National Radio Astronomy Observatory

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Very Large Array Program

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# ASTRONOMICAL REQUIREMENTS FOR FUTURE VLA PROCESSING

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The purpose of this report is to estimate the long range computing power which the VLA will need in order to satisfactorily handle the data flow and computational power in the late 1980's and 1990's. The heart of this report is contained in Tables 2 and 3 where several of us (RDE,EBF,FNO, Pat Palmer and Jacqueline van Gorkam) have summarized the major VLA projects, their I/O and computational requirements, expected over the next ten years.

The interpretation of these requirements in terms of alternative computer configurations are given in the report 'A Computer Plan for the VLA', by R. Duquet, G. Hunt and R. Burns, VLA Computer Memorandum No. 168. This report will be referred to as DHB.

The general outline of this document is as follows:

1. Evaluation of the Present Situation
    - A. Computer systems for VLA data analysis
    - B. The major reduction and analysis tasks
    - C. Present capabilities
    - D. Present bottlenecks

2. Anticipated Projects at the VLA in Five years
    - A. Continuum projects
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3. Estimation of Future Computer Demands

## 1. Evaluation of the Present System

The following section is, by and large, a summary of the discussion of the VLA computer resources as described by DHB. Here, we wish to stress the astronomical requirements and compare them with the existing systems.

### A. Computer systems for VLA data analysis:

At present four computer systems handle the bulk of the VLA reductions and they are described in DHB. They are:

1) MODCOMP on-line system at the VLA which collects, correlates and stores the visibility data.
2) DEC-10 system at the VLA which calibrates and edits the visibility data.
3) Four mapping and image display systems running AIPS software presently handle most of the reductions and analyses from the point of calibrated visibility data to a final product. Three of these systems are run on a VAX 11-780 computer system.
4) PIPELINE, consisting of various PDP 11-series computers,

array processors and special purpose hardware, which will soon increase the map making and cleaning capacity at the VLA.

B. The major reduction and analysis tasks:

The approximate breakdown of the percentage of computing resources now devoted to the major VLA reduction tasks are given in Table 1.

TABLE 1

PROPORTION OF TASK USEAGE AT THE VLA

| TASK | COMPUTER SYSTEM | PRESENT PROPORTION |
|---|---|---|
| On-line data collection | MODCOMP | not included |
| Visibility calibration | DEC-10 | 10% |
| Visibility I/O | DEC-10 | 7% |
| Mapping | VAX, PIPELINE | 20% ** |
| Deconvolution | VAX, PIPELINE | 37% ** |
| Selfcalibration | VAX | 4% ** |
| Tape to disk I/O | DEC-10, PIPELINE, VAX | 7% |
| Displays of all kind | DEC-10, PIPELINE, VAX | 9% |
| Map Analysis | VAX | 6% |

** heavy use of array processor not considered in percentage of cpu useage.

The table was derived from the task statistics in the VAX at the present time. The visibility calibration and I/O for the DEC-10 entry was calculated by assuming that its cpu power was about equal to that of one VAX 11-780 and that about 50% of the DEC-10 cpu time was used for data reduction. It is clear that the mapping and deconvolution take a majority of the computer resources and they will probably remain the most demanding tasks in the future. Both of these tasks and several others use the Fast Fourier Transform (FFT) as the crucial algorithm so a reasonable approximation to the VLA computer load would be to sum the rate of FFT's necessary to map, deconvolve and self-calibration a representative sample of observing projects.

C. Present capabilities:

In order to derive the present computational and data transfer capabilities for VLA data reduction, several bench mark tests were run on the VAX 11-780 and the PIPELINE systems. These tests included mapping a field 1024x1024 in size with 500,000 input visibility points; cleaning the resultant map with 3000 components and self-calibration of this visibility data base. From these and other tests, The present computational capabilities available at the VLA have been calculated by DHB in their Table 2. They find a total available computing power of 50 MIPS (millions of instructions per second) but a maximum useable computing power of about 15 MIPS with the present set of hardware. The efficiency of 30% is limited by the rate of data transfer to and from disk and cpu. In terms of the computational unit of a complex 2048 x 2048 FFT, which executes about 1.3 billion machine instructions, the 15 MIP computer power is equivalent to 500 FFT's in 12 hours.

Computer facilities outside of NRAO can help alleviate some of the computing load so the AIPS software in the VAX systems has been exported to many institutions. At the present time about 20 VAX's (4 with an array processor) are running AIPS about 15% of the time. The number of EXPORT systems and the average AIPS useage is expected to grow over the next five years. These total resources outside of NRAO are somewhat less than the NRAO resources and would not be able to handle the larger VLA problems. The outside systems will be desirable, especially in the latter stages of data analysis where the needed volume of data and the computational power is relatively low, and the advantage of performing the analysis in the home institution is large.

D. Present Bottlenecks:

The MODCOMP on-line system is nearly independent of the other VLA systems and its upgrading and improvement will be handled outside of the other NRAO/VLA computing systems. The MODCOMP system is now overloaded and minor improvements in the software and in the hardware are difficult to add. Plans for future development of this system are described in VLA Computer Memoranda No 166.

At the present time the DEC-10 is overloaded because all visibility data must pass through the system. When the PIPELINE begins routine reductions only the calibrator data will normally be processed in the DEC-10 and that system should be adequate for the calibration of VLA data.

It is in the area of mapping and deconvolution where the greatest bottleneck now occurs and will continue to occur in the future. This situation is largely the result of the increased use of the powerful deconvolution and self-calibration algorithms. These algorithms were largely unknown when the current VLA computer system was designed but they are now routinely used to improve the map quality by more than an order of magnitude. Many projects now require maps of size 2048, 4096, or larger, which are all but impossible to produce and clean. The PIPELINE, when fully operational, will be able to handle these larger maps, although not with the maximum desired throughput or flexibility.

The area of map analysis is presently software limited rather than computer limited; and may remain so in the forseeable future. Computer systems outside of NRAO can contribute signficantly to this facet of VLA data reduction because it requires much user interaction but does not require such large amounts of data storage and computing power. This analysis is most often handled by AIPS software on VAX computer systems and these systems are probably adequate to handle map analysis over the next five to ten years. At the present time, however, mapping, deconvolution and self-calibration monopolize the resources. As these tasks migrate to the PIPELINE and new generation NRAO computing systems, the existing systems (4 at NRAO and about 20 elsewhere) can adequately handle the map analysis and form a basis of evolution to the more powerful systems over the next 5 to 10 years.

An astronomer is forced, because of the present limitations, to map only that part of the primary beam which is of immediate interest. Often, the effects of strong sources outside the "interested" field of view distort the small maps and large amounts of computer resources and astronomer's time are wasted in trying to ascertain what is wrong with the data. A large field of view would have uncovered the strong sources and saved much computing time.

Perhaps even more importantly, this "tunnel vision" seriously reduces the chance of accidental discoveries of unusual or unsuspected radio emission outside of the main object. Such serendipitous discoveries have played a crucial role in the development of astronomy (eg. M. Harwit's book on Cosmic Discoveries). The VLA computer hardware and software should not exclude routine full field mapping.

## 2. Anticipated Projects within the next five years

### A. Continuum projects:

The continuum projects and the observational parameters which determine their computational and I/O requirements are given in Table 2. These requirements are based on reasonable projects and represent those of moderate difficulty and completeness. These are not worst cases. Some of these projects can be enhanced by hardware improvements (more correlator channels, >35 km baselines and wider IF bandwidth). A detailed description of the assumed and derived values for each column is given at the end of Table 2.

#### Full Field Mapping:

These include objects or groups of objects which fill the entire primary beam. Some examples are individual large galaxies, clusters of galaxies or counts of background sources. Especially in the larger arrays the field of view at full bandwidth is limited by bandwidth smearing. To obtain maximum signal-to-noise over the full field it would be necessary to use the spectral line mode to subdivide the 50 MHz bandwidth into smaller channels which are combined into a single map where the correct (u-v) coordinates are calculated for each frequency band. The number of channels presently available is limited by the correlator so the entries in Table 2 correspond to less than the full 50 MHz. If the correlator is expanded to provide more channels at the maximum bandwidth the number of channels would be increased for those projects with an asterisk in column 8. Only a modest increase in the computer capacity results since all channels are still combined into a single map.

Observations of this type would normally be over six hours long in order to obtain adequate (u-v) coverage. The entry of 6 observations in a 12 hour period results from the requirement to subdivide the observation in the data reduction in order to correct for non-coplanar and corrections which rotate with the primary beam. The field of view entered in Tables 2A and 2B is the half-power primary beam width although some objects will require the full primary beam width.

#### Small Objects:

For small objects the area of interest is determined by the size of the object which is significantly less than the size of the primary beam. We then have two cases. First, if the object is weaker than the background sources, which is generally true at frequencies 5 GHz or less, the area of the primary beam must be mapped to correct for confusion. At 5 GHz the confusion most likely occurs from only one or two discrete sources in the field and in this case we have specified a low resolution, larger map in the table. At 75 and 327 MHz all observations will be severely confused.

Secondly, if the object is stronger than any confusing sources, only an area twice as large as the object need be mapped. This applies at frequencies 15 GHz or greater and at lower frequencies for all strong sources.

The entry of 12 observations per day is required to correct for the primary beam ellipticity, non-isoplanicity of the field and for the non-coplanar aperature. These problems are discussed in more detail in Section 2B.

#### Snapshots:

These are objects which are sufficiently bright and confined that signal-to-noise and (u-v) coverage is sufficient in a short observation and large stastistical samples can be analysed. At 1.5 and 5 GHz all fields will be confused so that the entire primary beam should be mapped, as described above. The eventual possibility of doing snapshot observations in spectral line mode to give maximum sensitivity has not been included. At the higher frequencies the largest area assumed is that unaffected by bandwidth smearing in which case the parameters scale with frequency and array; hence, the single entry in the table. Observations for which this assumption is not true are included under full field mapping.

Surveys by scanning the primary beam:

These are the limiting case of the snapshot observations in which the observational aim is to cover the largest possible area on the sky. The two examples cited are from actual proposals and are indicative of the range of parameters involved. With greater computer resources it is likely that this class of observation will become more common in the future.

Point sources:

Point source observations which are unaffected by confusion are listed here. Parameters are only given for the A configuration at 5 GHz since the processing load is relatively insensitive to frequency or array.

Solar:

These include observations of large images with variable structure. The sampling time constant is determined by the variability rather than (u-v) coverage. Possible extensions of the VLA hardware to provide shorter time constants have not been included.

Phased array:

Since the phased array results in only a few output channels, no significant data processing load results. It is included for completeness.

B. A digression about large field maps:

A major computational uncertainty in Tables 2, 3A and 3B is associated with projects which have a long integration time and a large field of view. Two complexities invalidate the use of the 2-D FFT for producing accurate maps from the (u-v) data. First, a non-circularly symmetric primary beam response means that the effective primary beam correction is a function of time since the primary beam rotates with respect to the sky because the antennas are on an alt-az mount. The time scale for such changes is several hours except when a source passes close to the zenith. This correction has been ignored in VLA reduction but it is significant for full field mapping in all configurations. It is believed that the limitiation of 100:1 in dynamic range in the C- and D-configurations is mainly produced by this non-circularity problem. Linear polarization maps are probably limited to 5% and circularly polarized maps to as much as 10%.

Assuming that the primary beam response is known, two correction methods are possible. The long integration can be broken in several short pieces (snap-shots), each reduced separately with its peculiar primary beam correction, and then the set summed to give the map associated with the entire integration. Alternatively, the primary beam correction (multiplicative in the map plane) can be applied as convolution to the (u-v) in the relevant time segment. This method, however, may cause some problems with the clean deconvolution.

A more serious problem is caused by the inadequacy of the 2-D FFT to produce undistorted maps of a large field of view from a non-planar aperture. Although the VLA is a nearly flat array, the aperture synthesized over several hours or longer is not planar in general. The phase error introduced by using the 2-D FFT is proportional to the product of th departure of the aperture from a plane (about equal to the length of the array) with the departure of the sky from a plane (equal to the distance-squared from the field center). For a given map size the phase error increases with wavelength and for the A-configuration at the VLA it is a serious problem at 1.4 GHz or less. Table 4 shows the size of the phase error, W, at several VLA frequencies and configurations and for the VLBA.

TABLE 4

Phase Errors Associated with the 2-D FFT

| Frequency (GHz) | Configuration | Field of View (arcmin) | W (rad) |
|---|---|---|---|
| 0.327 | A | 260.0 | 170 |
| 0.327 | B | 260.0 | 52 |
| 1.4 | A | 30.0 | 9 |
| 1.4 | B | 30.0 | 3 |
| 5.0 | A | 10.0 | 3 |
| 1.4 | VLB | 10.0 | 114 |
| 1.4 | VLB | 1.0 | 1 |
| 5.0 | VLB | 10.0 | 400 |
| 5.0 | VLB | 1.0 | 4 |

The effect is most serious in A-configuration and at the lower frequencies. The VLBA will be concerned with the W-term as well. Neglect of this phase term causes a point-source to appear 'U-shaped', the size of the U varying with the distance squared from the phase center. Sidelobes from this distorted source are not correctly removed using clean since the beam shape is not invariant with position.

There are several methods for dealing with the W-term. For a short period of time the synthetic aperture is planar and a true map of the entire field of view can be obtained using a 2-D FFT. The number of snap-shots needed is equal to about 2*W and each must be mapped and cleaned separately (some consolidation of cleaning and self calibration is probably possible). This solution is identical to one proposed for the non-circularity of the primary beam corrections. The VLBA, however, is not a planar array because of the curvature of the Earth so this option is not available.

A 3-D FFT can be used on the (u-v-w) data to form an (x-y-z) volume distribution. The width in the w-plane is also 2*W. A meaningful deconvolution solution must be constrained to lie on the celestial sphere in the (x-y-z) volume, something which the clean algorithm could handle with minor modification.

A third alternative is called mozaicing. Instead of making one large 2-D FFT map with distortions a whole set of maps, covering the field of view, but each sufficiently small to avoid the distortions, is made. The number of maps is about W*W. The main drawback of mozaicing, apart from the large number of maps, is that the sidelobe or alias responses of sources outside of the small map cannot be surpressed using clean. Perhaps the best way of elliminating the sidelobes is to subtract the sources directly from the (u-v-w) data and then remap. Subtraction from the observed (u-v) data is more accurate than subtraction from the gridded (u-v) data as done by the Clark version of Clean. For large fields of view which are dominated by a small number of strong, isolated sources, this method may be efficient.

The non-coplanar aperture problem has largely been ignored at the VLA because the hardware for generating sufficiently large maps is not at hand. At 327 MHz the W-term problem may be the most important limitation to accurate mapping. For 1.4 and 5.0 GHz in the A-configuration the problem is significant but not catastrophic.

In Tables 2, 3A and 3B we have assumed that any observation affected by the W-term or possible non-circularly symmetric primary beam response will be broken into 3, 6 or 12 snapshot observations over 12 hours with each segment reduced separately. It will take several years of experience to decide on the optimum procedure and the severity of the problems. We believe that this solution is realistic in estimating the computing and I/O power necessary. However, if we ever expect to routinely map the entire primary beam in the A and B configurations (serendipity again), correct maps must be made.

C. Spectral line projects:

A list of the spectral line projects and the observational parameters are tabulated in Tables 3A and 3B. As with the continuum, these are moderately difficult projects. Many spectral line projects are limited with the present correlator and Table 3B contains parameters for these projects assuming an enhanced correlator. A detailed description of the assumed and derived parameters follows Tables 3A and 3B.

This table includes all the major classes of spectal line mapping projects currently being pursued at the VLA. They are divided into groups with similar instrumental requirements. Because of the great range in possible parameters for spectral line observing we have not tried to cover all possible array combinations but tried to pick the typical bad but not extreme cases. In each case we have tried to set the specifications by asking what parameters would provide useful astronomical information if there were no limit imposed by the computer on channel number or pixel size; but given the resolution and sensitivity of the VLA. In making this analysis it also became clear that some modest extensions of the present VLA correlator would also provide useful additional capacity. Although these enhancements are not included in Table 3A, they have been include in Table 3B to give an indication of possible future expansions which should not be excluded by too modest a long-term computing plan.

Extragalactic Emission:

For these projects the velocity range is set by the dynamics of the galaxy or cluster of galaxies. The velocity and spatial resolution are mainly limited by brightness sensitivity. Two orthogonal polarizations are assumed to optimize signal-to-noise. In most of these cases the resolution and image size-scale with distance so that the numerical map size is the same.

Extragalactic absorption:
The relatively strong continuum source makes higher resolution possible, but the image size is now limited by the size of the continuum source.

Galactic Center:
This is separated from the other galactic projects because of the greater velocity range required.

Galactic absorption:
Again, resolution is not limited by brightness sensitivity so large numerical map sizes and channel numbers are possible. For OH and H2CO the full primary beam must be mapped to avoid confusion from HI emission. The velocity range used for NH3 is set to cover 3 transitions simultaneously. The channels between these lines need not be mapped.

Galactic emission:
Although the thermal sources are again limited in spatial and velocity resolution by the brightness sensitivity, the maser sources can be observed with the highest spatial and velocity resolution. The recombination lines include H, He and C. They can be observed in all VLA bands but 15 GHz is taken as typical.

Stars:
The regions of stimulated emission are much smaller for these masers. In some of these cases it may be necessary to use a self-calibration procedure which includes all the different channel maps in the model.

D. Additional Projects at NRAO:

VLBA:
Within five years the NRAO may be operating a ten-element VLB array and it is important to comment on its data reduction impact. The reduction and analysis of VLBA data will be virtually identical to that of the VLA so anticipating both VLA and VLB computer problems seems sensible. It is estimated that VLB reduction and analysis, from mapping to a "final" product will take about 25% of the computing power needed by the VLA as outlined in Tables 2 and 3A (See Chapter V, VLBA Report, May 1982). We assumed that the computer requirements will roughly scale with the number of correlators. It must be emphasized that this estimate is very tentative and will depend on the nature of the radio emission associated with milliarcsecond structure. We have also assumed that the map sizes for VLB objects will not be larger than those studied by the VLA. It is possible that a joint USA/Canada VLB array could consist of up to 19 elements, with an estimated load of 50% of the VLA.

The VLA and VLBA may operate as one large array of 37 antennas in the 1990's. While it is unlikely that all elements with spacings from 1 km to 3000 km would be used to make a high resolution, large-field map, it does seem appropriate to use the VLA with the 5 New Mexico antennas as a "super" VLA. This would increase the resolution limit but the large fields of view would remain. The cost in additional computing power would be significantly greater than for the 27-element VLA.

Millimeter array:

The projected millimeter array may add little extra computational demands although the I/O demands may be significant. Some new hardware technology and software development may be necessary for processing multi-feed synthesis data. Here, the most important point is to keep the future system as flexible as possible.

Proposed 75 MHz array:

The proposed 75 MHz extension of the VLA would significantly add to the computer load. Because of the density of sources in the 75 MHz beam, very large maps with large W-terms will be needed. A realistic estimate of the load would probably be equal to the 327 MHz entry in Table 2A as a minimum. When such a system is running, NRAO should have sufficient expertise in the problems discussed in Section 2B to handle the data. The large, expected ionospheric refraction and the resultant distortion over the field of view may necessitate advances in self-calibration to deal with this non-isoplanicity.

D. Requirements for new hardware:

A number of the projects listed in Tables 3B need a larger number of channels and bandwidth than is currently available. The increase in I/O and computing power with the correlator expansion is modest for the continuum projects, but increases the computer demands for the spectral line projects by a factor of 1.7. While we do not want ot argue that the propsed system must be able to handle the load given in the hypothetical Table 3B, it should be taken as an indication of possible future developments which ought not be designed out.

Other future hardware developments which may impact the computational requirements are:

Gating hardware for pulsar observations.
Fast sampling for Solar observations.
More observing flexibility.
VLA outstations, whether or not associated with the VLBA.

E. Requirements for new software:

New software techniques are continally being discovered and their impact on the long term computer planning is difficult to assess. For example, the self-calibration technique was unknown when the original VLA computer systems were designed. A description of some new techniques which might impact the VLA computer plans follows. Unfortunately, the computer and I/O power is now sufficiently limited so that the coding and analysis of new techniques are hampered. A listing of some of the algorithms currently used or under investigation is given in Appendix 4 of DHB.

Better weighting algorithms for (u-v) data before mapping should be investigated. The (u-v) tracks generally give a lumpy aperture coverage on both the small- and large-scale. By producing a smoother aperture with appropriate (u-v) weighting, the resultant maps would have lower sidelobes and better signal-to-noise.

Deconvolution is the most computer intensive task for VLA reductions. Algebraic- and maximum entropy-type algorithms have been investigated but they can be an order of magnitude more expensive than the CLEAN algorithm. The VLA resources at the present time are not sufficient to properly analyse and test the more sophisticated algorithms. It is unlikely that a faster algorithm than clean will be found. However, more investigations for optimal deconvolution of extended sources is needed. Subtraction of clean components from the ungridded (u-v-w) data is also needed for wide-field mapping problems.

As yet no serious attempts have been made to estimate the reliability of the deconvolved maps. Such error estimation algorithms are now known but all have required too much computation time to be investigated.

Self-calibration techniques have extended the dynamic range of the VLA maps from 100:1 to over 10,000:1. The algorithm is not particularly expensive, compared with clean, and in almost all cases it need only be made on one channel in a set of continuum or spectral line data. More sophisticated time filtering and parameter fitting capabilities are needed to self-calibrate weak sources and for fields at low frequency which may be severely distorted by ionospheric refraction.

The non-circularity of several corrections associated with the primary beam and the W-term distort maps made from long integrations on extended sources. These software problems have already been discussion in Section 2B. The relative costs of the several alternative are not as yet determined.

Software associated with map analysis after good quality images have been produced is open ended. The two computations which may be somewhat computer and I/O intensive are; 1) the profile analysis of a set of spectral line maps and 2) subtraction of the continuum radio emission from the line maps directly from the (u-v) data. Such analyses can be generally handled on AIPS computing systems now available at NRAO and many other institutions. It is likely that when much of the mapping, deconvolution and self-calibration is moved to the next generation NRAO computer, AIPS on a VAX-type computers (perhaps with upgraded array processors) will be able to handle map analysis and display anticipated from Tables 2 and 3.

We strongly emphasize the uncertainty in attempting to predict the important advances in new techniques of VLA reduction and analysis. It does seem likely that the new algorithm will be costly.

F. Requirements for display:

The main interface between the observer and the computer is by a display. Data calibration and editing, and map analysis are now somewhat hampered by the lack of creative display software. New technologies (e.g. vector graphics, see SPG memo 11 by J. Torson), greater display power, intelligent combination of graphics and reduction software would improve thoughput by aiding the observer in detecting bad data and in deciding the best course to follow in the subsequent reductions. Although these requirements should not impact the computation and I/O capabilities outlines in Tables 2 and 3 they will require additional display hardware.

## 3. Estimation of Future Computer Demands

The estimation of the future computer demands from the astronomical point of view comes directly from Tables 2 and 3; specifically from the average and rate of FFT's needed to process the data. The explanation of these tables gives the assumptions that were made in obtaining these parameters. The summary of demands is

TABLE 5

VLA COMPUTER DEMANDS

| Type | 2-D FFT's in 12 h | Ratio with Current Power |
|---|---|---|
| Continuum | 3698 | 7.0 |
| Continuum (enh) | 3698 | 7.0 |
| Spectral Line | 8713 | 17.4 |
| Spectral Line (enh) | 13368 | 26.7 |

This estimate for the computing load is more than ten times than now currently available at the NRAO.

A detailed look at the computing and I/O demands in terms of computer configurations are analyzed in the report by DHB.

Finally, it should not go unnoticed that the problems described in this memorandum, and the resources needed to handle them, are such that this facility would be able to make a major impact on image analysis for all areas of astronomy.

TABLE 2

COL EXPLANATION

1...Class of project:

2...Number of observations in 12 hours to be separately reduced:
For long integrations on one field, mapping, and cleaning must be done on short segments of data in order to avoid non-coplanar aperture effects and to correct for non-circularly symmetric primary beam response. See discussion in Section 2B. For other projects this entry gives the number of separate fields.

3...Number of polarizations in input data:
2=only parallel polarizations; 4=all polarizations.
3=Average of the above two options.

4...Field of view in arcminutes:
Determined by either astronomical requirements or by the primary beam.

5...Angular resolution in arcseconds:
Determined either by astronomical requirements (such as brightness sensitivity) or by the VLA maximum baseline.

6...Number of pixels on map side:
3 (points per beam) * 60 * (field size) / (resolution) rounded to nearest hundred.

7...Sampling time required for less than 10% degradation:
277 * (resolution) / (field size); 60 sec maximum

8...Number of channels required for less than 10% bandwidth degradation:
2 * Number of pixels / 50 / freq(GHz), when limited by present correlator. Bandwidth is also less than 50 MHz.
Both AC and BD IF's are assumed.

9...Percentage of fields requiring self-calibration:

10...Percentage of fields requiring deconvolution (clean):

11...Repetition factor:
Number of times data is mapped and cleaned before obtaining a map free of errors

12...Number of input words obtained in 12 hours:
Input = Pol * Chnls * 351 * 2 * 43200 / Sample time
Assumes two words (16 bits each) per input datum

13...Number of 2-D FFTs for mapping, cleaning and self-calibration:
NFFT = Nobs * [(Pol/2 + (Pol-1) * 12 * DC% / 100) * Rep
+ 30 * SC% / 100]
Discussion of the equation is given by DHB

14...Percentage of anticipated observing time in future:
This percentage is based on the current observing statistics and it is modified by the anticipated effects of instrumental and computer improvements.

15...Average number of equivalent 2048x2048 FFT's needed in 12 hours:
NFFTAVG = OBS TIME% / 100 * NFFT * Pix * Pix
* Ln(Pix) / 32,000,000

TABLE 2 ASTRONOMICAL REQUIREMENTS - CONTINUUM

| (1) Class of Project | (2) No of obs. (in 12hr) | (3) Pol. | (4) Field 'arc | (5) Resoln "arc | (6) Pixels | (7) Sample time sec | (8) Chnls | (9) Self -cal % | (10) Deconvo -lution % | (11) Repeat factor | (12) Input words | (13) No. of 2-D FFTs | (14) obser time % | (15) Average equivalent 2048 FFTs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Full field mapping | | | | | | | | | | | | | | |
| A array | | | | | | | | | | | | | | |
| 1.4 GHz | 6 | 4 | 30.0 | 1.0 | 5400 | 9 | 32 ‡ | 75 | 100 | 2 | 4.2E+08 | 591 | 4 | 185 |
| 5 GHz | 6 | 4 | 10.0 | 0.3 | 6000 | 8 | 32 ‡ | 75 | 100 | 2 | 4.7E+08 | 591 | 5 | 289 |
| 15, 22 GHz | 6 | 4 | 3.0 | 0.1 | 5400 | 9 | 12 | 75 | 100 | 2 | 1.6E+08 | 591 | 2 | 93 |
| B array | | | | | | | | | | | | | | |
| 1.4 GHz | 6 | 4 | 30.0 | 3.3 | 1600 | 30 | 32 ‡ | 75 | 100 | 2 | 1.3E+08 | 591 | 5 | 17 |
| 5 GHz | 6 | 4 | 10.0 | 1.0 | 1800 | 27 | 12 | 75 | 100 | 2 | 5.3E+07 | 591 | 3 | 13 |
| 15, 22 GHz | 6 | 4 | 3.0 | 0.3 | 1600 | 30 | 4 | 75 | 100 | 2 | 1.6E+07 | 591 | 2 | 7 |
| C,D array | | | | | | | | | | | | | | |
| 1.4 GHz | 6 | 4 | 30.0 | 11.0 | 500 | 60 | 16 | 75 | 100 | 2 | 3.2E+07 | 591 | 2 | 1 |
| 5 GHz | 6 | 4 | 10.0 | 3.3 | 600 | 60 | 4 | 75 | 100 | 2 | 8.1E+06 | 591 | 5 | 2 |
| 15, 22 GHz | 6 | 4 | 3.0 | 1.1 | 500 | 60 | 2 | 75 | 100 | 2 | 4.0E+06 | 591 | 3 | 1 |
| Small objects | | | | | | | | | | | | | | |
| Weak sources, 75 and 327 MHz | 12 | 2 | 260.0 c | 5.0 | 9400 | 5 | 2 | 100 | 100 | 2 | 2.3E+07 | 672 | 6 | 1019 |
| 1.4 GHz | 6 | 4 | 30.0 c | 1.0 | 5400 | 9 | 2 | 50 | 100 | 2 | 2.6E+07 | 546 | 6 | 257 |
| 5 GHz | 6 | 4 | 10.0 c | 1.2 | 1500 | 33 | 2 | 50 | 100 | 2 | 7.3E+06 | 546 | 5 | 14 |
| 15,22 GHz | 6 | 4 | 0.5 a | 0.3 | 300 a | 60 | 2 | 50 | 100 | 2 | 4.0E+06 | 546 | 4 | 0 |
| Strong sources, all freq. | 6 | 4 | 0.5 a | 0.3 | 300 a | 60 | 2 | 100 | 100 | 2 | 4.0E+06 | 636 | 5 | 1 |
| Snapshots | | | | | | | | | | | | | | |
| Weak sources, 1.4 GHz | 100 | 3 | 30.0 c | 1.0 | 5400 | 9 | 2 | 50 | 100 | 1 | 2.0E+07 | 4050 | 4 | 1269 |
| 5 GHz | 100 | 3 | 10.0 c | 0.6 | 3000 | 17 | 2 | 50 | 100 | 1 | 1.1E+07 | 4050 | 5 | 456 |
| 15,22 GHz | 100 | 3 | 0.5 a | 0.3 | 300 a | 60 | 2 | 50 | 100 | 1 | 3.0E+06 | 4050 | 4 | 3 |
| Strong sources, all freq. | 200 | 4 | 0.5 a | 0.3 | 300 a | 60 | 2 | 100 | 100 | 1 | 4.0E+06 | 13600 | 9 | 20 |
| Survey by scanning primary beam | | | | | | | | | | | | | | |
| B array, 1.4 Ghz, 1 obs/min | 720 | 2 | 20.0 | 3.3 | 1100 | 46 | 2 | 20 | 100 | 1 | 2.7E+06 | 13680 | 1 | 36 |
| C array, 1.4 GHz, 6 obs/min | 4320 | 2 | 30.0 | 11.0 | 500 | 60 | 2 | 0 | 20 | 1 | 2.0E+06 | 14698 | 2 | 14 |
| Point sources | | | | | | | | | | | | | | |
| Astrometry (A array, 5 GHz) | 100 | 2 | 0.1 | 0.3 | 100 | 60 | 2 | 0 | 0 | 2 | 2.0E+06 | 200 | 3 | 0 |
| Monitoring, spectra | 100 | 4 | 0.1 | 0.3 | 100 | 60 | 2 | 50 | 0 | 2 | 4.0E+06 | 1900 | 2 | 0 |
| Flare stars | 10 | 4 | 0.1 | 0.3 | 100 | 3 b | 2 | 0 | 0 | 2 | 8.1E+07 | 40 | 1 | 0 |
| Detections | 24 | 2 | 0.1 | 0.3 | 100 | 60 | 2 | 0 | 0 | 2 | 2.0E+06 | 48 | 7 | 0 |
| Solar | | | | | | | | | | | | | | |
| Quiet | 2 | 4 | 30.0 | 10.0 | 500 | 60 | 2 | 0 | 100 | 2 | 4.0E+06 | 152 | 1 | 0 |
| Active | 20 | 4 | 30.0 | 10.0 | 500 | 3 b | 2 | 0 | 100 | 2 | 8.1E+07 | 1520 | 3 | 2 |
| Phased array | 0 | 2 | | | | | 1 | 100 | 0 | | | | 1 | |
| | | | | | | | | | | | | | | 3698 FFTs/12hr |

(a) Bandwidth limited field: scales with frequency and array so that number of pixels is constant.
[redacted]Avera[redacted]time [redacted]mine[redacted]aria[redacted]y.
[illegible]

TABLE 3A and 3B

COL EXPLANATION

1...Class of project:
2...Frequency in GHz:
3...Number of observations in 12 hours to be separately reduced:
For long integrations on one field, mapping, cleaning and selfcalibration must be done on short segments of data in order to avoid non-coplanar aperture effects and to correct for non-circularly symmetric primary beam response. See discussion in section 2B. For other projects this entry gives the number of separate fields.
4...Number of polarizations in input data:
2=both parallel polarizations; 4=all polarizations.
5...Field of view in arcminutes:
Determined either by astronomical requirements or by the primary beam.
6...Angular resolution in arcseconds:
Determined either by astronomical requirements (such as brightness sensitivity) or by the VLA maximum baseline.
7...Number of pixels on map side:
3 (points per beam) * 60 * (field size) / (resolution) rounded to nearest 100.
8...Sampling time required for less than 10% degradation:
277 * (resolution) / (field size); 60 sec maximum
9...Velocity range required in km/s:
Determined by astronomical requirements
10...Maximum velocity resolution in km/s:
Determined by astronomical requirements and signal/noise
11...Number of channels:
Nch = 1.3 * (vel range) * (vel resol), unless the correlator specifications are exceeded (*) in which case the number of channels in Table 2A has been set to the maximum possible. This may result in a poor compromise between channels, bandwidth, polarizations and interferometer pairs, however, the computation load will be reasonable. A 30% range is included for baseline determination.
12...Percentage of channels for which separate beams are needed:
%Beams = Pixels * Vel res / 1800. Assumes less than 10% error in beam location at the edge of the map.
13...Percentage of fields requiring self-calibration:
14...Percentage of fields requiring deconvolution (clean):
15...Is subtraction of component from visibility data required?
16...Number of input words obtained in 12 hours:
Input = Pol * Chnls * 351 * 2 * 43200 / Sample time
Assumes two words (16 bits each) per input datum
17...Number of 2-D FFTs:
NFFT = Nobs * [(Pol-1) * 1.3 * Nch * (1 + BEAMS% / 100
+ 10 * DC% / 100) + 15 * SC% / 100]
Assumes 10% of the channels are reduced three times as a repetition factor. Discussion of equation given by DHB.
18...Percentage of anticipated observing time in future:
19...Average number of equivalent 2048x2048 FFT's needed in 12 hours:
NFFTAVG = OB% /100 * NFFT * Pix * Pix
* Ln(Pix) / 32,000,000

TABLE 3A ASTRONOMICAL REQUIREMENTS - SPECTRAL LINE

| (1) Class of Project | (2) Freq. GHz | (3) No. of obs (in 12hr) | (4) Pol. | (5) Field 'arc | (6) Space Resoln. "arc | (7) Pixels | (8) Sample time sec | (9) Range km/s | (10) Velocity Resoln. km/s | (11) Chnls | (12) No. beams % | (13) Self cal. % | (14) Deconvo-lution % | (15) uv sub. | (16) Input words | (17) No. of 2-D FFTs | (18) Observ time % | (19) Average equivalent 2048 FFTs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Extragalactic emission | | | | | | | | | | | | | | | | | | |
| HI clusters | 1.4 | 1 | 2 | 30 | 5 | 1100 | 46 | 5000 | 20 | 16 * | 12 | 0 | 20 | yes | 2.1E+07 | 65 | 6 | 1 |
| HI galaxies | 1.4 | 2 | 2 | 30 c | 10 c | 500 | 60 | 1000 | 10 | 64 * | 3 | 0 | 75 | yes | 6.5E+07 | 1419 | 12 | 8 |
| ISM (individ. gal | 1.4 | 3 | 2 | 30 a | 1 | 5400 | 9 | 500 | 5 | 130 | 15 | 0 | 50 | | 8.5E+08 | 3118 | 6 | 1465 |
| recomb. line | 15 | 1 | 2 | 10 a | 10 | 200 | 60 | 1000 | 10 | 8 * | 1 | 100 | 50 | yes | 8.1E+06 | 78 | 1 | 0 |
| NH3 | 23 | 1 | 2 | 2 a | 5 | 100 | 60 | 500 | 2 | 8 * | 0 | 0 | 10 | | 8.1E+06 | 21 | 1 | 0 |
| H2O masers | 22 | 3 | 4 | 2 a | 0.06 b | 6000 | 8 | 500 | 2 | 4 * | 7 | 0 | 0 | | 5.8E+07 | 50 | 1 | 5 |
| OH masers | 1.6 | 3 | 4 | 30 a | 1 b | 5400 | 9 | 500 | 2 | 64 * | 6 | 0 | 0 | | 8.4E+08 | 794 | 1 | 62 |
| Extragalactic absorption | | | | | | | | | | | | | | | | | | |
| HI | 1.4 | 3 | 2 | 2 | 1 b | 400 | 60 | 1000 | 10 | 64 * | 2 | 100 | 50 | yes | 6.5E+07 | 1548 | 2 | 1 |
| OH | 1.6 | 2 | 4 | 2 | 1 b | 400 | 60 | 500 | 10 | 65 | 2 | 100 | 50 | yes | 1.3E+08 | 3083 | 3 | 3 |
| H2CO | 5 | 2 | 2 | 2 | 0.3 b | 1200 | 42 | 500 | 10 | 65 | 7 | 100 | 50 | yes | 9.5E+07 | 1055 | 2 | 7 |
| Galactic center | | | | | | | | | | | | | | | | | | |
| NH3 | 23 | 2 | 2 | 2 a | 5 | 100 | 60 | 400 | 1 | 16 * | 0 | 100 | 50 | | 1.6E+07 | 280 | 3 | 0 |
| H2CO | 5 | 1 | 2 | 9 a | 0.3 b | 5400 | 9 | 400 | 1 | 64 * | 3 | 100 | 50 | | 4.2E+08 | 517 | 1 | 40 |
| HI, OH | 1.4 | 1 | 2 | 30 a | 1 b | 5400 | 9 | 400 | 1 | 256 * | 3 | 100 | 50 | | 1.7E+09 | 2022 | 1 | 158 |
| recomb. line | 15 | 1 | 2 | 9 | 1 | 1600 | 31 | 1000 | 4 | 8 * | 4 | 100 | 50 | | 1.6E+07 | 78 | 1 | 0 |
| Galactic absorption | | | | | | | | | | | | | | | | | | |
| HI | 1.4 | 3 | 4 | 30 a | 1 b | 5400 | 9 | 100 | 1 | 130 | 3 | 100 | 100 | | 1.7E+09 | 16822 | 2 | 2635 |
| OH | 1.6 | 3 | 4 | 10 | 1 b | 1800 | 28 | 100 | 1 | 130 | 1 | 100 | 100 | | 5.7E+09 | 16791 | 2 | 255 |
| H2CO | 5 | 3 | 2 | 10 | 0.3 b | 6000 | 8 | 100 | 1 | 130 | 3 | 100 | 100 | | 9.5E+08 | 5639 | 2 | 1104 |
| NH3 | 22 | 1 | 2 | 2 a | 0.06 b | 6000 | 8 | 3.2 e | 0.01 e | 128 * | 0 | 100 | 100 | | 9.3E+08 | 1845 | 4 | 722 |
| Galactic emission | | | | | | | | | | | | | | | | | | |
| HI | 1.4 | 2 | 2 | 10 | 5 | 400 | 60 | 200 | 5 | 52 | 1 | | 50 | | 5.3E+07 | 813 | 2 | 0 |
| NH3 | 22 | 1 | 2 | 2 a | 5 | 100 | 60 | 3.2 e | 0.01 e | 128 * | 0 | 100 | 10 | | 1.3E+08 | 348 | 12 | 0 |
| recomb. lines | 15 | 2 | 2 | 4 a | 5 | 100 | 60 | 150 | 3 | 65 | 0 | 100 | 50 | yes | 6.6E+07 | 1044 | 11 | 0 |
| OH masers | 1.6 | 12 | 4 | 10 | 1 | 1800 | 28 | 100 | 1 | 130 | 1 | 100 | 50 | yes | 5.7E+08 | 36745 | 7 | 1952 |
| H2O masers | 22 | 2 | 4 | 2 | 0.06 | 6000 | 8 | 100 | 0.5 | 32 * | 2 | 100 | 5 | yes | 4.7E+08 | 409 | 6 | 240 |
| Stars | | | | | | | | | | | | | | | | | | |
| OH masers | 1.6 | 12 | 4 | 0.2 | 1 b | 100 | 60 | 60 | 0.5 | 156 | 0 | 100 | 50 | yes | 3.2E+08 | 43987 | 6 | 4 |
| H2O masers | 22 | 12 | 4 | 0.2 | 0.06 b | 600 | 60 | 60 | 0.5 | 32 * | 0 | 100 | 50 | yes | 6.5E+07 | 9168 | 3 | 20 |
| SiO masers | 44 | 12 | 4 | 0.2 | 0.03 b | 1200 | 42 | 60 | 0.5 | 16 * | 0 | 100 | 50 | yes | 4.7E+07 | 4675 | 2 | 30 |
| | | | | | | | | | | | | | | | | | | ----- |
| | | | | | | | | | | | | | | | | | | 8713 FFTs/12h |

(a) Limited by primary beamwidth.
(b) Limited by maximum VLA resolution.
(c) Scales with distance of object or frequency so that number of pixels is constant.
(d) Full primary beam needed for HI absorption because emission must be measured over the whole primary beam.
(e) Units are MHz. Specified to cover line structure.
(*) Limited by specification of present correlator.

TABLE 3B ASTRONOMICAL REQUIREMENTS - SPECTRAL LINE (Expanded correlator)

| (1) Class of Project | (2) Freq. GHz | (3) No. of obs (in 12hr) | (4) Pol. | (5) Field 'arc | (6) Space Resoln. "arc | (7) Pixels | (8) Sample time sec | (9) Range km/s | (10) Velocity Resoln. km/s | (11) Chnls | (12) No. beams % | (13) Self cal. % | (14) Deconvo lution % | (15) uv sub. | (16) Input words | (17) No. of 2-D FFTs | (18) Observ time % | (19) Average equivalent 2048 FFTs |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Extragalactic emission | | | | | | | | | | | | | | | | | | |
| HI clusters | 1.4 | 1 | 2 | 30 | 5 | 1100 | 46 | 5000 | 20 | 325 ‡ | 12 | 0 | 20 | yes | 4.3E+08 | 1319 | 6 | 21 |
| HI galaxies | 1.4 | 2 | 2 | 30 c | 10 c | 500 | 60 | 1000 | 10 | 130 ‡ | 3 | 0 | 75 | yes | 1.3E+08 | 2882 | 12 | 17 |
| ISM (individ. gal | 1.4 | 3 | 2 | 30 a | 1 | 5400 | 9 | 500 | 5 | 130 | 15 | 0 | 50 | | 8.5E+08 | 3118 | 6 | 1465 |
| recomb. line | 15 | 1 | 2 | 10 a | 10 | 200 | 60 | 1000 | 10 | 130 ‡ | 1 | 100 | 50 | yes | 1.3E+08 | 1031 | 1 | 0 |
| NH3 | 23 | 1 | 2 | 2 a | 5 | 100 | 60 | 500 | 2 | 325 ‡ | 0 | 0 | 10 | | 3.3E+08 | 845 | 1 | 0 |
| H2O masers | 22 | 3 | 4 | 2 a | 0.06 b | 6000 | 8 | 500 | 2 | 325 ‡ | 7 | 0 | 0 | | 4.7E+09 | 4056 | 1 | 397 |
| OH masers | 1.6 | 3 | 4 | 30 a | 1 b | 5400 | 9 | 500 | 2 | 325 ‡ | 6 | 0 | 0 | | 4.3E+09 | 4031 | 1 | 316 |
| Extragalactic absorption | | | | | | | | | | | | | | | | | | |
| HI | 1.4 | 3 | 2 | 2 | 1 b | 400 | 60 | 1000 | 10 | 130 ‡ | 2 | 100 | 50 | yes | 1.3E+08 | 3098 | 2 | 2 |
| OH | 1.6 | 2 | 4 | 2 | 1 b | 400 | 60 | 500 | 10 | 65 | 2 | 100 | 50 | yes | 1.3E+08 | 3083 | 3 | 3 |
| H2CO | 5 | 2 | 2 | 2 | 0.3 b | 1200 | 42 | 500 | 10 | 65 | 7 | 100 | 50 | yes | 9.5E+07 | 1055 | 2 | 7 |
| Galactic center | | | | | | | | | | | | | | | | | | |
| NH3 | 23 | 2 | 2 | 2 a | 5 | 100 | 60 | 400 | 1 | 520 ‡ | 0 | 100 | 50 | | 5.3E+08 | 8143 | 3 | 0 |
| H2CO | 5 | 1 | 2 | 9 a | 0.3 b | 5400 | 9 | 400 | 1 | 520 ‡ | 3 | 100 | 50 | | 3.4E+09 | 4091 | 1 | 320 |
| HI, OH | 1.4 | 1 | 2 | 30 a | 1 b | 5400 | 9 | 400 | 1 | 520 ‡ | 3 | 100 | 50 | | 3.4E+09 | 4091 | 1 | 320 |
| recomb. line | 15 | 1 | 2 | 9 | 1 | 1600 | 31 | 1000 | 4 | 325 ‡ | 4 | 100 | 50 | | 6.4E+08 | 2565 | 1 | 15 |
| Galactic absorption | | | | | | | | | | | | | | | | | | |
| HI | 1.4 | 3 | 4 | 30 a | 1 b | 5400 | 9 | 100 | 1 | 130 | 3 | 100 | 100 | | 1.7E+09 | 16822 | 2 | 2635 |
| OH | 1.6 | 3 | 4 | 10 | 1 b | 1800 | 28 | 100 | 1 | 130 | 1 | 100 | 100 | | 5.7E+08 | 16791 | 2 | 255 |
| H2CO | 5 | 3 | 2 | 10 | 0.3 b | 6000 | 8 | 100 | 1 | 130 | 3 | 100 | 100 | | 9.5E+08 | 5639 | 2 | 1104 |
| NH3 | 22 | 1 | 2 | 2 a | 0.06 b | 6000 | 8 | 3.2 e | 0.01 e | 416 ‡ | 0 | 100 | 100 | | 3.0E+09 | 5964 | 4 | 2335 |
| Galactic emission | | | | | | | | | | | | | | | | | | |
| HI | 1.4 | 2 | 2 | 10 | 5 | 400 | 60 | 200 | 5 | 52 | 1 | | 50 | | 5.3E+07 | 813 | 2 | 0 |
| NH3 | 22 | 1 | 2 | 2 a | 5 | 100 | 60 | 3.2 e | 0.01 e | 416 ‡ | 0 | 100 | 10 | | 4.2E+08 | 1097 | 12 | 0 |
| recomb. lines | 15 | 2 | 2 | 4 a | 5 | 100 | 60 | 150 | 3 | 65 | 0 | 100 | 50 | yes | 6.6E+07 | 1044 | 11 | 0 |
| OH masers | 1.6 | 12 | 4 | 10 | 1 | 1800 | 28 | 100 | 1 | 130 | 1 | 100 | 50 | yes | 5.7E+08 | 35745 | 7 | 1952 |
| H2O masers | 22 | 2 | 4 | 2 | 0.06 | 6000 | 8 | 100 | 0.5 | 260 ‡ | 2 | 100 | 5 | yes | 3.8E+09 | 3106 | 6 | 1824 |
| Stars | | | | | | | | | | | | | | | | | | |
| OH masers | 1.6 | 12 | 4 | 0.2 | 1 b | 100 | 60 | 60 | 0.5 | 156 | 0 | 100 | 50 | yes | 3.2E+08 | 43987 | 6 | 4 |
| H2O masers | 22 | 12 | 4 | 0.2 | 0.06 b | 600 | 60 | 60 | 0.5 | 156 ‡ | 0 | 100 | 50 | yes | 3.2E+08 | 43997 | 3 | 95 |
| SiO masers | 44 | 12 | 4 | 0.2 | 0.03 b | 1200 | 42 | 60 | 0.5 | 156 ‡ | 0 | 100 | 50 | yes | 4.6E+08 | 44009 | 2 | 281 |
| | | | | | | | | | | | | | | | | | | ----- |
| | | | | | | | | | | | | | | | | | | 13368 FFTs/12h |

(a) Limited by primary beamwidth.
(b) Limited by maximum VLA resolution.
(c) Scales with distance of object or frequency so that number of pixels is constant.
(d) Full primary beam needed for HI absorption because emission must be measured over the whole primary beam.
(e) Units are MHz. Specified to cover line structure.
(‡) Exceeds specification of present correlator.