Foreground Subtraction Method in HI intensity mapping & Tianlai Offline Data analysis

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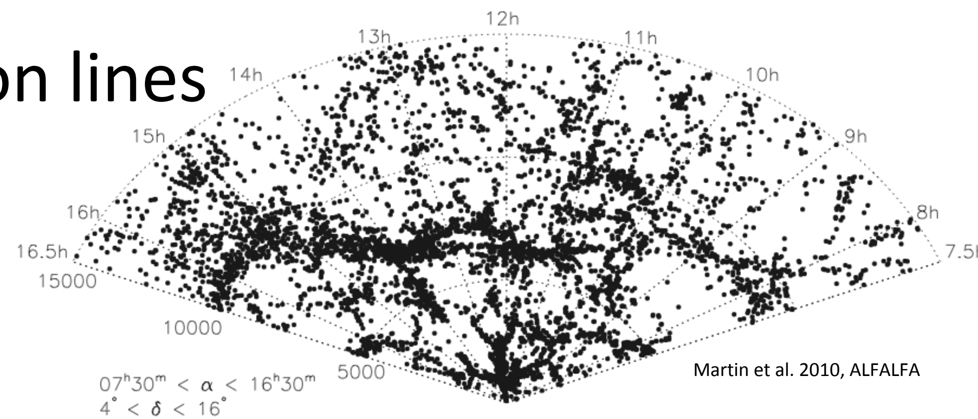
Outline

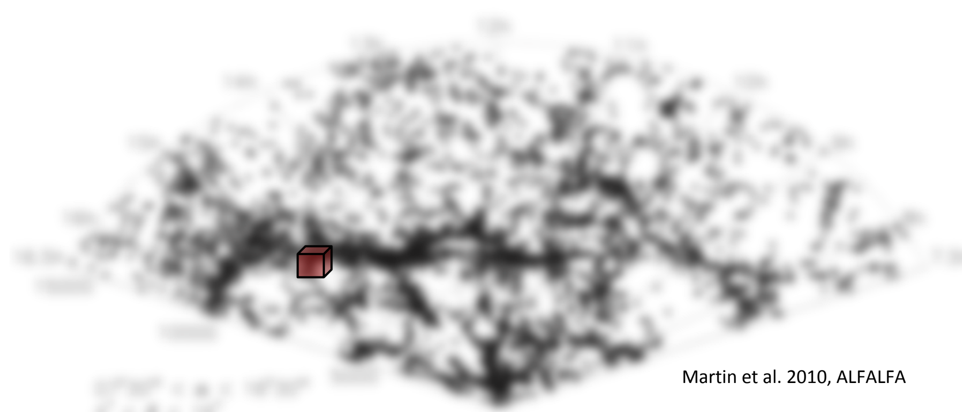
- Introduction
- Model dependent method
- Model independent method
- PCA method
- Tianlai offline data analysis

Introduction

- Intensity mapping (IM)
  - High redshift HI
  - IM with other emission lines
    - ^{3}He+
    - CO
    - CII
    - C、 O fine structure
    - X-ray



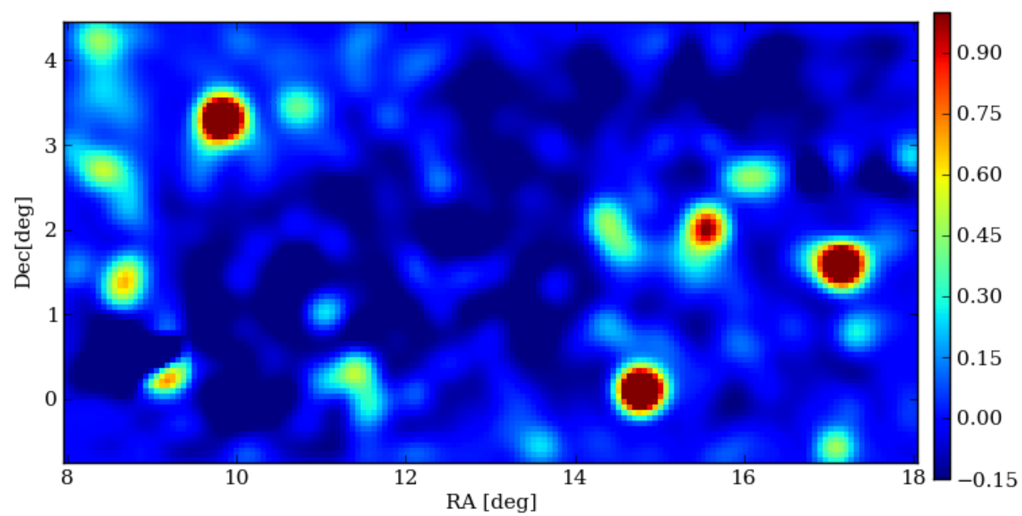
Martin et al. 2010, ALFALFA



Martin et al. 2010, ALFALFA

Introduction

- Highly contaminated by Foreground
  - The Galaxy Synchrotron emission
  - Nearby Radio Galaxies



Introduction

- Foreground Subtraction Method
  - The foreground emission have smooth radio spectrum (power law)
  - Line of sight (LoS)
  - Model dependent & Model independent

Model Dependent Method

- Foreground models
  - Galactic synchrotron emission

$$I_{\rm syn} = A_{\rm syn}\left(\frac{\nu}{\nu_*}\right)^{-\alpha_{\rm syn} - \Delta\alpha_{\rm syn}\,\log(\nu/\nu_*)}$$

  - Galactic Free-Free Emission

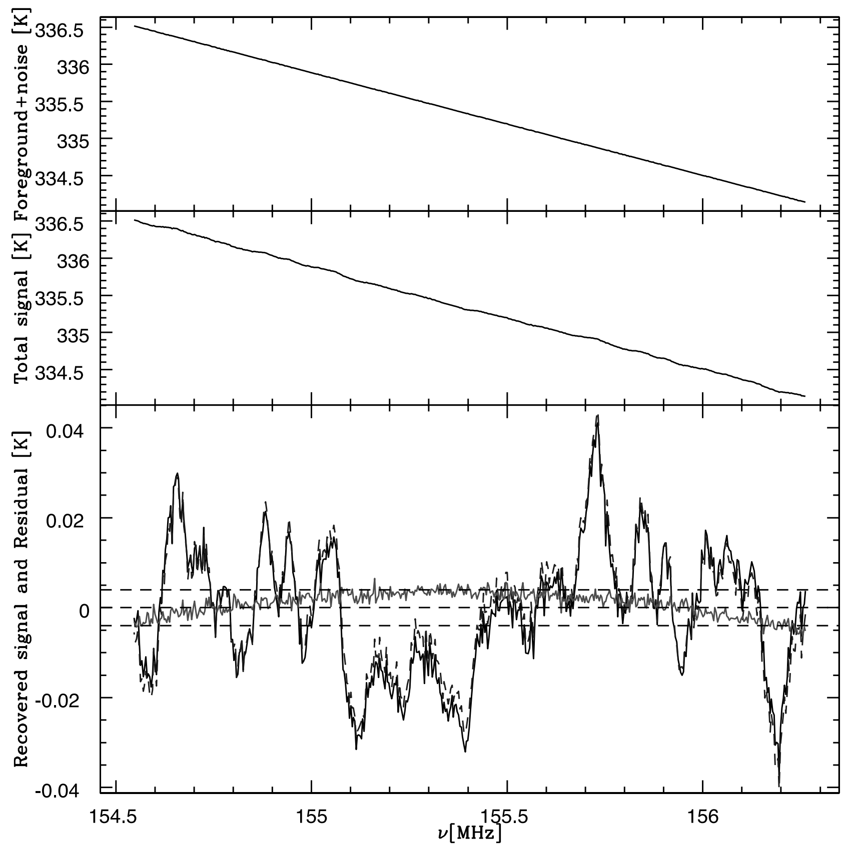
$$I_{\rm ps} = A_{\rm ps}\left(\frac{S_{\rm cut}}{\rm mJy}\right)^{\beta}\left(\frac{\nu}{\nu_*}\right)^{-\alpha_{\rm ps} - \Delta\alpha_{\rm ps}\,\log(\nu/\nu_*)}$$

  - Extragalactic Point Sources

$$\langle I_{\rm ps}\rangle = \left(\frac{dB}{dT}\right)^{-1}\int_0^{S_{\rm cut}} S\,\frac{dN}{dS}\,dS \int \left(\frac{150}{\nu}\right)^{\alpha} f(\alpha)\,d\alpha$$

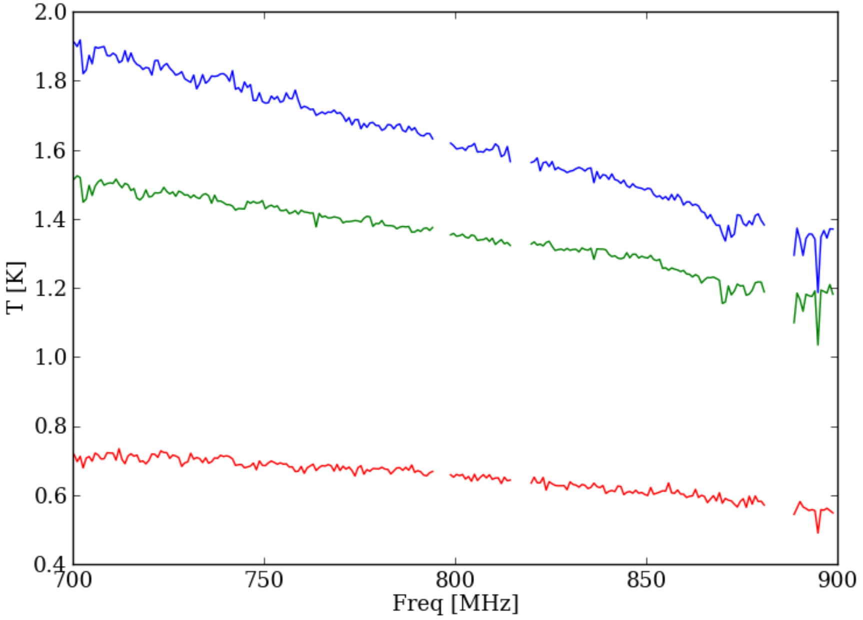
Model Dependent Method

- Polynomial Fitting
- Karhunen-Loeve (KL) Transform



Model Dependent Method

- The Problem
  - The foreground spectrum may NOT be fully described by the foreground model.



Model Independent Method

- ICA (Independent component analysis)
  - FastICA (Hyvarinen, et. al. 1999):
    - assume that the sources are statically independent from each other

$$J(y) \sim \sum_i k_i \left[\langle G_i(y) \rangle_\theta - \langle G_i(y_{\mathrm{G}}) \rangle_\theta \right]$$

$$G(y) = \mathrm{e}^{-y^2/2}, \quad G(y) = \frac{1}{a} \log\cosh(a\, y), \;\; 1 \le a \le 2.$$

  - HIEMICA (Le, et. al. 2015)
- PCA
  - Find the eigenvectors (modes) of foreground

PCA Method

- SVD
  - Find frequency frequency covariance of the foreground

$$C_{\nu\nu'} = \left\langle (\omega_A X_A)(\omega_B X_B^T) \right\rangle_{\nu\nu'} = U \Lambda V^T$$

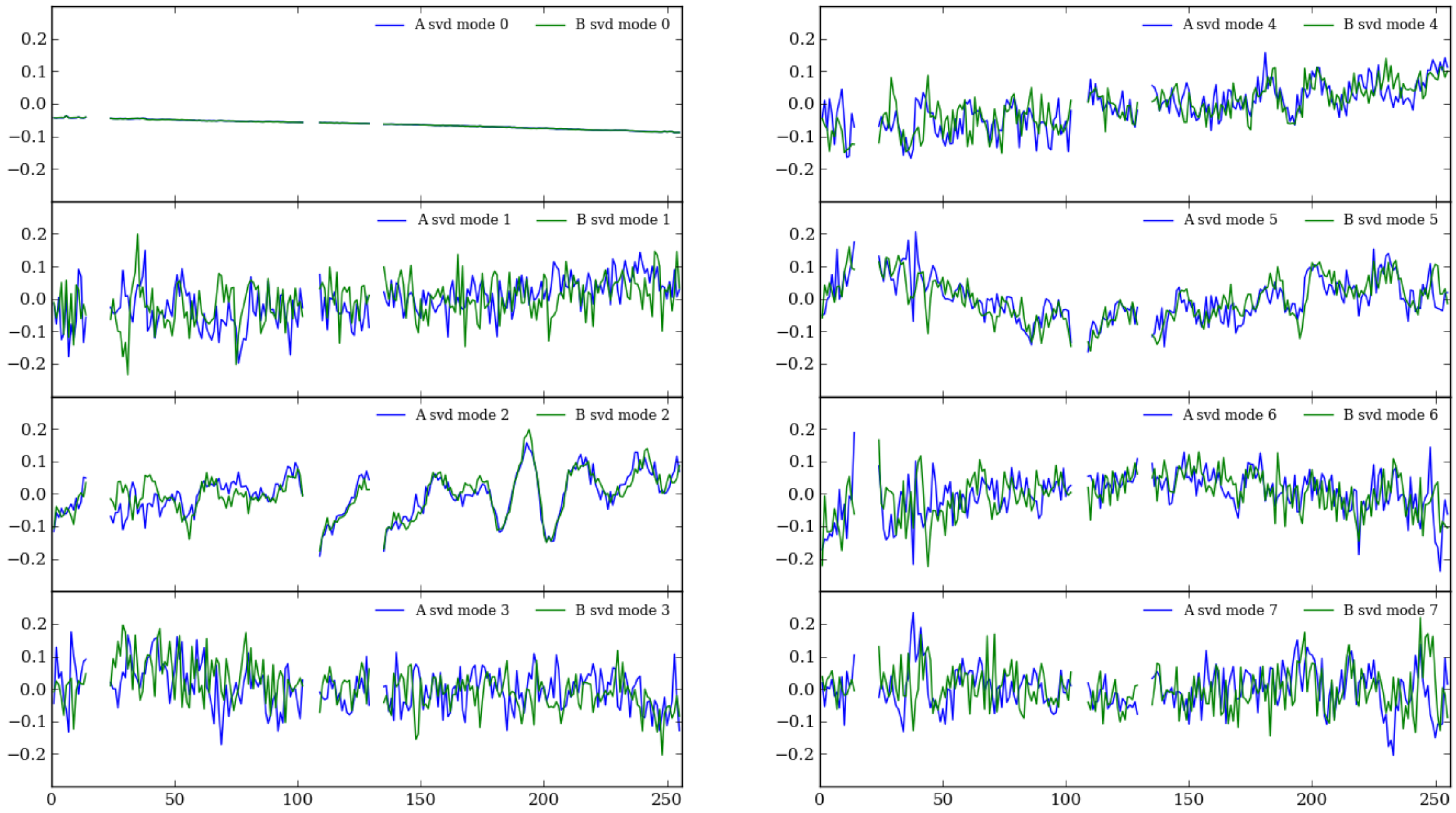
  - Find the line-of-sight (LoS) modes, by SVD

$$U = \left(u_1, u_2 \ldots\right) \qquad V = \left(v_1, v_2 \ldots\right)$$

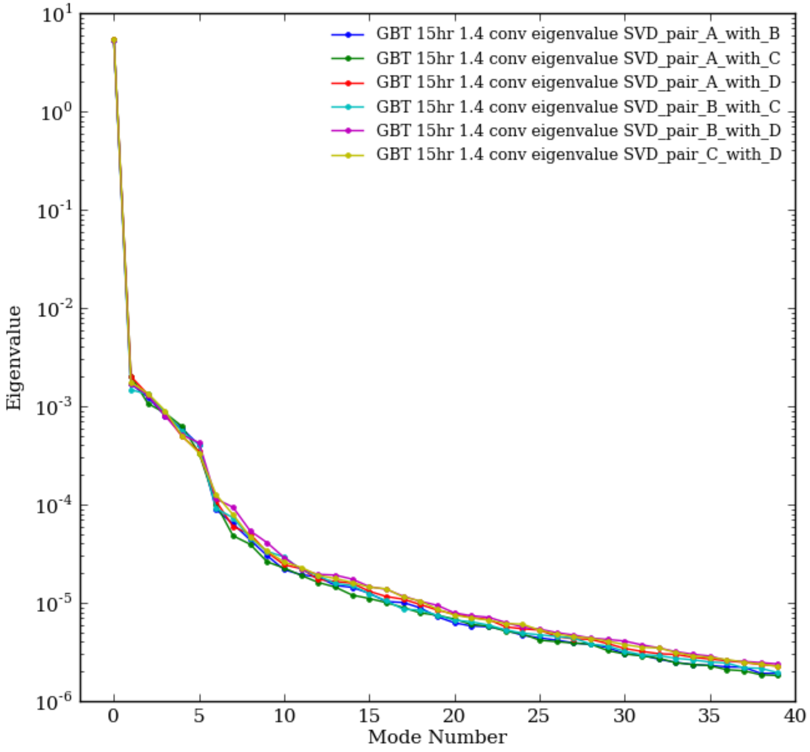
  - Subtract N nodes from each LoS

$$X_A^{cleaned} = (I - \sum_i u_i u_i^T) X_A$$

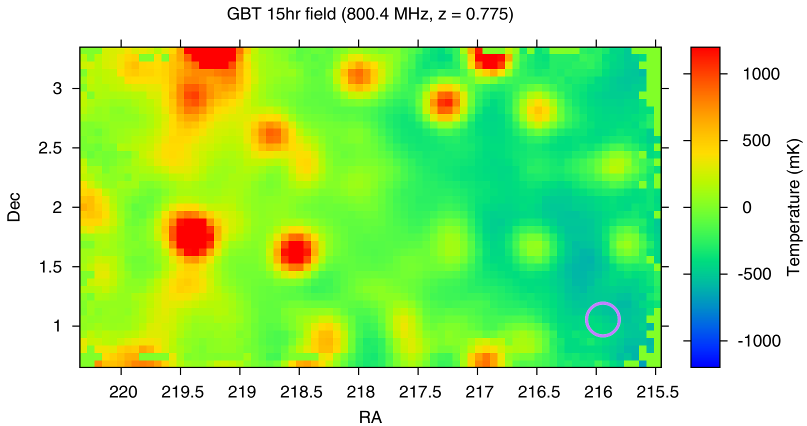
PCA Method


A svd mode 0
B svd mode 0
A svd mode 1
B svd mode 1
A svd mode 2
B svd mode 2
A svd mode 3
B svd mode 3
A svd mode 4
B svd mode 4
A svd mode 5
B svd mode 5
A svd mode 6
B svd mode 6
A svd mode 7
B svd mode 7
0.2
0.1
0.0
−0.1
−0.2
0
50
100
150
200
250

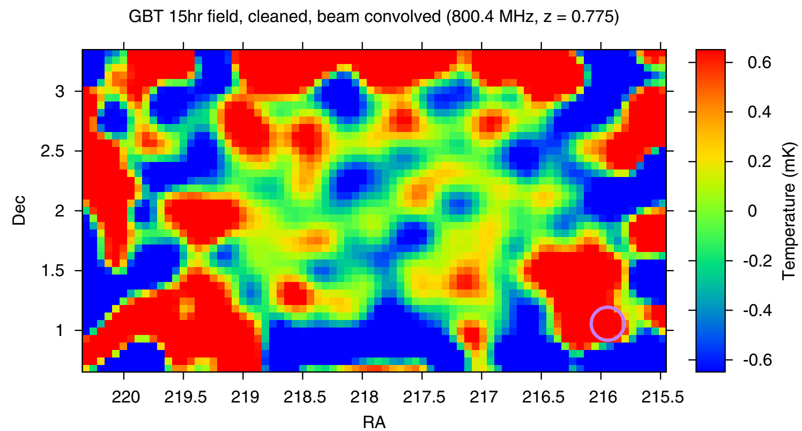
PCA Method



GBT 15hr 1.4 conv eigenvalue SVD_pair_A_with_B
GBT 15hr 1.4 conv eigenvalue SVD_pair_A_with_C
GBT 15hr 1.4 conv eigenvalue SVD_pair_A_with_D
GBT 15hr 1.4 conv eigenvalue SVD_pair_B_with_C
GBT 15hr 1.4 conv eigenvalue SVD_pair_B_with_D
GBT 15hr 1.4 conv eigenvalue SVD_pair_C_with_D
Eigenvalue
Mode Number



GBT 15hr field (800.4 MHz, z = 0.775)
Dec
RA
Temperature (mK)



GBT 15hr field, cleaned, beam convolved (800.4 MHz, z = 0.775)
Dec
RA
Temperature (mK)

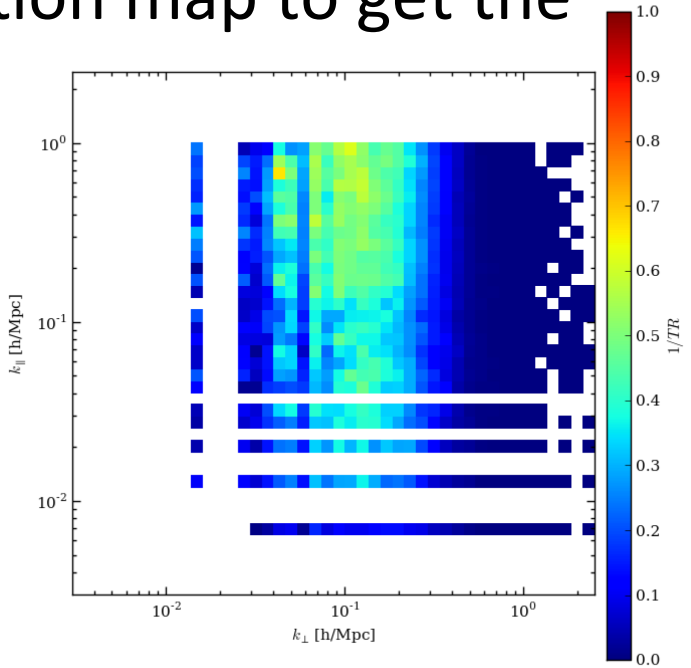
PCA Method

- Power spectrum compensation
  - Due to the non-smooth foreground modes, subtractions may kill power signal.
  - Subtract the signal only simulation map to get the signal loss transfer function

Cleaned Simulation × Simulation

$$TR = < \frac{[w_T \Pi_{T^{\mathrm{s}}+T^{\mathrm{r}}}(T^{\mathrm{s}} + T^{\mathrm{r}}) - w_T \Pi_{T^{\mathrm{r}}}(T^{\mathrm{r}})] \times T^{\mathrm{s}}}{w_A T^{\mathrm{s}} \times T^{\mathrm{s}}} >$$

Simulation × Simulation



PCA Method

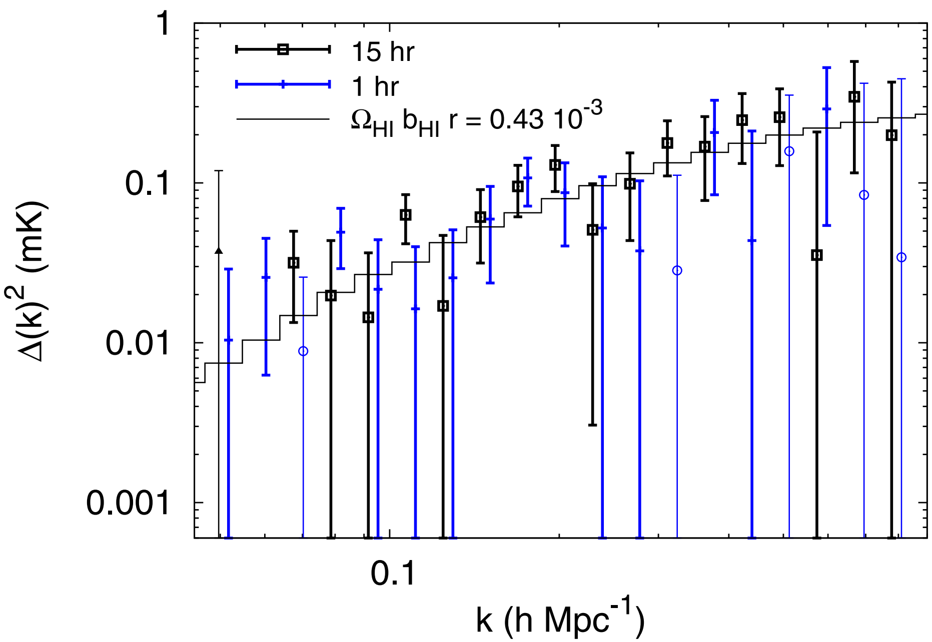
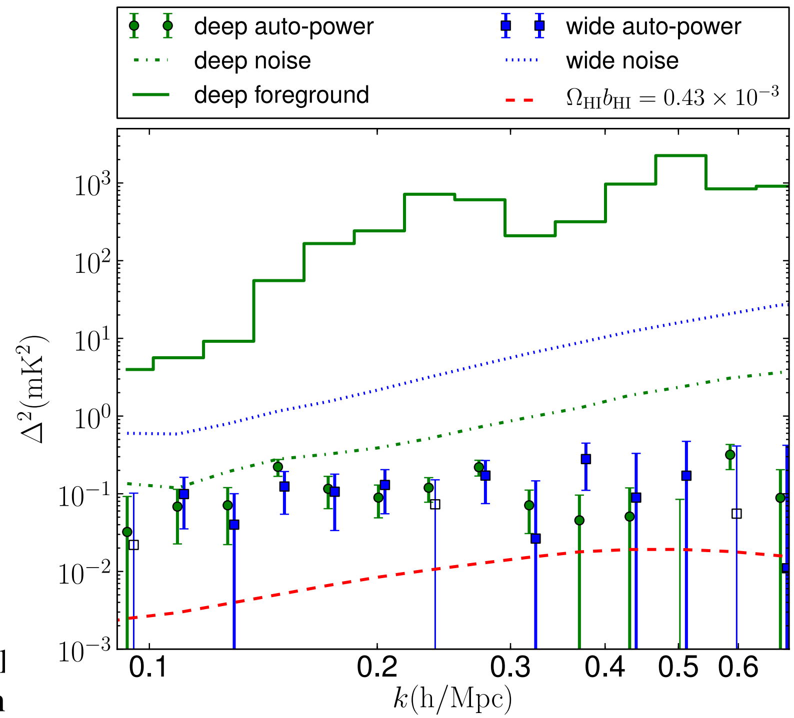


Figure 2. Cross-power between the 15 hr and 1 hr GBT fields and Wiggl
Negative points are shown with reversed sign and a thin line. The solid lin
the mean of simulations based on the empirical-NL model of Blake et al. (2011)
processed by the same pipeline.

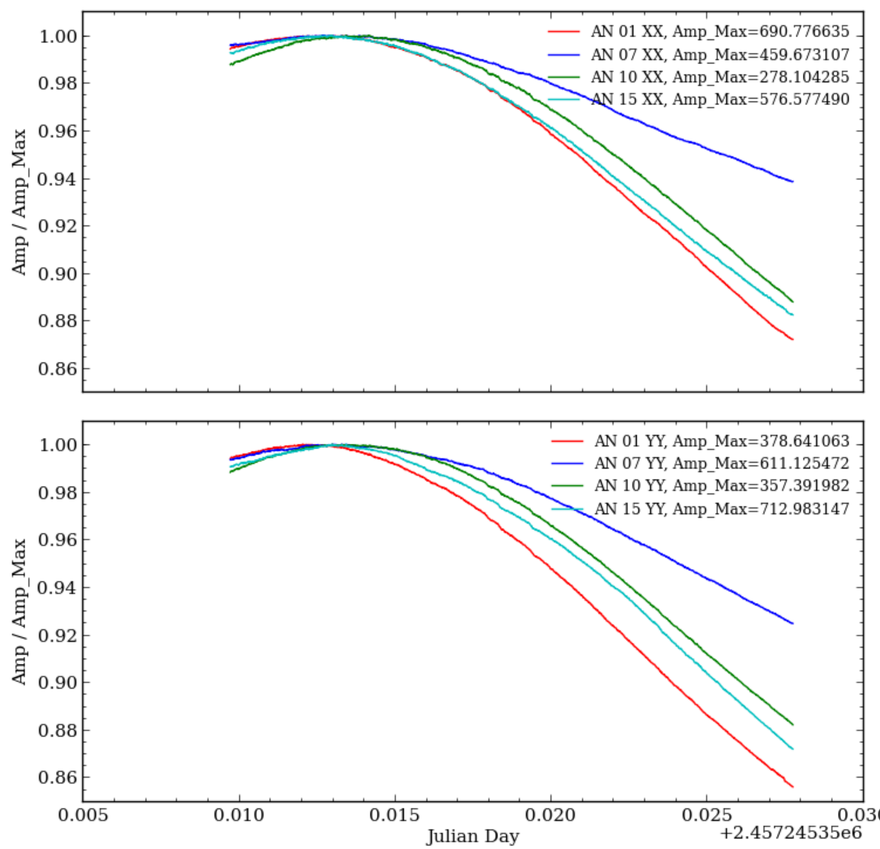
(A color version of this figure is available in the online journal.)



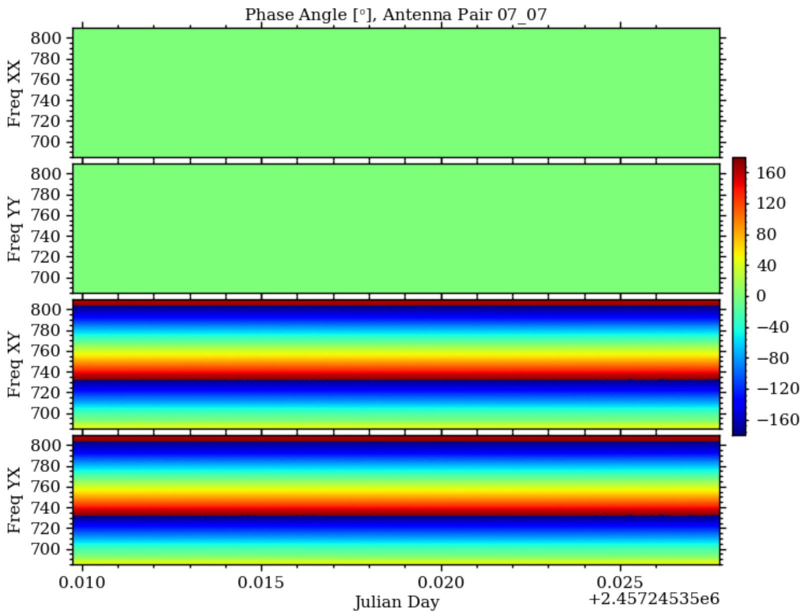
K. W. Masui et. al. 2012

E. R. Switzer et. al. 2013

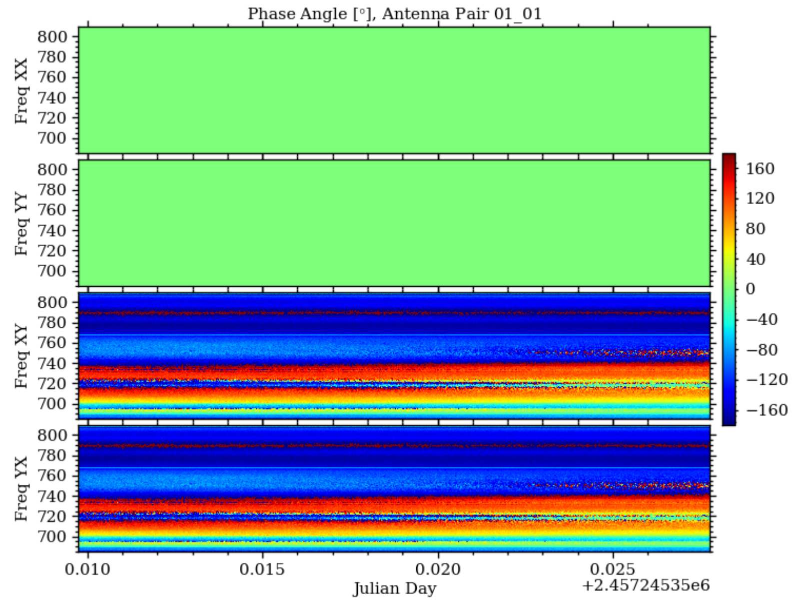
- Tianlai offline data analysis
  - Data reformat (uvfits, hdf5)
  - Data edit & RFI flagging
  - Calibration (phase, amplitude, polarization)
  - Foreground Subtraction & Map making
  - Power spectrum estimation



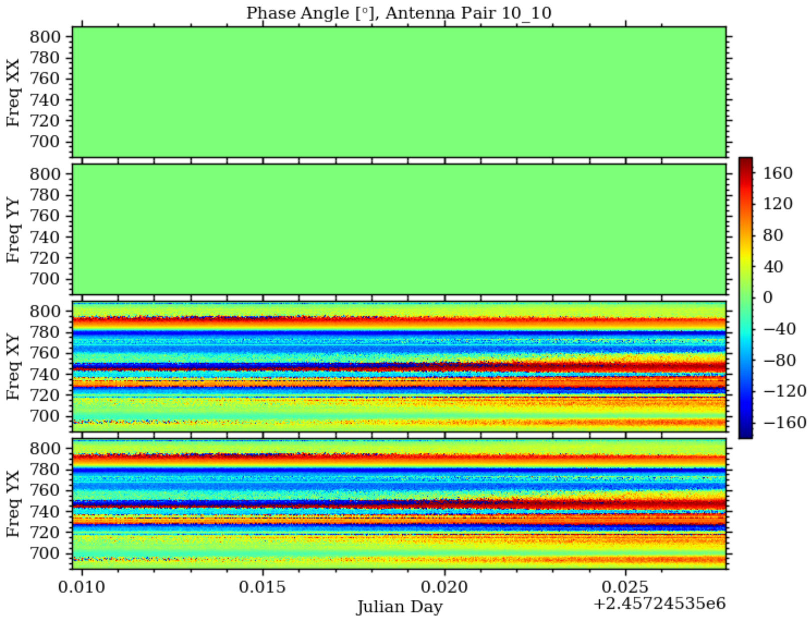
AN 01 XX, Amp_Max=690.776635
AN 07 XX, Amp_Max=459.673107
AN 10 XX, Amp_Max=278.104285
AN 15 XX, Amp_Max=576.577490
AN 01 YY, Amp_Max=378.641063
AN 07 YY, Amp_Max=611.125472
AN 10 YY, Amp_Max=357.391982
AN 15 YY, Amp_Max=712.983147
Amp / Amp_Max
Julian Day
+2.45724535e6



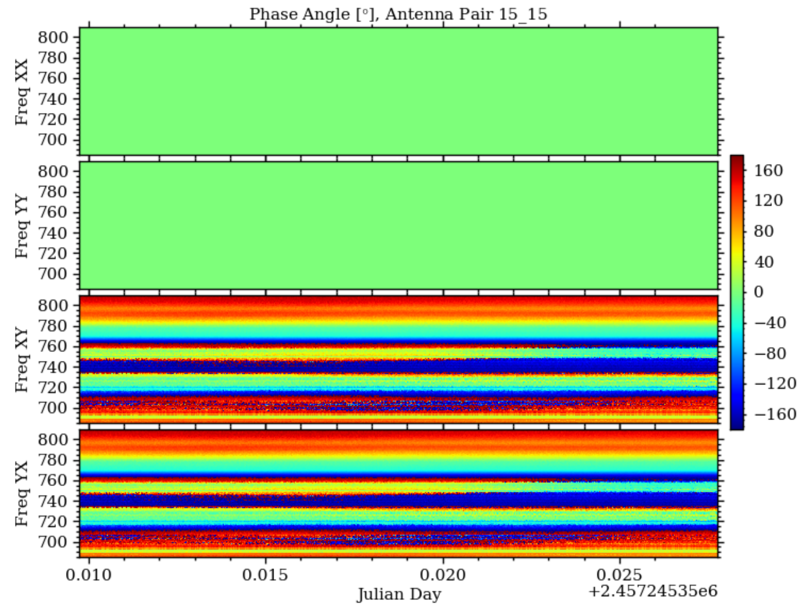
Phase Angle [°], Antenna Pair 07_07
Freq XX
Freq YY
Freq XY
Freq YX
Julian Day
+2.45724535e6



Phase Angle [°], Antenna Pair 01_01
Freq XX
Freq YY
Freq XY
Freq YX
Julian Day
+2.45724535e6



Phase Angle [°], Antenna Pair 10_10
Freq XX
Freq YY
Freq XY
Freq YX
Julian Day
+2.45724535e6



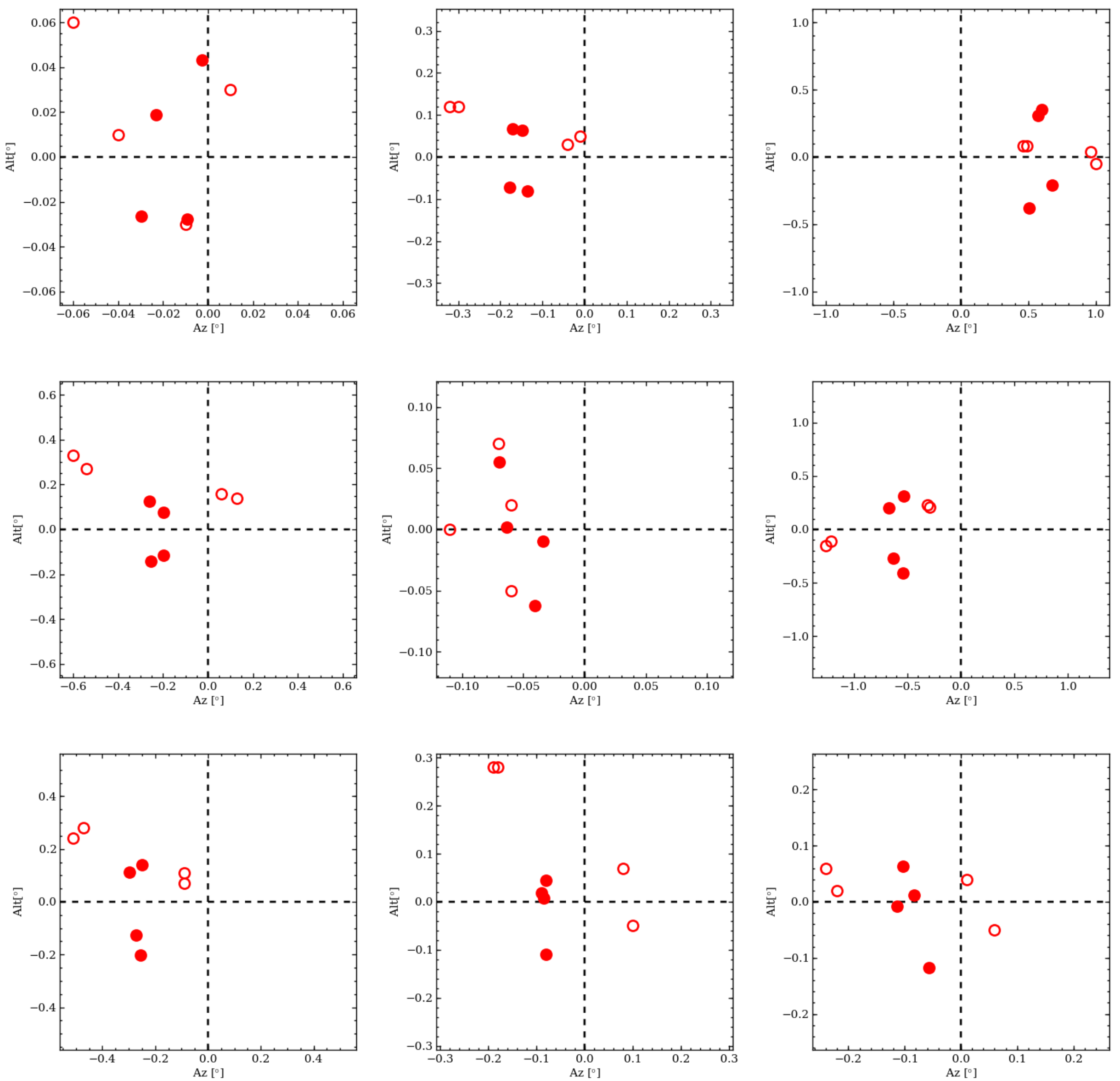
Phase Angle [°], Antenna Pair 15_15
Freq XX
Freq YY
Freq XY
Freq YX
Julian Day
+2.45724535e6

$$\chi^2 = \sum_i \left((R_X R_Y R_Z \boldsymbol{D}_i^{\rm ant} - \boldsymbol{D}^{\rm th}(t_i))^\dagger C^{-1} (R_X R_Y R_Z \boldsymbol{D}_i^{\rm ant} - \boldsymbol{D}^{\rm th}(t_i)) \right),$$

$$R_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix}, \; R_Y = \begin{bmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ \sin\beta & 0 & \cos\beta \end{bmatrix}, \; R_Z = \begin{bmatrix} \cos\gamma & \sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Table 1: The fitting results of 9 antennas

	α		β		γ	
Ant.	Best fit	Cent. $\pm 1\sigma \pm 2\sigma$	Best fit	Cent. $\pm 1\sigma \pm 2\sigma$	Best fit	Cent. $\pm 1\sigma \pm 2\sigma$
Ant01	-0.0230	$-0.0230^{+0.0520+0.1010}_{-0.0490-0.0970}$	-0.0440	$-0.0440^{+0.0930+0.1810}_{-0.0880-0.1570}$	0.0160	$0.0160^{+0.0590+0.1110}_{-0.0590-0.1150}$
Ant02	0.1480	$0.1480^{+0.0520+0.0970}_{-0.0520-0.1010}$	-0.0350	$-0.0350^{+0.0930+0.1850}_{-0.0880-0.1620}$	0.0640	$0.0640^{+0.0590+0.1150}_{-0.0560-0.1010}$
Ant03	0.2160	$0.2160^{+0.0490+0.0950}_{-0.0520-0.1010}$	0.6000	$0.6000^{+0.0880+0.1710}_{-0.0830-0.1570}$	0.0330	$0.0330^{+0.0590+0.1080}_{-0.0590-0.1180}$
Ant06	0.3420	$0.3420^{+0.0530+0.1010}_{-0.0530-0.1010}$	-0.0050	$-0.0050^{+0.0940+0.1770}_{-0.0940-0.1820}$	0.1910	$0.1910^{+0.0590+0.1110}_{-0.0590-0.1150}$
Ant07	0.0230	$0.0230^{+0.0520+0.1010}_{-0.0520-0.1010}$	-0.1020	$-0.1020^{+0.0800+0.1420}_{-0.0830-0.1530}$	-0.0020	$-0.0020^{+0.0590+0.1150}_{-0.0590-0.1150}$
Ant09	0.5770	$0.5770^{+0.0520+0.1010}_{-0.0490-0.0930}$	-0.7250	$-0.7250^{+0.0930+0.1790}_{-0.0930-0.1790}$	-0.1080	$-0.1080^{+0.0590+0.1150}_{-0.0560-0.1010}$
Ant10	0.2120	$0.2120^{+0.0520+0.0970}_{-0.0520-0.1010}$	-0.0630	$-0.0630^{+0.0880+0.1710}_{-0.0830-0.1440}$	0.1490	$0.1490^{+0.0590+0.1180}_{-0.0590-0.1110}$
Ant11	0.1090	$0.1090^{+0.0520+0.1010}_{-0.0520-0.1040}$	0.1920	$0.1920^{+0.0930+0.1740}_{-0.0930-0.1790}$	0.1700	$0.1700^{+0.0590+0.1150}_{-0.0590-0.1150}$
Ant15	0.1370	$0.1370^{+0.0520+0.1010}_{-0.0520-0.1040}$	-0.0160	$-0.0160^{+0.0880+0.1670}_{-0.0830-0.1620}$	0.0020	$0.0020^{+0.0590+0.1150}_{-0.0590-0.1180}$



Alt[°]
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