Assignment

- You wish to acquire an optical spectrum of an object with R magnitude of 20.3 that resembles a G0 star with the VLT and the FORS2 spectrograph

  `http://www.eso.org/sci/facilities/paranal/instruments/fors/index.html`

- A S/N of 20 is needed with a resolution of ~1.8 Angstrom to measure the Hydrogen-beta line

- Describe what instrument configuration you would need to use (grism choice, slit, filters) and how long the exposure would need to be for the above S/N [hint: ESO offers a Exposure Time Simulator]

- Discuss the impact of the moon phase and readout noise on the achieved S/N

Assignment : FORS2 on VLT

- Collimators: two scales, either 0.125”/pixel or 0.25”/pixel at default 2x2 mode
  HR collimator only needed for very narrow slits (=large light losses through slit for realistic seeing), so pick std scale at 0.25”

- Grism that cover Hβ at 4861Å:
  600B covering 3247-6324Å at 1.5Å/pixel -> not high enough resolution unless slit is very narrow
  1200B covering 3677-5153Å at 0.72Å/pixel - > OK
  1400V covers 4620-5892Å at 0.62Å/pixel -> OK
  1200g covers 4077-5553Å at 0.72Å/pixel -> OK, but only in visitor mode

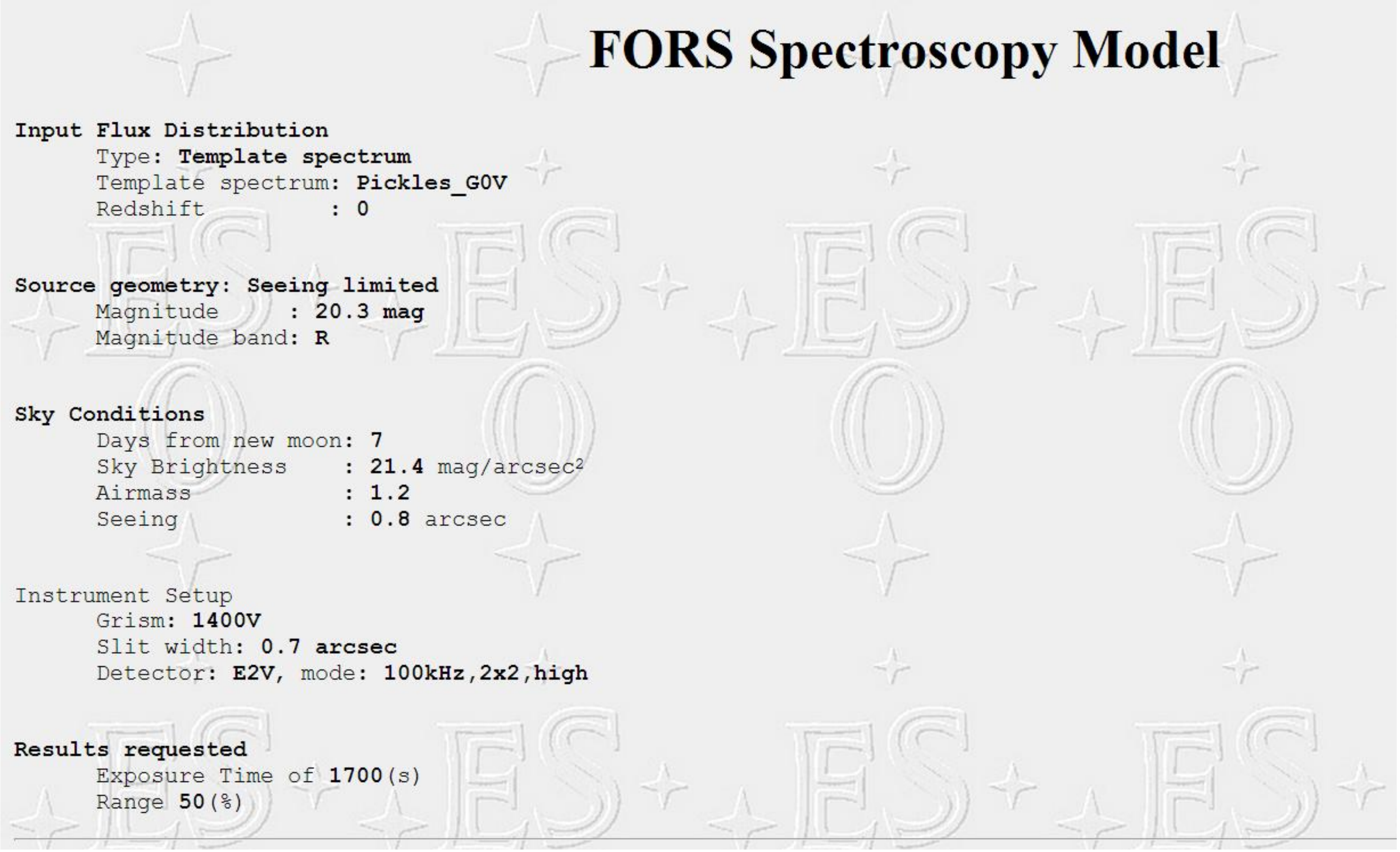
- Slit:
  for 1200B at 0.72A/pixel, our resolution demand equals 1.8/0.72= 2.5 pixels
  this is nicely sampled and would need a 2.5*0.25”=0.625” wide slit
  for 1400V we get 1.8A=2.9 pixels with a 0.73” wide slit, good match to the available 0.7” slit (another reason for sticking to std. collimator)

- Detector:
  E2V option more sensitive in the blue, so preferred over default MIT
  Good pixel sampling with standard 2x2 mode, smaller pixels in 1x1 mode would only increase the contribution of readout noise thus higher spatial resolution not desired

Assignment 2 : FORS2 on VLT

- Use ETC tool to compare S/N performance for different choices
- ETC also shows that 1400V+0.7” more efficient than 1200B+0.5”, i.e. shorter exposures are sufficient to reach S/N of 20, so final setup is 0.7” slit with E2V detector and the 1400V grism in standard collimator and readout mode.
- Use point-source G0 star template (zero-redshift) at R=20 as input flux model for ETC
- Vary moon phase and pick realistic seeing of ~0.8” and airmass of ~1.2
  - New moon S/N=20 at Hβ in ~1600s
  - Full moon S/N=20 in ~2700s ; avoid full moon but a week away from new moon we only need 1700s so best not to be too restrictive on moon phase
- Look at full output for specific source/background and readout noise levels
  - Readout noise comparatively small giving good choice of CCD sampling and larger contributions from sky and source
  - Moon impacts S/N but to improve schedulability of observation we can be a little flexible
  - Poor seeing will result in slit losses and longer exposures

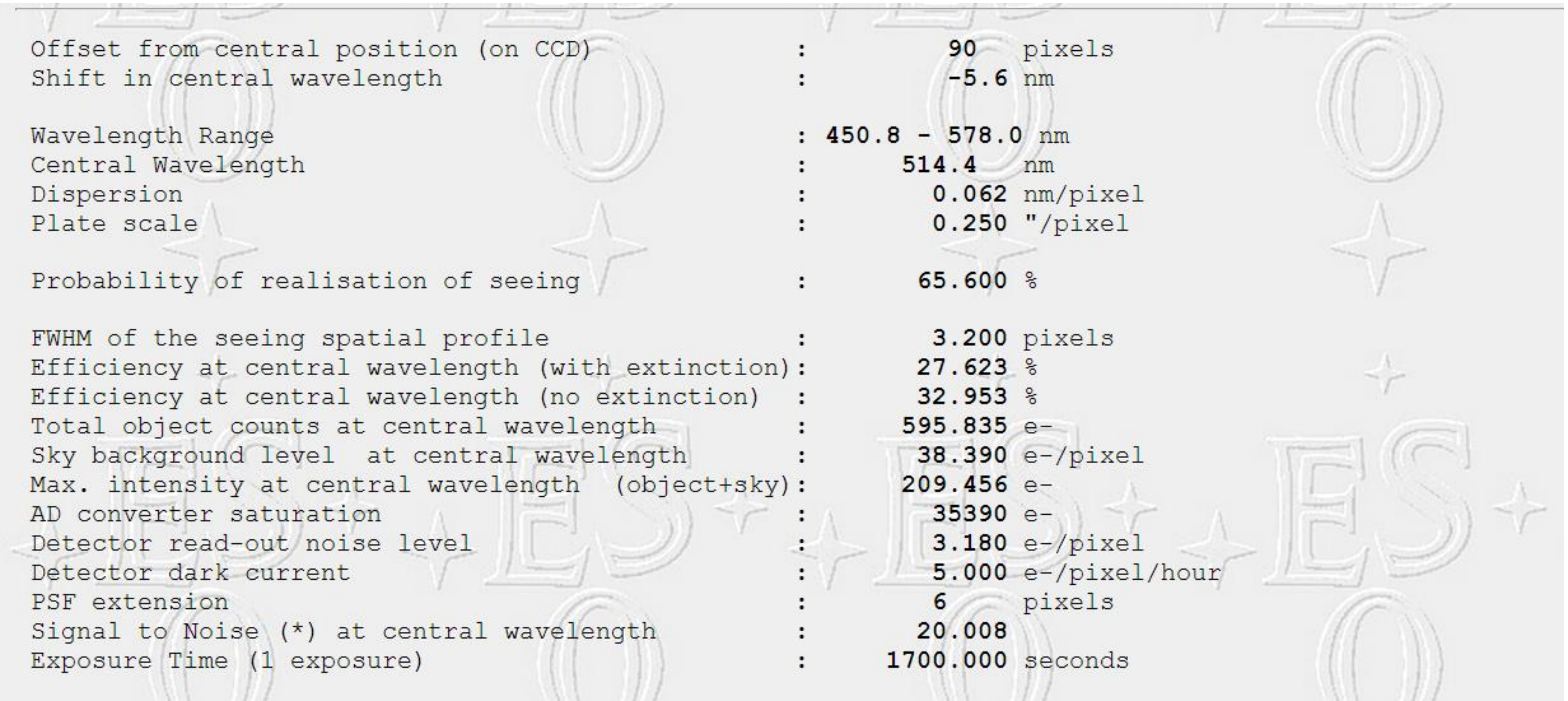
ETC input



FORS Spectroscopy Model

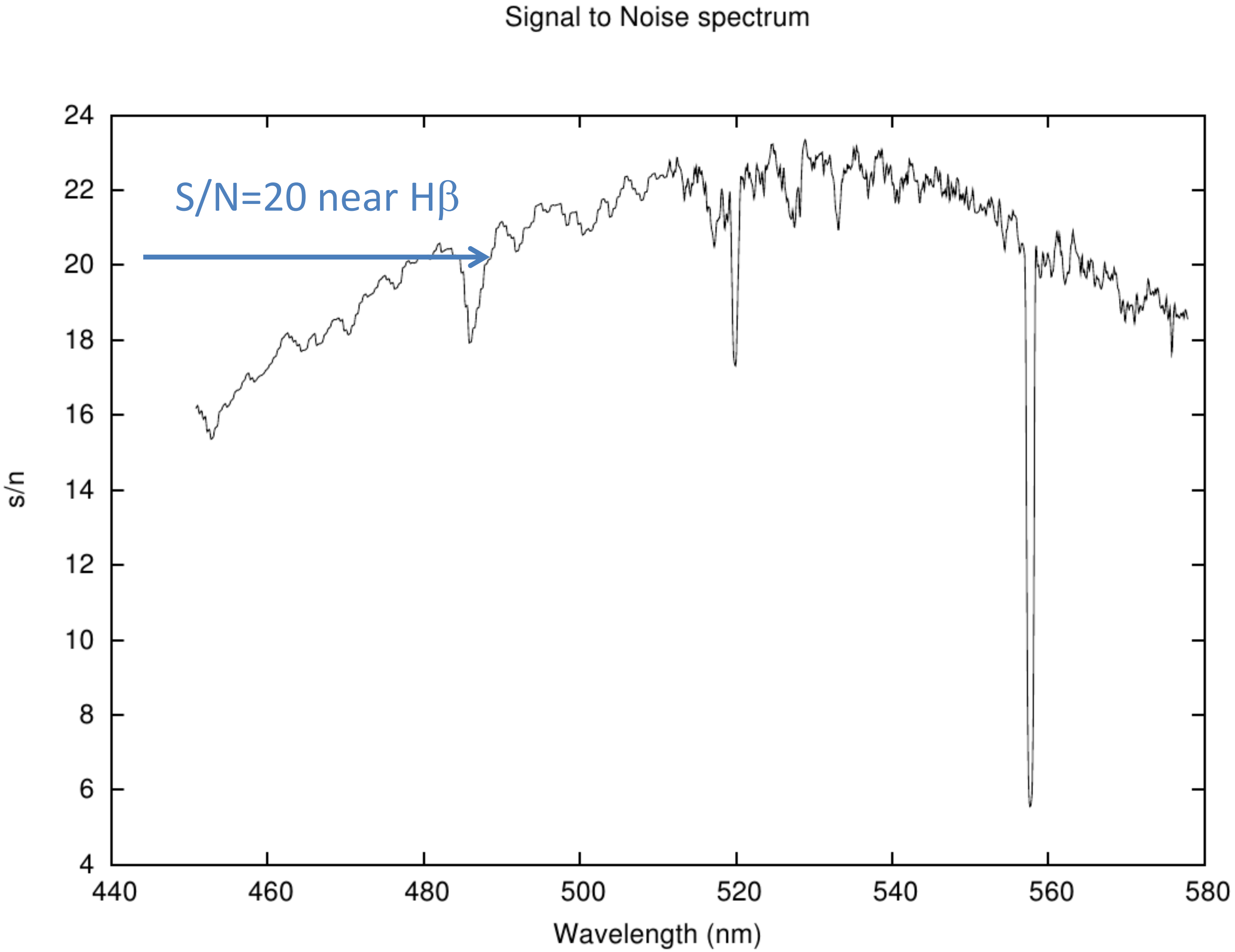
```
Input Flux Distribution
      Type: Template spectrum
      Template spectrum: Pickles_G0V
      Redshift         : 0


Source geometry: Seeing limited
      Magnitude     : 20.3 mag
      Magnitude band: R


Sky Conditions
      Days from new moon: 7
      Sky Brightness    : 21.4 mag/arcsec²
      Airmass           : 1.2
      Seeing            : 0.8 arcsec


Instrument Setup
      Grism: 1400V
      Slit width: 0.7 arcsec
      Detector: E2V, mode: 100kHz,2x2,high


Results requested
      Exposure Time of 1700(s)
      Range 50(%)
```

ETC output



```
Offset from central position (on CCD)             :          90   pixels
Shift in central wavelength                       :          -5.6 nm

Wavelength Range                                  : 450.8 - 578.0 nm
Central Wavelength                                :        514.4   nm
Dispersion                                        :          0.062 nm/pixel
Plate scale                                       :          0.250 "/pixel

Probability of realisation of seeing              :         65.600 %

FWHM of the seeing spatial profile                :          3.200 pixels
Efficiency at central wavelength (with extinction):         27.623 %
Efficiency at central wavelength (no extinction)  :         32.953 %
Total object counts at central wavelength         :        595.835 e-
Sky background level  at central wavelength       :         38.390 e-/pixel
Max. intensity at central wavelength  (object+sky):        209.456 e-
AD converter saturation                           :          35390 e-
Detector read-out noise level                     :          3.180 e-/pixel
Detector dark current                             :          5.000 e-/pixel/hour
PSF extension                                     :        6       pixels
Signal to Noise (*) at central wavelength         :         20.008
Exposure Time (1 exposure)                        :       1700.000 seconds
```

ETC output


Signal to Noise spectrum
S/N=20 near Hβ
s/n
24
22
20
18
16
14
12
10
8
6
4
440
460
480
500
520
540
560
580
Wavelength (nm)

Astrophysical Techniques

Radio / submm Astronomy

Book: An introduction to Radio Astronomy, Burke & Graham-Smith, CUP

Danny Steeghs

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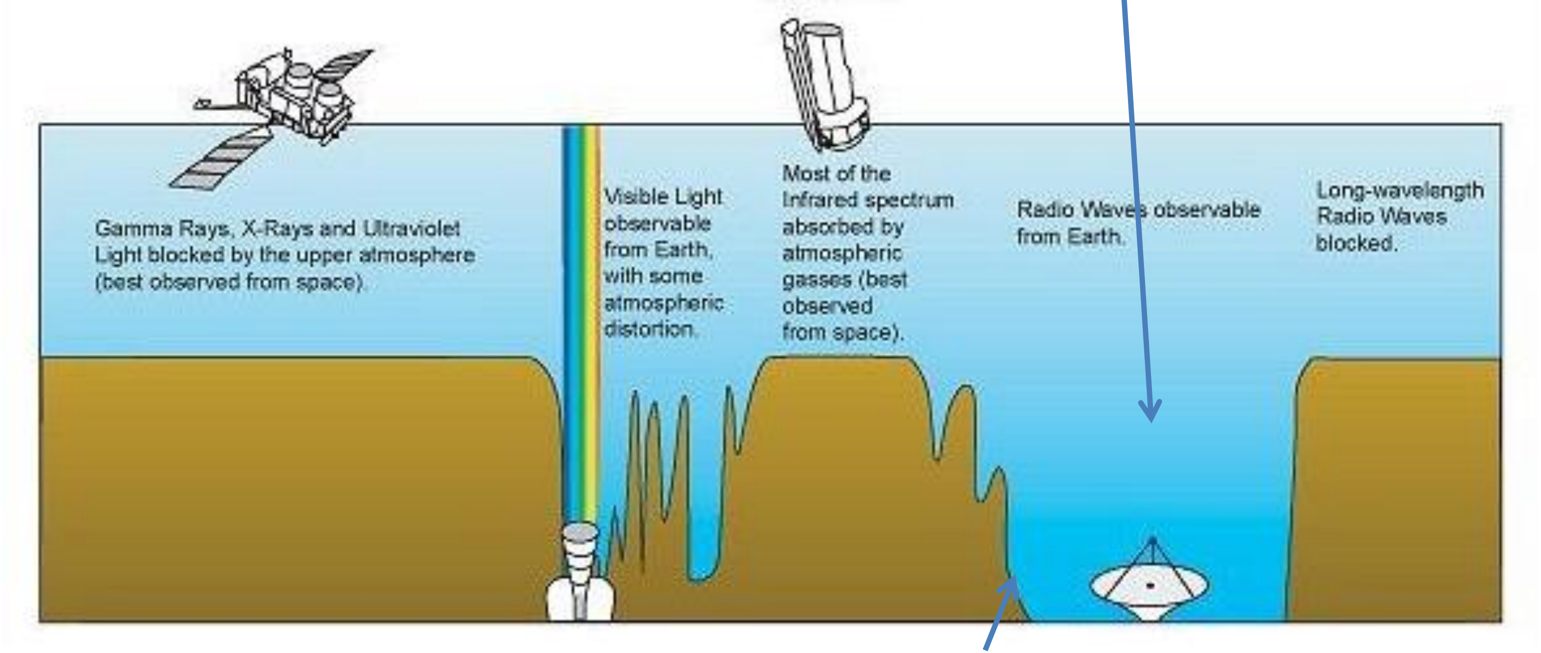
Observing in the radio/submm

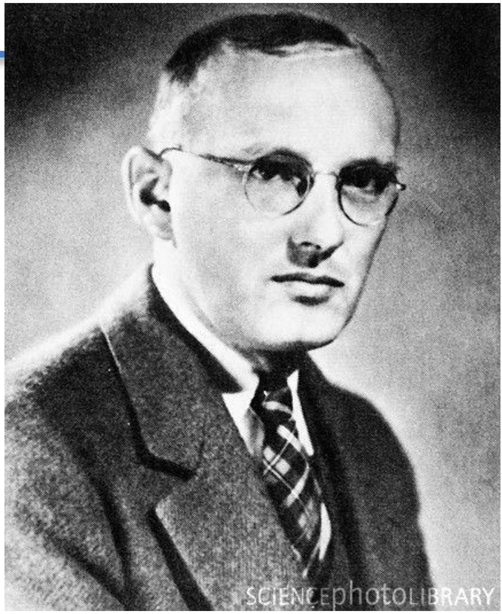
- At radio frequencies, the light from astronomical sources can reach the Earth’s surface with little disruption



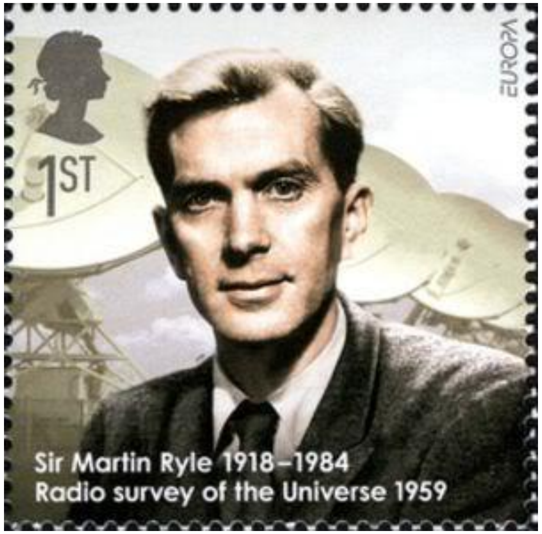
- At sub-millimeter wavelengths, the atmosphere is more opaque, so observations are sensitive to water vapour in the atmosphere, but some windows are clearer than others
- Not used for astronomy until the second half of the twentieth century, since the signal needs radio technology to detect it

Historical context

- Radio interference from astronomical sources was noticed by Karl Jansky of Bell Labs in the late 1930s
- Technology largely developed during World War II [radar]
- Pursued academically since the 1940s
- A lot of early work (particularly into interferometry) done by Martin Ryle and Antony Hewish at Cambridge University in the 1940s-60s
- Techniques developed for single dishes and interferometers
- Examples
  - Jodrell Bank (Lovell) – 1957
  - Arecibo - 1963
  - Very Large Array (VLA) – 1976

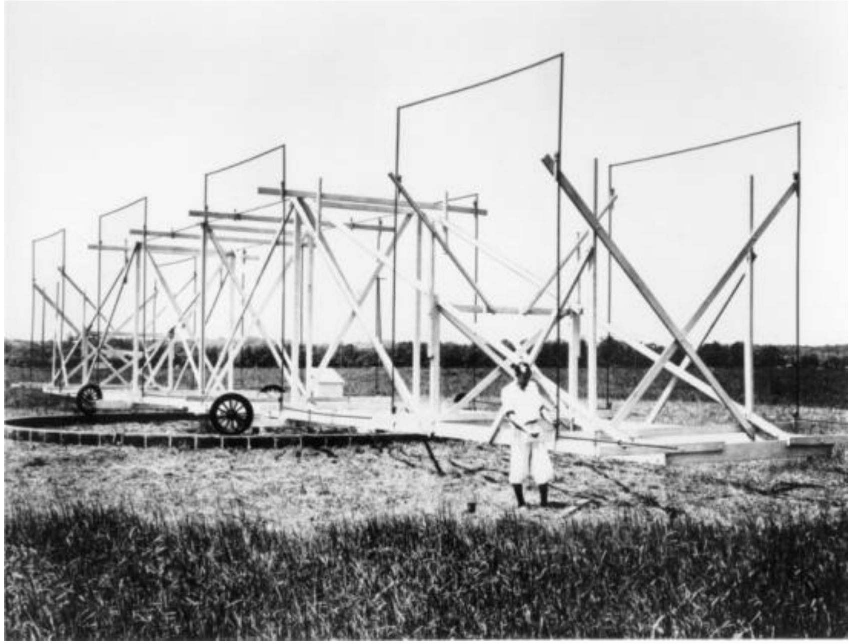


Karl Jansky

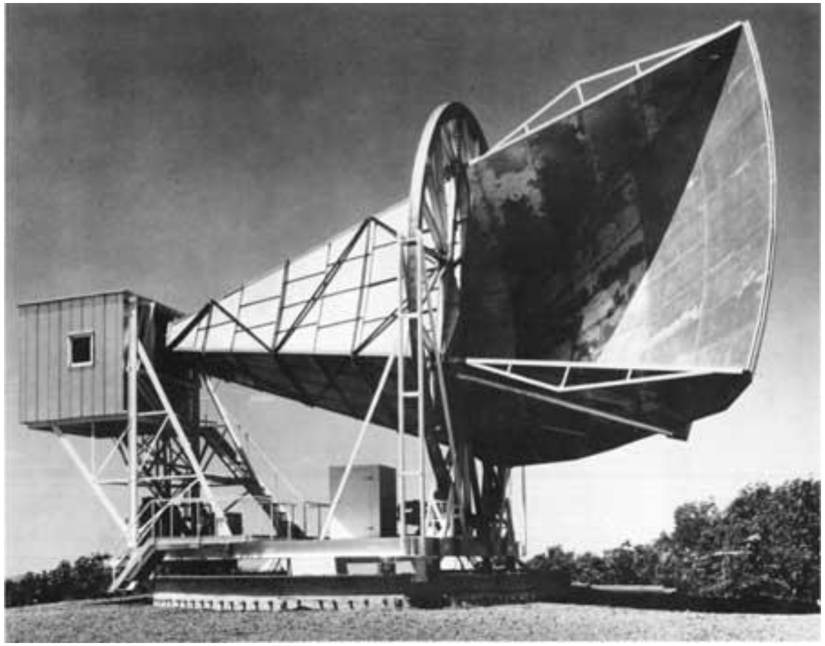


Royal Mail, 2010

Historical Context



Jansky and his gear



Bell labs CWB horn (3K = 1mm)

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Main Emission Mechanisms

- **Blackbody continuum radiation**
    - Thermal blackbody typically peaks at IR wavelengths, but will be shifted to the sub-mm at low temps or high redshift

- **Synchrotron continuum radiation**
    - Relativistic electrons accelerated in a magnetic field (e.g. in pulsars, radio galaxies, AGN, Supernova remnants)
    - Non-thermal, can be polarised

- **Free-Free (Bremsstrahlung) continuum radiation**
    - Acceleration of a free electron in the field of an ion in a plasma
    - Thermal process (e.g. in HII regions)

- **Radio/sub-mm emission Lines**
    - 21cm HI emission – transition between hyperfine levels in 1s state
    - CO rotational transitions (FIR, but shifted to submm at high z)
    - Other molecular and atomic gas transitions (rotational and fine structure)
    - Masers

The Ingredients of Star Formation

Radio line emission from Carbon Monoxide

Molecular Gas

Catalyzes Molecule Formation

Far-IR & Sub-mm continuum

Dust

Gas forms stars

Gas metal-enriched by stars

Dust generated in Supernovae and Stellar Winds

Stars

UV + Optical

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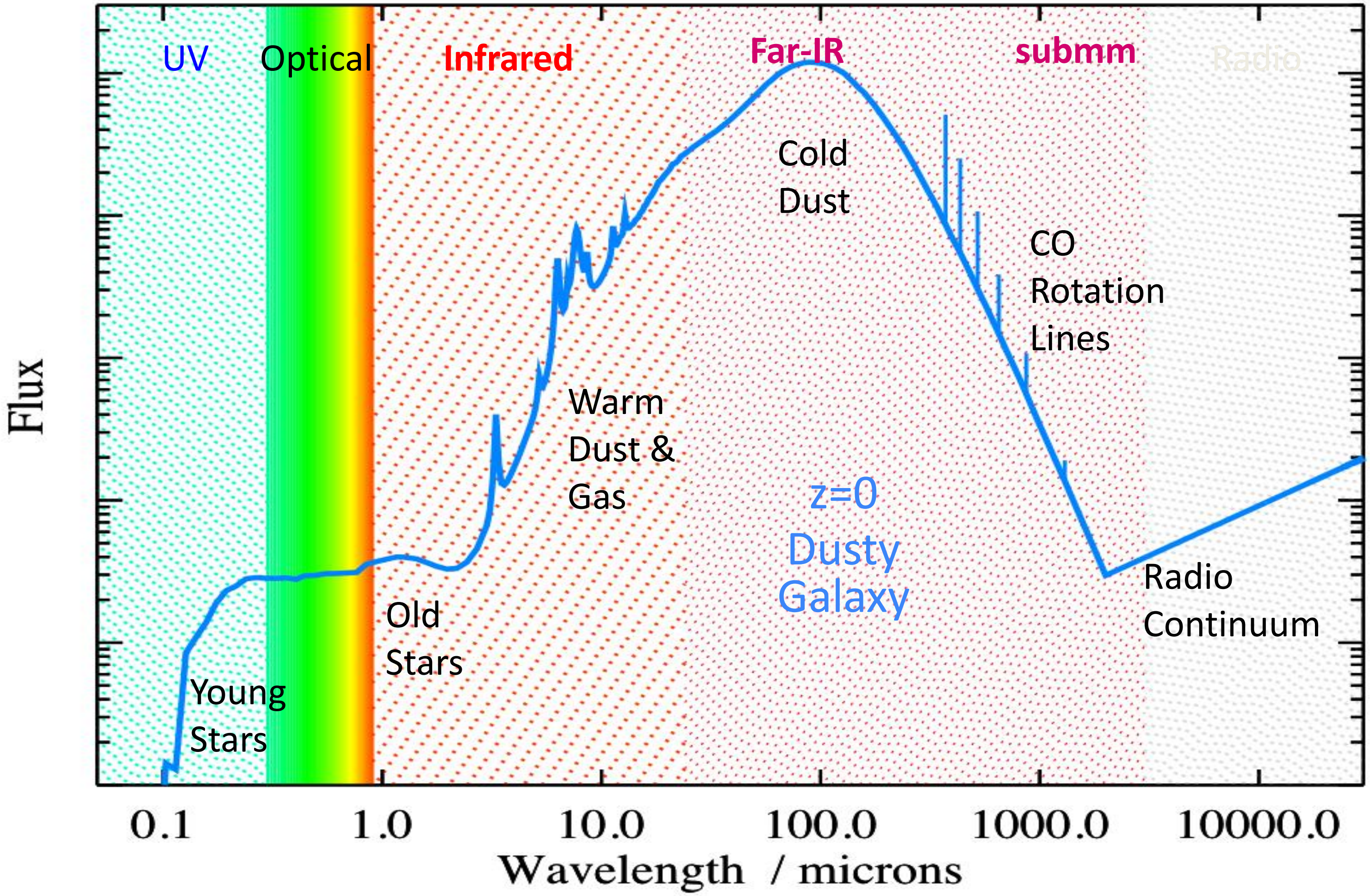
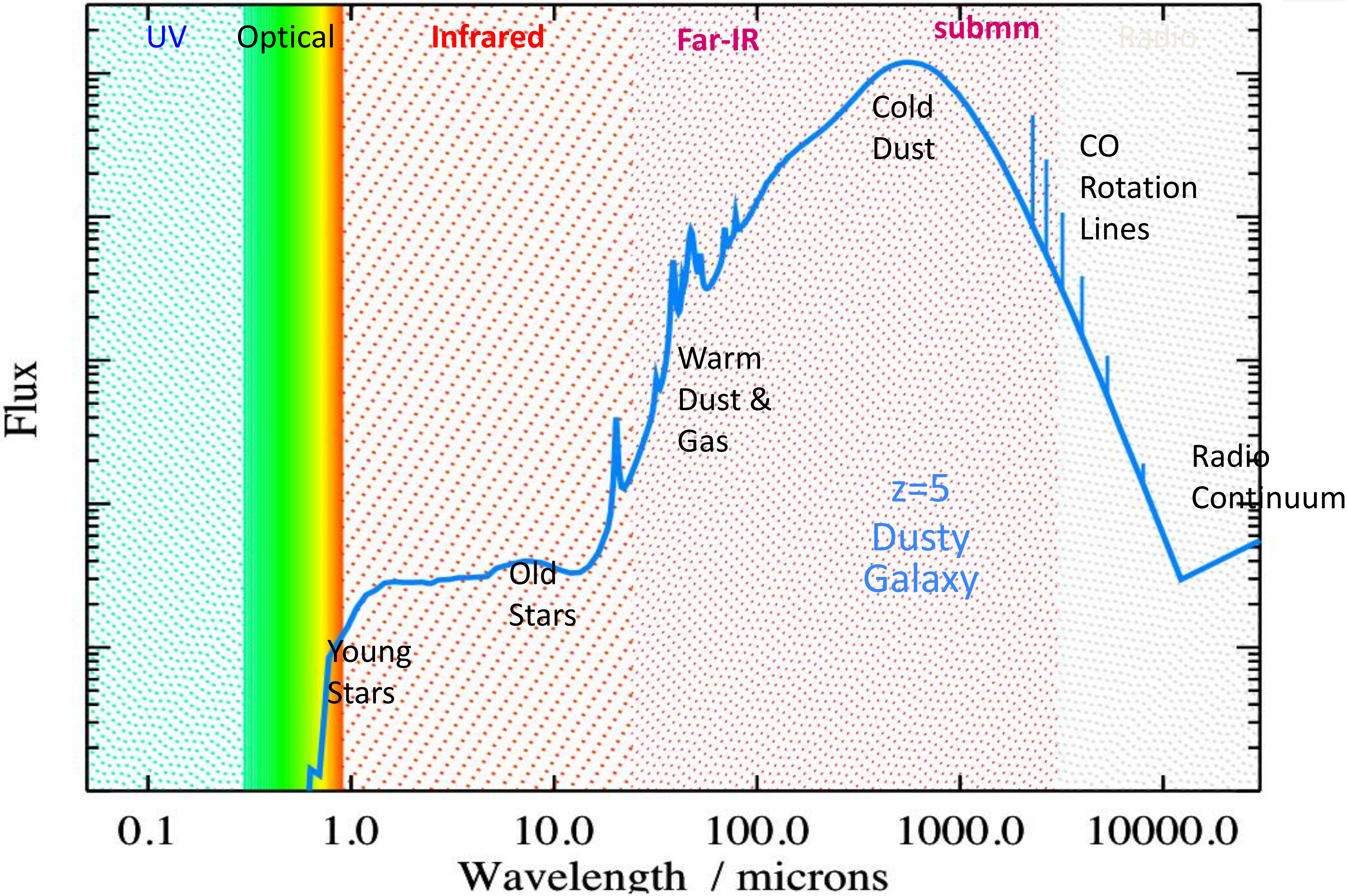
Thermal Blackbody Radiation

Dusty star-forming galaxies will suffer from heavy extinction in the optical/UV but the reprocessed radiation is emitted as thermal blackbody radiation



Shifting to higher z…

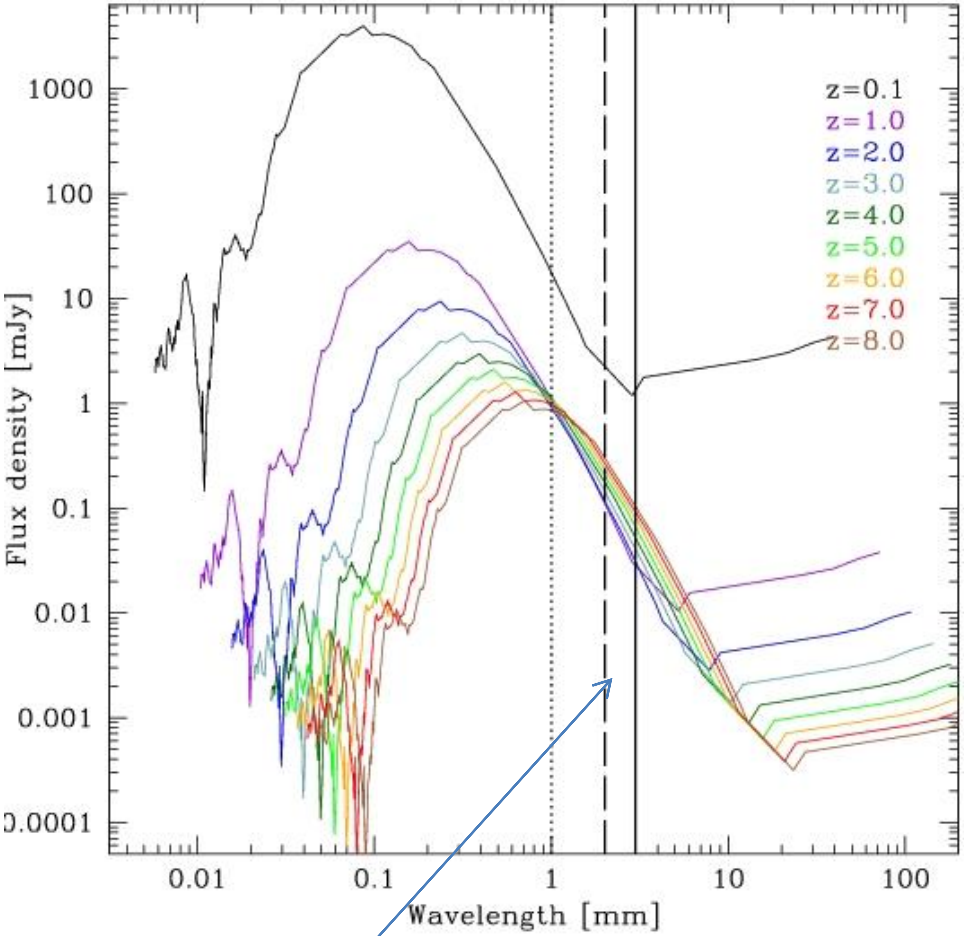


The negative K-correction

- As a dusty object gets more distant, it becomes fainter
- But as redshift increases, you're closer to the dust peak

⇒ For a blackbody source, a given objects will appear about the same brightness with increasing redshift at sub-millimeter wavelengths

- z=8 objects are theoretically as easy to see as z=1 objects of the same luminosity
- Phenomenon known as the '*negative K-correction*' [bolometric correction]

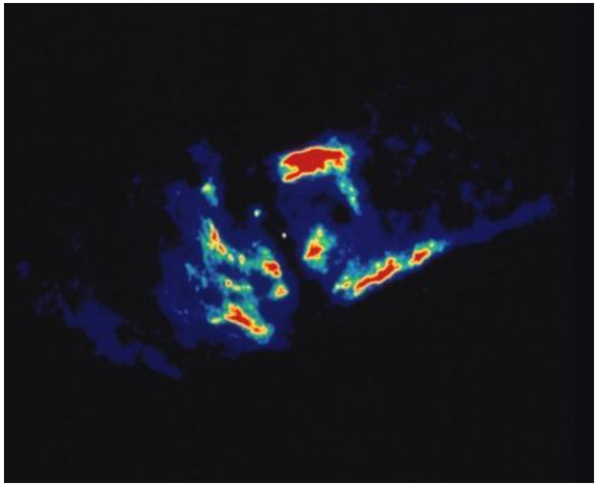


typical atmospheric window

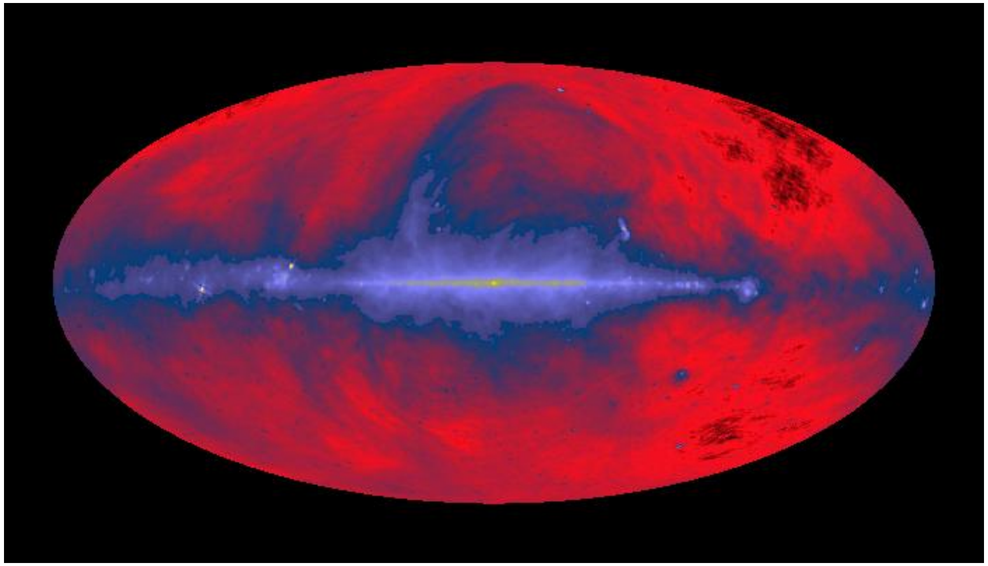
Thermal Blackbodies at low z

- Some Galactic and low-z sources can also be very luminous in the sub-mm
- This is usually because of very low temperatures

- Examples include:
  - disks around stellar remnants and protostars
  - Cool molecular clouds (e.g. in the Galactic plane)
  - Planets in our solar system

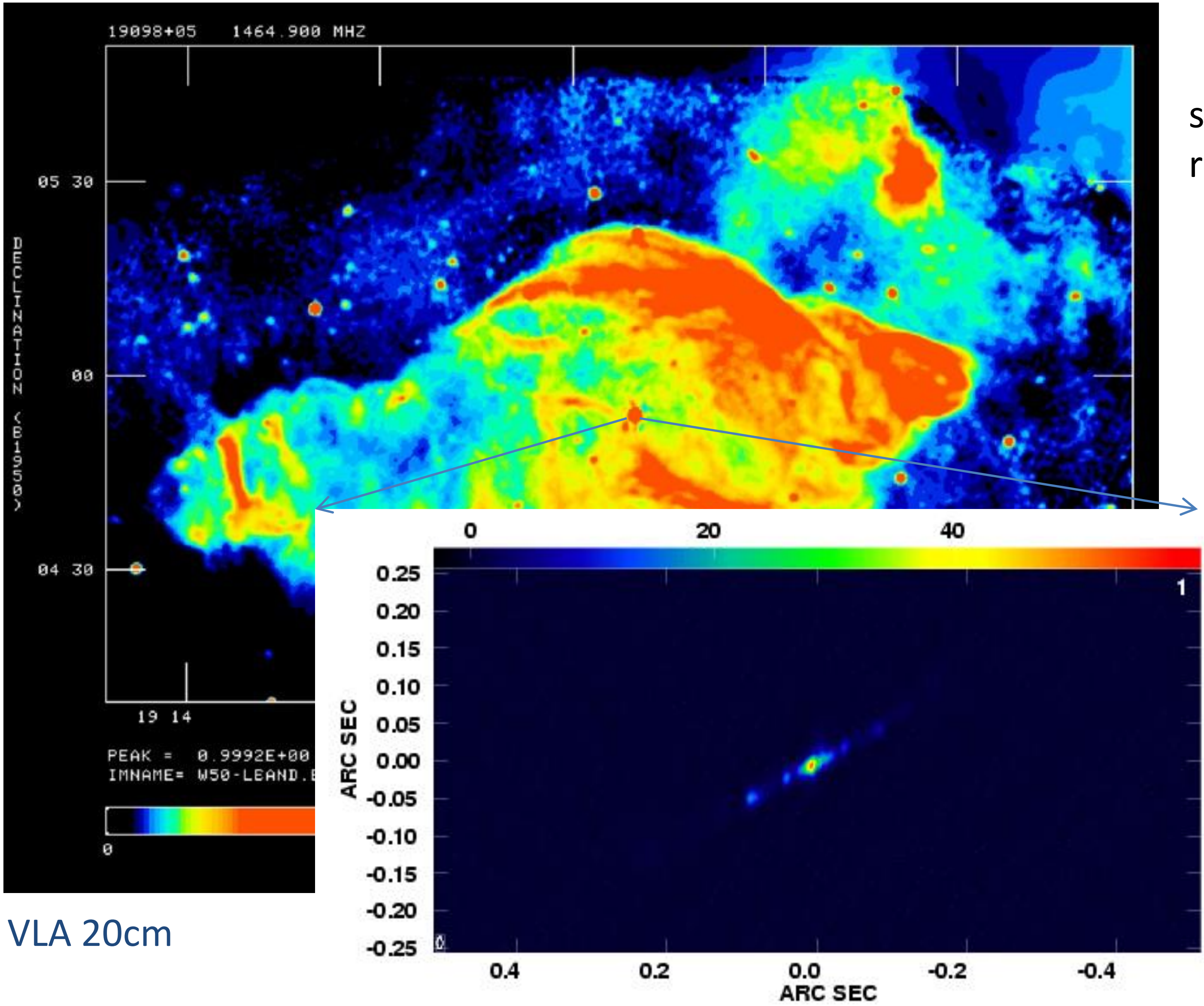


HII region



The radio sky at 408MHz dominated by galactic emission

SS433 Galactic Binary



supernova
remnant

MERLIN
VLBI

jet from accreting
compact object

VLA 20cm

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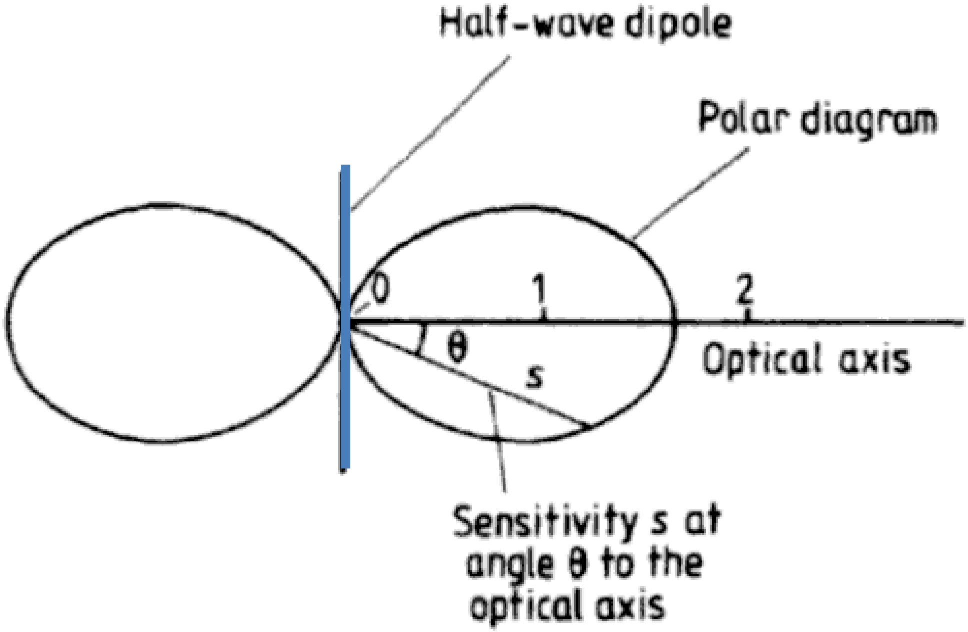
Radio basics : dipole antenna



Antenna gain **G**

Effective Area : $A_{eff} = \lambda^2 \mathbf{G}/4\pi$

Half-wave dipole

I

Collinear array with two half-wave dipoles

II

Collinear array with four half-wave dipoles

III

N=1
‘slit’

↓

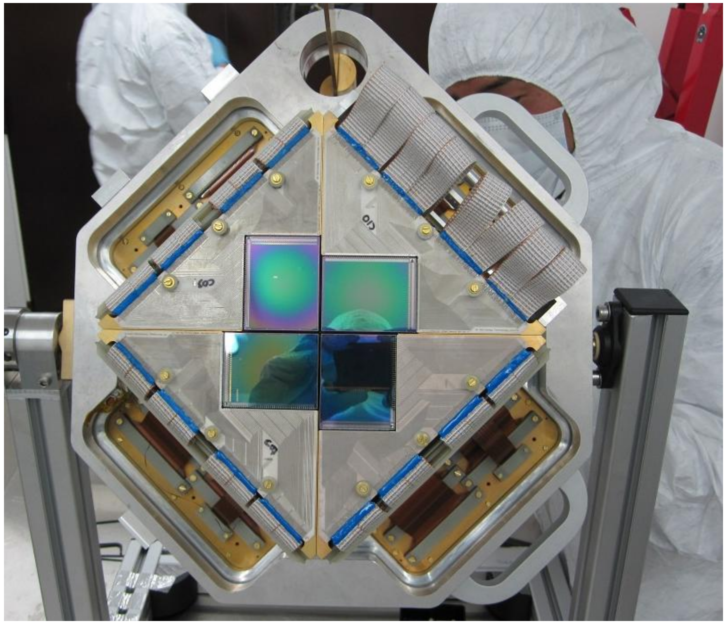
N=many
‘grating’

Bolometers

- Based on resistivity changes in response to illumination
- An individual bolometer can be considered a pixel element in a bolometer array
- Typically sensitive over a broad wavelength range (~100 GHz) [continuum]

- Latest instruments (e.g. SCUBA-2) have TES (transition edge superconducting) detectors and SQUID (superconducting quantum interference device) amplifiers

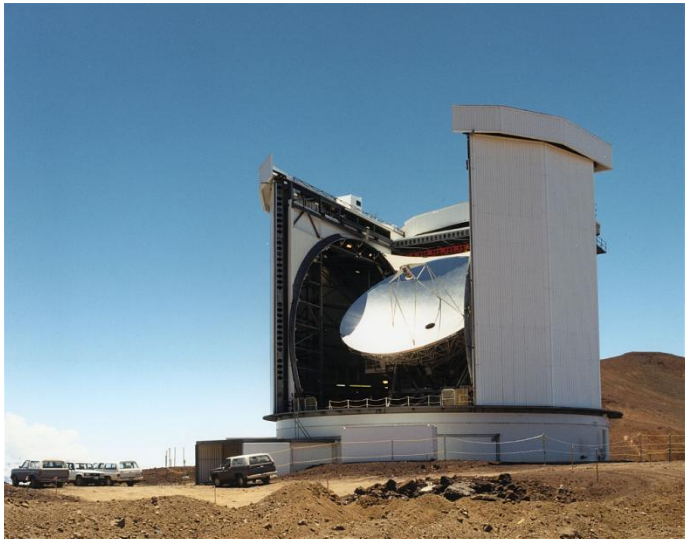
- Key examples:
  - MAMBO on the IRAM 30m telescope 117 pixels, 1.2mm
  - LABOCA (295 pix, 870μm) and SABOCA (39 pix, 350μm) on APEX
  - SCUBA-2 (5120 pix, 850 and 450μm) has just replaced SCUBA (37 pix)



SCUBA-2 array

Heterodyne Receivers

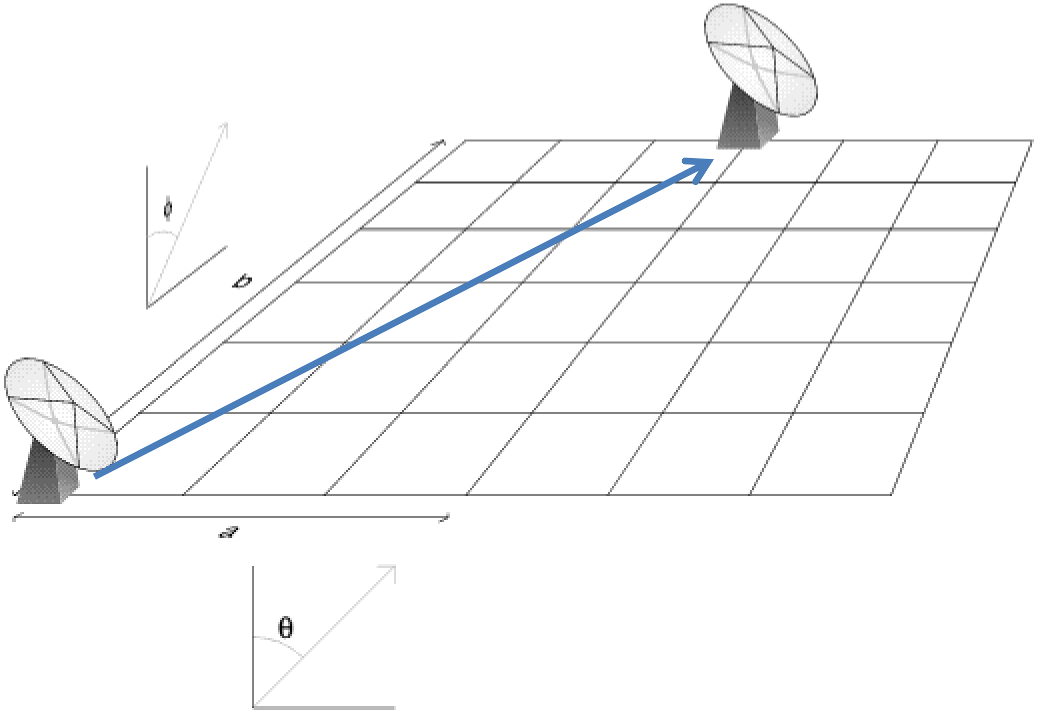
- Incoming radiation mixed with local source at known frequency (*the local oscillator*), such that detection occurs at the beat frequency (*sidebands*)
- One can recover amplitude and phase of source wave, but control detector frequency via local oscillator freq.
- Historically used to do high-frequency work with low(er) frequency detectors
- Used for single dish narrow-band work (emission lines)

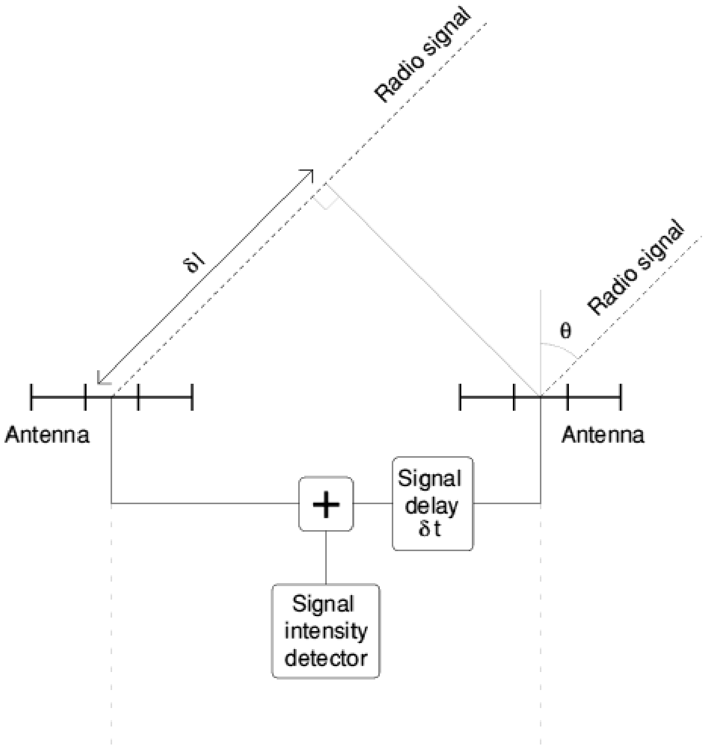


HARP on the JCMT

16-pixel heterodyne array receiver

Interferometry

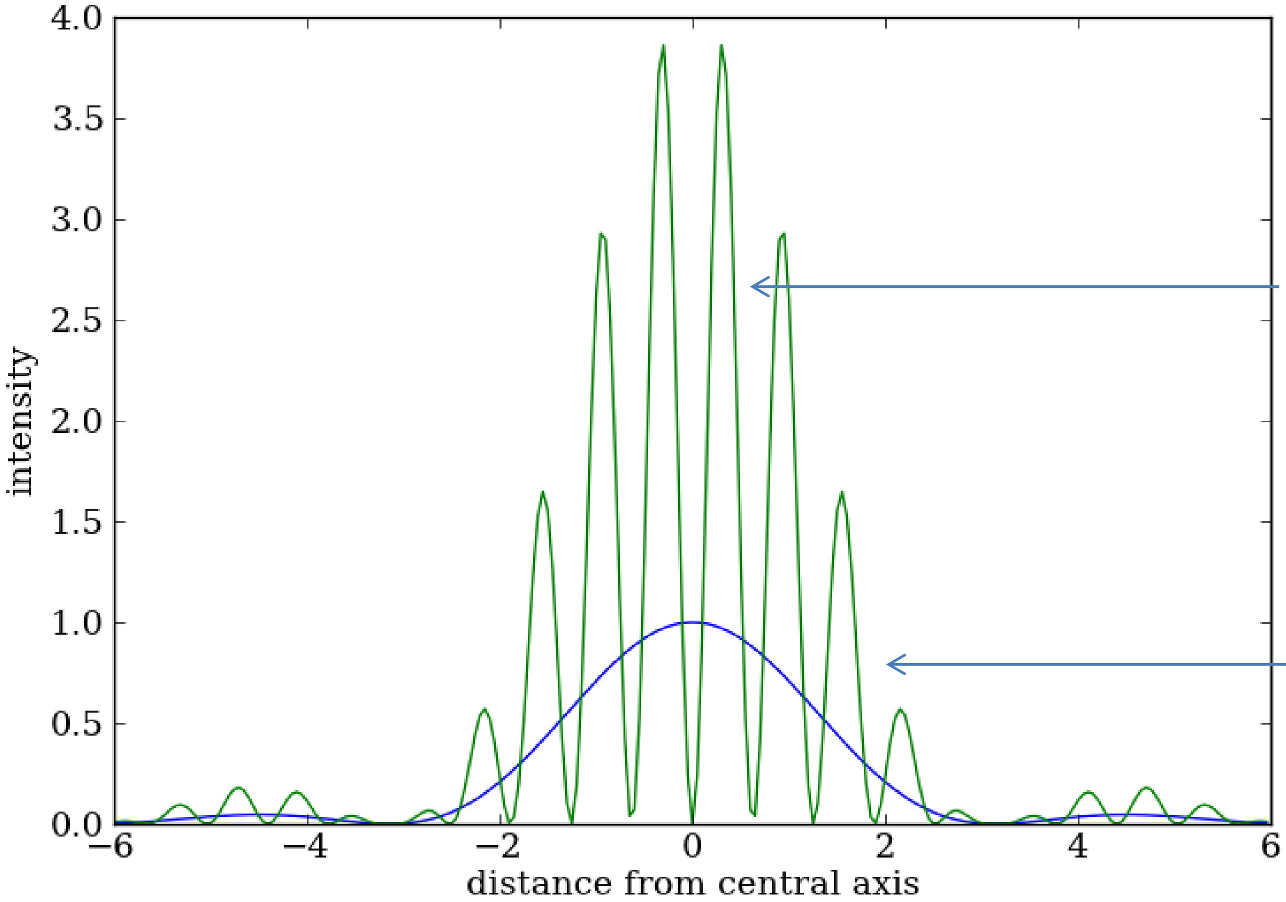




Position of antenna	(a,b)
Projection to plane perp. to source	$(x,y)= (a\cos\theta, b\cos\phi)$
Fourier conjugate	$(u,v) =(kx,ky)=2\pi/\lambda(x,y)$

The 'UV-plane': Fourier plane perpendicular to line of sight to source

Fringes



point source
2 apertures separation d
resolution $\propto \lambda/2d$

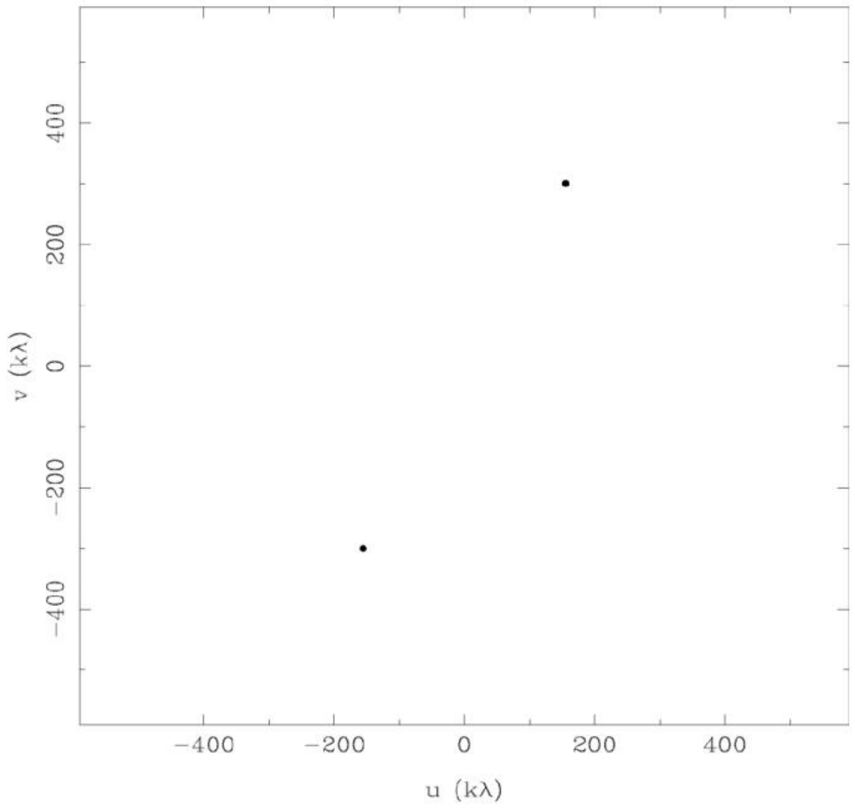
point source
1 aperture
resolution $\propto \lambda/D$

Interferometer records one component of the 2D Fourier transform of the image/source plane (visibility function)

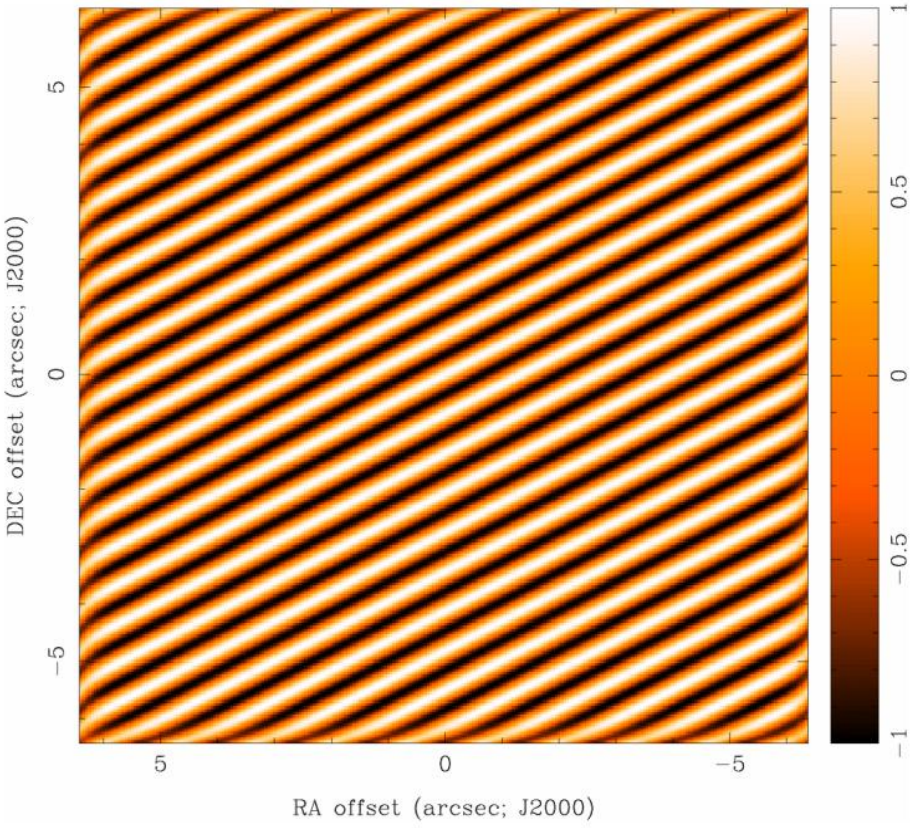
Image formation via inverse Fourier transform

2 Antenna Beam

- Each baseline measures an amplitude and phase



uv coordinates



xy coordinates

Observing Considerations

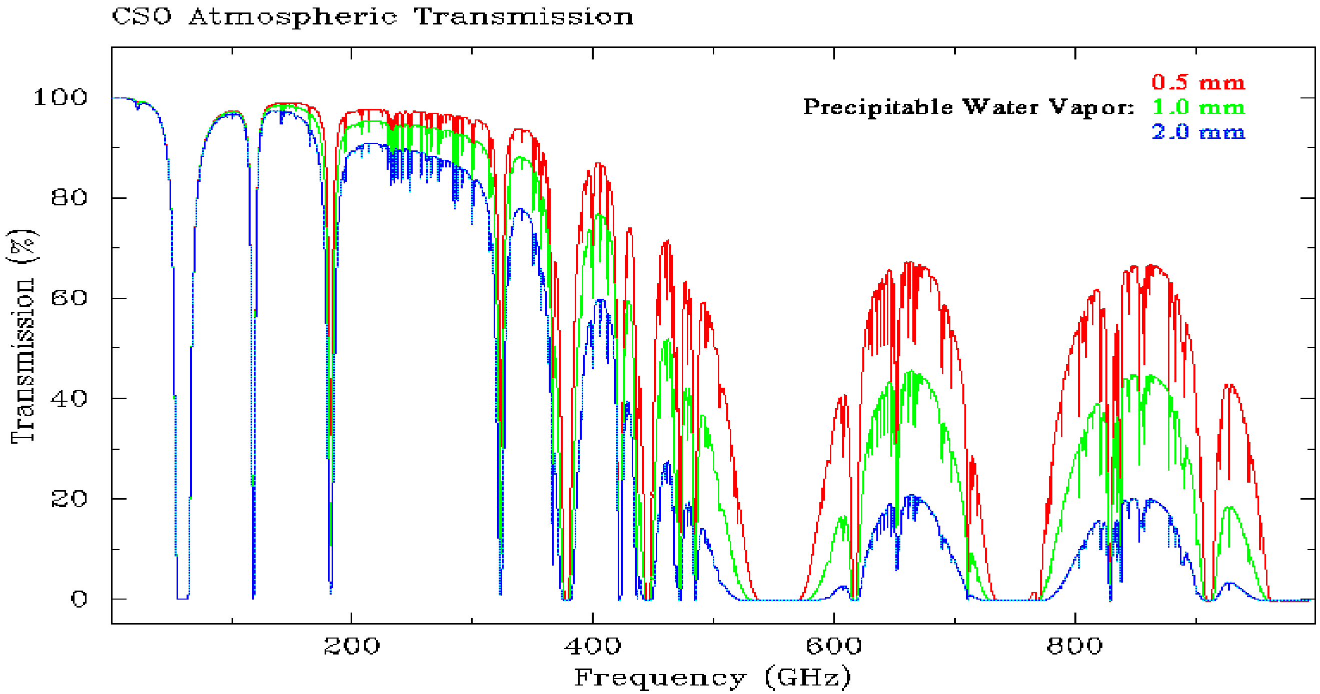
- Day vs Night?
  - Most radio frequency observations can be taken during daylight, in cloudy weather or even in light drizzle
  - Clearly at submm/mm wavelengths, both heat and moisture (see PWV) is bad. These observations are usually done at night, although on the ALMA site daytime observations will be possible
  - Hot temperatures (around daytime) or rapidly changing temperatures (around dawn) can cause atmospheric turbulence (see phase stability)

- Phase Stability
  - For interferometers, phase stability needs to be measured and checked regularly. Bracketing short science observations with calibration observations can add sizeable overheads

- Flux and Pointing Calibration
  - Radio telecopes often have small fields of view and large beams, so pointing can be an issue, particularly at short wavelengths. It needs to be checked on a bright source through the night, again adding overheads
  - Absolute flux cal is usually done once per track at radio wavelengths

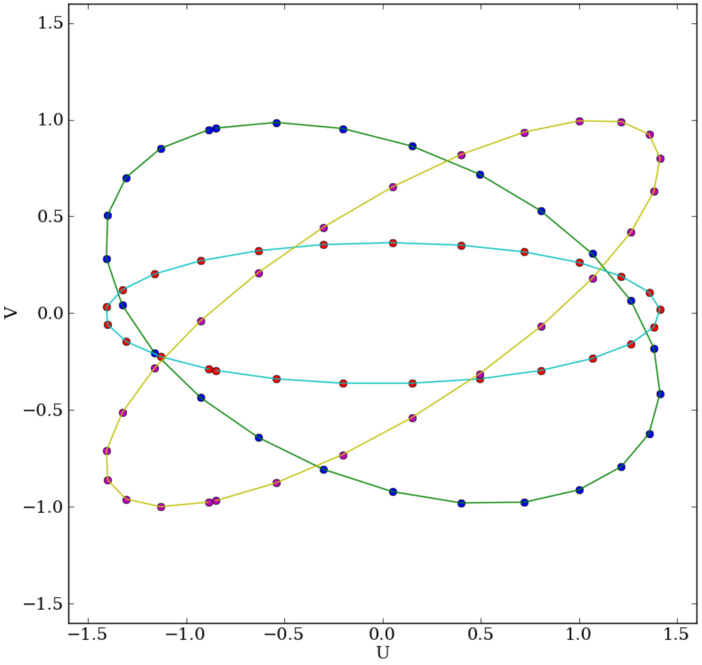
Observing Considerations

- **PWV** [compare with airmass at optical]
  - Precipitable Water Vapour – usually measured in mm, maps directly onto the atmospheric opacity at a given wavelength
  - Measures the column of water in the atmosphere (and hence atmospheric attenuation). Must be measured by observer or observatory
  - This correction is vital at submm and mm wavelengths where water in the atmosphere is the biggest contributor to absorption



Observing Considerations

- uv-plane coverage
  - If using a linear or sparse array, the uv-plane coverage of a short observation can be very poor.
  - Earth (rotation) synthesis helps, but ideally needs 12 hour tracks.
  - Far northern or southern sources may only be above the horizon for a short time: uv-plane coverage will never be good
  - Earth rotation synthesis doesn't help at all with equatorial sources, since they move in straight lines in uv-space.



uv-tracks for different declinations, same hour angle coverage

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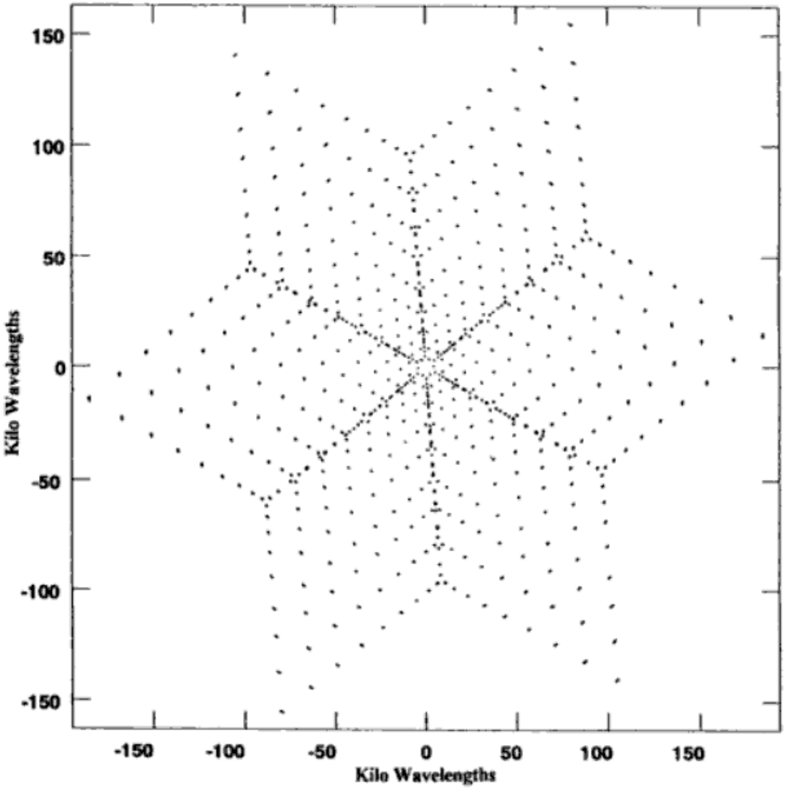
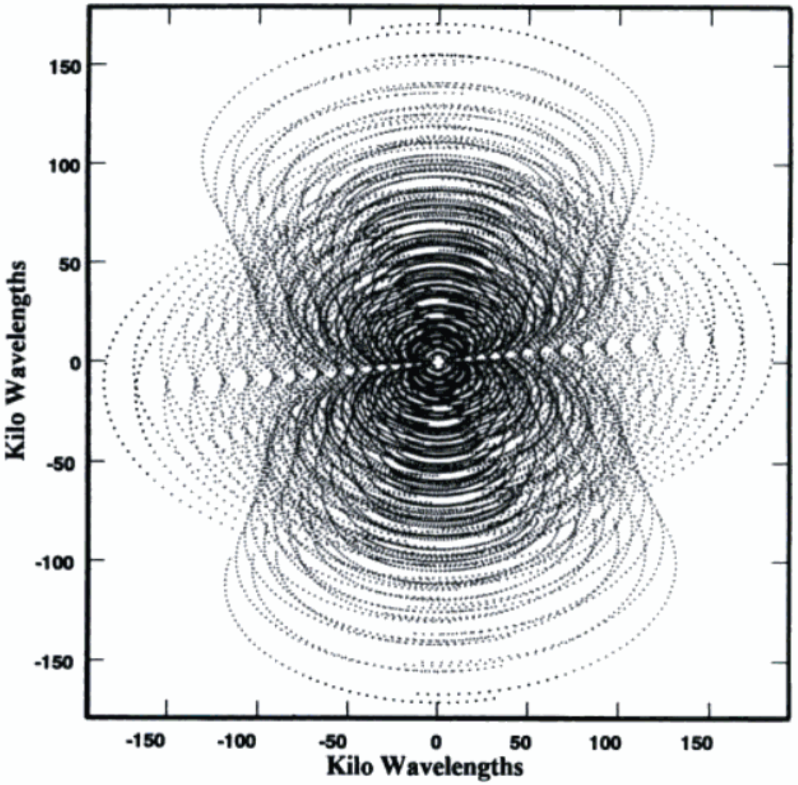
UV coverage with arrays



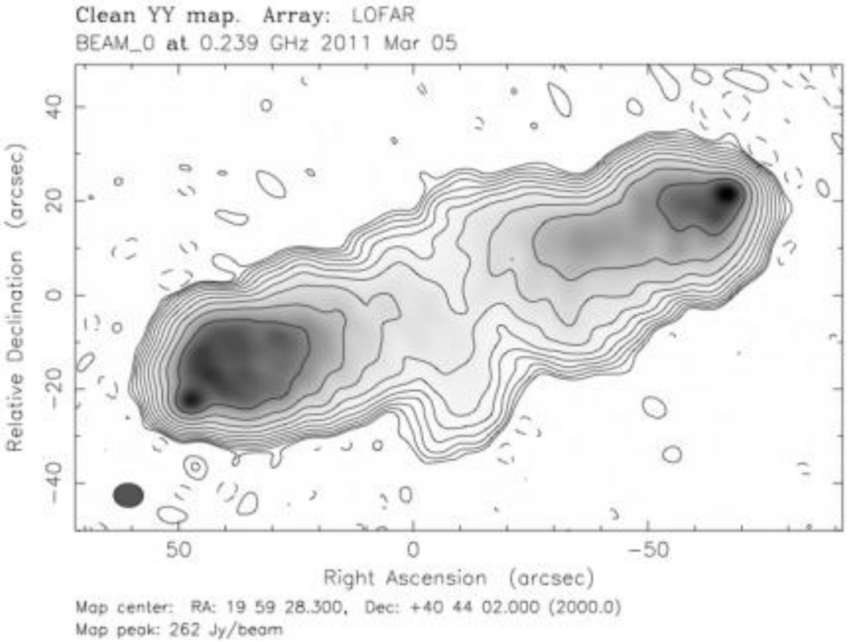
VLA Y-shaped array
instantaneous coverage at zenith



VLA
8hr long tracks for dec=30

from Burke & Graham-Smith 2002

LOFAR



UK station

Into the Future - ALMA

The Atacama Large Millimeter Array (ALMA)

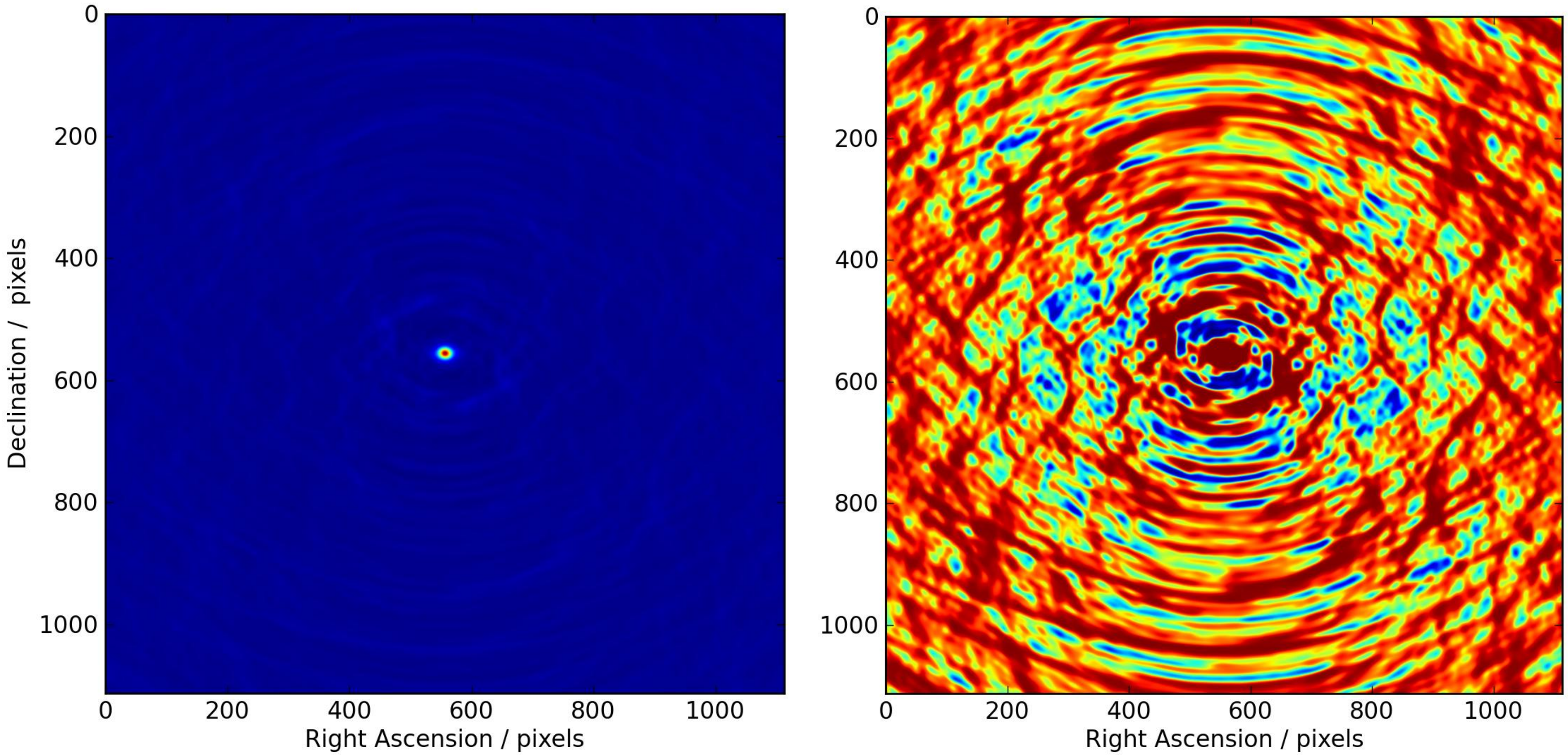
- First science phase in progress
- It will be the world's best telescope at millimeter wavelengths - by orders of magnitude
- 50 x 12m antennas (with 12+7m compact array)

It is sited at over 5000m (16000ft) in altitude in the Chilean Andes - so high that oxygen is required for workers at the high site.

Antennae are built at a base camp halfway up the mountain and then moved into place.

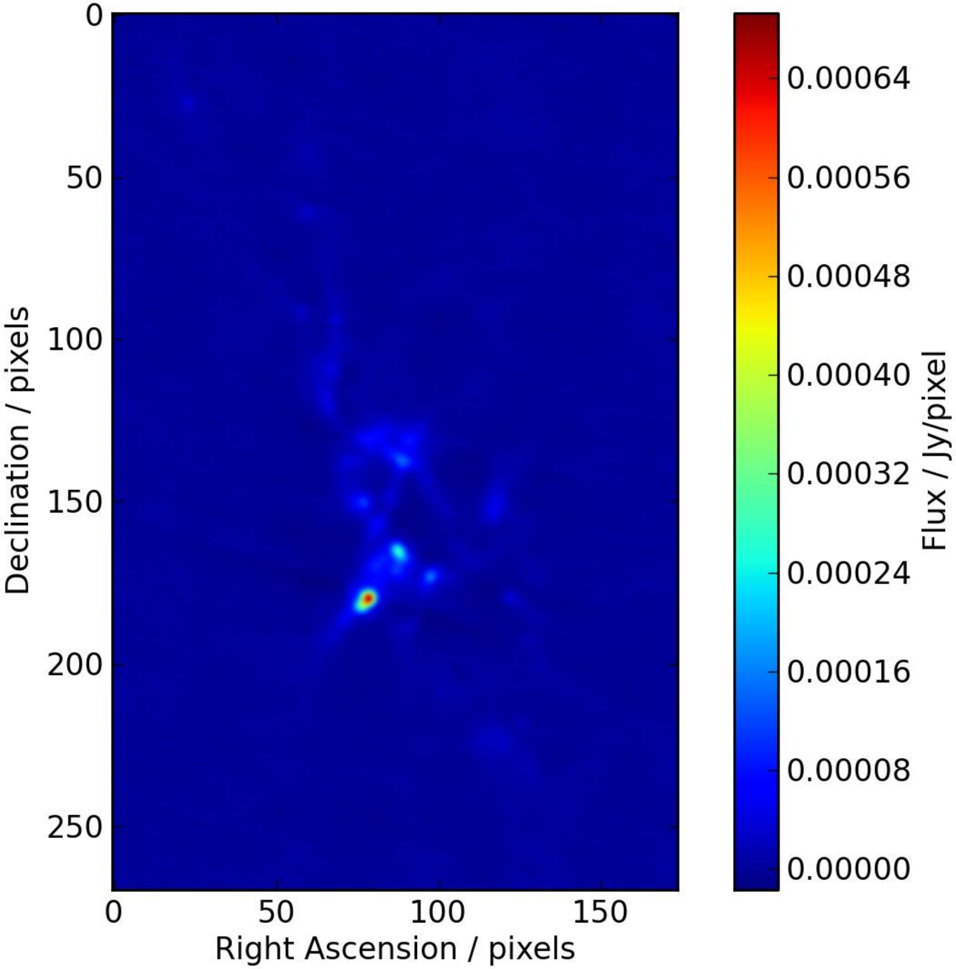
ALMA simulation

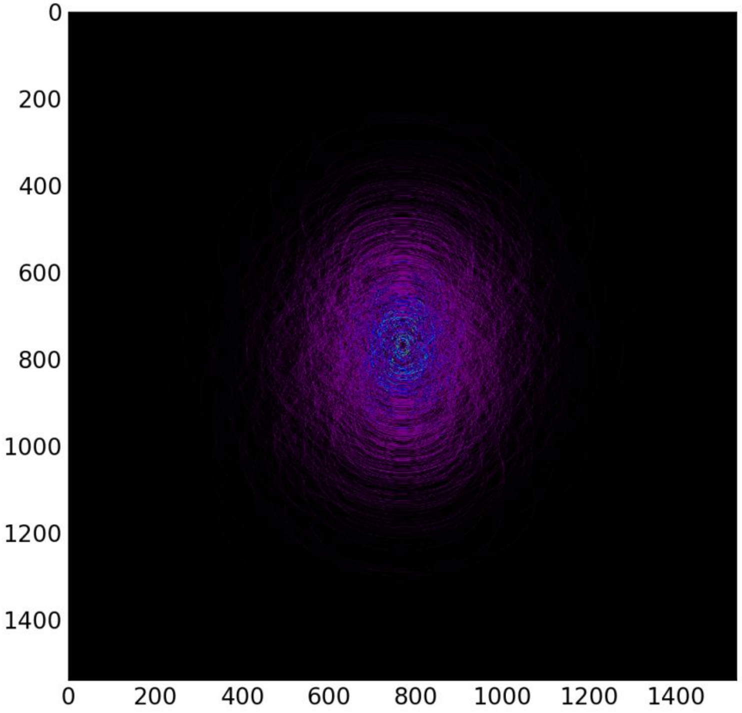
simulated PSF



ALMA simulation

input source

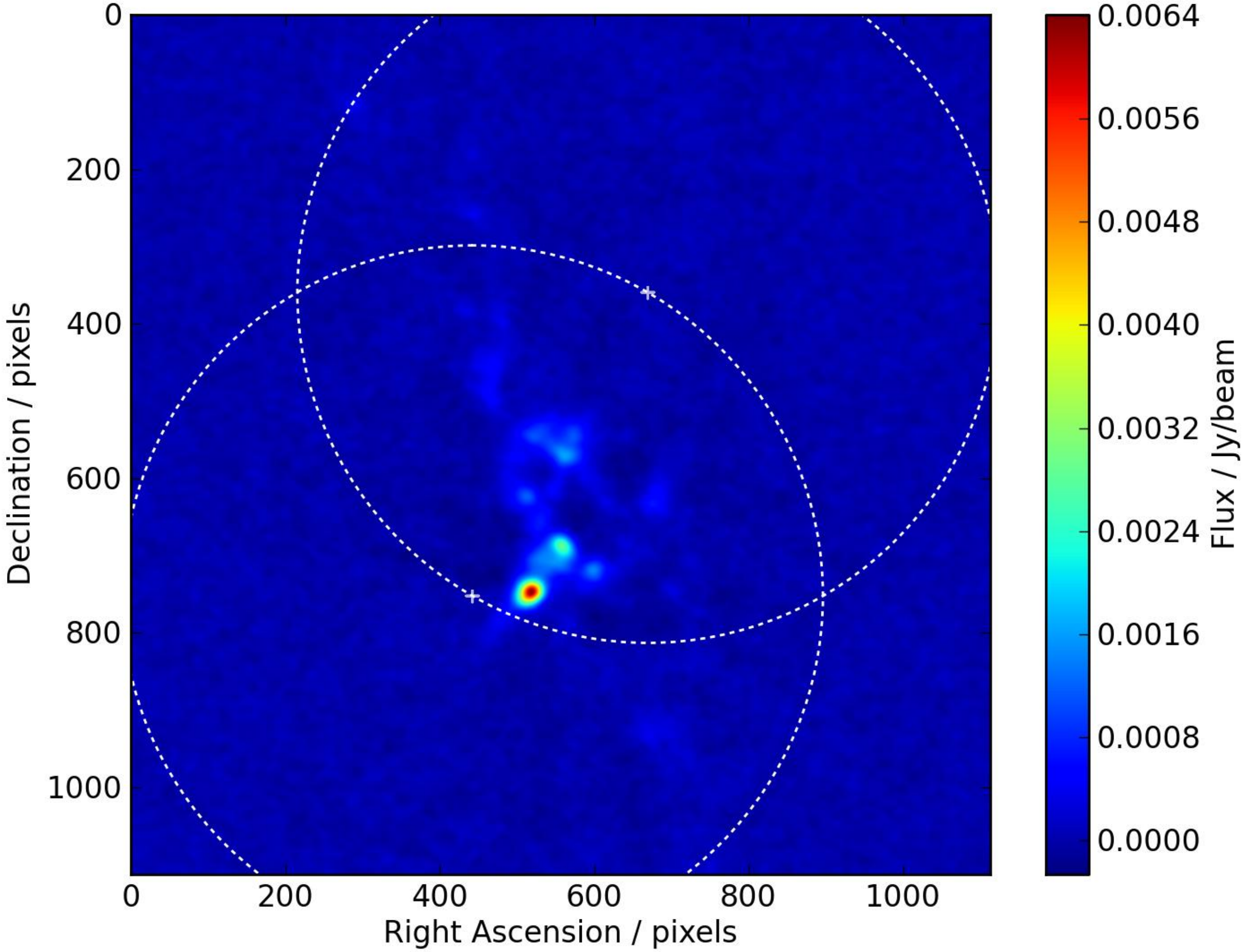




UV coverage with 8hr obs (δ=-35^{o})

ALMA simulation

reconstructed, cleaned image



Optional Exercise

- Consider a radio source at declination -35° with a flux of 0.15 mJy at 1.8GHz to be observed with the ATCA array in Australia
- Discuss which array configurations involving 5 dishes are relevant if you are interested in a beam resolution of better than 25"
- What exposure times are needed to get a >5 sigma detection in the continuum near 1.8 GHz
- Discuss why the declination of the source is relevant by comparing a similar calculation for a source at δ=-5°
- Mention any additional calibration data you need to obtain and the role of PWV

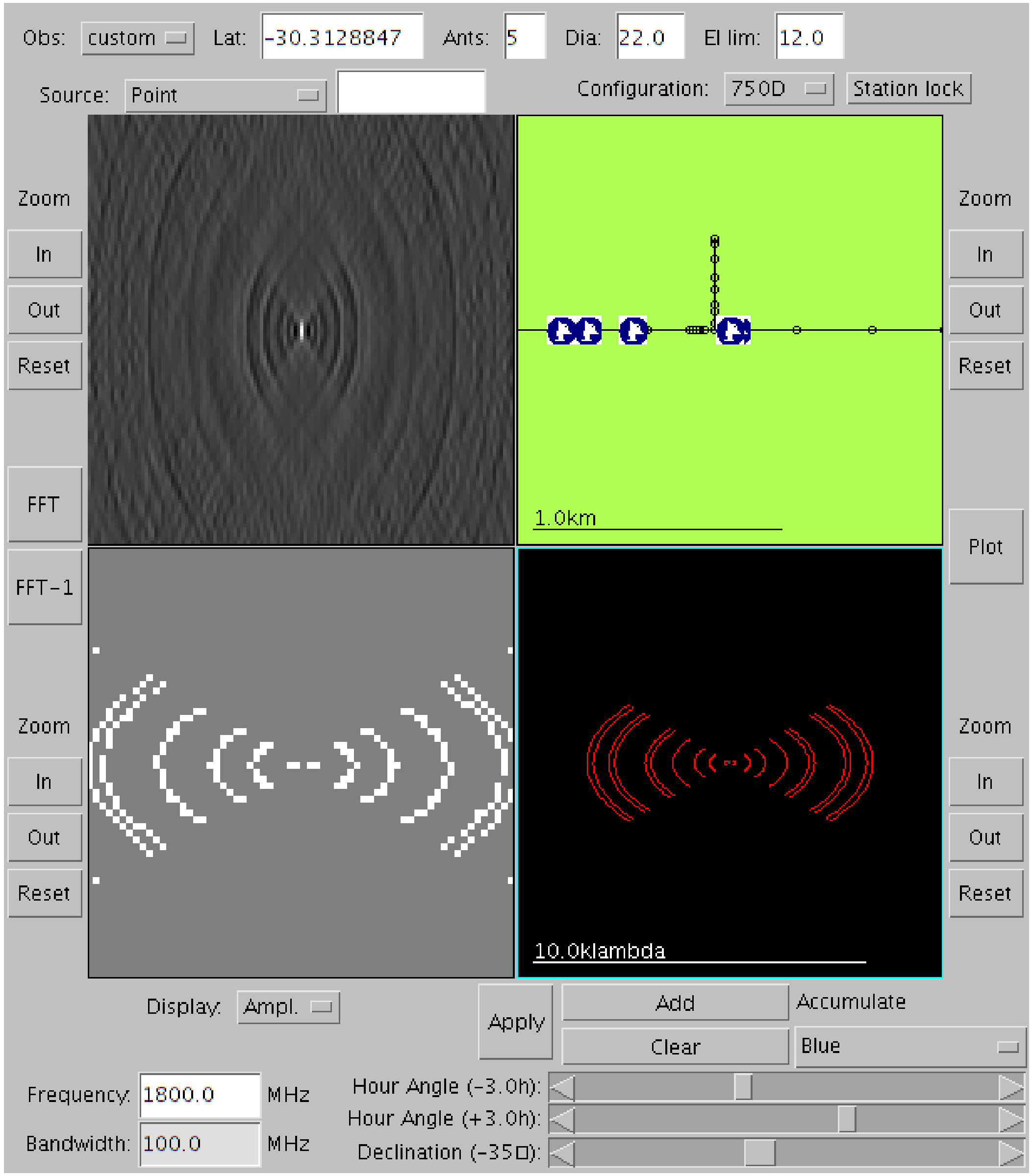
- Relevant tools:

  `http://www.narrabri.atnf.csiro.au/cgi-bin/obstools/atsen8.pl`
  `http://www.narrabri.atnf.csiro.au/astronomy/vri.html`

VRI tool

point source
test (dirty image)

visibilities



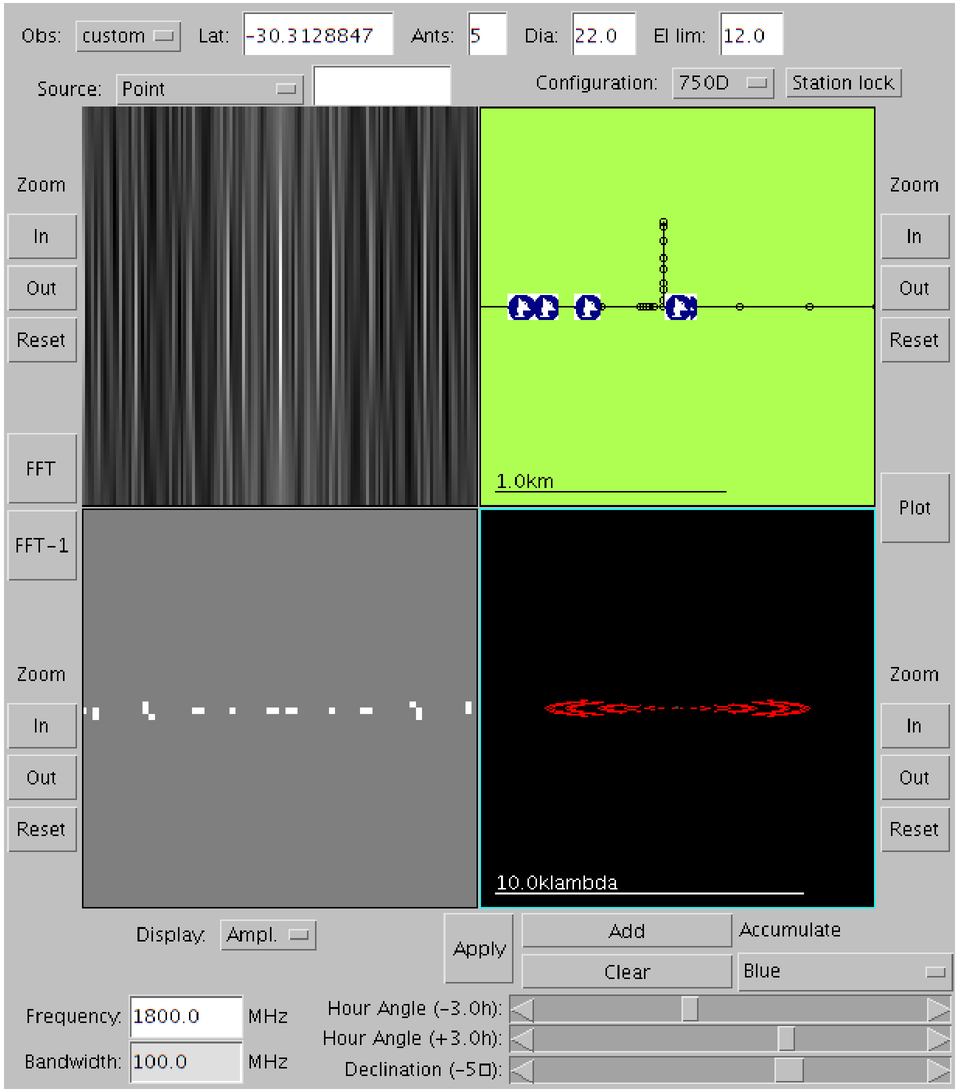
Obs: custom
Lat: -30.3128847
Ants: 5
Dia: 22.0
El lim: 12.0
Source: Point
Configuration: 750D
Display: Ampl.
Frequency: 1800.0 MHz
Bandwidth: 100.0 MHz
Hour Angle (-3.0h):
Hour Angle (+3.0h):
Declination (-35□):

Example:
5 dishes in
750m baseline
array

UV coverage
for δ=-35°
6 hours

VRI tool

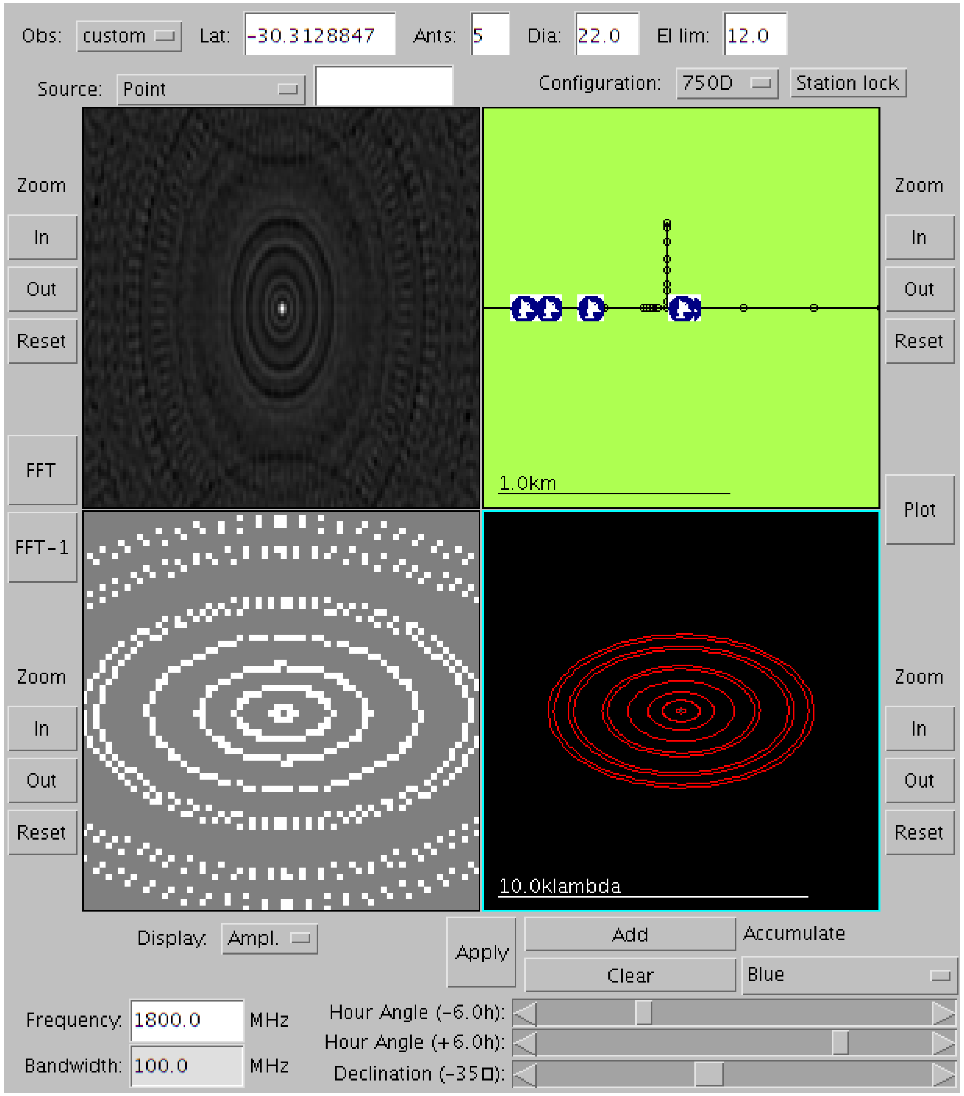
Largely 1D constraints due to low dec



Obs: custom
Lat: -30.3128847
Ants: 5
Dia: 22.0
El lim: 12.0
Source: Point
Configuration: 750D
Display: Ampl.
Accumulate
Blue
Frequency: 1800.0 MHz
Bandwidth: 100.0 MHz
Hour Angle (-3.0h):
Hour Angle (+3.0h):
Declination (-5□):

UV coverage for δ=-5° 6 hours

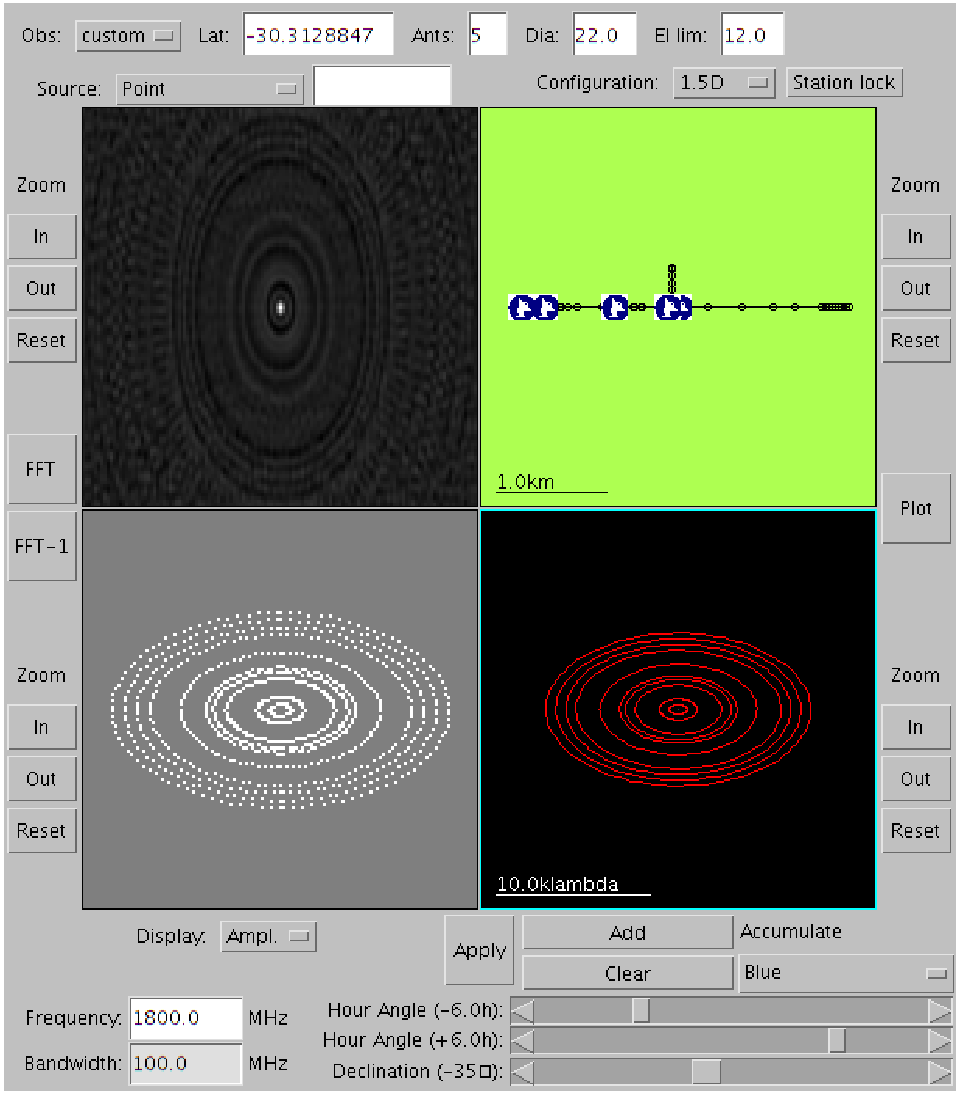
VRI tool



Obs: custom
Lat: -30.3128847
Ants: 5
Dia: 22.0
El lim: 12.0
Source: Point
Configuration: 750D
Display: Ampl.
Accumulate
Blue
Frequency: 1800.0 MHz
Bandwidth: 100.0 MHz
Hour Angle (-6.0h):
Hour Angle (+6.0h):
Declination (-35□):

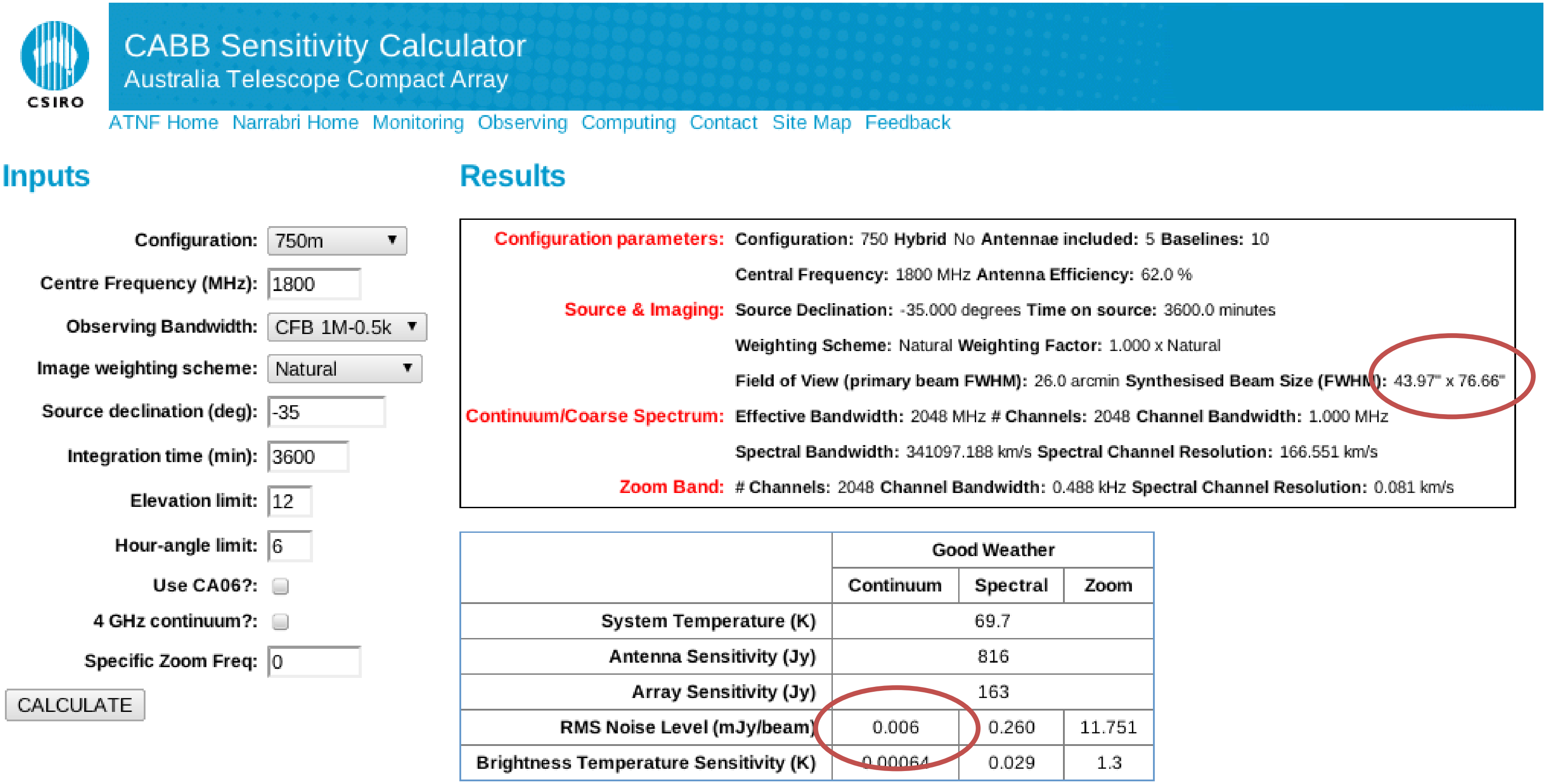
UV coverage
for δ=-35°
12 hours

VRI tool


Obs: custom
Lat: -30.3128847
Ants: 5
Dia: 22.0
El lim: 12.0
Source: Point
Configuration: 1.5D
Display: Ampl.
Frequency: 1800.0 MHz
Bandwidth: 100.0 MHz
Blue

1.5km baseline

Sensitivity Calculator



CABB Sensitivity Calculator
Australia Telescope Compact Array

Inputs

Configuration: 750m
Centre Frequency (MHz): 1800
Observing Bandwidth: CFB 1M-0.5k
Image weighting scheme: Natural
Source declination (deg): -35
Integration time (min): 3600
Elevation limit: 12
Hour-angle limit: 6
Use CA06?: ☐
4 GHz continuum?: ☐
Specific Zoom Freq: 0

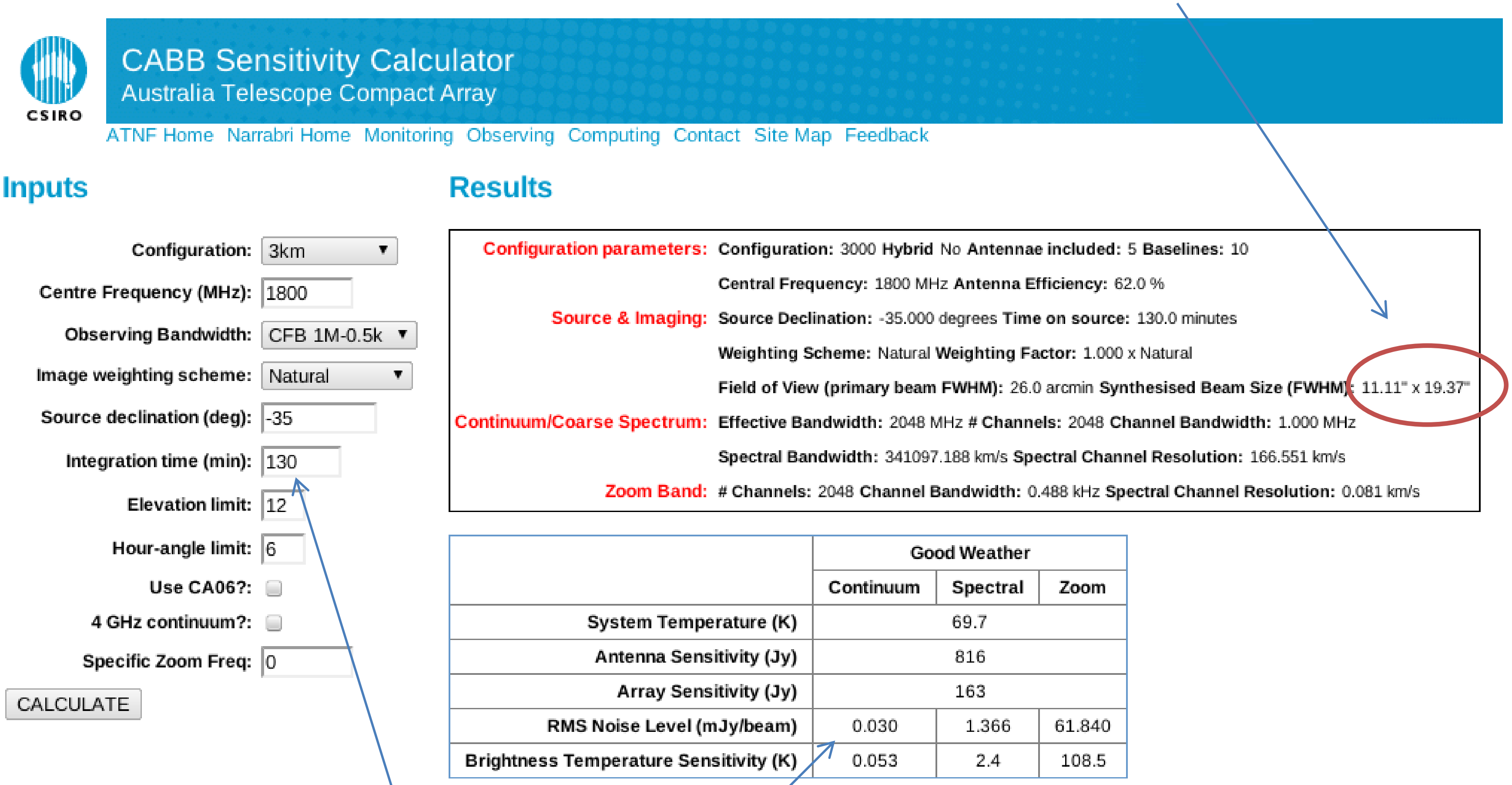
Results

Configuration parameters: **Configuration:** 750 **Hybrid** No **Antennae included:** 5 **Baselines:** 10
Central Frequency: 1800 MHz **Antenna Efficiency:** 62.0 %
Source & Imaging: **Source Declination:** -35.000 degrees **Time on source:** 3600.0 minutes
Weighting Scheme: Natural **Weighting Factor:** 1.000 x Natural
Field of View (primary beam FWHM): 26.0 arcmin **Synthesised Beam Size (FWHM):** 43.97" x 76.66"
Continuum/Coarse Spectrum: **Effective Bandwidth:** 2048 MHz **# Channels:** 2048 **Channel Bandwidth:** 1.000 MHz
Spectral Bandwidth: 341097.188 km/s **Spectral Channel Resolution:** 166.551 km/s
Zoom Band: **# Channels:** 2048 **Channel Bandwidth:** 0.488 kHz **Spectral Channel Resolution:** 0.081 km/s

	Good Weather		
	Continuum	**Spectral**	**Zoom**
System Temperature (K)	69.7		
Antenna Sensitivity (Jy)	816		
Array Sensitivity (Jy)	163		
RMS Noise Level (mJy/beam)	0.006	0.260	11.751
Brightness Temperature Sensitivity (K)	0.00064	0.029	1.3

Sensitivity Calculator

3km baseline offers enough resolution <25” in both axes



CABB Sensitivity Calculator
Australia Telescope Compact Array

Inputs

Configuration: 3km
Centre Frequency (MHz): 1800
Observing Bandwidth: CFB 1M-0.5k
Image weighting scheme: Natural
Source declination (deg): -35
Integration time (min): 130
Elevation limit: 12
Hour-angle limit: 6
Use CA06?: ☐
4 GHz continuum?: ☐
Specific Zoom Freq: 0

Results

Configuration parameters: **Configuration:** 3000 **Hybrid** No **Antennae included:** 5 **Baselines:** 10
Central Frequency: 1800 MHz **Antenna Efficiency:** 62.0 %
Source & Imaging: **Source Declination:** -35.000 degrees **Time on source:** 130.0 minutes
Weighting Scheme: Natural **Weighting Factor:** 1.000 x Natural
Field of View (primary beam FWHM): 26.0 arcmin **Synthesised Beam Size (FWHM):** 11.11" x 19.37"
Continuum/Coarse Spectrum: **Effective Bandwidth:** 2048 MHz **# Channels:** 2048 **Channel Bandwidth:** 1.000 MHz
Spectral Bandwidth: 341097.188 km/s **Spectral Channel Resolution:** 166.551 km/s
Zoom Band: **# Channels:** 2048 **Channel Bandwidth:** 0.488 kHz **Spectral Channel Resolution:** 0.081 km/s

	Good Weather		
	Continuum	Spectral	Zoom
System Temperature (K)	69.7		
Antenna Sensitivity (Jy)	816		
Array Sensitivity (Jy)	163		
RMS Noise Level (mJy/beam)	0.030	1.366	61.840
Brightness Temperature Sensitivity (K)	0.053	2.4	108.5

5σ for 0.15 mJy needs rms=0.03, achieved in ~130mins

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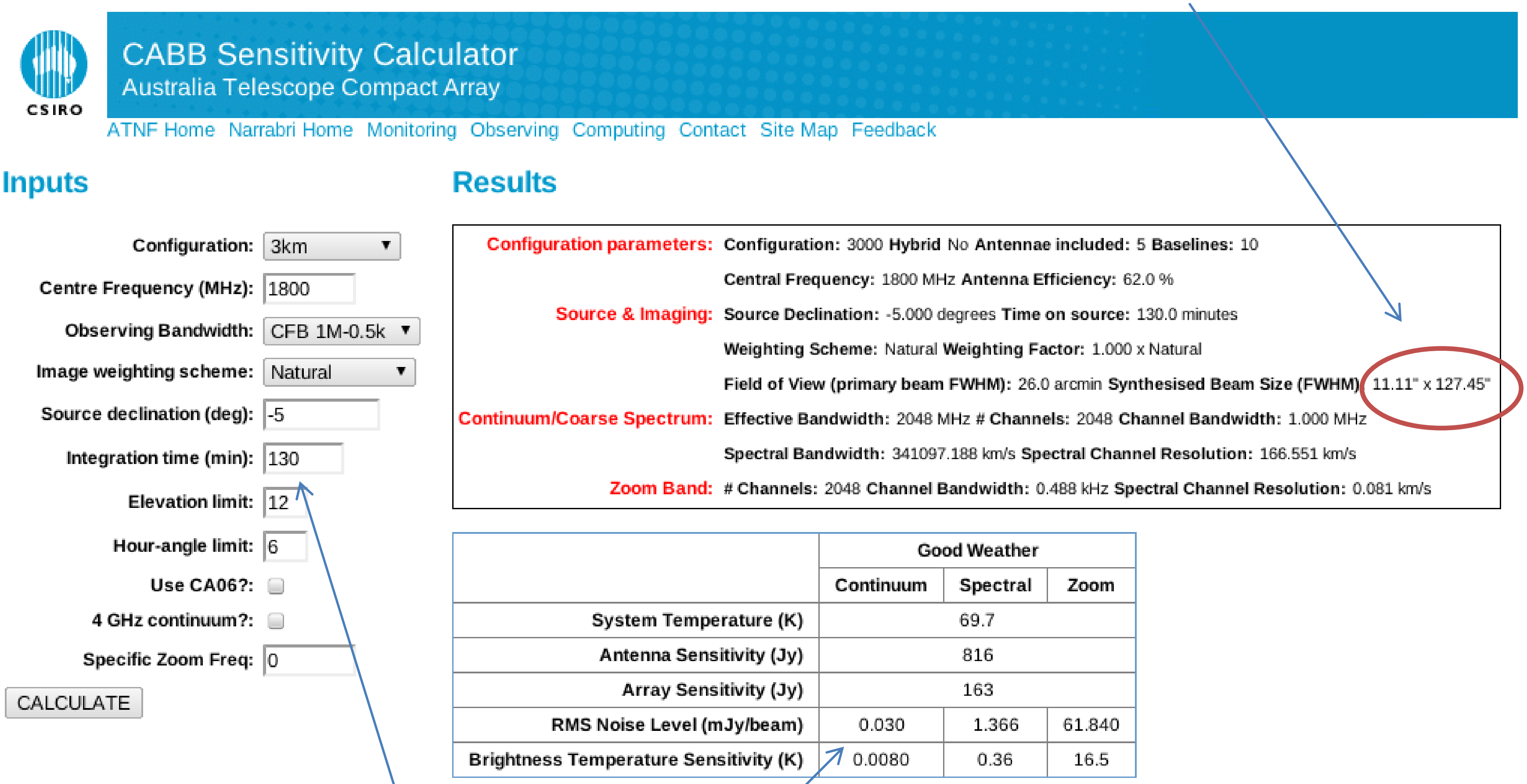
Sensitivity Calculator

low dec case results in poor beam resolution in one direction



CABB Sensitivity Calculator
Australia Telescope Compact Array

Inputs

Configuration: 3km
Centre Frequency (MHz): 1800
Observing Bandwidth: CFB 1M-0.5k
Image weighting scheme: Natural
Source declination (deg): -5
Integration time (min): 130
Elevation limit: 12
Hour-angle limit: 6
Use CA06?: ☐
4 GHz continuum?: ☐
Specific Zoom Freq: 0

Results

Configuration parameters: **Configuration:** 3000 Hybrid No **Antennae included:** 5 **Baselines:** 10
Central Frequency: 1800 MHz **Antenna Efficiency:** 62.0 %
Source & Imaging: **Source Declination:** -5.000 degrees **Time on source:** 130.0 minutes
Weighting Scheme: Natural **Weighting Factor:** 1.000 x Natural
Field of View (primary beam FWHM): 26.0 arcmin **Synthesised Beam Size (FWHM):** 11.11" x 127.45"
Continuum/Coarse Spectrum: **Effective Bandwidth:** 2048 MHz **# Channels:** 2048 **Channel Bandwidth:** 1.000 MHz
Spectral Bandwidth: 341097.188 km/s **Spectral Channel Resolution:** 166.551 km/s
Zoom Band: **# Channels:** 2048 **Channel Bandwidth:** 0.488 kHz **Spectral Channel Resolution:** 0.081 km/s

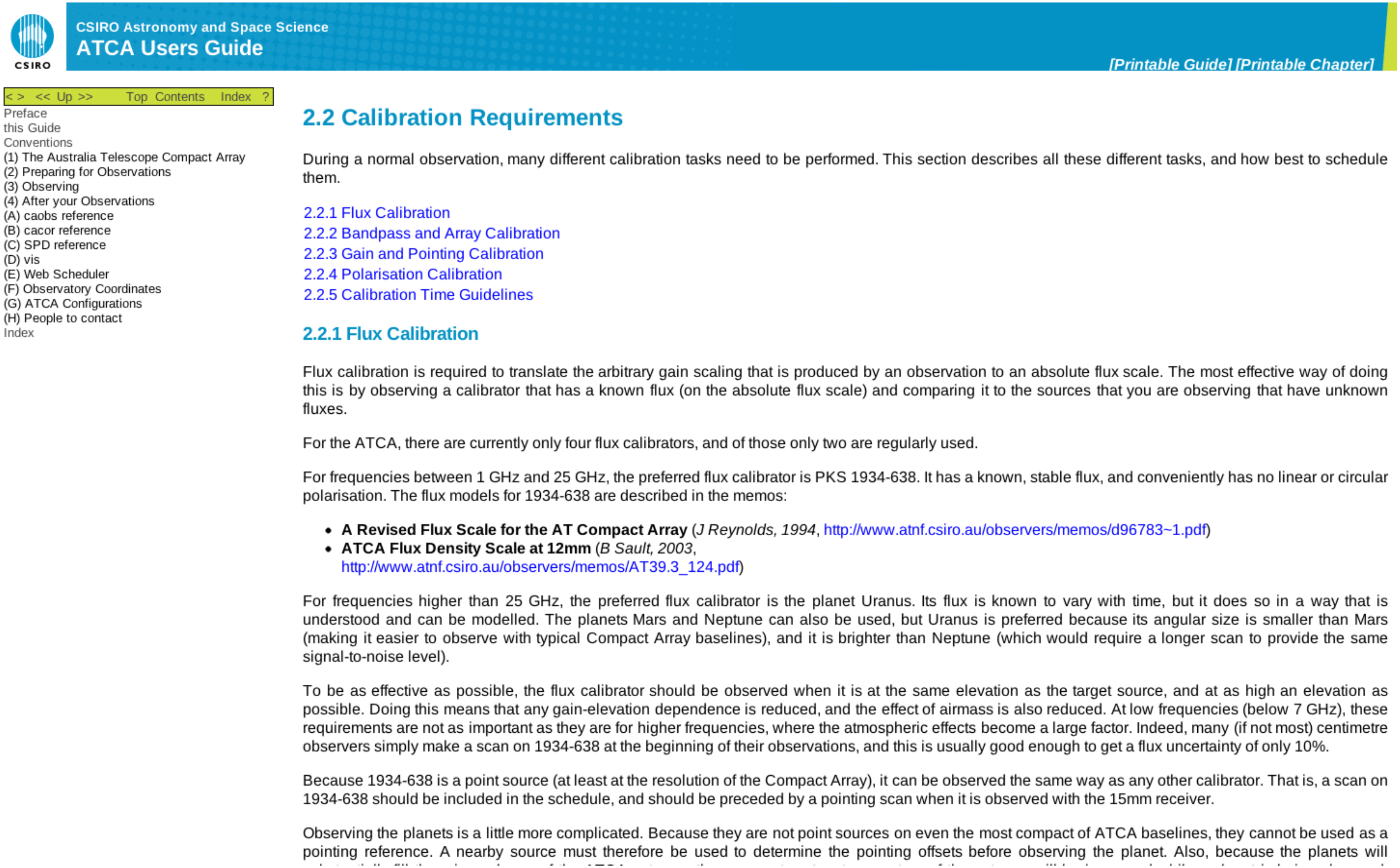
	Good Weather		
	Continuum	Spectral	Zoom
System Temperature (K)	69.7		
Antenna Sensitivity (Jy)	816		
Array Sensitivity (Jy)	163		
RMS Noise Level (mJy/beam)	0.030	1.366	61.840
Brightness Temperature Sensitivity (K)	0.0080	0.36	16.5

nominal flux limit unchanged

Considerations

- Image formation compromised for low dec sources
- Beating down the noise may only take a couple of hours, but UV coverage will be poor
- All this makes observing non-point sources more difficult to assess
- As this involves an array, we need phase calibrator as well as flux calibrator source observations with the same configuration
- PWV is not important as 1.8 GHz is long enough wavelength (16.6cm) to avoid water vapour absorption that controls sub-mm

Calibration data



CSIRO Astronomy and Space Science
ATCA Users Guide

[Printable Guide] [Printable Chapter]

2.2 Calibration Requirements

During a normal observation, many different calibration tasks need to be performed. This section describes all these different tasks, and how best to schedule them.

2.2.1 Flux Calibration

Flux calibration is required to translate the arbitrary gain scaling that is produced by an observation to an absolute flux scale. The most effective way of doing this is by observing a calibrator that has a known flux (on the absolute flux scale) and comparing it to the sources that you are observing that have unknown fluxes.

For the ATCA, there are currently only four flux calibrators, and of those only two are regularly used.

For frequencies between 1 GHz and 25 GHz, the preferred flux calibrator is PKS 1934-638. It has a known, stable flux, and conveniently has no linear or circular polarisation. The flux models for 1934-638 are described in the memos:

- **A Revised Flux Scale for the AT Compact Array** (*J Reynolds, 1994*, http://www.atnf.csiro.au/observers/memos/d96783~1.pdf)
- **ATCA Flux Density Scale at 12mm** (*B Sault, 2003*, http://www.atnf.csiro.au/observers/memos/AT39.3_124.pdf)

For frequencies higher than 25 GHz, the preferred flux calibrator is the planet Uranus. Its flux is known to vary with time, but it does so in a way that is understood and can be modelled. The planets Mars and Neptune can also be used, but Uranus is preferred because its angular size is smaller than Mars (making it easier to observe with typical Compact Array baselines), and it is brighter than Neptune (which would require a longer scan to provide the same signal-to-noise level).

To be as effective as possible, the flux calibrator should be observed when it is at the same elevation as the target source, and at as high an elevation as possible. Doing this means that any gain-elevation dependence is reduced, and the effect of airmass is also reduced. At low frequencies (below 7 GHz), these requirements are not as important as they are for higher frequencies, where the atmospheric effects become a large factor. Indeed, many (if not most) centimetre observers simply make a scan on 1934-638 at the beginning of their observations, and this is usually good enough to get a flux uncertainty of only 10%.

Because 1934-638 is a point source (at least at the resolution of the Compact Array), it can be observed the same way as any other calibrator. That is, a scan on 1934-638 should be included in the schedule, and should be preceded by a pointing scan when it is observed with the 15mm receiver.

Observing the planets is a little more complicated. Because they are not point sources on even the most compact of ATCA baselines, they cannot be used as a pointing reference. A nearby source must therefore be used to determine the pointing offsets before observing the planet. Also, because the planets will