LECTURE NO. 14

# VLA OBSERVING STRATEGIES

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## 1. INTRODUCTION

This Lecture discusses the choice of parameters for VLA continuum observing based on a mixture of astronomical and instrumental criteria. Its goal is to suggest an orderly way in which to use the material of Lectures 2, 3, 4, 5, 6 and 13 to decide on critical parameters when planning and executing VLA observations. It also suggests strategies for avoiding some of the mapmaking pathologies which were emphasized in the previous Lectures.

Figure 14-1 shows a decision tree for preparing VLA continuum observations; the first half of this Lecture deals with the "limbs" of this tree. The second half (Sections 7 to 10) deals with calibration strategy, on-line observing strategy, and the observing proposal.

## 2. CHOICE OF ARRAY CONFIGURATION

### A. Resolution $\theta_{HPBW}$ - How Much is Enough?

An untapered map made from uniformly-weighted ≥4-hr tracks in a standard VLA configuration at high declinations (where foreshortening of the array is unimportant) has a half-power beamwidth given approximately by:

$$\theta_{HPBW} = 1.25'' \,(1480/\nu_o)\,(3.285)^{n-1} \qquad (14\text{-}1)$$

where $\nu_o$ is the observing frequency in MHz and n = 1,2,3,4 for the A,B,C and D configurations respectively.

The <u>minimum</u> resolution appropriate for the observations will be determined by the need to separate or resolve important features of the structure in the region to be mapped. For observations of extended emission, the <u>maximum</u> resolution that is appropriate should also be determined by considering the total integration time needed to achieve the required brightness sensitivity. There is no point observing extended emission using such high angular resolution that the interesting features of the source are close to or below the rms noise on the final map.

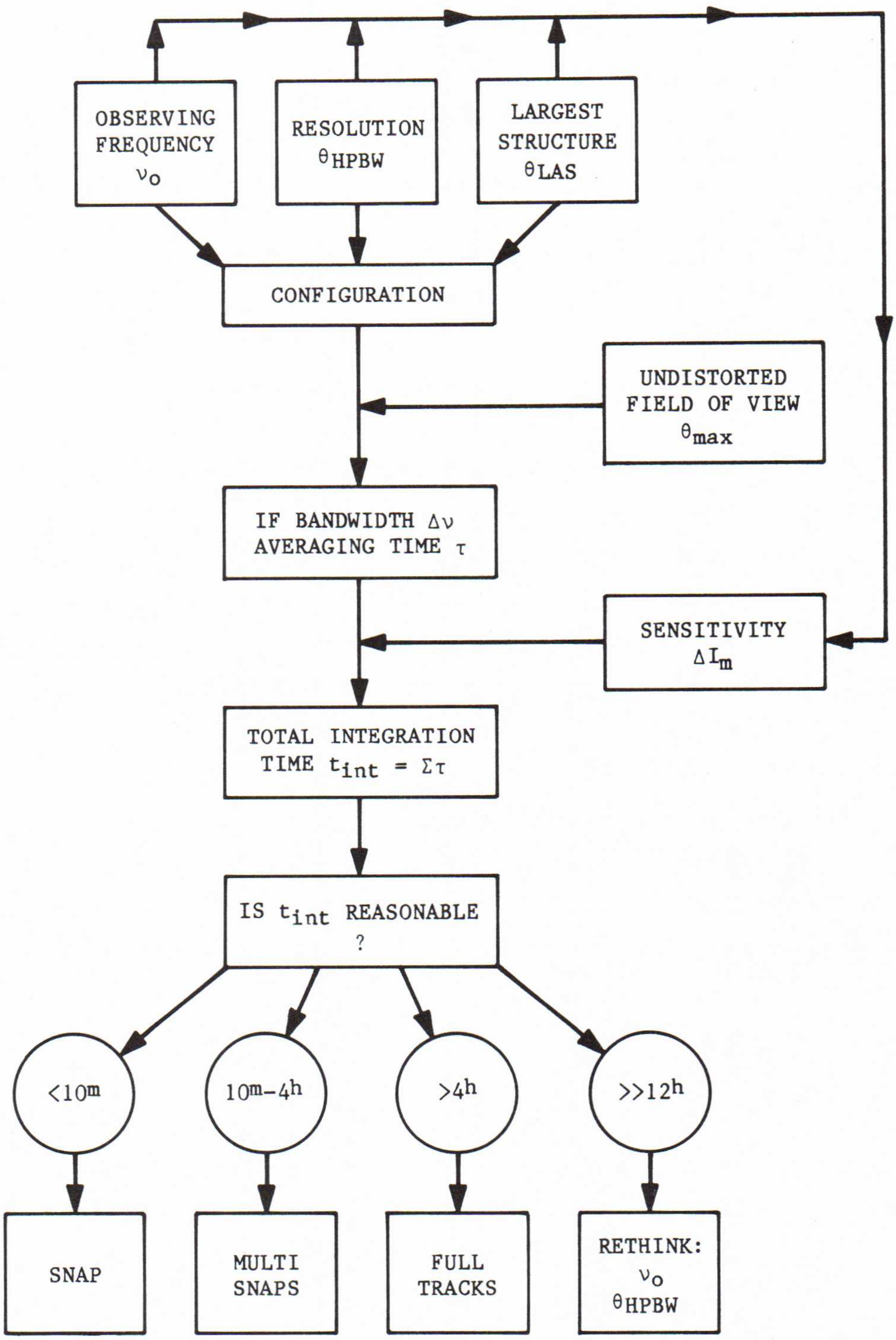


Figure 14-1. Factors Entering Into VLA Observing Strategy - A Suggested Decision Tree.

Recall from Lecture 3 that a point source with flux density S has an apparent brightness of S Janskys per synthesized beam regardless of the area $\Omega_s$ of the synthesized beam. At a given frequency, all VLA configurations are thus equally sensitive to a point source (apart from the effects of confusion and phase stability). In contrast, the apparent brightness of an extended emission region in a synthesized map depends on the details of the region's structure and of the (u,v) sampling. When planning observations, we can however make the first-order assumption that an extended region with uniform brightness B Janskys per square arcsec has a flux density per synthesized beam of $B\Omega_s$. If the rms noise on the map is $\Delta I_m$, the signal-to-noise ratio of the extended emission on the map is $B\Omega_s/\Delta I_m$, which decreases in proportion to the beam area $\Omega_s$. Ensure that you do not observe with such small values of $\Omega_s$ that interesting extended structure is undetectable, given the time available and your choice of the IF bandwidth (see Sections 3 and 4 below). For a Gaussian beam with half-power widths $\theta_1$ and $\theta_2$ (arcsec), the beam area $\Omega_s = 1.133\theta_1\theta_2$ square arcsec.

For example, consider a smooth two-dimensional emission region 30" across with a peak intensity per synthesized beam $B\Omega_s$ of 1 mJy/beam on an untapered VLA 20cm map made with the B configuration (resolution ≃ 4.2"). It will have a peak intensity of only 0.093 mJy/beam on an untapered 20cm map made with the same HA coverage and (u,v) weighting in the A configuration (resolution ≃ 1.3"). It could be detected at the 10σ level in about 16 min of integration in the B configuration (using the sensitivity data given in Table 14-1 below), but a 10σ detection in

Table 14-1

Rms Noise on Maps Made with 27 Antennas*

| Band Designation | 20cm<br>L | 6cm<br>C | 2cm<br>U | 1.3cm<br>K | |
|---|---|---|---|---|---|
| RMS Noise $\Delta I_m$ in 5-min snapshot (50 MHz bandwidth) | 0.18 | 0.12 | 0.90 | 1.2 | mJy |
| RMS Noise $\Delta I_m$ in 12-hr integration (50 MHz bandwidth) | 0.015 | 0.010 | 0.075 | 0.10 | mJy |

*Larger sources can be mapped by combining a few snapshots taken at different hour angles.

the A configuration using the same bandwidth would require about 31 hours of on-source integration! When studying extended emission, it is therefore extremely important not to use a configuration giving higher angular resolution than is strictly necessary.

Note that the effects of spectral index and resolution combine to make extended steep-spectrum emission much harder to detect in a given configuration at the higher frequencies. For example, suppose that an extended region has a peak intensity of 1 mJy per beam in the A configuration at 20cm - a 10$\sigma$ detection would be made in 16 minutes at 20cm. If the region has a $\nu^{-1}$ spectrum, the peak intensity in the A configuration at 6cm would be 0.027 mJy/beam and a 10$\sigma$ detection at this frequency would require 160 hours of integration. The choice of frequency is therefore critical when trying to detect steep-spectrum extended emission using a given configuration.

For sources with compact flat-spectrum components and extended steep-spectrum emission, the dynamic range needed to map the extended structure increases very rapidly with increasing frequency. Suppose that the extended emission referred to in the previous example surrounded a 5 mJy point source with a $\nu^{-0}$ spectrum. The dynamic range required for 10$\sigma$ detection of the extended structure would be 50:1 in the A configuration at 20cm. This is easy to obtain. The dynamic range required in the A configuration at 6cm would be 1850:1, a much more formidable target.

A similar caution against the use of unnecessarily high resolution applies to detection experiments at the higher frequencies. While the sensitivity to a point source is independent of the array configuration (apart from the effects of confusion), the phase stability and hence the ability to integrate coherently between calibrations will generally be poorer in the more widely separated configurations (see Lecture 4). The phase stability will be highly weather-dependent, so that no general guidelines can be given, but it is clear for example that the A configuration is rarely a wise choice for 1.3cm point source detection experiments.

There are circumstances however when enhanced resolution improves the ability to detect interesting features in a source - for example when searching for pointlike "hot spots" or linear "jets" in more diffuse emission such as large-scale "lobes". The flux density per synthesized beam of two-dimensional emission is roughly proportional to the beam area $\Omega_s$ while that of linear emission is proportional to the beam width $\theta_{HPBW}$ and that of a point source is independent of beam size. These dependencies allow compact structure to be recognized more easily on higher-resolution maps by reducing confusion with more extended emission.

These competing factors affecting the choice of resolution cannot be estimated reliably in advance if the source structure to be expected is unknown or poorly known. The safest strategy is then to guess on the side of low resolution in an initial experiment - it may be easier to justify reobserving a detected region at higher resolution than to justify reobserving at lower resolution what appeared to be empty sky!

B. Choice of Frequency $\nu_o$ at Given Resolution $\theta_{HPBW}$

Returning to Equation (14-1), note that the scaling factor between "adjacent" VLA configurations (e.g. B and C) is 3.285. The ratio between the default VLA frequencies for 50 MHz bandwidth at 20cm and 6cm is (4885/1465) = 3.33; similarly the ratio between the default frequencies at 6cm and 2cm is (14960/4885) = 3.06. The VLA therefore has very similar resolutions at 20cm in the A configuration, at 6cm in the B configuration and at 2cm in the C configuration. (Similar three-frequency scalings apply for the B,C and D configurations).

The choice of observing frequency <u>at a given resolution</u> will be determined by astronomical criteria. A high frequency might be chosen for polarimetry because Faraday effects decrease with increasing frequency: degrees of linear polarization are therefore generally higher at higher frequencies and electric vectors lie closer to their intrinsic position angles. The spectral index of the emission being studied also influences the choice - optically thick thermal emission may be easier to detect at 2cm than 6cm despite the noisier system at 2cm, whereas transparent synchrotron sources will be easiest to detect at a given resolution at 20cm.

The frequency-scaling of the standard VLA configurations to give similar resolutions at several different frequencies is a powerful tool for studies of the frequency-dependence of the properties of extended emission. Scaled-configuration observations can be used to produce maps of spectral index, Faraday rotation or depolarization properties of extended sources that are free from the major uncertainties due to differing resolutions at the different frequencies. It is important to match the hour angle ranges of scaled-configuration observations at different frequencies, to ensure that the effects of foreshortening, etc. on the (u,v) coverages are similar for the observations at the different frequencies. Note however that even the scaled configurations may sample the visibility function of a source differently at different frequencies if its structure changes radically over the frequency range of interest. This situation may arise if there are large spectral index gradients across the source in either its total or its polarized emission.

C. Non-Standard Configurations - Hybrid, Mixed and Sub-Arrays

The above has been concerned primarily with observations in the standard (A,B,C,D) configurations of the VLA. Other options are available, namely hybrid arrays, combinations of observations made with different standard configurations on different occasions, and sub-arrays. Hybrid arrays are available during reconfiguration periods, when the arms of the VLA may be of different lengths, or may have a non-standard mixture of long and short baselines. They offer some advantages over single standard configurations. For example, they can provide wider ranges of spacing than a standard configuration (giving sensitivity to a wider range of angular scales). They may also assist self-calibration of data from the compact configurations by providing them with some long spacings.

The parameter you must consider to evaluate whether you will need a non-standard configuration is $\theta_{LAS}$, the largest angular scale of structure which you require to be well-sampled in your final map. This parameter will be the angular diameter of the most extended structural component in your source. (Do not confuse it with $\theta_{max}$, the required field of view, which we discuss later - $\theta_{LAS}$ for observing a Gaussian source 10" in extent in the presence of a point confusing source 1' away would be 10"). The ratio $(\theta_{LAS}/\theta_{HPBW})$ tells you the ratio of the longest to the shortest baseline required in your observations. If this ratio exceeds 40:1, which is the ratio of longest to shortest baselines in a standard VLA configuration, you must consider the use of non-standard configurations.

Perley (1981b) discusses the merits of hybrid and mixed VLA configurations. Combinations of data from two different standard configurations generally have better (u,v) coverage than any hybrid array. For example, Fig. 14-2 to 14-4 show the (u,v) coverage of the VLA at $+60^{o}$ declination for 12 hrs observing in the A configuration, 12 hrs observing in a hybrid configuration with some antennas on the inner stations, and 6 hrs of A configuration observing combined with 6 hrs in the C configuration. The "hole" at the center of the (u,v) coverage in Figs. 14-2 is clearly filled best by combining data from the A and C configurations.

Hybrid configurations do however make it possible to observe southern sources with nearly circular beams by using an overextended N arm. Figure 14-5 shows the (u,v) coverage for the B configuration at $-40^{o}$ declination, compared with that of a hybrid configuration in which the East and West arms are in the B configuration while the North arm is in the A configuration. The spacings obtained from the longer North arm fill in a region around the v axis left empty by the standard B configuration. Hybrid configurations may also satisfy "impatient" users who cannot wait for both parts of a mixed array to be scheduled, or whose sources might exhibit time-variable large-scale structure (e.g. the Sun).

The use of sub-arrays is generally not as effective as timesharing the entire VLA. Consider that the number of interferometer pairs in a subarray is N(N-1)/2 where N is the number of antennas in the sub-array. A sub-array with 13 antennas therefore has 78 interferometers, whereas a 27-antenna standard configuration has 351. An hour of observing in which two such sub-arrays perform different tasks produces 156 interferometer-hours of data. In contrast, two half-hours of observing with the full VLA devoted to each task in turn produces 351 interferometer-hours of data. Dedicating two sub-arrays to different tasks thus reduces the amount of information gathered by a factor of about two, compared with time-sharing the whole VLA between the two tasks. This inefficiency will manifest itself in poorer sensitivity and

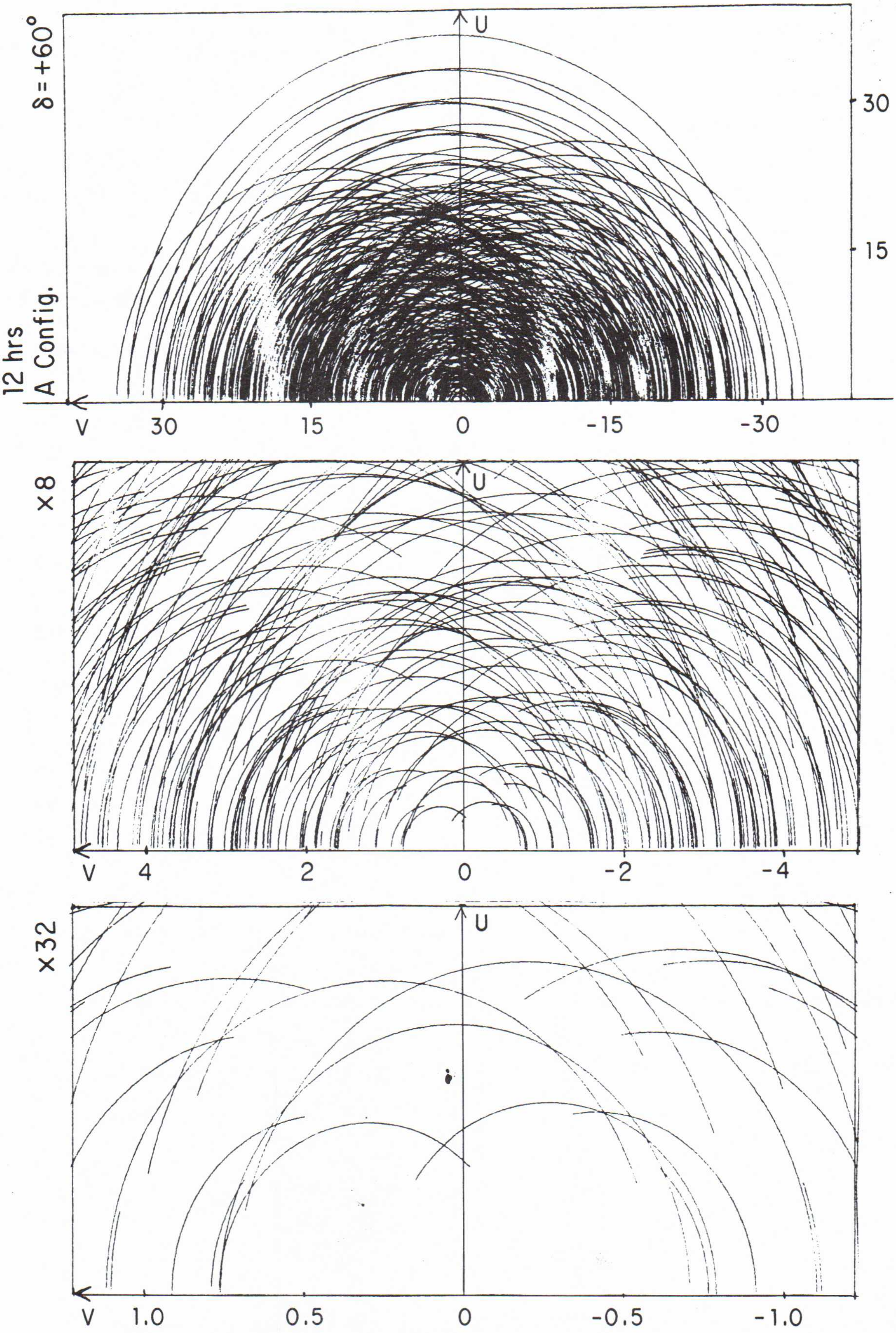


Figure 14-2. (u,v) coverage for δ = +60° in the A configuration. (12 hour tracks)

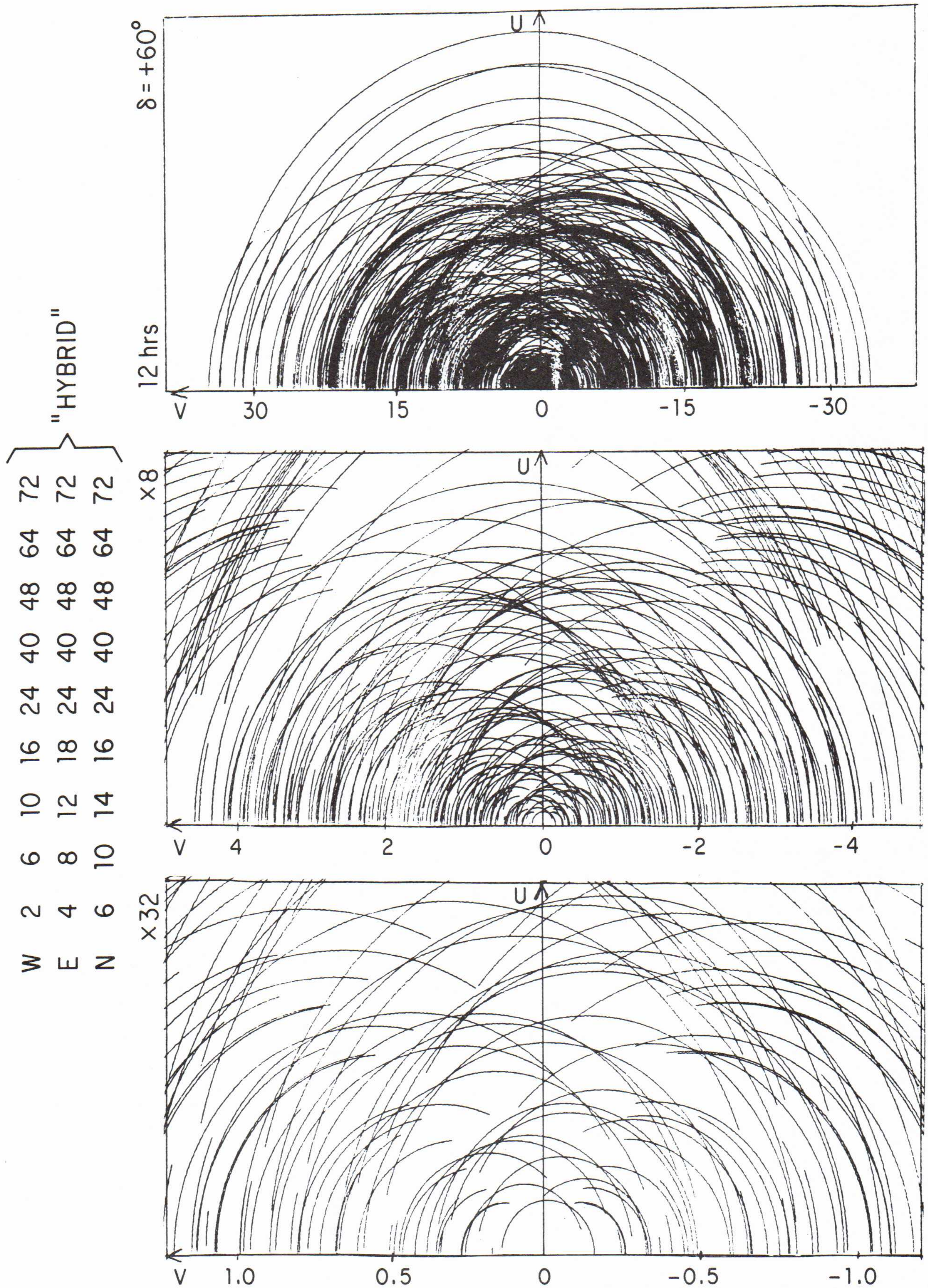


Figure 14-3. (u,v) coverage for $\delta = +60^{\circ}$ in a hybrid configuration. (12 hour tracks)

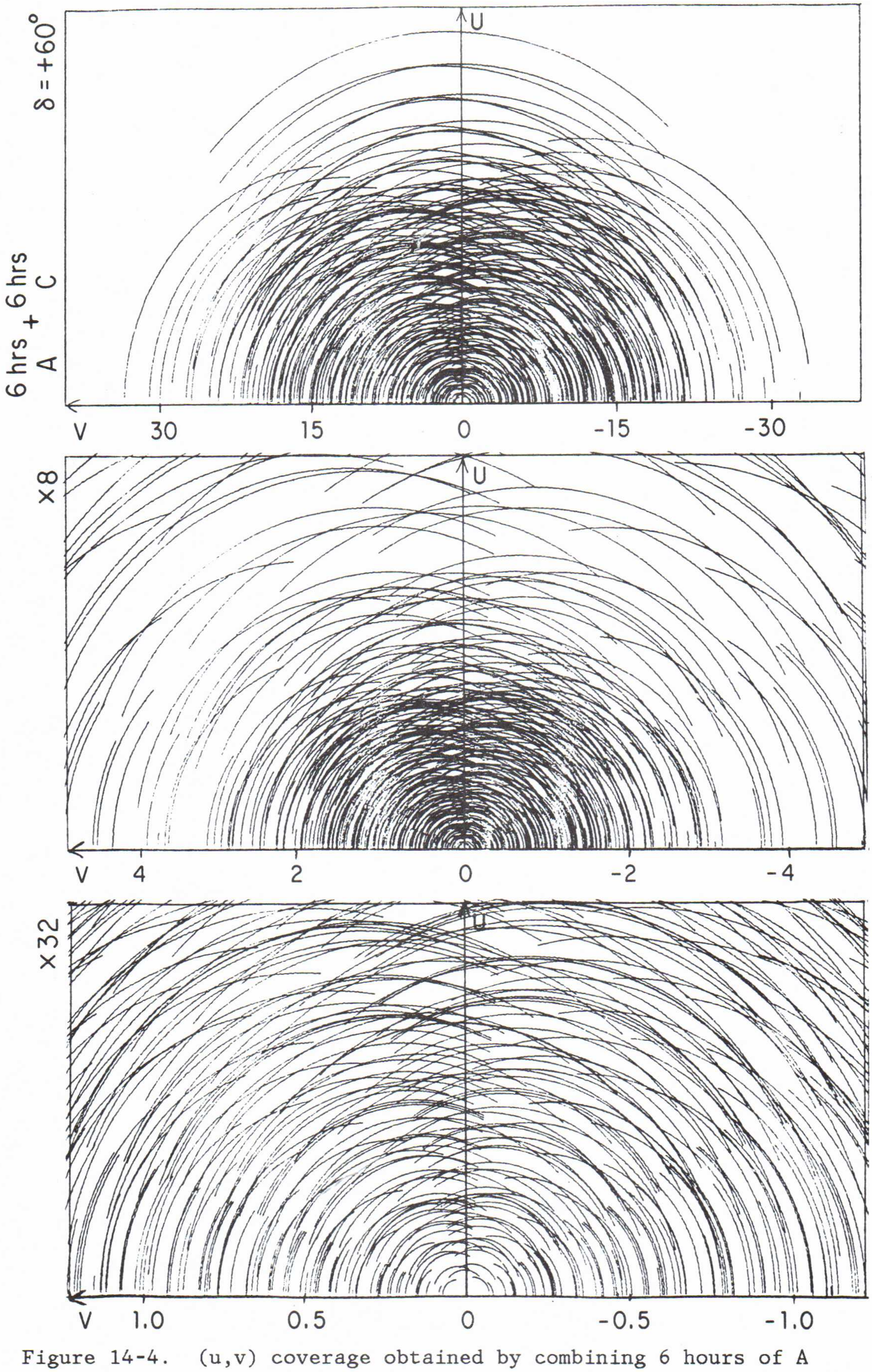


Figure 14-4. (u,v) coverage obtained by combining 6 hours of A configuration data with 6 hours of C configuration data at $\delta = +60°$. Note the superior coverage of the inner (u,v) plane relative to Figs. 14-2 and 14-3.

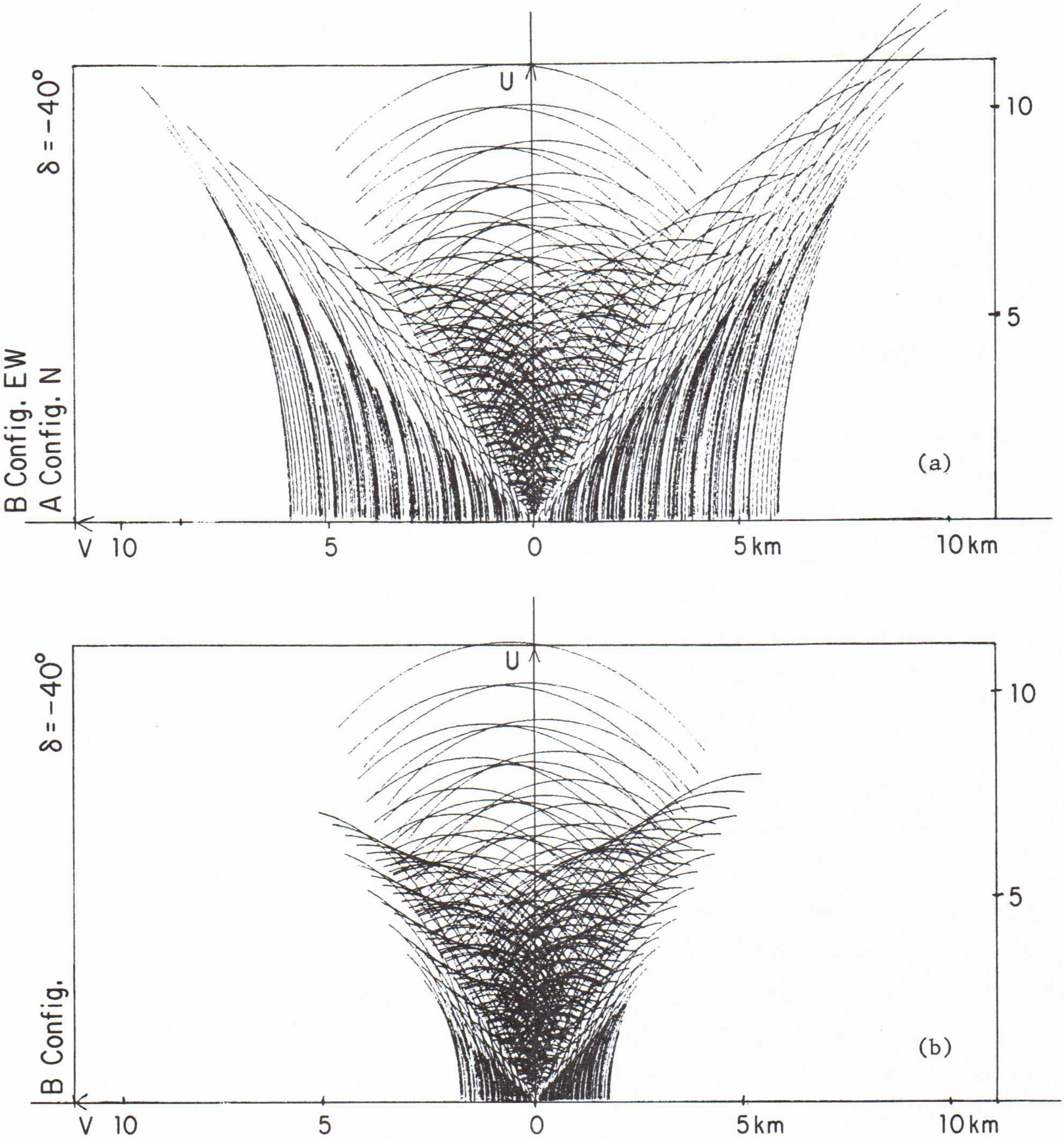


Figure 14-5. (u,v) coverage at $\delta = -40°$ for observations with (a) VLA E and W arms in B configuration, N arm in A configuration, (b) entire VLA in B configuration.

(u,v) sampling in the sub-array data. The use of sub-arrays is therefore generally undesirable unless your program calls for strictly simultaneous observations of a source at several frequencies (e.g. instantaneous spectra of very rapid variables) or for observations of a large number of compact sources with only modest demands on sensitivity and dynamic range (e.g. astrometry of strong sources).

D. Interference and the Detailed Choice of Frequency

External interfering signals are partially rejected by the VLA because only the component of the interference which (a) varies at the sidereal fringe rate and (b) correlates with the correct delay will affect the output (very strong interference may also degrade the noise performance). This rejection is best at the longer baselines, so the A and B VLA configurations are less susceptible to external interfering signals than are the C and D configurations. Interference is rarely detected or suspected at C, U or K Bands.

Interference is however a factor in choosing an observing frequency within the VLA L Band (1340 to 1730 MHz), particularly when using non-standard frequencies (e.g. at the opposite edges of the band to determine Faraday rotation parameters). Frequency allocations in the band include aeronautical radio navigation, meteorological aids, and fixed and mobile use. Many of the possible external interfering signals are therefore time variable so no guarantees can be offered regarding freedom of any non-standard frequency from interference.

There is also self-generated interference throughout L Band, mainly at harmonics of 50 MHz; this internal interference should be below the noise in any continuum map made with an IF bandwidth greater than 6.25 MHz, but may be a serious problem for spectral-line programs. Table 8-6 of Lecture 8 lists some well-known L Band interference frequencies. Before using a non-standard L Band frequency, consult with VLA scientific staff (particularly Arnold Rots or Rick Perley) for advice and lore based on recent observers' experiences.

Note also that the protected band from 1400 to 1427 MHz is not at present interference-free at the VLA. A signal at 1796 MHz from a recently installed communications system near the VLA appears at 1404 MHz due to a spurious response in the VLA's L-Band upconverters. This spurious signal is present at all times, and the band from 1403.5 to 1404.5 MHz should be avoided until the conversion to FET front ends at L Band is completed.

## 3. FIELD OF VIEW RESTRICTIONS

Once you have settled on the resolution $\theta_{HPBW}$ and observing frequency $\nu_o$ for your program, the next level on the decision tree

(Fig. 14-1) is the choice of IF bandwidth $\Delta\nu$ and averaging time $\tau$. These must be chosen in a manner consistent with the field of view requirements of your program. The next step is therefore to consider the radius $\theta_{max}$ from the phase center over which you require the data to be minimally distorted by the effects discussed in Lecture 5.

A. IF Bandwidth $\Delta\nu$

The choice of the IF bandwidth for VLA observations is most important, as an unsuitable choice may lead (a) to irrecoverable distortion of the map if the bandwidth is too great or (b) to loss of sensitivity if it is too small. As discussed in Lecture 5, observations made with finite bandwidth suffer radial smearing and reduction in amplitude away from the field (phase) center. These effects are discussed in detail by Perley (1981a), and are graphed in Figs. 14-6 and 14-7.

The first step in choosing the IF bandwidth for your observations is to ask over what field radius $\theta_{max}$ (arcsec) you require either the radial smearing to be less than n% or the reduction in amplitude of a point source to be less than m%, due to finite IF bandwidth. Then enter Fig. 14-6 at ordinate (1 + n/100), or Fig. 14-7 at ordinate (1 - m/100), and read the corresponding value of the normalized parameter $\beta$ from the abscissa. Call this value $\beta_{max}$. Then compute the maximum allowable IF bandwidth $\Delta\nu_{max}$ (MHz) consistent with these constraints from the relation:

$$\Delta\nu_{max} = \beta_{max}\nu_o\theta_{HPBW}/\theta_{max} \qquad (14\text{-}2)$$

where $\nu_o$ is your observing frequency in MHz and $\theta_{HPBW}$ is the half-power beamwidth in arcsec at which you expect to make your maps. Unless you are prepared to relax your smearing/attenuation criterion slightly, select the closest VLA bandwidth that is <u>narrower</u> than the computed value $\Delta\nu_{max}$. If you are prepared to relax it, choose the closest <u>wider</u> bandwidth.

For example, suppose you are prepared to tolerate an amplitude loss of 10% at 45" from the map center in an A configuration observation at 1465 MHz. Entering Fig. 14-7 at $I/I_o = 0.9$ gives $\beta_{max} = 0.8$, from which

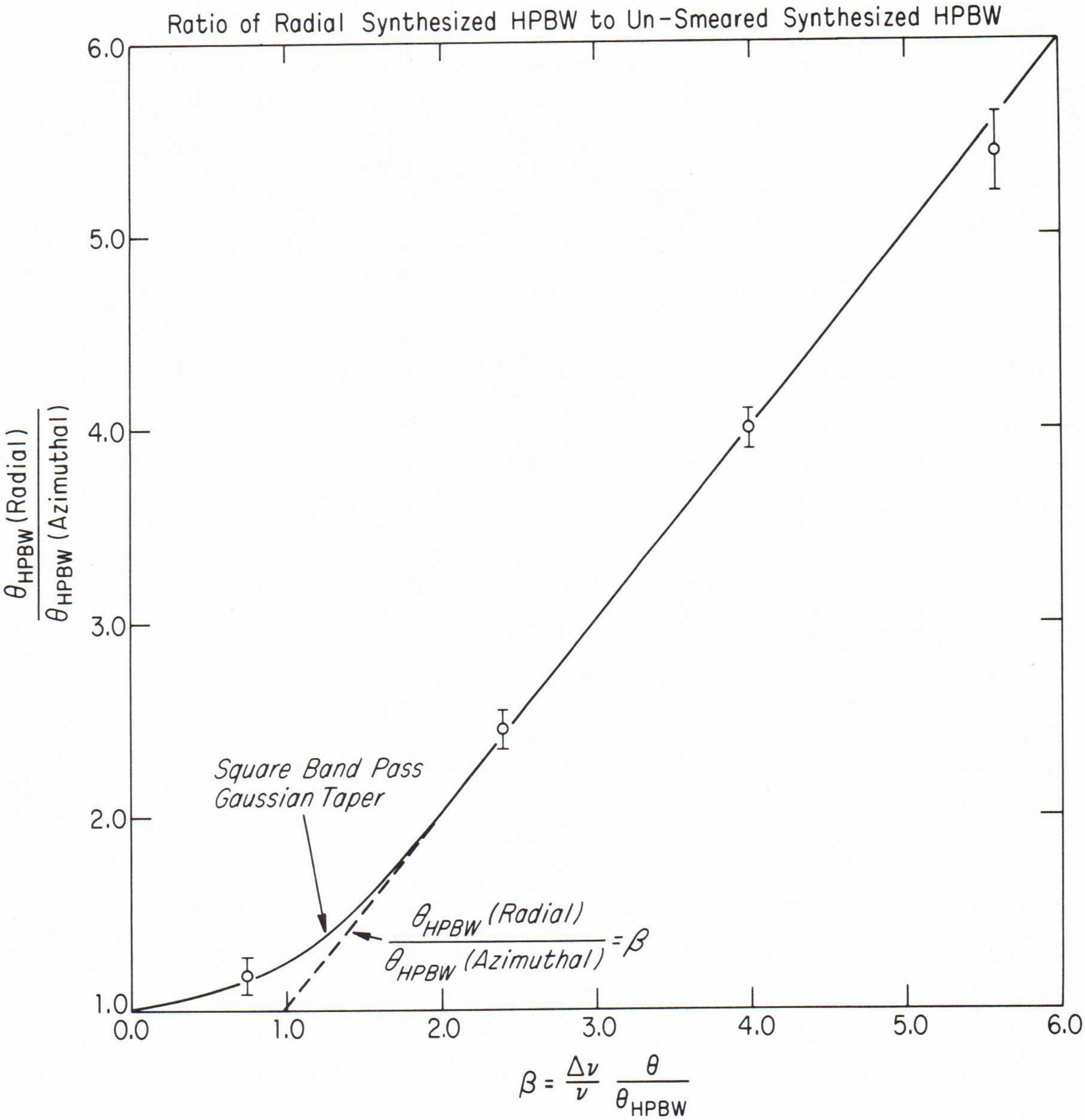


Figure 14-6. Ratio of radial to azimuthal beamwidth, due to finite IF bandwidth $\Delta\nu$, plotted as a function of the dimensionless parameter $\beta$. $\theta$ is angular distance of the feature from the phase center, in the same units as the beamwidth $\theta_{HPBW}$.

$\Delta\nu_{max}$ = 0.8 × 1465 × 1.25" / 45" = 32 MHz. You would then either choose $\Delta\nu$ = 25 MHz, or relax the criterion and use $\Delta\nu$ = 50 MHz.

Your choice of $\theta_{max}$ may be determined by the need to map an extended structure with minimal distortion, or by the need to include a strong confusing source in the minimally-distorted field of view. The latter need arises because you may wish to subtract or CLEAN the confusing source's sidelobes from the region of interest. The value of

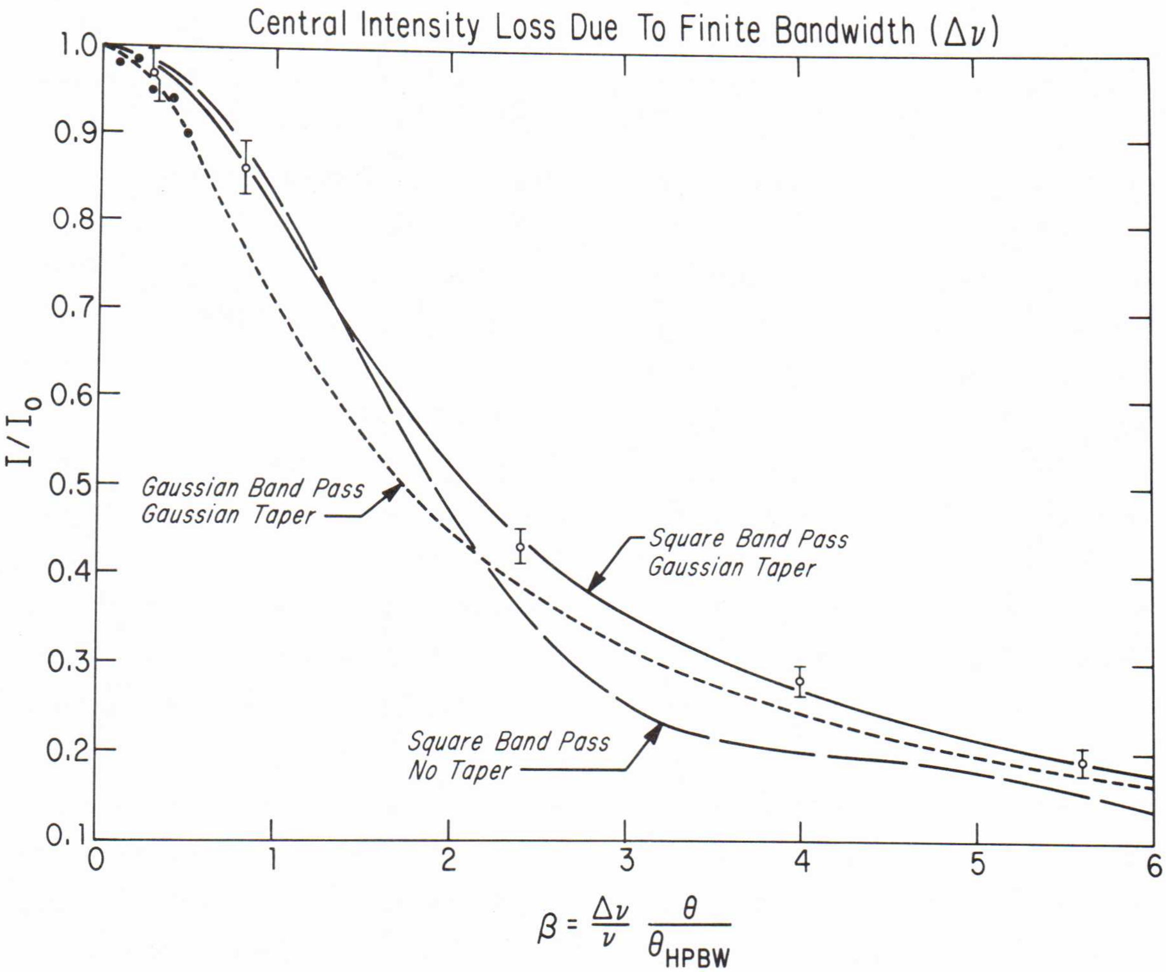


Figure 14-7. Central intensity loss, due to fininte IF bandwidth $\Delta\nu$, plotted as a function of the dimensionless parameter $\beta$. $\theta$ is angular distance of the feature from the phase center, in the same units as the beamwidth $\theta_{HPBW}$.

$\theta_{max}$ will always be greater than, or about equal to, the value of $\theta_{LAS}$ used earlier to select the configuration. In general, choose the phase center so as to minimize the required $\theta_{max}$ for your observations. This will avoid the use of unnecessarily narrow bandwidths (and thus of unnecessarily low sensitivity). When using a wide field to include a confusing source, this may mean displacing the phase center away from the "target" source towards the confusing source. If the field is dominated by a strong point source (a factor of ten or more brighter than other structure), this strong source should however be placed near the phase center of the map whenever high dynamic range is required. This will minimize the total distortion due to bandwidth, pointing, averaging time and (u,v) truncation effects (see Clark 1981).

feature is moving perpendicular to the fringes produced by that interferometer and is least when the feature is moving parallel to the fringes. The magnitude of the effect therefore depends on hour angle and declination, as described in Lecture 5, Equations (5-15) and (5-16). For a source at the north celestial pole however, the average reduction in amplitude $R_A = I/I_o$ varies as:

$$I/I_o = 1 - (\pi\tau\omega_o\theta/6\theta_{HPBW})^2 \tag{14-3}$$

where $\omega_o$ is the angular velocity of the Earth's rotation.

The exact expression for the amplitude reduction $R_B$ due to the bandwidth effect, for the case of a square bandpass and Gaussian tapering in the (u,v) plane which best represents the VLA situation, was given in Equation (5-7) of Lecture 5. For the range $0 < \beta \leq 1$, in which the amplitude reduction $R_B = I/I_o < 0.8$, this expression can be approximated with:

$$I/I_o \simeq 1 - \beta^2/5$$

$$= 1 - [\Delta\nu\theta/\nu_o\theta_{HPBW}]^2/5 \tag{14-4}$$

We can therefore approximate the averaging time $\tau$ which produces the <u>same</u> intensity reduction for a source near the pole as an IF bandwidth $\Delta\nu$ as:

$$\tau = 6\Delta\nu/[\sqrt{5}.\pi.\omega_o.\nu_o]$$

$$\tau = 1.2 \times 10^4.(\Delta\nu/\nu_o) \text{ sec} \tag{14-5}$$

Equation (14-5) gives a reasonable criterion for the <u>maximum</u> averaging time which should be used in conjunction with a given IF bandwidth $\Delta\nu$ at observing frequency $\nu_o$. Notice that it does not depend on VLA configuration or on $\theta_{max}$, due to the first-order similarities between the bandwidth and averaging time smearing effects.

Note that you may have to exceed the value of $\tau$ calculated from Equation (14-5), because the shortest available averaging time is the 10 seconds set by the on-line computers. Also, note that FILLER requires the same averaging time for the source and calibrator observations. If the calibrator observations are only a few minutes in duration (as is often the case at the lower frequencies), averaging times longer than 30 seconds may be undesirable simply because they permit only crude editing of the calibrator data.

## 4. TOTAL INTEGRATION TIME $t_{int} = \Sigma\tau$

Once you have determined the IF bandwidth $\Delta\nu$ from the field of view criteria, the next step in the decision tree (Fig. 14-1) is to estimate the total integration time $t_{int}$ required for given sensitivity on your final map. Here you will use the expression for the rms noise $\Delta I_m$ on a map made with an N-antenna array:

$$\Delta I_m = F(w)\Delta S / \sqrt{[N(N-1)/2 \times n \times (t_{int}/10) \times (\Delta\nu/46)]} \qquad (14\text{-}6)$$

where n is the number of independent IFs contributed to the map per antenna (n = 2 for I maps made from both left and right circular polarized channels, or for maps of $P = \sqrt{[Q^2+U^2]}$), $t_{int}$ is in seconds, and $\Delta\nu$ is in MHz. In the numerator, F(w) = 1.0 for natural weighting and 1.5 for uniform weighting, while $\Delta S$ is the single-interferometer sensitivity derived in Lecture 3 (Table 3-3), namely 26 mJy at 20cm, 17 mJy at 6cm, 130 mJy at 2cm and 180 mJy at 1.3cm.

Table 14-1 gives the rms noise on untapered maps made with 27 antennas using the "50 MHz" bandwidth ($\Delta\nu$ = 46) for integration times typical of snapshots and of more complete syntheses.

The sensitivity required for your observation will be determined (a) by the significance level you require for a detection in order to achieve your astronomical goals and (b) whether or not the emission of interest is extended (see the discussion in Section 2A above). If you are interested in polarimetry of the sources, the sensitivity required for the polarization measurements will normally drive the choice of total integration time for the experiment.

If the first estimate of $t_{int}$ is significantly greater than 12 hrs, consider carefully whether your choices of frequency and configuration are optimal. You may wish to re-enter the decision tree with different starting parameters before considering the proposal planning further. If your proposal is for 2cm or 1.3cm, you may wish to wait (until mid-1983) for full installation of the cooled FET front ends for these frequencies - these should reduce the value of the single-interferometer sensitivity ΔS in the numerator of Equation (14-6) to 50 mJy at 2cm and 105 mJy at 1.3cm. If the total integration time required is >4 hrs, a full HA track is probably desirable. If it is <4 hrs, your observing strategy should be determined by the need for dynamic range and the availability of other sources to merge with the program.

If you require high dynamic range, or wish to map an extended structure, it is generally better to fill in the (u,v) plane more uniformly by distributing several hours of observing over a wide range of hour angle (a large number of short scans). When the total integration time is less than 4 hrs, for which (u,v) tracks on different baselines begin to overlap, dynamic range is generally improved by distributing the observations over several shorter scans. It is difficult to give firm guidelines for doing this however, as the dynamic range achieved in a given observation is also sensitive to weather conditions, elevation angle of the observations, etc. In general, however, a series of spaced 10-15 min scans giving the desired total integration time will give reasonable results.

If the total integration time required is much less than 1 hr, consider the use of "snapshot" mode (see the next Section).

## 5. USE OF THE VLA IN "SNAPSHOT" MODE

The Y layout of the VLA makes it the first radio aperture synthesis instrument in which the instantaneous synthesized beam has a respectable shape and sidelobe level. It is therefore possible to do interesting science with very brief observations if the sources to be studied are both bright and compact. Snapshot mode observing may be ideal for observers who wish to study statistical properties of large samples of sources (and also to overdose on VLA image processing). To illustrate the power of snapshot mode, compare the two 20cm A configuration maps of the source 0055+300 (NGC315) shown as Fig. 14-8(a) and 14-8(b). Map (a) is from a 3-min snapshot at 50 MHz bandwidth, and has a signal-to-noise of about 200:1. Map (b) is from a 9-hour

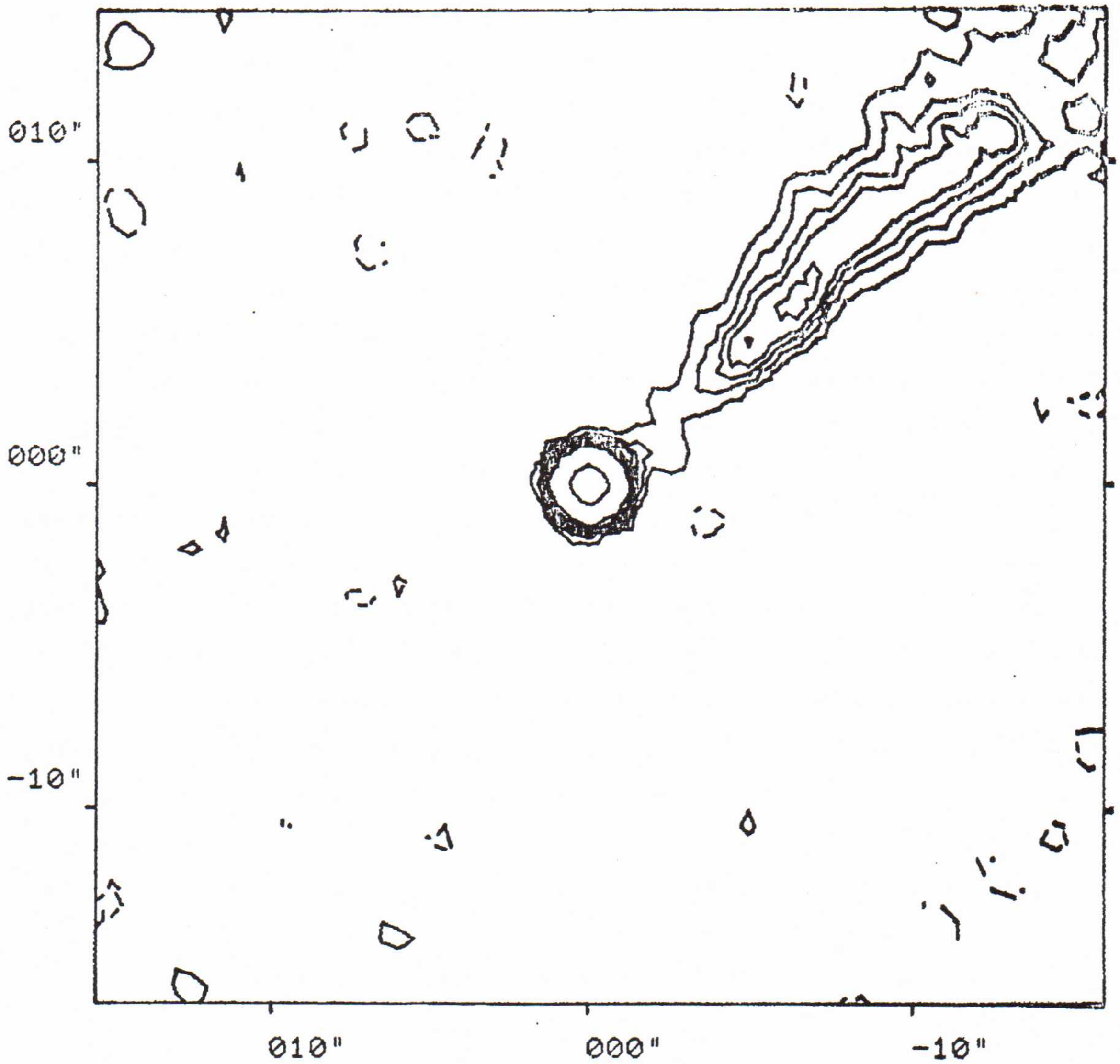


Figure 14-8(a). Contour plot of 20cm A configuration snapshot of the source 0055+300, made from 3 minutes of data at 50 MHz bandwidth. The contour levels are drawn at -2, 2, 4, 6, 8, 12, 20, 30 and 200 mJy/beam. The contour around the peak shows the HPBW. Compare with Fig. 14-8(b).

synthesis at 25 MHz bandwidth. It has a signal-to-noise of about 1500:1, limited by dynamic range. Apart from the obvious differences in signal-to-noise, the maps show identical jet structures within 15" of the 0.4-Jy unresolved peak. In what follows, I consider a single "snapshot" to be a VLA observation of about 3-5 min duration (shorter snapshots are not recommended because of the risk that all of the data will be lost if the instrument takes unusually long to settle down following a drive from the previous source).

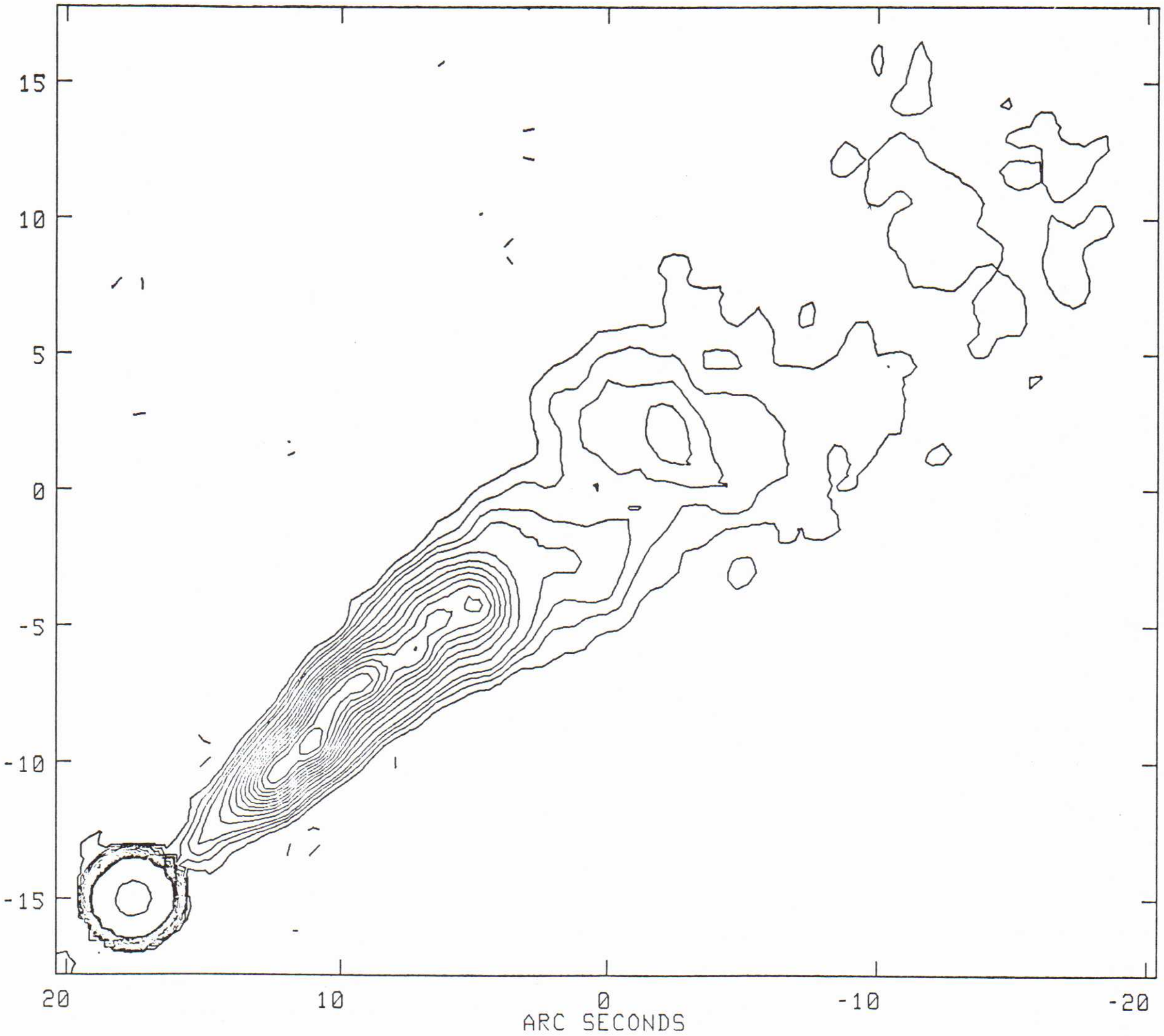


Figure 14-8(b). Contour plot of 20cm A configuration synthesis of the source 0055+300, made from 9 hours of data at 25 MHz bandwidth. The contour levels are drawn at -0.5, 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15 and 200 mJy/beam. The contour around the peak shows the HPBW. Compare with Fig. 14-8(a).

A. Limitations of Snapshot Mode

The clearest limitation of snapshot observing is sensitivity (see Table 14-1); it is suitable only for bright sources. At 20cm, the high sidelobe levels of beams synthesized from snapshots exacerbate the problems created by confusing sources, so snapshots of fields near the galactic plane using the more compact arrays will frequently be dominated by sidelobe clutter from confusing sources rather than by the noise that is quantified in Table 14-1. These problems are less severe at 6cm due to the smaller primary beam and the typical source spectrum (see Section 6).

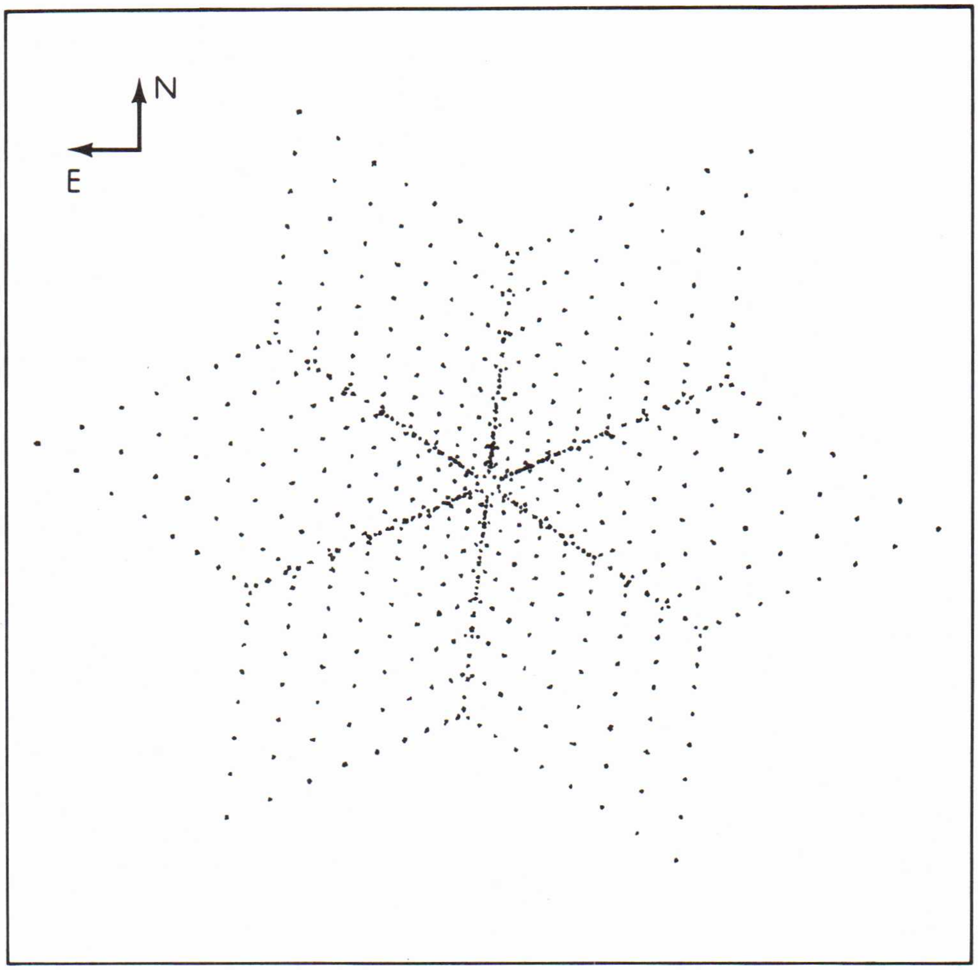


Figure 14-9. The (u,v) plane coverage for an instantaneous sampling of data for a source at $\delta = 30^\circ$ and H = 0 for a 27-antenna VLA.

The second limitation of snapshot observing is the restricted field of view over which the (u,v) coverage of a snapshot (e.g. Fig. 14-9) satisfies the sampling theorem and thus permits reconstruction of the correct sky brightness distribution. Table 14-2 codifies this limitation for the standard configurations and frequencies.

Polarization calibration may be difficult for short snapshot programs; it is not easy to verify the instrumental polarization calibration for a program whose total observing time is only a few hours, as this calibration requires at least three observations of a calibrator spanning a change in parallactic angle $\psi$ of $\Delta\psi \geq 90^\circ$ (see Lecture 6). "Standard" instrumental polarization parameters may have to be used in such cases. Position angle calibration may also be difficult if the standard polarization calibrators (discussed in

Table 14-2

Approximate Mappable Field for Single Snapshot*

| | A | B | C | D |
|---|---|---|---|---|
| 20cm | 38" | 2' | 7' | 15' |
| 6cm | 10" | 36" | 2' | 5' |
| 2cm | 4" | 10" | 40" | 90" |
| 1.3cm | 2" | 7" | 27" | 60" |

*Larger sources can be mapped by combining a few snapshots taken at different hour angles.

Lecture 6) are not readily observable during the time allocated to a snapshot program. Snapshooters interested in polarimetry should ensure that suitable polarization calibration is possible when designing their program, mainly by giving attention to its LST range.

Snapshots are most effective when the sources are observed within about 2 hrs of the meridian. At large hour angles, foreshortening of the array will lead to poorer sampling of the (u,v) plane, elliptical beams, etc.

The time taken to calibrate a snapshot data set is determined mainly by the total observing time. Snapshot programs require the same calibration effort as simple synthesis programs of the same total duration. The mapmaking, CLEANing, and map display steps of snapshot observing can have a very heavy impact on computer time and the observer's time however. As a snapshot map of a given source may be as large as a full synthesis map of the same source, snapshot programs also make heavy demands on disk storage. This can be especially true for snapshots made in the more compact arrays at 20cm and 6cm, which are particularly prone to degradation by sidelobe clutter from confusing sources (see Section 6 below on confusion). Snapshooters must therefore be careful to coordinate their data reduction requirements with those of other users, and to employ efficient reduction strategies, including backing up of inactive map and beam images whenever possible.

## B. Multiple Snapshots versus Extended Snapshots

The question often arises of whether (for example) an observation requiring 15 min of integration time is best made as one continuous 15-min observation or by combining the data from three separate 5-min snapshots. Under some circumstances, a single 15-min observation may give better dynamic range, because ionospheric or tropospheric phase gradients in the form of "wedges" may calibrate out of a single short observation, leaving only a position shift. In contrast, three shorter observations that are more dispersed in time might encounter different wedges and therefore combine to give a map with poorer final dynamic range. Basically, if the total time taken to acquire the data is longer than the time scale for significant changes in the phase screen in front of the region of sky being mapped, the dynamic range of the resulting map will be degraded unless self-calibration can be used. In these circumstances, a single observation may be preferable, as well as being easier to schedule.

The advantages of combining data from several shorter snapshots are (a) greater protection against total loss of the data for a given source due to equipment failures or short-term weather, and (b) more even sampling of the (u,v) plane than in a single extended snapshot. The single extended snapshot may however prove to be better for observations which must be made at low elevations, where phase "wedges" are more likely to arise, and in cases where self-calibration (Lecture 13) cannot be used. This may be particularly true for observations of weak or complex low-declination sources for which the total hour-angle coverage is anyway limited by the short time that a given source is above the horizon.

# 6. CONFUSION

The number of extragalactic sources N per square arc minute of sky with flux densities greater than S mJy at 6cm can be written approximately as:

$$N(>S) = 0.032\, S^{-1.13} \tag{14-7}$$

over the flux density range which is relevant for confusion calculations at the VLA (e.g. Ledden et al. 1980). The corresponding expression at 20cm is:

$$N(>S) = 0.10\ S^{-0.9} \tag{14-8}$$

The analogs of these expressions for 2cm and 1.3cm are not known directly from measured source counts. They could be estimated from the 6cm count in Equation (14-7) by scaling flux densities to 6cm with an effective mean spectral index of about 0.6.

Maps made at 20cm will therefore contain, on average, one extragalactic source of flux density 110 mJy closer to the field center than the 15' HWHM of the primary beam. The 6cm primary beam (4.5' HWHM) will similarly contain, on average, one extragalactic source of flux density 2 mJy, the 2cm beam (1.85' HWHM) a source of <0.1 mJy and the 1.3cm beam (1' HWHM) a source of <0.01 mJy.

Individual pathological cases aside, confusion is thus unlikely to be a problem except at 20cm and 6cm in the more compact configurations. Confusion may have two effects on a VLA observation. These are (1) degradation of the rms fluctuation level on a map by sidelobes or aliasing of confusing sources, and (2) identification of the wrong radio source as the target object in a detection experiment, or as part of the structure of an extended feature.

If you know you will be making observations near a bright confusing source, you may consider two strategies for reducing its effects on your final maps. One is to plan to make wide-field maps containing both the target source and the confusing source and subsequently to subtract or CLEAN the confusing source and its sidelobes from the region containing the emission that is of interest. This is probably the best technique if the angular separation of the confusing source from the region of interest is only one or two times the size of the field of view which you would otherwise have been interested in mapping. In such cases the confusing source may be close enough that you do not require an unacceptably narrow bandwidth in order to include it in the minimally-distorted field around your target. A displacement of the phase center away from the target but towards the confusing source may be desirable in such cases.

This problem is likely to be encountered particularly often by snapshooters using the compact configurations at 20cm and 6cm, because the sidelobes resulting from the "snowflake" pattern of (u,v) coverage in a snapshot (Fig. 14-9) extend widely across the maps. The "snowflake" sidelobes in a snapshot map can be de-emphasised by using super-uniform weighting (Lecture 2). This will alleviate contamination of a snapshot field by sidelobes of more distant confusing sources. The problems of aliasing confusion may also be reduced in snapshot mapping by use of the direct Fourier transform for map sizes < 256x256. (For larger map sizes the CPU time required for the direct transform will normally be prohibitive).

A second approach, suitable for more distant confusing sources, is to choose your IF bandwidth and phase center so that the response to the confusing source is adequately reduced by the combined effects of bandwidth attenuation and primary beam attenuation. Which of these methods is more suitable must be judged by the observer on a case-by-case basis.

The situation where the confusing source lies in the target field itself requires no action at the time of the observations, as the source and its sidelobe pattern can be CLEANed as part of the normal data reduction. In detection experiments, confusion may make the interpretation of a positive detection questionable if a source is detected near, but not at, the target position. In such cases the source count equations (14-7) and (14-8) can be used to estimate the probability that the detected source occurs in the mapped field by chance.

## 7. CALIBRATION STRATEGY

Calibration sources should generally be chosen from the VLA Calibrator List maintained at the site by R.A.Perley, E.B.Fomalont et al., unless the observer has personal knowledge that a source is unresolved in the VLA configuration to be used, and has a position measured in the VLA reference system to better than 0.1 arcsec. The basic questions to be decided by the observer are: how often to calibrate, and how close the calibrators should be to the target sources. The adopted strategy will depend on whether the observer attempts to calibrate only the instrumental fluctuations of the VLA, or these fluctuations plus the gain and phase variations introduced by the ionosphere and troposphere.

A. Instrumental Calibration

The instrumental calibration should (a) detect grossly malfunctioning antennas so that faults might be corrected while the observations are in progress, and (b) monitor the overall amplitude and phase stability of the instrument sufficiently often that hourly changes can be corrected for by interpolation throughout the run. Most instrumental fluctuations (apart from phase jumps) are slow, and observation of an unresolved strong calibrator every 20-60 min will normally be adequate for instrumental monitoring. Bear in mind that if the instrumental calibration detects phase jumps, you may have to discard all of the data between consecutive calibration observations for the antenna-IF in which the jump occurred, unless the source(s) being mapped is (are) strong enough that the precise time of the phase jump can be located in the source data.

Calibrators for purely <u>instrumental</u> monitoring should be chosen primarily for their strength rather than for extreme closeness to the program source(s), particularly at 2cm and 1.3cm, where the VLA has degraded sensitivity. The interval between calibrations may vary with the total length of the program; very short programs should look at a calibrator at the beginning and the end to reassure the observer that no drastic changes have occurred during the run. It is always worth beginning a run with an observation of a calibration source, so that the user can sample the data using the on-line display and come to a quick assessment of phase stability over the longer baselines, etc. Calibration of the instrumental effects more rapidly than every 30 min should hardly ever be necessary at 20cm or 6cm.

The length of time spent on each calibration scan should be sufficient to achieve a signal-to-noise (over the 26 baselines contributing to each antenna gain solution) commensurate with the required calibration accuracy. Never plan to calibrate for less than 2 min however, as very short scans may be lost due to unusually long settle-down times, etc.

B. Atmospheric Calibration

A more important, and more difficult, calibration is that of the amplitude and phase fluctuations resulting from changes in the propagation properties along the atmospheric path to the source. Here it is important to realise that NO CALIBRATION BASED ON OBSERVATIONS OF A REFERENCE SOURCE THAT IS NOT IN THE SAME MAP FIELD CAN BE GUARANTEED TO IMPROVE THE DATA QUALITY. This is not to say that attempts to calibrate atmospheric fluctuations using a distant reference source are always a waste of time, merely that such calibration may or may not be successful. If the angular separation of the source and calibrator exceeds the scale size of the atmospheric cells responsible for the amplitude and phase variations, the fluctuations seen in the calibrator data may not be correlated with those occurring in the source data. In such cases, corrections interpolated from the calibrator observations into the source data may make the atmospheric amplitude and phase noise in the source data worse by a factor of $\simeq \sqrt{2}$. At the other extreme, if the source and calibrator are typically seen through the same atmospheric cell, then the fluctuations observed in the calibrator will faithfully track those occurring in the source. Amplitude and phase corrections interpolated from the calibrator may then greatly improve the quality of the source data. The basic problem is that no guarantees can be given about the scale size of the atmospheric cells on any given day so it is very difficult for the observer to judge how reliable amplitude and phase referencing from a distant calibrator may be.

The most reliable method for removing atmospheric fluctuations from the data is to use self-calibration, IF THE SOURCE MEETS THE BASIC CRITERIA FOR USE OF THIS ALGORITHM (as discussed in Lecture 13). This means in practice that the source must be bright, and preferably must contain a well-defined unresolved component that is bright enough to be used as an amplitude and phase reference over the typical fluctuation time of the atmospheric screen. External calibration is still useful in such cases, for two reasons. First, the external calibrator may be used to provide a flux-density and position scale for the final self-calibrated map (on which this information will otherwise be lost in general). Second, observations of the time scale of the amplitude and phase fluctuations on an unresolved calibrator near your source will give you an estimate of the coherence time of the atmosphere while your observations were in progress. This will usually determine the quantity called $\tau_{gains}$ in Lecture 13, and will therefore allow you to select a suitable averaging time $\tau$ for the self-calibration. It will also allow you to determine whether or not self-calibration may be expected to work, following the arguments given in Section 6C of Lecture 13.

It is fortunate that the class of source for which maps of high dynamic range are most important is also the class for which self-calibration is most likely to work well - namely, sources with weak extended structures around bright small-diameter components. There is however a range of flux densities and structural complexities over which self-calibration cannot be guaranteed to work in typical atmospheric coherence times, and for which external calibration is therefore still required. If you cannot, or do not wish to, rely on self-calibration to remove atmospheric effects from your data then you must choose your external calibrator(s) as close as possible to the source(s) you are observing, and hope that the amplitude and phase stability you observe on the calibrator scans meet the needs of your experiment. If the within-scan and scan-to-scan amplitude or phase fluctuations on a calibrator a few degrees from your source are small (less than 10% or 20 degrees), it is unlikely that large fluctuations are occurring on your source. If you see large fluctuations on the calibrator, you are in trouble, which may or may not be mitigated by correcting the source data for the observed fluctuations. If you see slow drifts in the calibrator amplitude and phase, long-term (BOXCAR) averaging of these and interpolating them as corrections into the source data should improve the output maps. If you see rapid fluctuations, point-to-point (2POINT) interpolation of these may make matters better or make matters worse. In this case you have little choice but to try mapping your source data with both long-term averaging and local interpolation of corrections from the calibrator data, to see which leads to the better final maps.

The calibrator data may also tell you that there were periods of both good and bad stability during the run. Deletion of the bad periods is very likely to improve the quality of the final maps. Except when using self-calibration, initial mapping with a reduced amount of data of better amplitude and phase stability can give better results than mapping with a larger amount of poorer data, because the actual synthesized beam will be closer to the theoretical "dirty" beam in the former case. This will allow CLEAN to do a better job, increasing the dynamic range of your maps.

Significant atmospheric amplitude and phase fluctuations can occur on time scales of minutes, even at 20cm and 6cm (fluctuations at 20cm are mainly ionospheric and should become less troublesome towards solar minimum). It is therefore completely impractical to adopt a [calibrator/source/calibrator] cycle which will guarantee following the fastest fluctuations. Under many observing conditions calibration every 20 min or so will follow the longer-term atmospheric fluctuations at 20cm and 6cm. Calibration every 10 min or so will be safer at 2cm and 1.3cm. Keep in mind however that NO external referencing, no matter how rapid, can be GUARANTEED to remove atmospheric fluctuations from the source data. Observers must decide for themselves how this particular roulette game should be played during their run.

Observers doing detection experiments will not have such severe requirements on dynamic range (and hence on phase stability) as observers mapping complex structures. (The loss of gain due to poor phase stability in a detection run can be estimated during the data reduction by calibrating with a >2 hr BOXCAR interpolation in the gain table, then making a map of a calibrator).

The calibration done to monitor atmospheric fluctuations will, of course, calibrate the instrumental fluctuations also.

C. Flux-density Calibration

If the LST range of the proposal permits, you should observe 3C286 for a few minutes at each of the frequencies at which you have made source observations, as 3C286 is the flux-density standard to which all VLA measurements are ultimately referred. Failing this, you should observe 3C48 or one of the circumpolar flux density calibrators that is monitored regularly by Rick Perley, and consult with him about recent flux-density measurements of the selected source. Do not simply take the most recent flux density for an arbitrary calibrator from the Calibrator List, as most of these small-diameter sources are highly variable. The flux densities recorded in the Calibrator List will rarely be sufficiently current to be usable for flux density calibration; use them only to estimate the integration times needed on your calibrator scans.

D. Polarization Calibration

This has been discussed in detail in Lecture 6 so only a brief summary is repeated here.

To calibrate the position angle scale, observe 3C286 or 3C138 at least once during the run at each relevant frequency. It is advisable to alert the telescope operator to the presence of this angle calibration in your run, so that the 3C286 or 3C138 observation can be extended if necessary to prevent its loss due to an equipment failure. Note that this calibration is essential if you wish to make any use of your polarization orientation data.

To calibrate the instrumental polarizations, you should observe one unresolved source, whether polarized or not, at least three times over a range in parallactic angle $\psi$ of $\Delta\psi \geq 90^{\circ}$ (see Lecture 6). When determining the integration time for this calibration, bear in mind that the instrumental polarizations whose amplitudes and relative position angles are to be determined will normally produce polarized intensities that are only a few per cent of the flux density of the calibrator. See Lecture 6 for discussion of the signal-to-noise requirements of this calibration, which should be done at each frequency for which polarimetry is required. The most efficient way to do this is to cycle through the frequencies used for the source observations each time the array is pointing at the chosen calibrator. In long synthesis programs, the observations of the synthesis calibrator will normally provide the instrumental polarization calibration.

If the instrumental polarization calibration is omitted (e.g. due to short duration of the observing session, or to instrumental misbehavior), you should make the instrumental polarization corrections using "standard" files for the necessary parameters (Lecture 6). Failure to obtain an instrumental calibration will limit your ability to determine small degrees of polarization, and to CLEAN polarized extended structures properly (as antenna-to-antenna polarization differences distort the polarization maps in ways which do not satisfy the convolution theorem).

At 20cm, the position angle calibration may in effect be time variable due to fluctuations in the ionospheric Faraday rotation. It is very desirable to monitor one polarized calibrator in the same area of the sky as your source(s) throughout the run, to check whether its apparent position angle changes significantly. If this calibration shows that the ionospheric changes are less than about 20 degrees, interpolation of the observed changes as a function of time when making the AC phase correction will probably be satisfactory. If larger changes are seen, try running the FARAD program to repair them using an ionospheric model and measured critical frequencies; except when the rotation changes are small (< 20 degrees), the success of this repair cannot be guaranteed, however. The observation of the polarized calibrator should be thought of as a "warning light" for the existence of ionospheric rotation problems, not necessarily as a means for correcting them. Applying FARAD's corrections to the data on this calibrator will also check whether they are indeed improving the angle calibration. Ionospheric effects will normally be negligible at 6cm, 2cm or 1.3cm, so this calibration is not required at these wavelengths.

## 8. STORMY WEATHER AND WHAT TO DO ABOUT IT

"You can't tell the phase stability by looking out of the window"
---- attributed to B.G.Clark

Some programs have frequency agility, and observers may wish to adjust their observation files to take account of the weather prevailing during their run. The import of the above quote is that you have to observe to find out how good (or bad) the phase stability is. Clear blue skies do not guarantee good phase stability, particularly in spring and summer. Thunderstorms do however guarantee bad phase stability.

If your proposal has frequency agility, it is a good idea to monitor the on-line computer's "D10" display over a long baseline as your run starts. Look at the phase on a strong calibrator for a few minutes. Fluctuations of order a radian on a time scale of minutes are unmitigated bad news, and the only possible strategy is to move the observations to lower frequencies if this makes any astronomical sense. The converse is not true, however. Short-term (minute-by-minute) phase stability to within a few degrees does not guarantee that the observations will be of good quality for synthesis. This requires stability over the time scale of your calibration cycle (unless you are going to self-calibrate). You should therefore pay attention to the stability of the phase between adjacent scans of your calibrator, as well as to that within the scans, to assess whether you have the stability needed for synthesis. If the longer-term stability is marginal, i.e. of order 30-40 degrees, you might consider editing your observing file to achieve a faster calibration cycle. Users of 1.3 and 2cm might consider preparing several observing files with different calibration cycle times before the observations begin; this makes it easier to alter the strategy once the run has begun.

Snapshots require phase stability only for the duration of the individual snapshot. Instabilities over the calibration cycle but not on the time scale of the snapshots themselves may lead to snapshot maps with fair dynamic range but uncalibrated position shifts.

In any case, the stability to be expected during a run is very hard to assess in advance (unless it is very bad), and observers must be prepared to observe for a while before making gross adjustments to their observing strategy.

## 9. THE OBSERVING PROPOSAL

A few guidelines can be given for writing a VLA proposal to maximise its chances of being scheduled in the competition for observing time. Above all else, the project must be one whose scientific goals favorably impress the referees. A "highly-placed source who wishes to remain anonymous" notes that more concisely-written proposals are more likely to be received favorably by the referees, all else being equal.

The proposal cover sheet should be filled out in as much detail as possible; filling out item 17 on the cover sheet (Fig. 14-10) fully for each source, or for typical sources, will lead you to consider the issues discussed in this Lecture. Your entries here should demonstrate to the referees and to the scheduling committee that the proposal is well suited to the VLA configuration that you are requesting.

(17) Number of sources _____ (If more than 10 sources please attach list. If more than 30 give only selection criteria and LST range(s).)

| Name | coord (1950.0) RA hh mm | Dec $\pm$xx°.x | Config. | Band (cm) | Band width (MHz) | Total flux (Jy) | Largest ang. size | Weakest signal (mJy/beam) | Required dynamic range | Possible LST range hh - hh | Time requested |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | | | | | | | | | | | |
| 2. | | | | | | | | | | | |
| 3. | | | | | | | | | | | |
| 4. | | | | | | | | | | | |
| 5. | | | | | | | | | | | |
| 6. | | | | | | | | | | | |
| 7. | | | | | | | | | | | |
| 8. | | | | | | | | | | | |
| 9. | | | | | | | | | | | |
| 10. | | | | | | | | | | | |

Figure 14-10. Sample of Item 17 from standard VLA proposal cover sheet.

The distribution of observing time allotted to successful proposals during April 1982 is shown as a histogram in Fig. 14-11. The median observing time scheduled is 7 hrs, reflecting the large number of proposals for which less than full HA tracks are appropriate. Note however that about 8% of all the projects scheduled used more than 24 hrs of observing time; well-justified long projects can successfully compete for time!

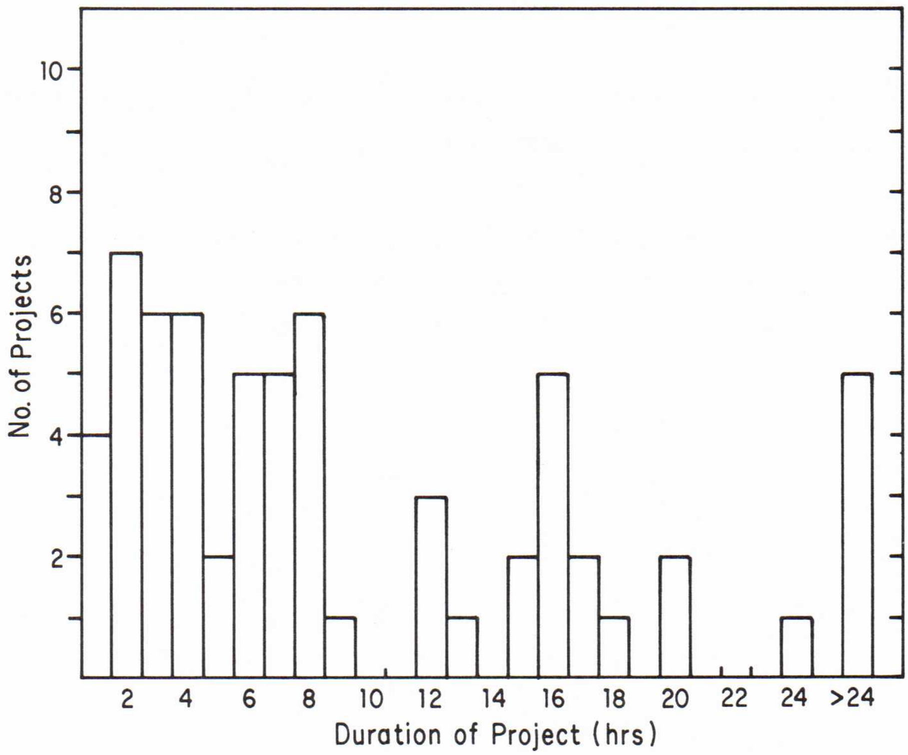


Figure 14-11. Histogram of durations of projects scheduled for VLA observations during April, 1982.

Finally, submit your proposal well before the deadline given for your desired configuration(s). Proposals may be submitted between the deadline dates, and users who do so reduce the strain on the proposal processing system. The pressure of proposals for a given configuration also influences the length of time that the VLA is scheduled to spend in that configuration.


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