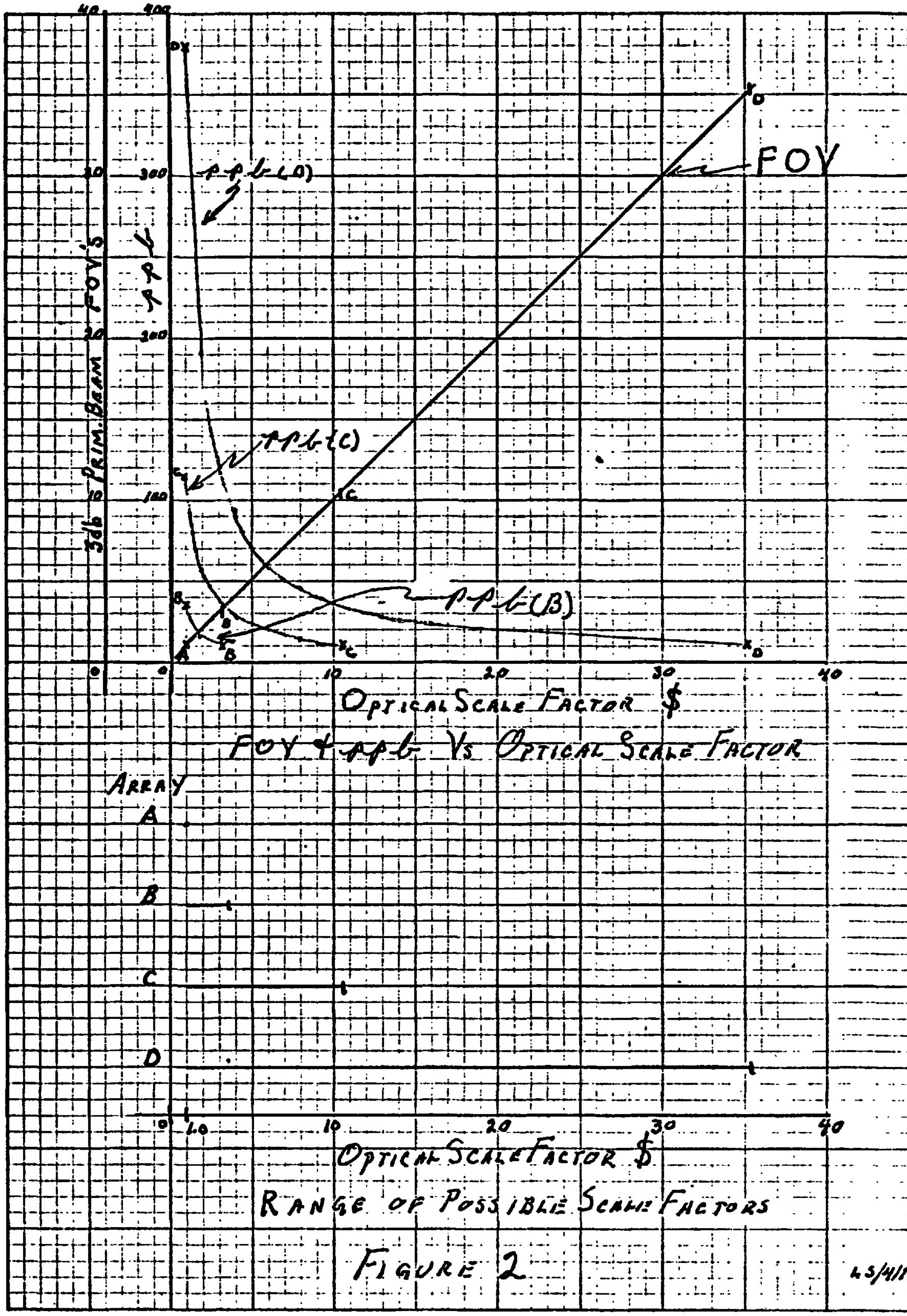
Array	FOV (Multiples of 3db FOV)
A	1
B	3.3
C	10.8
D	35.4

Figure 2 summarizes the FOV's and ppb's available from the hybrid processor for various arrays. The independent variable is the "optical scale factor \$"; essentially the magnification applied to the uv data in writing it into the optical processor. The range of \$ values applicable to each array are shown.

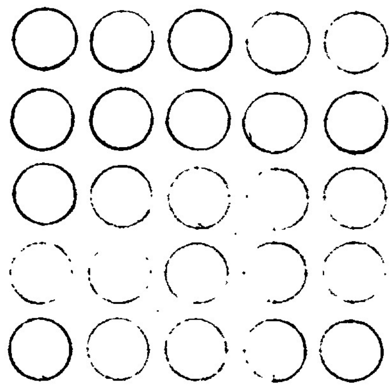
Some conclusions can be drawn and some questions raised. In the case of the B-array, it is likely that one would compromise between the two tables and accept perhaps 20 ppb ($\simeq$ 10 ppb at 3db level) and a slightly larger FOV (x1.6). For the case of the D-array things are not so clear. Perhaps one would map to one or at most two primary beam FOV's, but surely the resulting 190 ppb is unacceptably large. Our goal of cost effective processing suggests that a multiplexing scheme which will speed things up is probably more attractive. The time consuming operations are film recording and map scanning. Film writing speed can be increased by preprocessing the visibility data and taking advantage of its reduced space-bandwidth product. Map readout speed can be increased by sampling only a realistic number of points in the output map.

One (of many) time-space encoding formats which seems to offer some practical savings in recorder and scanner time requirements follows. It may not be optimum or even practical; suggestions on this important topic are welcome.

In the D-array the integration time would be increased by about a factor of 30, thus reducing the number of data and the corresponding film recording time by a factor of 30. Further, the spatial size of the coverage in radio space is 35 times (linear) smaller. Let us then encode a given D-array coverage in optical space at a scale (\$=6) which results in a 5 x 5 array of D-array coverages in the A-array space-bandwidth area; something like the sketch.



The above graphs show how the ppb and FOV scale with $ (optical scale factor). $ is the magnification (linear) ratio between the actual optical analog data and its unmagnified radio equivalent.



If each coverage were mapped individually (say by positioning it at the center of the exit pupil) then the output plane would have 62 ppb and the theoretically available FOV would be 6 primary beams. Assuming a more realistic FOV of 1 primary beam, there would be about 19 synthesized beams in the FOV and at 10 ppb, about 40,000 map data points. This could be read out in about 1/2 second with the present transport and sensor array design. Thus it seems that a D-array map could be processed at a system rate of 2 per second.

An additional factor of 5 to 10 in map rate could possibly be realized by taking further advantage of the spatial redundancy in the D-array uv coverage combined with a sensor array specifically designed for fast read out of the smaller maps.

Are there better time-space multiplexing techniques which can be used?

IV. FORMAT

FORMAT is a computational transfer function between calibrated telescope data and the digital input to the CRT film recorder. It implements astronomical and hybrid processor related functions. It generates certain test and calibration signals and encodes the complex visibility on a real spatial carrier. We will summarize these functions and treat them in some conceptual detail below. First, some very important points with respect to processor operation, flexibility and the observer-data-processor interaction need to be made.

In formating the uv data, the observer has complete control over the placement (geometric and radiometric) of his data in the optical processor. He can select the optimum encoding for his coverage and his source. For example, sub-array and small hour angle coverages may be weighted and encoded in a manner different than full 12 hour coverage. Or, a strong source in the first sidelobe of the primary beam might obscure some feature of interest; choice of a different carrier frequency direction would relieve this problem. With flexibility in uv data formating and encoding, the observer is insured the opportunity to optimize his map quality and minimize errors. Residual errors and clutter can be distributed throughout the map in a manner which minimizes their effect on the astronomy of interest.

Although not complex, optimum use of FORMAT requires an understanding of interferometry. Default options or automated FORMAT based on statistical data associated with the coverage should be provided for others.

Following an outline suggested by Rots, we divide FORMAT into the following specific operations:

1. Select and set basic map parameters,
2. Characterize visibility data with respect to dynamic range and uv distribution,
3. Select and set data dependent parameters,
4. Set observer determined parameters,
5. Select and set hybrid processor constrained parameters,
6. Generate calibration and other test signal data,
7. Generate exposure data based on the above,
8. Introduce CRT deflection linearity calibration data, and
9. Expose film.

I see FORMAT as a minicomputer (perhaps combined with the supervisory computer) containing a number of software systems. These include FORMAT operations for uv film generation, xy map generation, b-t digital archive generation (and reading if desired). Here we are principally concerned with the uv FORMAT, the others being important to the possible time shared operation of this component and cost effective use of the hybrid processor to solve more than the mapping problem.

Mapping could be a process similar to that used by the observer when he makes an observing run. That is, he will come to the hybrid processor with calibrated data and a processing program deck. The processing program deck contains the following basic data:

1. Source, file #,
2. Map size, FOV, number ppb, coverage to be mapped, map offset, etc.,
3. Data address to be used in determining visibility dynamic range and uv distribution,
4. Desired weights and tapers,
5. Restrictions on or specification of carrier frequency and phase,
6. Test, reference and special calibration data.

Once loaded into the processor, this general sequence of events will occur.

1. uv scale factors (in optical processor) will be set. That is, specific values of $ will be chosen based on FOV, ppb, array size and uv coverage to be mapped. (Figure II.)
2. $|V|$ as a function of u and v will be fit with a circular symetric two dimensional Gaussian.*
3. Net Gaussian uv taper will be calculated based on desired astronomical taper, complementary taper required by the processor and the Gaussian fit to $|V|_{(uv)}$.
4. Determine carrier frequency, phase, and direction - a significantly different problem for encoding A-array data than for encoding D-array data.
5. Generate test and calibration signals.
6. Generate exposure data based on carrier frequency, complex visibility, net taper, test and calibration signals.
7. Generate CRT address data from uv values corrected for recorder deflection nonlinearity. (The linearity correction being previously determined in a separate open loop recorder position calibration operation.)
8. Expose film.

* This information is required to set the proper value of complementary taper required by the processor.

V. RELATED TOPICS

Here we are concerned with miscellaneous topics which seem to have some relation to a hybrid processor. These topics include observation support, post observation support, map quality requirements, spectral line reduction techniques, cost effective processing concepts, time shared processor, time shared CRT recorder, sub-array operation, less than 12 hour coverage, and CLEAN.

Observation Support

It seems to me that the minimum support which must be provided the observer is to deliver calibrated data and some validation of his observation. Probably, the best way to validate the data is to provide him with a map. It need not be a perfect (high quality) map, but it should be of sufficient quality to demonstrate the acquisition of his objective. It could be limited in size, angular resolution or dynamic range, but in general it must be good enough for the observer to be confident that his observation is going well. The quality and the amount of processing required to support spectral line observation may be different than that required for continuum observation.

Post Observation Support

The support required after the observation ranges from simple mapping to full map reduction. It is difficult to say more without saying a lot more.

Observation and post observation support requirements are important considerations in determining the size, speed, quality (error size) and to some extent the location of a hybrid processor. Cost and the cost effective mapping and reduction are also influenced by these considerations.

Time Sharing

Time sharing of both the CRT recorder and the optical processing channel is possible. Both components are capable of performing more than their fundamental role and offer potential economies in other services. For example the CRT recorder, in addition to being used to write the uv data for the optical processor can also be used to generate high quality photographic maps. These maps would be written in a two dimensional raster format based on the output of this processor or any other mapping instrument. Further information is required from the recorder manufacturer with respect to recording time required for a 4000 x 4000 point map.

The CRT recorder can also be used to generate or read a digital archive for the visibility data. Again, further information is required from the manufacturer. A meeting is scheduled in CV for May 4 and 5 with CELCO, a very good custom CRT system manufacturer.

The optical processing channel can also be time shared in the sense that a large "batch" spectral line mapping job can be interupted for a few seconds to permit for example, the remapping of a previously recorded source at a different taper. This is done in 20 seconds/map if numerical results are required. It can also be viewed directly on the projection screen. Introducing various tapers does not require generating a new uv film. A simple Gaussian (amplitude) filter is introduced into the signal or reference beam to generate the desired taper. Variations on this theme and others need to be examined. For example, map phase center can be offset by introducing a linear phase shift in the uv plane. This can also be done without generating a new data film by using prisms of the proper pitch.

Are there other simple multiplicative or convalutional operations which would be of value in examining the maps?

Map quality, spectral line reduction techniques, sub-array and snapshot modes point source subtraction and CLEAN are all left at this point for oral discussion.