On detecting 21-cm signal using drift scan

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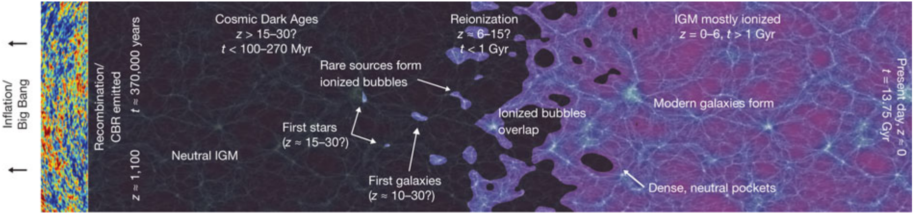
The Redshifted HI 21cm Signal from EoR:



Robertson et al (2010)

- By $z \sim 30$ density perturbations grow sufficiently to collapse and form first luminous sources. (Cosmic Dawn)
- These sources ionize the nearby neutral hydrogen (HI) clouds. (Epoch of Reionization)
- By $z \sim 6$, EoR ends.
- In our study the data we use corresponds to $z \sim 8.2$

What do we need for the detection?

The HI signal is $\sim$ 5 orders of magnitude weaker than foreground contaminations. For detection we need:

- system stability
- smooth bandpass
- very high precision calibration
- treatment of foreground;
  - avoidance (low SNR)
  - subtraction (better SNR but prone to contaminating ‘EoR window’)
  - suppression
- minimum number of operations in the data analysis
- around thousand hours of data integration to reduce thermal noise

Why do we do Drift Scan?

In contrast with tracking mode observation, in drift scan:

- sky drifts with respect to fixed phase center of the telescope
- primary beam and systematics remain stationary in the entire run of the observation
- smaller *w*-term in zenith drift scan
- slightly better SNR (lower cosmic variance) and reduction in total required data integration (Trott 2014)

Paul, Sethi, et al. (2014)

Drift Scan Formalism: HI Signal

Frequency space

- Correlation function in frequency space:

$$\left\langle V_\nu(\mathbf{u}_\nu, w_\nu, t) V^*_{\nu'}(\mathbf{u}'_{\nu'}, w'_{\nu'}, t') \right\rangle = \bar{I}_\nu \bar{I}_{\nu'} \int \frac{d^3k}{(2\pi)^3} P_{HI}(k) e^{ik_\parallel |\dot{r}| \Delta\nu}$$

$$e^{ir_\nu k_{\perp 1} \cos\phi \Delta H} Q_\nu(\mathbf{k}_\perp, \mathbf{u}_\nu, w_\nu, \Delta H = 0) Q^*_{\nu'}(\mathbf{k}_\perp, \mathbf{u}'_{\nu'}, w'_{\nu'}, \Delta H)$$

- Here the Fourier beam Q is:

$$Q_\nu(\mathbf{k}_\perp, \mathbf{u}_\nu, w_\nu, \Delta H) = \int d^2\theta A_\nu(\boldsymbol{\theta}) \exp\left[-2\pi i \left(\boldsymbol{x}_u \cdot \boldsymbol{\theta} - \frac{1}{2} y \theta^2\right)\right]$$

with

$$x_u = u_\nu - \frac{r_\nu}{2\pi}\left(k_{\perp 1} + k_{\perp 2} \sin\phi \Delta H\right)$$

$$x_v = v_\nu - \frac{r_\nu}{2\pi}\left(k_{\perp 2} - k_{\perp 1} \sin\phi \Delta H\right)$$

$$y = w_\nu + \frac{r_\nu}{2\pi} k_{\perp 1} \cos\phi \Delta H$$

Drift Scan Formalism: HI Signal

Delay Space

- For analytical result, keep frequency dependance only in $\Delta\nu$,

$$V2(u,v,\tau,\Delta t) \simeq \bar{I}^2 \frac{B}{|\dot{r}|} \int \frac{d^2 k_\perp}{(2\pi)^2} P_{HI}(k) e^{irk_{\perp 1}\cos\phi \Delta H} \times Q(\mathbf{k}_\perp, \mathbf{u}, w, \Delta H = 0) Q^*(\mathbf{k}_\perp, \mathbf{u}, w', \Delta H)$$

- For large beams (e.g. PAPER, MWA) Fourier Beam Q is small ($< 2\lambda$).

$$V2(u,v,\tau,\Delta t) \simeq \bar{I}^2 \frac{B}{r^2|\dot{r}|} P_{HI}(k) e^{2\pi i u \cos\phi \Delta H} Q^*(\mathbf{u}, \Delta H)$$

- For Gaussian Beam $A(l,m) = e^{-(l^2+m^2)/\Omega_g}$:

$$Q(\mathbf{u}, \Delta H) = \frac{\pi \Omega_g}{1 - i\pi\Omega_g u \cos\phi \Delta H} \exp\left[-\frac{\pi^2 \Omega_g (u^2+v^2)\sin^2\phi \Delta H^2}{1 - i\pi\Omega_g u \cos\phi \Delta H} \right]$$

Correlation Matrix in time:

$$V2(u, v, \tau, \Delta t) = \bar{I}^2 \frac{B}{r^2|\dot{r}|} P_{HI}(k) e^{2\pi i u \cos\phi \Delta H} Q^*(\mathbf{u}, \Delta H)$$

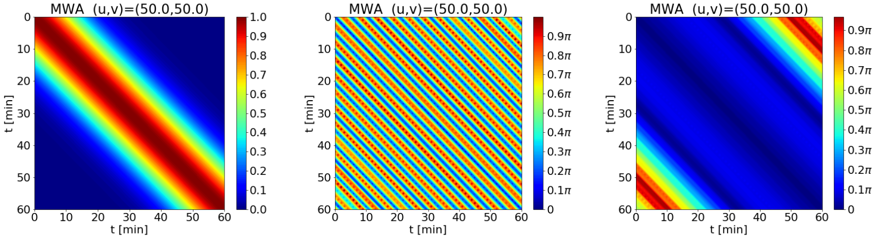


Figure: Amplitude (left) and phase (middle) of correlation function $V2$. In right panel $e^{-2\pi i u \cos\phi \Delta H}$ is multiplied to remove fast fluctuations.

Properties of HI visibility correlation:

Numerical Solution for MWA beam

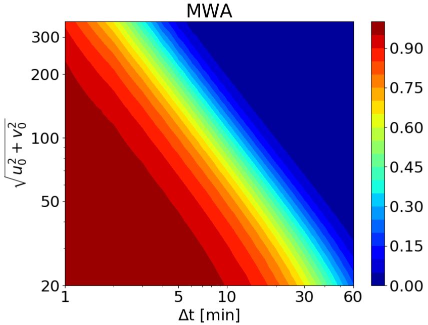


Figure: Baseline vs drift time. It shows de-correlation time is inversely proportional to baseline.

Drift Scan Formalism: Extragalactic Point Source

Foregrounds

- $I_\nu(\boldsymbol{\theta}, t)$ of point sources is modelled as:

$$I_\nu(\boldsymbol{\theta}, t) = \sum_i F_\nu^i \delta^2(\boldsymbol{\theta} - \boldsymbol{\theta}_i(t))$$

- Thus visibility of point sources becomes:

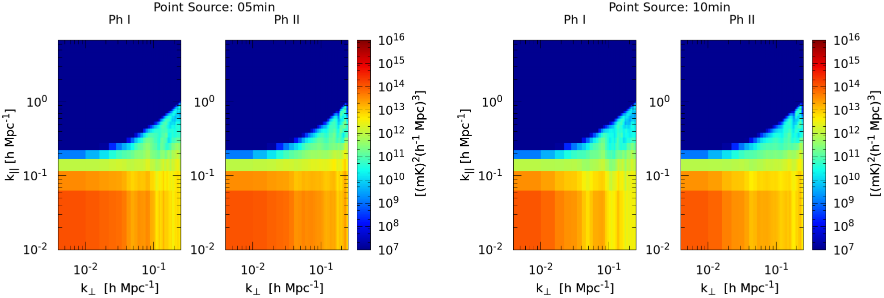
$$V_\nu(\mathbf{u}_\nu, w_\nu, t) = \sum_i F_\nu^i A_\nu(\boldsymbol{\theta}_i(t)) \exp\left[-2\pi i \left(\mathbf{u}_\nu \cdot \boldsymbol{\theta}_i(t) + w_\nu(n_i(t) - 1)\right)\right]$$

- More than 15000 point sources, brighter than 1Jy, are simulated on southern hemisphere.
- The sky is allowed to drift at time steps of 30sec with fixed beam.
- For MWA, visibilities $V_\nu(\mathbf{u}_\nu, w_\nu, t)$ are computed with full frequency dependance.

Extragalactic Point Source – Simulation

Foregrounds

- EoR window is clean ($\sim 10^2$).
- Wedge is weakening !
- Long baselines weakens first.
- Better UV coverage leads to faster weakening.



Drift Scan Formalism: Diffuse Galactic Emission (DGE)

Foregrounds

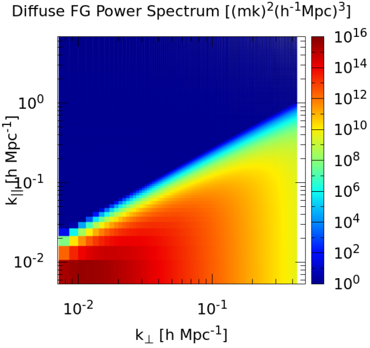
- DGE is assumed to be optically thin, statistically homogeneous, isotropic, and described by a power spectrum C_q.
- 2-point correlation function of DGE in frequency space:

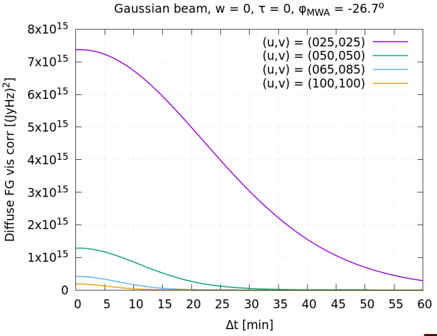
$$\left\langle V_\nu(\mathbf{u}_\nu, w_\nu, t) V^*_{\nu'}(\mathbf{u}_{\nu'}, w'_{\nu'}, t') \right\rangle = \int \frac{d^2q}{(2\pi)^2} C_q(\nu, \nu') e^{iq_1 \cos\phi \Delta H} \times Q_\nu(\mathbf{q}, \mathbf{u}_\nu, w_\nu, \Delta H = 0) Q^*_\nu(\mathbf{q}, \mathbf{u}_{\nu'}, w_{\nu'}, \Delta H)$$

- In delay space: $\left\langle V_\tau(\mathbf{u}, w, t) V^*_\tau(\mathbf{u}, w', t') \right\rangle$
- This function is most sensitive to modes such that $\mathbf{q} = 2\pi\mathbf{u}$.
- These expressions are similar to that of HI-signal ($r\ \mathbf{k}_\perp \rightarrow \mathbf{q}$).

Drift Scan Formalism: DGE – Numerical Solution

For Gaussian beam $e^{-\theta^2/\Omega_g}$, Fourier beam is calculated analytically.





HI Weights:

- We saw correlation function

$$V2(u, v, \tau, \Delta t) = \bar{I}^2 \frac{B}{r^2|\dot{r}|} P_{HI}(k) e^{2\pi i u \cos\phi \Delta H} Q^*(\mathbf{u}, \Delta H)$$

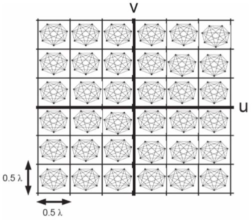
- Effect of drift scan on correlation function can be captured by defining a quantity called HI-weights.

$$W_{HI}(u, v, w, w', \Delta t) = \frac{V2(\tau, u, v, w, w', \Delta t)}{V2(\tau, u, v, w = 0, w' = 0, \Delta t = 0)}$$

- It is independent of $P(k)$ and τ.
- *Weights* take care of the decorrelation due to different w-terms and time intervals.

Optimal Power Spectrum Eastimator:

- Grids are populated with visibilities and are cross correlated.
- HI weights ensure coherant addition of power. [Paul et al (2016)]
- Noise bias is avoided by $i \neq j$.

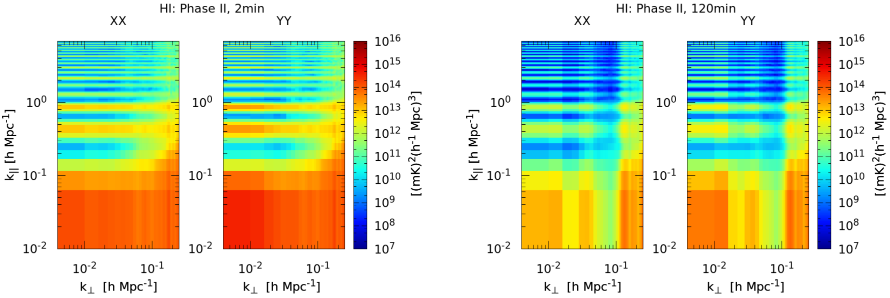


Paul et al (2016)

$$T_B^2 \tilde{P}_{HI}(k) \propto \frac{\sum_{i\neq j} \frac{1}{\sigma_{ij}^2} \left(\frac{V_\tau^i(\mathbf{u}_0, w_0, t) V_\tau^{\prime * j}(\mathbf{u}_0, w_0', t')}{W_{ij}} \right)}{\sum_{i\neq j} \frac{1}{\sigma_{ij}^2}}$$

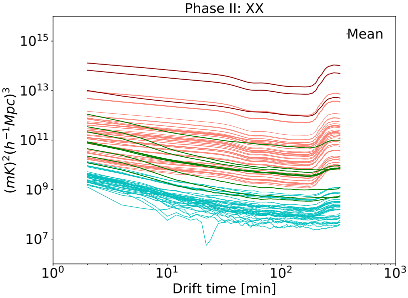
$$\sigma_g = \left(\sum_{i\neq j} \sigma_{ij}^{-2} \right)^{-0.5} \qquad (\sigma_{ij} = \sigma / W_{ij})$$

2D Power spectra $P(k_\perp, k_\parallel)$



Phase II

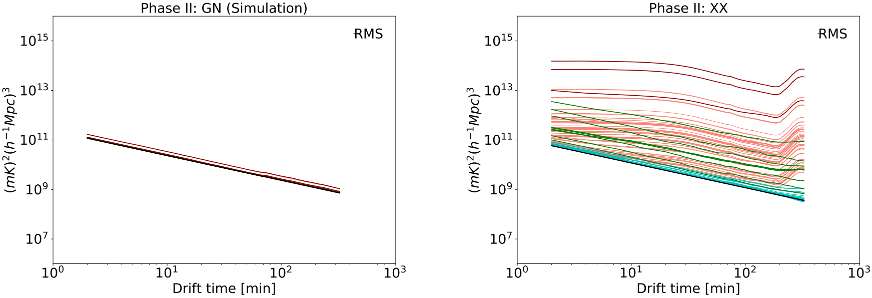
Averaged over all uv grids. $P(k_{\parallel})$ for all $k_{\parallel}$ bins are plotted. Red curves are FG dominated $k_{\parallel}$ bins. Blues are noise dominated. Black line is $1/t$.



Noise Characterisation in Data

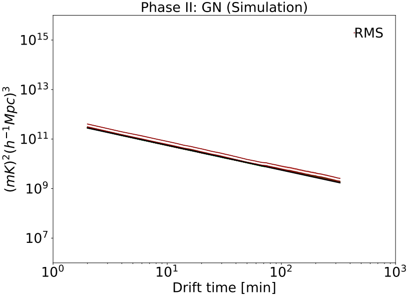
- All visibilities falling in a grid are cross correlated without any constraint. HI *weights* are **NOT** used.
- RMS is computed using all uv-grids (5254).
- For comparision with both data sets, simulation with Gaussian noise (GN) visibilities is also performed with zero mean.
- Cross correlation ($\sim VV^*$) would have RMS $\propto T_{sys}^2/\sqrt{N_{corr}}$.
- Since $N_{corr} \propto t^2$, so RMS $\propto T_{sys}^2/t$.

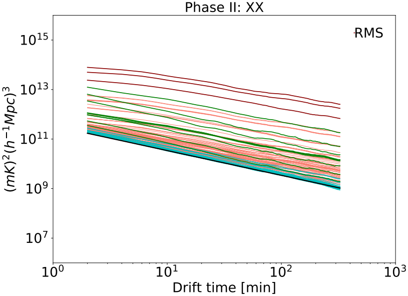
Noise Characterisation in Data



T_{sys} is found to be $\sim$ 290K.

Noise Characterisation in Data

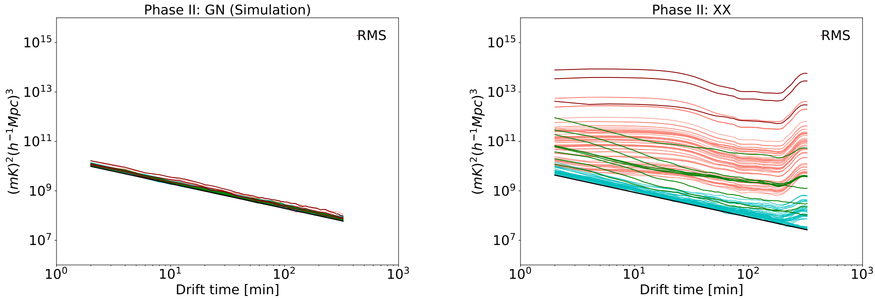




Baselines less than 100λ are ignored.

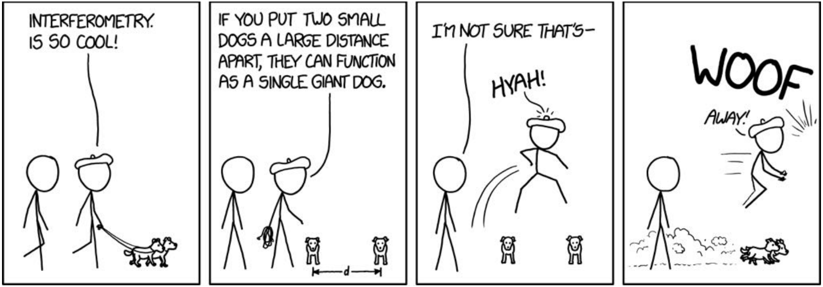
Noise Characterisation in Data

averaging in 2 stages (first over 100-100 grids)



Summary

- Drift scan analysis is a promising tool to study HI 21-cm signal.
- Drift scan maybe favoured because: small w terms, stability of the system, better SNR.
- We studied some general properties of 2-point correlation function with drift time.
- HI *Weights* take care of the decorrelation due to different parameters.
- As expected from simulations, foregrounds are confined in wedge.
- As demonstrated using data, EoR window is noise dominated.
- Using all uv-cells:
    - RMS in clean modes behave like noise and fall as $1/t$.
    - Galactic plane does not affect clean modes.



xkcd

Thank You & HAPPY HOLI...!