Understanding and calibrating ionospheric effects

Dr Natasha Hurley-Walker
Curtin University / ICRAR

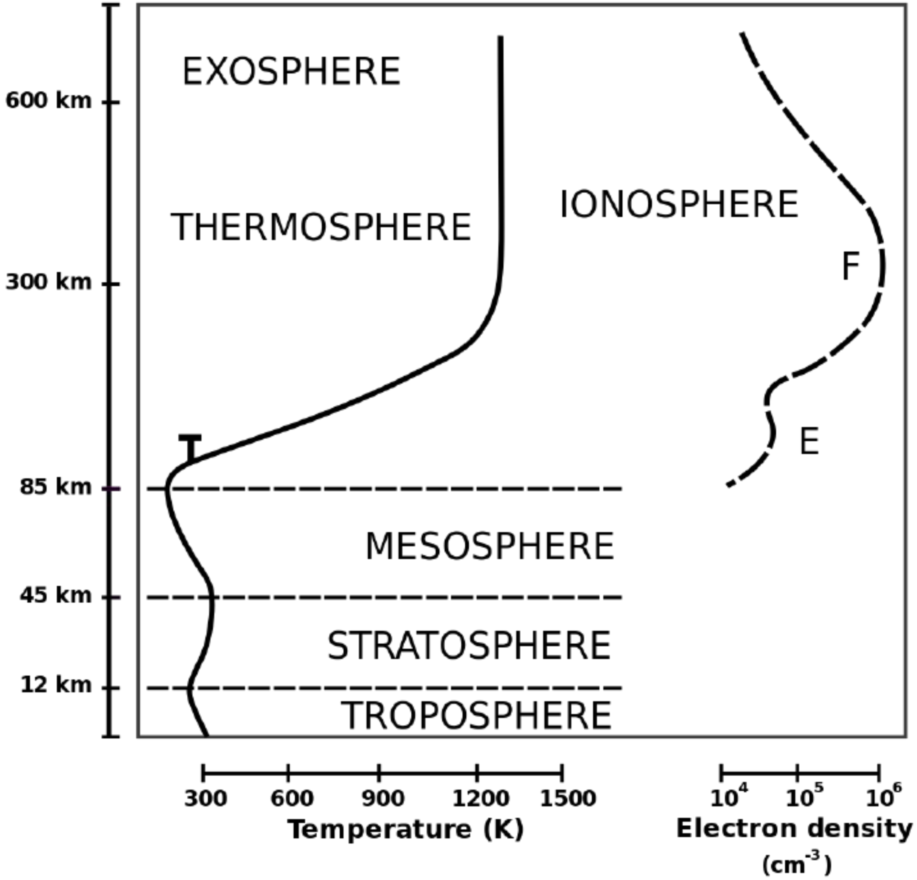
International Centre for Radio Astronomy Research

Curtin University

THE UNIVERSITY OF WESTERN AUSTRALIA

Government of Western Australia
Department of the Premier and Cabinet
Office of Science

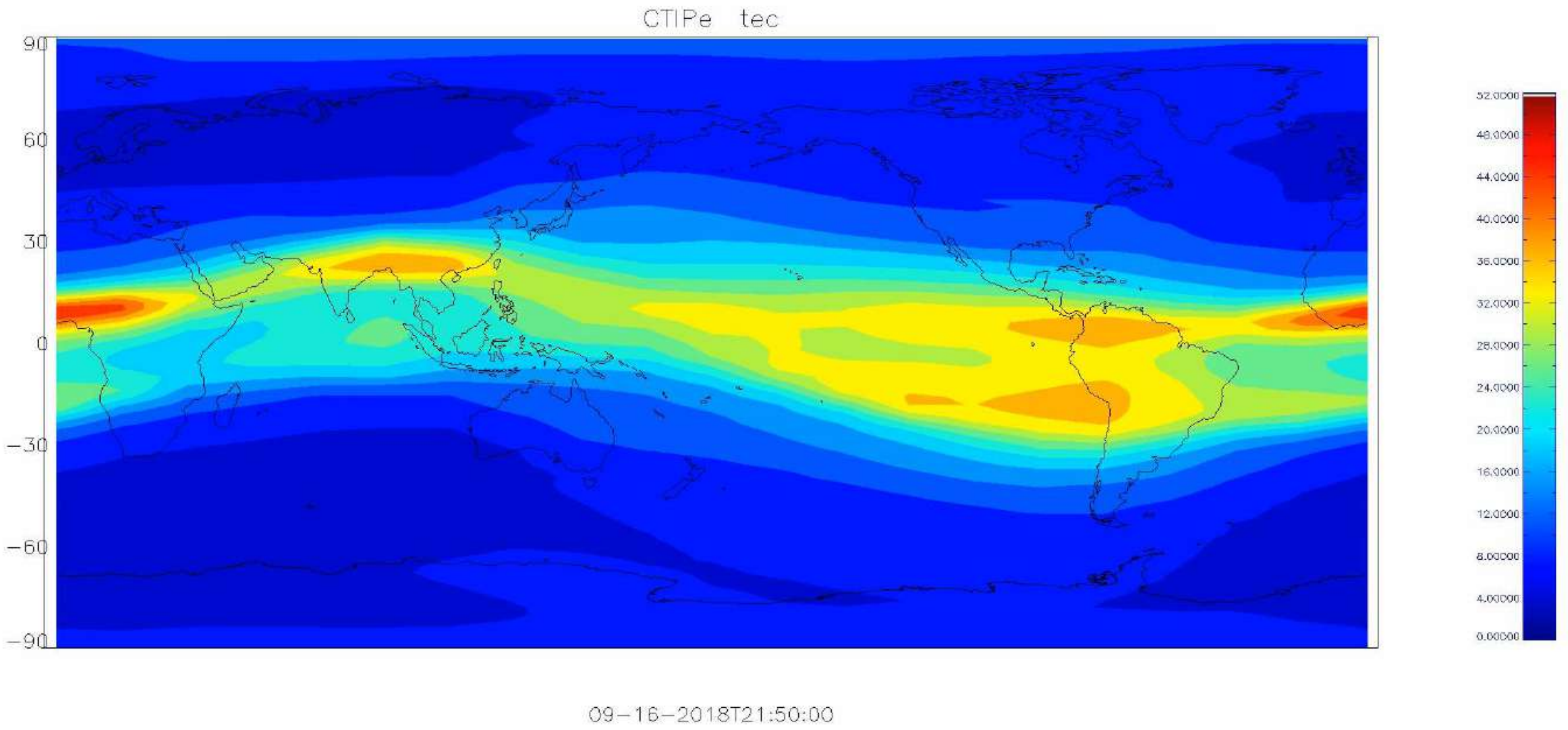
Ionosphere



By Bhamer, updated to SVG by tiZom - English Wikipedia, Public Domain, https://commons.wikimedia.org/w/index.php?curid=2178742

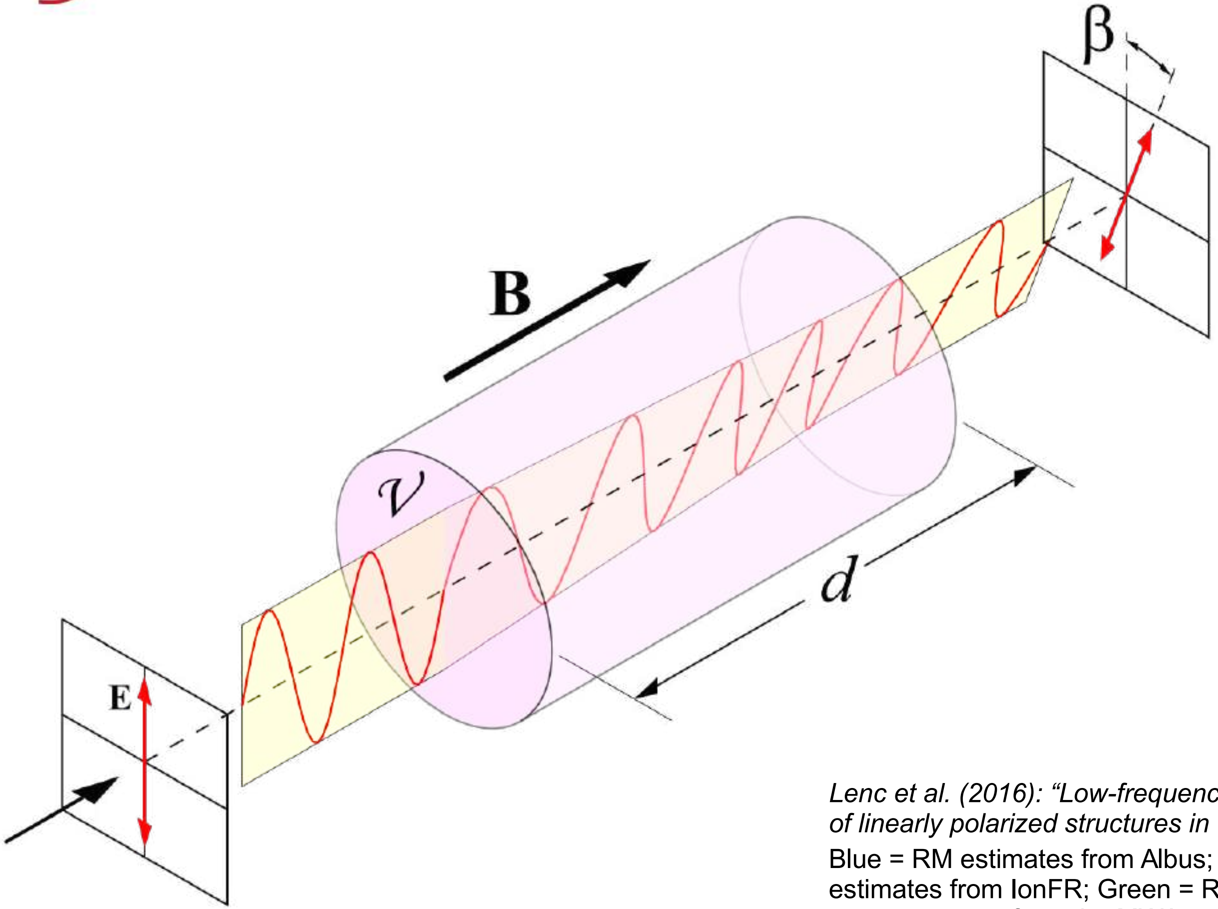
- Multiple layers during the day
- Transitions to fewer at night
- Small-scale turbulence
- Large-scale coherent features

Global ionospheric variations

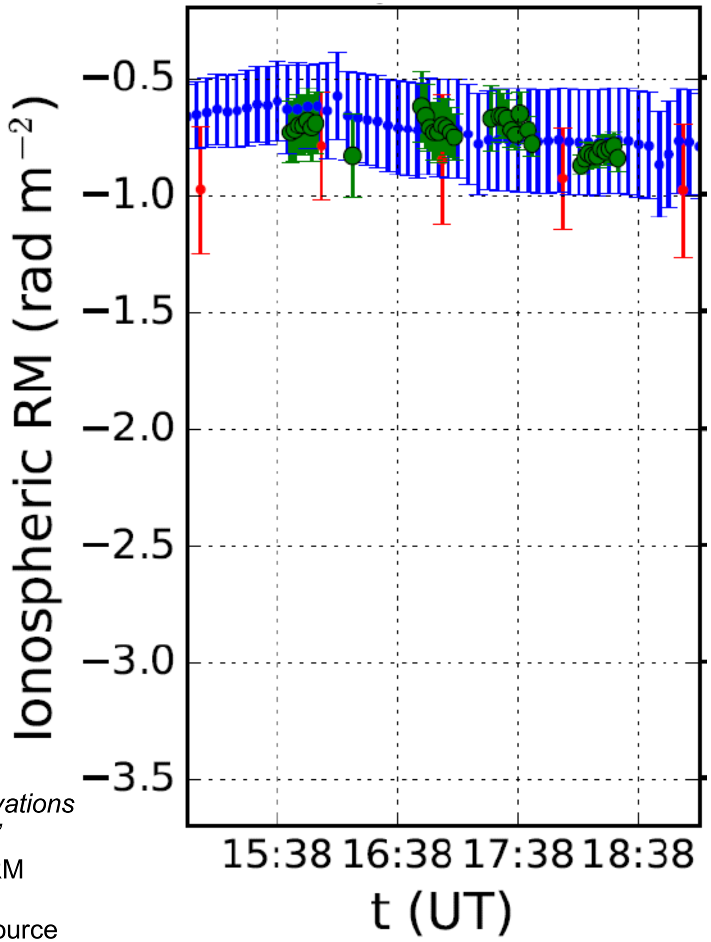


https://services.swpc.noaa.gov

Faraday rotation



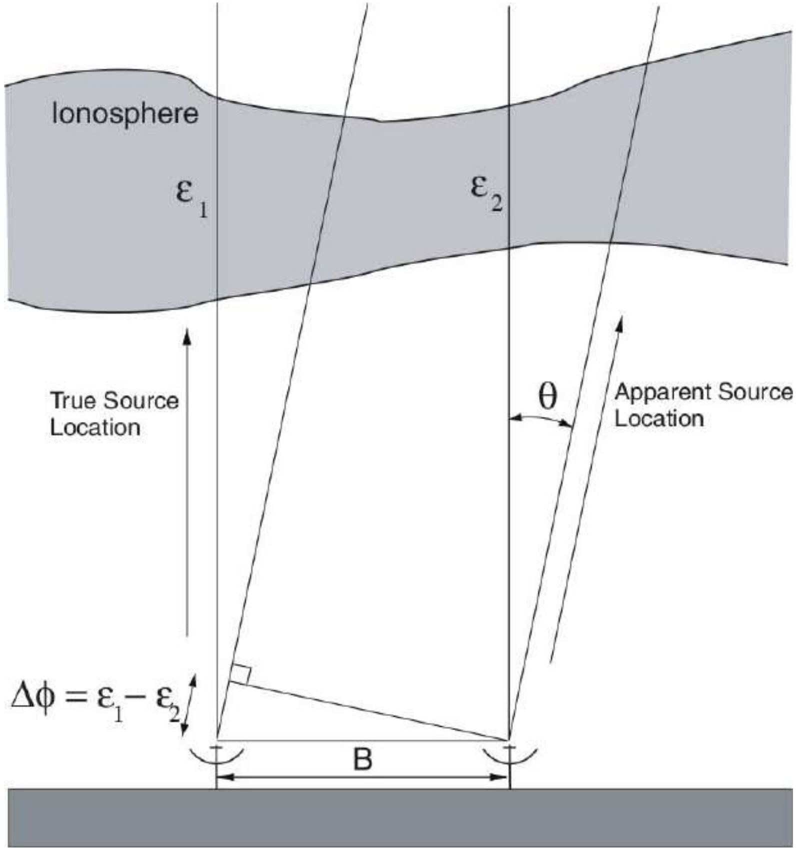
By DrBob https://en.wikipedia.org/wiki/File:Faraday-effect.svg



Lenc et al. (2016): "Low-frequency observations of linearly polarized structures in the ISM"

Blue = RM estimates from Albus; Red = RM estimates from IonFR; Green = RM measurements from the MWA toward a source of known RM

Refraction

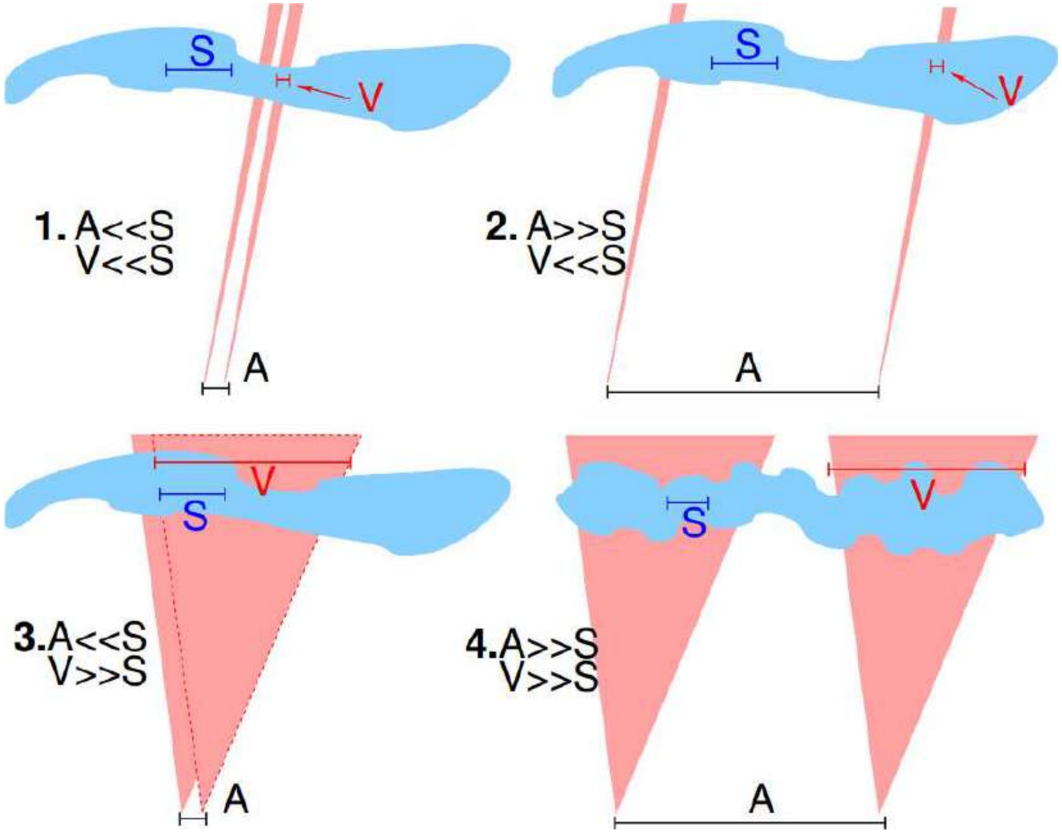


$$\theta = \frac{-1}{8\pi^2} \frac{e^2}{\eta_0 m_e} \frac{1}{\nu^2} \nabla_\perp \mathrm{TEC}$$

Different phase delays ε_1 and ε_2 yield geometric phase delay $\Delta\Phi$, due to the incoming signal emanating from a different [apparent] direction.

Cohen & Rottgering (2009): "Probing Fine-Scale Ionospheric Structure with the VLA"

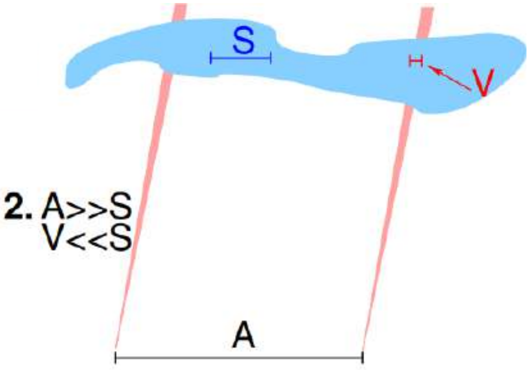
Design implications



Lonsdale (2005): "Configuration Considerations for Low-Frequency Arrays"

- **A** = **A**rray size
- **V** = field of **V**iew
- **S** = ionospheric **S**cale

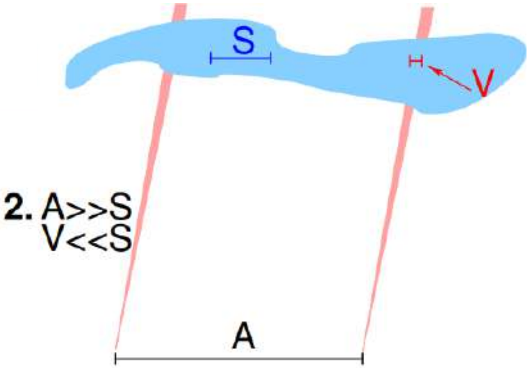
Regime 2: A>>S, V<<S: VLA



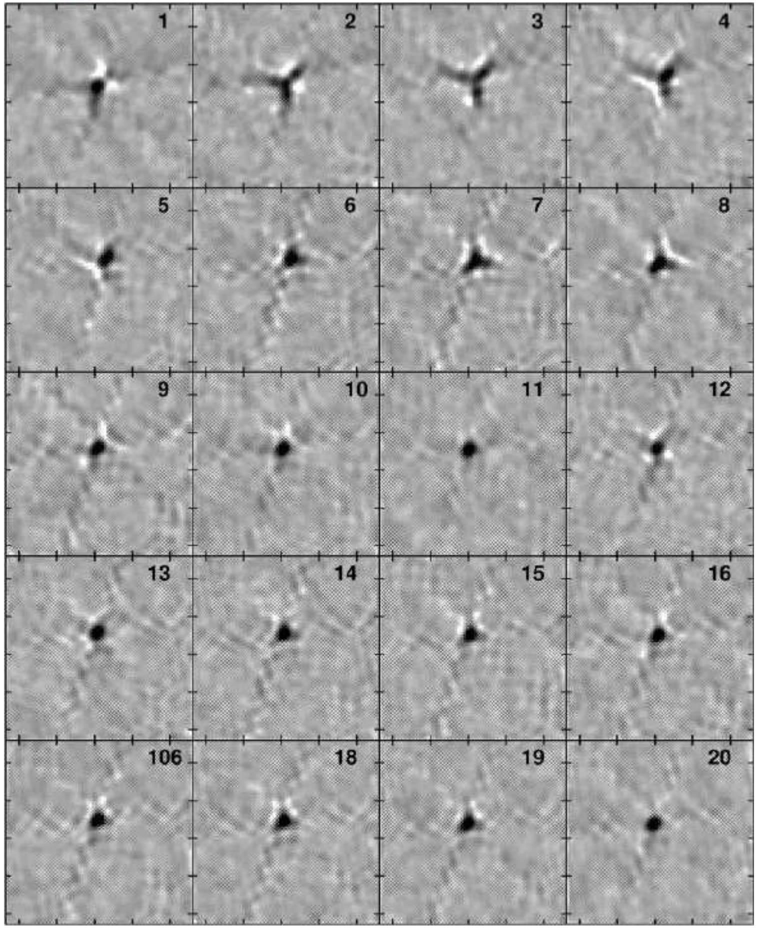
Seeing same dTEC

Regime 2: A>>S, V<<S: VLA

Seeing different dTEC

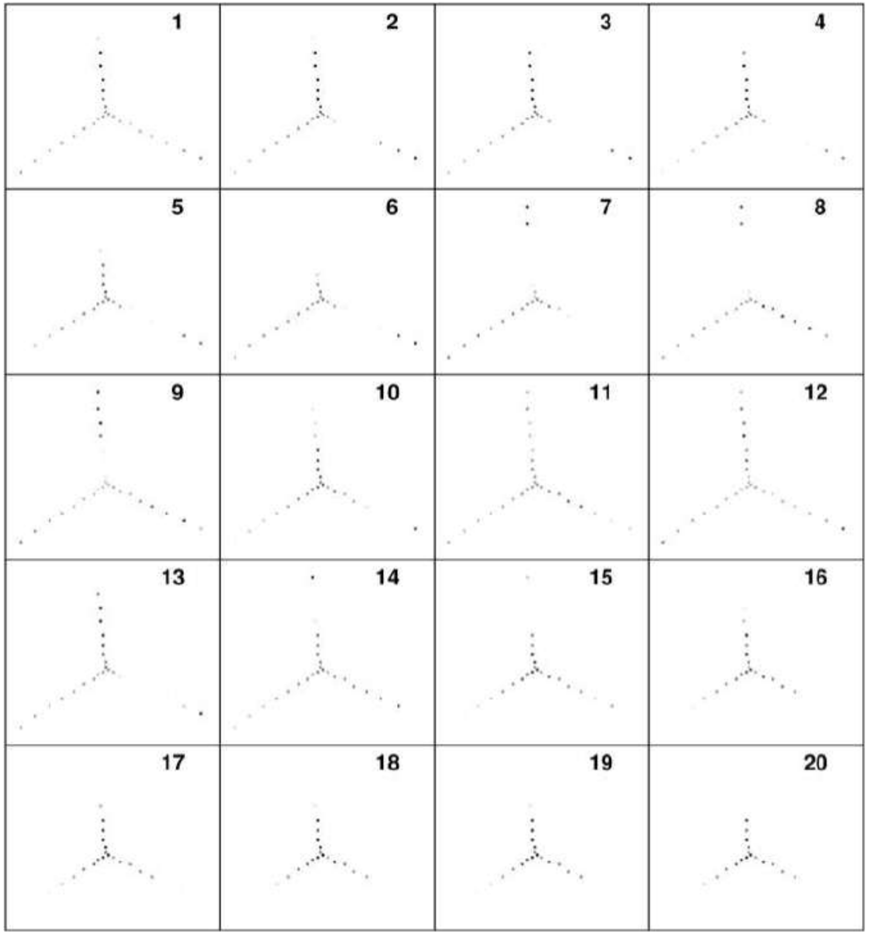


Regime 2: A>>S, V<<S: VLA



← 1-min snapshots of bright source w/ VLA (A) at 74MHz

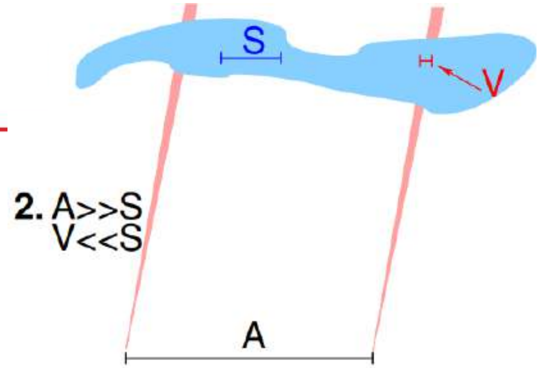
30-s interval phase gradients across the VLA (A) →



Cotton (2005): "Lessons from the VLA Long Wavelength Sky Survey (VLSS)"

Regime 2: A>>S, V<<S: VLA

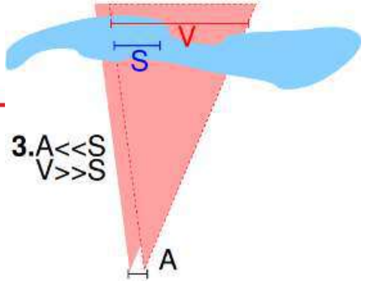
Seeing different dTEC



Δθ will be solved for when calculating the complex antenna gains

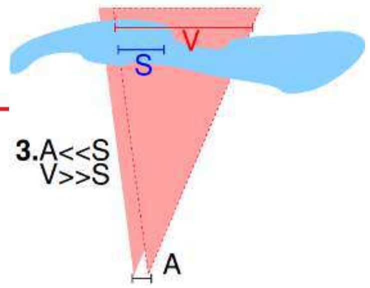
Self-calibration on short timescales may be necessary

Regime 3: A<<S, V>>S: MWA 128T

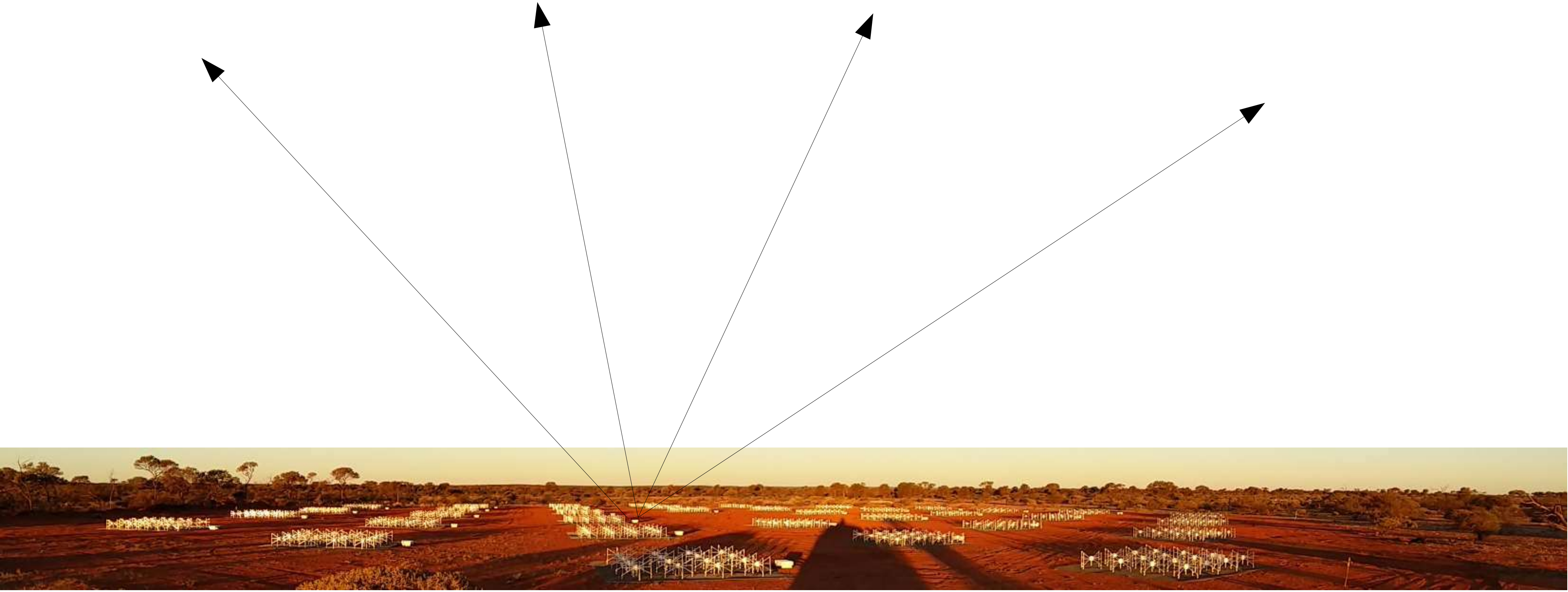


Seeing same dTEC

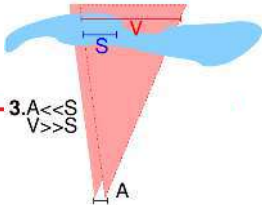
Regime 3: A<<S, V>>S: MWA 128T

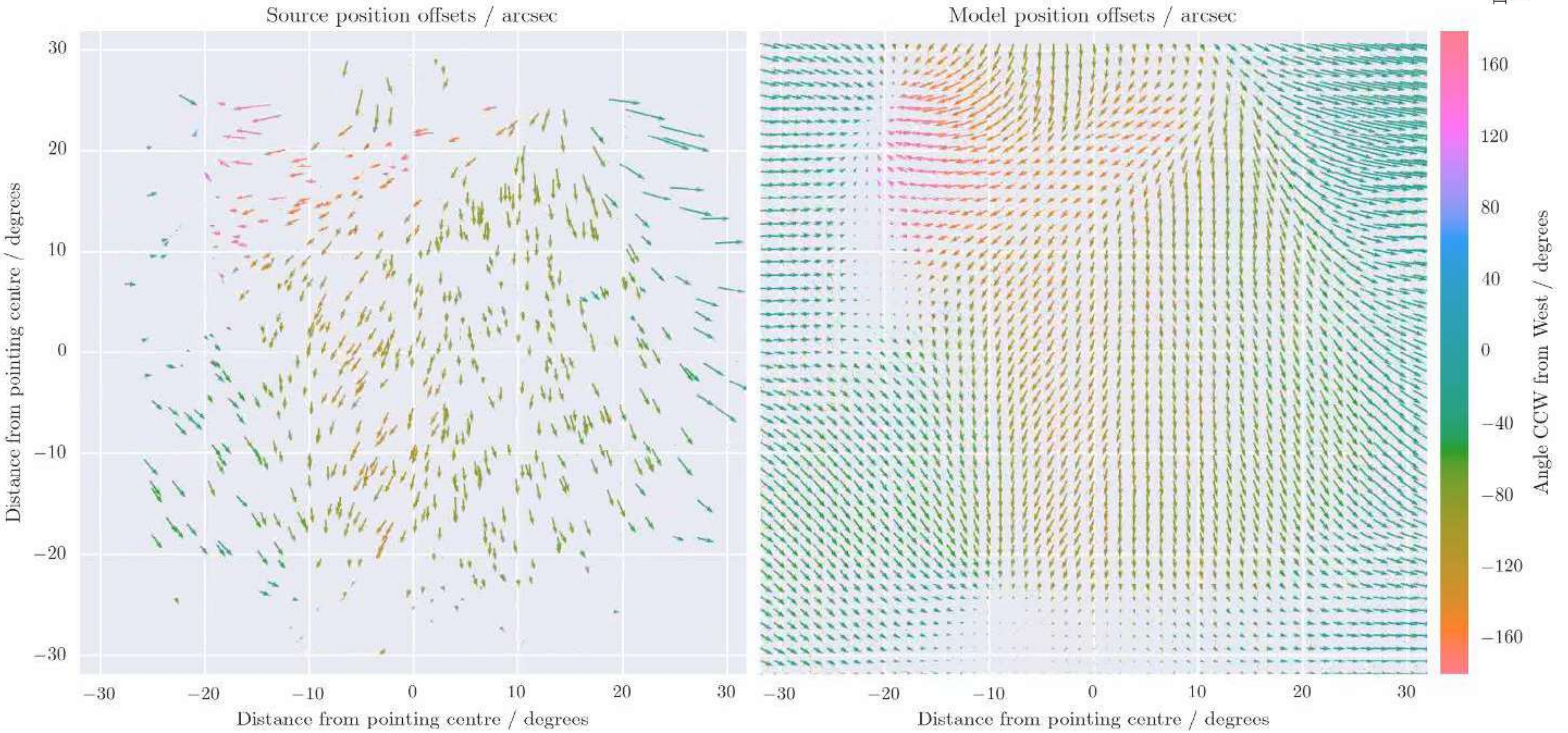


Seeing different dTEC

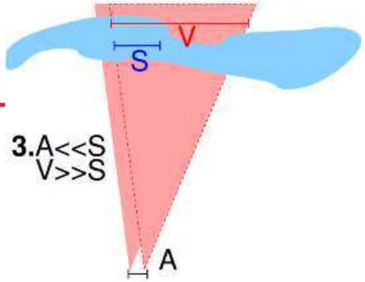


Regime 3: A<<S, V>>S: MWA 128T





Regime 3: A<<S, V>>S: MWA 128T



Seeing different dTEC

Δθ varies spatially and cannot be “fixed” in the visibilities

As there is no antenna dependence, it can be fixed perfectly in image space

Regime 3: A<<S, V>>S: MWA 128T

De-distorting ionospheric effects in the image plane

N. Hurley-Walker[a], P. J. Hancock[a]

[a] International Centre for Radio Astronomy Research, Curtin University, Bentley, WA 6102, Australia

Abstract

The Earth's ionosphere refracts radio waves incident on an interferometer, resulting in shifts to the measured positions of radio sources. We present a method to smoothly remove these shifts and restore sources to their reference positions, in both the catalogue and image domains. The method is applicable to instruments and ionospheric weather such that all antennas see the same ionosphere. The method is generalisable to repairing any sparsely-sampled vector field distortion to some input data. The code is available under the Academic Free License[1] from `https://github.com/nhurleywalker/fits_warp`.

Keywords: Astrometry, Radio Astronomy, Algorithms, Ionosphere

1. Introduction

In recent years there has been a resurgence in low-frequency radio observing, in part due to endeavors to detect the Epoch of Reionisation via its redshifted 21-cm emission. Covering frequencies between 30 and 300 MHz, low-frequency telescopes built in the last decade include the Long Wavelength Array (LWA; Taylor et al. 18), the Low-Frequency Array (LOFAR; van Haarlem et al. 26) and the Murchison Widefield Array (MWA; Tingay et al. 23, Lonsdale et al. 13). Construction of the low-frequency component of the Square Kilometer Array is

e and m_e are the electron charge and mass, η_0 is the vacuum permittivity, and ν is the radio observing frequency. The negative sign indicates that the direction of refraction is toward decreasing TEC.

Lonsdale [12] explore some of the considerations for designing low-frequency radio telescopes in this regime. Figure 1 of that paper shows a schematic overview of the different conditions that may be faced by these arrays: a telescope may have short baselines, in which case all antennas see the same $\nabla_\perp$TEC along a particular line-of-sight, or it may have long baselines, in which case antennas could see a different $\nabla_\perp$TEC. A telescope

Search or jump to... Pull requests Issues Marketplace Explore

nhurleywalker / **fits_warp**

Unwatch 1 | Star 3 | Fork 2

Code | Issues 0 | Pull requests 0 | Projects 0 | Wiki | Insights | Settings

Warp catalogues and images to dedistort the effects of the ionosphere

Edit

Manage topics

18 commits | 1 branch | 0 releases | 2 contributors | AFL-3.0

Branch: master | New pull request | Create new file | Upload files | Find file | Clone or download

nhurleywalker Updated README to reflect new S/N cut optionality — Latest commit 2f6199f on 1 Jun

.gitignore	ignore pycharm files	4 months ago
LICENCE.md	add licence	4 months ago
README.md	Updated README to reflect new S/N cut optionality	4 months ago
fits_warp.py	Fixed typo	4 months ago
requirements.txt	add requirements	4 months ago

README.md

fits_warp

Aim: Warp catalogues and images to remove the distorting affect of the ionosphere.

Authors: Natasha Hurley-Walker and Paul Hancock

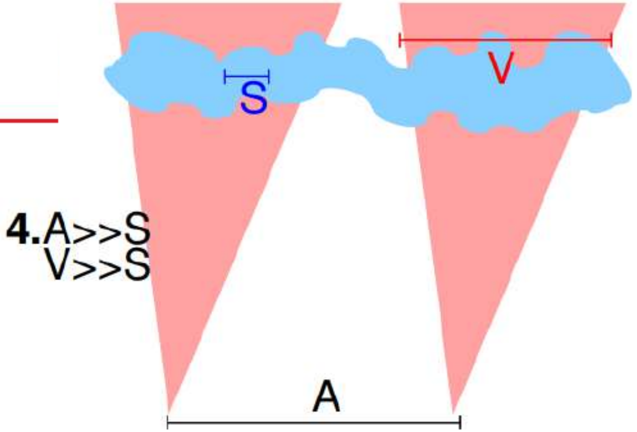
Usage

```
usage: fits_warp.py [-h] [--xm XM] [--infits INFITS] [--suffix SUFFIX]
```

https://github.com/nhurleywalker/fits_warp

Hurley-Walker & Hancock (2018): De-distorting ionospheric effects in the image plane

Regime 4: A, V >> S



LOFAR

GMRT

Direction-dependent peeling

- What is peeling?
  - Phase-rotate your data to a source
  - Solve for the antenna gains *toward that source*
  - Multiply a model of the source by those gains
  - Subtract the gain-modified source from the visibilities
  - Repeat ad nauseum

Direction-dependent peeling

- What is peeling?
  - Phase-rotate your data to a source
  - Solve for the antenna gains *toward that source*
  - Multiply a model of the source by those gains
  - Subtract the gain-modified source from the visibilities
  - Repeat ad nauseum
- Why peeling?
  - Because this is both an *image*-based problem AND an *antenna*-based problem
  - You cannot create a set of solutions in either *(u,v)* or *(l,m)* space and apply to the whole observation
  - But, you can find and apply solution in one direction, and another, and another…

Direction-dependent peeling

- What is peeling?
  - Phase-rotate your data to a source
  - Solve for the antenna gains *toward that source*
  - Multiply a model of the source by those gains
  - Subtract the gain-modified source from the visibilities
  - Repeat ad nauseum
- Why peeling?
  - Because this is both an *image*-based problem AND an *antenna*-based problem
  - You cannot create a set of solutions in either *(u,v)* or *(l,m)* space and apply to the whole observation
  - But, you can find and apply solution in one direction, and another, and another…
- How do I do this?
  - That depends...

Signal-to-noise

- Creating complex (2-parameter) gains for:
  - Each polarisation
  - Each frequency
  - Each antenna
  - Each direction
  - Each time interval
  - = huge signal-to-noise problem
- Other sources (in sidelobes, in main lobe) reduce S/N on source (in direction) of interest

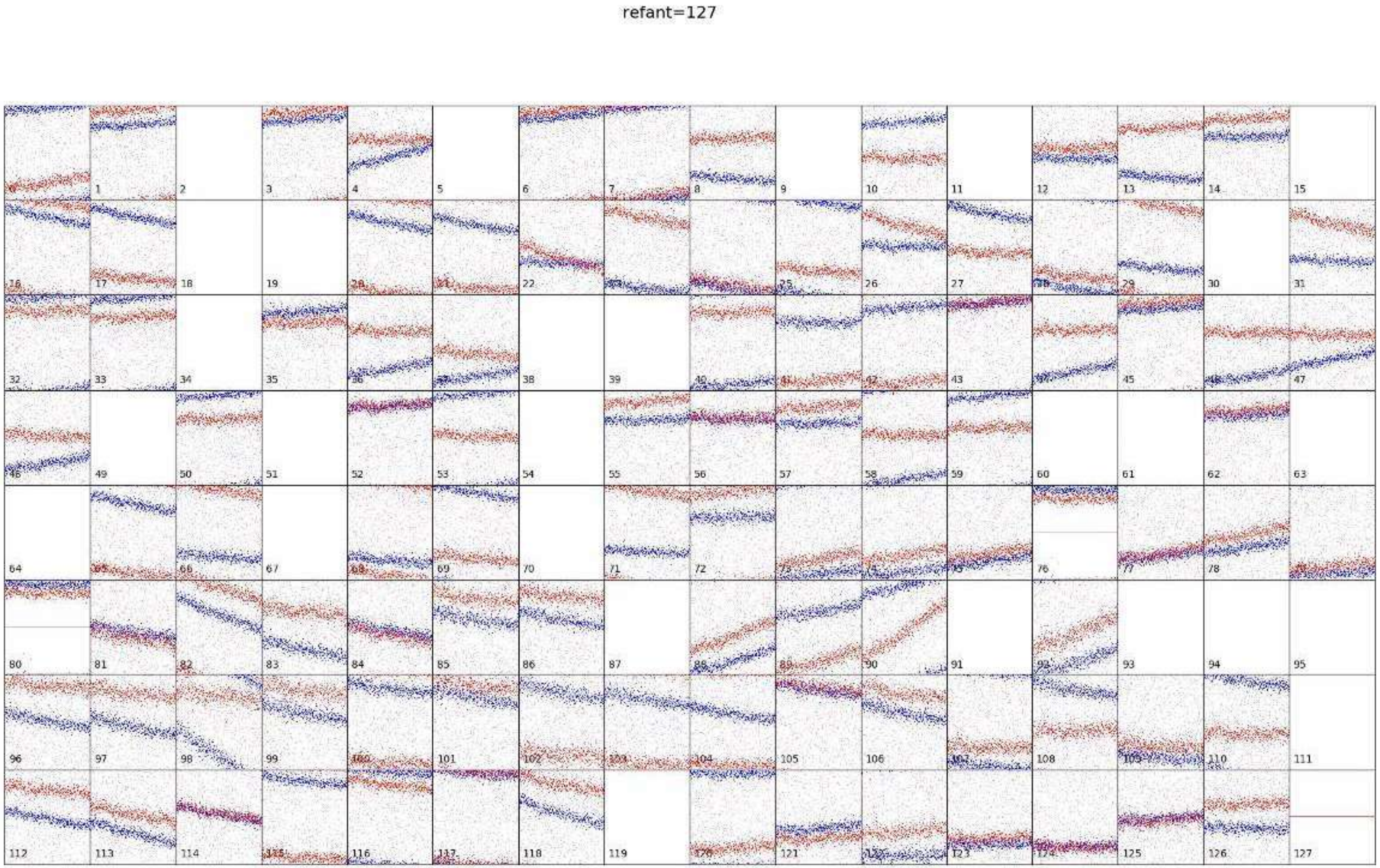
Signal-to-noise

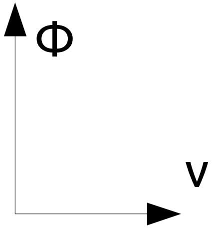
- Creating complex (2-parameter) gains for:
  - Each polarisation
  - Each frequency
  - Each antenna
  - Each direction
  - Each time interval
  - = huge signal-to-noise problem
- Other sources (in sidelobes, in main lobe) reduce S/N on source (in direction) of interest
- Every extra calibration parameter = less final S/N on astronomical problem
  - e.g. Mouri & Koopmans (2018) “Quantifying Suppression of the Cosmological 21-cm Signal due to Direction Dependent Gain Calibration in Radio Interferometers” http://adsabs.harvard.edu/abs/2018arXiv180903755M

Signal-to-noise

- Creating complex (2-parameter) gains for:
  - Each polarisation
  - Each frequency
  - Each antenna
  - Each direction
  - Each time interval
  - = huge signal-to-noise problem
- Other sources (in sidelobes, in main lobe) reduce S/N on source (in direction) of interest
- Every extra calibration parameter = less final S/N on astronomical problem
  - e.g. Mouri & Koopmans (2018) “Quantifying Suppression of the Cosmological 21-cm Signal due to Direction Dependent Gain Calibration in Radio Interferometers” http://adsabs.harvard.edu/abs/2018arXiv180903755M
- How to increase S/N?

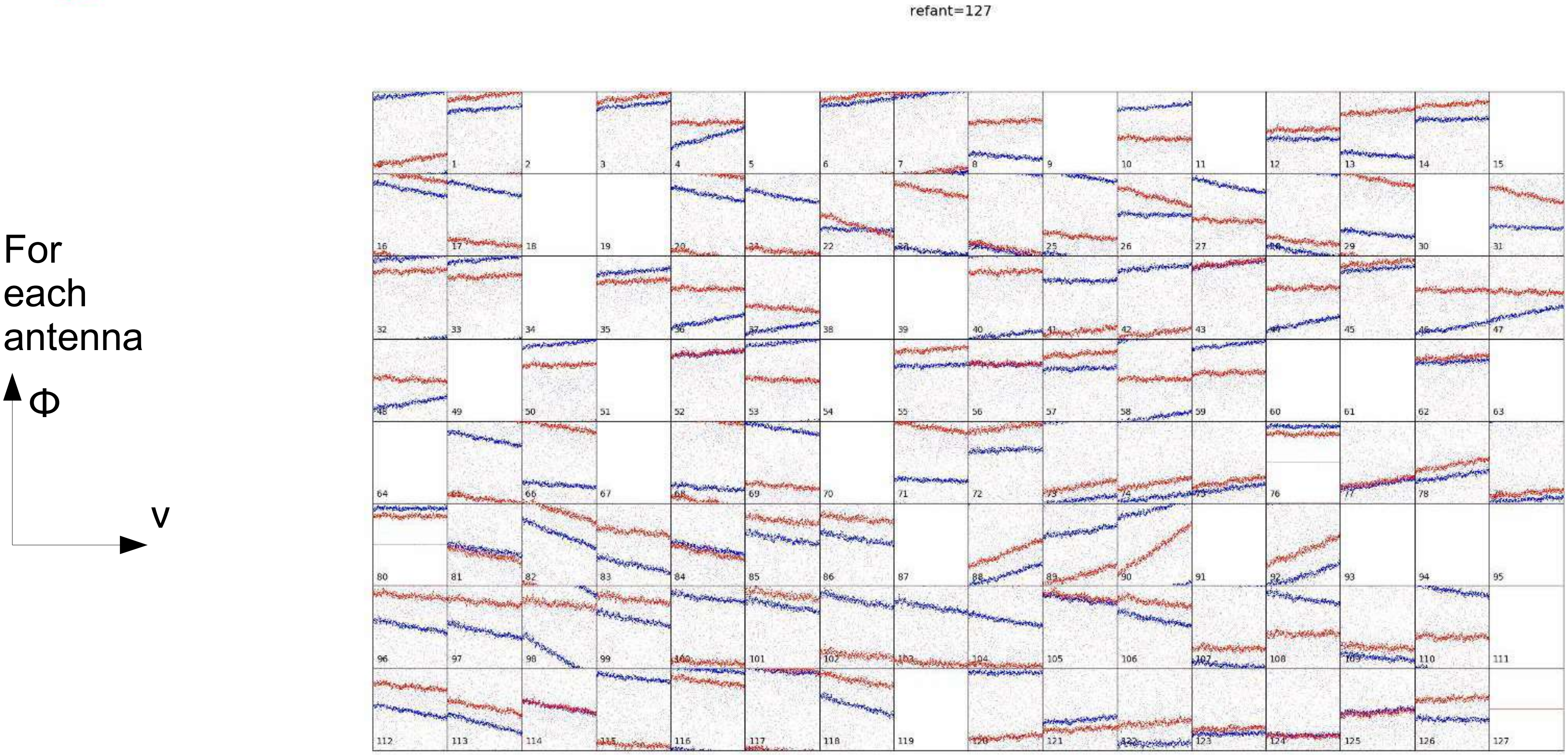
Building S/N: Appropriate time intervals (1s)



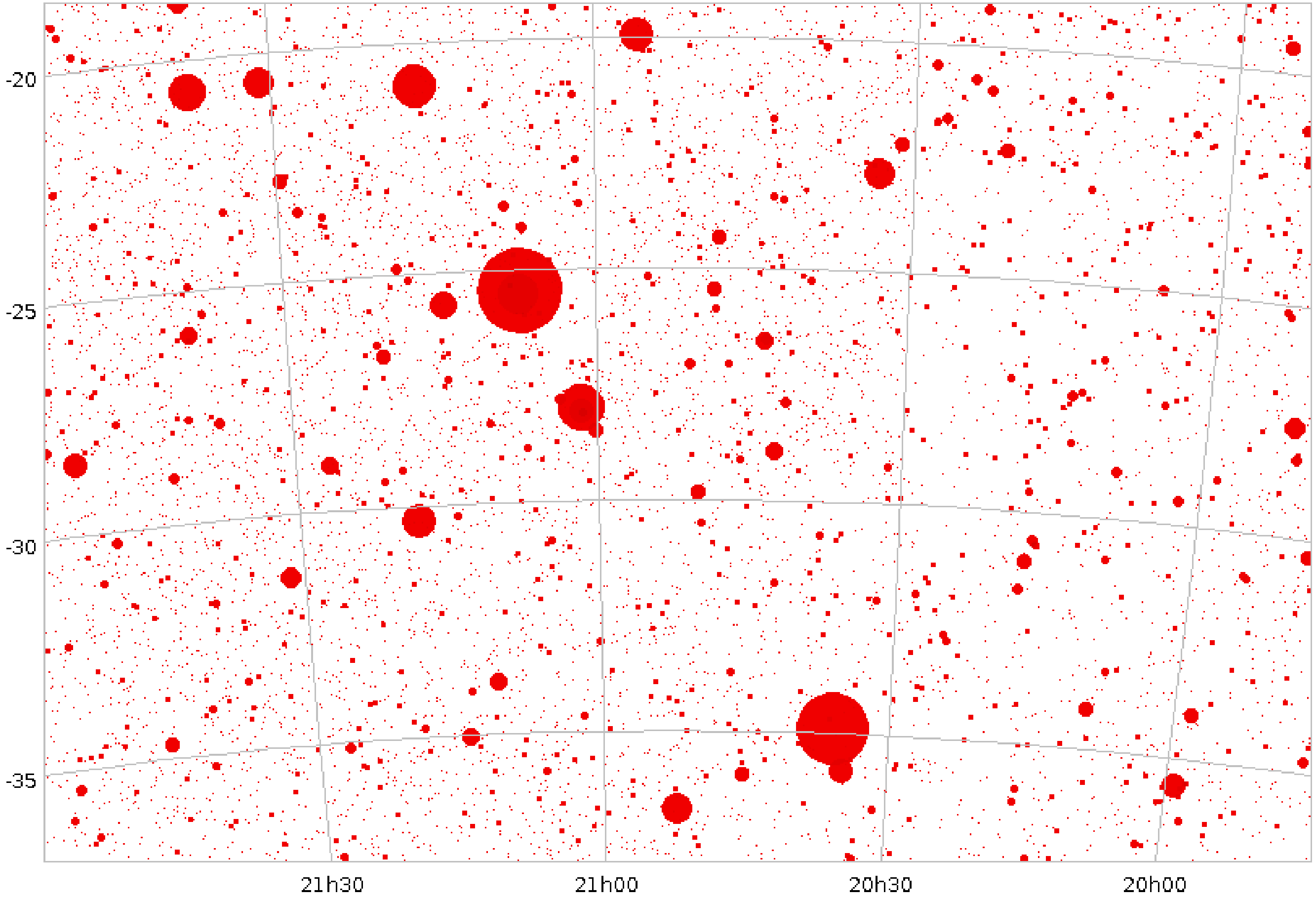


Building S/N: Appropriate time intervals (5s)

For each antenna

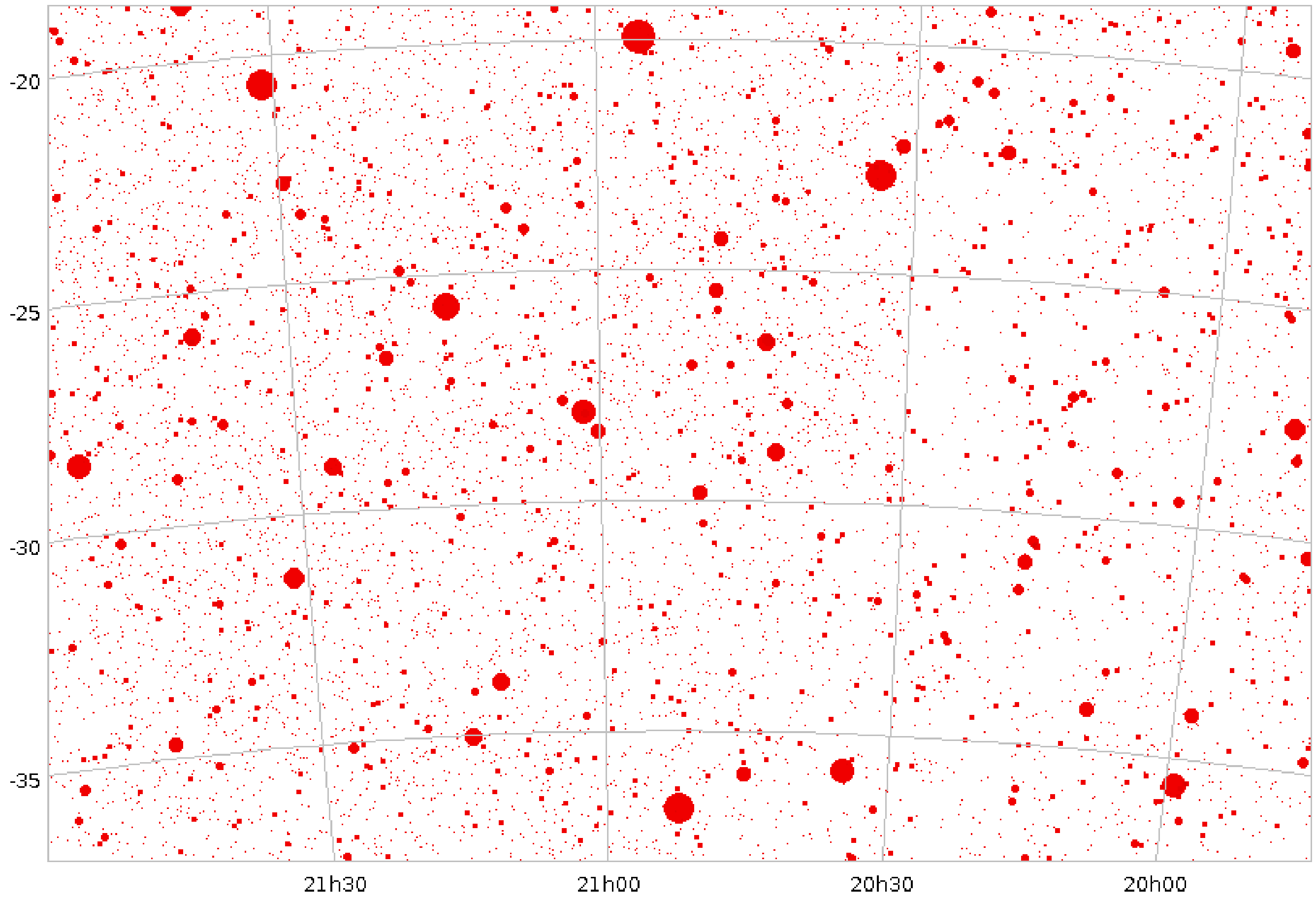


Building S/N: Ranking sources



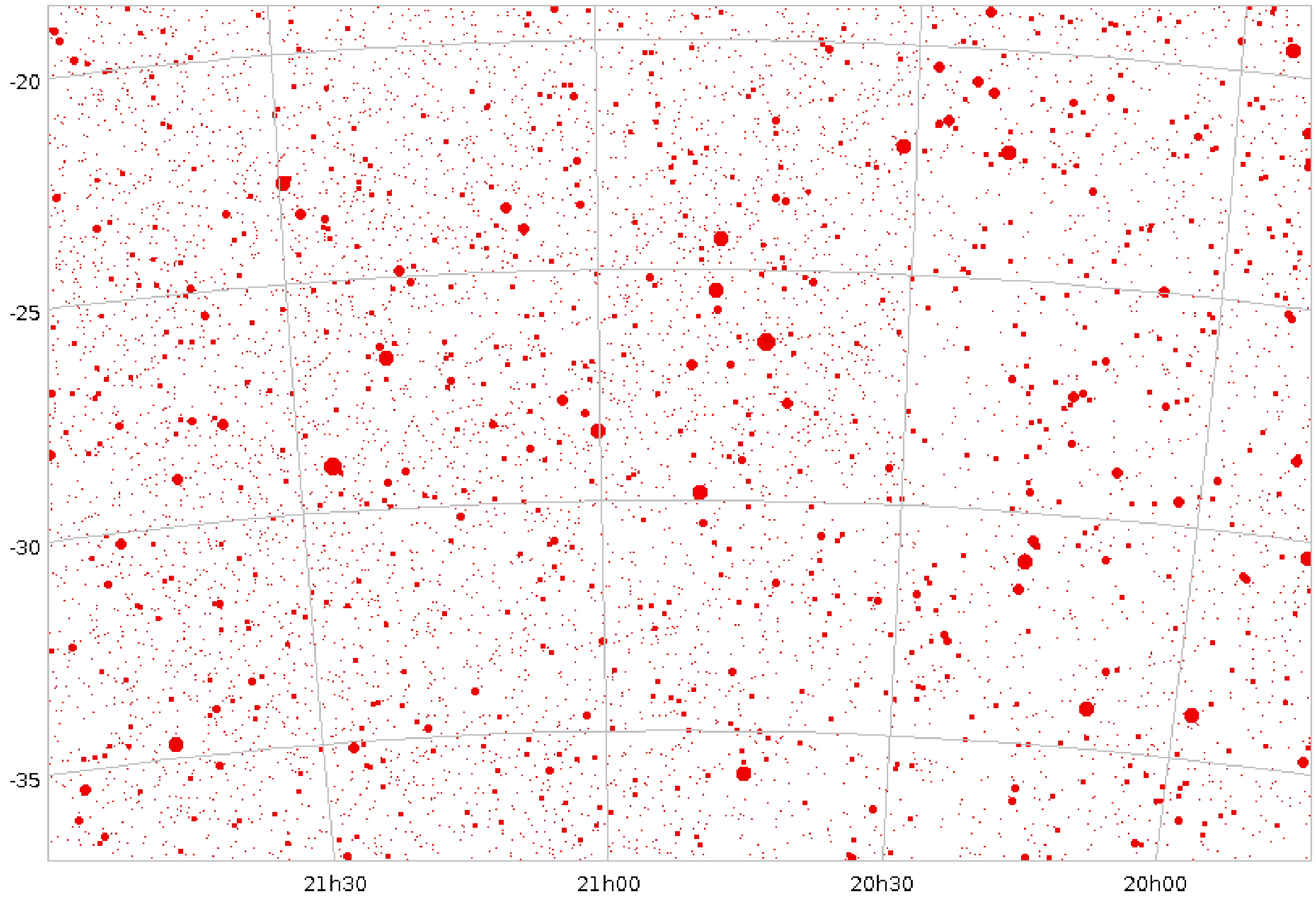
- e.g. RTS
- Rank the sources by apparent brightness and peel sequentially

Building S/N: Ranking sources



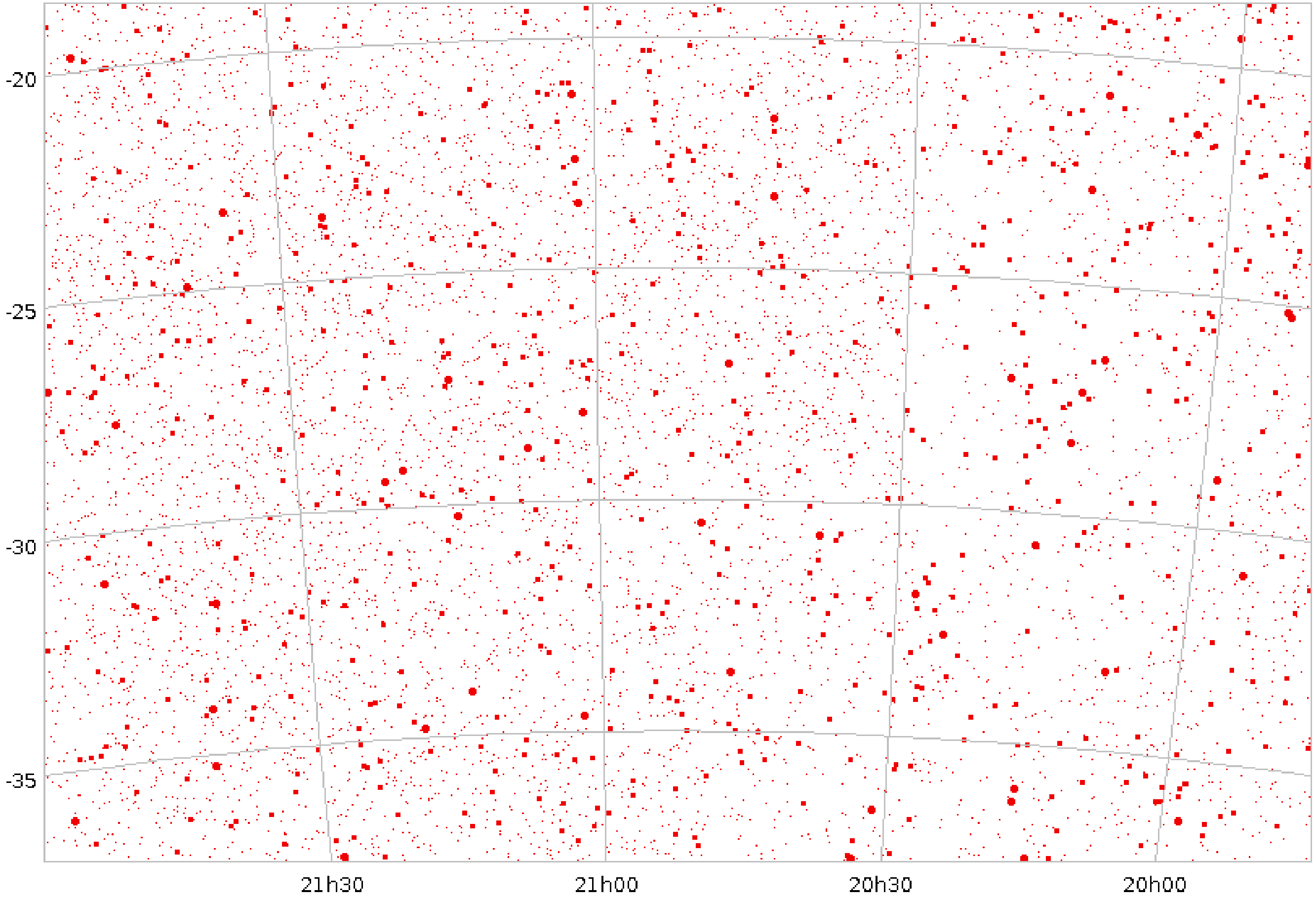
- e.g. RTS
- Rank the sources by apparent brightness and peel sequentially

Building S/N: Ranking sources



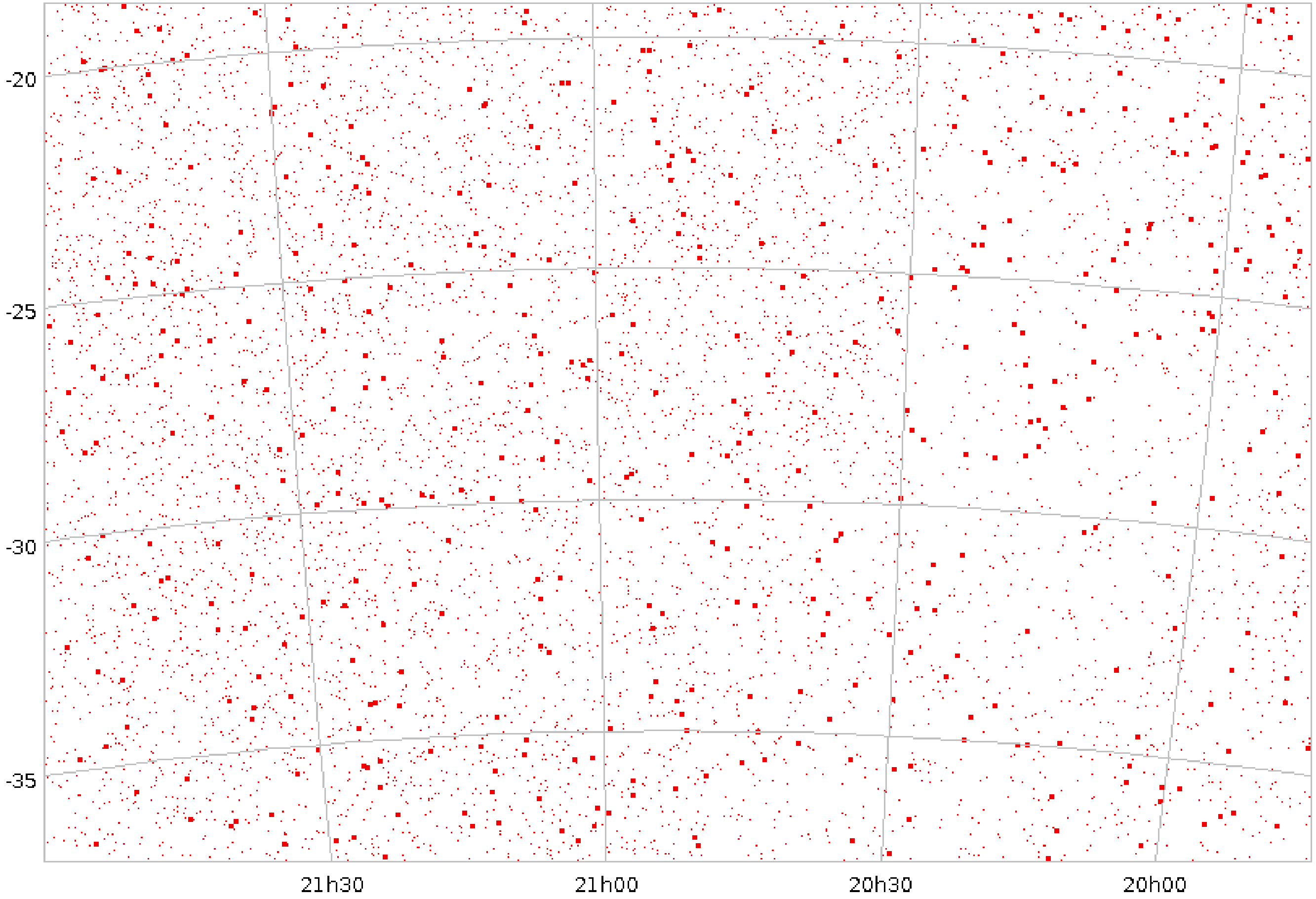
- e.g. RTS
- Rank the sources by apparent brightness and peel sequentially
- Best S/N toward that direction

Building S/N: Ranking sources



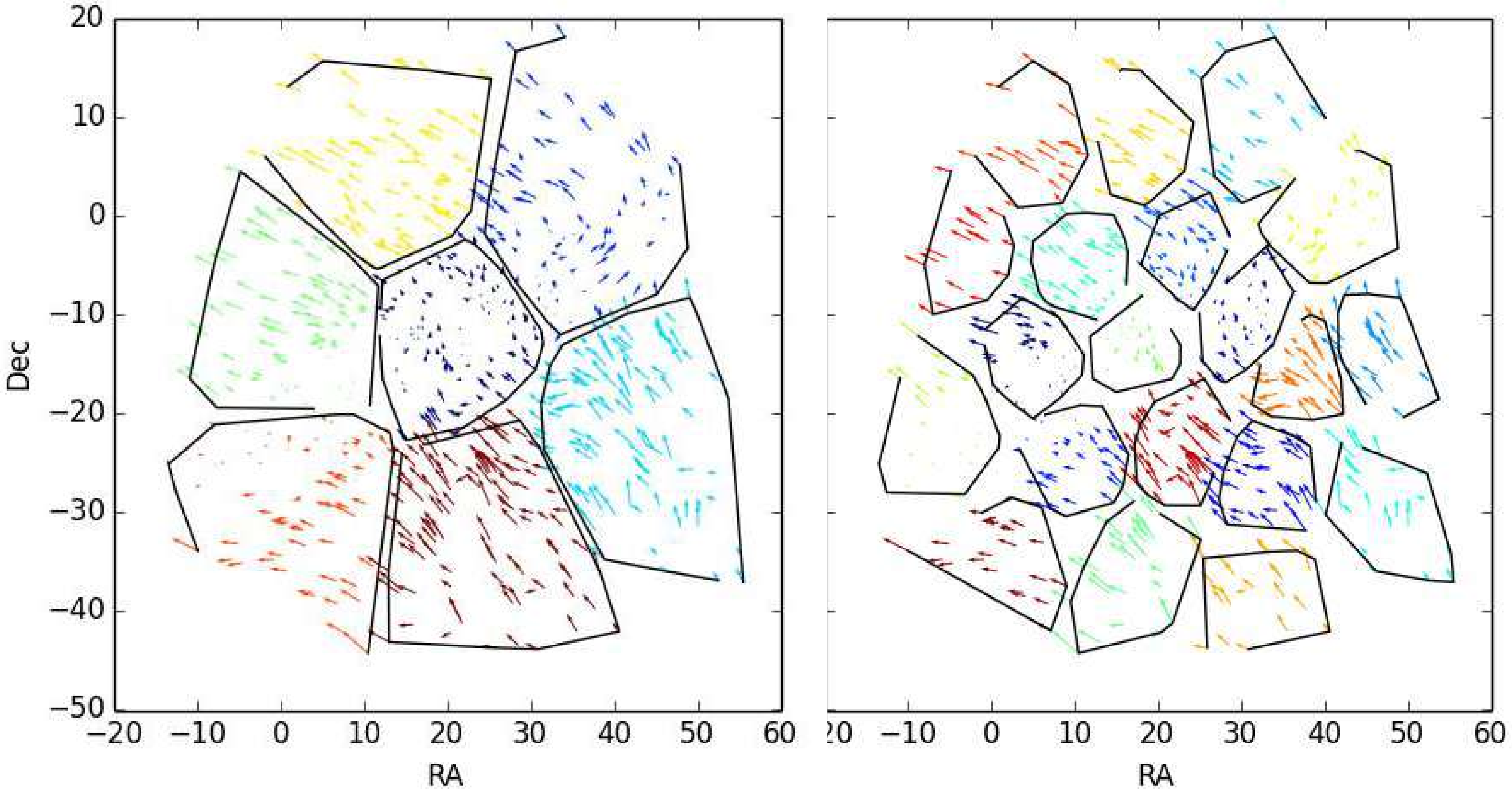
- e.g. RTS
- Rank the sources by apparent brightness and peel sequentially
- Best S/N toward that direction

Building S/N: Ranking sources



- e.g. RTS
- Rank the sources by apparent brightness and peel sequentially
- Best S/N toward that direction
- Eventually your sky model needs to contain multiple sources

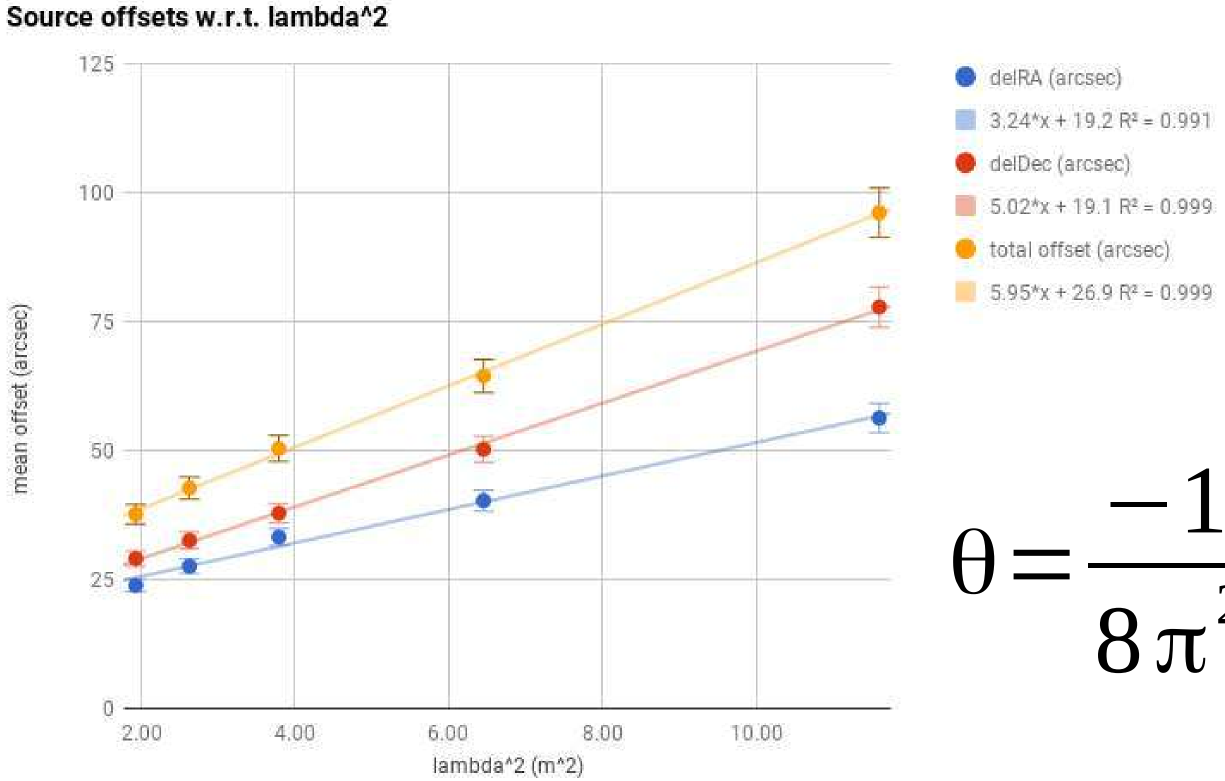
Building S/N: clustering sources



- e.g. Ionpeel, RTS, Factor
- Cluster size should be < S
- Sky model and primary beam model must be very accurate

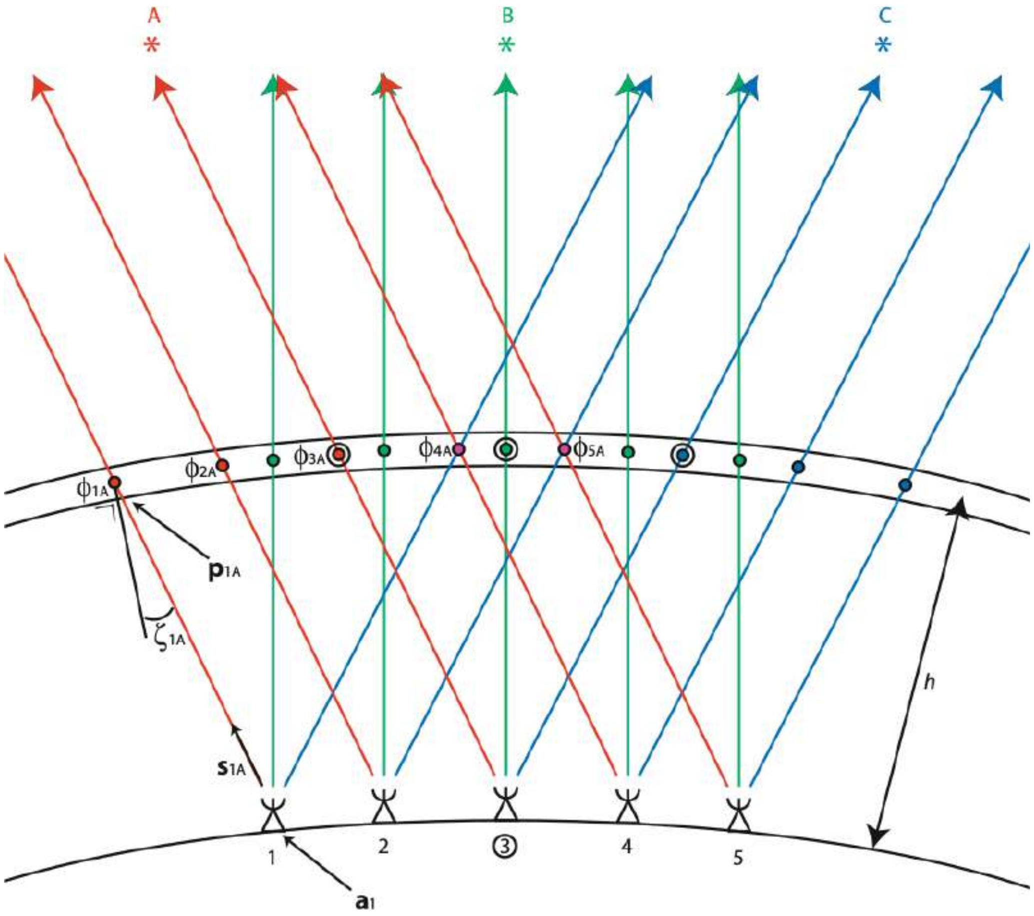
Building S/N: frequency-dependence

- e.g. Ionpeel, RTS, Factor



$$\theta = \frac{-1}{8\pi^2} \frac{e^2}{\eta_0 m_e} \frac{1}{\nu^2} \nabla_\perp \mathrm{TEC}$$

Building S/N: modelling the ionosphere

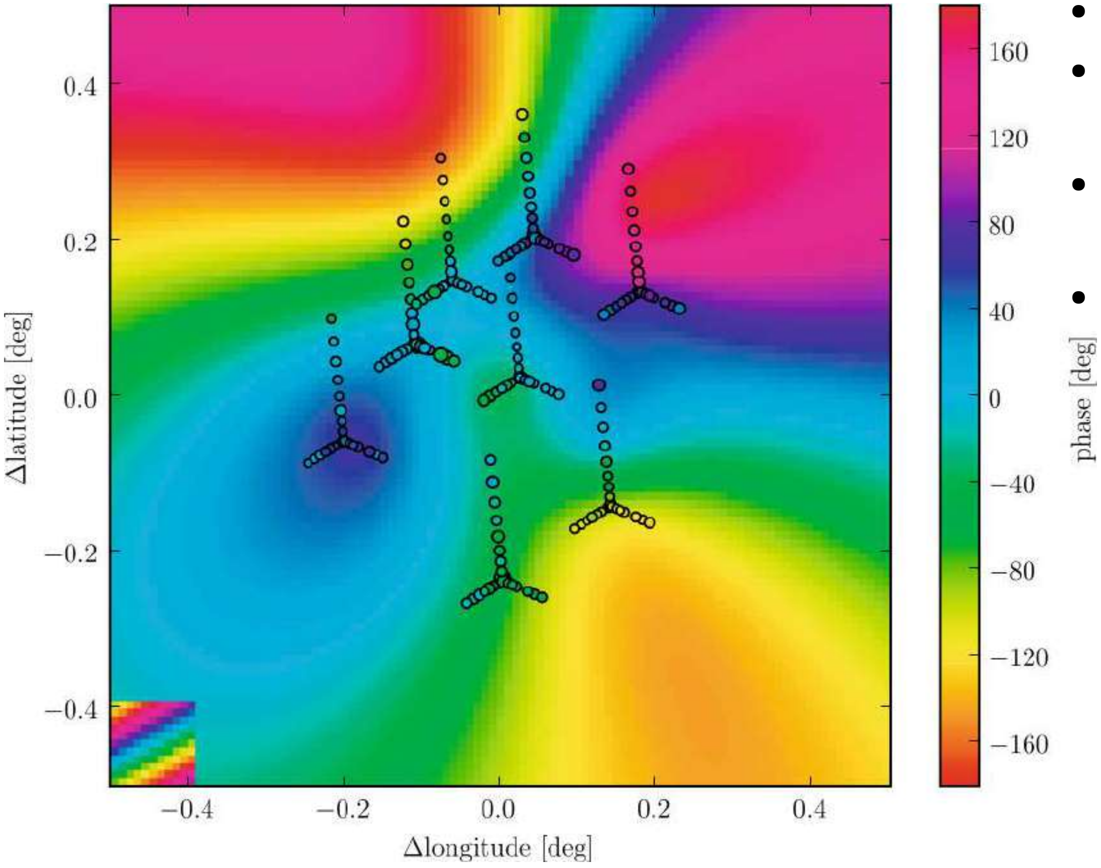


- e.g. SPAM
- Allows multiple antennas to contribute to the same phase screen solutions

5 antennas observe 3 calibrator sources (colored red/green/blue and labelled A to C) within the FoV. The (colored) LoSs from the array towards the sources run parallel for each source and pierce the phase screen at fixed height h (colored circles). (Note 1C & 4A and 2C & 5A overlap). Total (integrated) phase rotation along any LoS through the ionosphere is modeled by an instantaneous phase rotation at the phase screen height.

Intema et al. (2008): "Ionospheric calibration of low frequency radio interferometric observations using the peeling scheme"

Building S/N: modelling the ionosphere



- e.g. SPAM
- Allows multiple antennas to contribute to the same phase screen solutions
- Maps the ionospheric phase variations above the array
- (Assuming they really are at the same height… see Martin, Bray & Scaife (2016))

Example of an ionospheric phase screen model fit. The color map represents an ionospheric phase screen at 200 km height that was fitted to the peeling phase solutions of 8 calibrator sources at time-interval n = 206 of 10 s during a VLSS observing run of the 74 MHz VLA in BnA-configuration

Intema et al. (2008): "Ionospheric calibration of low frequency radio interferometric observations using the peeling scheme"

Ionospheric calibration software summary

Package	Instrument	Author(s)	Webpage
Obit	VLA	Bill Cotton	www.cv.nrao.edu/~bcotton/Obit.html
SPAM	GMRT, VLA	Huib Intema	www.intema.nl/doku.php?id=huibintemaspam
Fits_warp	MWA	H-W & Hancock	github.com/nhurleywalker/fits_warp
RTS	MWA	Mitchell & Ord	sysadmin@mwa128t.org
Ionpeel	MWA	Andre Offringa	sysadmin@mwa128t.org
LEAP	MWA	Rioja & Dodson	Maria.rioja@icrar.org
Sagecal	LOFAR	Sarod & Smirnov	sourceforge.net/projects/sagecal/
DDFacet	LOFAR	Tasse & Smirnov	github.com/saopicc/DDFacet
Factor	LOFAR	van Weeren	www.astron.nl/citt/facet-doc/