

International Centre for Radio Astronomy Research

#### Understanding and calibrating ionospheric effects

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



#### lonosphere



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

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



#### **Global ionospheric variations**



09-16-2018T21:50:00

https://services.swpc.noaa.gov



#### Faraday rotation



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



#### Refraction



Different phase delays  $\varepsilon_1$  and  $\varepsilon_2$  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**



- A = Array size
- V = field of View
- **S** = ionospheric **S**cale

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







#### 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)  $\rightarrow$

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







#### Seeing different dTEC

 $\Delta \theta$  will be solved for when calculating the complex antenna gains

**2.** A>>S V<<S S

Α

Self-calibration on short timescales may be necessary









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

**3**.A<<S V>>S S







Seeing different dTEC

 $\Delta \theta$  varies spatially and cannot be "fixed" in the visibilities

3.A<<S V>>S

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

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#### 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<sup>1</sup> 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,  $\eta_0$  is the vacuum permittivity, and  $\nu$  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

#### https://github.com/nhurleywalker/fits\_warp

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

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#### 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]



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



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  - 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...



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  - 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



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  - 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



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- How to increase S/N?



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

refant=127

For each antenna ▲ Φ





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

refant=127

For each antenna ▲ Φ







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





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





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





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





#### Building S/N: frequency-dependence

• e.g. lonpeel, RTS, Factor





## 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.

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



## Building S/N: modelling the ionosphere

bhase [deg]



- 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

Interna 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/