HI IM Simulations with BINGO, MeerKAT, FAST and SKA-I

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Contents

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1. Overview

The intention is to add various components of the sky using simulated data and the telescope models to create an observed map of the sky, and then apply contaminant removal techniques to obtain 21-cm signals that we are interested in.

So far, we have prototyped some simulations with BINGO (The approach is generalizable to MeerKLASS, FAST and SKA-I). Simulations include, sky maps, power spectra and distribution/histogram for each particular component (HI, Galaxy, Pointsource, Foreground, Thermal noise) at specific frequencies:

1. HI:
   `https://github.com/elimboto/hi_im/tree/master/BINGO/HI`
2. Thermal noise:
   `https://github.com/elimboto/hi_im/tree/master/BINGO/Thermal_Noise`
3. Galaxy (for galactic emission only):
   `https://github.com/elimboto/hi_im/tree/master/BINGO/Galaxy`
4. Pointsource (for extragalactic point sources only):
   `https://github.com/elimboto/hi_im/tree/master/BINGO/Pointsource`
5. Foreground (both galaxy and point sources combined):
   `https://github.com/elimboto/hi_im/tree/master/BINGO/Foreground`

The focus is to include consideration of 1/f impact, beam effects - Non Gaussianity on HI IM, and apply PCA & GNILIC foreground subtraction methods.

2. HI IM Development and PCA Foreground Subtraction for MeerKAT, BINGO, FAST and SKA-I

In this chapter we will develop capabilities to simulate sky signals for HI, foreground/synchrotron from our Milk Way Galaxy and emissions from extragalactic point sources. After adding noise together with signal components of the sky, thereafter we will apply foreground removal techniques, preferably, PCA and GNILIC to strip out contaminations and obtain the original HI sky signals.

2.1 Thermal Noise

We will have to simulate the full sky 21-cm, foreground, mostly synchrotron, and emission from point sources maps, mask them to appropriately select the corresponding region of the sky for each telescope, and finally add noise. The idea is to have the sky maps with all its components and apply contaminants cleaning technique to come up with HI sky signal map. With HI signal we can do a couple of analyses and cosmological probes. Below, we explain how to model noise.

1. Noise for each pixel,
$$\sigma = \frac{T_{\text{sys}} + T_{\text{sky}}}{\sqrt{\triangle t \triangle \nu}}, \tag{2.1.1}$$
where T_{sys} is the system temperature, T_{sky} is the sky temperature, $\triangle t$ is the integration time for each pixel and $\triangle \nu$ is the frequency bandwidth (measure of resolution).

2. We pixelize the survey area, using the beam size, θ_{FWHM} as a pixel size. So, for 21-cm, a pixel size is given by
$$\theta_{\text{FWHM}} = \frac{\lambda_\nu}{D}. \text{ In most cases, the usual formula is } \theta_{\text{FWHM}} = \left(\frac{1.22\lambda_\nu}{D}\right). \tag{2.1.2}$$
Here λ_ν is the wavelength corresponding to a particular frequency ν, and D is the telescope dish diameter.

3. For each frequency, we will have N number of pixels given by
$$N_{\text{pix}} = \frac{\Omega_{\text{sur}}}{\theta^2_{\text{FWHM}}}, \tag{2.1.3}$$
where Ω_{sur} is the survey area in square degrees.

4. Integration time for each pixel, $\triangle t$ is then given by
$$\triangle t = \frac{T_{\text{Tot}}}{N_{\text{pix}}}, \tag{2.1.4}$$
where T_{Tot} is the total integration time.

5. This useful relation
$$\theta_{\text{FWHM}}(\nu) = \theta_{\text{FWHM}}(\nu_0)\frac{\nu_0}{\nu} \tag{2.1.5}$$
comes from (2) above. The measure of $\theta_{\text{FWHM}}(\nu)$ is usually in arc minutes (arcmin).

6. We will use the Python Healpy to generate the noise maps, taking into consideration the Nsides.

2.2 Masking

2.2.1 Declination (Dec) and right ascension, RA

Declination is the angular distance of a point north or south of the celestial equator. Declination is one of the two angles that locate a point on the celestial sphere in the equatorial coordinate system, the other being hour angle. Points north of the celestial equator have positive declinations, while those south have negative declinations. Declinations with magnitudes greater than 90° do not occur, because the poles are the northernmost and southernmost points of the celestial sphere. To make the point clear, celestial equator has a declination of 0°, north celestial pole has a declination of +90°, south celestial pole has a declination of −90°.

In other words, declination is a range of degrees from $-\pi/2$ south of the celestial equator to $\pi/2$ north of the celestial equator.

Right ascension, RA, is the angular distance measured eastward along the celestial equator from the vernal equinox to the hour circle of the point in question. When combined with declination, these astronomical coordinates specify the direction of a point on the celestial sphere in the equatorial coordinate system.

In regard to Figure 2.1, the angles θ and ϕ are related to the coordinates x, y and z by equations

$$\begin{cases} x = r\cos\phi\sin\theta \\ y = r\sin\phi\sin\theta \\ z = r\cos\theta \end{cases} \tag{2.2.1}$$

RA $\sim \phi \in [0, 2\pi]$, Dec $\sim [-\pi/2, \pi/2]$, and $\theta \in [0, \pi]$ is calculated from the equation

$$\theta,\ \text{Colatitude} = \frac{\pi}{2} - \text{Dec angle}. \tag{2.2.2}$$

For example, the BINGO declination of $[-50°, -40°] \implies \theta \in [130°, 140°]$. The FAST maximum declination range is $[-14°, 65°]$.

Key words: Masking, noise, resolution, sensitivity

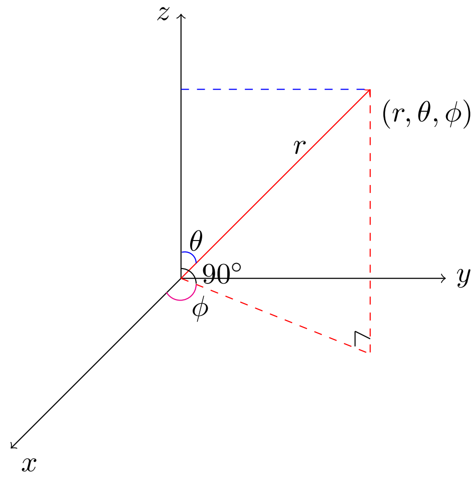

Figure 2.1: 3-D representation of Cartesian coordinates

- The angle θ is defined in range $[0, \pi]$ and therefore it cannot directly represent declination $[-\pi/2, \pi/2]$.
- θ is the polar angle or colatitude on the sphere, ranging from 0 at the North Pole to π at the South Pole.
- ϕ The azimuthal angle on the sphere, $\phi \in [0, 2\pi[$.

3. Mathematics

We will cover a wide range of mathematics that interact with our ongoing research, from statistics to mathematical physics and beyond.