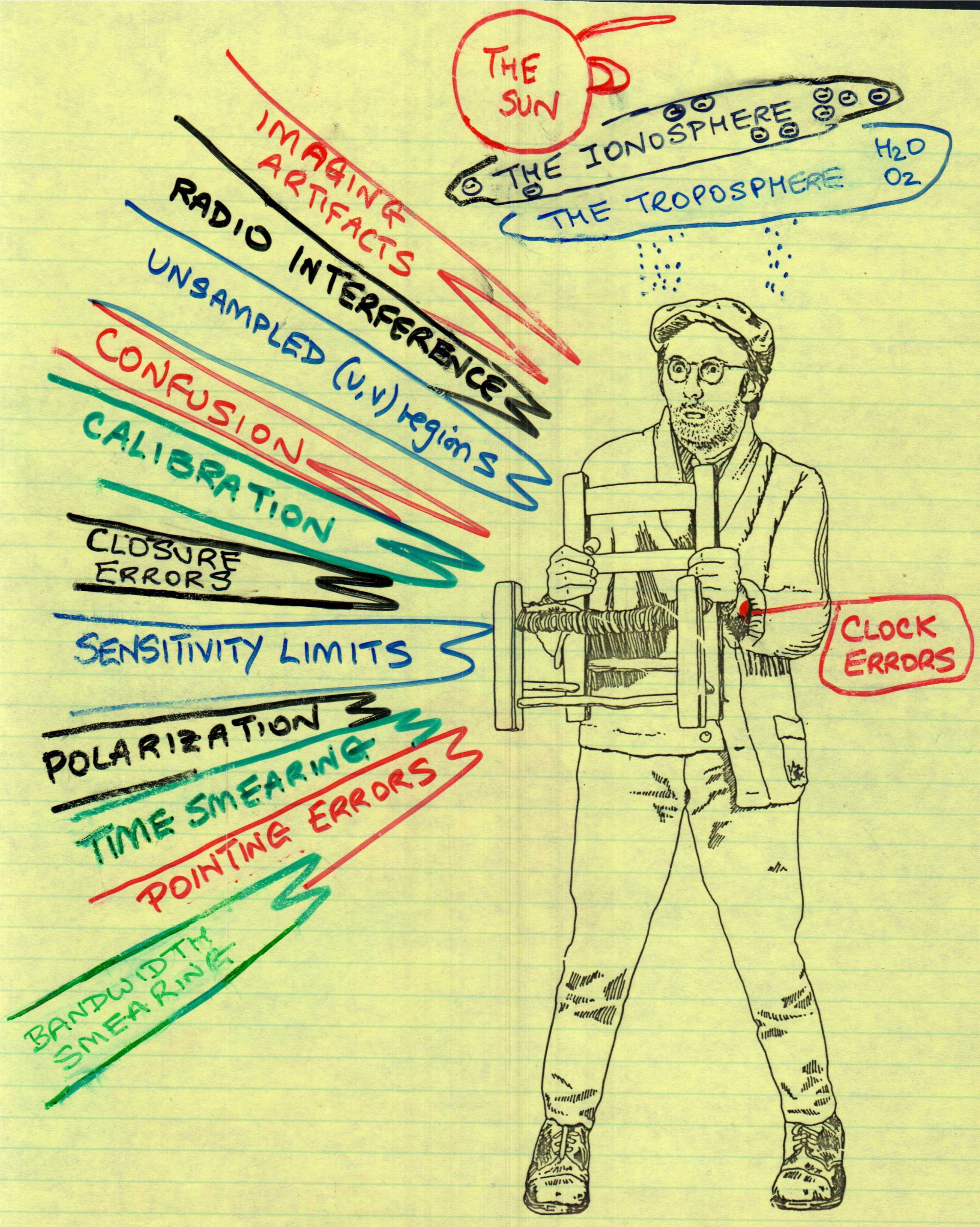
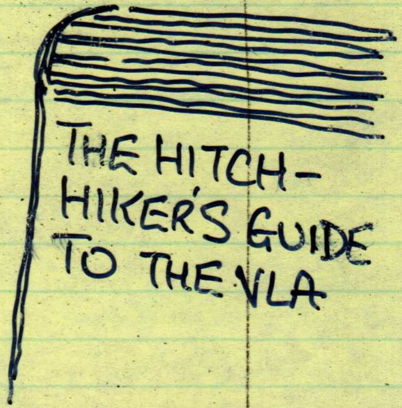

THE SUN
THE IONOSPHERE
THE TROPOSPHERE
H_2O
O_2
IMAGING ARTIFACTS
RADIO INTERFERENCE
UNSAMPLED (u,v) regions
CONFUSION
CALIBRATION
CLOSURE ERRORS
SENSITIVITY LIMITS
POLARIZATION
TIME SMEARING
POINTING ERRORS
BANDWIDTH SMEARING
CLOCK ERRORS

19. OBSERVING STRATEGIES I.

HOW TO KEEP IT ALL UNDER CONTROL IF THERE'S A VLA OBSERVING PROPOSAL IN YOUR FUTURE . . . .

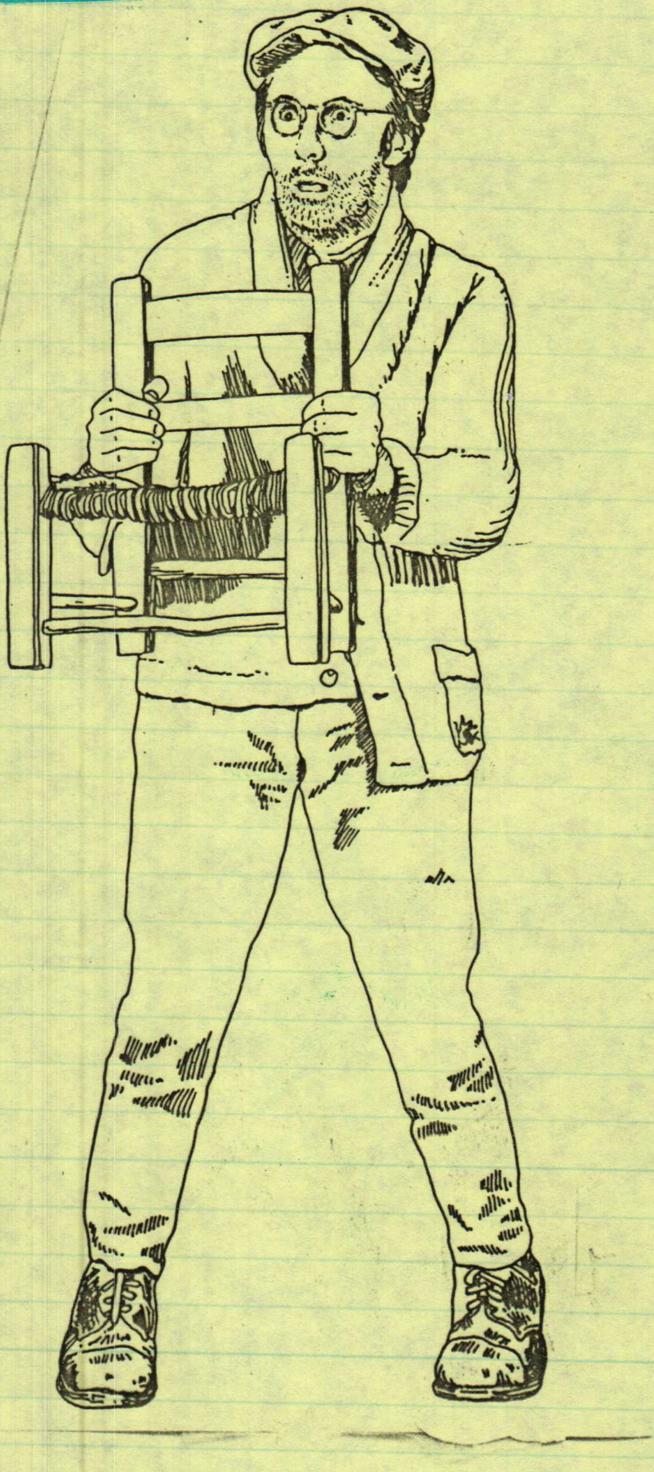
OR



N.B. You may not know enough about your source to do exact sums everywhere here (in fact you need to know a great deal about it to do all of this). Where you don't have good #'s you have to wing it or use some astrophysical ideas, but it will also help you write the proposal to see where the missing pieces of this puzzle etc.

VLA OBSERVING STRATEGY #1

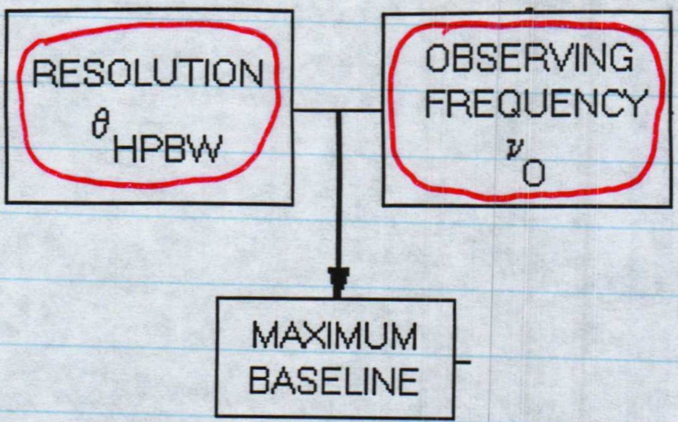
DON'T PANIC !!



Plan - Lecture 19

1. How to plan continuum observing
   - imaging goals → critical observing parameters
2. How to plan spectroscopic observing
   - a few key differences from continuum case
3. Calibration strategies (Walker, Fomalont, Brinks, Uson)
4. Proposal strategy *(if time)*
5. NRAO aids to strategy preparation
   - information sources
   - software

STARTING-POINT ON CONTINUUM "TREE"



Angular Resolution

- Specify θ_{HPBW} — FWHM of synthesized beam
- How much is enough?
- Maximum useful θ_{HPBW} may be set by
  - need to *separate* interesting structures
  - need to separate source from *confusion*
- Minimum useful θ_{HPBW} may be set by
  - need to detect interesting *extended* structures
  - sensitivity limits
  - dynamic range limits
- Detection experiments: large u-$v \rightarrow$ worse phase coherence

Observing Frequency ν_0

- Astronomical Factors
  - source spectra (thermal *vs.* nonthermal)
  - optical depth (see deeper at high ν)
  - polarimetry Cotton
    - Faraday thin at high ν
    - Faraday thick at low ν
- Instrumental Factors
  - antenna efficiency Napier
  - pointing Beasley
  - receiver sensitivity D'Addario
  - primary beam size Napier
- "Weather" at high frequencies Fomalont
- Interference at low frequencies
  Ionosphere Fomalont

Radio Frequency Interference

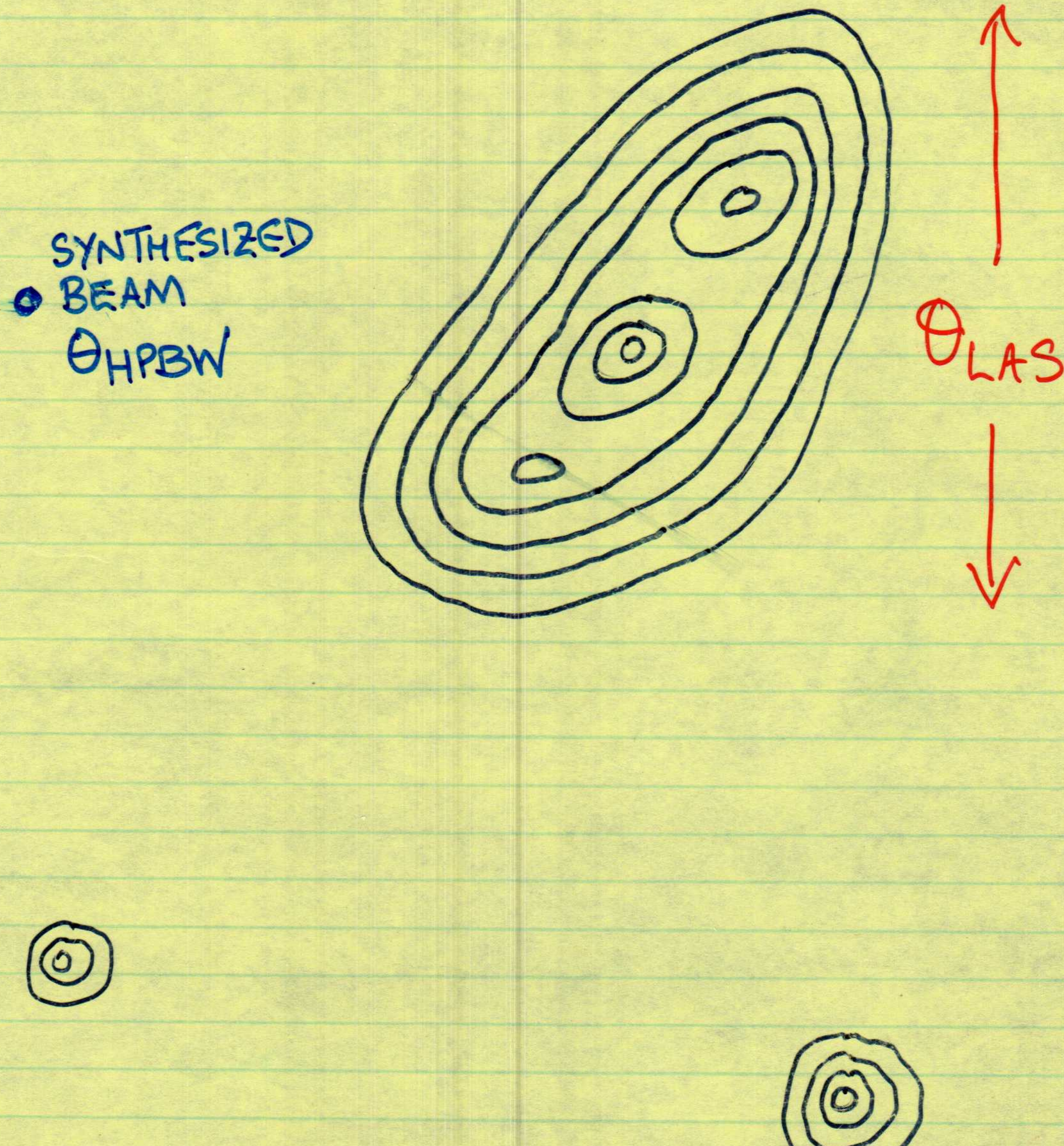
- Worst below 2 GHz
- Worst in compact configurations
- Worst at $u = 0$ (fringe freq $\nu_f = \omega_e u \cos\delta$)
- Consult VLA RFI information before using non-standard frequencies
  - L Band table in lecture notes
  - VLA Observational Status Report
  - `http://www.nrao.edu/doc/vla/interference/`

Resolution Formulae

- VLA $\theta_{\mathrm{HPBW}} = 1.''3 \times \frac{1.5}{\nu_0} \times 3.3^{n-1}$
  - n=1 for A configuration
  - n=2 for B configuration
  - n=3 for C configuration
  - n=4 for D configuration
  - ν_0 in GHz
- Beam area $\Omega_{\mathrm{s}} = 1.13\theta^2_{\mathrm{HPBW}}$

Resolution Strategy

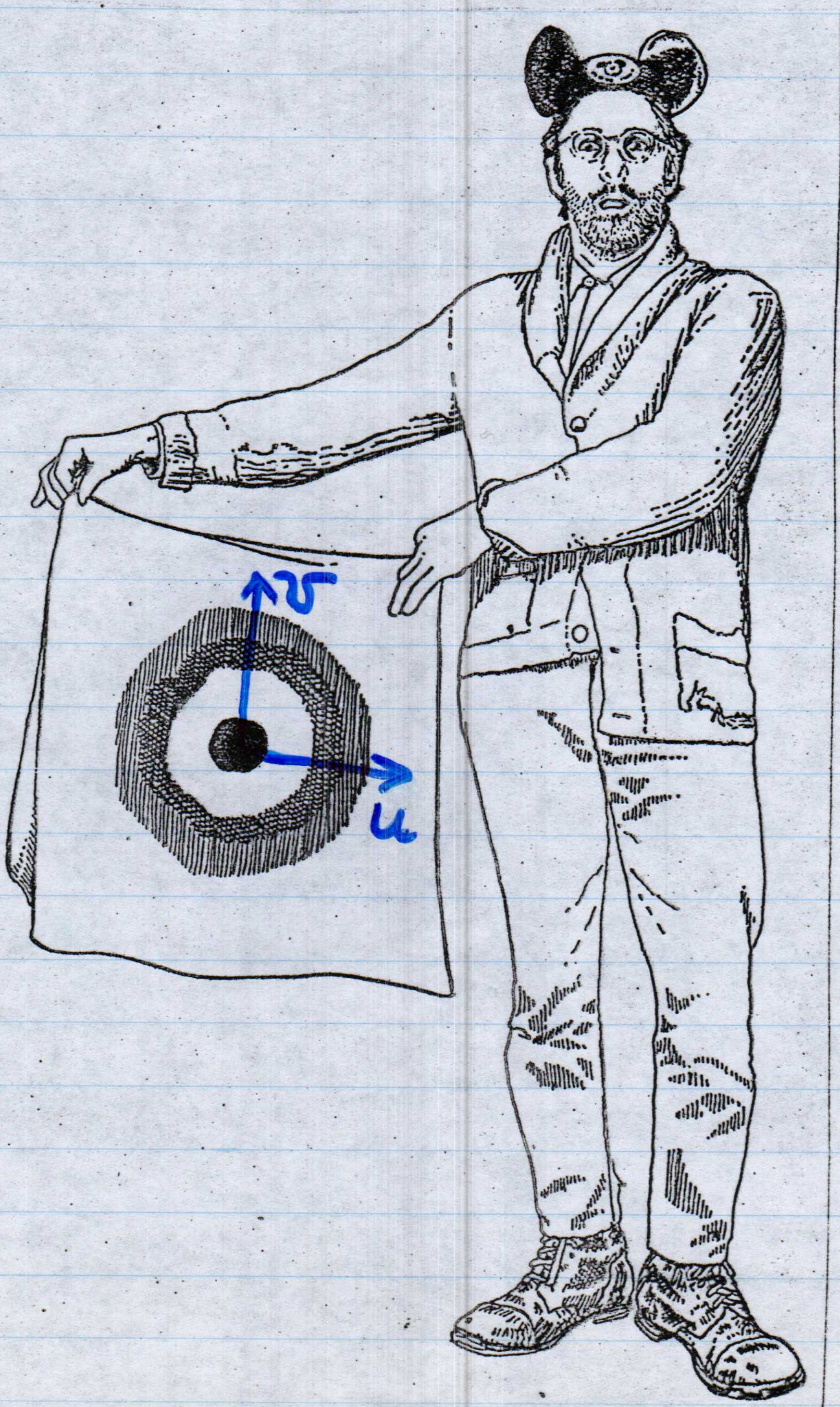
- Try *conservative* $\theta_{\rm HPBW}$ first
  - maximum that is enough to separate *interesting* features
- Work down decision tree with this $\theta_{\rm HPBW}$
- Find needed total integration time $t_{\rm int}$
- If short, smaller $\theta_{\rm HPBW}$ may work too!
- If long, rethink!



θ_{HPBW} → **LONGEST** baseline (km) $= \dfrac{2\lambda(\text{cm})}{\theta_{HPBW}('')}$

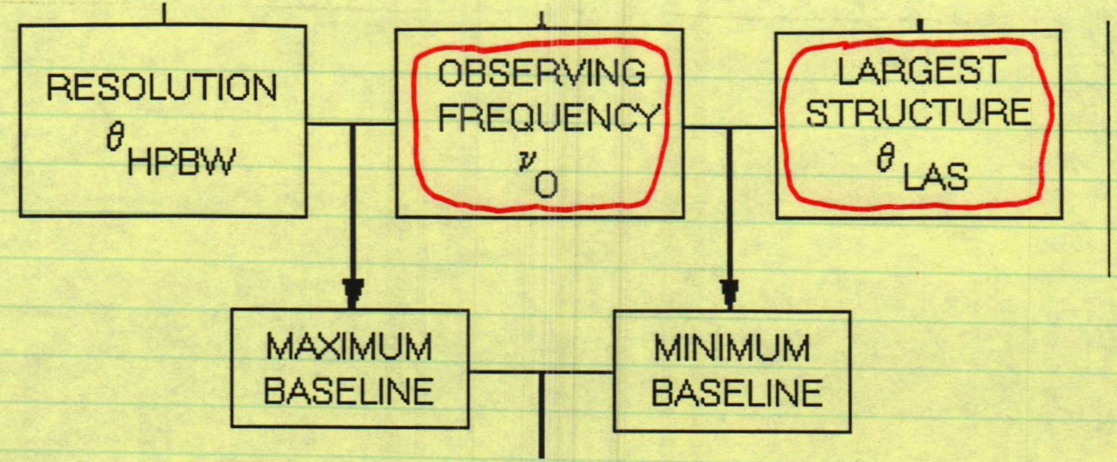
θ_{LAS} → **SHORTEST** baseline (km) $= \dfrac{\lambda(\text{cm})}{\theta_{LAS}('')}$

CHOICE OF CONFIGURATION



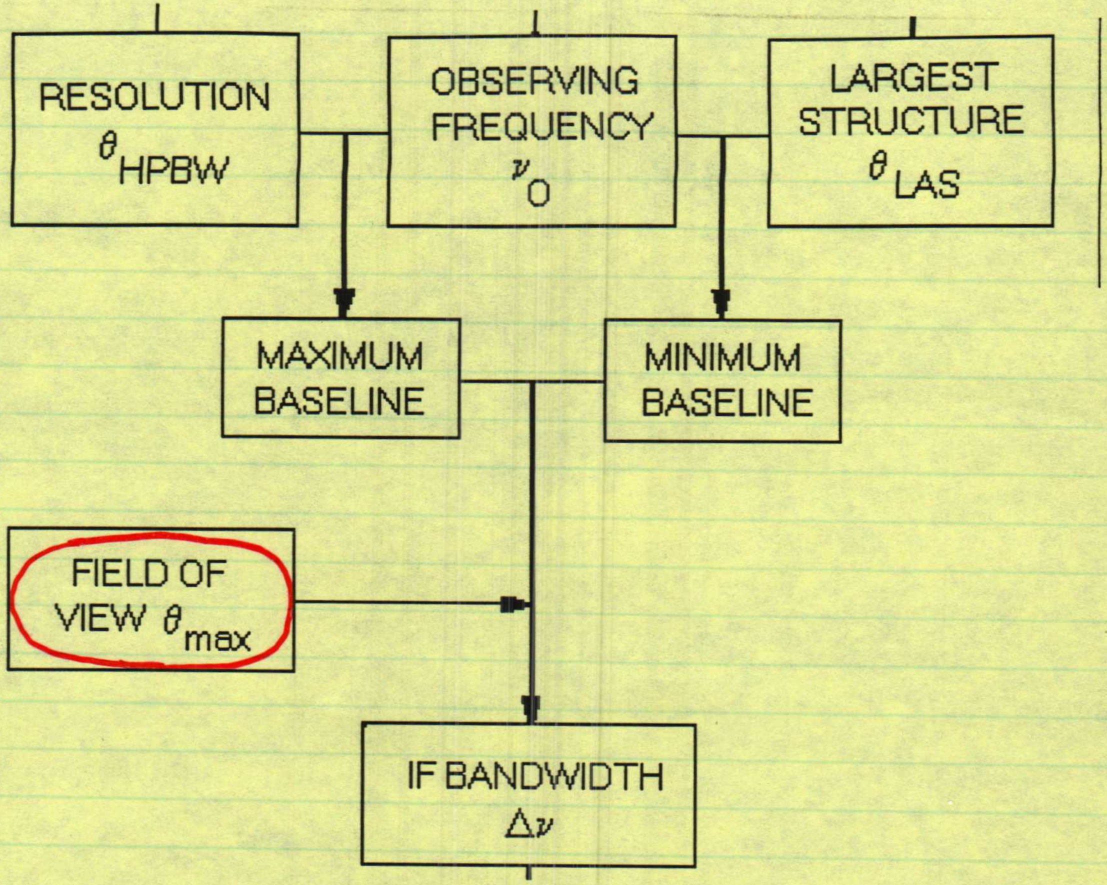
Longest and Shortest Baselines

- θ_{HPBW} and $\nu_0 \rightarrow$ *longest* baseline needed
  - Longest $a(\mathrm{km}) \approx \frac{2\lambda_0(\mathrm{cm})}{\theta_{\mathrm{HPBW}}(\mathrm{arcsec})}$
- Don't forget about *shortest!!*
  - What is largest structural scale θ_{LAS} to be imaged?
  - Shortest $a(\mathrm{km}) \approx \frac{\lambda_0(\mathrm{cm})}{\theta_{\mathrm{LAS}}(\mathrm{arcsec})}$ (~50% response)
  - One VLA configuration $\rightarrow \approx$20–40:1 in $\theta_{\mathrm{LAS}}/\theta_{\mathrm{HPBW}}$
- Fitting to actual VLA configurations:
  - First pick widest configuration from θ_{HPBW}, ν_0
  - VLA $\theta_{\mathrm{HPBW}} = 1.''3 \times \frac{1.5}{\nu_0} \times 3.3^{n-1}$ A n=1 B n=2 etc.....
  - Does this contain shortest baseline needed?
  - If not, use *multiple* (adjacent) configurations



RESOLUTION
θ_{HPBW}
OBSERVING
FREQUENCY
ν_O
LARGEST
STRUCTURE
θ_{LAS}
MAXIMUM
BASELINE
MINIMUM
BASELINE

FIELD OF VIEW RESTRICTIONS



RESOLUTION θ_{HPBW}
OBSERVING FREQUENCY ν_0
LARGEST STRUCTURE θ_{LAS}
MAXIMUM BASELINE
MINIMUM BASELINE
FIELD OF VIEW θ_{max}
IF BANDWIDTH $\Delta\nu$

Field of View Considerations

- Consider beam smearing ≡ loss of point source response from:
  - finite IF bandwidth $\Delta\nu$ Beasley, Cornwell, Perley
  - finite visibility averaging time τ_a Perley

  for features away from delay and phase tracking center.
- Decide how far—θ_{max}—from d.t.c., p.t.c. you must image with some ($\leq m$%) distortion
- Use m, θ_{max} to find β_{max} for bandwidth smearing (scales as $\beta = [\Delta\nu/\nu] \times [\theta_{max}/\theta_{HPBW}]$) Old Lecture 13 Perley
- $\Delta\nu_{max} = \beta_{max} \times \nu_0 \times \theta_{HPBW}/\theta_{max}$
- Choose $\Delta\nu < \Delta\nu_{max}$ from allowed settings
- Choose $\tau_a <$ "equivalent distortion time" $\tau_{\Delta\nu}$

Old Lecture 13 in "White Book"

Useful Formulae for Distortion Effects

Use $\frac{I}{I_0}$ (observed/undistorted intensity of point source)

- Bandwidth smearing, square band, Gaussian u-v taper:
  - Exact: $\frac{I}{I_0} = \frac{\sqrt{\pi}}{\gamma\beta}\mathrm{erf}\frac{\gamma\beta}{2}$ $(\gamma \equiv 2\sqrt{\ln 2} = 1.665)$
  - Low-order: $\frac{I}{I_0} \approx 1 - \frac{1}{3}\left(\frac{\gamma\Delta\nu\theta}{2\nu_0\theta_{\mathrm{HPBW}}}\right)^2$
- Low-order time average smearing (approx): $\frac{I}{I_0} \approx 1 - \frac{\gamma^2}{12}\omega_e^2\tau_{\mathrm{a}}^2\left(\frac{\theta}{\theta_{\mathrm{HPBW}}}\right)^2$
- Rough equivalence between distortions: $\tau_{\Delta\nu} \approx \frac{\Delta\nu}{\omega_e\nu_0} = 1.375 \times 10^4\,\frac{\Delta\nu}{\nu_0}\mathrm{sec}$ $\omega\tau \approx \frac{\Delta\nu}{\nu}$
  - independent of baseline length, $\theta_{\max}$

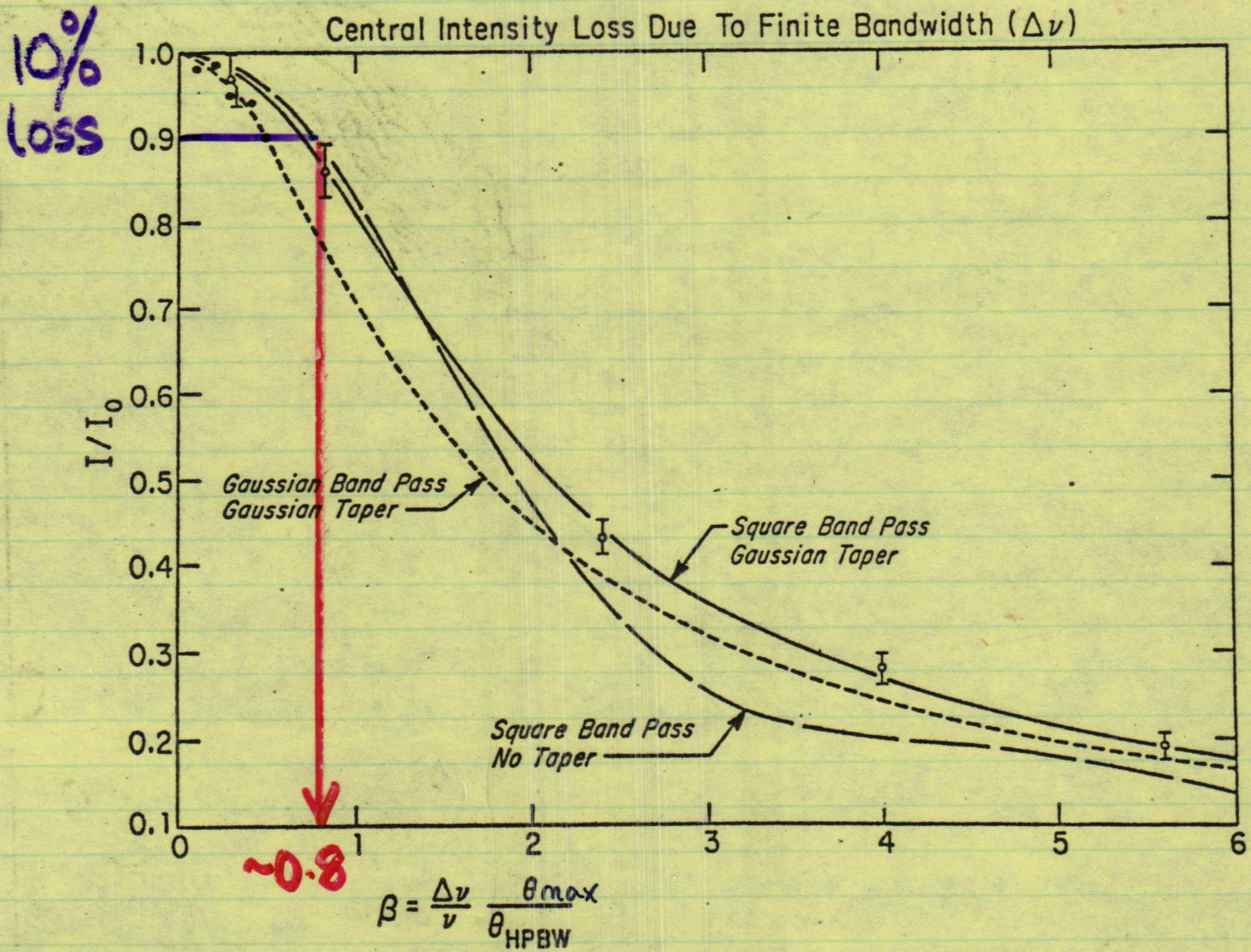
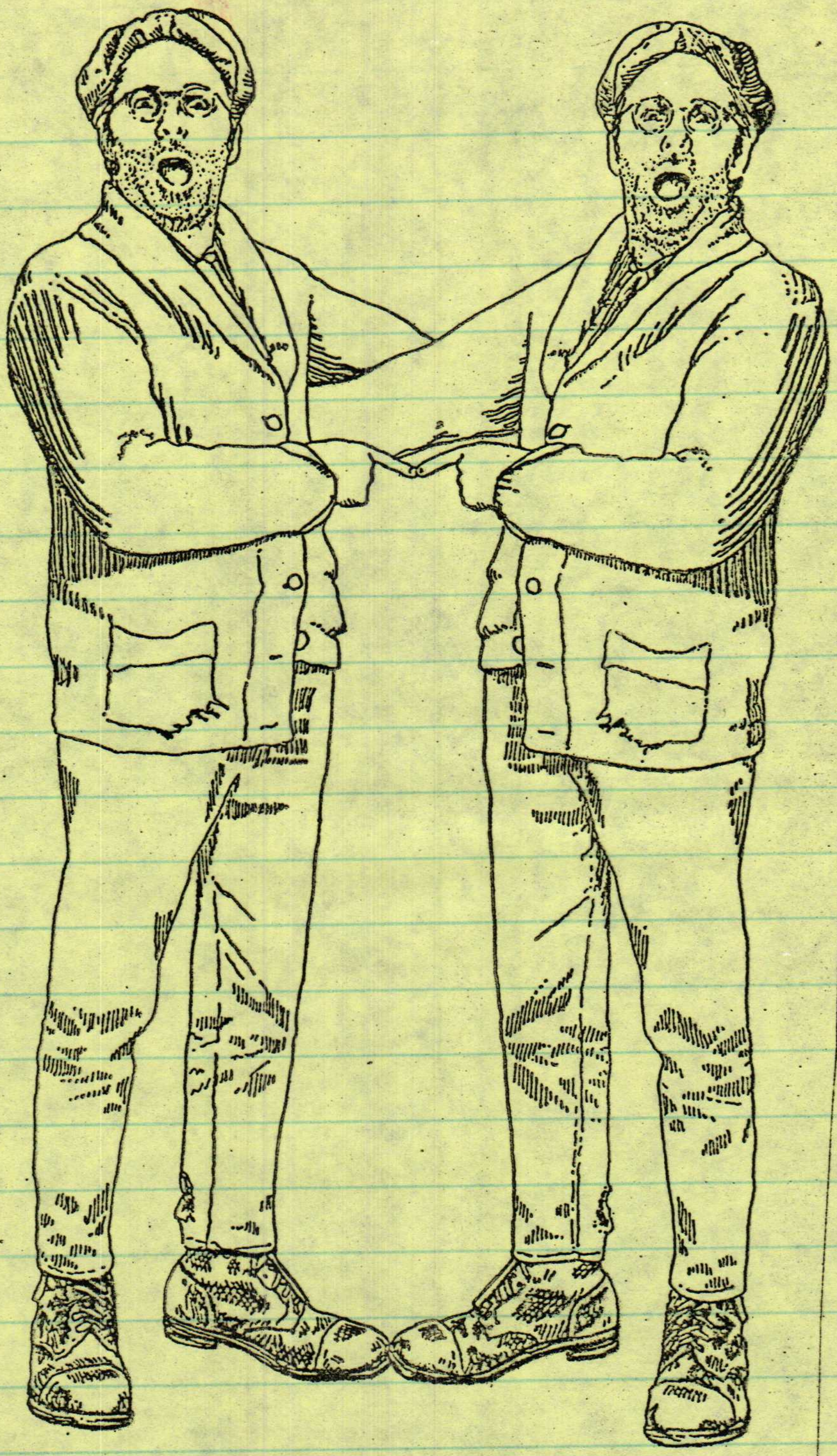


Figure 14-2: Central intensity loss, due to finite IF bandwidth $\Delta\nu$, plotted as a function of the dimensionless parameter β. θ is angular distance of the feature from the phase center, in the same units as the beamwidth θ_{HPBW}.



CONFUSION and
ALIASING

Confusion

i.e., sources you don't want but which are in your field of view. They create two types of problem:

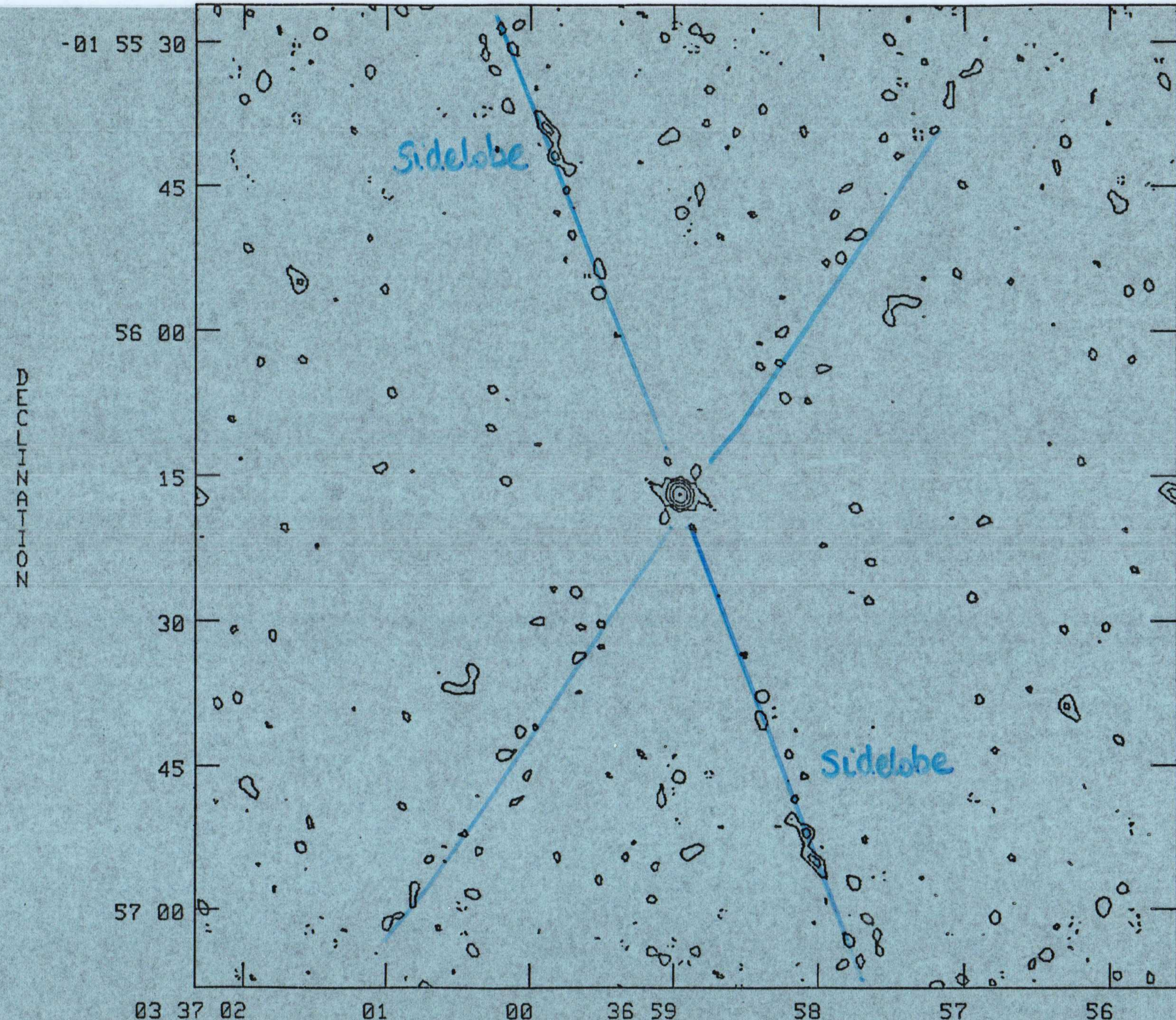
- Sidelobes of confusing sources limit r.m.s. of image and will not deconvolve if *aliased*.
- "Wrong source" in detection experiment.

Cornwell

Confusion is worst:

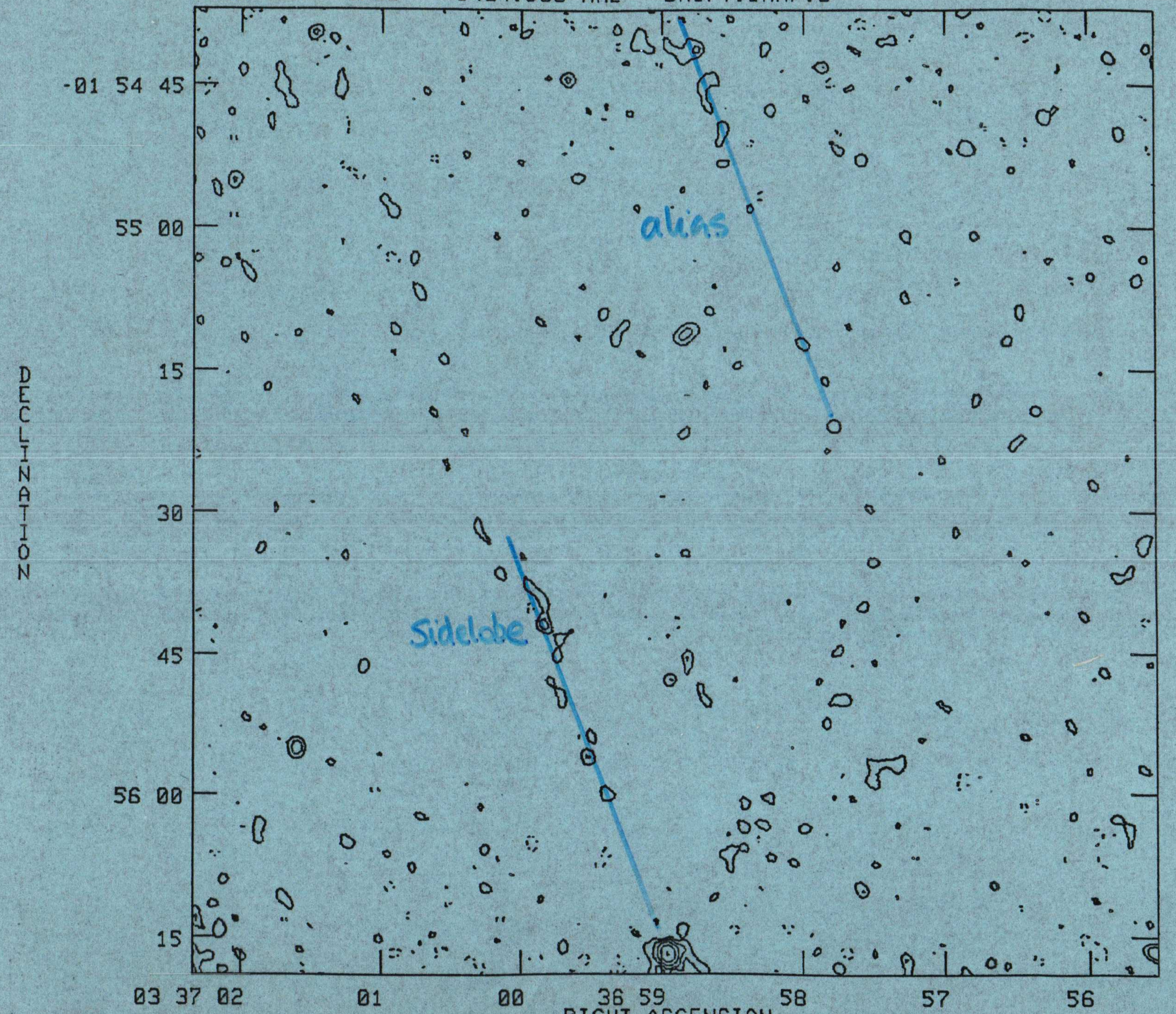
- at low ν (bigger primary beam)
  - 327 MHz, expect several Jy in primary beam
  - 1.5 GHz, expect a 110 mJy source in primary beam
  - 4.9 GHz, expect a 2 mJy source in primary beam
- in compact arrays (less bandwidth suppression)
- at low galactic latitudes (more "junk" in sky)

0336-019 IPOL 1464.900 MHZ SHIFT.IMAP.5



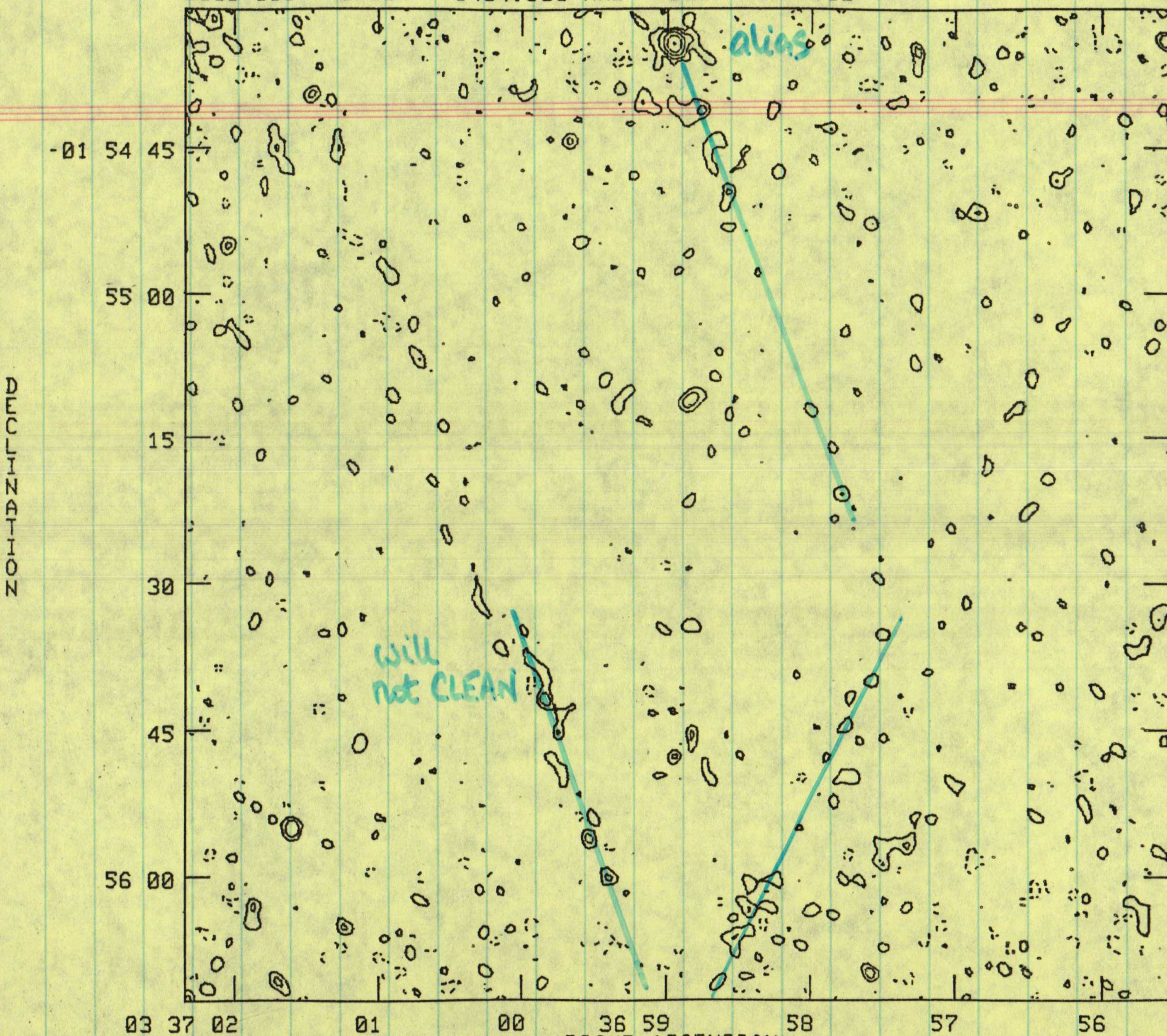
PEAK FLUX = 0.1866E+01 JY/BEAM
LEVS = 0.1866E-01 * (-12.5, -6.3, 6.3, 12.5, 25.0, 50.0, 95.0)

0336-019 IPOL 1464.900 MHZ SHIFT.IMAP.6

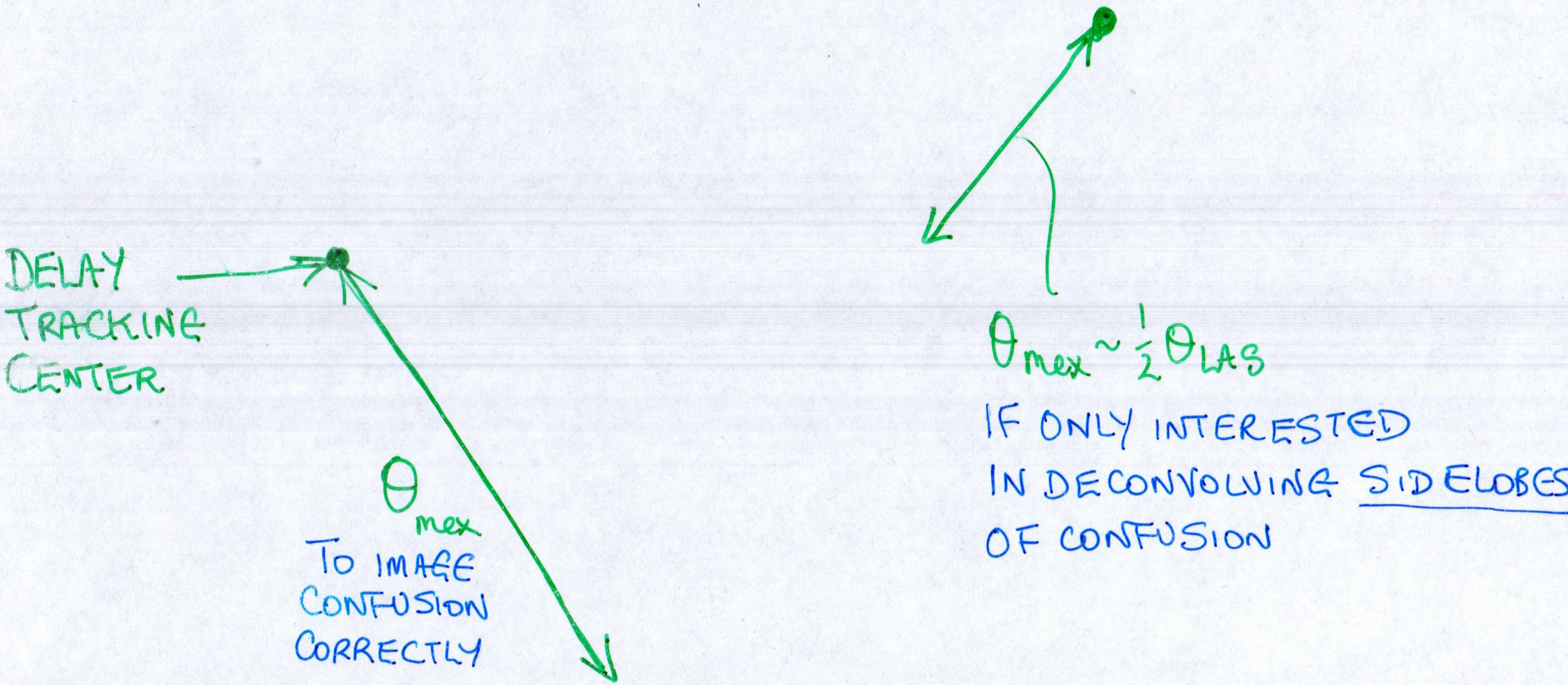


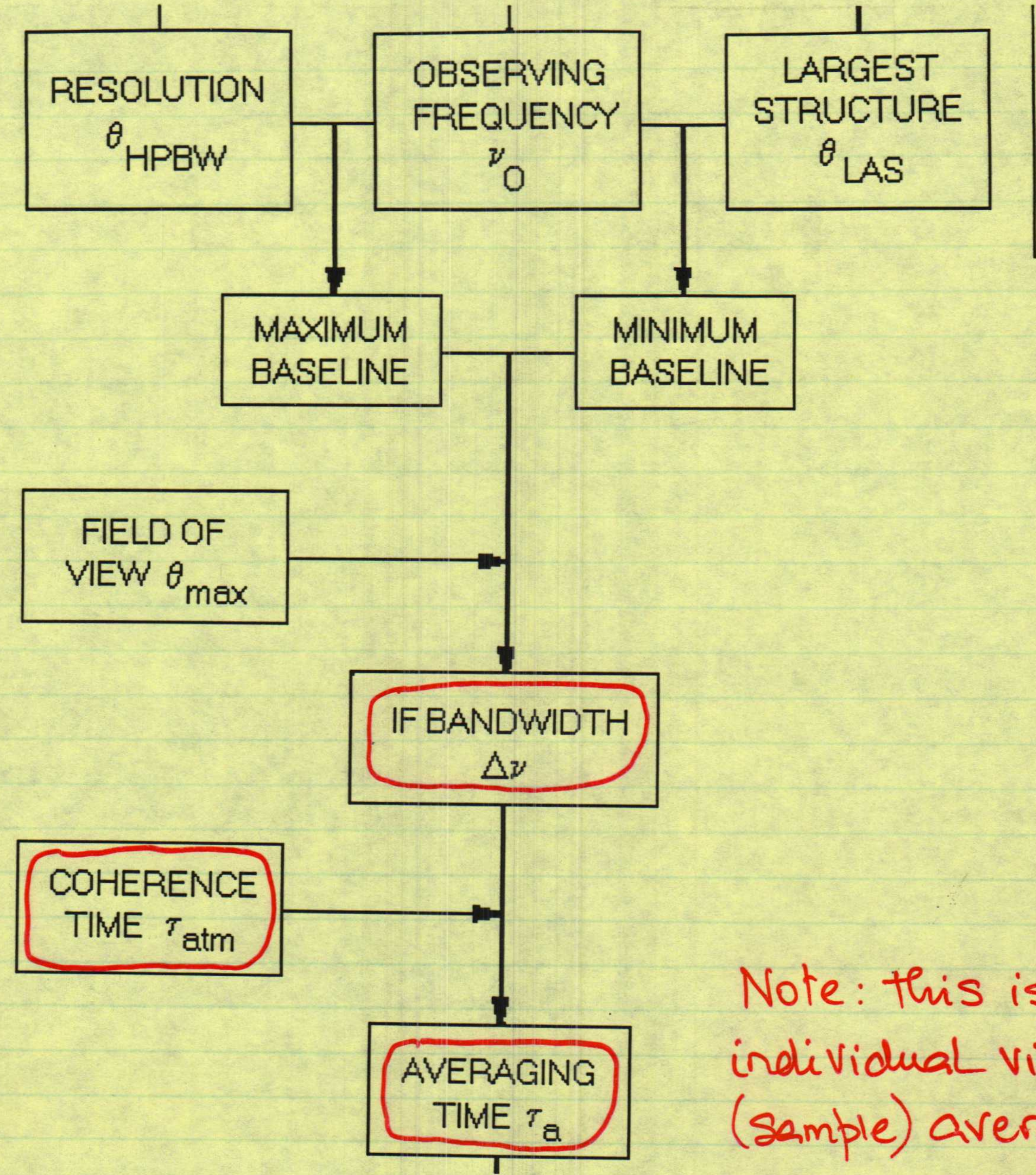
PEAK FLUX = 0.1892E+01 JY/BEAM
LEVS = 0.1892E-01 * (-12.5, -6.3, 6.3,
12.5, 25.0, 50.0, 95.0)

0336-019   IPOL   1464.900 MHZ   SHIFT.IMAP.12



PEAK FLUX = 0.1666E+01 JY/BEAM
LEVS = 0.1666E-01 * (-12.5, -6.3, 6.3,
12.5, 25.0, 50.0, 95.0)

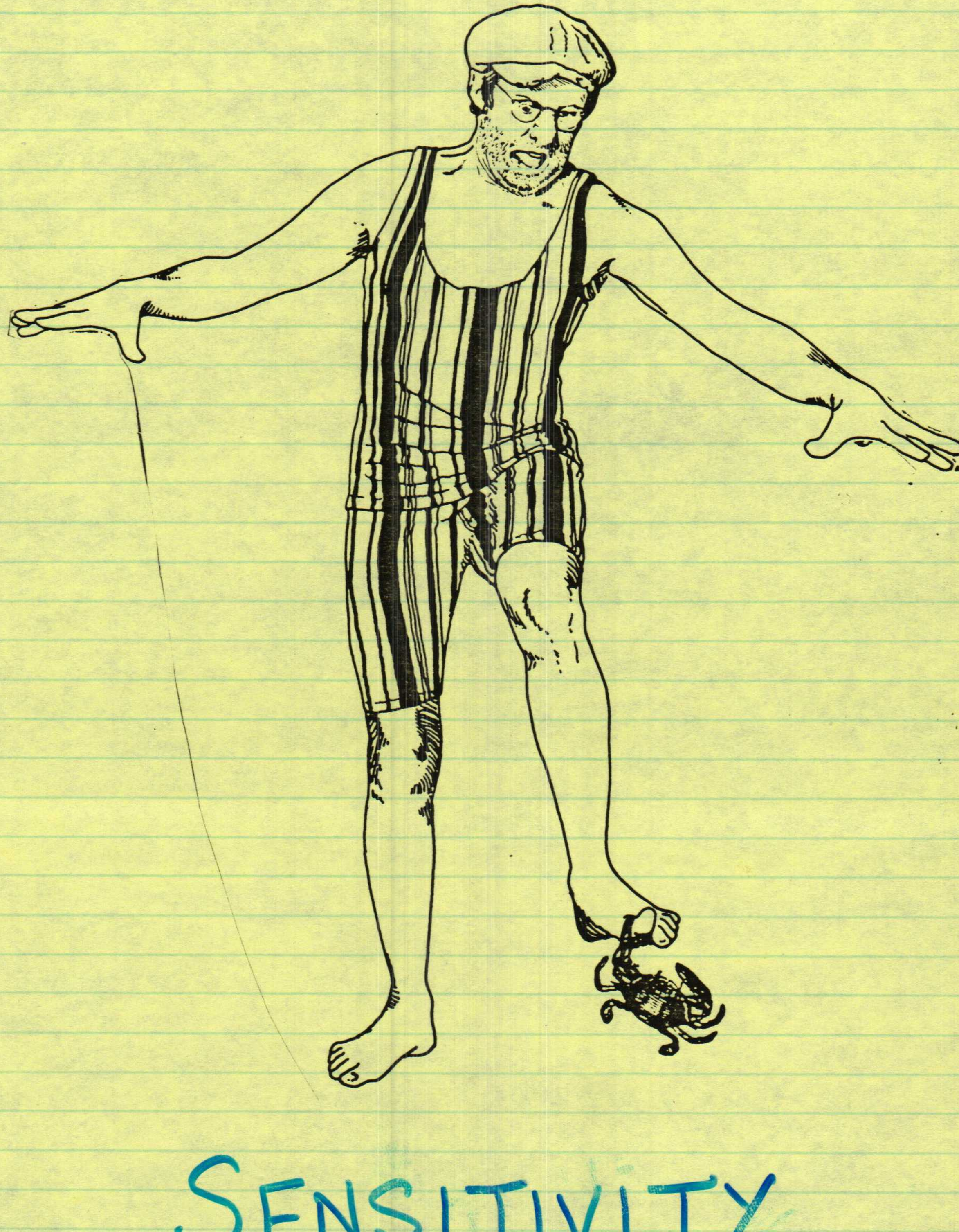

DELAY TRACKING CENTER
θ_{max}
TO IMAGE CONFUSION CORRECTLY
$\theta_{max} \sim \frac{1}{2}\theta_{LAS}$
IF ONLY INTERESTED IN DECONVOLVING SIDELOBES OF CONFUSION



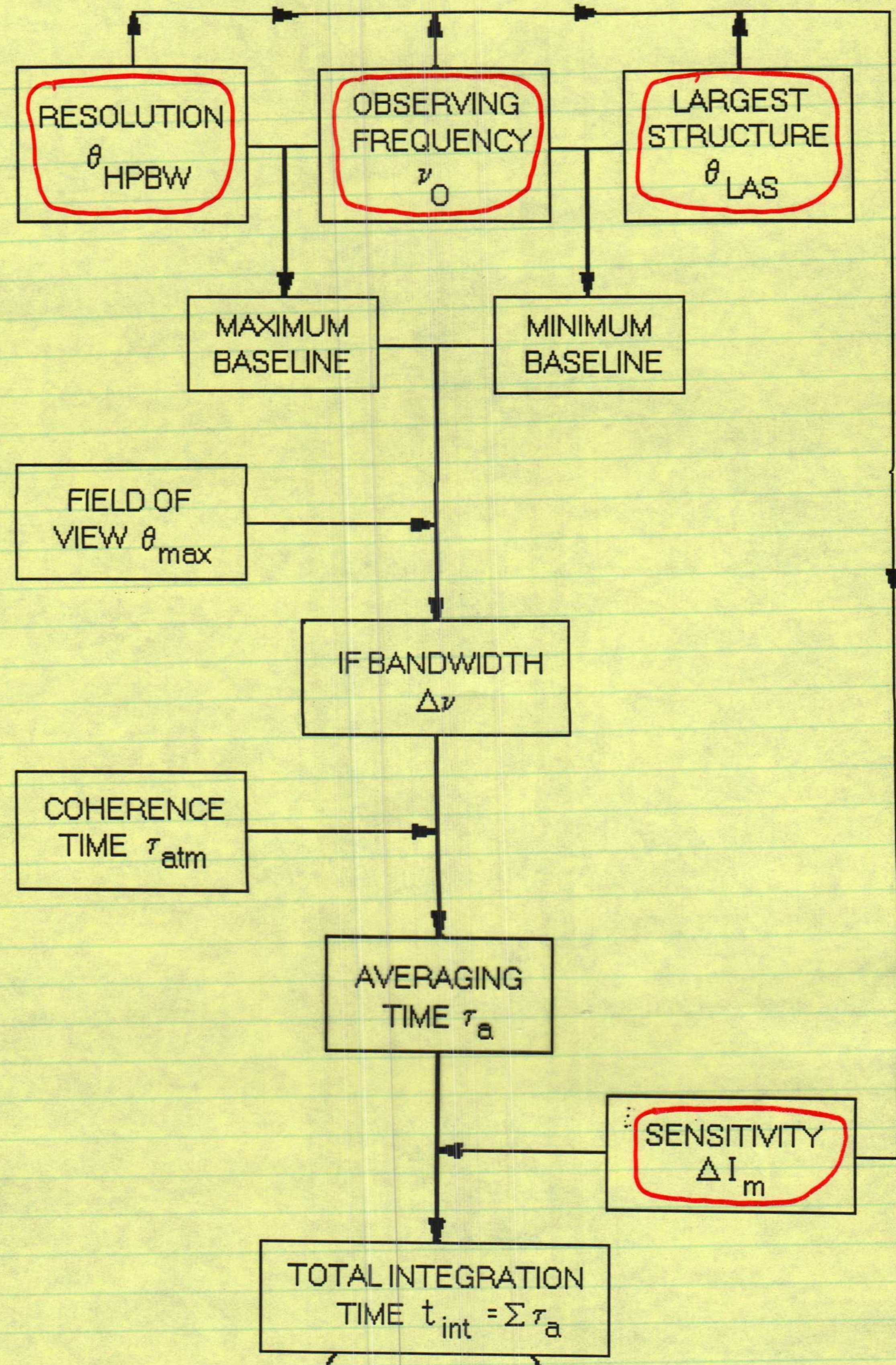
Note: this is the individual visibility (sample) averaging time, NOT total integration time!

Averaging Time τ_a

- No longer than bandwidth distortion equivalent
- No longer than expected phase coherence time Cornwell fomalont
- In range selectable at VLA (>1.67 sec)!



SENSITIVITY


RESOLUTION θ_{HPBW}
OBSERVING FREQUENCY ν_0
LARGEST STRUCTURE θ_{LAS}
MAXIMUM BASELINE
MINIMUM BASELINE
FIELD OF VIEW θ_{max}
IF BANDWIDTH $\Delta\nu$
COHERENCE TIME τ_{atm}
AVERAGING TIME τ_a
SENSITIVITY ΔI_m
TOTAL INTEGRATION TIME $t_{int} = \Sigma \tau_a$

Sensitivity

Now specify the r.m.s. noise ΔI_m needed in the final image. (mJy per beam area)

- Consider resolution of extended structures!
- Use polarized intensity if doing polarimetry!

Knowing the bandwidth $\Delta\nu$ and the sensitivity parameter ΔS of the system you will use at frequency ν_0, compute the total integration time t_{int} needed to reach ΔI_m.

Is the result reasonable?

- "yes" → you're done!
- "no" → rethink!

The Sensitivity Equation

$\Delta I_m = F_w \Delta S \,/\sqrt{\frac{nN(N-1)}{2} t_{\text{int}} \Delta\nu}$ where D'Addario

- N is the number of antennas in the array
- n is the number of IF's contributing (usually 2) maybe 4
- t_{int} is in seconds
- $\Delta\nu$ is in MHz
- F_w is 1.0—1.5 depending on u-v weighting Cornwell
- ΔS is the single-interferometer sensitivity per sec per MHz

Get ΔS for your ν_0 from VLA documents:

- these lecture notes (current)
- VLA Observational Status Report (future)

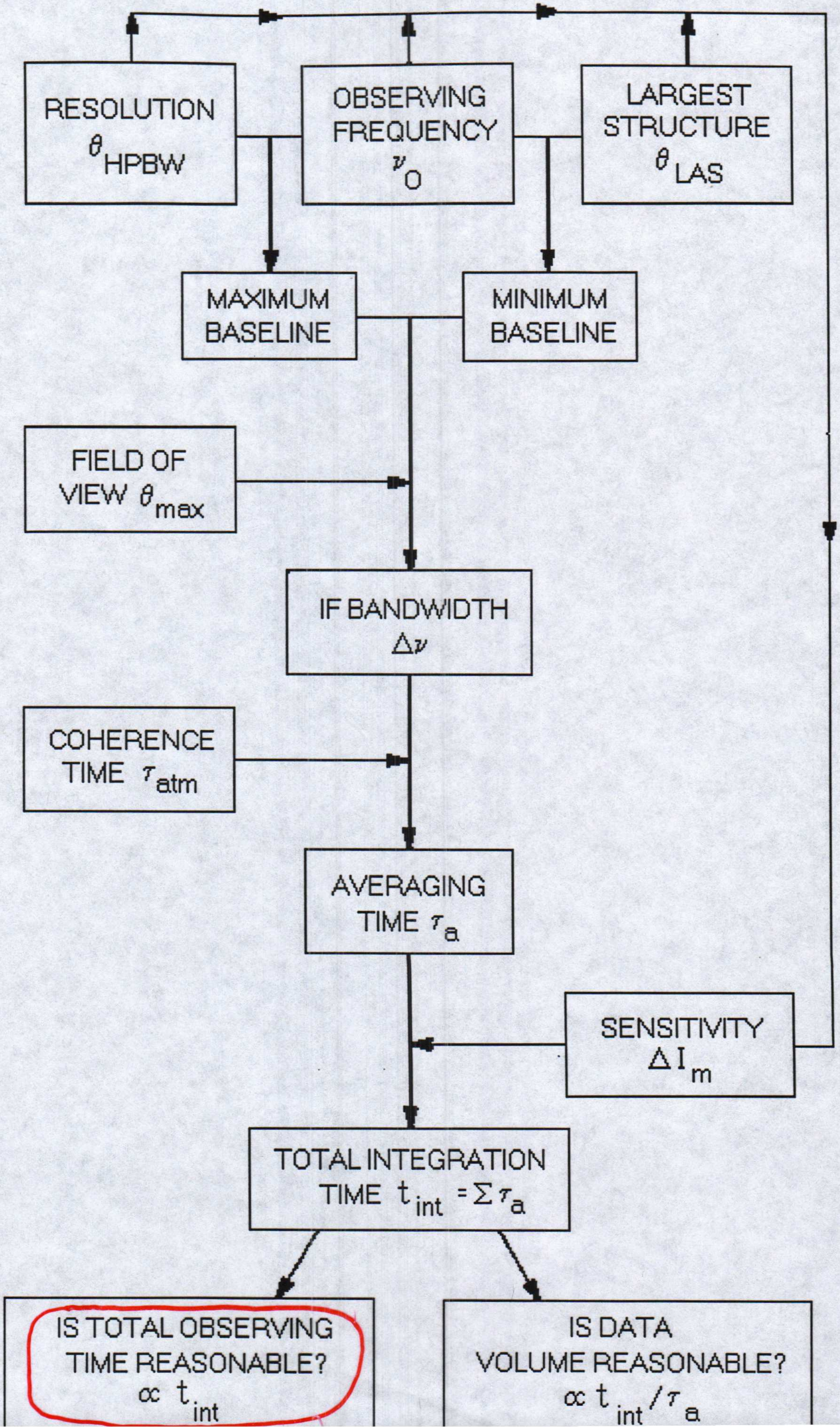
HOW LONG WILL IT TAKE

?

$t_{int} \ll 4^{hr}$ → SNAPSHOTS possible?

$t_{int} \sim 4^{hr}$ → full HA track?

$t_{int} \geq 12^{hr}$ → rethink? OR WRITE A VERY GOOD CASE IN PROPOSAL!!!


RESOLUTION θ HPBW
OBSERVING FREQUENCY ν O
LARGEST STRUCTURE θ LAS
MAXIMUM BASELINE
MINIMUM BASELINE
FIELD OF VIEW θ max
IF BANDWIDTH Δν
COHERENCE TIME τ atm
AVERAGING TIME τ a
SENSITIVITY ΔI m
TOTAL INTEGRATION TIME t int = Σ τ a
IS TOTAL OBSERVING TIME REASONABLE? ∝ t int
IS DATA VOLUME REASONABLE? ∝ t int / τ a

"SNAPSHOT" IMAGING

"Instantaneous" (1 – 5 min) coverage useful for:

many bright compact sources in shortest possible time

LIMITATIONS

1) Sensitivity (short t_{int})

2) High sidelobes of dirty beam ("snowflake")
   - → super-uniform weighting useful
   - → best in unconfused fields (high ν_0, high b)
   - → may still need to make large images

3) Limited reliable field of view / angular scale ("holes" in coverage)

4) Short programs cannot do polarization (D, χ) calibration as well as long ones
   - → may need to co-ordinate calibration with other observers

Best strategies: observe within $\pm 2^h$ of meridian
reduce with { super-uniform weight / ungridded subtraction }
AIPS: MX, IMAGR

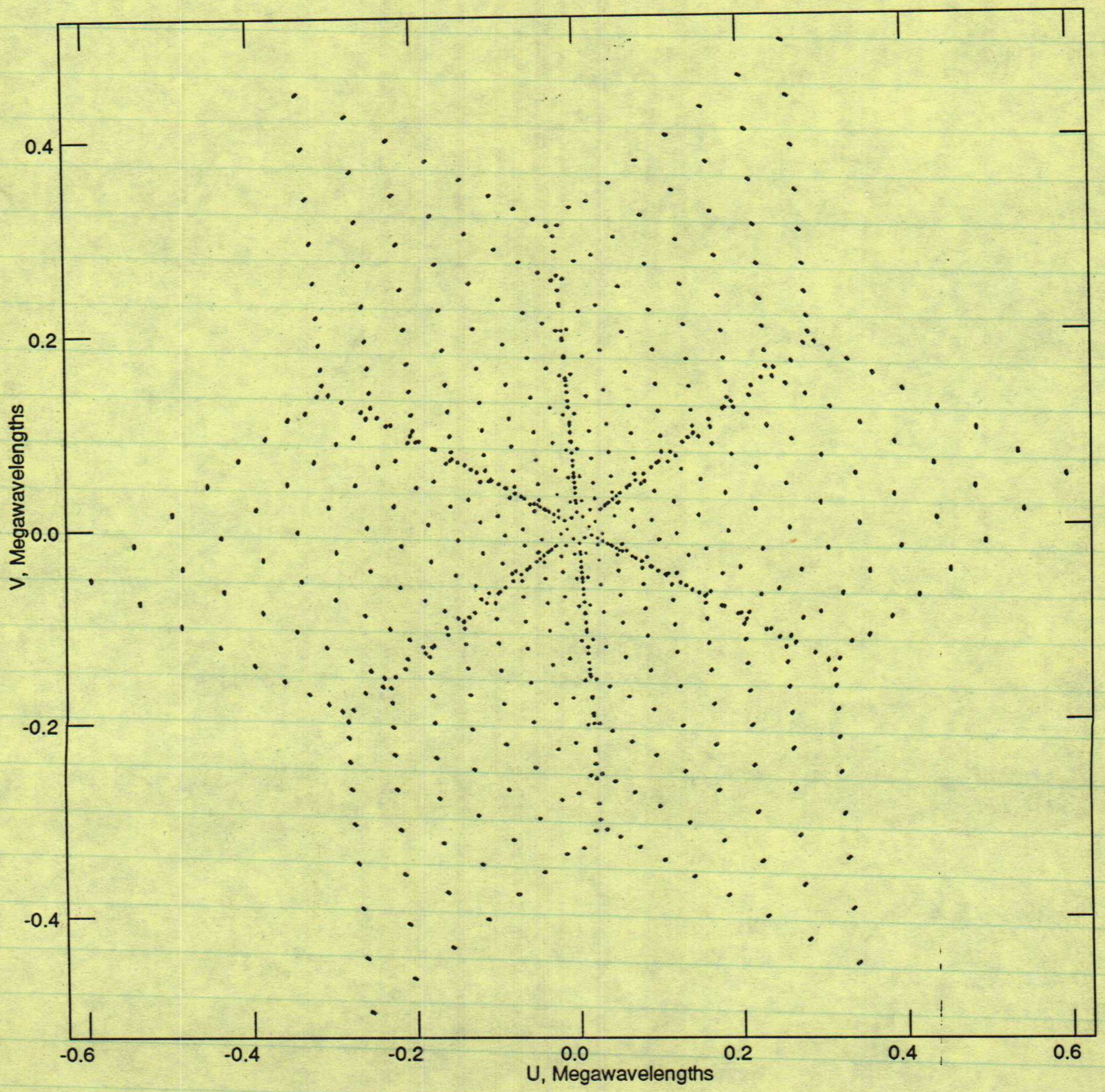


Figure 6: The u-v plane coverage at 4.9 GHz for instantaneous sampling of a source at $\delta = 30°$ and hour-angle 0^h with the VLA in the A configuration.

CONSIDER
COMBINING
SEVERAL CONFIGURATIONS
. . . .

Mixed Configurations

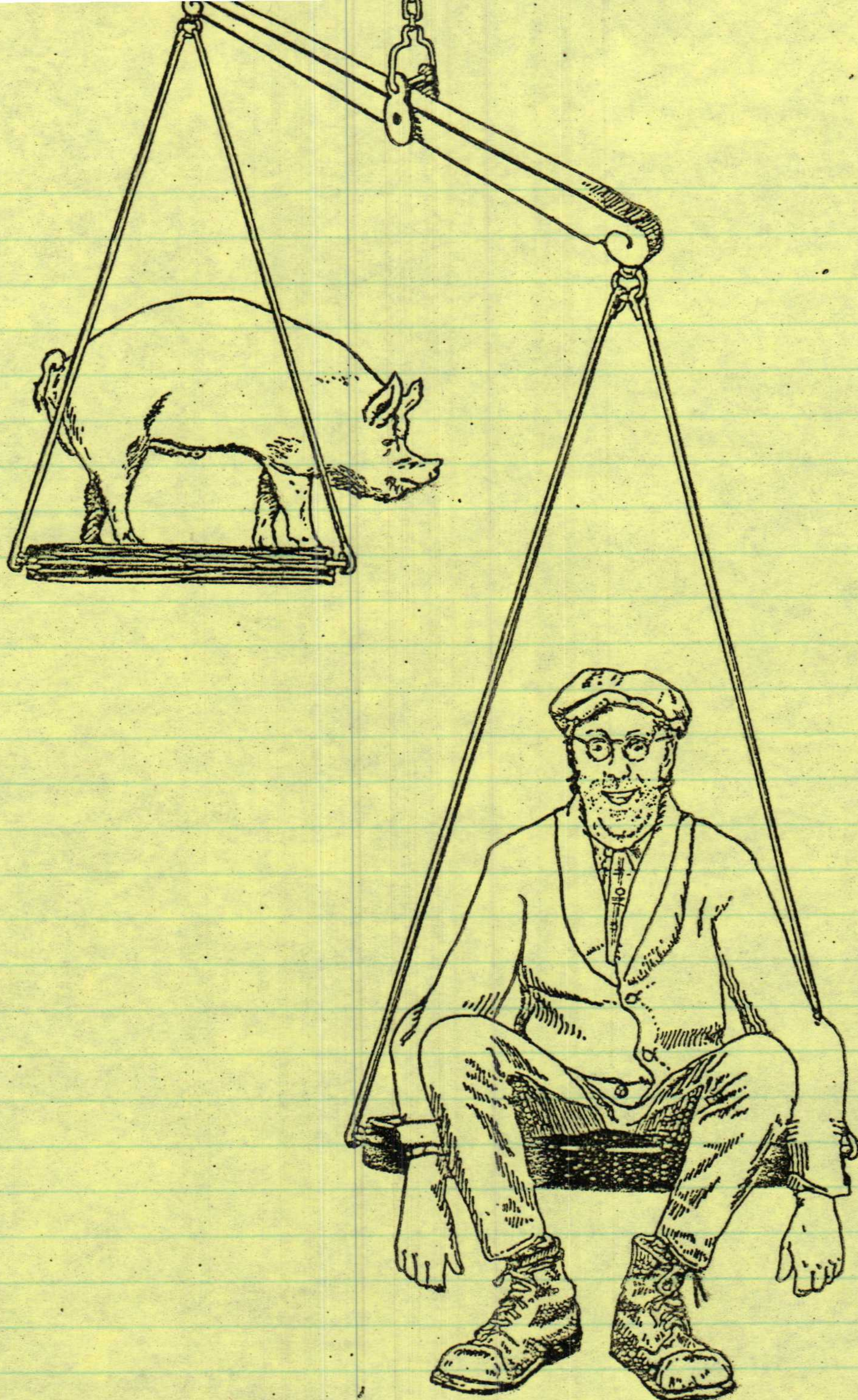
- Multiple configurations for large $\theta_{\mathrm{LAS}}/\theta_{\mathrm{HPBW}}$ (>40:1)
  - Add single-dish and mosaicing for *huge* sources? Holdaway, $\theta_{LAS} \gtrsim$ FWHM of primary beam!
- Long North Arm for $\delta < -15°$
- Sub-arrays inefficient (unless synoptic multi-ν)

Scaled Arrays

- Astrophysics → change ν_0 without changing θ_{HPBW}?
  - spectral index
  - Faraday rotation
  - depolarization
- Intervals between some VLA bands ≈ 3.3 (L→C→U)
- Ratios between VLA configurations ≈ 3.3
- Can have *similar* *u*-*v* coverage at several frequencies

⇓

helps you make images with identical restoring beams and similar sensitivities to extended / compact structures at several frequencies. GOOD!



CALIBRATION

(Reference, Self, etc.....)

What calibrations do you have to do?

Of Lecture 5 factors,

VLA hardware automates — System Temp. Correction; Round Trip Phase; Geodetic effects

VLA staff calibrate — Pointing; Baselines; Clock setup; Delays

You can calibrate
(for polarimetry) — { "Leakage" terms; Polarization position angle }
(for spectroscopy) — Bandpass (A, ϕ)

You <u>must</u> calibrate — Flux density scale; Position reference frame; Short-term { amplitudes; phases }

3C286 → Flux densities of unresolved calibrators, pol. p.a.

Unresolved calibrator(s) <u>near</u> your target source →
- position reference frame
- short-term amplitudes/phases
- leakage terms in polarization
- bandpass

Q. Should I bother with external calibration if I know I will self-calibrate my source later?

A. Generally, yes, because external calibration tells you –

(a) flux scale
(b) position scale
(c) polarization p.a. scale
(d) instrumental polarization
(e) instrumental anomalies
(f) good and bad segments of phase stability
(g) characteristic timescale of atmosphere

last three may not be obvious from weak source data, though source may still selfcal if you can "latch" parameters.

POINT SOURCE "first guess" often works, but a good subset of externally calibrated data may converge faster + avoid false symmetries

Calibration Strategy

PHASE + POSITION + AMPLITUDE — use unresolved calibrators from VLA manual (**check** for resolution nodes in your config. at your ν_0 !)

ON-CAL TIME DEPENDS ON $\Delta\nu$, CAL FLUX

FLUX DENSITY — use 3C286 or 3C48

Don't use **old** flux densities of **phase** calibrators!

Instrumental Calib.

Generally $\gtrsim 30^{min}$ cycle on **strong** source will do (but be prepared to discard data between cals if you find **phase jumps**)

Atmospheric (Troposphere / Ionosphere) Calib.

NO GUARANTEES ! Cycle time depends on array, frequency (fomelout)

Self-calibrate **if you can**

Choose strong unresolved calibrator as close to synthesis source as possible and HOPE it shows $\Delta\phi \lesssim 20^\circ$ within **and between** scans.

* Can estimate τ_{gains} for selfcal from nearby cal
make preliminary model using "good" periods.

Polarization Calib.

1. Observe 3C286 } for p.a. calibration
   3C138 } (essential)

2. Observe unresolved calibrator over
   Δ(parallactic angle) $\geq 90°$ [$\gtrsim 3$ scans]
   to → instrumental polarization (desirable)
   (synthesis calibrator may provide this data)

N.B. Both may be difficult to schedule in short snapshot programs.

3. At <2GHz, observe polarized unresolved calibrator as close to synthesis source as possible → changes in ionospheric Faraday rotation. (desirable)

Bandpass Calib. → Strong source linefree.

40—50 GHz (Q Band)

- Use short time between reference calibrators
  - Dry night-time, ~15 min
  - Bad days, need self-cal, SiO maser referencing
- Reference Pointing from 8 GHz (X Band)
  - Primary Beam only 1′
  - Update pointing (~4 min) every hour
- Measure Zenith Opacity (Tipping Scan)
  - About 10 minutes, once per run
- Only 10 antennas!

↑

Affects resolution, sensitivity calculations

No "standard configurations" yet

Consult http://www.nrao.edu/doc/vla/qband/qband_info.html

STORMY WEATHER

– and what to do about it

Thunderstorms → poor phase stability

Clear skies → ??

OBSERVE phase stability on

STRONG CALIBRATORS

LONG BASELINES

If poor ($\gtrsim 20^\circ$ between calibrators:)

1) SELFCAL LATER (if you can)

2) ADJUST TO LOWER-ν PROGRAM

3) SPEED UP CALIBRATOR CYCLE ?
(especially if calibrators near sources)

Spectroscopy Strategies

(Details where they differ from continuum case)

- *Start* by specifying frequency ν_0!
  - species, transition
  - Doppler corrections (z, motions of Earth ...)
  - check that you're in tuning range of system!
  - check for RFI (redshifted H I, galactic OH)
  - if project is ν-agile (*e.g.* H$n\alpha$), consider same instrumental parameters (sensitivity, pointing) as for continuum

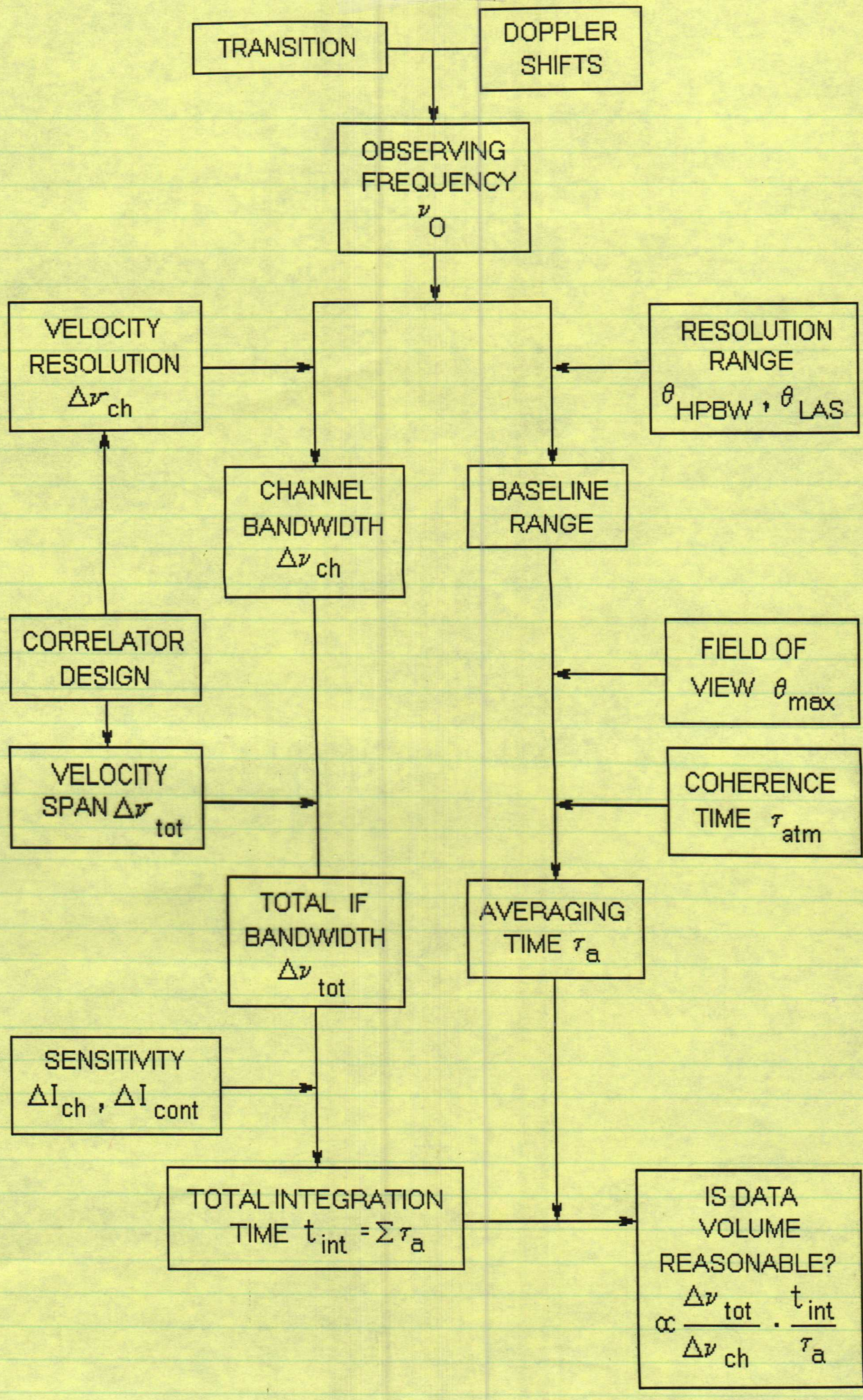
Spectroscopy Strategies, continued

There are *two* IF bandwidths to choose:

- Total $\Delta\nu_{\rm tot}$ across all channels Brinks, Uson
  - Consider total velocity range needed
  - Consider need for line-free channels
- Individual channel $\Delta\nu_{\rm ch}$
  - Sets velocity *resolution*
  - Usually sets bandwidth smearing → small for individual channels! $\Delta\nu/\nu_0 \sim \Delta v/c$ Uson
  - Coupled to $\Delta\nu_{\rm tot}$ via correlator design Brinks

Spectroscopy Strategies, continued

- Averaging time τ_a
  - No longer compare with bandwidth smearing!
  - Evaluate from time-average smearing alone
  - Consider dataset size ($\propto t_{int}/\tau_a$)
- Total integration time t_{int} Brinks, Uson
  - Consider sensitivity per line channel $\Delta\nu_{ch}$
  - Continuum sensitivity in line-free channels?
  - Narrow $\Delta\nu_{ch}$ may $\rightarrow$ *long* t_{int}!
- Night-time astronomy? Brinks
  - compact arrays + narrow $\Delta\nu_{ch}$ $\rightarrow$ more problems with far-out sidelobe responses to strong sources, *e.g.*, active Sun.


TRANSITION
DOPPLER SHIFTS
OBSERVING FREQUENCY ν_0
VELOCITY RESOLUTION Δv_{ch}
RESOLUTION RANGE θ_{HPBW}, θ_{LAS}
CHANNEL BANDWIDTH $\Delta\nu_{ch}$
BASELINE RANGE
CORRELATOR DESIGN
FIELD OF VIEW θ_{max}
VELOCITY SPAN Δv_{tot}
COHERENCE TIME τ_{atm}
TOTAL IF BANDWIDTH $\Delta\nu_{tot}$
AVERAGING TIME τ_a
SENSITIVITY ΔI_{ch}, ΔI_{cont}
TOTAL INTEGRATION TIME $t_{int} = \Sigma\tau_a$
IS DATA VOLUME REASONABLE?
$\propto \frac{\Delta\nu_{tot}}{\Delta\nu_{ch}} \cdot \frac{t_{int}}{\tau_a}$

HINTS FOR PROPOSERS

1. Write concisely
2. Check catalog of VLA observations before writing in detail. (VLASORS)
3. Justify choices { CONFIGURATION, FREQUENCY, TOTAL TIME, etc
4. Think about observing and calibration strategy <u>before</u> submitting. ALLOW CALIBRATION <u>TIME</u> $\gtrsim 10\%$!
5. Submit before deadline for first configuration needed

Table 19–11 Near Term VLA Proposal Deadlines		
Observing Dates	Config	Proposal Deadline
19 Jan 1996 - 05 Feb 1996	CnB	01 Oct 1995
09 Feb 1996 - 15 Apr 1996	C	01 Oct 1995
26 Apr 1996 - 27 May 1996	DnC	01 Feb 1996
31 May 1996 - 02 Sep 1996	D	01 Feb 1996
late Sep 1996 - 02 Dec 1996	A	01 Jun 1996
mid Dec 1996 - 30 Dec 1996	BnA	01 Oct 1996

Resources for VLA Proposal Planning

- VLA WWW Home Page
  - http://www.nrao.edu/doc/vla/html/VLA.html

    NRAO Home
  - VLA Observational Status Summary
  - observation archive indexes
  - recent L Band interference plots
  - up-to-date Q Band information
  - proposal submission information
- Observation planning software available by ftp:
  - VLAPLAN
  - VLASORS
  - OBSERVE

VLAPLAN

- "This lecture in software"
- MS-DOS spreadsheet-like program
- you input imaging requirements
- it recommends VLA configurations
- it warns of parameter conflicts
- it advises how to resolve conflicts
- shows context-sensitive graphs
  - bandwidth smearing
  - time-average smearing
  - primary beam
  - visibility-baseline plots

Now ftp from `ftp.aoc.nrao.edu` in `/pub/vlaplan`.
Read `vlaplan2.doc` first.
Can access via VLA WWW Page mid-June 1995.

VLASORS

- MS-DOS database and query program
- contains VLA Calibrator List
- contains VLA observation archives (listing, not the data!)

Now ftp from `ftp.aoc.nrao.edu` in `/pub/vlasors`.
Read `read.me` first.

OBSERVE

- The actual VLA schedule preparer
- Sun/IBM Unix systems
- Contains VLA Calibrator List
- Models on-line system accurately
- Can use to model exact calibration overhead
- Check drive times, limits, shadowing, etc.
- Check parallactic angle coverage
- **Some familiarization time required!!**

Now ftp from `ftp.aoc.nrao.edu` in `/pub/observe`.