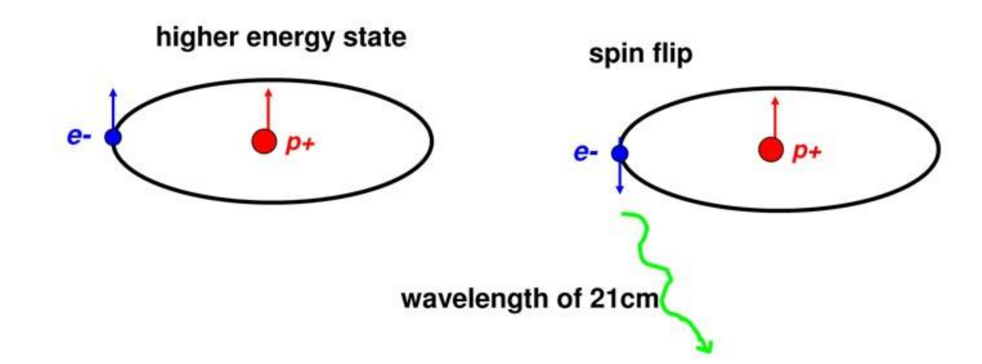
Hydrogen Intensity Mapping Simulator: interpolation improvements and radio point source compatibility with application to GaLactic and Extragalactic All-Sky MWA Survey (GLEAM) dataset

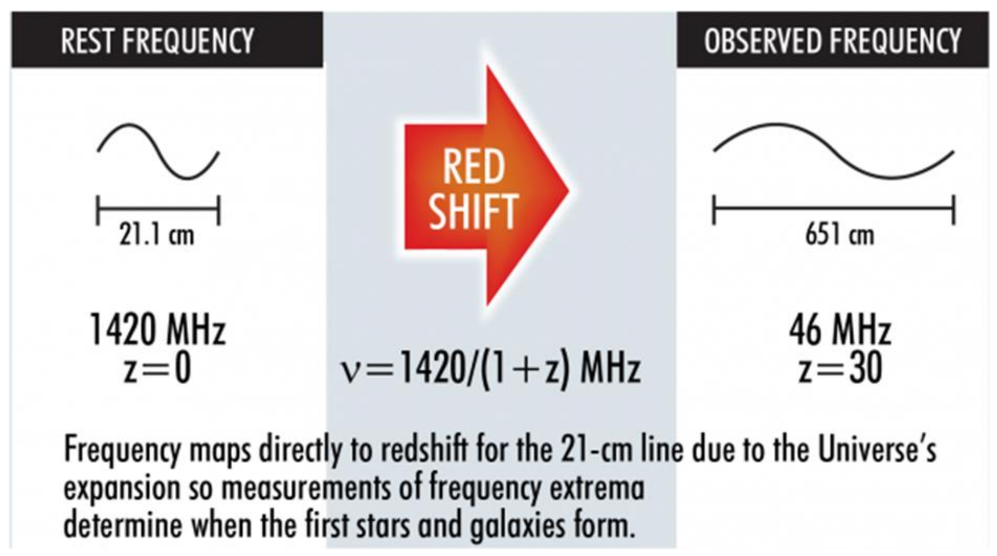
Zhi Chen, Physics, Stony Brook University, Stony Brook, NY 11794

Anze Slosar, Physics, Brookhaven National Laboratory, Upton, NY 11973

Abstract

BMX is a radio telescope built at Brookhaven National Laboratory to serve as a prototype to experiment with methods for mapping the structure of the Universe by detecting 21cm hydrogen emission lines. The biggest challenge of this technique is the presence of galactic foreground. Galactic foreground are radio frequency signals emitted from galaxies that contaminate hydrogen signals, so an effective filtering method is necessary for this technique. My role in this project is to improve a simulator that simulates complex visibility given mock data collected by a simulated telescope looking at a fixed sky. I have successfully implemented Lanczos interpolation which significantly improves the complex visibility curve as it generates a theoretically smooth curve for the foreground data set. In addition, an implementation of calculating complex visibility for radio point sources also helped to examine radio point source datasets, which can be compared with hydrogen and foreground signal data. The goal of this simulator is to decontaminate real datasets by removing signals other than hydrogen signals.

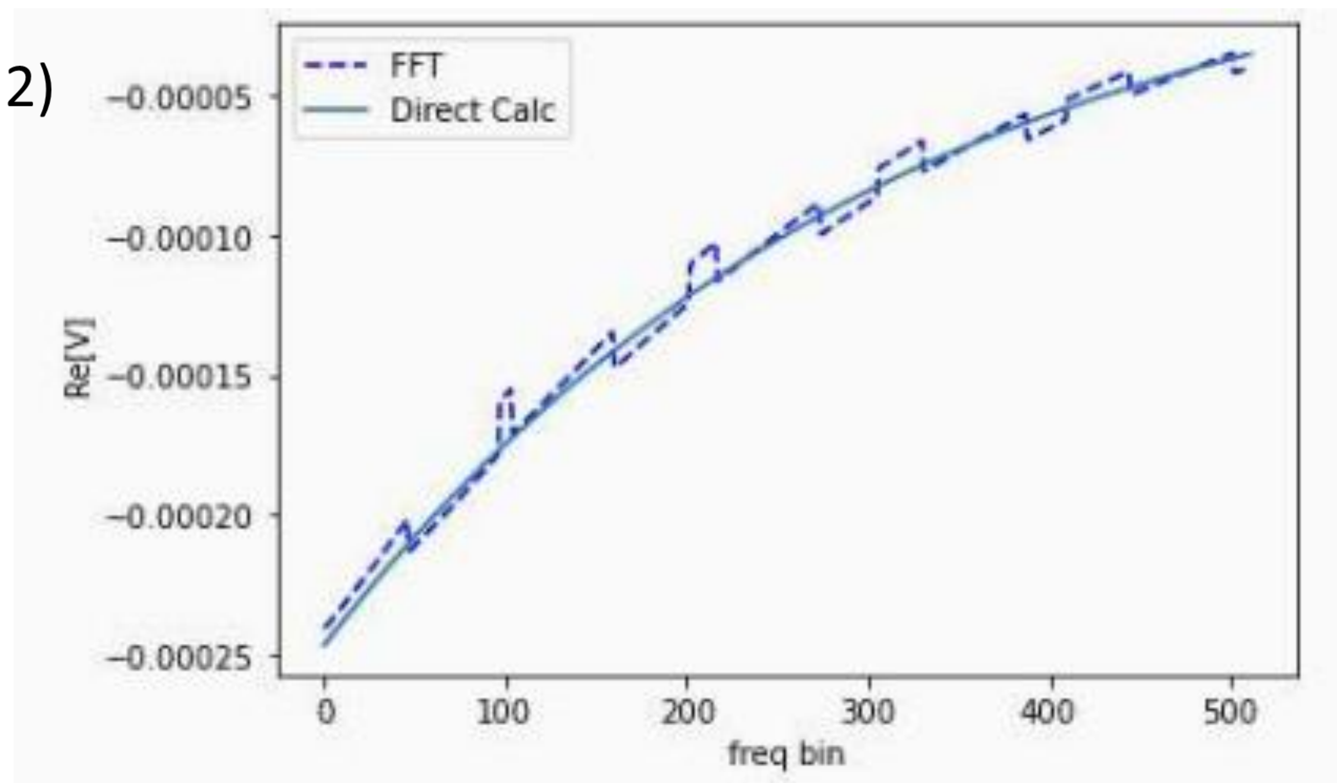




Introduction

For decades, cosmologists are trying to model the general structure of the Universe through variety of methods. One of the relatively new but very promising method is hydrogen intensity mapping. Neutral hydrogen has two energy states, which correspond to two different spin configurations (shown on the left) .Once the electron experiences a spin flip (from high energy to low), a photon with rest wavelength of 21cm will be emitted. The wavelength will be stretched once it reaches Earth since the signal will be redshifted due to Universe expanding. Then we can infer the position and time period of the signal emission by determine the redshift. Since there are countless neutral hydrogen clouds floating in the Universe, there should be enough signals coming from all directions for us to map out the general structure of the Universe.

2)



Methods (Interpolation)

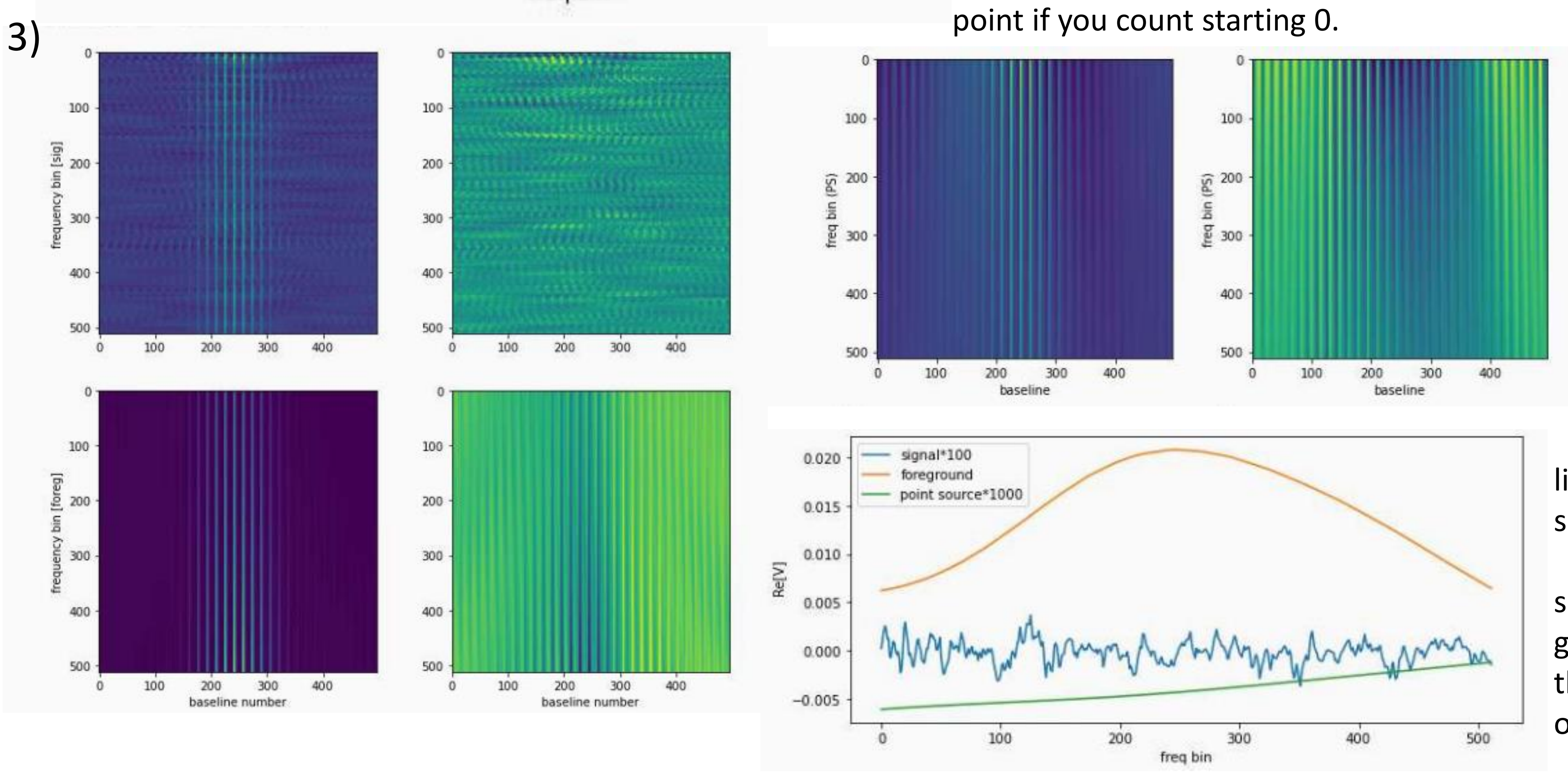
Imcurio needed a better interpolation method: Lanczos Interpolation. L(x) is a normalized sinc function as window function to interpolate data points. "a" is an integer that defines the kernel size. 'a' is usually 2 or 3, but it is defined to be 5 since it appears that larger 'a' produces better results. We needed a 2D interpolation and Lanczos interpolation is convenient to expand to higher dimension due to its property. s_i refers to the data in the ith index of the dataset, and x refers to the point of interpolation. For example, if x = 1, then the interpolated data will be exactly the second data point if you count starting 0.

$$L(x)=\begin{cases}1 & \text{if } x=0,\\ \dfrac{a\sin(\pi x)\sin(\pi x/a)}{\pi^2x^2} & \text{if } -a\le x<a \text{ and } x\neq 0,\\ 0 & \text{otherwise.}\end{cases}$$

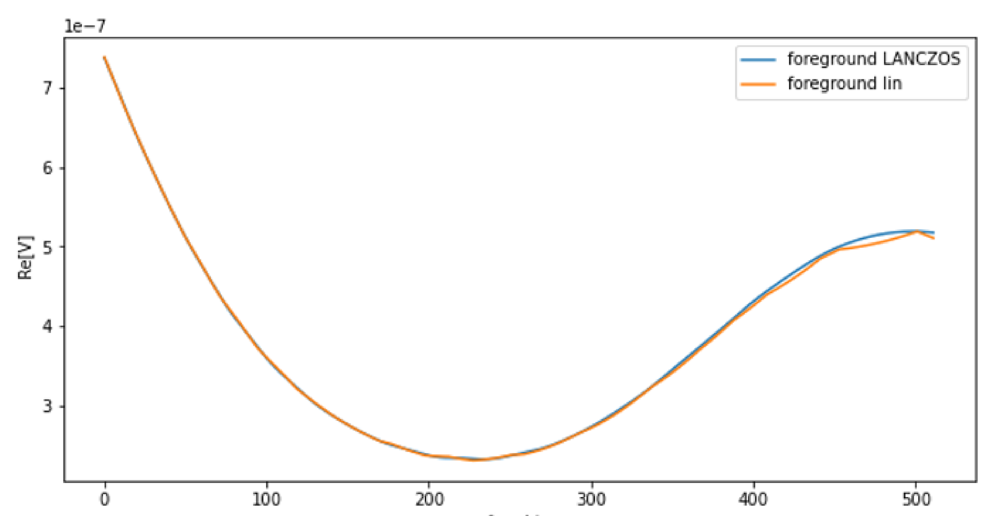
$$S(x)=\sum_{i=\lfloor x\rfloor-a+1}^{\lfloor x\rfloor+a} s_i L(x-i),$$

$$L(x,y)=L(x)L(y)$$

3)



1)



$$\int_c^d f(x)\delta(x-a)dx=\begin{cases}f(a), & a\in(c,d)\\ 0, & \text{otherwise}\end{cases}$$

$$V(u,v)=\iint F(l,m)B(l,m)^2\delta^2(l-l',m-m')e^{-2\pi i(ul+vm)}dldm$$

$$V(u,v)=\iint I(l,m)B(l,m)^2e^{-2\pi i(ul+vm)}dldm$$

$$\boxed{V(u,v)=F(l',m')B(l',m')^2e^{-2\pi i(ul'+vm')}}$$

Methods (Point Source)

Imcurio uses the fast fourier transform (FFT) module in numpy to convert spectral flux density to complex visibility. However, FFT is not an ideal for point sources. Point sources can be described using dirac-delta functions. By using their property, directly calculating complex visibility is a much better option. Let I(l,m) = F(l,m)δ^2(l−l',m−m'), we can redefine the complex visibility for point sources.

Then the next step is to apply this point source compatibility to a real dataset called GLEAM. GLEAM contains 200,000+ radio point sources with their position, spectral index, and spectral flux density. The main obstacle faced during this phase is data rotation. Due to the default position of the telescope defined in beam, it is necessary to rotate all the data such that the telescope is the correct position with respect to the dataset.

Discussion/Conclusion

1) Imcurio now utilizes lanczos interpolation which outperforms linear interpolation. The foreground visibility curve generates a much smoother curve by using lanczos interpolation.

2) FFT has its limitation when calculating point sources, since point sources are in theory infinitely small pixels. FFT will put data points on a grid line which includes unwanted data points for point sources, and the jagged lines in the complex visibility curve also reflect this. On the other hand, directly calculate complex visibility gives the exact answer.

3) left column shows real part of visibility and right column shows complex. The first row shows the image plot for signal, second row for foreground, and last row for point source. Bottom right plot shows a more quantitative view for three data types. Foreground have the largest magnitude while point sources happen to have less magnitude compare with hydrogen. Also see a smooth curve for point source just like foreground while the signal is not.

4)Next step: Need to create power spectra for these data and weighting the spectra by some frequency to some power, i.e. nu^a, such that signals other than hydrogen is suppressed

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Stony Brook University

Zhi Chen Team 6