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Eficiência do GNILC na remoção do ruído $1/f$ em experimentos de mapeamento de intensidade do HI

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Efficiency of $1/f$ noise removal in HI intensity mapping experiments by GNILC

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*"Anyhow - I sat by your side, by the water
You taught me the names of the stars overhead that I
wrote down in my ledger
Though all I knew of the rote universe were those
pleiades loosed in December
I promised you I'd set them to verse so I'd always
remember"*

Emily - Joanna Newsom

Resumo

Um dos maiores mistérios na cosmologia moderna é a natureza e dinâmica da energia escura, o componente que é tido como sendo a causa da aceleração na expansão do Universo. Neste contexto, a medição das Oscilações Acústicas de Bárions, regiões de maior densidade de matéria marcadas na distribuição das galáxias desde a época da Recombinação, através da observação da radiação de 21cm do HI, serve como régua padrão para o estudo da história de expansão do Universo e, consequentemente, estudo da natureza da energia escura. Este trabalho explora a eficiência do método chamado *Generalized Needlet Internal Linear Combination*, ou GNILC, na recuperação de um mapa de HI mais ruído térmico quando diferentes valores para os parâmetros que caracterizam o ruído $1/f$ são testados e achou que só há uma boa recuperação para grandes escalas, $\ell \leq 20$, e um superestimação de aproximadamente 29% para as menores. Entretanto, os parâmetros do próprio GNILC não foram variados e, portanto, antes de descartá-lo como um bom método de separação, simulações mais abrangentes devem ser testadas.

Palavras-chave: cosmologia; análise de dados; ruído $1/f$; separação de componentes

Abstract

One of the greatest mysteries of modern cosmology is the nature and dynamics of dark energy, the component which is believed to be the cause of the Universe's accelerated expansion. In this context, the measurement of Baryon Acoustic Oscillations, matter overdensities imprinted in galaxy distribution since recombination epoch, through the observation of HI redshifted 21cm radiation serves as a standard ruler for the Universe's expansion history and, consequently, dark energy's nature. This work explores the efficiency of a component separation technique called Generalized Needlet Internal Linear Combination in recovering a map of HI plus thermal noise signal as different $1/f$ noise model parameters are varied and found that this method results in a good recuperation only for large scales, $\ell \leq 20$, and overestimates the HI plus thermal noise signal around 29% for smaller scales. However, GNILC's parameters were not varied and, therefore, before discarding it as a valid separation method, one should conduct more embracing simulations.

Key words: cosmology; data analysis; $1/f$ noise; component separation

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Chapter 1

Introduction

The standard cosmological model describes a flat Friedmann-Robertson-Walker Universe containing cold dark matter (CDM) and a cosmological constant (Λ), hence, it's called the Λ CDM model. This cosmological constant was once referred by Einstein as his greatest mistake, as it was originally introduced in his equations to provide a static Universe as a solution for them [1].

However, in 1929, Edwin Hubble, working in Carnegie Observatories in Pasadena, California, measured the redshift of a number of distant galaxies and plotted it against their relative distance. The data clearly showed a positive linear relation between both quantities, indicating an expanding Universe [2] and the need for a cosmological constant in the equations disappeared.

In 1998, two separate teams of astronomers observing distant type 1a supernovae, one led by the American Saul Perlmutter and the other by the Australians Nick Suntzeff and Brian Schmidt, published their results proving that not only our Universe was expanding, but expanding in an accelerating way [3] and, so, the cosmological constant entered again in the spotlight representing dark energy, an unknown type of energy that would be responsible for this accelerating effect of space.

Even though cosmic microwave background (CMB) measurements have been able to constrain with great accuracy [4] Λ CDM parameters, dark energy's equation of state parameter, ω , has yet to be consolidated. This model of Universe assumes $\omega = -1$, where $\omega = P/\rho$ (P and ρ , respectively, pressure and energy density), however, different models have different assumptions, e.g. ω constant, but not -1 or even a function of the scale factor, a [5].

Baryon Acoustic Oscillations (BAO) appear in this context as one of the most powerful tool for constraining the properties of dark energy, serving as a standard ruler for the study of the Universe's expansion history [6]. It originates from small overdensities of dark matter in the primordial Universe, where there were not yet baryons and photons separately, but rather a photon-baryon plasma. As these overdensities

attracted more matter gravitationally, acoustic oscillations arising from the interaction between gravitational attraction and radiation pressure from the plasma traveled through it and, by the time Recombination took place, these matter waves froze at a certain scale. Naturally, more galaxies were formed at this precise distance, 150Mpc. Thus, BAO are primordial sound waves imprinted in large-scale clustering of galaxies that have a fixed size at Recombination and, therefore, measuring their apparent size as a function of redshift z can provide insight about the Universe's expansion history.

A cheap and efficient way of detecting BAOs comes from the detection of hyperfine 21cm spin-flip transition of neutral hydrogen (HI) intensity mapping (IM). Intensity mapping is an observational technique in which no individual galaxies need to be resolved, as it computes the average brightness intensity of the sky signal coming from a certain area [7].

There are several HI intensity mapping efforts, such as CHIME [8], BINGO [9], FAST [10] and SKA [4].

HI signal is expected to be around 4 orders of magnitude smaller than the background signal [11], which is composed of astrophysical foreground and electrical noises. Inserted in this undesired signal there is a particular electronic noise called $1/f$ (or pink/flicker) noise.

As the name states, this kind of noise has a spectrum that decays with the inverse frequency f and is intrinsic to any electronic device. It was first observed in 1925 by J.B. Johnson in vacuum tubes and, shortly after, W. Schottky tried to provide a first attempt of a theoretical explanation based on the physics of electron transport inside vacuum tubes [12]. Throughout the years, this type of noise behavior has been observed in a large range of physical situations, with spectral index usually between 0.5 and 2, and, until now, the effort to find a fundamental description for it has had little success [13].

The BINGO telescope (Baryon acoustic oscillations with Integrated Neutral Gas Observations) will use receivers that intend to suppress the $1/f$ noise, aiming to achieve a knee frequency of order $\sim 10\text{MHz}$ [14], but this cleaning isn't perfect and the remaining $1/f$ has to be removed using a component separation technique.

This thesis proposes to study the efficiency of a component separation method called Generalized Needlet Internal Linear Combination (GNILC) [5] in recovering a HI map in BINGO's redshift range as different parameters of the $1/f$ noise model proposed by [13] are varied, as proposed by [15].

The understanding of noise parameters in the simulation will be useful when the actual data analysis starts, becoming an important part of the data analysis effort.

Chapter 2

FWR Universe

2.1 Overview: Energy $\Leftrightarrow$ geometry

Within the realm of General Relativity, gravity is no longer interpreted as an attractive force between masses, but as a manifestation of the curvature of the spacetime due to the presence of matter in it. This interlinked notion is expressed mathematically through the Einstein equation [16],

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi GT_{\mu\nu}. \quad (2.1)$$

The $g_{\mu\nu}$ above is known as the metric tensor and is responsible for the geometric properties of spacetime itself: distances, angles and curvature. From this tensor, the other elements, $R_{\mu\nu}$ (Ricci tensor) and R (Ricci scalar curvature) are derived. Both indexes vary from zero (time coordinate) to three (1,2 and 3 are spacial coordinates)

On the right-hand side of eq. 2.1, the energy-momentum tensor, $T_{\mu\nu}$, describes the matter and energy distribution in the Universe. In this way, it's easily seen that the Einstein tensor, $G_{\mu\nu}$, clearly reveals how matter distribution directly affects the Universe's geometry.

In general, the energy-momentum tensor, $T^{\mu\nu}$, describes the flux of P^μ (component of the 4-momentum vector $\mathbf{P} = m\mathbf{U} = (E, m d\mathbf{x}/d\tau)$) through a surface of constant x^ν perpendicular to P^μ .

The notion that our Universe is homogeneous and isotropic for scales larger than 150Mpc (*The cosmological principle*) and in expansion, leads to its description through the Friedmann-Robertson-Walker (FRW) metric, which has a line element of the form [17, 18]:

$$ds^2 = -dt^2 + a^2(t) \left[\frac{dr^2}{1 - \kappa r^2} + r^2(d\theta^2 + \sin^2 \theta d\phi^2) \right], \quad (2.2)$$

Figure 2.1: Visualization of the shape of different curvature Universes (NASA/WMAP Science Team).

in units of $c=1$. The r, θ and ϕ are the comoving spherical coordinates, that is, they expand alongside with the space itself, t is the cosmic time, κ the Gaussian curvature of spacetime ($\kappa = -1, 0$ or $+1$ for open, flat and closed Universes, respectively) and $a(t)$ is called the scale factor, which relates comoving distance (d_c) and physical distances (d_p) as $d_c: d(t) = a(t)d_c$. By definition, $a(t_0) = 1$, where the subscript denotes the quantities at the present day [19].

In such a Universe, a perfect fluid is considered to be the source of the energy-momentum tensor [20],

$$T^{\mu\nu} = (\rho + P)U^\mu U^\nu + Pg^{\mu\nu}. \quad (2.3)$$

or simply,

$$T_{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & a^2 P & 0 & 0 \\ 0 & 0 & a^2 P & 0 \\ 0 & 0 & 0 & a^2 P \end{pmatrix}. \quad (2.4)$$

In this matrix, ρ is the sum of the densities (and P of pressures) of all components that constitute the Universe: baryonic matter (b), dark matter (dm), radiation (rad), dark energy (de) and any other that has to be taken into account.

Energy conservation requires $T^{\mu\nu}_{;\nu} = 0$, where the semicolon denotes the covariant derivative. This condition leads to the continuity equation,

$$\dot{\rho} + 3H(1 + \omega)\rho = 0, \quad (2.5)$$

with the dot representing the temporal derivative, $H = \dot{a}/a$, the Hubble parameter, and ω the equation of state (EoS) parameter, $\omega = P/\rho$. The general solution of this differential equation as a function of the redshift z , defined as the stretch a wavelength suffers due to the expansion of spacetime is

$$z \equiv \frac{\lambda_{\text{observed}} - \lambda_{\text{emitted}}}{\lambda_{\text{emitted}}} = \frac{1 - a}{a}, \quad (2.6)$$

$$\rho(z) = \rho(0) \exp \left[3 \int_0^z \frac{1 + \omega(z')}{1 + z'} dz' \right], \quad (2.7)$$

for each component [6]. For constant ω , (eq. 2.7) turns into

$$\rho(z) = \rho(0)(1 + z)^{3(1+\omega)}. \quad (2.8)$$

Einstein's relation (eq. 2.1), along with (eq. 2.5) gives two results:

$$H^2(t) = \frac{8\pi G}{3}\rho(t) - \frac{\kappa}{a^2(t)}, \quad (2.9)$$

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho + 3P). \quad (2.10)$$

The curvature κ in eq. 2.9 can be interpreted as an additional term in the density ρ , with the definition: $\kappa/a^2(t) = (8\pi G/3)\rho_\kappa$ and then eq. 2.9 can be written in the simpler form

$$H^2(t) = \frac{8\pi G}{3}\rho(t) = \frac{8\pi G}{3} \sum_i \rho_i(t). \quad (2.11)$$

From eq. 2.9 the critical density ρ_c for a flat Universe is

$$\kappa = 0 \rightarrow \rho_c = \frac{3H^2}{8\pi G}. \quad (2.12)$$

It is convenient to normalize the energy density for all species in the Universe relative to ρ_c , thus, the density parameter $\Omega(t)$ is defined as

$$\Omega(t) = \frac{\rho(t)}{\rho_c(t)}, \quad (2.13)$$

and eq. 2.11 can be rewritten as [19],

$$\Omega(t) - 1 = \frac{\kappa}{(aH)^2}. \quad (2.14)$$

This clearly shows the dependence between geometry and energy density, for correctly measuring the density parameter, the curvature can be specified.

Nevertheless, current data from WMAP suggests that our Universe is flat ($\Omega_k = 0$) with only 0.4% margin of error.

A standard way of expressing eq. 2.11 is [11],

$$E^2(z) \equiv \frac{H^2(z)}{H_0^2} = \sum_{i=1}^N \Omega_i (1 + z)^{-3(1+\omega_i)}, \quad (2.15)$$

where the Ω_i is the value of the i^{th} component density parameter today and H_0 the Hubble constant. In eq. 2.15 it is taken for granted that the different densities are independent and separately conserved.

Since the densities of matter and radiation are $\rho_m \propto a^{-3}$ and $\rho_{rad} \propto a^{-4}$ [19] eq. 2.15 is more directly written as,

$$E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_{rad}(1+z)^4 + \Omega_{de}f(z)}. \quad (2.16)$$

Here $f(z)$ is given by eq. 2.7 divided by $\rho(0)$ [11].

2.1.1 Dark energy

The concordance model

The cosmological constant Λ was first included by Einstein in his equations (which described a contracting Universe) in order to achieve the current consensus that the Universe was static. However, after numerous evidences of a expansion of space, Λ was again included in eq. 2.1 in order to obtain such a solution [17]. This modified equation becomes:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + \Lambda g_{\mu\nu} = 8\pi GT_{\mu\nu}, \quad (2.17)$$

and results in modifications in eq. 2.9 and eq. 2.10 as well [17, 18],

$$H^2(t) = \frac{8\pi G}{3}\rho(t) - \frac{\kappa}{a^2(t)} + \frac{\Lambda}{3}, \quad (2.18)$$

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}. \quad (2.19)$$

The purpose behind the insertion of the cosmological constant is better demonstrated by eq. 2.19. It is seen that a positive Λ leads to an increase in acceleration $\ddot{a}$ and, in time, this factor can become larger than the gravitationally contracting one and rule the overall dynamics [21]. Such an effect is realized at recent times and is what currently explains the dimming effect in distant supernovae, granting the 2011 Nobel Prize to Riess, Schmidt and Perlmutter [22].

In the same way as with the curvature constant, Λ can also be related to a density term ρ_Λ (or ρ_{de}). Therefore eq. 2.11 and eq. 2.15 are still valid.

Figure 2.2: Qualitative illustration of the density evolution of components. It can be observed that for very large redshifts, or very low scale factor, the Universe was radiation dominated, it spent most of its time during a matter dominated era and at the present time we live in a dark energy dominated era.

Even though this model relating dark energy to the cosmological constant, referred to as Λ CDM (CDM stands for Cold Dark Matter), struggles with inconsistencies [11, 18, 23], it is the one that best fits the latest WMAP, Planck, SDSS, DES and other surveys results.

Modelling the vacuum as a quantum field using Quantum Field Theory, the ground state (also known as vacuum energy), the predicted density $\rho \approx 10^{74} \text{GeV}^4$ is obtained. However, Λ CDM model predicts a value of $\rho \approx 10^{-47} \text{GeV}^4$. This amounts to a difference of 121 orders of magnitude between the two theories.

The coincidence problem is an unexpected surprise: even though matter and dark energy densities evolve in completely different ways, they are about the same order today.

Interaction models to the dark sector

The cosmological constant provides the simplest explanation of the observed accelerated expansion, but, as mentioned, even though is an excellent fit to the data, has its problems [23]. This way, alternative models have been proposed in the literature.

The continuity equation implicitly assumes that there is no interaction, apart from gravitational, between different species in the Universe, however the current large densities for dark energy ($\sim 70\%$) and dark matter ($\sim 25\%$) makes reasonable to speculate that there might be an interaction between them, most conveniently modelled as a decay of dark energy into dark matter [24, 25]. This way, eq. 2.5 for these two components can be rewritten as:

$$\begin{aligned}\dot{\rho}_{de} + 3H(1 + \omega_{de})\rho_{de} &= -Q, \\ \dot{\rho}_{dm} + 3H\rho_{dm} &= Q,\end{aligned}\tag{2.20}$$

where Q represents the interaction [18, 24]. This coupling is expected to be small, since the Λ CDM model fits observational data very well [18].

The interaction term expansion to first order gives

$$Q = H(\xi_1\rho_{dm} + \xi_2\rho_{de}),\tag{2.21}$$

where the ξ constants are to be determined observationally. While they are not measured, different interaction models can be studied by assuming various values for ξ_1 and ξ_2 .

One of the goals of these alternative models for DE is to investigate and solve the coincidence problem. Using eq. 2.20, for example, [18] states that, due to interaction, the ratio between densities provides a parameter ζ to quantify the severity of the coincidence problem,

$$r = \frac{\rho_{dm}}{\rho_{de}} \sim a^{-\zeta}.\tag{2.22}$$

For $\zeta = 3$, Λ CDM is recovered and for $\zeta = 0$ the problem is solved. By a suitable choice of interaction term, any scaling behavior for r can be reproduced and cases where the coincidence problem is less severe, that is $\zeta < 3$ are obtained [24].

Some efforts have been made to uncover DE's nature using the interaction model eq. 2.1.1 as in [18], [26], [25] and [27].

Using eq. 2.1.1, for example, [27] uses the Fisher matrix formalism to constrain ξ parameters in eq. 2.21 through BAO and redshift-space distortion information provided by the J-PAS survey. It finds that J-PAS shall be able to determine the interaction parameter with a maximum precision of $\sigma \sim 0.02$ for ξ_1 and $\sigma \sim 0.01$ for ξ_2 in eq. 2.21. Around the fiducial value for the EoS parameter, $\omega_{de} = -1$, the study finds σ_ω about $0.04 - 0.05$. Naturally, the research imposed some limitations to the data and a more embracing analysis is yet to be done.

Another study is made by [25] in which the Plank data is used for the analysis of different interaction models shown in table 2.3.

Model	Q
I	$3\xi_2 H \rho_d$
II	$3\xi_2 H \rho_d$
III	$3\xi_1 H \rho_c$
IV	$3\xi H (\rho_d + \rho_c)$

Figure 2.3: Different values for the interaction Q to be analyzed.

It concludes that only for models II, III and IV the coupling constants are all positive from Planck data constraints which indicates that there is energy flow from DE to DM, as required to alleviate the coincidence problem. These models also present the possibility to minimize the discrepancy of the Hubble parameter value given by the Planck and the Hubble Space Telescope measurements.

A limitation of this study is the fact that the EoS is fixed, that is, independent of time and in a more realistic scenario it is expected not to be and, therefore, wider models have to be investigated.

A model for DE decay is studied in [26], in which dark energy particles of mass $m \sim 10^{-3}$ GeV and represented by the potential $V(\phi) = |2m\phi - 3\lambda\phi^2|^2 + Q(\phi)$ go from a false vacuum, or the metastable minimum to the stable, or true, one. It's suggested that this quintessence model can alleviate the coincidence problem by providing a field theory mechanism of DE decay into DM.

As seen, the investigation of dark energy's nature and dynamics is, currently, a very active area.

2.2 Baryon Acoustic Oscillations

Baryon acoustic oscillations, or BAOs, are primordial sound waves descendant from the oscillations caused by the radiation pressure and gravity competition in overdense points of the baryon-photon plasma of the early Universe. This effect is imprinted in galaxy clustering distribution as a shell of a slight matter overdensity of radius 150 Mpc, that was established by conditions in the early Universe ($\sim 380,000$ years after the Big Bang).

Figure 2.4: BAOs consist of spherical shells of matter over-density in which galaxies are more likely to be found today. This characteristic radius scale evolved only due to the expansion of the Universe, thus provides a standard ruler to measure the expansion rate. Credit: Chris Blake and Sam Moorfield [28].

Figure 2.5: The BAO peak in the 2-point correlation function $\xi(s)$ for before and after recombination eras. DR11 CMASS clustering measurements (black circles) and best-fit for each case (solid line) [29]

Since they have a fixed known size at recombination epoch, measuring its apparent size as a function of the redshift can provide a standard ruler for distance measurements, therefore helping to understand the expansion history and, consequently, they give insight about the dark energy behind it.

To understand BAO formation, the snapshots below fig. 2.6 of the BAO formation process taken from [6] illustrates the evolution of a single spherical perturbation in a period when the Universe was a hot plasma formed by photons and matter tightly

coupled via Thompson scattering. Photon and neutrino densities were divided by 4 and 3, respectively, so they can fit the snapshots.

As the matter (cold dark matter and baryon) perturbation grows due to gravitational attraction, the radiation pressure also increases, exciting a spherical wave eventually leading to an expansion of the photon-baryon fluid shell. The weakly interacting neutrinos rapidly leak away and have no participation in the process (first row of figure 2.6).

Since CDM only interacts via gravitation, its density continues to grow at the center of the perturbation. As photons decouple, the pressure and velocity of the baryon-photon fluid decrease towards zero. At the end of recombination, the photons stream away leaving a shell of baryons stagnated at approximately 150Mpc and a dark matter perturbation near the origin (Second row of figure 2.6).

The horizon at which baryons were released from the Compton drag of photons is called the sound horizon [17], $r_s(z_{drag})$ and is given by

$$r_s(z_{drag}) = \int_0^{\eta_{drag}} c_s(\eta) d\eta \quad (2.23)$$

where η is the conformal time, $\eta \equiv \int a^{-1} dt$ and c_s is the effective sound speed of the coupled baryon–photon plasma,

$$c_s = \sqrt{\frac{1}{3(1 + R_s)}}. \quad (2.24)$$

The factor R_s represents the ratio between baryonic matter and radiation densities, $R_s = 3\rho_b/4\rho_{rad}$.

Over time, the two overdensities of dark matter and baryon attract one another until equilibrium is reached. Galaxies form predominantly in the central perturbation, but with a 1% enhancement at the remaining shell [11]. As the Universe evolves and expands, the physical radius of the BAOs are expected to enlarge due to the dark energy's presence, but retaining the shape, in this way, justifying their evolution as a way to quantify the space expansion (Final row of figure 2.6).

Figure 2.6: Snapshots of BAOs' formation

2.2.1 Constrains in Dark Energy

Distances

There are three important definition of distances in the study of scales in the Universe [2]: the comoving distance $D(z)$, the angular diameter distance $D_A(z)$ and luminosity distance $D_L(z)$.

The comoving distance is the path of a radial photon:

$$D(z) = c \int_0^z \frac{dz'}{H(z')}, \quad (2.25)$$

which depends on the Hubble parameter only and, therefore, the curvature.

The comoving angular diameter distance is defined as the quantity that results in the object's comoving size dl when multiplied by the object's angular size $d\alpha$, that is, $dl = D_A d\alpha$. Expressed in more convenient terms, it's written [18]

$$D_A(z) = \frac{c}{H_0(1+z)} \int_0^z \frac{dz'}{E(z')}. \quad (2.26)$$

The physical luminosity distance is defined as the quantity that will maintain the Euclidean relation for flux in the comoving frame, $F = \frac{L}{4\pi d_L^2}$. Since all physical and comoving distances are related through the scale factor $d_{physical} = a(t)D_{comoving}$, D_L is

expressed as [18]:

$$D_L(z) = \frac{c(1+z)}{H_o} \int_0^z \frac{dz'}{E(z')}. \quad (2.27)$$

Both quantities are related, $D_L = (1+z)^2 D_A$.

One can see that direct measurements of distance can determine the Hubble parameter, thus probe the expansion evolution.

Baryon acoustic oscillations measurement

As mentioned, the importance of measuring BAOs is to help understanding dark energy and a way to do it is to constrain the value of its equation of state parameter ω_{de} . This can be done using two distance measurements, the line of sight ($r_{//}$) and transverse ($r_{\perp}$) apparent sizes of BAOs.

These apparent sizes are related to cosmological quantities as expressed in eq. 2.28 and eq. 2.29 [6, 17].

Figure 2.7: BAO as viewed from Earth. The transverse radius defines an angular opening $\Delta\theta$ and the difference in redshift, $\Delta z = z_2 - z_1$, between the line of sight extremes of the BAO can be related to $r_{//}$.

$$r_{//} = \frac{c\Delta z}{H(z)} \quad (2.28)$$

and

$$r_{\perp} = d_A(z)(1+z)\Delta\theta \quad (2.29)$$

Once a large enough number of measurements are taken to quantify $H(z)$ in two independent ways (directly and through $d_A(z)$, as already mentioned), one can constrain ω_{de} using eq. 2.16.

2.3 21cm hydrogen line

It is known that hydrogen constitutes approximately 75% [30] of the baryon composition of the Universe. As such, it is convenient to associate the HI (neutral hydrogen) distribution with the matter distribution itself. This is the idea behind the use of the HI 21cm emission line to do intensity mapping technique, which will be explained in the next section.

This line is the transition between the HI hyperfine levels of $1s_{1/2}$, $F = 1 \rightarrow F = 0$, a spin-flip transition, with highly precise measurement of the transition frequency: $\nu_{01} = 1.420405751786(30) \times 10^9$ Hz (or $\lambda \sim 21$ cm), at the atom's reference frame [31].

The average brightness temperature of the HI signal is given by [7]:

$$T_{HI} = 0.3K \left(\frac{\Omega_{HI}}{10^{-3}} \right) \left(\frac{\Omega_m + a^3 \Omega_{de}}{0.29} \right)^{-1/2} \left(\frac{1+z}{2.5} \right)^{1/2} \quad (2.30)$$

which is calculated to be $\sim 100\mu K$ for a redshift ~ 0.5 .

The brightness temperature, T_b , is the temperature which would result in the given brightness $B(\nu)$ if inserted into the Rayleigh-Jeans law [31],

$$B(\nu) = \frac{2\nu^2 k_B}{c^2} T_b. \quad (2.31)$$

However, since the very definition of BAO detectability hinges in density fluctuations, a more interesting quantity would be temperature fluctuations about this mean [30].

$$\delta T_{HI} \approx 27x_{HI}(1 + \delta_b) \left(\frac{\Omega_b h^2}{0.023} \right) \left(\frac{0.15(1+z)}{10\Omega_m h^2} \right)^{1/2} \times \left(\frac{T_s - T_R}{T_s} \right) \left(\frac{\partial_r v_r}{(1+z)H(z)} \right) mK. \quad (2.32)$$

Here the x_{HI} is the neutral fraction of hydrogen, δ_b the fractional overdensity of baryons, T_s the spin temperature (the excitation temperature of the line), T_R the background radio source brightness temperature along the line of sight, $\partial_r v_r$ comes from the velocity gradient along the line of sight and h is the dimensionless Hubble parameter, $h = H_o/100 \text{ Km Mpc}^{-1} \text{ s}^{-1}$. Only if $T_s \neq T_R$ a HI signal will be observed.

Three processes will determine the spin temperature of the 21cm line: emission of 21cm photons, collisions with other H atoms or electrons and resonant scattering of $Ly\alpha$ photons that cause a spin-flip via a intermediate state.

Even though HI is very abundant, this particular spontaneous transition is extremely improbable, it happens only once every 10^7 years. Given this enormous time, the resulting intensity is very low, which hampers the detection.

2.4 Intensity mapping

The basic idea behind intensity mapping (IM) is the detection of integrated emission from spectral lines in galaxies to track the growth and evolution of cosmic structures, that is, the identification of individual galaxies is no longer required [5, 32]. Since these fluctuations trace the underlying large scale matter distribution with the frequency dependence providing information about the distribution of emission along the line of sight, in the context of BAO observation, IM technique presents itself as the ideal one, for it reaches the experimental purpose in a faster and more economic way.

Unlike traditional surveys, IM surveys detect all sources of brightness, not only those above some flux limit and, therefore, are a better technique to the study of faint sources [32].

Figure 2.8: Comparison between the galaxy survey of the Very Large Array (VLA) (Left), a radio telescope with 27 dishes, with a single-dish carbon-monoxide (CO) IM instrument (COMAP) (Right) as they observe the same 2.5 deg^2 sky patch. VLA takes 3 times the observation time COMAP takes to cover this area while only detecting 1% of the total number of CO-emitting galaxies. Sources bright enough to detect with 1 hour of VLA time are marked in red [32].

As the line-emitting galaxies are a discrete, biased tracer of the underlying dark matter fluctuations, the intensity mapping power spectrum will consist of clustering and shot noise components as functions of some redshift z :

$$P_k(z) = \langle I(z) \rangle^2 b^2(z) P_m(k, z) + P_{\text{shot}}(z), \quad (2.33)$$

where $b(z)$ is the bias, $\langle I(z) \rangle$ the average intensity, and $P_{\text{shot}}(z)$ the shot noise power spectrum. Both $\langle I(z) \rangle$ and $P_{\text{shot}}(z)$ are determined from the first and second moments of the line luminosity function (number of galaxies per luminosity interval)

$$\Phi(L, z) = dn(z)/dL, \text{ eqs. 2.34.}$$

The bias is defined as the ratio of galaxy to total matter perturbation, that is,

$b = \delta_g/\delta_m$ [17]. In general it can depend on time and/or scale.

$$\begin{aligned}\langle I(z) \rangle &\propto \int_0^\infty L \Phi(L, z) dL, \\ P_{shot}(z) &\propto \int_0^\infty L^2 \Phi(L, z) dL.\end{aligned}\tag{2.34}$$

This IM basic formalism is presented in the Line-Intensity Mapping: 2017 Status Report [32].

Since the luminosity function depends on the particular cosmological model used, the power spectrum above can be used to test the standard cosmological model in different epochs.

BINGO, which stands for Baryon acoustic oscillations with Integrated Neutral Gas Observations, is an intensity mapping instrument conceived to measure BAOs through the observation of the 21cm line of HI [7, 9, 14, 33].

Figure 2.9: BINGO telescope original concept. Since the construction site was changed, a new design is under evaluation.

It is a static telescope programmed to observe a stripe of 15 degrees of the sky, taking advantage of the Earth's rotation [34], during the period of 4 years. Currently it is estimated a possible measurement of the acoustic scale down to 2% uncertainty [34], resulting in a maximum of 8% uncertainty at the estimation for the EoS parameter ω_{de} [35], but these values can be updated as the project evolves. It will operate in a frequency range of 960MHz and 1260MHz, corresponding to the redshift interval

$z \sim 0.13 - 0.48$ with a mean $z = 0.3$ [7]. In this redshift range dark energy dominates the Universe's dynamic (fig. 2.2)(represents 68% of all energy), and so, it's a good interval to study dark energy's nature.

This project is better detailed in the next chapter.

Chapter 3

The BINGO Telescope

Since the accelerating expansion of our Universe was confirmed in 1998, the nature of the postulated component responsible for this effect, the dark energy, has become one of the greatest mysteries of modern cosmology. It is in this context that the BINGO radio telescope is included.

As mentioned in the earlier chapter, BAO measurements provide powerful insight about cosmological parameters used to constrain dark energy's EoS parameter ω_{de} . In this way, BINGO's goal is to make the first detection of BAOs in radio wavelength though the detection of redshifted 21cm emission of neutral hydrogen using the IM technique to construct a 3D map of total matter (baryonic+dark) distribution [36].

The telescope is static, therefore, uses Earth's rotation to observe the sky, and to be constructed in the state of Paraíba in northeast region of Brazil. Its design consists of two $\sim 40\text{m}$ mirrors, a focal plane containing 50 horns, receivers operating at total system noise temperature of approximately 70K and will observe in the frequency range of 0.96 – 1.26 GHz, which corresponds to a redshift range of $z = 0.13 - 0.48$ [33].

The BINGO consortium is composed by Universidade de São Paulo (USP), Instituto Nacional de Pesquisas Espaciais (INPE) and Universidade Federal de Campina Grande (UFCG), all in Brazil, University of Manchester and University College London in the United Kingdom, ETH Zurich in Switzerland, Kwa Zulu Natal University in South Africa and, in China, YangZhou University and Jiao Tong University (Shanghai) [14].

Figure 3.1: Design for the BINGO telescope: The sky signal reflects in the primary mirror (main reflector) (1), slightly tilted in relation to the ground, onto the secondary mirror (2). The rays then are focused to the horns (3). Both mirrors are static.

3.1 The instrument

The telescope consists of 2 mirrors, the main reflector, which is parabolic with a radius of 20m and 140m of focal length and the secondary, which is hyperbolic with radius of 17m and foci distance of 252m. They result in the mapping of a 15° declination strip of the sky every 24h, 50 feedhorns, low side-lobe levels (about -40dB in relation to the main beam [37]), and an excellent polarization performance. Since the mean wavelength of operation is 30cm, the surface profile of the telescope mirror should have an root mean square error of 15mm to achieve maximum efficiency. Between the edge and center feedhorns, there is only a 1dB difference on the gain of the telescope's beams [14].

BINGO's receivers must be able to detect and distinguish the faint HI signal, With characteristic energy $100\mu\text{K}$, from the foreground continuum emission from the Galaxy, about $\sim 1\text{K}$ with spacial fluctuations of $\sim 100\text{mK}$ [11]. With this purpose, every pixel in the intensity map must have an integration time of 1 day and this time can be summed up

by the many returns to the same spot over the course of the entire campaign, which is expected to last for 4 years [14]. Furthermore, between these returns the receiver must be stable enough to ensure a low difference in the gains.

Each receiver chain contains a correlation system with uncooled amplifiers (chosen because of their good performance at low frequencies and low cost and maintenance) operating at a total system noise temperature of $\sim 70K$ [9] and in the frequency range 0.96 - 1.26GHz. After one year of observation, it is expected that a noise of only $60\mu K$ will be obtained in a one degree pixel in a 1MHz frequency channel.

Figure 3.2: A block diagram of BINGO's correlation receiver. The correlation is achieved through the hybrids, or magic tees.

The designed feedhorns have $\sim 1.9m$ diameter and $\sim 4.3m$ in length to allow the required field of view, are conical and corrugated in order to provide the necessary low side-lobes and good polarization performance and will receive an external layer of foam to guarantee thermal stability during operation (fig.3.3).

Figure 3.3: (A) A prototype of BINGO's horn (B) Horn blueprint with details on the corrugation (C) Horn mouth; the green rings are machined and contain sockets for suspension rings.

Initially, BINGO's telescope was supposed to be built in Uruguay, but due to budget issues the project was moved to Brazil where different sites were investigated. Finally, Serra do Urubu ($07^{\circ}02'57''\text{S}$, $38^{\circ}15'46''\text{W}$), in the state of Paraíba, Brazil, was chosen to be the site for BINGO's construction, for it has low levels of Radio Frequency Interference (RFI) (fig. 3.4), topography that can support the design and there are several campi from UFCG near enough to provide local support.

The total cost of the project is estimated at US\$ 4.2 million with US\$ 3 million dedicated to the electronic and horns and US\$ 1.2 million destined to site preparation and structure construction.

Figure 3.4: RFI measurements for Serra do Urubu. The maximum signal recorded is shown in red, the mean is in blue, the dark green dotted line shows the calibration signal (almost imperceptible, hidden behind the blue line) and the orange dashed line shows the level of the quiet sun. Measurements were performed with a discone antenna with an integration time of 10 minutes [33].

3.2 Beyond BAO

Even though the main goal of BINGO is to measure the BAO scale, other scientific goals can be achieved with the project.

Different models of modified gravity can be distinguished according to the redshift space distortion provided by the 21cm IM, the sum of masses of the neutrinos can be measured [38] and more Fast Radio Bursts can be discovered and studied using BINGO's observations [36, 37]. These are a few examples of parallel science that can be developed.

3.3 Other experiments

BINGO's main competitors are SKA (Square Kilometer Array), FAST (Five hundred meter Aperture Spherical Telescope) and CHIME (Canadian Hydrogen Intensity Mapping Experiment).

3.3.1 SKA

Figure 3.5: Artistic illustration of the SKA at night [39].

The SKA project is an international collaboration to build the world's largest radio telescope.

The SKA Organization has its headquarters at Jodrell Bank Observatory, near Manchester, UK, but eleven countries are currently members: Australia, Canada, China, Germany, India (associate member), Italy, New Zealand, South Africa, Sweden, the Netherlands and the United Kingdom.

It will be co-located in Africa and in Australia. South Africa's Karoo region will host the core of the high and mid frequency dishes, ultimately extending over the African continent. Western Australia's Murchison Shire will host the low-frequency antennas [39].

With eventually over one million square metres of collecting area, it will operate over a wide range of frequencies and exceed the image resolution quality of the Hubble Space Telescope by a factor of 50 times [40].

SKA will challenge Einstein's gravitational theory by strong-field tests of gravity using pulsars, investigate dark energy through the redshifted 21cm neutral hydrogen emission and gravitational effects of galaxies on the path of radio waves, search for FRB, study magnetic fields in space, help in solar physics studies and search for amino acids spectral signatures, assisting projects like SETI (Search for Extraterrestrial Intelligence).

3.3.2 FAST

Figure 3.6: FAST telescope at the Dawodang depression [41].

FAST is currently the largest single dish radio telescope in the world, located in the Dawodang depression in China [42].

The telescope has a fixed primary reflector of 500m radius, but only a circle of 300m radius is illuminated at any time and focuses radio waves on a receiving antenna suspended 140m above it. The frequency range it is working is 70MHz to 3GHz, but it can eventually be extended up to 8GHz.

The project aims the survey of 21cm HI emission, detection of molecular lines, FRB and pulsar observations and extraterrestrial search for life.

It's funded by the National Development and Reform Commission (NDRC) and managed by the National Astronomical Observatories of Chinese Academy of Sciences (NAOC), with the government of Guizhou province as a cooperation partner.

3.3.3 CHIME

Figure 3.7: CHIME telescope.

CHIME is a telescope located at Dominion Radio Astrophysical Observatory, a national facility for astronomy operated by the National Research Council of Canada [43].

Like BINGO, CHIME is a static telescope conceived mainly to map 21cm radio emission of intergalactic hydrogen through the measurement of BAOs and study dark energy through the expansion history of the universe.

It consists of four adjacent $20\text{m} \times 100\text{m}$ cylindrical reflectors pointing north-south (fig. 3.7) that results in a large instantaneous field of view ($\sim 200\text{deg}^2$) and observes in the bandwidth $400 - 800\text{ MHz}$.

The digitized signals collected by CHIME are processed to form a 3D map of hydrogen density and, at the same time, these signals can be combed for fast, transient radio emission, which is ideal for FRB and pulsars detection.

Chapter 4

Models for simulations

In this chapter we will present an overview of the instrumental part of signal detection and processing, as well as the models used for simulating the different types of signals and the GNILC method is described.

First, an introduction on antenna and BINGO's receiver will be presented in section 4.1. Then, for the foreground emissions we have synchrotron, cosmic microwave background, free-free, point sources in section 4.2. Section 4.3 describes the instrumental signals, such as thermal and 1/f noises. Finally, section 4.4 is reserved to the explanation of the GNILC method of component separation.

4.1 Signal detection and processing

In this section, the instrumental part will be portrayed as a background knowledge to the noise simulations to be presented in the next section. First an introduction to the general idea of antenna and receivers operation, in particular BINGO's receiver and how it is expected to deal with the 1/f noise.

4.1.1 Antenna and receivers

An antenna gathers the incoming radiation (IR) field and conducts it through the terminals until it reaches the receivers. Its response to the IR, as a function of direction is a function $A(\theta, \phi)$, called the antenna pattern and it commonly consists of a number of "lobes". These "lobes" indicate the strength of radiation capture at a certain angle, the lobe with the maximum response is called the main lobe and the others, the side lobes. They are all separated by "nulls", angles in which the capture is zero (fig.4.1).

As signals are usually expressed in terms of temperature, the temperature associated with the IR detected by the antenna is defined as follows [44]:

$$T_A = \int A(\theta, \phi) T_{sky}(\theta, \phi) d\Omega, \quad (4.1)$$

where $T_{sky}(\theta, \phi)$ is the pattern of the incoming signal from all contributions from the sky. The integral is calculated in a sphere surrounding the antenna.

Figure 4.1: Antenna pattern of transmission.

This temperature generates a noise power given by

$$P_A = \kappa T_A \Delta\nu, \quad (4.2)$$

where κ is the Boltzmann constant and $\Delta\nu$ the signal's bandwidth.

The receiver is a device which detects and measures the radiation captured by the antenna. The most common type used in radio astronomy is the *superheterodyne receiver*, a type of receiver that uses frequency mixing to convert the detected signal to a intermediate frequency that can be more conveniently processed than the original one. It's basic composition is formed by an amplifier, a mixer (where a strong oscillating signal with frequency ν_o is added to the income, producing a intermediary frequency signal), another amplifier, a square-law detector, a filter, an integrator and a recorder [44]. BINGO will not use such receiver, but a coherent one, to be presented further on.

As the IR travels through the receiver, it gathers power due to the thermal noise provided by the device's components (T_R), thus, the total (or system) noise power becomes

$$P_{sys} = \kappa T_{sys} \Delta\nu, \quad (4.3)$$

where $T_{sys} = T_A + T_R$.

As this noise is inherent to the system, there is a minimum achievable sensitivity the receiver can obtain given by the ideal radiometer's equation [31],

$$\sigma = \frac{T_{sys}}{\sqrt{\Delta\nu\tau}} \quad (4.4)$$

where $\Delta\nu$ is the radiometer's bandwidth and τ the integration time.

However, eq. 4.4 is usually an underestimation of sensitivity, for when the input has very low power it becomes necessary to pass it through amplifiers in order to provide sufficient power at the output. For linear amplifiers, $P_{out} = GP_{in}$.

Unfortunately, the signal's amplification is not perfect, it is subjected to instabilities over both time and frequency and, as a result, the amplified signal presents small gain variations δG . These gains are problematic because they can mimic a change in the system temperature due to an astronomical source, making the receiver's response in both situations, indistinguishable. That is, after the amplification the power variation ΔP as the receiver detects an astronomical source of temperature T_{astro} , ($T_{sys} \rightarrow T_{sys} + T_{astro}$) is equal to ΔP where $G \rightarrow G + \delta G$. This fluctuation directly affects the sensitivity by lifting it by a factor of

$$\sigma_{gain} = \frac{\delta G}{G} T_{sys}. \quad (4.5)$$

Hence, the actual minimum sensitivity of the receiver can be stated as [11]

$$\sigma_{total} = T_{sys} \left[\frac{1}{\Delta\nu\tau} + \left(\frac{\delta G}{G} \right)^2 \right]^{1/2}. \quad (4.6)$$

Usually, these δG gains fluctuations are due to the $1/f$ noise generated by the receiver's amplifiers [45].

4.1.2 Magic Tee

BINGO's receiver structure and parameters were discussed in chapter 3, so this section will focus on the workings of one specific component of it, the Magic Tees [11]. These devices are 180° hybrid couplers described by an anti-symmetric scattering matrix

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix} = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{2}} & 0 & 0 & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} & 0 & 0 & -\frac{1}{\sqrt{2}} \\ 0 & -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix}, \quad (4.7)$$

where the a 's are the inputs' amplitudes and the b 's the outputs'. It is noticeable that this device divides equally the power from one port between the other two of the remaining three ports. The phase shift the signal experiences depends upon the port it has come from, port 3 divides the signal without phase change and port 4 divides it with a relative phase of 180° .

Figure 4.2: Magic Tee design. Ports 1 and 2 are inputs, reference and sky signal respectively, and 3 and 4 are the summed and differentiated outputs.

As visualized in fig. 4.3 a simplified understanding of the signal's path through the receiver is: it goes through the first hybrid, a set of two parallel amplifiers, a second hybrid and finally a square-law detector. A quick analysis of this basic composition will show how it reduces the effect of noise instabilities.

Figure 4.3: A schematic view of BINGO's pseudo-correlation receiver.

For the first hybrid, the inputs a_1 (S, for sky signal) and a_2 (R, for reference signal) result in the outputs b_3 and b_4 :

$$\begin{aligned} b_3 &= \frac{1}{\sqrt{2}}(S + R) \\ b_4 &= \frac{1}{\sqrt{2}}(S - R). \end{aligned} \tag{4.8}$$

After this, these signals go through two parallel amplifiers of G_1 and G_2 amplification factors. Since the paths they take are slightly different, they are subjected to the addition of different noises, denoted by ϵ_1 and ϵ_2 ,

$$\begin{aligned} B_3 &= \sqrt{G_1}(b_3 + \epsilon_1) \\ B_4 &= \sqrt{G_2}(b_4 + \epsilon_2). \end{aligned} \quad (4.9)$$

These amplified signals enter the final hybrid resulting in c_1 and c_2 given, again, by eq. 4.7.

$$\begin{aligned} c_1 &= \frac{1}{\sqrt{2}}(B_3 + B_4) \\ c_2 &= \frac{1}{\sqrt{2}}(B_3 - B_4). \end{aligned} \quad (4.10)$$

The final stage consists of passing c_1 and c_2 through a square-law detector and differentiating their powers. This kind of detector generates outputs proportional to the square of the inputs' amplitudes, therefore, denoting $P_1 = c_1^2$ and $P_2 = c_2^2$ their difference is given by:

$$P_1 - P_2 = \sqrt{G_1 G_2}(S^2 - R^2) \quad (4.11)$$

For an insight of how BINGO's receiver signal will be visualized, a simple model for the gains and input amplitudes can be used for analysis.

The reference temperature is to be matched with T_{sys} , in this way, $R = T_{sys}$ and $S = T_{sys} + T_{HI}$, where T_{HI} is the temperature associated with the neutral hydrogen emission ($T_{sys} \gg T_{HI}$). Both amplifiers are expected to have the same average gain $\bar{G}$, but different gain fluctuations δG .

$$\begin{aligned} R &= T_{sys} \\ S &= T_{sys} + T_{HI} \\ G_1 &= \bar{G} + \delta G_1 \\ G_2 &= \bar{G} + \delta G_2 \end{aligned} \quad (4.12)$$

Substituting eq. 4.12 in eq. 4.11 and expanding until first order terms:

$$P_1 - P_2 = 2\bar{G}T_{sys}T_{HI} + 2\sqrt{2}\bar{G}T_{sys}\epsilon_2. \quad (4.13)$$

where it's useful to remember that for $x \ll 1$ we have $(1 + x)^n \sim 1 + nx$.

Since δG terms don't appear in eq. 4.13, it's easily seen that this structure's merit is

in the fact that it "pushes" the $1/f$ influence, to second order.

Thermal (white) noise is known to have null temporal average, so the second term disappears, for it's related to this noise eq. 4.9. Then, eq. 4.13 becomes proportional only to T_{HI} ,

$$\langle \Delta P \rangle = 2\bar{G}T_{sys}T_{HI}. \quad (4.14)$$

This magic tee's full cleaning of $1/f$ is, naturally, a optimal situation. In reality, the final output will yet be contaminated by this noise, and, a component separation process for the final removal is needed.

It is in the context that GNILC will be presented in this work.

4.2 Foregrounds

In this section, all codes were provided by Dr. Lucas Olivari, who is currently working at USP. The foreground codes and documentation for this section are available at [46].

4.2.1 Synchrotron

The synchrotron radiation is produced when charged particles interact with a magnetic field. This process dominates the radio emission from the Galaxy, hence, it hides completely the HI emission that we want to resolve.

The synchrotron brightness temperature is parametrized as a power law [46]:

$$T_{syn}(\nu, p) = T_o(p) \left(\frac{\nu}{\nu_o} \right)^{\beta(p) + C \log(\frac{\nu}{\nu_p})}, \quad (4.15)$$

where β is the power law parameter that can depend on p (the pixel being observed or line-of-sight), $T_o(p)$ is the template at frequency ν_o , C is the curvature amplitude and ν_p is the pivot frequency. The values used for these two last parameters are given by [47], $C=0.3$ and $\nu_p = 23GHz$. The template being used is the reprocessed [48] map at 408 MHz of [49] in which the small scale fluctuations are artificially added using a method described in [50].

4.2.2 Cosmic microwave background

Cosmic microwave background (CMB) is an almost isotropic radiation with mean temperature $T_{CMB} \simeq 2.726K$ and anisotropies at the level of one part in 10^5 [51].

The CAMB software was used to calculate the CMB power spectrum, using the standard Λ CDM model, and the SYFAST routine [52] to generate a Gaussian map realization to it.

The simulated CMB map of temperature anisotropies expressed in brightness temperature:

$$\Delta T_B(\nu, p) = \frac{x e^x}{(e^x - 1)^2} \Delta T_T(p), \quad (4.16)$$

where $x = h\nu/k_B T_{CMB}$ and $T_T(p)$ is the map expressed in thermodynamic temperature.

4.2.3 Free-free

This emission, also known as bremsstrahlung, arises from electron-ion scattering in interstellar plasma and has this name because of the unbounded states of the incoming and outgoing electron.

Small scale fluctuations are artificially added using a method described in [50] and, once added, the following relationship given by [53] can be used. The free-free spectrum is then defined by:

$$T_{ff} \approx 10mK \left(\frac{T_e}{10^4 K} \right)^{0.667} \left(\frac{\nu}{GHz} \right)^{-2.1} \left(\frac{I_{H\alpha}}{R} \right). \quad (4.17)$$

Here, $I_{H\alpha}$ is the $H\alpha$ template by [34], T_4 is the electron temperature in units of 10^4 K and T_e the electron temperature, 7000K.

4.2.4 Extragalactic point sources

Extragalactic point sources is an inhomogeneous mix of radiation from objects considered point-like relative to IM experiments resolution, such as radio galaxies and quasars.

The differential count dN/dS (number per steradian, N, per unit flux, S) of point sources was calculated using the fitted fifth order polynomial found by [9],

$$\log \left(\frac{S^{2.5}}{N_0} \frac{dN}{dS} \right) = \sum_{i=0}^5 a_i \left[\log \left(\frac{S}{S_0} \right) \right]^i, \quad (4.18)$$

where the normalizing constants N_0 and S_0 are, respectively, $1 J_y s^{-1}$ and $1 J_y$. The coefficients a_i were found using a least-square fitting shown in [9]: $a_0 = 2.593$, $a_1 = 0.093$, $a_2 = -0.0004$, $a_3 = 0.249$, $a_4 = 0.090$ and $a_5 = 0.009$.

The mean temperature can be calculated as

$$\bar{T}_{ps} = \frac{c^2}{2k_B\nu^2} \int_0^{S_{max}} S \frac{dN}{dS} dS, \quad (4.19)$$

with $S_{max} = 1J_y$ and ν , the observed frequency, k_B the Boltzmann constant and c the light velocity in vacuum.

Around this background temperature, there are two more sources of fluctuations, Poisson distributed sources ($S_{max} \lesssim 0.001J_y$) and clustered sources ($0.001 < S < 1J_y$).

For the first the power spectrum is given by [5],

$$C_\ell^{Poisson} = \left(\frac{c^2}{2k_B\nu^2} \right)^2 \int_0^{S_{max}} S^2 \frac{dN}{dS} dS. \quad (4.20)$$

But for the second, these sources must be injected in real space, since they have a too low density. To do this, the mean brightness temperature is estimated as

$$T_{ps}(\nu, \hat{n}) = \left(\frac{c^2}{2k_B\nu^2} \right) \Omega_{pix}^{-1} \sum_{i=1}^N S_i(\nu), \quad (4.21)$$

with $S_i(\nu)$ representing the flux of the i^{th} point source at frequency ν .

The N point sources are then distributed randomly in such way the underlying source count is respected.

The power spectrum due to the clustered sources is estimated as

$$C_\ell^{cluster} = \omega_\ell \bar{T}_{ps}^2, \quad (4.22)$$

where ω_ℓ is the Legendre transform of the angular correlation function, $\omega(\theta)$. Battye et al. (2013) [9] found $\omega_\ell \approx 1.8 \times 10^{-4} \ell^{-1.2}$ at 1.4GHz.

Figure 4.4: Foreground generated maps. All but CMB map have a histogram equalized color scale for better visualization. The unit is mK.

4.3 Instrumental noise

4.3.1 Thermal noise

This type of noise is assumed to have an amplitude which respects a Gaussian distribution, with null temporal mean, over the sky and is constant across different frequency channels.

Since it is inherent to the instrument, this noise induces a minimum sensitivity to the signals' resolution. This quantity is given by the well-known radiometer equation [5, 7]:

$$\sigma = \frac{T_{sys}}{\sqrt{t_{pix} \Delta \nu}}, \quad (4.23)$$

where the integration time per pixel, t_{pix} , is defined as:

$$t_{pix} = n_f t_{obs} \frac{\Omega_{pix}}{\Omega_{sur}}. \quad (4.24)$$

The equation above gives us n_f as the quantity of horns, t_{obs} the total observation time, Ω_{sur} the survey area and $\Omega_{pix} = \theta_{FWHM}^2$, the beam area.

4.3.2 $1/f$ noise

The term " $1/f$ noise" refers to the type of noise with PSD (power spectrum density) of the form $S(f) \propto 1/f^\alpha$ where the spectral index α identifies specific types such as pink/flicker noise ($\alpha = 1$) and red noise ($\alpha = 2$) [21]. In most cases, α is equal to 1 [11].

The frequency taken into account for the noise is the inverse of the observation time ($f = 1/t_{obs}$).

It is straight-forward to notice that for $1/f$ noise long time-scale fluctuations will have more power than short time scale fluctuations.

Figure 4.5: The $1/f$ PSD.

Figure 4.6: The $1/f$ TOD. It manifests as small gain fluctuations provided by the receiver system already described.

Even though it is widely observed in a broad range of scientific areas (fig. 4.7) (music, biology, electronic and geology, for example) and has been submitted to a possible physical explanation within the time of its discovery [12], a fundamental description of $1/f$ noise is yet to be found.

Figure 4.7: The left graphic shows the power spectrum of the east-west component of ocean current velocity. The right one shows the sea level at Bermuda. Both are in logarithmic scale and clearly exhibit the $1/f$ slope. These examples are presented at [12].

Since it was originally observed in vacuum tubes, this first attempt to a explanation

for the arise of this noise is to describe the release of electrons as a relaxation law, with relaxation rate λ , as electrons are liberated from vacuum tubes, $N(t) = N_0 e^{-\lambda t}$ [12]. This way, a train of pulses is given by,

$$N(t, t_k) = N_0 e^{-\lambda(t-t_k)} \quad (4.25)$$

. with Fourier Transform,

$$F(\omega) = \int_{-\infty}^{\infty} \sum_k N(t, t_k) e^{i\omega t} dt = \frac{N_0}{\lambda + i\omega} \sum_k e^{i\omega t_k}$$

and PSD,

$$S(\omega) = \lim_{T \rightarrow \infty} \frac{1}{T} \langle |F(\omega)|^2 \rangle = \frac{N_0^2 n}{\lambda^2 + \omega^2},$$

where n is the pulse average.

However, only one relaxation process is not sufficient to describe the whole range of observed indexes and, therefore, it's better to be assumed to be a superposition of this processes with rates varying from λ_1 to λ_2 :

$$\begin{aligned} S(\omega) &= \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \frac{N_0^2 n}{\lambda^2 + \omega^2} d\lambda = \\ &= \frac{N_0^2 n}{\omega(\lambda_2 - \lambda_1)} \left[\arctan\left(\frac{\lambda_2}{\omega}\right) - \arctan\left(\frac{\lambda_1}{\omega}\right) \right] = \\ &= \begin{cases} N_0^2 n, & se \ 0 < \omega << \lambda_1 << \lambda_2 \\ \frac{N_0^2 n \pi}{2\omega(\lambda_2 - \lambda_1)}, & se \ \lambda_1 << \omega << \lambda_2 \\ \frac{N_0^2 n}{\omega^2}, & se \ \lambda_1 << \lambda_2 << \omega \end{cases} \quad (4.26) \end{aligned}$$

The subsequent step taken was to assume $dS(\lambda) = A/\lambda^\beta$, so

$$S(\omega) \propto \int_{\lambda_1}^{\lambda_2} \frac{1}{\lambda^2 + \omega^2} \frac{d\lambda}{\lambda^\beta}.$$

For $\lambda_1 << \lambda << \lambda_2$ we have:

$$S(\omega) \propto \frac{1}{\omega^{\beta+1}} \int_{\lambda_1}^{\lambda_2} \frac{1}{1 + \frac{\lambda^2}{\omega^2}} \frac{d(\frac{\lambda}{\omega})}{(\frac{\lambda}{\omega})^\beta}$$

which leads to:

$$\frac{1}{\omega^{\beta+1}} \int_{\frac{\lambda_1}{\omega}}^{\frac{\lambda_2}{\omega}} \frac{1}{1 + x^2} \frac{dx}{x^\beta} \rightarrow$$

$$\frac{1}{\omega^{\beta+1}} \int_0^\infty \frac{1}{1+x^2} \frac{dx}{x^\beta} \propto \frac{1}{\omega^{\beta+1}} \quad (4.27)$$

As β is a new unbounded parameter that was introduced ad hoc, a priori, this model covers all types of $1/f$ PSDs. However, this model is too specific to embrace most physical situations $1/f$ appears and it remains as only one first attempt to describe the phenomenon mathematically.

At a first look, one problem this type of noise introduces is that it is unbounded and goes to infinity as frequency goes to zero, violating energy's conservation. However, since observations are not taken over infinite time, this paradox is easily bypassed, for the lowest frequencies are naturally cut off and data calibration effectively acts as a high-pass filter [13]. Another problem it presents is that these fluctuations don't need to be Gaussian distributed, and so, don't average to zero like white noise.

It is common in astronomy to define the PSD of a receiver contaminated with $1/f$ noise as follows: for data stream of length T_{obs} ($T_{obs} = 1/f_T$), sampled with frequency f_s , for a system with knee frequency f_k (defined as the frequency to which white and $1/f$ noise have the same PSD value), system temperature T_{sys} and bandwidth $\delta\nu$, the PSD of $1/f$ noise fluctuation is given by an empirical model [54–56]:

$$S(f) = \begin{cases} 0, & \text{if } f > f_s \\ \frac{T_{sys}^2}{\delta\nu} \left(\frac{f_k}{f}\right)^\alpha, & \text{if } f_s \geq f \geq f_T \\ 0, & \text{if } f < f_T \end{cases} \quad (4.28)$$

The total power injected by the $1/f$ fluctuations is given by the integration of eq. 4.28 from 0 to ∞ . This is also the variance in the time stream.

$$(\sigma_{1/f})^2 = \int_0^\infty S(f)df = \begin{cases} \frac{T_{sys}^2 f_k^\alpha}{\delta\nu} \left(\frac{f_s^{1-\alpha} - f_T^{1-\alpha}}{1-\alpha} \right), & \text{if } \alpha \neq 1 \\ \frac{T_{sys}^2 f_k}{\delta\nu} (\log f_s - \log f_T), & \text{if } \alpha = 1 \end{cases} \quad (4.29)$$

This model above is the one usually used to simulate this kind of noise, but it only considers total correlation across different channels. To consider different scenarios, [13] modifies eq. ?? inserting a new β parameter that is responsible for quantifying the strength of correlation in spectroscopic receivers.

However, no physical interpretation is assumed as the origin of these $1/f$ frequency correlations and, due this lack of knowledge, a simple power law is proposed by [13]:

$$S(f, \omega) = \frac{T_{sys}^2}{\delta\nu} \left[1 + C(\beta, N_\nu) \left(\frac{f_k}{f}\right)^\alpha \left(\frac{1}{\omega \Delta\nu}\right)^{\frac{1-\beta}{\beta}} \right]. \quad (4.30)$$

Here, α is the same spectral index presented earlier, ω is the Fourier mode of the

spectroscopic frequency ν , $\Delta\nu$ is the total bandwidth of the receiver and $C(\beta, N_\nu)$ a normalization factor given by $(N_\nu - 1)/(2N_\nu\delta\nu)$ with N_ν representing the number of channels. The spectral index β is defined in the interval $[0,1]$ where $\beta = 0$ describes a $1/f$ noise identical in every receiver channel and $\beta = 1$ a noise that is independent in every channel.

The unity term inside the brackets in eq. 4.30 describes the thermal noise contribution.

With the introduction of the spectral mode ω another knee frequency arises, intrinsically related to the temporal knee frequency f_k ,

$$\omega_k = \frac{(f_k T_{obs})^{\frac{\alpha\beta}{1-\beta}}}{\Delta\nu}. \quad (4.31)$$

This model assumes the $1/f$ fluctuations in the time-ordered data (TOD) to be expressed as a multiplicative variation around the system temperature.

$$\Delta T_{1/f}(t, \nu) = \delta G(t, \nu) T_{sys}. \quad (4.32)$$

For finding δG , a function $Z(f, \omega)$, with Gaussian variables x and y , is defined as follows:

$$Z(f, \omega) = \sqrt{S(f, \omega)}(x + iy), \quad (4.33)$$

x and y have zero mean and unit variation.

The gain variation is it's Fourier transform,

$$\delta G(t, \nu) = \int \int Z(f, \omega) e^{2\pi i(t f + \nu \omega)} df d\omega. \quad (4.34)$$

Even though eq. 4.30 is more embracing then eq. 4.28, it has it's limitations as well. It considers the $1/f$ noise to be Gaussian and α, β e f_k to be constants in time, which are not necessarily true conditions in real data.

Nevertheless, due to the lack of knowledge regarding a truer way to describe this noise, this model will be used in this thesis' analysis.

An apparent signal of $1/f$ presence in a observation map is that it introduces stripes parallel to the scan circle strategy [21, 57, 58] to it (fig. 4.8). Even tough BINGO telescope is static, the stripes appear due to Earth's motion. These stripes turn up because the mean level of the noise are, in general, different for each circle of measurements, as shown by [54].

Figure 4.8: This qualitative example, with only white and $1/f$ noise, shows the striped structure $1/f$ introduces to maps. The scale quantifies fluctuations around the average in mK.

4.4 Generalized Needlet Internal Linear Combination

The Generalized Needlet Internal Linear Combination, or GNILC, is a component separation method proposed by [59].

For this method, the observed signal, $x_i(p)$, in a given frequency i and direction (pixel) p is assumed to be the sum of all astrophysical emissions and instrumental noise. Illustratively, it can be represented as:

$$x_i(p) = s_i(p) + n_i(p), \quad (4.35)$$

where $s_i(p)$ represents the wanted signal and $n_i(p)$ every other signal to be removed.

To simplify the notation, it can also be represented as a $1 \times n_{ch}$ vector, where the n_{ch} is the number of channels (frequency bins):

$$\mathbf{x}(\mathbf{p}) = \mathbf{s}(\mathbf{p}) + \mathbf{n}(\mathbf{p}). \quad (4.36)$$

Throughout the thesis, the wanted signal is assumed to be the HI plus thermal noise and the "noise", or unwanted signal, are the foregrounds plus $1/f$. The reason for this choice is that both HI and thermal noise are about the same order of magnitude in some multipole scales and so, as we try to recover HI, some thermal noise will be recovered as

well.

This way, to try avoiding creating artificial artifacts, the best strategy is to recover both signals as one component.

The GNILC method can be summarized as follows:

A set of windows is defined in harmonic space so that specific different ranges of angular scales of the input map are isolated. They are called needlets.

Needlets are a particular construction of wavelets family that can be interpreted as band-pass filters (fig. 4.9), $h_l^{(j)}$, in harmonic space and can be defined such that

$$\sum_j [h_l^{(j)}] = 1, \quad (4.37)$$

where j defines an interval of multipoles.

Figure 4.9: Example of a particular set of needlets taken from [59]. The needlets peaks are at $\ell = [0, 64, 96, 128, 160, 192, 224, 256, 383]$. It is easy to notice how they work as a band-pass filter in harmonic space.

Since the observed signal is defined in a sphere, the observed sky, it can be decomposed into spherical harmonics:

$$S_{obs}(\hat{n}) = \sum_{\ell=1}^{\ell_{max}} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\hat{n}) \quad (4.38)$$

The $a_{\ell m}$ harmonic coefficients are filtered and transformed back into a map, so the

statistical information contained there is only relative to a certain range of angular scales. It means that, for each frequency map there are several needlet maps.

This step permits a more localized analysis of the signal, for the GNILC steps from now on are all computed at each needlet scale separately.

Next, the data covariance matrix is computed at pixel p and pair of frequencies a and b .

$$\hat{R}_{ab}(p) = \sum_{p' \in D(p)} x_a(p') x_b^T(p'), \quad (4.39)$$

where $D(p)$ is a domain of pixels centered at p . This domain is chosen so to avoid artificial correlations between the HI and foreground signals.

From a initial estimate of HI angular power spectra, referred to here as the prior, HI plus noise maps y are simulated and the covariance matrix calculated in the same way as above,

$$\hat{R}_{(s)ab}(p) = \sum_{p' \in D(p)} y_a(p') y_b^T(p'). \quad (4.40)$$

As a mathematical trick, the data covariance $\hat{R}_{ab}(p)$ is transformed, $\hat{R}_{ab} \rightarrow \hat{R}_{(s)ab}^{-1/2} \hat{R}_{ab} \hat{R}_{(s)ab}^{-1/2}$ and diagonalized, resulting in:

$$\hat{R}_{(s)ab}^{-1/2} \hat{R}_{ab} \hat{R}_{(s)ab}^{-1/2} = U_N D_N U_N^T + U_S U_S^T. \quad (4.41)$$

Here, D_N collects the m largests eigenvalues and U_N the corresponding eigenvectors. The remaining U_S provides the $n_{ch} - m$ eigenvectors related to the HI plus thermal noise subspace.

To estimate the foreground subspace dimension m , Akaike Information Criterion is used. It states the m will be such that the expression inside parentheses in eq. 4.42 is minimized, it is:

$$\min \left(2m + \sum_{i=m+1}^{n_{ch}} [\mu_i - \log \mu_i - 1] \right) \quad \text{with} \quad m \in [1, n_{ch}], \quad (4.42)$$

where μ_i are the eigenvalues of the transformed covariance matrix.

To the observed data, a Internal Linear Combination (ILC) filter is applied. An estimate for the wanted signal is given as:

$$\hat{s} = Wx, \quad (4.43)$$

where W is a weight matrix and x the data vector described in eq. 4.36. The weight

matrix in our case is then given by,

$$W = \hat{S}(\hat{S}^T \hat{R}^{-1} \hat{S})^{-1} \hat{S}^T \hat{R}^{-1}. \quad (4.44)$$

where $\hat{S}$ is the estimate HI plus noise mixing matrix, $\hat{S} = \hat{R}_{(s)}^{1/2} U_S$.

At this point, we have an estimate for the reconstructed signal $\hat{s}$ for each needlet scale. Finally, for each frequency channel, the needlet maps are added to give a complete GNILC reconstructed HI plus thermal noise map.

A detailed description of the GNILC method is given in [5] and [59].

Chapter 5

Application of GNILC

5.1 Experimental setup

In this chapter, the efficiency of GNILC in reconstructing HI plus thermal noise map in the presence of $1/f$ noise and the foregrounds already described will be analyzed, but with attention on how the change of $1/f$ parameters influence this process. The experimental aspects are:

Parameter	Value
System temperature	70 K
Bandwidth	300MHz: [960,1260]
Number of feed horns	50
Observation time	1 year
Beam resolution	40 arcmin
Number of channels	30
Velocity of observation	1 pixel/s
Needlet set	peaks: [0, 128, 383]

Table 2: Simulation parameters

A GAL070 *Planck* HFI Galactic mask was used, which limits the survey area to 71% of the sky. This mask has a cosine apodization of width 3.5 to avoid boundary artifacts in the power spectrum estimation.

For generating all maps, HEALpy package was used, with $N_{side} = 128$ (pixel size ≈ 27 arcmin).

As seen in eq. 4.30, $1/f$ noise is described by 3 parameters: the spectral index α , spectroscopic index β and knee frequency f_k . These are the ones to be varied.

Parameter	Values
α	0.75, 1.0 and 1.25
f_k	0.0001, 0.00001 and 0.000001 Hz
β	0.001, 0.25, 0.5, 0.75 and 1.0

Table 3: $1/f$ parameters used in these simulations.

It is known that electronic $1/f$ has a spectral index near unit, values around this were chosen. The same logic is applied to the knee frequency, for BINGO it is currently 10mHz.

A greater range of values is left for the new parameter introduced by this new model for the noise, β , to better analyze it's particular effect.

As a way to quantify GNILC's performance, two quantities are defined in [5] as functions of the input power spectrum C_ℓ^S and reconstructed power spectrum C_ℓ^R :

$$N_{GNILC} = \frac{1}{N_\ell n_{ch}} \sum_i^{n_{ch}} \sum_\ell^{\ell_{max}} \frac{C_\ell^R(\nu_i) - C_\ell^S(\nu_i)}{C_\ell^S(\nu_i)} \quad (5.1)$$

and

$$N_{GNILCabs} = \frac{1}{N_\ell n_{ch}} \sum_i^{n_{ch}} \sum_\ell^{\ell_{max}} \left| \frac{C_\ell^R(\nu_i) - C_\ell^S(\nu_i)}{C_\ell^S(\nu_i)} \right| \quad (5.2)$$

where N_ℓ is the total number of multipoles considered (in this case, 150) and ν_i specifies a frequency channel.

The difference between them is that eq. 5.1 measures the relative bias, e.g. if it returns a negative value, it means that GNILC underestimated the HI plus noise signal or if GNILC underestimates half of the data and overestimates the other half, eq. 5.1 would return zero.

The second expression accounts for the absolute bias, e.g. if half the data underestimates and power spectrum by one 1% and the other half overestimates by the same amount, then eq. 5.2 would return 2%.

Naturally, the ideal scenario would be both quantities returning the value zero, indicating a perfect HI plus noise map reconstruction.

5.2 Results

For this study, the steps taken were first to simulate all background and HI TODs and degrade ("blur") them to simulate a IM experiment with a 40arcmin resolution, since HealPy provides maps with greater resolution. Later, both thermal and $1/f$ noise TODs

were added, but without the blurring process, for they are provided by the electronics and don't suffer with observation's constraints.

This total map is passed onto the GNILC code along with a $H\text{I} + \text{thermal noise}$ map, which is called "target" or "prior", so the reconstructed signal can be recovered.

These steps can be visualized in fig. 5.1.

Figure 5.1: (A) is the total map with background, HI and noises, (B) is the target map, or prior, which contains only HI and thermal noise signals, (C) GNILC's reconstruction of the prior and (D) the residual map, it is, the difference between the prior and recovered maps. All but the first map show the fluctuation signal in relation to the mean, (A) takes the offset to be the weakest signal. The unit is mK.

The following tables summarize the quantities eq. 5.1 and eq. 5.2 for all combinations of the parameters described above:

Values for $\alpha = 0.75$, $f_k = 0.000001$ and varying β

β	N_{GNILC}	$N_{GNILC_{abs}}$
0.001	7.28%	29.30%
0.25	7.45%	29.13%
0.5	7.96%	29.37%
0.75	8.05%	28.96%
1.0	7.87%	29.17%

Values for $\alpha = 0.75$, $f_k = 0.00001$ and varying β

β	N_{GNILC}	$N_{GNILC_{abs}}$
0.001	7.91%	29.26%
0.25	8.02%	29.50%
0.5	7.81%	29.35%
0.75	7.98%	29.33%
1.0	7.85%	29.24%

Values for $\alpha = 0.75$, $f_k = 0.0001$ and varying β

β	N_{GNILC}	$N_{GNILC_{abs}}$
0.001	8.30%	29.42%
0.25	7.96%	29.28%
0.5	7.98%	29.33%
0.75	8.59%	29.62%
1.0	8.63%	29.31%

Values for $\alpha = 1.0$, $f_k = 0.000001$ and varying β

β	N_{GNILC}	$N_{GNILC_{abs}}$
0.001	7.80%	29.22%
0.25	7.72%	28.99%
0.5	7.72%	28.99%
0.75	7.69%	29.29%
1.0	7.60%	29.37%

Values for $\alpha = 1.0$, $f_k = 0.00001$ and varying β

β	N_{GNILC}	$N_{GNILC_{abs}}$
0.001	7.84%	29.42%
0.25	7.71%	29.46%
0.5	7.46%	29.16%
0.75	7.43%	29.08%
1.0	7.43%	29.04%

Values for $\alpha = 1.0$, $f_k = 0.0001$ and varying β

β	N_{GNILC}	$N_{GNILCabs}$
0.001	8.08%	29.29%
0.25	7.69%	29.25%
0.5	7.82%	29.42%
0.75	8.38%	29.27%
1.0	8.33%	29.26%

Values for $\alpha = 1.25$, $f_k = 0.000001$ and varying β

β	N_{GNILC}	$N_{GNILCabs}$
0.001	7.70%	28.92%
0.25	7.66%	29.11%
0.5	7.26%	29.10%
0.75	7.68%	29.17%
1.0	7.84%	28.85%

Values for $\alpha = 1.25$, $f_k = 0.00001$ and varying β

β	N_{GNILC}	$N_{GNILCabs}$
0.001	7.65%	29.17%
0.25	7.51%	28.94%
0.5	8.03%	29.33%
0.75	8.16%	29.32%
1.0	7.86%	29.07%

Values for $\alpha = 1.25$, $f_k = 0.0001$ and varying β

β	N_{GNILC}	$N_{GNILCabs}$
0.001	7.82%	29.38%
0.25	8.22%	29.05%
0.5	8.05%	29.47%
0.75	8.23%	28.91%
1.0	8.43%	29.19%

It's easily seen that there is no great difference in the recovery of HI plus thermal noise map due to the presence of several "different" $1/f$ noise signals. The extremes values for N_{GNILC} are 7.26% ($\alpha = 1.25$, $f_k = 10^{-6}Hz$, $\beta = 0.5$) and 8.63% ($\alpha = 0.75$, $f_k = 10^{-4}Hz$, $\beta = 1$) and for $N_{GNILCabs}$ are 28.85% ($\alpha = 1.25$, $f_k = 10^{-6}Hz$, $\beta = 1$) and 29.62% ($\alpha = 0.75$, $f_k = 10^{-4}Hz$, $\beta = 0.75$).

Most importantly, it should be noted that all N_{GNILC} are positive, which reveals some leakage of noise and/or foreground to the recovered HI plus noise map. This overestimation of the reconstructed noise signal by GNILC is the total opposite of what was reported in [5], which presented an underestimation in practically all it's scenarios of simulations. Furthermore, the values in this report, especially for $N_{GNILCabs}$, are much bigger than the ones presented at [5].

However, [5] does not take $1/f$ noise into account. In this way, one can conclude that $1/f$ noise has a large influence on the recovery of HI plus noise signal, for it results in a big absolute deviation in respect to the prior.

The visualization of the results are very similar to eq. 5.1, because of the little apparent difference the diverse parameters cause in the recovery, nevertheless, for a distinct analysis approach, one can plot the C_ℓ of crucial maps: prior, reconstructed and residual signals.

This quantity, C_ℓ , is given by

$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2 \quad (5.3)$$

where the $a_{\ell m}$ are the coefficients of the signal expansion of into spherical harmonics [2, 17].

The following figures show these plots for the extremes values of N_{GNILC} and $N_{GNILCabs}$ already mentioned.

Figure 5.2: For $N_{GNILC} = 7.26\%$, $N_{GNILCabs} = 29.10\%$ and the parameters are: $\alpha = 1.25$, $f_k = 0.000001$ and $\beta = 0.5$.

Figure 5.3: For $N_{GNILC} = 7.84\%$, $N_{GNILCabs} = 28.85\%$ and the parameters are: $\alpha = 1.25$, $f_k = 0.000001$ and $\beta = 1$.

Figure 5.4: For $N_{GNILC} = 8.63\%$, $N_{GNILCabs} = 29.31\%$ and the parameters are: $\alpha = 0.75$, $f_k = 0.0001$ and $\beta = 1$.

Figure 5.5: For $N_{GNILC} = 8.59\%$, $N_{GNILCabs} = 29.62\%$ and the parameters are: $\alpha = 0.75$, $f_k = 0.0001$ and $\beta = 0.75$.

Analyzing these C_ℓ graphics, one should notice that for large scales, it is, $\ell \leq 20$ the recovery is very precise and as ℓ grows, the difference between expected and recovered signals rapidly grows.

Chapter 6

Conclusion

BINGO is a novel telescope designed to make the first detection on radio wavelength of the BAO scale, though the detection of the 21cm HI emission and, consequently, the construction of a 3D map of total matter distribution. In this way, providing independent cosmological data to complement optical surveys at the redshift interval $z = 0.13 - 0.48$.

Beyond this main goal, it will also contribute with parallel science, such as in the detection of FRBs.

It is based on simplicity and low cost: the mirrors are static, therefore, use the Earth's rotation to map 15° strip of the sky and the receivers are standard with room-temperate amplifiers. The telescope is scheduled to begin the construction at early 2019 in Paraíba, northeast of Brazil, and will operate for 3 to 4 years.

Nevertheless, for accurate understanding of the physics involved, the signals must be processed and efficiently separated. The $1/f$ noise is intrinsic to electronic devices, as does thermal noise, and, therefore, constitutes an important and difficult component to be removed.

In this context, GNILC method was used to study the effects of $1/f$ noise in the reconstruction of HI plus thermal noise signal.

As was seen, the presence of this noise results in a overestimation of around 7% (or, in absolute bias, 29%) to the HI plus noise signal intended to be recovered. Even though this is a discouraging result, one should notice that GNILC's parameters were not varied, (e.g., the quantity and peaks of needlets), hence, there is scope for improvement in the process so as to overcome this drawback.

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