16. 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. It suggests an orderly way in which to use the material of Lectures 2, 4, 5, 6, 7, 8, and 9 to choose critical parameters when planning and executing VLA observations. It also suggests strategies for avoiding some of the pathological image defects that were emphasized in previous lectures. Unlike most of the other lectures in this series, this one is explicitly oriented toward specifics of VLA continuum observing, though the general principles apply to observations made with other synthesis arrays.

Figure 16–1 shows a decision tree for preparing VLA continuum observations; Sections 2 to 6 of this Lecture detail the various levels of this tree. Note that some system parameters (e.g., sensitivities) that affect these decisions will improve with time as a result of hardware upgrades, etc. NRAO publishes a *VLA Observational Status Report* that summarizes relevant system parameters at least once per year. You should check the most recent copy of this *Report* when planning a VLA proposal.

Sections 7 to 9 of this Lecture discuss calibration strategy, on-line observing strategy, and the observing proposal itself.

2. Choice of Array Configuration and Observing Frequency

2.1. Resolution $\theta_{\rm HPBW}$—How much is enough?

An image made from untapered uniformly-weighted ≥ 4 hour tracks in a standard VLA configuration at positive declinations where foreshortening of the array is unimportant has a synthesized beam B with a half-power beamwidth given approximately by

$$\theta_{\rm HPBW} = 1''\!.25 \times \frac{1480}{\nu_0} \times 3.285^{n-1}\,, \tag{16–1}$$

where ν_0 is the observing frequency in MHz and $n = 1, 2, 3,$ or 4 for the **A**, **B**, **C**, or **D** configurations respectively.

The *minimum* resolution (i.e., maximum value of $\theta_{\rm HPBW}$) appropriate for the observations will be determined by the need to separate or resolve important features of the structure in the region to be imaged. For observations of extended emission, the *maximum* resolution (minimum $\theta_{\rm HPBW}$) that is appropriate should also be considered, by estimating the total integration time $t_{\rm int}$ needed to achieve the required brightness sensitivity. There is no point observing extended emission using such a small beamwidth $\theta_{\rm HPBW}$ that the interesting features of the source are close to or below the r.m.s. noise ΔI_m on the final images. To make sure that this does not happen, you must consider the *apparent brightness* (flux density per synthesized beam area) that you expect such features to have at the resolution you will use for your final images.

Recall from Lecture 6 that a *point* source with flux density S Jy images with an apparent brightness of S Jy per synthesized beam area regardless of the area Ω_s of the

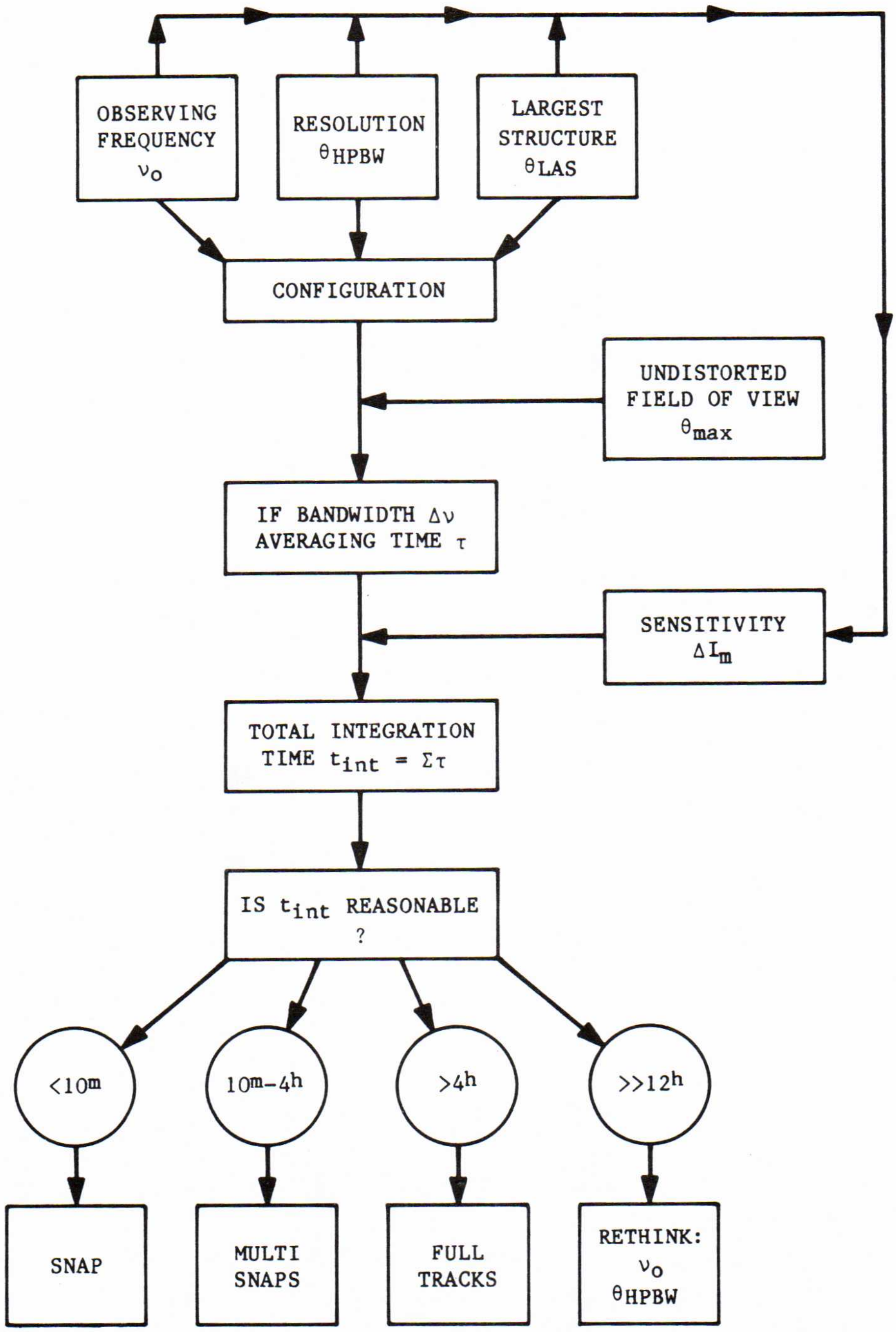

Figure 16–1. Factors Entering Into VLA Observing Strategy—A Suggested Decision Tree.

synthesized beam. It follows that, at a given frequency, all VLA configurations are equally sensitive to a given point source (apart from the effects of confusion and phase stability). In contrast, as described in Lecture 6, the apparent brightness of an *extended* emission region in a synthesized image depends on the region's detailed structure, on how well the visibility function $V(u,v)$ is sampled by the observations, and on the weighting and tapering functions D_k and T_k applied to the data at the imaging stage (Lecture 5, Section 2.2; and Lecture

6). When deciding on an observing strategy, it is usually sufficient however to assume that:

(a) an extended region with uniform true brightness I Jy per arcsec^2 will be imaged with an apparent brightness $\approx I\Omega_s$ Jy per synthesized beam area, and

(b) the *final* synthesized beam will be a Gaussian 'CLEAN' beam, so that its area in square arcsec can be calculated approximately as $\Omega_s \approx 1.13\theta_1\theta_2$ arcsec^2, where θ_1 and θ_2 are the major and minor half-power widths of the Gaussian in arcsec.

If the r.m.s. noise on the image is ΔI_m Jy per synthesized beam, the signal-to-noise ratio of such extended emission on the image will be $\sim I\Omega_s/\Delta I_m$, which increases as the synthesized beam area Ω_s. Ensure that you do not observe with such small values of Ω_s that interesting extended structure is undetectable, given the total integration time $t_{\rm int}$ available and your choice of the IF bandwidth $\Delta\nu$ (see Sections 3 and 4 below).

For example, consider a smooth two-dimensional emission region 30″ across with a peak apparent brightness $I\Omega_s$ of 1 mJy per beam area on an untapered VLA 20 cm image made with the **B** configuration (resolution $\approx 4\overset{''}{.}2$). It will have a peak apparent brightness of only 0.093 mJy per beam area on an untapered 20 cm image made with the same hour angle coverage and *u-v* weighting in the **A** configuration (resolution $\approx 1\overset{''}{.}3$). It could be detected at the 10σ level in about 16 min of integration at 50 MHz bandwidth in the **B** configuration (using the sensitivity data given in Table 16–1), but a 10σ detection in 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 a smaller beam area Ω_s than is strictly necessary.

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

For sources with compact flat-spectrum components *and* extended steep-spectrum emission, the dynamic range needed to image the extended structure increases rapidly with increasing frequency. Suppose that the extended emission referred to in the previous example surrounded a 5 mJy point source with a ν^0 spectrum. The dynamic range required for 10σ detection of the extended structure would be 50 : 1 in the **A** configuration at 20 cm. This is easy to obtain. The dynamic range required in the **A** configuration at 6 cm would be 1850 : 1, a non-trivial target without self-calibration.

You should also avoid unnecessarily high resolution in detection experiments at high frequencies. While the theoretical 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 be poorer on longer baselines (see Lecture 4, Section 4.4). The phase stability will be highly dependent on the state of atmosphere over the array (the "weather"), so one cannot predict the severity of this effect in advance—but it is clear, for example, that the **A** configuration is rarely a wise choice for 1.3 cm 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". While the flux density per synthesized beam of two-dimensional emission is roughly proportional to the beam *area* Ω_s, that of linear emission is proportional to the beam *width* θ_{HPBW}, and that of a point source is *independent* of beam size. These dependencies allow compact structure that is embedded in, or confused with, more extended emission to be recognized most easily on high-resolution images.

These competing factors affecting the choice of resolution cannot be estimated reliably in advance if the source structure is unknown or poorly known. If you are not sure what to expect your source to look like, the safest strategy is to guess on the side of low resolution in an initial observation. A preliminary low resolution image may tell you the source's total angular extent and could also warn you of any surrounding emission. This information would allow you to optimize the observing parameters for a more time-consuming high resolution study. It is also easier to justify reobserving a detected emission region at higher resolution than it is to justify reobserving at lower resolution what appeared to be empty sky!

2.2. Choice of frequency ν_0 at given resolution θ_{HPBW}.

The choice of observing frequency *at a given resolution* 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 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 2 cm than 6 cm despite the noisier system at 2 cm, whereas transparent synchrotron sources will be easiest to detect at a given resolution at 20 cm.

Returning to Equation 16–1, note that the scaling factor between "adjacent" VLA configurations (e.g., **B** and **C**) is 3.285. This factor is close to the ratios between the default VLA frequencies at 20 cm and 6 cm and between those at 6 cm and 2 cm. The VLA therefore has similar resolutions at 20 cm in the A configuration, at 6 cm in the **B** configuration, and at 2 cm in the **C** configuration. (Such rough three-frequency scalings also apply for the **B**, **C**, and **D** configurations, of course.) These scalings make the VLA a powerful tool for studies of the frequency-dependence of the properties of extended emission. "Scaled-configuration" VLA observations can be used to produce maps of spectral index, Faraday rotation or depolarization properties of extended sources that are relatively free from uncertainties stemming from differing resolutions at the different frequencies.

Note that use of the "scaled configurations" *optimizes your chances* of measuring frequency-dependent properties of a source accurately, but does not by itself *guarantee* success. Further careful planning, and *post hoc* examination of the visibility data, are also important. For example, the hour-angle ranges of "scaled-configuration" observations should be matched at the different frequencies. Also, even scaled configurations may sample parts of the visibility function of a source with differing sensitivities at different frequencies if the source structure changes radically over the frequency range of interest. This may happen if there are large spectral index gradients across the source in either its total or its polarized emission. Care must also be exercised when interpreting the final images if the databases at the two frequencies are differently affected by missing antennas or by bad data. In such cases, the reliability of inter-frequency comparisons may still depend on how well the deconvolution algorithm (Lecture 7) can interpolate in the u-v plane.

Finally, do not forget that the VLA continuum system allows you to observe at two independent sky frequencies within each "band"—this capability can be used to increase sensitivity, to fill in the u-v plane more densely by crude "bandwidth synthesis" (see Lecture 8, Section 1.1) or to study spectral or Faraday depth changes in your source across a "band" (the latter being especially worthwhile in practice at the VLA's L Band—1340 to 1730 MHz).

2.3. More than one configuration?

The above was concerned primarily with observations in the standard (**A**, **B**, **C**, **D**) configurations of the VLA, but other options are available. You may need to combine observations made in more than one VLA configuration if your observations require a *range* of baselines that exceeds the range provided by a standard configuration. The next step in planning your observations therefore involves thinking about θ_{LAS}, the largest angular scale of structure that you must sample well to produce an astrophysically useful final image. θ_{LAS} will be the angular diameter of the most extended structure that you need to reconstruct accurately in the final image—usually the diameter of the most extended component of astrophysical interest in your source. (Do not confuse it with θ_{max}, the required field of view, which is discussed below—when observing a source 10″ in extent in the presence of a point confusing source 1′ away, you would set $\theta_{\mathrm{LAS}} = 10''$, not $\theta_{\mathrm{LAS}} = 1'$.)

As the ratio of the longest to the shortest baseline in a standard configuration of the VLA is about 40 : 1, each standard configuration can be used to image reliably up to $\theta_{\mathrm{LAS}} \approx 40\theta_{\mathrm{HPBW}}$ where θ_{HPBW} is given by Equation 16–1 at the specified frequency. If the values of θ_{LAS} and θ_{HPBW} needed for your experiment do not *both* fall between θ_{HPBW} and $40\theta_{\mathrm{HPBW}}$ calculated from Equation 16–1 for a given standard configuration and frequency, you should consider taking data in more than one VLA configuration. Obviously, any observation requiring $\theta_{\mathrm{LAS}}/\theta_{\mathrm{HPBW}} > 40:1$ falls in this category, but so do some with $\theta_{\mathrm{LAS}}/\theta_{\mathrm{HPBW}} < 40:1$; for example, your optimum θ_{HPBW} might fall mid-way between two resolutions given by allowed values of n and ν_0 in Equation 16–1.

For example, Figures 16–2 and 16–3 show the *u*-*v* coverage of the VLA at +60° declination for 12 hours observing in the **A** configuration, and for 6 hours of **A** configuration observing combined with 6 hours in the **C** configuration. The "hole" at the center of the *u*-*v* coverage in Figure 16–2 is well filled by mixing data from the **A** and **C** configurations. You should consider mixing standard-configuration observations for any sources for which $\theta_{\mathrm{LAS}}/\theta_{\mathrm{HPBW}}$ will be significantly $> 40:1$. The total integration times to be spent observing in the different configurations should however be computed separately, as in Section 4 below; for most projects you will not need as long a total integration time in the more compact configurations as you will in the more scattered ones.

2.4 Hybrid configurations.

"Hybrid" configurations are those that become available during reconfiguration periods, when the arms of the VLA may be of different length, or may have a non-standard assortment of long and short baselines. Some hybrid configurations provide wider ranges of *u*-*v* spacing than can a standard configuration (thus giving sensitivity to a wider range of angular scales). Some can assist self-calibration of data from a compact configuration by providing it with some unusually long spacings.

Hybrid configurations with long North arms are now regularly scheduled at the VLA. They are useful if you want to image regions south of $\delta \approx -15°$, where the north-south extent of the *u*-*v* coverage of the standard configurations is seriously foreshortened by projection. Figure 16–4 shows the *u*-*v* coverage for the **B** configuration at −40° 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 that is left empty by the standard **B** configuration. This **A**/**B** hybrid would be available for a brief period about every sixteen months, during a reconfiguration from **A** to **B**. The other such hybrids (**B**/**C** and **C**/**D**) are also scheduled between the appropriate reconfigurations.

Perley (1981b) examined whether other hybrid VLA configurations could usefully extend the ratio of maximum to minimum baselines in synoptic observations with the VLA.

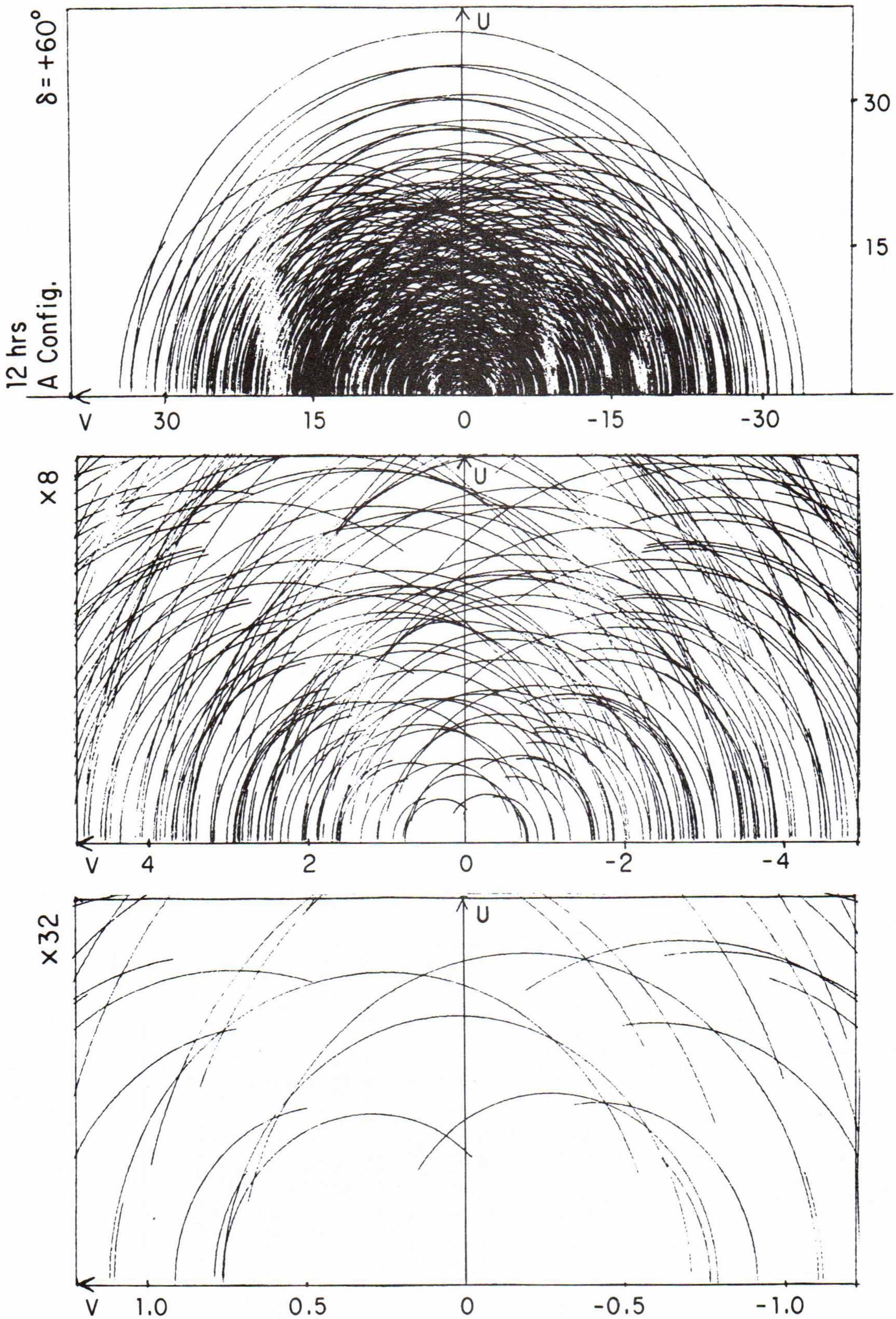

Figure 16–2. *u-v* coverage for $\delta = +60°$ in the **A** configuration (12-hour tracks).

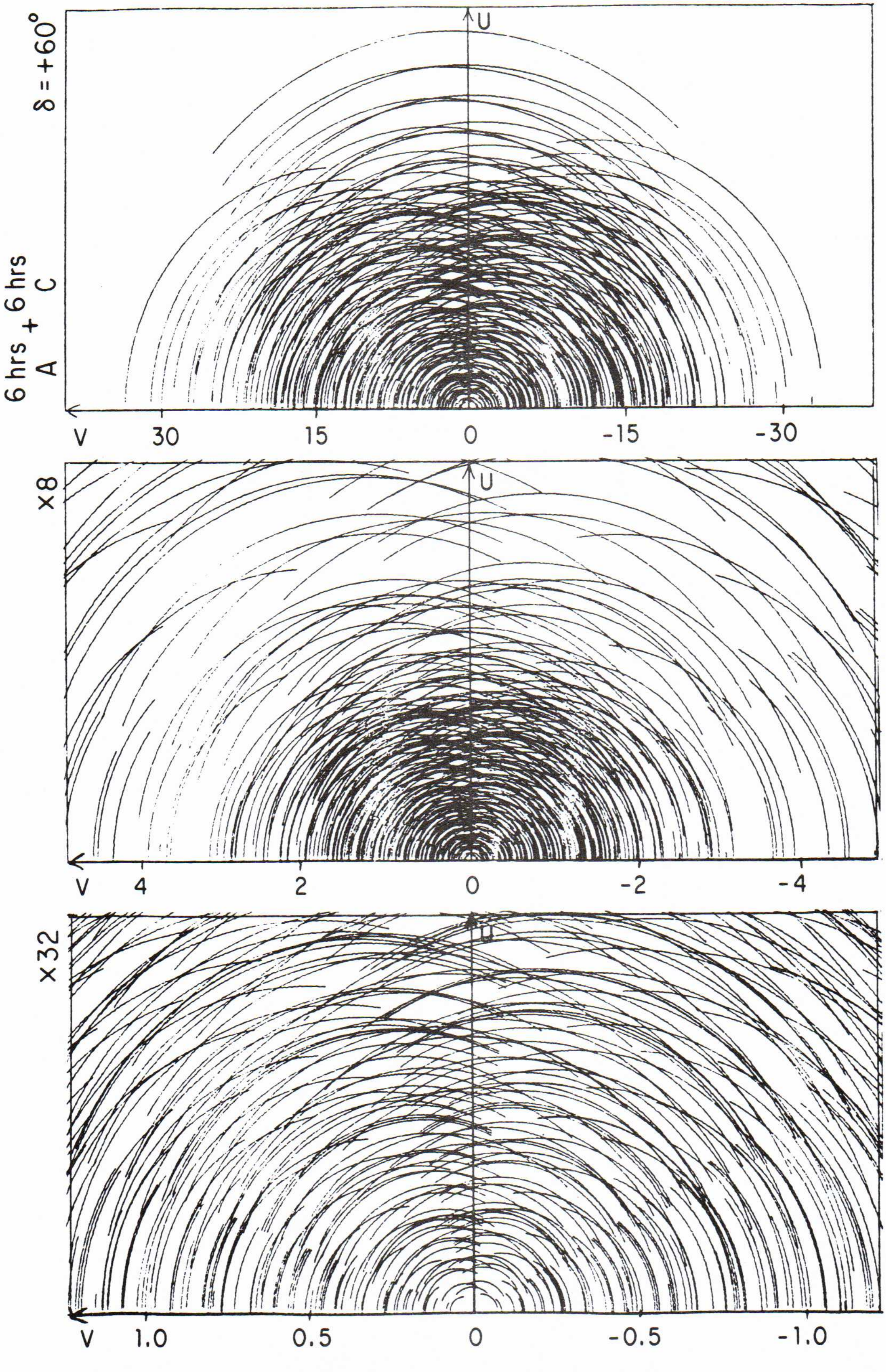

Figure 16–3. *u-v* coverage obtained by combining 6 hours of **A** configuration data with 6 hours of **C** configuration data at $\delta = +60°$. Note the superior coverage of the inner *u-v* plane, relative to Fig. 16–2.

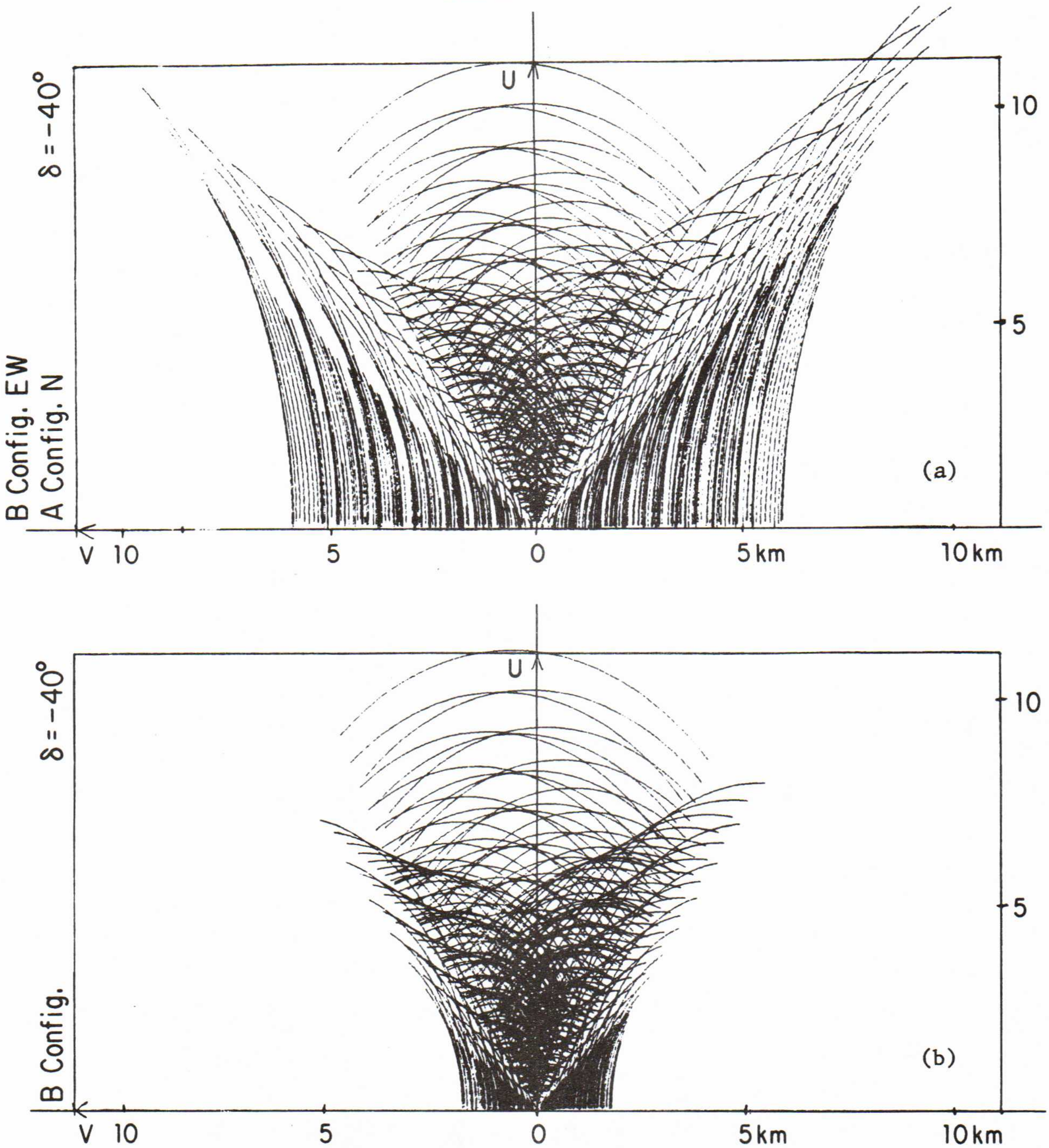

Figure 16–4. *u-v* coverage at $\delta = -40°$ with **(a)** *(top)* the VLA East and West arms in **B** configuration and the North arm in **A** configuration, and **(b)** *(bottom)* the entire VLA in **B** configuration.

In general, you get better *u-v* coverage by mixing data from two different standard configurations than you do from the same total time spent in *any* hybrid configuration, so no other hybrid configurations are regularly scheduled.

2.5. Sub-arrays.

"Sub-arrays" are nonstandard configurations obtained by dividing the VLA into as many as three smaller arrays that are then devoted to different observing programs at the same time. The use of sub-arrays is generally not as efficient as time-sharing the entire VLA, however. The number of interferometer pairs in a sub-array is $N(N-1)/2$ where N is the number of antennas in the sub-array. Sub-arrays with 13 and 14 antennas therefore have 78 and 91 interferometers respectively, whereas a 27-antenna standard configuration has 351. An hour of observing in which two such sub-arrays each perform different tasks therefore produces 169 interferometer-hours of data. In contrast, two half-hours of observing, with the full VLA devoted to each task in turn, produce 351 interferometer-hours of data. Dedicating two roughly equal 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 loss of information will manifest itself in poorer sensitivity and *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 strong sources at several frequencies (e.g., instantaneous spectra of rapid variables) or for observations of a large number of compact sources with only modest demands on sensitivity and dynamic range in each image (e.g., astrometry of strong sources).

2.6. Interference and the detailed choice of frequency ν_0.

External interfering signals are partially rejected by interferometers because only the component of the signals that (a) varies at the sidereal fringe rate, and (b) correlates with the correct delay, will affect the output (strong interference may also degrade the noise performance). This rejection is better at the longer baselines, so the VLA's **A** and **B** configurations are less susceptible to external interfering signals than are its **C** and **D** configurations. (Delay rejection is not usually significant for narrow-band interfering signals).

Interference is rarely detected or suspected at C, U or K Bands ("6 cm", "2 cm" or "1.3 cm"). It is however a factor in choosing a continuum observing frequency within the VLA L Band (1340 to 1730 MHz), particularly when using non-standard frequencies (e.g., when seeking to observe at the opposite edges of the band to determine Faraday rotation parameters)[1]. Frequency allocations in the L band include aeronautical radio navigation, meteorological aids, and fixed and mobile use. Many of the possible external interfering signals are time variable, so freedom from external interference can never be guaranteed anywhere at L Band outside the protected radio astronomy bands. (Note that use of the protected band at 1400 to 1427 MHz may itself be undesirable for some continuum observations, owing to the contribution of galactic neutral hydrogen line emission to the system temperature in this band).

There is also self-generated interference throughout L Band at the VLA, mainly at the harmonics of 50 MHz; this internal interference should be below the noise in any continuum image made with an IF bandwidth $\Delta\nu > 6.25$ MHz, but may be a serious problem for spectral-line programs.

Before using a non-standard L Band frequency, consult with VLA scientific staff (particularly Pat Crane, the VLA frequency co-ordinator) for advice and lore based on recent observers' experiences.

3. Field of View Restrictions

Once you have settled on the resolution $\theta_{\rm HPBW}$ and observing frequency ν_0 for your program, the next level on the decision tree (Fig. 16–1) is the choice of IF bandwidth $\Delta\nu$ and averaging time τ_a. These must be made consistent with the field of view requirements of

[1] Spectral line observers do not, of course, have the same freedom to choose the center frequencies and bandwidths for their projects, so L band interference may determine whether a given spectral line experiment is possible.

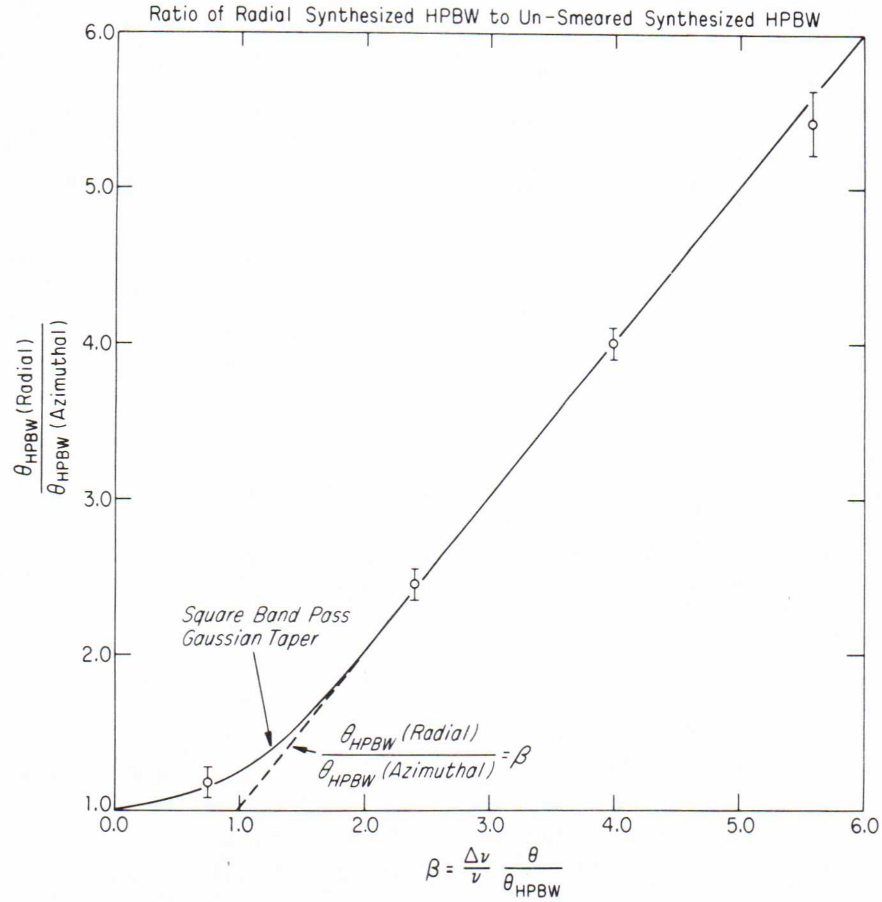

Figure 16–5. The ratio of radial to azimuthal beamwidth, resulting from finite IF bandwidth $\Delta\nu$, plotted as a function of the dimensionless parameter β. θ is the angular distance of the feature from the phase center, in the same units as the beamwidth $\theta_{\mathbf{HPBW}}$.

your program. The next step is therefore to consider the radius $\theta_{\max}$ (from the center of the field of view) over which you require the data to be minimally distorted by the bandwidth smearing and time-average smearing effects discussed in Lectures 2 and 8.

3.1. IF bandwidth $\Delta\nu$.

The choice of the IF bandwidth for VLA continuum observations is most important, as an unsuitable choice may lead (a) to irrecoverable distortion of the image if the bandwidth is too great, or (b) to loss of sensitivity if it is too small. As discussed in Lectures 2 and 8, observations made with finite bandwidth suffer both radial smearing and reduction in amplitude of the point source response away from the delay tracking center. These effects are discussed in detail by Perley (1981a), and their magnitudes are also graphed in Figures 16–5 and 16–6.

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 Figure 16–5 at ordinate $1 + n/100$, or Figure 16–6 at ordinate $1 - m/100$, and read the corresponding value of the normalized parameter β 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

$$\Delta\nu_{\max} = \frac{\beta_{\max}\nu_0\theta_{\mathbf{HPBW}}}{\theta_{\max}}, \tag{16–2}$$

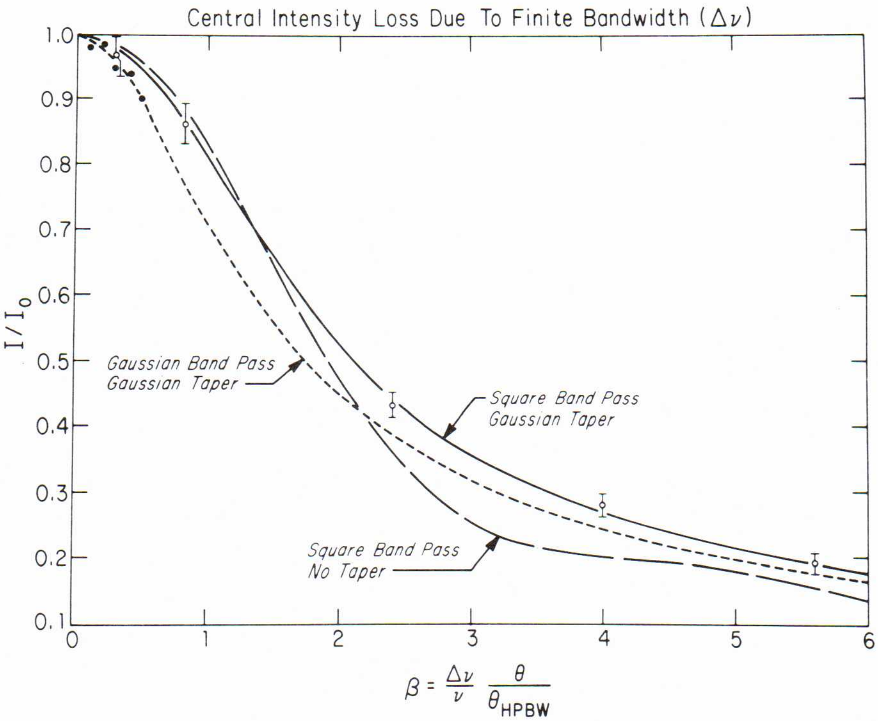

Figure 16–6. The central intensity loss, due to finite IF bandwidth $\Delta\nu$, plotted as a function of the dimensionless parameter β. θ is the angular distance of the feature from the phase center, in the same units as the beamwidth θ_{HPBW}.

where ν_0 is your observing frequency in MHz and θ_{HPBW} is the half-power beamwidth in arcsec at which you expect to make your images. Unless you are prepared to relax your smearing/attenuation criterion slightly, select the closest VLA bandwidth that is ***narrower*** than the computed value $\Delta\nu_{max}$. If you are prepared to relax it, choose the closest ***wider*** bandwidth.

For example, suppose you are prepared to tolerate an amplitude loss of 10% for a point source at 45″ from the image center in an **A** configuration observation at 1465 MHz. Entering Figure 16–6 at $I/I_0 = 0.9$ gives $\beta_{max} = 0.8$, from which $\Delta\nu_{max} = 0.8 \times 1465 \times 1''.25/45'' = 32$ MHz. You would then either choose $\Delta\nu = 25$ MHz, or relax the criterion and use $\Delta\nu = 50$ MHz.

Your choice of θ_{max} may be determined by the need to image 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' a confusing source's sidelobes from the region of interest. The value of θ_{max} will always be greater than, or about equal to, the value of θ_{LAS} used earlier when selecting the configuration. In general, choose the delay and pointing center to minimize the required θ_{max} for your observations. When using a wide field to include a confusing source, consider displacing the delay center away from the "target" source towards the confusing source. This will avoid the use of unnecessarily narrow bandwidths (and thus of unnecessarily low sensitivity). If the field is ***dominated*** by a strong point source (more than ten times brighter than other structure), ***this*** source should be placed near the delay center and image center whenever high dynamic range is required. This strategy will minimize the total distortion of the image resulting from bandwidth, pointing, averaging time and ***u-v*** truncation effects involving the strong source (see Clark 1981).

For point source detection experiments the above criteria will normally select the 50

MHz bandwidth, unless the search position is exceptionally inaccurate or the field is known to be highly confused. The 50 MHz bandwidth is also normally required at 2 cm and 1.3 cm, because at these wavelengths the usable field of view is limited by the primary HPBW of the antennas for the narrower bandwidths, and because the system temperatures are greater than at 20 cm or 6 cm.

When deciding on the value of $\theta_{\rm max}$ that is appropriate for an image of an extended source, also consider the detectability of the extended emission *at the resolution you will be using for your images* (see Sections 2 and 4). There is no point ensuring that extended structure is not smeared radially by the bandwidth effect if low signal-to-noise on the same structure introduces uncertainties larger than the bandwidth distortions. As the signal-to-noise on extended emission itself depends on the choice of IF bandwidth, this calculation may need to be iterated until a suitable compromise is reached.

Users of extremely narrow bandwidths should note that when observing in continuum mode the VLA bandwidths narrower than 6.25 MHz suffer large closure errors because the quadrature networks do not work well. If such narrow bandwidths are essential for your observations, consider observing with the spectral-line system, where these problems are avoided. Note however that the VLA spectral-line system does not support polarimetry at present.

Spectral-line observers will normally choose their IF bandwidth from constraints other than those discussed above. For spectral-line imaging, bandwidth smearing is determined by the *channel* bandwidth, which will normally be set (to a small value) by determining the velocity resolution needed for the project, rather than by field of view requirements.

3.2. Visibility averaging time τ_a.

The choice of the visibility averaging time τ_a for VLA observations is less critical than the choice of IF bandwidth $\Delta\nu$, because the default 10-sec averaged visibilities (**A** and **B** configurations) and 30-sec averaged visibilities (**C** and **D** configurations) are preserved on the archive tape created by the VLA on-line system. If you change your mind about visibility averaging times, the off-line data base can be "refilled" from the archive tape with a changed value of τ_a. This is costly in CPU cycles, however, so should be avoided by choosing τ_a carefully when the off-line data base is first created.

The effects of finite averaging time τ_a were discussed in Lecture 2 (Section 11) and in Lecture 8 (Section 1.2). As τ_a is increased, phase winding of a feature at radius θ from the phase center causes both a smearing of the synthesized beam and a loss of the averaged intensity for a point source. The effect is worst on a given baseline when the feature is moving perpendicularly to the fringes produced by that interferometer and is zero when the feature is moving parallel to the fringes. The magnitude of the effect therefore depends on hour angle and declination, as noted in Lecture 2. For a point source at the north celestial pole however, the average reduction in amplitude $R_A = I/I_0$ varies as

$$\frac{I}{I_0} = 1 - \left(\frac{\pi \tau_a \omega_e \theta}{6\theta_{\rm HPBW}}\right)^2 , \qquad (16\text{–}3)$$

where ω_e is the angular velocity of the Earth's rotation, I is the peak response to the source in the image, and I_0 is the peak response in the absence of time-average smearing.

For the case of a square bandpass and Gaussian tapering in the *u-v* plane, which is closest to the VLA case, and in the regime ($0 < \beta \le 1$) where the amplitude reduction produced by bandwidth smearing $R_B = I/I_0 < 0.8$, the expression for bandwidth smearing (e.g., Lecture 8, Section 1.1) can be approximated by

$$\frac{I}{I_0} \approx 1 - \frac{\beta^2}{5} = 1 - \frac{1}{5}\left(\frac{\Delta\nu\theta}{\nu_0\theta_{\rm HPBW}}\right)^2 . \qquad (16\text{–}4)$$

The averaging time $\tau_{\Delta\nu}$ that produces the *same* intensity reduction for a source near the pole as does an IF bandwidth $\Delta\nu$ can therefore be approximated (for small intensity reductions) by

$$\tau_{\Delta\nu} \approx \frac{6\Delta\nu}{\sqrt{5}\pi\omega_e\nu_0} = 1.2 \times 10^4 \frac{\Delta\nu}{\nu_0} \text{ sec}\,. \tag{16–5}$$

Equation 16–5 gives a reasonable criterion for the *maximum* averaging time τ_a which should be used with a given IF bandwidth $\Delta\nu$ at observing frequency ν_0. Notice that $\tau_{\Delta\nu}$ in Equation 16–5 does not depend on VLA configuration or on $\theta_{\max}$, owing to the first-order similarities between the bandwidth and time average smearing effects.

Note that you may often have to exceed the value of $\tau_{\Delta\nu}$ calculated from Equation 16–5 because the shortest available averaging time is the 1.67 seconds (two IFs), or 6.67 seconds (four IFs) set by the VLA's on-line computers. Also, note that the 'FILLER' program used to transport VLA data from the on-line computers to the off-line system 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}

Once you have determined the IF bandwidth $\Delta\nu$ from the field of view criteria, the next step in the decision tree (Fig. 16–1) is to estimate the total on-source integration time t_{int} required for given sensitivity on your final image[1]. Here you will use the expression for the r.m.s. noise ΔI_m on an image made with an N-antenna array:

$$\Delta I_m = F_w \Delta S \Bigg/ \sqrt{\frac{nN(N-1)}{2}\frac{t_{\text{int}}}{10}\frac{\Delta\nu}{46}}\,, \tag{16–6}$$

where n is the number of independent IFs contributed to the image per antenna ($n = 2$ for images of Stokes I from both left and right circular polarized channels at one sky frequency, or for images of $P = \sqrt{Q^2 + U^2}$ at one sky frequency), 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 (see Lecture 6 for more details), while ΔS is the VLA single-interferometer sensitivity given in Table 6–3 of Lecture 6, namely 73 mJy at 92 cm, 28 mJy at 20 cm, 18 mJy at 6 cm, 52 mJy at 2 cm, and 180 mJy at 1.3 cm.

Table 16–1 gives the theoretical r.m.s. noise on I and P images made at the VLA without tapering using 27 antennas and the maximum interference-free continuum bandwidths, for integration times typical of snapshots and of more complete syntheses. (Interference

[1]Spectral-line observers should make this calculation for their channel images setting $\Delta\nu$ equal to the channel bandwidth.

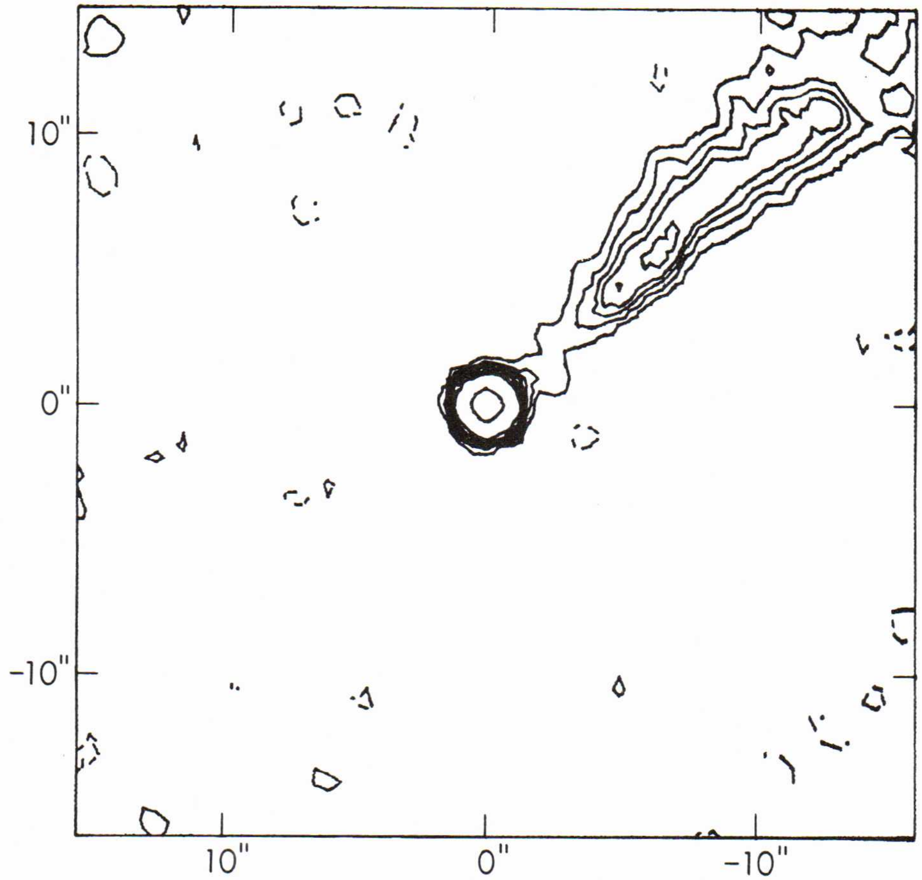

Figure 16–7(a). Contour plot of a 20 cm **A** configuration snapshot of the source 0055+300, made from 3 minutes of data at 50 MHz bandwidth. The contour levels are drawn at −2, 2, 4, 6, 8, 12, 20, 30, and 200 mJy/beam. The contour around the peak shows the HPBW. Compare with Fig. 16–7(b).

will normally restrict observations at 92 cm to a 3 MHz bandwidth).

Table 16–1.
R.m.s. Noise on Images Made with 27 VLA Antennas*

Band Designation:	92 cm	20 cm	6 cm	2 cm	1.3 cm
	P	L	C	U	K
Band Width $\Delta\nu$ (MHz)	3	50	50	50	50
r.m.s. noise in 5-min snapshot (mJy/beam)	2.0	0.19	0.12	0.36	1.24
r.m.s. noise in 12-hr integration (mJy/beam)	0.16	0.016	0.010	0.030	0.103

*For two IFs and natural weighting. For uniform weighting, multiply all entries by 1.5 (for a first approximation).

The sensitivity required for your observation will be determined by (a) the significance level you require for a detection in order to achieve your astronomical goals, and (b) whether the interesting emission is extended (see Section 2.1 above). If you are interested in polarimetry of the sources, calculate the sensitivity required for the polarization measurements first—this will normally drive the choice of total integration time for the experiment.

If the first estimate of t_{int} is significantly greater than 12 hours, consider carefully whether your choices of frequency and configuration are optimal. You may wish to re-enter the decision tree (Figure 16–1) with different starting parameters before considering the proposal planning further. If the total integration time required is more than 4 hours, a full hour angle track is probably desirable.

If you estimate $t_{\rm int} < 4$ hours, your observing strategy should be determined by the need for dynamic range and by the availability of other sources to merge with the program. The *u-v* tracks on different VLA baselines begin to overlap after about 4 hours of observing. If you require high dynamic range, or wish to image an extended structure, with less than 4 hours integration time it is therefore best to fill in the *u-v* plane as uniformly as possible throughout a 4-hour range of hour angle around meridian transit. This can usually be done satisfactorily by distributing the observing over several short (e.g., ~ 10-minute) scans spaced equally through this 4-hour range. Note however that the dynamic range achieved in a given observation is sensitive to atmospheric and ionospheric conditions, to the elevation angle range of the observation, and to your calibration strategy (Section 7 below), as well as to the *u-v* coverage.

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

5. Use of the VLA in "Snapshot" Mode

The "Y" layout of the VLA produces an *instantaneous* synthesized beam with 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 synthesis image processing!). To illustrate the power of snapshot made, compare the two 20 cm **A** configuration images of the source 0055+300 (NGC 315) shown as Figure 16–7(a) and 16–7(b). Contour map (a) is from a 3 minute snapshot at 50 MHz bandwidth, and has a signal-to-noise of about 200 : 1. Contour map (b) is from a 9 hour 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 images show identical jet structures within 15″ of the 0.4 Jy unresolved peak.

In what follows, I consider a single "snapshot" to be an observation of about 1–5 minutes' duration. Snapshots < 1 minute long involve some risk because much of the data for a source could be lost if the instrument took unusually long to settle down after a drive from the previous source. Even shorter snapshots may be appropriate if you want to image many (> 1000) fields that are near to one another on the sky (so that antenna drive times are also short) and it does not matter if the occasional observation is abbreviated or even lost.

5.1. Limitations of "snapshot" mode.

The clearest limitation of snapshot observing is sensitivity (see Table 16–1); it is suitable only for bright sources. At 20 cm, 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 VLA configurations will frequently be dominated by sidelobe clutter from confusing sources rather than by the noise that is quantified in Table 16–1. These problems are less severe at 6 cm and shorter wavelengths, because of the smaller primary beam and the typical source spectrum (see Section 6 below).

The second limitation of snapshot observing is the restricted angular size scale $\theta_{\rm LAS}$ over which the *u-v* coverage of a snapshot (e.g., Fig. 16–8) satisfies the sampling theorem and thus permits reconstruction of the correct sky brightness distribution. Table 16–2 codifies

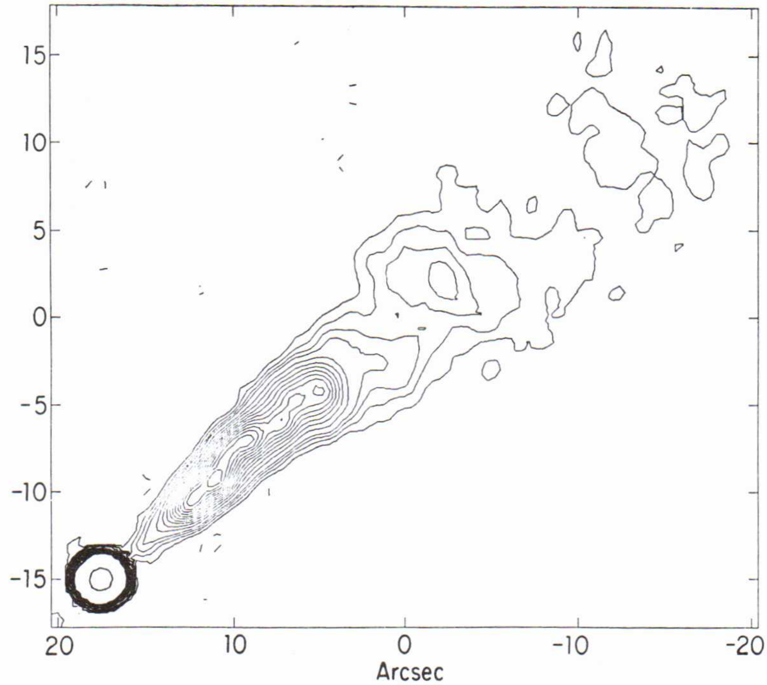

Figure 16–7(b). Contour plot of a 20 cm **A** configuration synthesis of the source 0055+300, made from 9 hours of data at 25 MHz bandwidth. The contour levels are drawn at −0.5, 0.5, 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, and 200 mJy/beam. The contour around the peak shows the HPBW. Compare with Fig. 16–7(a).

this limitation for the standard VLA configurations and frequencies.

Table 16–2.
Approximate Values of $\theta_{\rm LAS}$ for a Single Snapshot*

	A	**B**	**C**	**D**
92 cm	170″	9′	30′	70′
20 cm	38″	2′	7′	15′
6 cm	10″	36″	2′	5′
2 cm	4″	10″	40″	90″
1.3 cm	2″	7″	27″	60″

*Larger structures can be imaged by combining a few snapshots taken at different hour angles.

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 χ of $\Delta\chi \geq 90°$ (see Lecture 4, Section 7.1). "Standard" instrumental polarization parameters may then have to be used—note that these are available only for a few "standard" combinations of VLA observing frequencies and bandwidths (the default frequencies for 50 MHz bandwidths at 20cm, 6cm and 2cm, and the default frequencies for 25 MHz and 12.5 MHz bandwidths at 6cm). Position angle calibration may also be difficult if the standard polarization calibrators (discussed in Lecture 4) 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, by giving attention to its LST range and the choice of observing frequencies and bandwidths.

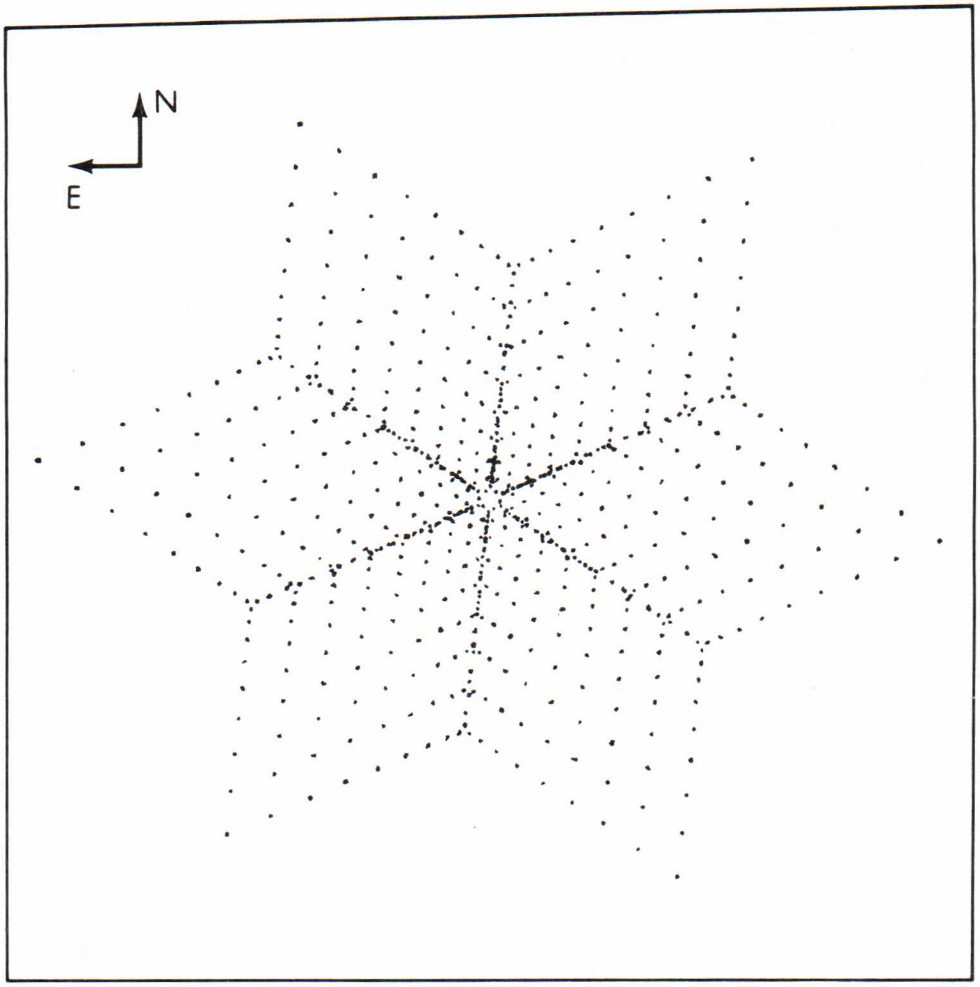

Figure 16–8. The *u-v* plane coverage for an instantaneous sampling of data for a source at $\delta = 30°$ and $H = 0$ by the 27-antenna VLA.

Snapshots are most effective when the sources are observed within about 2 hours of the meridian. At larger hour angles, foreshortening of the array will lead to poorer sampling of the *u-v* plane, elliptical synthesized 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 image construction, deconvolution and display steps of snapshot observing can require large amounts of computer time and your time, however. As a snapshot image of a given source may be as large as a full synthesis image 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 configurations at 20 cm and 6 cm, which are particularly prone to degradation by sidelobe clutter from confusing sources (see Section 6 below). Snapshooters must therefore be prepared to coordinate their data reduction requirements with those of other users, and to adopt efficient reduction strategies, including backing up of inactive source and beam images and *u-v* data sets whenever possible.

5.2. Multiple snapshots versus extended snapshots.

The question often arises of whether (for example) an observation requiring 15 minutes of integration time is best made as one continuous 15 minute observation or by combining the data from three separate 5 minute snapshots. Under some circumstances, a single 15 minute 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 an image with poorer final dynamic range. 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 imaged, the dynamic range of the result will be degraded unless self-calibration (Lecture 9) 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 through equipment failures or short-term bad weather, and (b) more even sampling of the *u-v* plane than in a single extended snapshot. Multiple snapshots are particularly useful when observing at wavelengths of 18cm and longer in the **C** and **D** configurations, as they allow better imaging of confusing sources that may otherwise limit the achieved dynamic range (see Section 6 below). The single extended snapshot may however prove to be better for observations that must be made at low elevations, where phase "wedges" are more likely to arise, and in cases where self-calibration 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 6 cm can be written approximately as

$$N(>S) = 0.032S^{-1.13} \tag{16–7}$$

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

$$N(>S) = 0.10S^{-0.9}. \tag{16–8}$$

The analogs of these expressions for 2 cm and 1.3 cm are not known directly from measured source counts. They could be *estimated* from the 6 cm count in Equation 16–7 by scaling flux densities to 6 cm with an effective mean spectrum of $\sim \nu^{-0.6}$.

Images made at 20 cm 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 of the VLA antennas. The 6 cm primary beam (4.′5 HWHM) will similarly contain, on average, one extragalactic source of flux density 2 mJy, the 2 cm beam (1.′85 HWHM) a source of < 0.1 mJy and the 1.3 cm beam (1′ HWHM) a source of < 0.01 mJy.

Individual pathological cases aside, confusion is thus unlikely to be a problem except at 20 cm and 6 cm in the VLA's more compact configurations. Confusion may have two effects on the interpretation of a synthesis image:

(1) degradation of the r.m.s. fluctuation level on the image by sidelobes or by 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 images. One is to plan to make wide-field images 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. The ungridded subtraction technique[1] (Lecture 8, Section 1.3) helps this strategy considerably, as only the parts of the wide field that contain significant emission need to be computed and 'CLEAN'ed. 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 that you would otherwise have been interested in imaging. The confusing source may then be close enough that you do not require an unacceptably narrow bandwidth to include it in the minimally-distorted field around your target. If the confusing source is very strong you may want to displace the delay tracking center away from the target and towards the confusing source in order to minimize distortions of the response to the confusing source by bandwidth smearing and other effects.

This problem is likely to be encountered particularly often by snapshooters using the compact configurations at 20 cm and 6 cm, because the sidelobes resulting from the "snowflake" pattern of u-v coverage in a snapshot (Fig. 16–8) extend widely across the images. Snapshooters should therefore plan to reduce their data using the ungridded subtraction algorithm both because it permits imaging of multiple subfields and because it eliminates the effects of sidelobe aliasing.

A second approach, suitable for more distant confusing sources, is to choose your IF bandwidth and delay tracking and pointing centers so that the response to the confusing source is adequately reduced by the combined effects of bandwidth smearing and of primary beam attenuation. Because the attenuation produced by bandwidth smearing increases with baseline length $\sqrt{u^2 + v^2}$ (see Lectures 2 and 8), this attenuation does not filter confusing sources from the short-baseline data as effectively as it does from the long-baseline data. If a distant confusing source still dominates the data after attenuation by the primary beam, this approach may therefore leave wide-angle "ripple" in the final image. In such cases, the pointing center should be chosen to minimize the response to the confusion rather than to maximize the response to the target source. The most difficult case of all arises when the response to the confusing source is strong even after this stratagem has been adopted. Here, variable pointing errors and the rotation of the primary sidelobe pattern of the antennas on the sky (due to the VLA's altitude-azimuth antenna mounts) may make the confusing source appear to vary throughout a VLA observation; it is hard to make images of high dynamic range in this case (see also Lecture 8, Section 2.1).

If the confusing source lies in the target field itself, nothing need be done at the time of the observations, as the source and its sidelobe pattern can be 'CLEAN'ed 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 (16–7 and 16–8) can be used to estimate the probability that the detected source occurs in the image by chance.

7. Calibration Strategy

Calibration sources should generally be chosen from the *VLA Calibrator List* maintained at the site by the NRAO staff, unless you are sure that a calibrator candidate is unresolved in the VLA configuration to be used, and has a position measured in the VLA

[1] coded in NRAO's Astronomical Image Processing System as the program 'MX'.

reference system to better than 0.1 arcsec. The basic issues to be decided by the observer are: how often to calibrate, and how close the calibrators should be to the target sources. Your strategy will depend on whether you attempt to calibrate only the instrumental fluctuations of the VLA, or these fluctuations plus the gain and phase variations introduced by the ionosphere and troposphere (see Lecture 4 for details).

7.1. 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 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 minutes will normally be adequate for instrumental monitoring.

Bear in mind that if the instrumental calibration detects a phase jump, you may have to discard all the data between consecutive calibration observations for the antenna-IF in which the jump occurred, unless the source being imaged is strong enough that the precise time of the phase jump can be located in the source data. If the source is strong enough, you may need to edit the data only between the gain table entries immediately before and after the phase jump—once a phase jump is localized, the gain table entries before and after it can be calibrated separately (from the earlier and later calibration observations, respectively). Of course, you you may not need to edit phase jumps in the data for strong sources at all if you will later use self-calibration to image such sources.

Calibrators for purely instrumental monitoring should be chosen primarily for their strength rather than for extreme closeness to the program source(s), particularly at 1.3 cm, 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 you 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 minutes should hardly ever be necessary at 20 cm or 6 cm.

The length of time spent on each calibration scan should be enough 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 minutes at a time, however, as shorter calibrator scans may be lost as a result of unusually long settle-down times, etc. Typical VLA observing programs spend from 5% to 10% of their time on calibration at the lower frequencies; more calibration may be needed at the higher frequencies where the calibration sources are weaker and therefore need to be observed for longer total integration times.

7.2. Atmospheric calibration.

It is more important, and also more difficult, to calibrate the amplitude and phase fluctuations resulting from changes in the propagation properties along the atmospheric path to the source. Unfortunately, *no calibration based on observations of a reference source that is not in the same isoplanatic patch as the interesting source can be guaranteed to improve the data quality.* This does not mean that attempts to calibrate atmospheric fluctuations using distant reference sources are a waste of time, but you must recognize 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. Corrections interpolated from the calibrator observations into the source data under these circumstances may then make the atmospheric amplitude and phase noise in the source data *worse* by a factor of $\approx \sqrt{2}$. At the other extreme, if the source and calibrator are typically within the *same* isoplanatic patch, the fluctuations observed in the calibrator will faithfully track those occurring in the source. Amplitude and phase corrections interpolated into the source data from the calibrator data in time series may then greatly improve the quality of the final image. The basic problem is that the scale size of the isoplanatic patch for your source will vary from day to day and even from hour to hour (as a function of the "weather" and of the position of your source above the horizon). It is therefore difficult to judge how reliable amplitude and phase referencing from a distant calibrator may be before the observations begin.

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 approach* (as discussed in Lecture 9). This means in practice that the source must produce sufficient signal to noise in the typical fluctuation time scale for the atmospheric phase screen over the baselines that will be used for the self-calibration.

External calibration is useful even when you know you will be able to self-calibrate your final images, for several reasons. External calibrators will provide flux-density and position scales for self-calibrated images (on which this information will otherwise generally be lost). Observations of the time scale of the phase fluctuations on an unresolved calibrator near your source can also be used to estimate the coherence time of the atmosphere while your observations were in progress. This will enable you to judge a suitable averaging time τ_{sc} for the self-calibration (Lecture 9, Section 5.3). Such observations may also tell you that some parts of your data were obtained under more stable atmospheric conditions than others; the "good" parts may then yield a good initial model of your source to help self-calibration of the whole data set converge quickly.

It is fortunate that the class of source for which images 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, as discussed in Lecture 11. 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°), 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 images. If you see rapid fluctuations, local point-to-point ('2POINT') interpolation of these may make matters better or make them worse. You then have little choice but to try making images from your data with both long-term averaging and with local interpolation of phase corrections from the calibrator data, to see empirically which approach gives better final images (using the final dynamic range, r.m.s. noise level, and/or any prior knowledge of the source properties to make this judgement).

Deletion of data from some or all baselines during periods of unusually bad phase stability will usually improve the quality of images made by external calibration. If you cannot use self-calibration, imaging with a reduced amount of data of better amplitude and phase stability can give better results than imaging with a large amount of poor data, because the actual synthesized beam will be closer to the theoretical "dirty" beam in the former case. This allows deconvolution algorithms to do a better job, increasing the dynamic range of your final images. Note that tapering the final images is a way of down-weighting the data from the longer baselines where phase stability is poorer. Be ready to sacrifice resolution in favor of forming the theoretical beam more closely if the phase stability is poor, when your astronomical goals can still be met at lower resolution.

Significant atmospheric amplitude and phase fluctuations can occur on time scales of minutes, even at wavelengths of 6 cm and longer. At times of solar activity, *ionospheric* fluctuations will dominate at 18 cm and longer—they can also be rapid on the long baselines but are generally less troublesome near the minima of the sunspot cycle. It is completely impractical to adopt a *calibrator/source/calibrator* cycle that will guarantee following the fastest fluctuations of either kind. Calibration every 20 minutes or so will often follow the longer-term atmospheric fluctuations at 20 cm and 6 cm, especially in the more compact VLA configurations. Calibration every 10 minutes or so is safer at 2 cm and 1.3 cm, especially if the external calibrator is not too far from the source being imaged. Keep in mind however that *no* external referencing, no matter how rapid, can be *guaranteed* to remove atmospheric fluctuations from the source data, and that time spent driving to and observing calibrators is time deleted from integration on your target source. You must decide for yourself how to play this particular roulette game during a given run.

Observers doing detection experiments will require such high dynamic range (and hence high phase stability) as observers imaging complex emission regions. (The loss of gain due to poor phase stability in a detection experiment can be estimated during the data reduction by calibrating with a $>$ 2 hour 'BOXCAR' interpolation in the gain table, then imaging a calibrator source and determining its apparent flux density.)

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

Finally, note the significance of the choice of the gain table interval for the VLA off-line data base created by the 'FILLER' program *if you will not self-calibrate* your data. The off-line gain table interval (which you specify to the array operator at the time of the observations) sets the minimum time scale of instrumental or atmospheric fluctuations that can be corrected by an external calibration. (Self-calibration algorithms construct their own gain tables based on the integration time τ_{sc} specified for the gain determination). The VLA default gain table interval of 10 minutes is adequate for a stable array and atmosphere, but shorter intervals are often appropriate if you will rely on external calibration.

7.3. Flux-density calibration.

If the LST range of your observing run permits, you should observe 3C 286 for a few minutes at each of the frequencies at which you have made source observations, as 3C 286 is the flux-density standard to which all VLA measurements are ultimately referred. Failing this, you should observe 3C 48 or consult with VLA staff about recent determinations of the amplitude gains of the antennas from other observations before finalizing your observing program. Do not simply take the most recent flux density for an arbitrary calibrator from the *VLA Calibrator List*, as most of these small-diameter sources are highly variable. The flux densities recorded in the *VLA Calibrator List* will rarely be sufficiently current to be useful in determining the absolute flux density scale for your observations; use them only to estimate the integration times needed to achieve the desired gain accuracy from your calibrator scans.

7.4. Polarization calibration.

This was previously discussed in Section 7 of Lecture 4, so only a brief recapitulation is given here.

To calibrate the ***instrumental polarizations***, you should observe one unresolved source, whether polarized or not, at least three times. These observations should be distributed so they cover a range in parallactic angle χ of $\Delta\chi \geq 90°$, to separate any polarization of the calibrator from the required instrumental terms (see Lecture 4). Programs involving long ($\geq$ 4 hr) syntheses of single sources will normally be able to derive the instrumental polarization calibration from the observations of the external synthesis calibrator. When determining the integration time for the instrumental polarization calibration, bear in mind that the leakage terms (the D's of Lecture 4) whose relative amplitudes and phases are to be determined will normally produce polarized intensities that are only a few percent of the flux density of the calibrator. The instrumental polarization calibration 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.

If the instrumental polarization calibration is omitted (e.g., because the observing session is too short, or the instrument misbehaved), you may be able to make the instrumental polarization corrections using the "standard" files of the necessary parameters that are maintained by the VLA staff. Note however that these are available only for a few combinations of observing frequency and bandwidth (see Section 5.1 above for the details). If you do not obtain an instrumental calibration, your ability to determine small degrees of polarization, and to 'CLEAN' polarized extended structures properly will be limited[1].

To calibrate the ***polarization position angle*** scale, observe 3C286 or 3C138 at least once during your observing run at each relevant frequency. You will determine the apparent position angles of the linear polarization of these sources after you have finished observing and after calibrating the total intensity data. The difference between the apparent and the nominal values of these position angles values is corrected later in the data reduction by adjusting the phase difference between the left and right circular polarizations, using a procedure that is described in detail in the *VLA Cookbook*. It is advisable to alert the array operator to the presence of the calibration in your program, so that the observations of 3C286 or 3C138 can be extended or rescheduled if necessary to prevent losing them due to an equipment failure. Note that this calibration is ***essential*** if you wish to make any use of your polarization position angle data.

At wavelengths of 18cm and longer, the position angle calibration may appear to be time variable because of fluctuations in the ionospheric Faraday rotation (Lecture 4, Section 7.3). If you will make use of the polarization position angle information at these long wavelengths, it is therefore a good idea to monitor one polarized calibrator ***in the same part of the sky as your source(s)*** throughout your observing run, to check whether its apparent position angle changes significantly. If this further calibration shows that the ionospheric changes are less than about 20°, it will probably be satisfactory to interpolate the observed position angle changes as a function of time when adjusting the relative phase of the left and right circularly polarized channels. If larger changes are seen, it may be possible to compensate for them using an ionospheric model and measured critical frequencies (by running the VLA's 'FARAD' program once the relevant critical frequency data have been received at the VLA—often several months after the observing). Except when the rotation changes

[1]Antenna-to-antenna polarization differences distort the polarization images in ways that do not satisfy the convolution theorem.

are small (< 20°), the success of this repair cannot be guaranteed, however. The observation of the polarized calibrator is best thought of as a "warning light" for the existence of ionospheric Faraday 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 6 cm, 2 cm or 1.3 cm, 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 observing programs have frequency agility. When this is the case, on-site observers may wish to adjust their observation files to take account of the weather prevailing during their observing program—this is a prime reason for being on-site when your observations begin. 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 VLA on-line computer's amplitude-phase ("D10") display over a long baseline as your observations start. 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°, you might consider editing your observing file to achieve a faster calibration cycle. Users of 1.3 and 2 cm wavelengths might consider preparing several observing files with different calibration cycle times before the observations begin; this makes it easier to alter the strategy while they are in progress.

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 images with fair dynamic range but uncalibrated position shifts.

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

9. The Observing Proposal

A few guidelines can be given for writing a VLA proposal to maximize 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. Before you begin writing a proposal, it is also worth checking whether any source you are interested in has previously been observed at the VLA—catalogs of the observed sources, with relevant instrumental parameters, can be obtained by writing to Teresa McBride at the VLA or by accessing

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

Name	Epoch 1950☐ 2000☐ RA hh mm	Dec ±xx°x	Config.	Band (cm)	Band width (MHz)	Total Flux line (Jy)	Total Flux cont. (Jy)	Largest ang. size	Weakest signal (mJy/beam)	Required dynamic range	Possible LST range hh - hh	Time requested

Figure 16–9. A sample of Item 18 from the standard VLA proposal cover sheet.

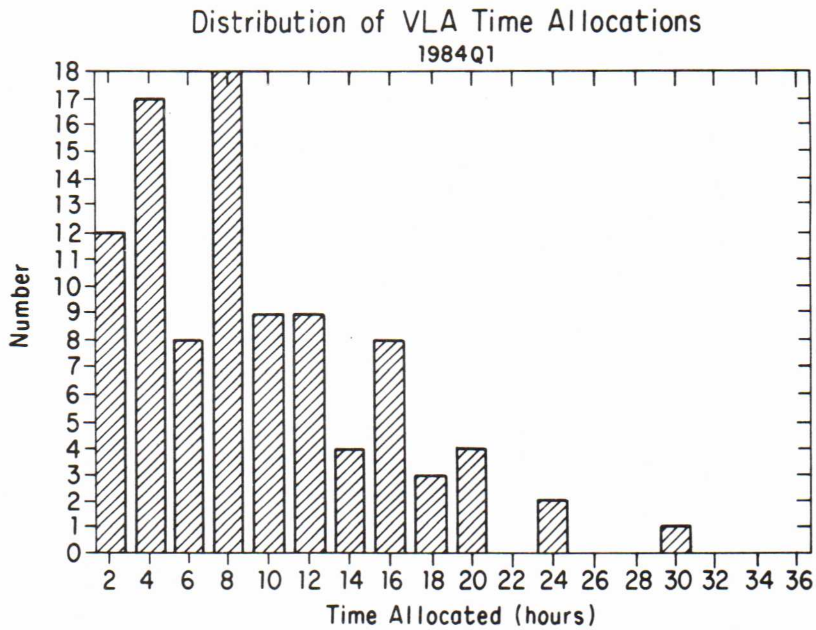

Figure 16–10. A histogram of durations of projects scheduled for VLA observations for the first two months of 1984, when the array was in the **B** configuration.

the relevant disk files on the VLA DEC–10 computer. See the *NRAO Newsletter* of July 1, 1985, p. 13, for details and for a brief description of NRAO policy regarding access to archived data sets.

The proposal cover sheet should be filled out in as much detail as possible. Filling out item 18 on the cover sheet (Fig. 16–9) fully for each source, or for typical sources, will lead you to consider the issues discussed in this Lecture. Your entries here should show the proposal referees and the VLA scheduling committee that the proposal is well suited to the VLA configuration(s) you are requesting.

The distribution of observing time allotted to successful proposals during the first two months of 1984, when the VLA was in the **B** configuration, is shown as a histogram in Figure 16–10. The median observing time scheduled is 7 hours, reflecting the large number of proposals for which less than full hour angle tracks are appropriate. Note however that some of the projects scheduled used more than 16 hours of observing time—well-justified long projects can successfully compete for time!

Finally, submit your proposal to the NRAO Director in Charlottesville well before the deadline given for your desired configuration(s). These deadlines and the VLA configuration schedule are published regularly in the *NRAO Newsletter* and in the *AAS Newsletter*. Proposals may be submitted between the deadline dates, and indeed NRAO encourages this for several reasons—(a) the pressure of proposals for a given configuration influences the length of time that the VLA is scheduled to spend in that configuration, (b) early submission may give you a chance to reply to unfavorable referees' comments before the scheduling committee assigns time for the requested configuration(s), and (c) observers who submit early reduce the strain on the proposal processing system near the time of the deadline.

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