The ATCA as a Millimetre Interferometer

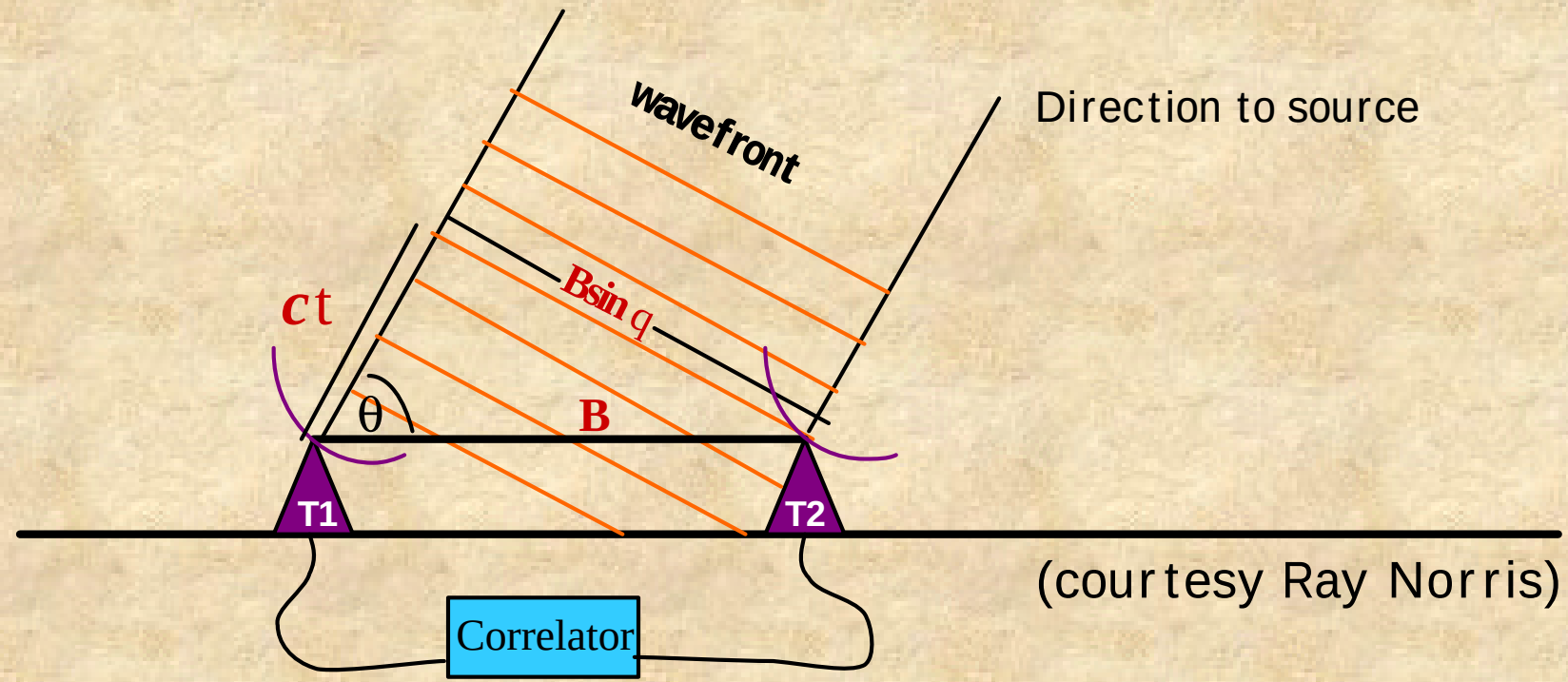
Tony Wong, ATNF

Melbourne Workshop

29 Nov 2001

Radio interferometry

- **An interferometers measures coherence in the electric field between pairs of points (baselines).**

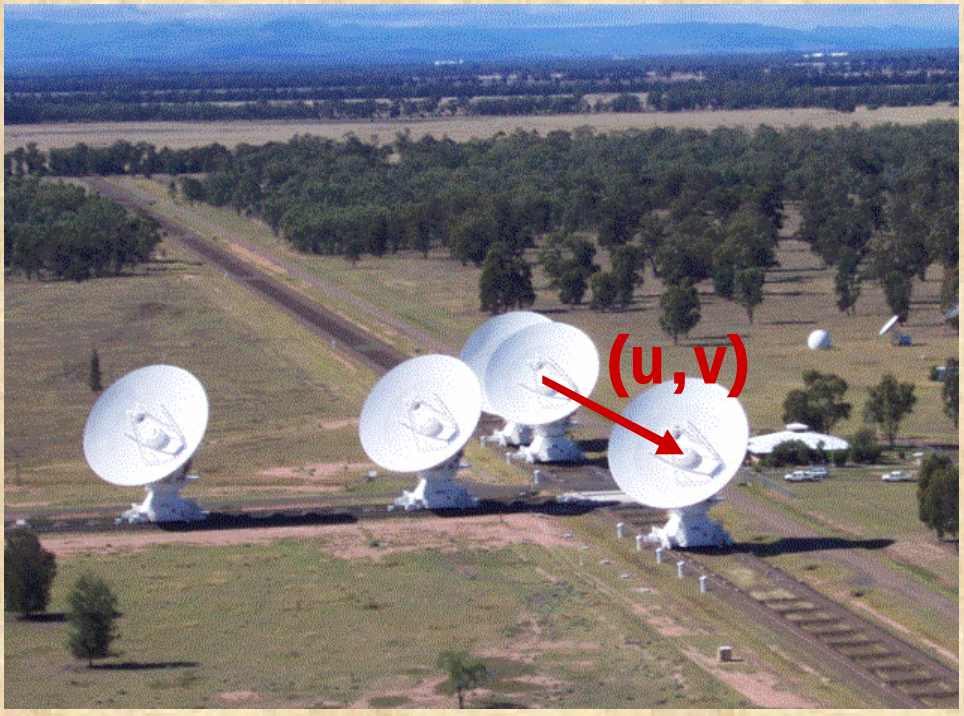


(courtesy Ray Norris)

- **Incoming signals are corrected for geometric delay t and multiplied to yield a complex visibility, $V = |V|e^{if}$, which has an amplitude and phase.**

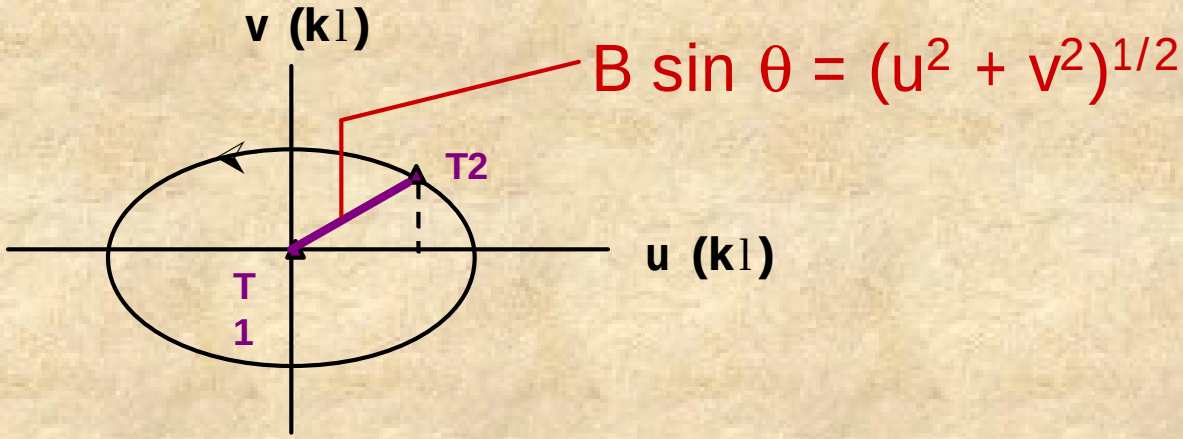
Radio interferometry

- The projection of a baseline onto the plane normal to the source direction defines a vector in (u,v) space, measured in wavelength units.



Radio interferometry

- **As the source moves across the sky (due to Earth's rotation), the baseline vector traces part of an ellipse in the (u,v) plane.**



- **Can take advantage of Earth's rotation to measure visibility in different parts of the (u,v) plane.**

Radio interferometry

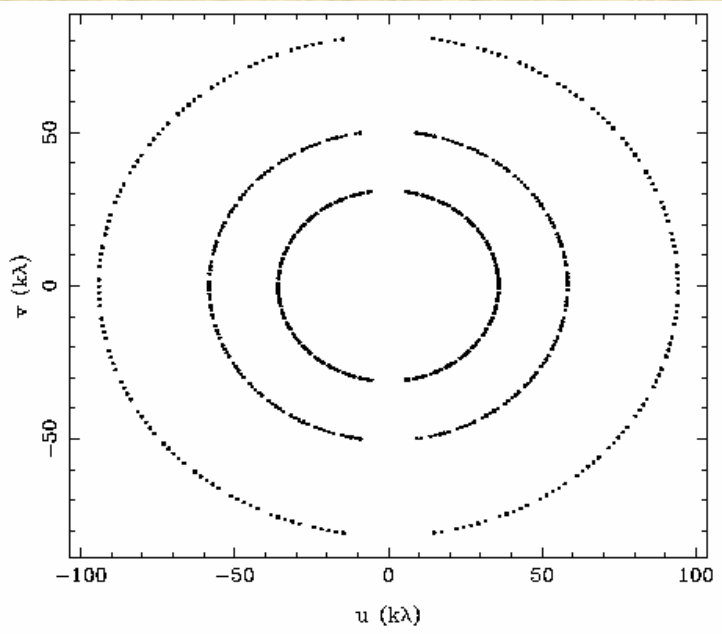
- **The Fourier transform of the complex visibility with respect to (u,v) gives the sky intensity distribution.**
- **Angular resolution of the map q_{syn} is determined by the longest baseline $|u_{max}|$:**

$$q_{syn} \sim \lambda / B_{max} \sim 1/|u_{max}|$$

- **At λ =21 cm, max. baseline of 3 km Þ u_{max} of 14000 Þ q_{syn} = 14".**
- **At λ =3 mm, max. baseline of 3 km Þ u_{max} of 10^6 Þ q_{syn} = 0.2".**
- **Going to higher frequencies allows higher angular resolution to be achieved with the same telescope!**

Radio interferometry

- **An accurate image requires that the visibility be measured at many points in the (u,v) plane.**



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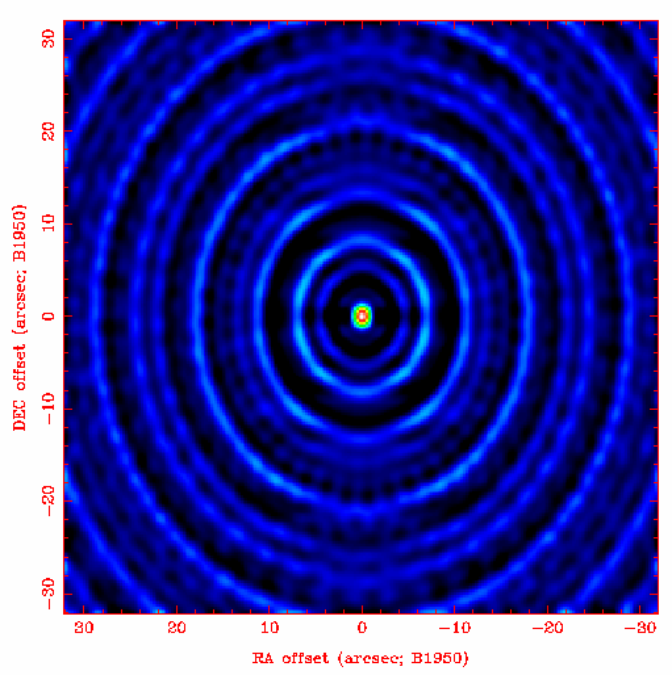

Point source imaged with 3 antennas (3 baselines)

Radio interferometry

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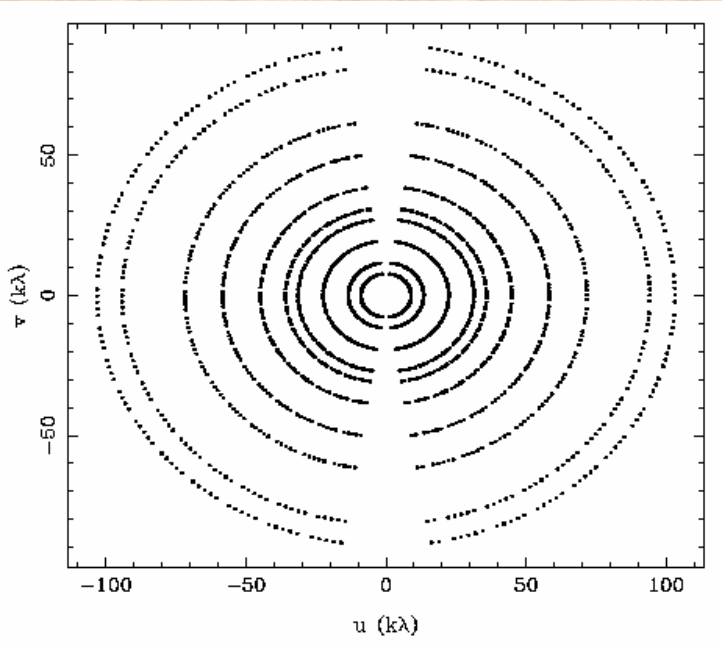

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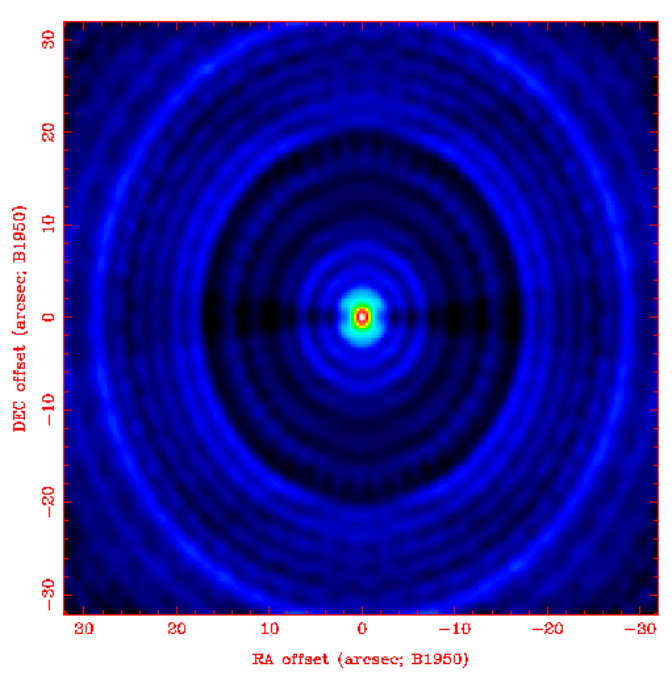


Point source imaged with 5 antennas (10 baselines)

Millimetre interferometry

Millimetre interferometry poses special challenges:

1. **Significant atmospheric opacity, much of which is due to H_2O vapor (and is hence variable).**
2. **Fluctuations in H_2O vapor content above the antennas produce atmospheric phase noise that increases with baseline length & with frequency.**
3. **Instrumental requirements (e.g. surface, pointing, baseline accuracy) become more severe.**
4. **Need more bandwidth to cover same velocity range:**

$$1\ \mathrm{MHz} \approx \lambda_{mm}\ \mathrm{km\ s^{-1}}$$

Australia Telescope Compact Array

- Six 22m antennas near Narrabri, five movable on a 3 km E-W track.
- National Facility open to proposers worldwide.
- Operates from 1-10 GHz, but was designed to allow operation at high (>10 GHz) frequencies.
- 3mm (85-105 GHz) and 12mm (16-25 GHz) upgrades in progress; provision for 7mm (35-50 GHz) upgrade.

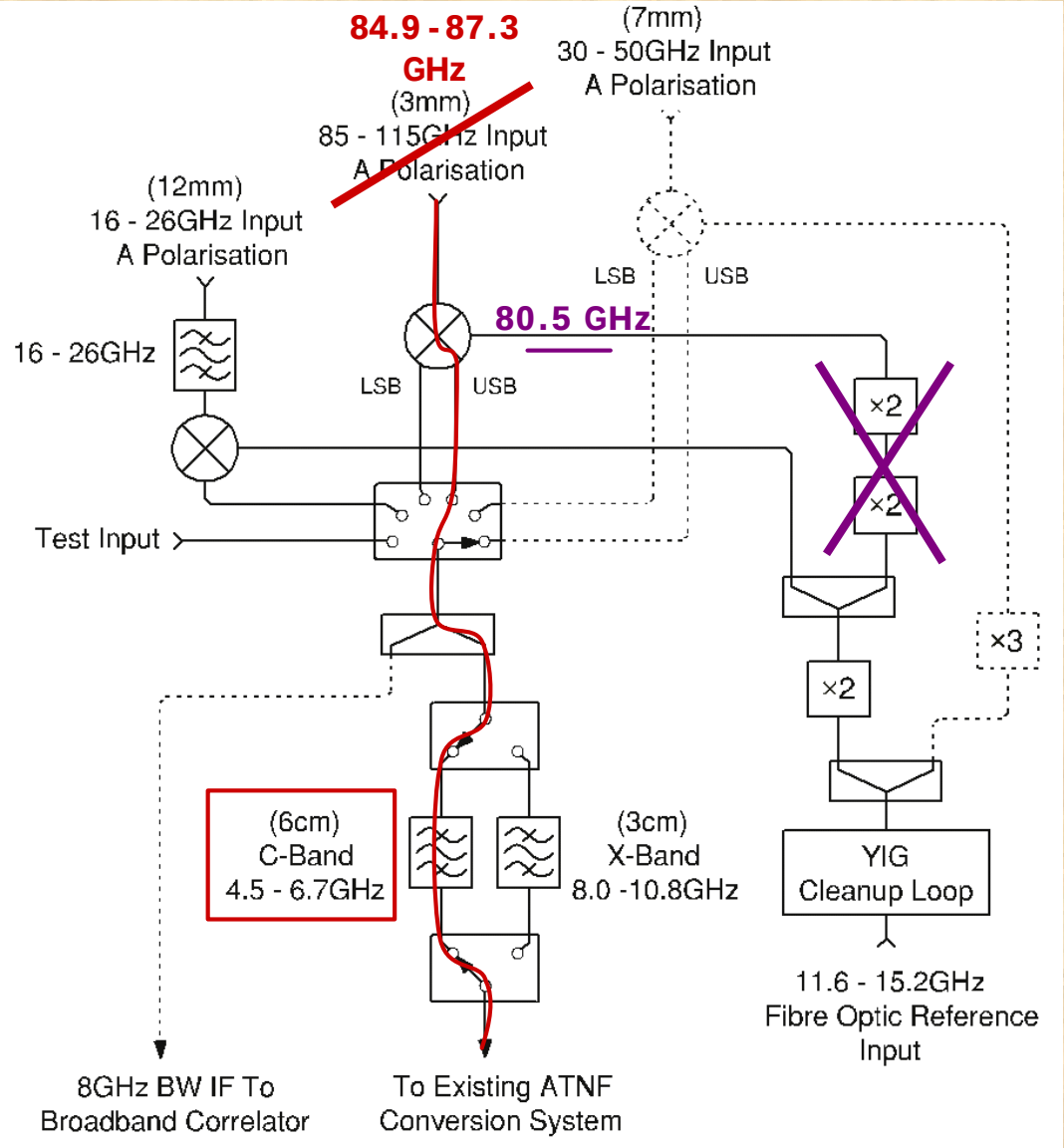
Timeline of the 3mm Upgrade

- **1988:** Official opening of ATCA.
- **1996:** Australian Gov't announces funding for high-frequency upgrade under Major National Research Facilities (MNRF) program.
- **1998:** Official launch; construction of N-S track begun.
- **1999:** Solid panels installed to increase usable surface from 15m diameter to 22m.
- **2000 Nov:** First fringes on 1-baseline system!
- **2001 Sep:** 3-baseline system in operation.
- **mid-2002:** First configurations including N-S track.
- **mid-2003:** Expected completion of 5-element system.

Receiver Technology

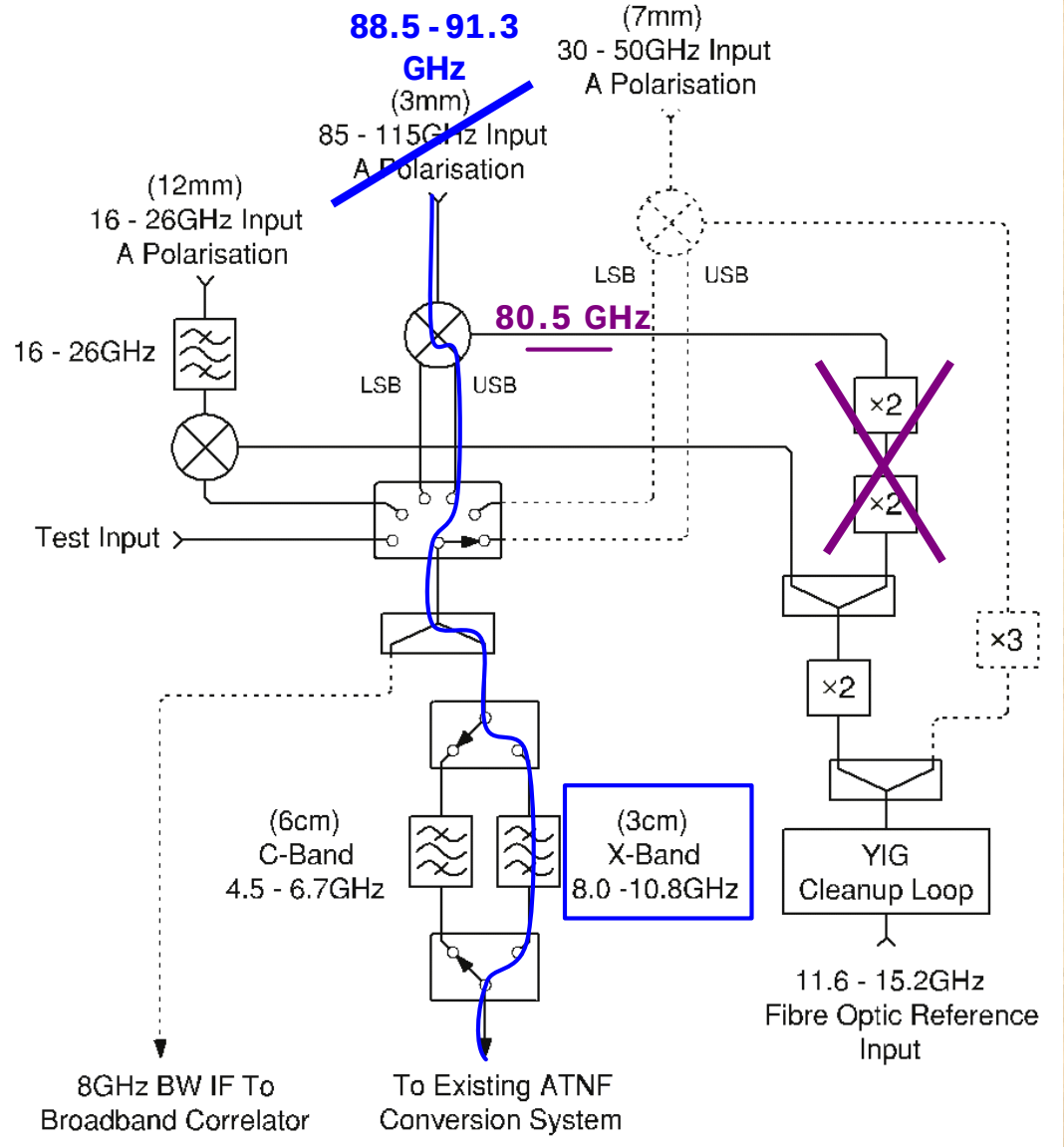
- Indium phosphide (InP) HEMT MMIC amplifiers cooled to ~20 K.
- Other mm arrays use SIS mixers, which can achieve lower noise but must be cooled to 4 K.
- Since most signal processing is best done at low frequencies (<1 GHz), signal must be "mixed down" to an intermediate freq.
- SIS design: first mix down to a low frequency, then amplify.
- MMIC design: first amplify, then mix down.

3mm Receiver System



- **At present, the tuning range is limited since we are using a fixed frequency LO at 80.5055 GHz.**
- **The sky frequency range is 84.9-87.3 GHz using the C-band filter module or 88.5-91.3 GHz using the X-band module.**

3mm Receiver System



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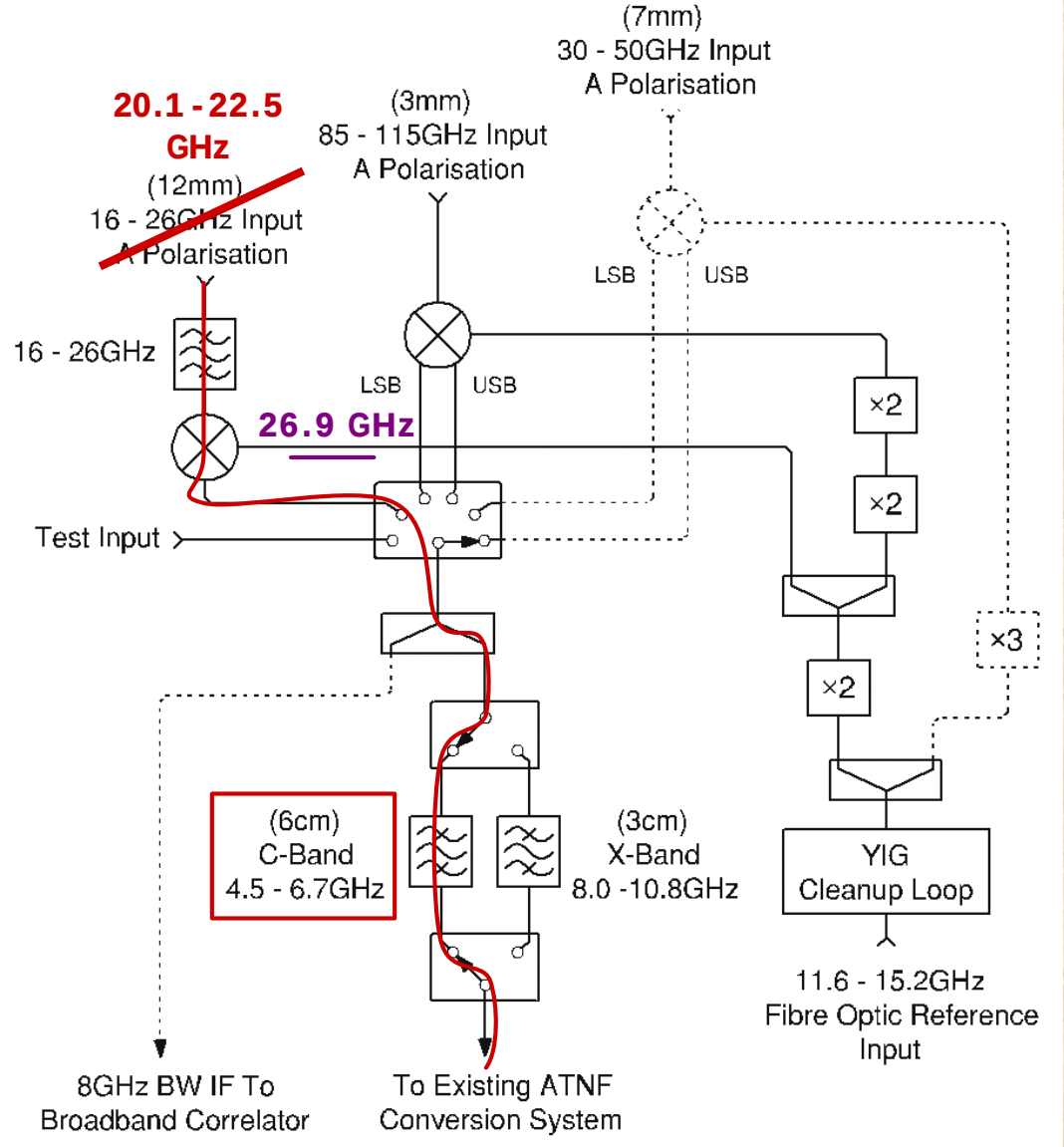
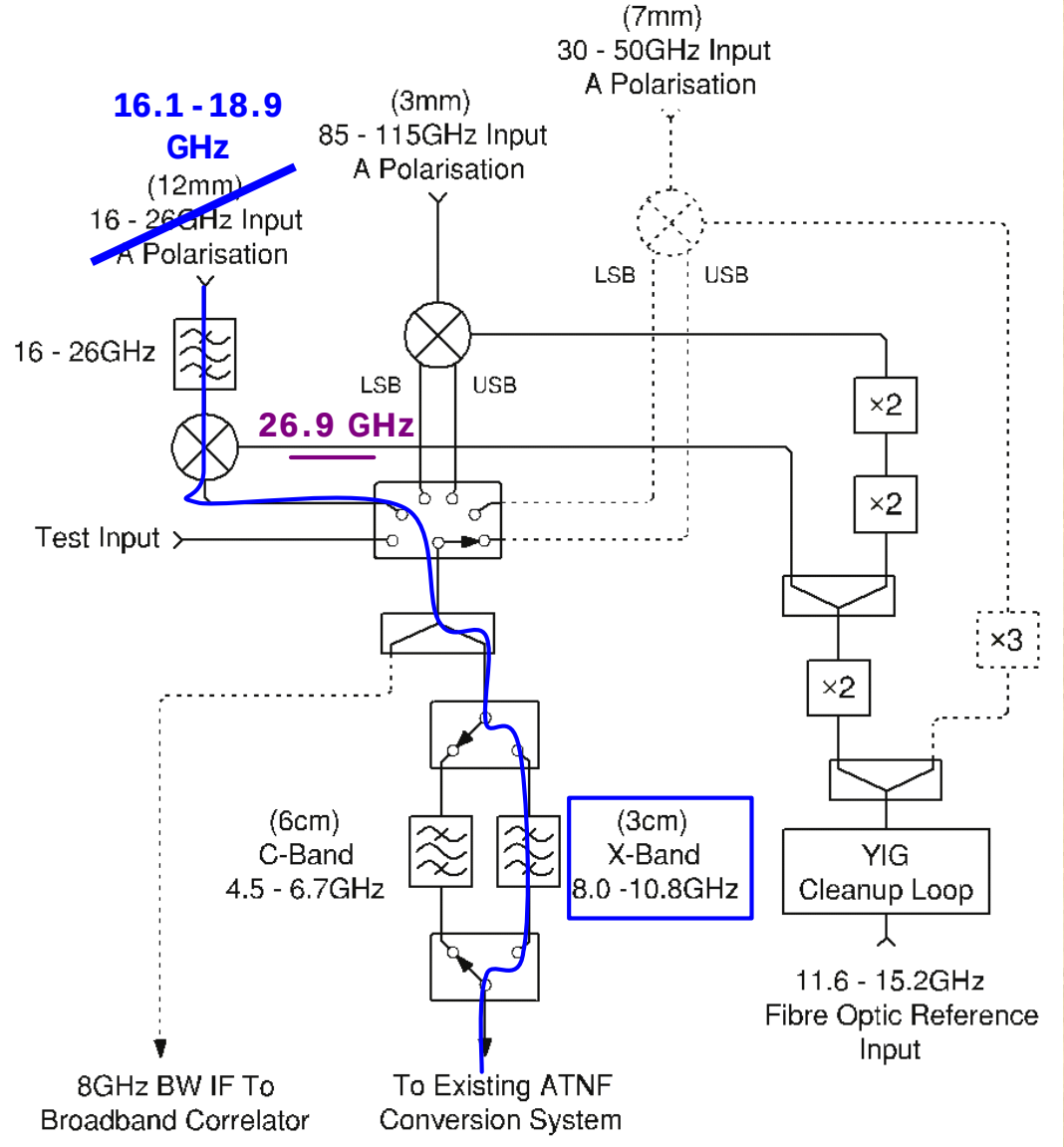
12mm Receiver System



- **The 12mm system is similarly limited to two frequency bands of 16.1-18.9 GHz and 20.1-22.5 GHz.**
- **The LO frequency is fixed at 26.8885 GHz.**

12mm Receiver System



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“Final” 3mm System

- Frequency coverage of 85-105 GHz (with possible high-frequency extension to 110 or 115 GHz).
- Five antennas, max. baseline 3 km, some antennas stationed on N-S arm.
- Dual linear polarisation on all receivers.
- High-frequency LO reference (11.6-15.2 GHz) to be distributed via optical fiber, providing LO signal from 96-104 GHz (8x).
- Wide bandwidth (2 GHz) correlator (talk by W. Wilson)
- Phase correction via water vapour radiometry at 22 GHz (talk by R. Sault)

Comparison with other mm arrays

Array	Total Area (m^2)	Altitude (km)	SSB Tsys @ 90 GHz	h_a	Freq. range (GHz)	Pol	Max. BW (GHz)	Max. Bsln (km)	Line sens. (mJy)	Cont. sens. (mJy)
BIMA (10*6.1m)	290	1.0	150	0.7	70-115, 210-270	1	0.8	1.5	23	1.4
OVRO (6*10.4m)	510	1.2	300	0.7	86-116, 210-270	1	1.0 [2.0]	0.2-0.4	23	1.5 [1.1]
NMA (6*10m)	470	1.3	400	0.65	85-116, 126-152, 213-237	1	1.0	0.4	43	2.4
IRAM PdB (5[6]*15m)	880 [1060]	2.6	150	0.7	80-115, 210-250	1	0.5	0.4	8.2 [6.7]	0.63 [0.5]
ATCA (5*22m)	1900	0.2	250	0.4	85-105	2	0.2 [2.0]	3.0	7.9	1.0 [0.3]

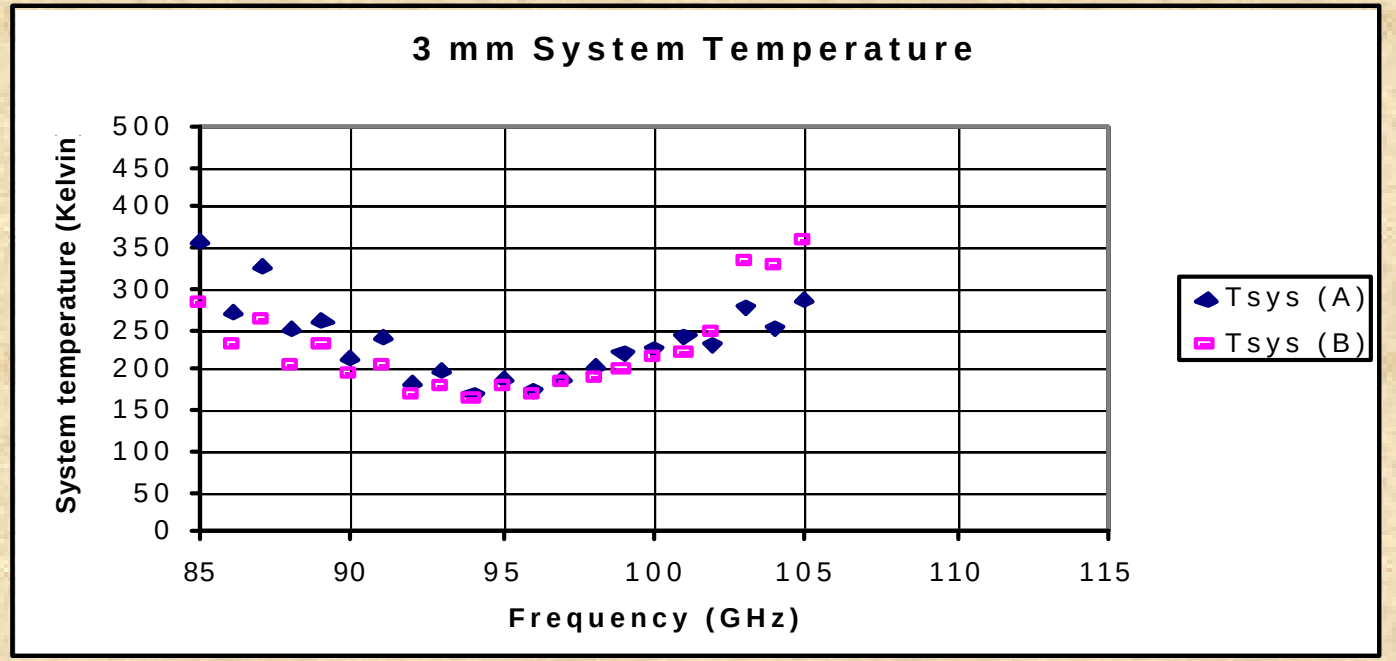
Sensitivity estimates are for 1 hr integration at 90 GHz, all pols. combined.
Line sensitivity is for a 10 km/s channel.
Actual sensitivity will depend on atmospheric phase.

Current System Performance

System Temperature

- **Calibration of the visibility amplitude is typically performed by comparing it with the system temperature, the equivalent noise temperature presented to the detector:**

$$T_{sys} \approx T_{rec} + T_{sky} = T_{rec} + T_{atm}(1-e^{-t})$$



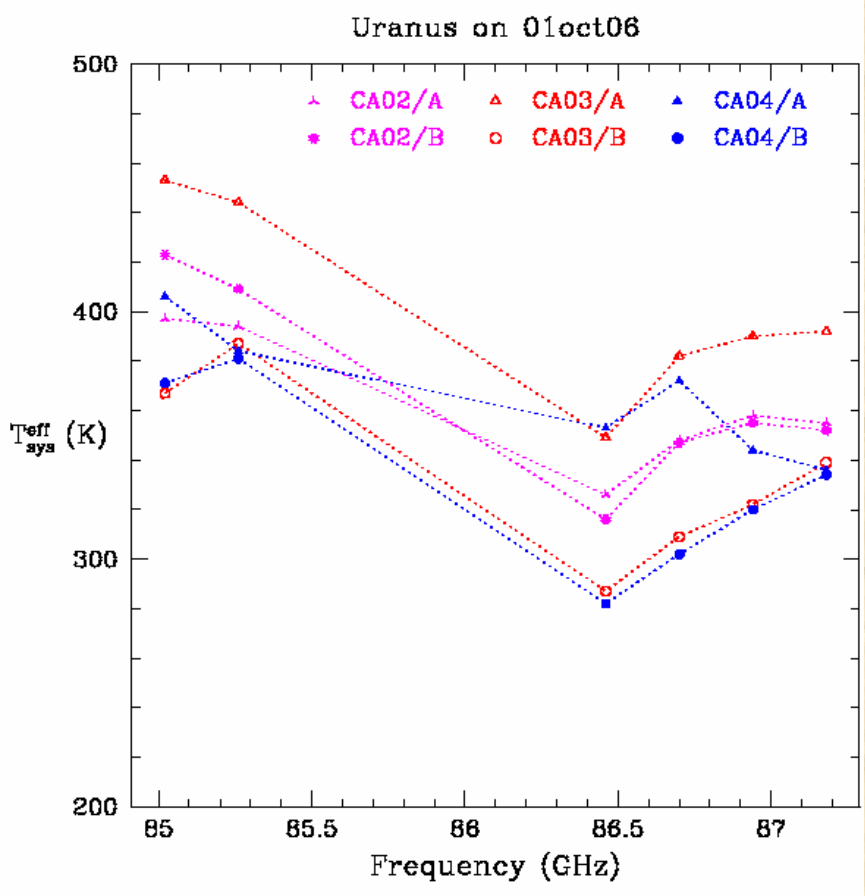
System Temperature

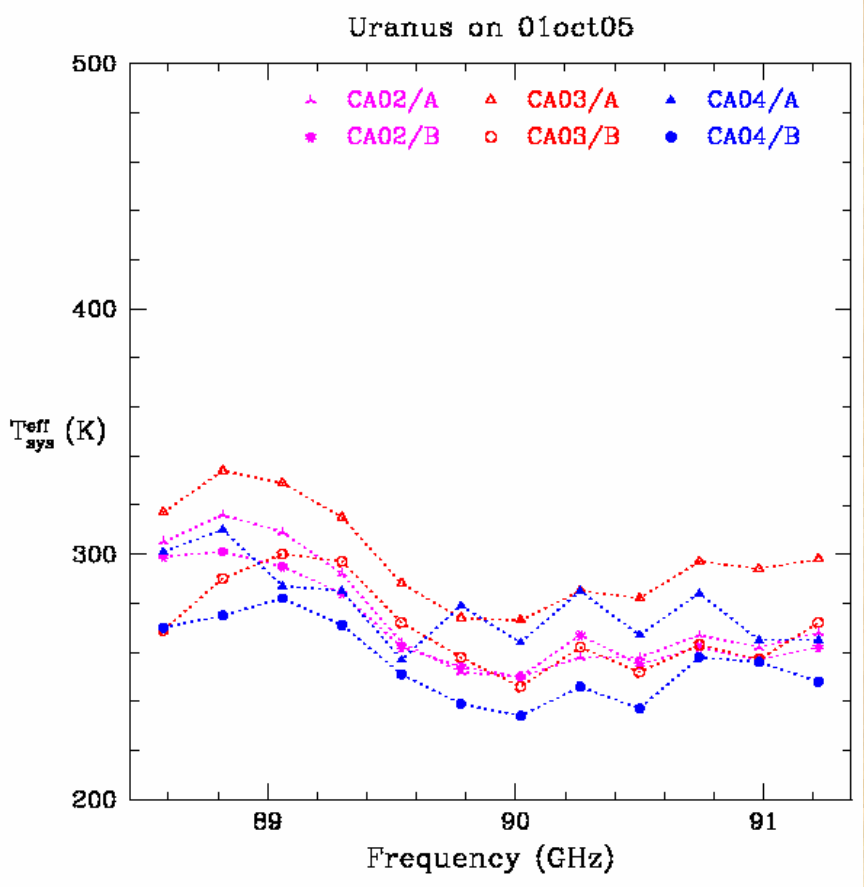
- However, T_{sys} does not take into account atmospheric absorption, which can strongly attenuate the true signal.
- The effective system temperature (taking this into account) can be estimated using the chopper wheel method.

$$T_{sys,eff} = T_{sys}\ e^{t}$$

- Currently, paddle measurements cannot be scheduled in advance, but must be made interactively. This should change by mid-2002.

System Temperature

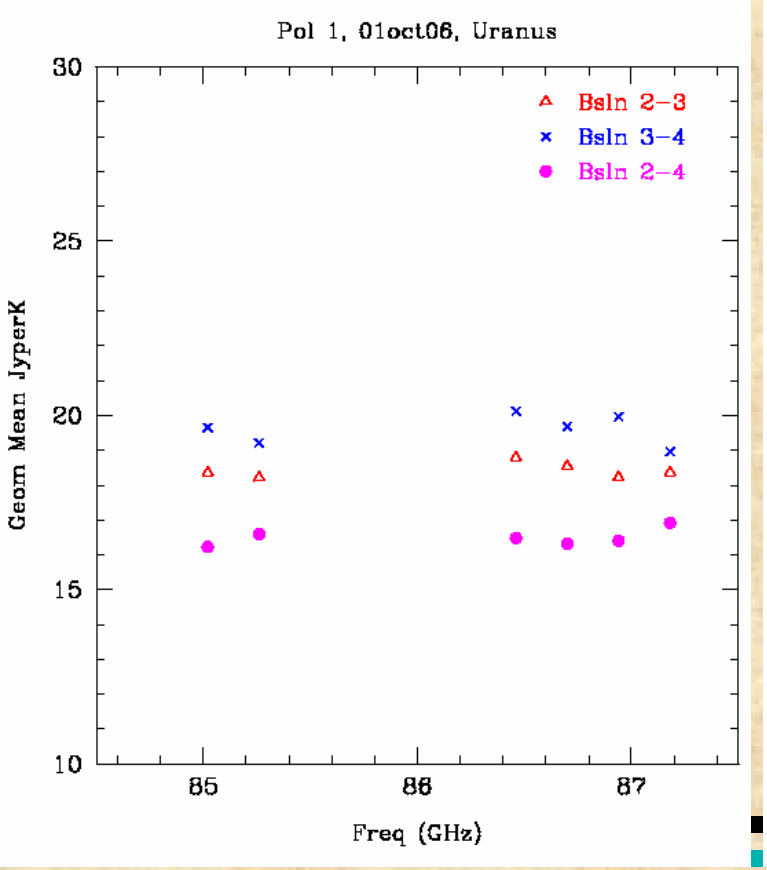


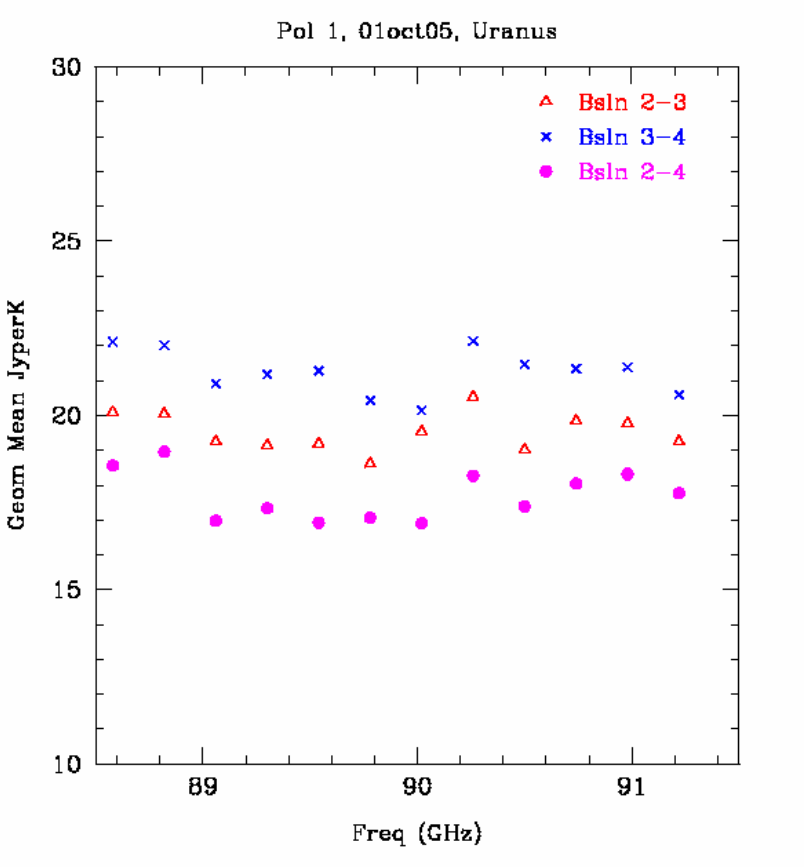


$T_{sys,eff}$ **measured in good nighttime weather.**

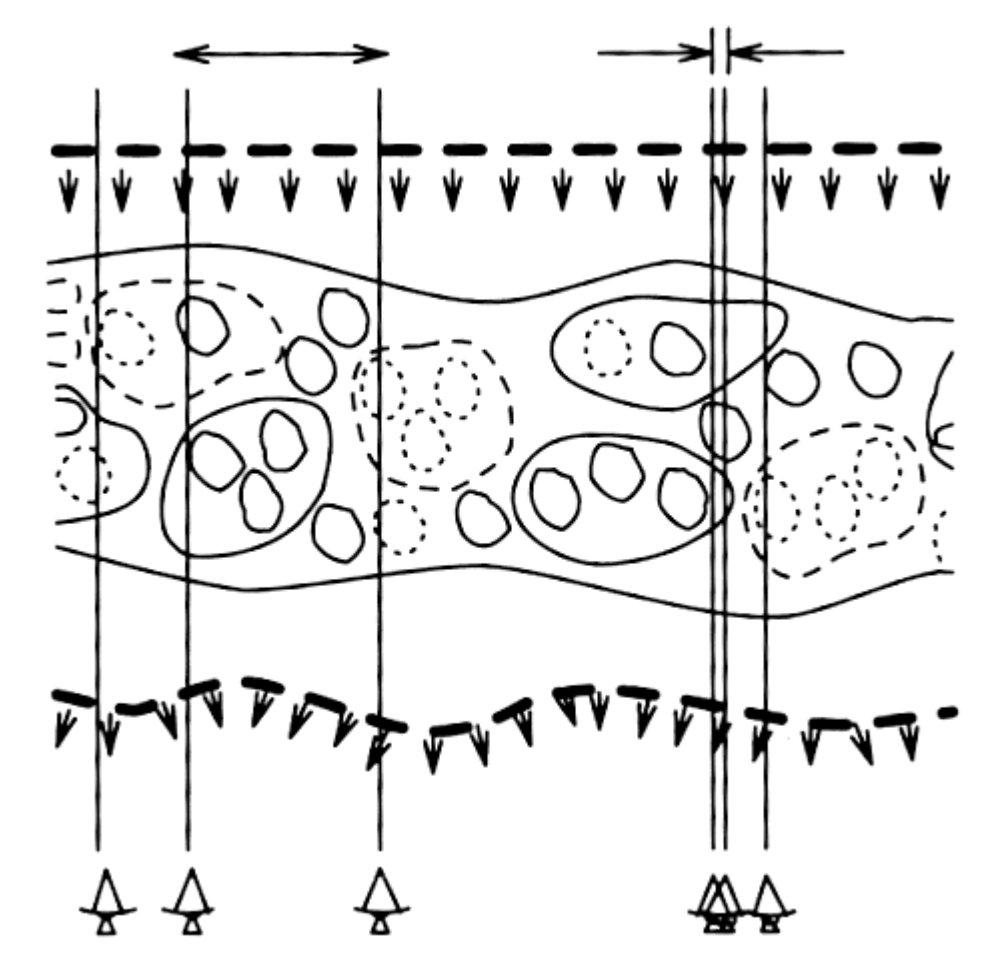
Antenna Sensitivity

- For a source of known flux, the measured **amplitude** and $T_{sys,eff}$ can be used to estimate the sensitivity.
- **18 Jy/K** corresponds to an aperture efficiency of **0.4** (i.e., 40% of total dish area is effectively in use).





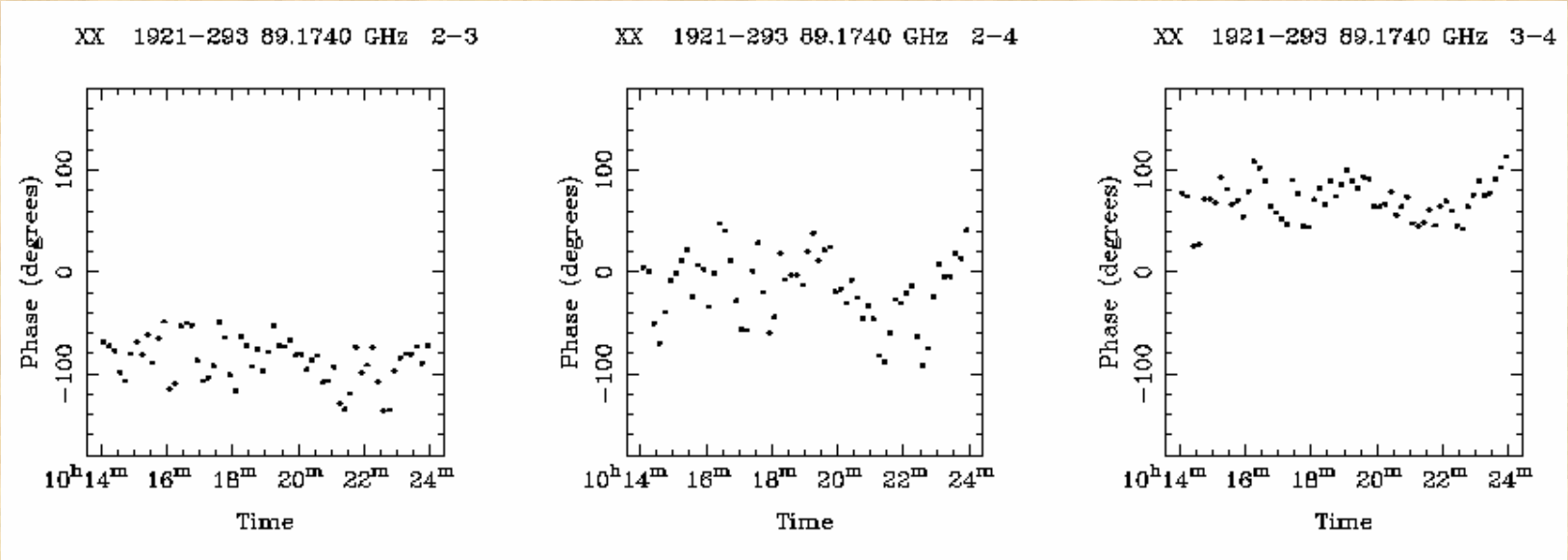
Phase Stability



Desai 1998

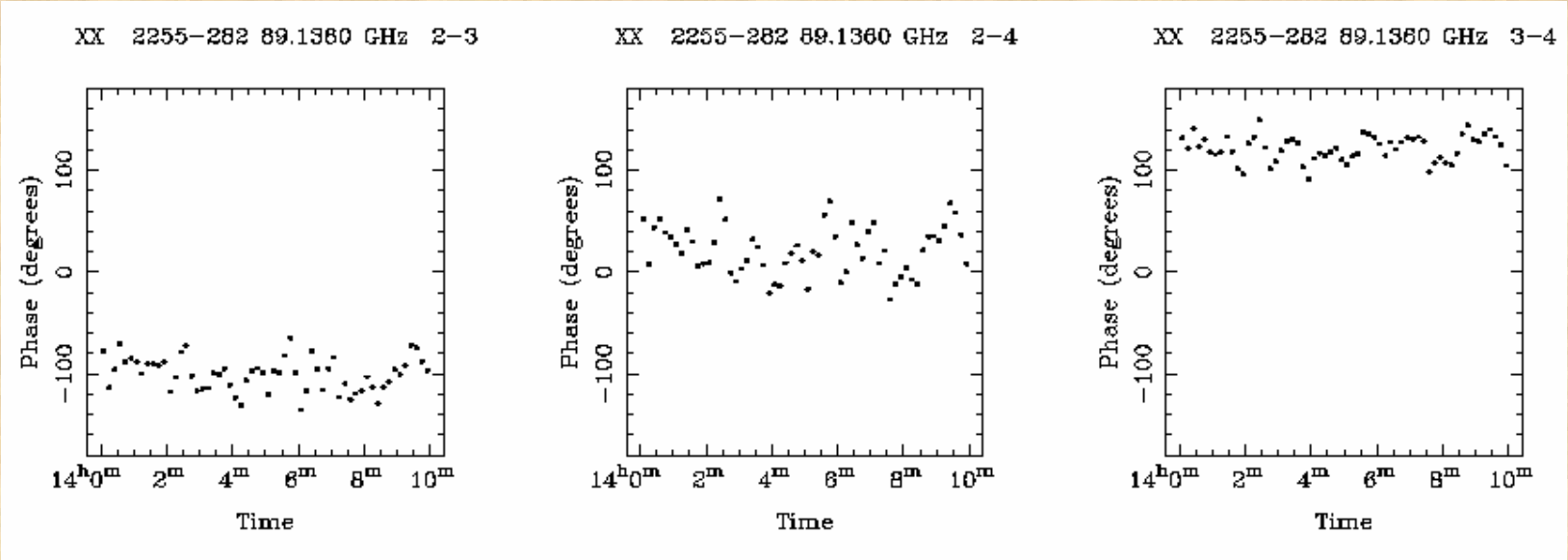
Changes in refractive index of atmosphere due to precipitable water vapor (PWV) lead to "corrugations" in wavefront of an incoming plane wave.

Clear Night, 8pm local time



B:	75m	120m	45m
f_{rms}:	22°	34°	19°

4 hours later (midnight)



B:	75m	120m	45m
f_{rms}:	22°	34°	19°
f_{rms}:	16°	24°	13°

Phase Stability

- **Effect of phase noise on a visibility measurement can be expressed as**

$$\langle V \rangle / V_0 = \exp\left(-\, f_{rms}^2 / 2\right)$$

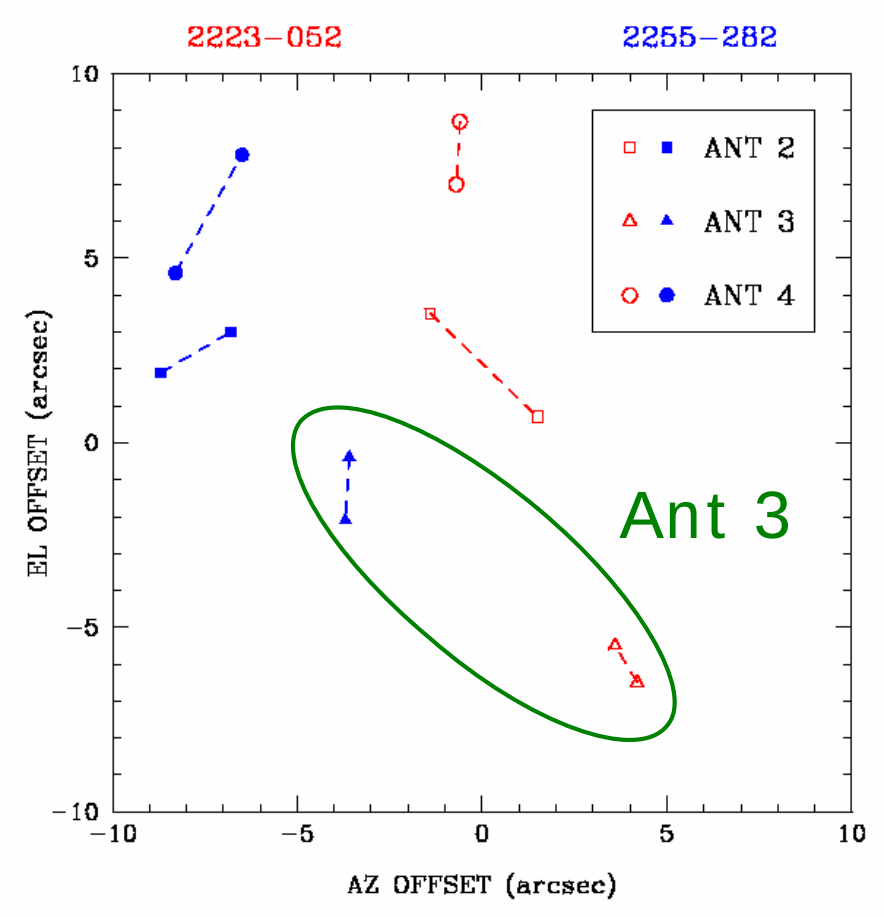
where f_{rms} is the RMS phase variation during the averaging time, and V_0 is the true amplitude.

- **For f_{rms}=30º (280 mm), $\langle V \rangle / V_0$=0.87 and the visibility amplitude will be reduced by 13% due to phase noise (also called decorrelation).**

- **Thus, f_{rms} (a fn of weather, freq, baseline length) determines how long you can go between phase calibrator observations ® may need to calibrate every few minutes ("fast switching").**

Antenna Pointing

For mosaicing, want typical pointing error $\Delta q < 0.05 q_B$ (14% amplitude error at half power point). Thus need ~2" pointing accuracy at ATCA (HPBW 30"–40")!



"Pointing up" on bright source:

Recent tests show that pointing solution on a given source can change by 1"-4" in 15 min., while pointing on a different source 24° away can change the solution by 8" or more!

Some Words of Advice

- Calibrate the phase often enough so that f_{rms} is less than 30º over the calibration interval.
- You may be better off pointing on a weaker, nearby point source than on a brighter, more distant source.
- Regularly observing a "test" quasar, in addition to your phase calibrator, provides a useful diagnostic of how good your phase calibration really is.
- Check the 3mm webpages often: http://www.atnf.csiro.au/people/twong/3mmguide

Questions to Consider

1. What new science could be done with observations of polarised emission?
2. What is the priority for imaging sources at moderate (0 > d > –45º) declinations?
3. What is the priority for extending the frequency coverage to 110 GHz? 115 GHz?
4. What is the priority for observing compact sources (<15”) vs. extended sources?
5. What steps can be taken to coordinate quasar flux measurements between different mm arrays?

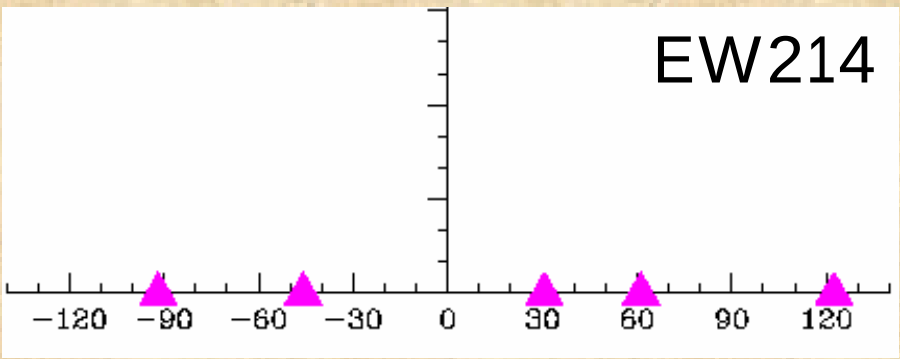
Parting Thoughts

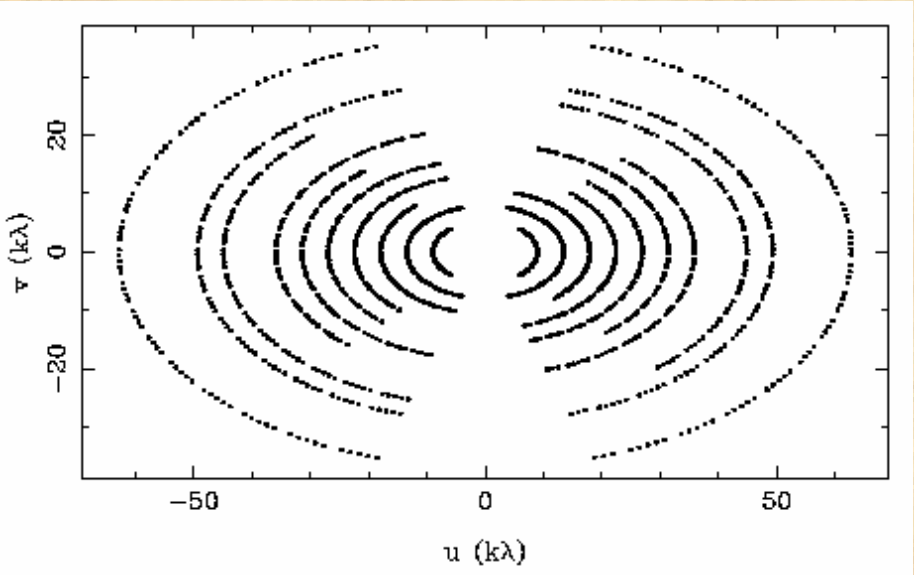
- **Speakers: Please make sure you've given us copies of your viewgraphs/powerpoint. (Conference summary to be published in PASA).**
- **Next ATCA proposal deadline 15 Feb for observing season May-Aug 2002.**
- **3mm/12mm proposals must have ATNF collaborator.**
- **Next mm workshop, probably focused on observing techniques and results, in a year's time (probably in Sydney).**
- **Thanks to Andrew Melatos, students & staff of U. Melbourne!**

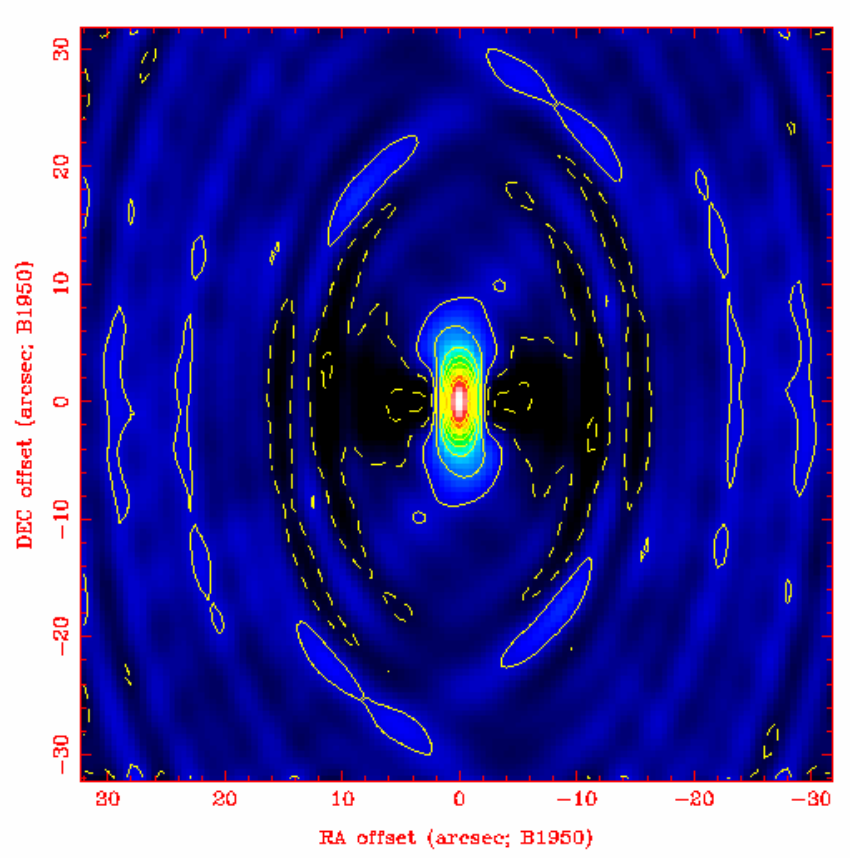
Future Considerations

Baseline Coverage

- **Existing E-W configurations not well-suited for mm obs, which must be done at low airmass (elev > 30°).**



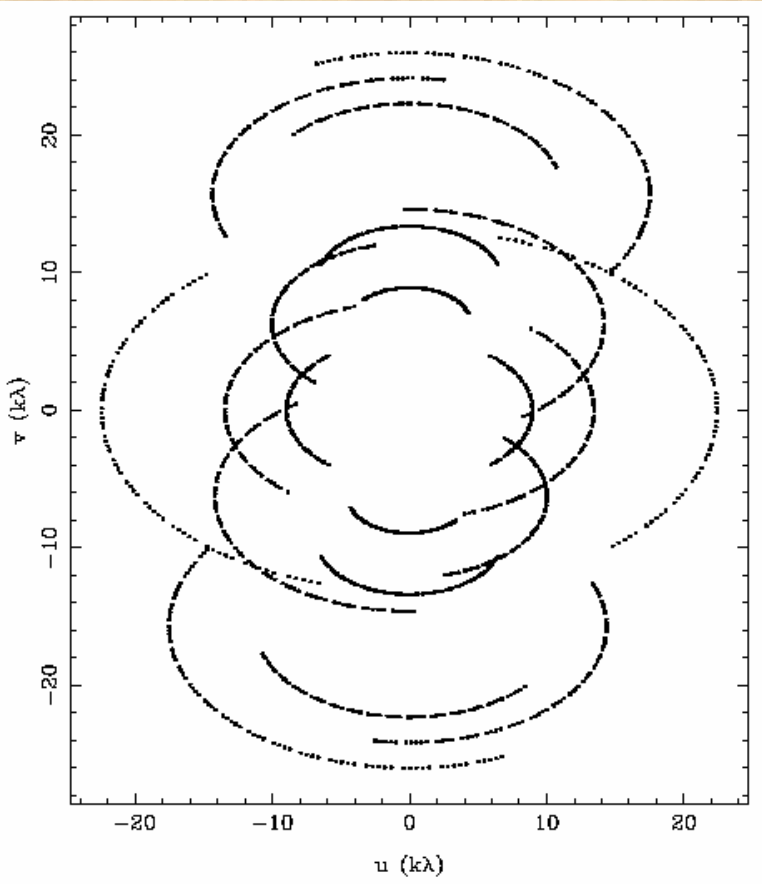


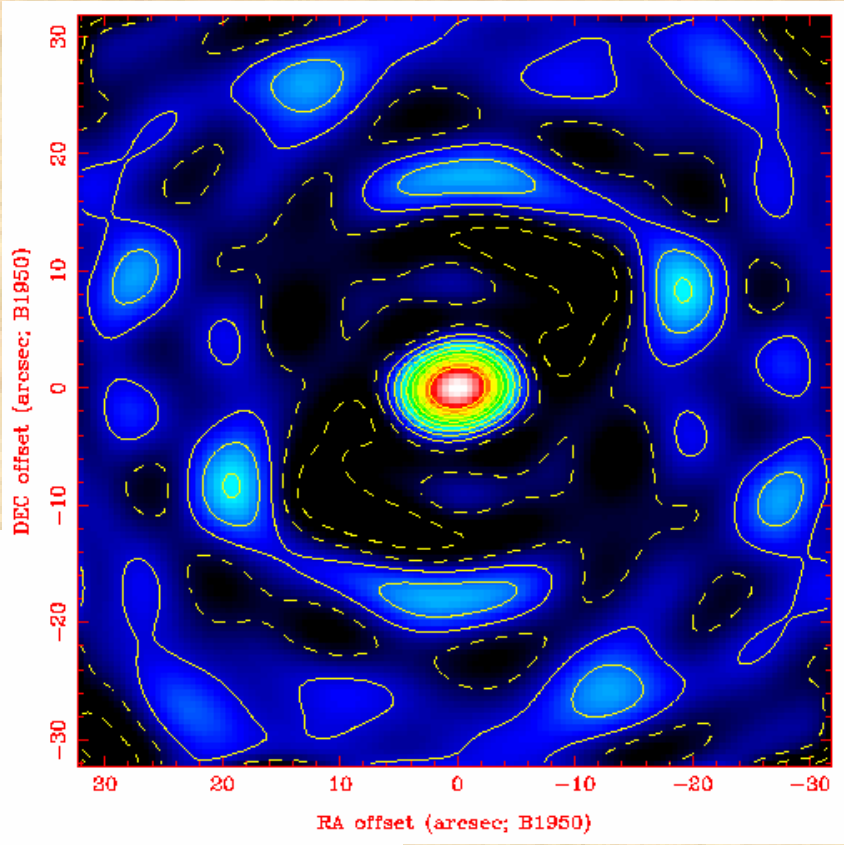


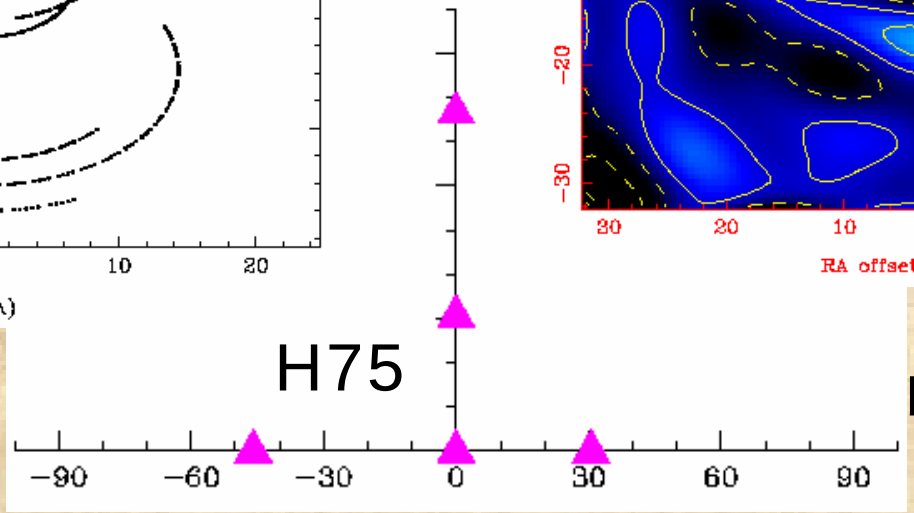
d=-35º, beam=7.7” x 2.7”

Baseline Coverage

- **N-S arm will improve "snapshot" u-v coverage.**



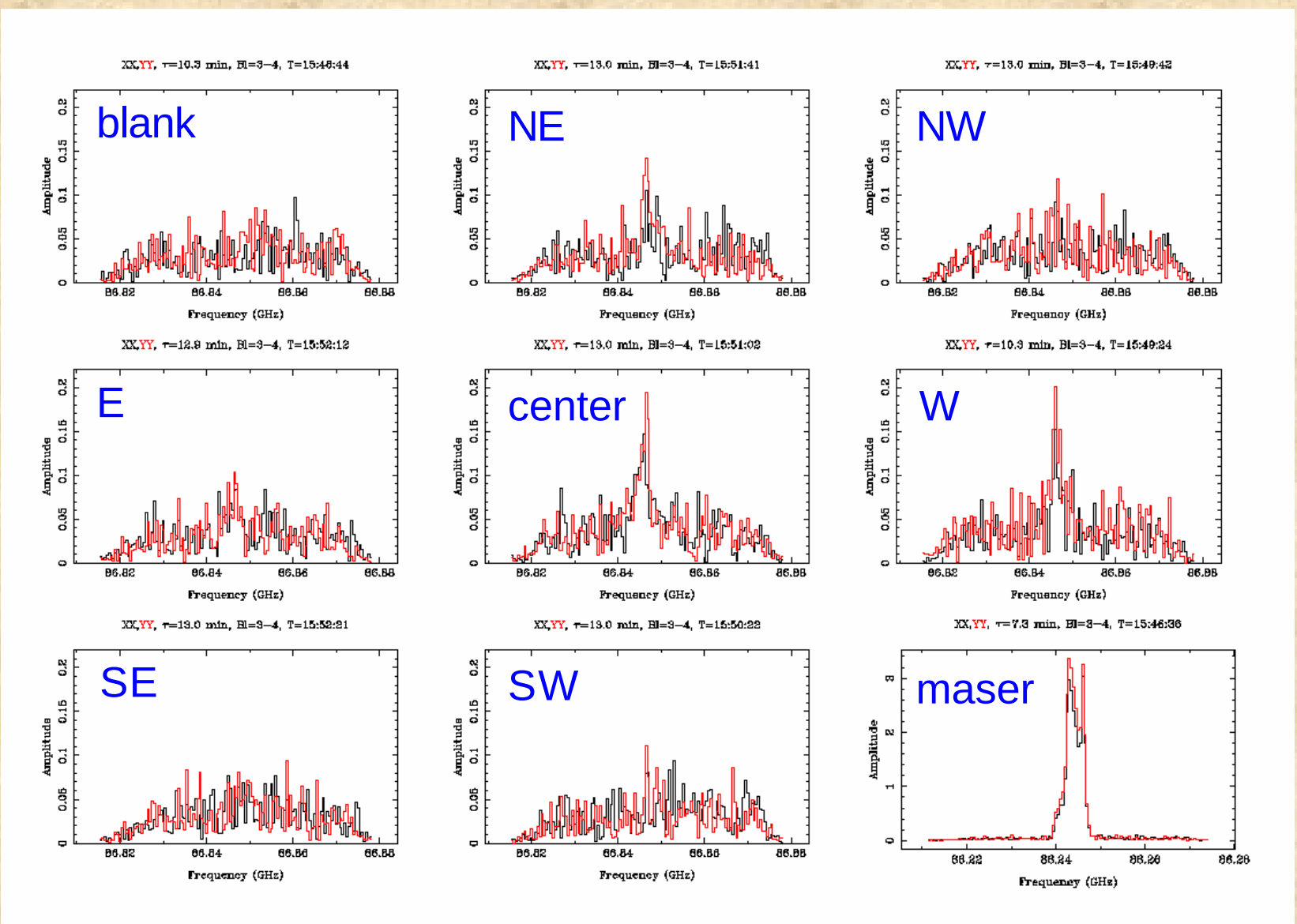




beam=6.6" x 4.9"

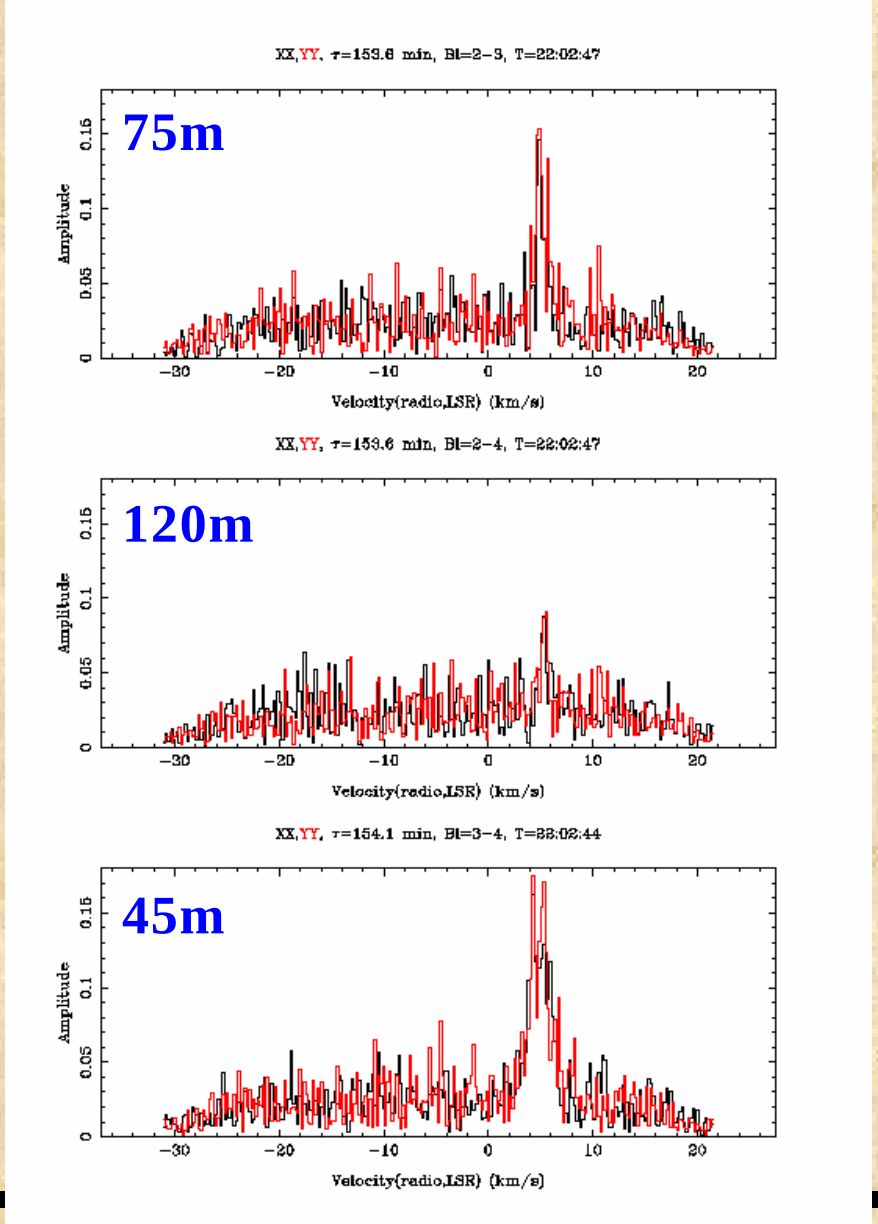
Real Spectra!

Thermal SiO in NGC 6334 I(N)



Single-baseline ATCA, July 2001

HCO^+ in IRAS 08076-3556



- **Drives the Herbig-Haro object HH120 in the Gum Nebula.**