Multi-frequency estimation of the cosmic radio dipole from continuum radio surveys

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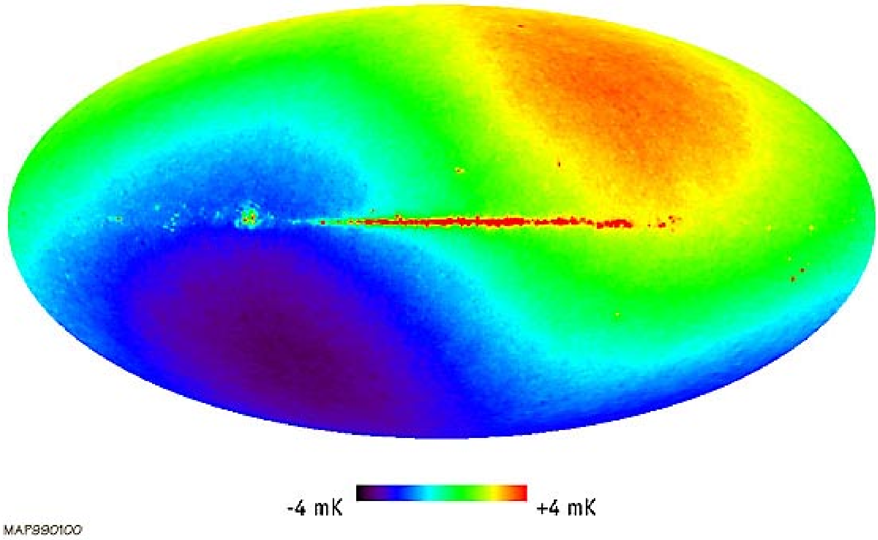
Motivation



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[1] https://wmap.gsfc.nasa.gov/media/ContentMedia/map_model_1.gif

- Isotropic temperature distribution, variations at percent level
- CMB dipole at order $\Delta T/T \sim 10^{-3}$
- several contributions:
  $\mathbf{d}_{cmb} = \mathbf{d}_{kinetic} + \mathbf{d}_{primordial} + \mathbf{d}_{ISW} + \mathbf{d}_{foregrounds} + \mathbf{d}_{noise}$
- results in a dipole with $v = 370.06 \pm 0.09$ km/s
  Planck Collaboration et al., 2015

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The kinetic dipole in other frequency bands

Our peculiar velocity should affect all extragalactic observations, e.g. number counts

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega}(> S) \propto S^{-x} \text{ , with } S(\nu) \propto \nu^{-\alpha} \tag{1}$$

Doppler shift

$$S_{obs}(f_{obs}) \propto S_{rest}(f_{obs})\delta^{1+\alpha} \leftarrow \delta(v,\theta) = (1 + \frac{v}{c}\cos\theta)\frac{1}{\sqrt{1-\beta^2}} \tag{2}$$

aberration

$$d\Omega' = d\Omega\left(1 - 2\frac{v}{c}\cos\theta\right) \tag{3}$$

In total and approximation in first order of δ

$$\left(\frac{\mathrm{d}N}{\mathrm{d}\Omega}\right)_{obs} = \left(\frac{\mathrm{d}N}{\mathrm{d}\Omega}\right)_{rest}\left[1 + [2 + x(1+\alpha)]\frac{v}{c}\cos\theta\right] \tag{4}$$

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Dipole amplitude is given by:

$$d = [2 + x(1 + \alpha)]\frac{v}{c} \tag{6}$$

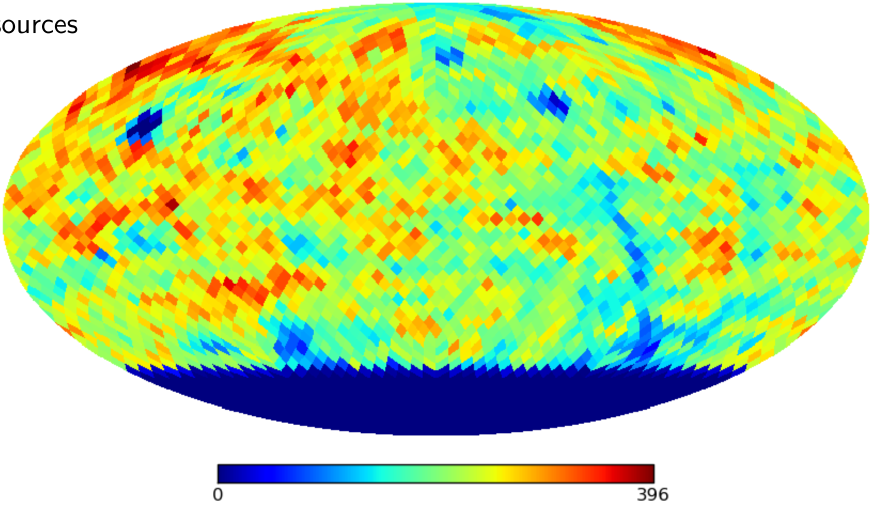
Fitting a power law to the number counts:

Survey	ν [MHz]	x	$d \times 10^2$
NVSS	1400	1.233 ± 0.008	0.51 ± 0.04
WENSS	325	0.850 ± 0.009	0.43 ± 0.02
TGSS	150	0.788 ± 0.009	0.42 ± 0.02

with spectral index $\alpha = 0.75 \pm 0.25$ (Garn et al., 2008) and CMB dipole velocity $v = 370.06 \pm 0.09$ km/s(Planck Collaboration et al., 2015)

623604
sources

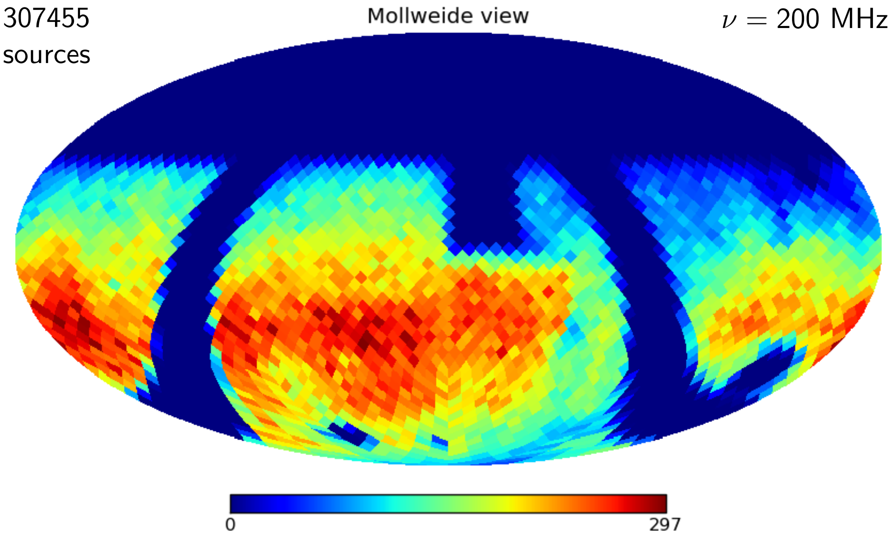
$\nu = 150$ MHz



TIFR GMRT Sky Survey (TGSS) first Alternative Data Release (ADR1)

307455 sources

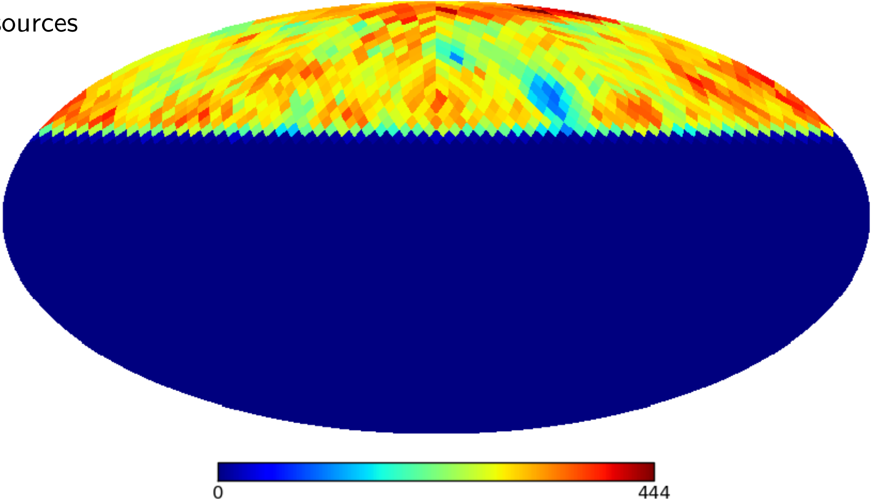
$\nu = 200$ MHz



GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM)

229420 sources

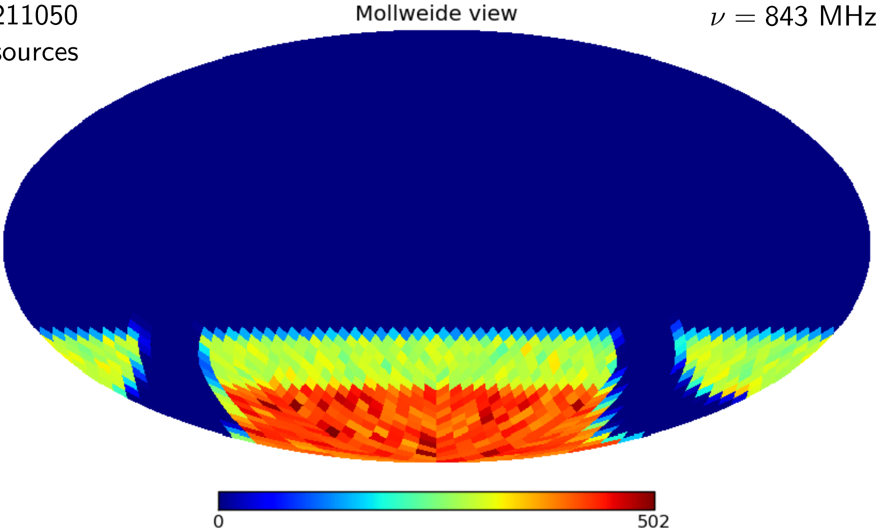
$\nu = 325$ MHz



WEsterbork Northern Sky Survey (WENSS)

211050 sources

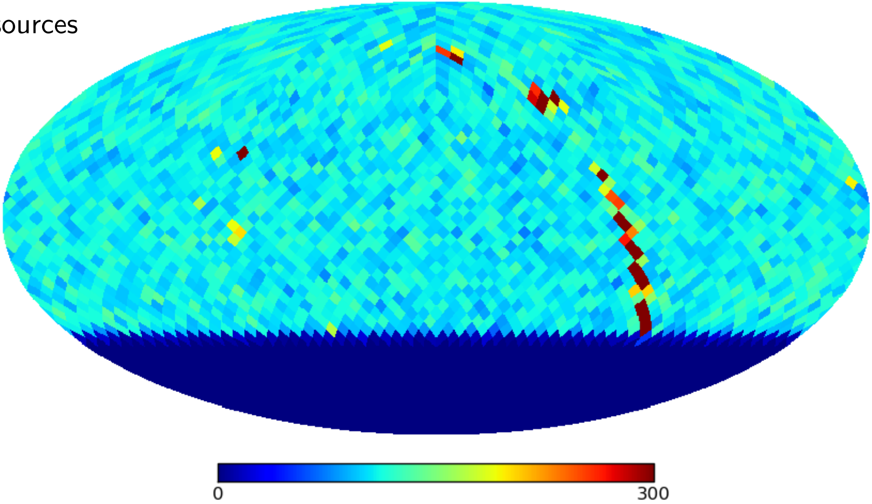
$\nu = 843$ MHz



Sydney University Molonglo Sky Survey (SUMSS)

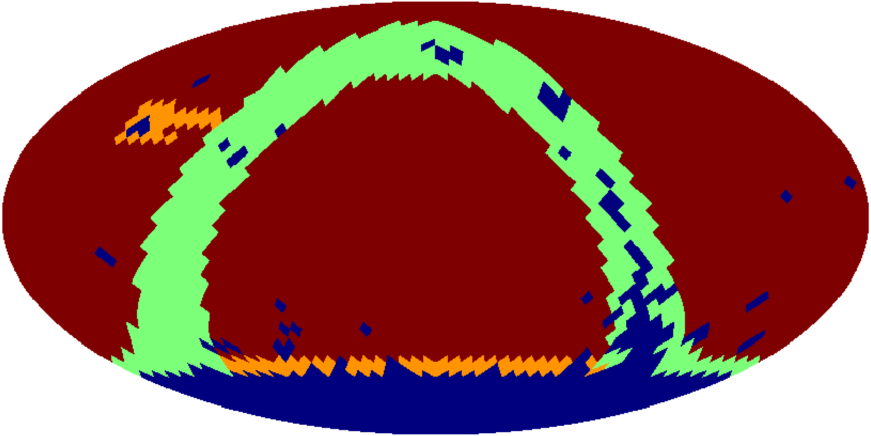
1.7 million sources

$\nu = 1.4$ GHz

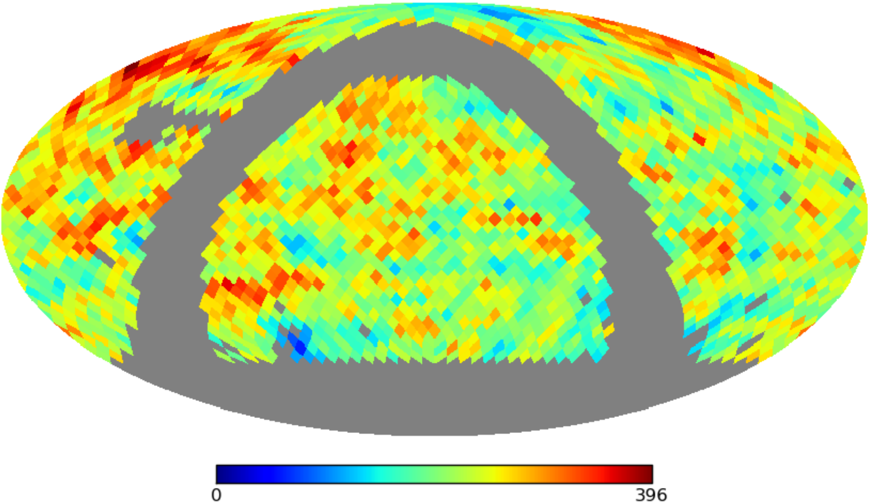


NRAO VLA Sky Survey (NVSS)

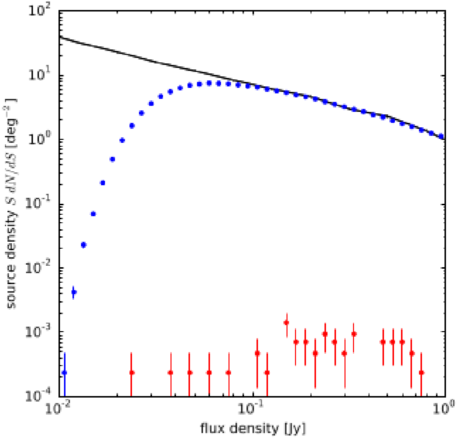
Masking



Masking

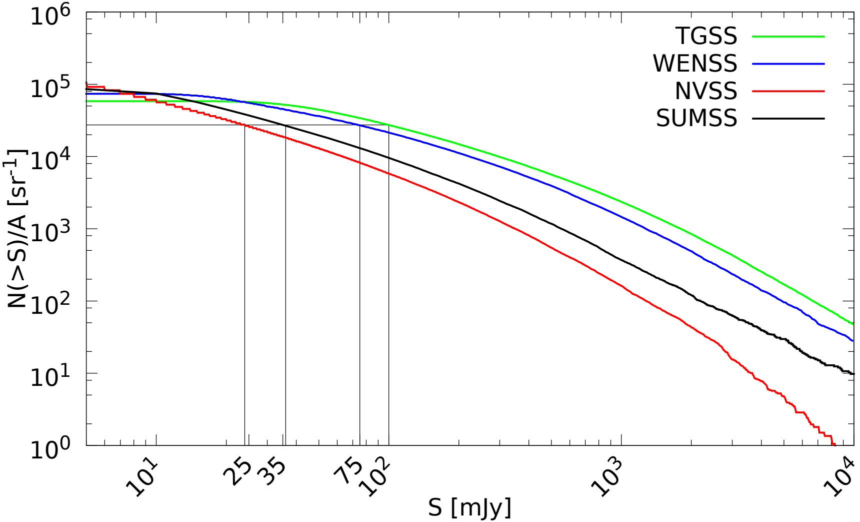


flux threshold



TGSS ADR1 [Intema et al. 2017]

- reliability: complementary to false detection fraction
- false detection fraction $< 0.1\%$
- completeness: fraction of measured sources to model
- resulting in minimum flux threshold



TGSS
WENSS
NVSS
SUMSS
N(>S)/A [sr^{-1}]
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^1
25
35
75
10^2
10^3
10^4
S [mJy]

Quadratic estimator

- Tool needed to compare the expected dipole amplitude to the catalogues
- Possible estimator introduced (Blake and Wall, 2002), (Singal, 2011), (Rubart and Schwarz, 2013)
- We are choosing now a quadratic estimator, based on a χ^2 test

$$\chi^2 = \sum_i \frac{(N_{i,o} - N_{i,m})^2}{N_{i,m}} \tag{7}$$

with $N_{i,m} = m(1 + \vec{d} \cdot \vec{e_i})$ and the e_i grid defined by HEALPix (Górski et al., 2005)

Results

Results of three catalogues at different frequencies and sky coverages:

Estimator	S_{limit} [mJy]	N	RA [$^\circ$]	Dec [$^\circ$]	d $\times 10^2$	χ^2/df
NVSS	25	220 237	143 $\pm$ 12	-11$\pm$ 15	1.8 $\pm$ 0.5	1.25
SUMSS	35	61 642	115 $\pm$ 11	5 $\pm$ 13	3.2 $\pm$ 0.5	1.49
WENSS	75	59 677	135 $\pm$ 12	12 $\pm$ 16	2.0$\pm$ 0.8	1.52
TGSS ADR1	100	217914	146 $\pm$ 13	2 $\pm$ 19	5.6 $\pm$ 0.4	2.07
expected			168	-7	0.4-0.5	

Table: Results of the quadratic estimator for NVSS, SUMSS, WENSS and TGSS ADR1. (Paper in prep.)

The error bars include statistical errors, estimated from full sky simulations of the measured dipole and errors due to the pixel size.

Discussion

Radio dipole directions agree with CMB dipole directions within errors $\rightarrow$ consistent with proper motion. Radio dipole amplitude is frequency dependent and larger than expected
$\rightarrow$ incosistent with proper motion.
Possible issues

- shot noise
- direction dependent systematics
- matter dipole (Rubart et al., 2014,Nusser and Tiwari, 2015)