MeerFish

This is a (non-exhaustive) description of the analysis framework used in the MeerFish code (github.com/meerklass/MeerFish). Please contact the author (steve.cunnington@port.ac.uk) if you feel something is missing/incorrect or needs further clarification.

We begin by defining the H$\textsc{i}$ power spectrum as

$$P_{\text{HI}}(k^{\text{f}}, \mu^{\text{f}}, z) = \alpha_{\parallel}^{-1}(z)\alpha_{\perp}^{-2}(z)\overline{T}_{\text{HI}}^2(z)\left(b_{\text{HI}}(z) + f(z)\mu^2 + b_{\phi}^{\text{HI}}(z)f_{\text{NL}}\mathcal{M}(k,z)^{-1}\right)^2$$
$$\times\ P_{\text{m}}(k,z)\,\mathcal{B}_{\text{beam}}^2(k,\mu,z) \tag{1}$$

where $\overline{T}_{\text{HI}}$ is the background mean H$\textsc{i}$ brightness temperature, b_{HI} is the linear bias for H$\textsc{i}$, and f is the growth rate of structure. For the H$\textsc{i}$ bias, we fit to hydrodynamical simulations (Villaescusa-Navarro et al., 2018) providing the model

$$b_{\text{HI}}(z) = 0.842 + 0.693z - 0.0459z^2\,. \tag{2}$$

The mean H$\textsc{i}$ brightness temperature is modelled using

$$\overline{T}_{\text{HI}}(z) = 180\,\Omega_{\text{HI}}\frac{h\,(1+z)^2}{H(z)/H_0}\,\text{mK}\,, \tag{3}$$

where we use the model for Ω_{HI} based on the one used in SKA Cosmology SWG et al. (2020) but adapted based on the latest Ω_{HI} constraints at higher redshift from MeerKLASS intensity mapping (Cunnington et al., 2022)

$$\Omega_{\text{HI}}(z) = 0.00067432 + 0.00039z - 0.000065z^2\,. \tag{4}$$

In Equation 1, we include the possibility for local primordial non-Gaussianity (PNG) to influence the power, which occurs by the bias acquiring a scale-dependent correction given by the $b_{\phi}f_{\text{NL}}\mathcal{M}^{-1}$ term. f_{NL} modulates the PNG contribution and we assume $f_{\text{NL}} = 0$ as fiducial default. b_{ϕ}^{HI} is the PNG bias parameter for H$\textsc{i}$, adopted by the standard universality assumption of the halo mass function

$$b_{\phi}^{\text{HI}}(z) = 2\,\delta_{\text{c}}\,(b_{\text{HI}}(z) - 1)\,, \tag{5}$$

where $\delta_{\text{c}} = 1.686$. The final factor relating to PNG is given by

$$\mathcal{M}(k,z) = (2/3)k^2 T_{\text{m}}(k)D_{\text{md}}(z)/(\Omega_{\text{m}}H_0^2)\,, \tag{6}$$

where T_{m} is the matter transfer function and D_{md} is the linear growth factor normalized to $1/(1+z)$.

P_{m} (in Equation 1) is the matter power spectrum obtained from a Boltzmann solver (we used CAMB as standard Lewis et al., 2000), and the transverse

fluctuations contributing to the power are affected by the telescope beam which acts as

$$\mathcal{B}_{\text{beam}}(k, \mu, z) = \exp\left[-\frac{1}{2}k_\perp^2 R_b^2\right] = \exp\left[-\frac{k^2}{2}(1 - \mu^2)R_b^2\right] \tag{7}$$

where $R_b = \chi(z)\,\theta_{\text{FWHM}}(z)/2\sqrt{2\ln 2}$. θ_{FWHM} is radio telescope specific but for a generic dish size with diameter D_{dish} and observations at a frequency ν, we can say $\theta_{\text{FWHM}} = c\,/\,(\nu D_{\text{dish}})$.

Lastly, in Equation 1, the Alcock-Paczynski (Alcock and Paczynski, 1979) dilation parameters for the transverse and radial directions are given by

$$\alpha_\perp(z) = \frac{D_A(z)/r_s}{(D_A(z)/r_s)_f}, \quad \alpha_\parallel(z) = \frac{(H(z)r_s)_f}{H(z)r_s}. \tag{8}$$

and the true wavenumbers are distorted by

$$k_\perp = k_\perp^f/\alpha_\perp, \quad k_\parallel = k_\parallel^f/\alpha_\parallel. \tag{9}$$

where the fiducial indices denote the fiducial (reference) cosmology assumed in the measured wavenumbers, and the wavenumber without an f index denotes the true wavenumbers for the true cosmology. These are conventionally transposed into k and μ using the factor $F_{\text{AP}} = \alpha_\parallel/\alpha_\perp$, where

$$k = \frac{k_f}{\alpha_\perp}\left[1 + (\mu_f)^2\left(F_{\text{AP}}^{-2} - 1\right)\right]^{1/2} \tag{10}$$

$$\mu = \frac{\mu_f}{F_{\text{AP}}}\left[1 + (\mu_f)^2\left(F_{\text{AP}}^{-2} - 1\right)\right]^{-1/2}. \tag{11}$$

Finally, to correct for any change in volume caused by the different cosmologies, the power spectrum model must be multiplied by $\alpha_\parallel^{-1}\alpha_\perp^{-2}$, which explains this factor at the front of Equation 1.

Similarly to the H I power spectrum, we can generically model the *galaxy* power spectrum as

$$P_g(k^f, \mu^f, z) = \alpha_\parallel^{-1}(z)\,\alpha_\perp^{-2}(z)\left(b_g(z) + f(z)\mu^2 + b_\phi^g(z)f_{\text{NL}}\mathcal{M}(k, z)^{-1}\right)^2 P_m(k, z). \tag{12}$$

Observed power spectra noise and errors: Neglecting shot-noise, which will be minimal for a H I intensity mapping survey (Villaescusa-Navarro et al., 2018; Spinelli et al., 2020), the observed H I power spectrum is given as

$$P_{\text{HI}}^{\text{obs}}(k^f, \mu^f, z) = P_{\text{HI}}(k^f, \mu^f, z) + P_N(z), \tag{13}$$

where P_N is the noise power spectrum contribution, which for H I intensity mapping is given by the telescope's thermal noise, which is modelled as

$$P_N = V_{\text{pix}}\sigma_N^2 \tag{14}$$

where the pixel volume is determined by the pixel area $A_{\rm pix}$ so that

$$V_{\rm pix} = \Omega_{\rm A} \int_{z_0}^{z_1} {\rm d}z \frac{{\rm d}V}{{\rm d}z{\rm d}\Omega} = \Omega_{\rm A} \int_{z_0}^{z_1} {\rm d}z \frac{c\chi^2(z)}{H(z)}\,, \tag{15}$$

where $\Omega_{\rm A} = A_{\rm pix}(\pi/180)^2$ and the redshift intervals are determined by the frequency of observation ν and the telescope's frequency resolution $\delta\nu$ so that $z_0 = \nu_{\rm 21cm}/(\nu+\delta\nu) - 1$ and $z_1 = \nu_{\rm 21cm}/(\nu-\delta\nu) - 1$, with $\nu_{\rm 21cm} = 1420.4\,{\rm MHz}$, the frequency of the 21cm line. The RMS of the noise fluctuations is given by the radiometer equation;

$$\sigma_{\rm N}(\nu) = \frac{T_{\rm sys}(\nu)}{\sqrt{2\,\delta\nu\,t_{\rm pix}}}\,. \tag{16}$$

The system temperature is given by

$$T_{\rm sys}(\nu) = T_{\rm rx}(\nu) + T_{\rm spl} + T_{\rm CMB} + T_{\rm gal}(\nu) \tag{17}$$

where the contribution from spill-over is $T_{\rm spl} = 3\,{\rm K}$, the background contribution from the CMB is $T_{\rm CMB} = 2.73\,{\rm K}$ and the contribution from our own Galaxy is $T_{\rm gal} = 15\,{\rm K}(408{\rm MHz}/\nu)^{2.75}$, which is tuned to the match the average sky temperature excluding $|b| < 10°$ in galactic latitude. Lastly, the receiver temperature is

$$T_{\rm rx}(\nu) = 7.5\,{\rm K} + 10\,{\rm K}\left(\frac{\nu}{\rm GHz} - 0.75\right)^2\,, \tag{18}$$

which follows Cunnington (2022) which tuned this model to match recent intensity mapping observations with the MeerKAT pilot survey (Wang et al., 2021). The time per pixel $t_{\rm pix}$ in the noise RMS (Equation 16), is given by the total observation time $t_{\rm obs}$ from the survey, shared among each pixel. Thus we define it as

$$t_{\rm pix} = N_{\rm dish}t_{\rm obs}\,\left(\theta_{\rm FWHM}/3\right)^2/A_{\rm sur} \tag{19}$$

where we assume each pixel is $1/3$ the size of the telescope's beam size (approximately correct for MeerKAT map-making). In single-dish mode, we get a set of observations per dish, hence observation time per pixel is multiplied by the number of dishes $N_{\rm dish}$.

The observed counterpart for the galaxies will contain shot-noise as the noise contribution defined as

$$P_{\rm g}^{\rm obs}(k^{\rm f}, \mu^{\rm f}, z) = P_{\rm g}(k^{\rm f}, \mu^{\rm f}, z) + P_{\rm SN}(z)\,, \tag{20}$$

where $P_{\rm SN} = 1/\bar{n}_{\rm g}$ is the galaxy shot noise, with $\bar{n}_{\rm g}$ as the galaxy number density for the survey.

The errors on the power spectrum can then be estimated as

$$\sigma^2(k, \mu) = \frac{P_{\rm obs}^2(k, \mu)}{N_{\rm modes}(k, \mu)}\,, \tag{21}$$

where the number of *unique* modes is given by

$$N_{\mathrm{modes}}\,(k,\mu) = \frac{k^2 \Delta k \Delta \mu}{8\pi^2} V_{\mathrm{sur}}\,. \tag{22}$$

where the survey volume is determined by the minimum and maximum redshift $(z_{\mathrm{min}}, z_{\mathrm{max}})$ of the survey and its area A_{sur};

$$V_{\mathrm{sur}} = \Omega_{\mathrm{sur}} \int_{z_{\mathrm{min}}}^{z_{\mathrm{max}}} \mathrm{d}z \frac{c\,\chi^2(z)}{H(z)}\,, \tag{23}$$

where $\Omega_{\mathrm{sur}} = A_{\mathrm{sur}}(\pi/180)^2$.

Multipole expansion: It is convenient to adopt the multipole expansion of the anisotropic power spectrum in Equation 1 (Cunnington et al., 2020; Bernal et al., 2019; Soares et al., 2021). This is achieved using

$$P(k,\mu) = \sum_\ell P_\ell(k)\mathcal{L}_\ell(\mu)\,, \tag{24}$$

$$P_\ell(k,z) = (2\ell + 1) \int_0^1 \mathrm{d}\mu\,P(k,\mu,z)\mathcal{L}_\ell(\mu)\,, \tag{25}$$

where

$$\mathcal{L}_0 = 1, \quad \mathcal{L}_2 = \frac{3\mu^2 - 1}{2}, \quad \mathcal{L}_4 = \frac{35\mu^4 - 30\mu^2 + 3}{8}\,. \tag{26}$$

and the errors on these multipoles is given by

$$\sigma_{P_\ell}(k) = \sqrt{(2\ell + 1)^2 \int_0^1 \mathrm{d}\mu\,\sigma^2(k,\mu)\mathcal{L}_\ell^2(\mu)}\,. \tag{27}$$

Fisher forecasting: To include our observable in a Fisher forecast, we consider that the set of fluctuations $\delta(\boldsymbol{x})$ within a survey map's pixels with position $\boldsymbol{x}$ can be reasonably modelled as a Gaussian distribution with mean of zero and pixel covariance $\mathbf{C} \equiv \langle \delta^*(\boldsymbol{x})\delta(\boldsymbol{x})\rangle$. The Fisher information matrix is then given by (Tegmark, 1997; Seo and Eisenstein, 2003, 2007)

$$F_{ij} = \frac{1}{2}\,\mathrm{tr}\left[\frac{\partial \mathbf{C}}{\partial \theta_i}\mathbf{C}^{-1}\frac{\partial \mathbf{C}}{\partial \theta_j}\mathbf{C}^{-1}\right] \tag{28}$$

where θ_i and θ_j are from the set of parameters $\boldsymbol{\Theta}$ that influence the covariance and their derivatives are evaluated at the fiducial values θ_{fid}, which coincides with the maximum of the likelihood distribution. The Cramer-Rao bound ensures that no unbiased method can measure θ_i with error bars less than $\sqrt{F_{ii}^{-1}}$.

For the multipole expansion formalism, we define the Fisher matrix following Taruya et al. (2011),

$$F_{ij}|_{\ell_{\mathrm{max}}} = \frac{V_{\mathrm{sur}}}{4\pi^2} \sum_{\ell,\ell'}^{\ell_{\mathrm{max}}} \int_{k_{\mathrm{min}}}^{k_{\mathrm{max}}} k^2 \mathrm{d}k \frac{\partial P_\ell(k)}{\partial \theta_i} \left[\widetilde{C}^{\ell\ell'}(k)\right]^{-1} \frac{\partial P_{\ell'}(k)}{\partial \theta_j}\,, \tag{29}$$

where the *reduced* covariance is given by

$$\widetilde{C}^{\ell\ell'}(k) = (2\ell+1)(2\ell'+1) \int_0^1 \mathrm{d}\mu \mathcal{L}_\ell(\mu)\mathcal{L}_{\ell'}(\mu) P_{\mathrm{obs}}(k,\mu)^2 \,, \tag{30}$$

For computing the derivatives for the Fisher matrix, we follow Blanchard et al. (2020) and say that given Equation 25 we have

$$\frac{\partial P_\ell(k)}{\partial \theta_i} = (2\ell+1) \int_0^1 \mathrm{d}\mu \frac{\partial}{\partial \theta_i} \left[P(k,\mu)\mathcal{L}_\ell(\mu) \right] \,, \tag{31}$$

since the integration limits do not depend on the parameters, and hence the derivative can be taken inside the integral. We then compute all derivatives numerically using a 5-point stencil, generically defined for a function $\mathcal{F}$ as

$$\frac{\partial \mathcal{F}}{\partial \theta} = \frac{-\mathcal{F}(\theta+2\delta\theta) + 8\mathcal{F}(\theta+\delta\theta) - 8\mathcal{F}(\theta-\delta\theta) + \mathcal{F}(\theta-2\delta\theta)}{12\,\delta\theta} \,, \tag{32}$$

where $\delta\theta$ is chosen such that it gives converged derivatives. Generally, we find that $\delta\theta \sim 10^{-2}$ is an appropriate choice for all parameters.

Cross-correlation and multi-tracer: A cross-correlation power spectrum between the HI and galaxies is given by (dropping redshift dependence for brevity)

$$\begin{aligned} P_{\mathrm{HI,g}}(k^{\mathrm{f}},\mu^{\mathrm{f}}) = \alpha_\parallel^{-1}\alpha_\perp^{-2}\, r_{\mathrm{HI,g}}\overline{T}_{\mathrm{HI}} \left(b_{\mathrm{HI}} + f\mu^2 + b_\phi^{\mathrm{HI}} f_{\mathrm{NL}}\mathcal{M}(k)^{-1} \right) \\ \times \left(b_{\mathrm{g}} + f\mu^2 + b_\phi^{\mathrm{g}} f_{\mathrm{NL}}\mathcal{M}(k)^{-1} \right) P_{\mathrm{m}}(k)\,\mathcal{B}_{\mathrm{beam}}(k,\mu) \,, \end{aligned} \tag{33}$$

where $r_{\mathrm{HI,g}}(z)$ is the cross-correlation coefficient between the two tracers to modulate stochastic suppression in the cross-correlation. Similarly to the single tracer, the *multi-tracer* Fisher matrix will be given by

$$F_{ij}|_{\ell_{\max}} = \frac{V_{\mathrm{bin}}}{4\pi^2} \sum_{\ell,\ell'}^{\ell_{\max}} \int_{k_{\min}}^{k_{\max}} k^2 \mathrm{d}k \frac{\partial \boldsymbol{P}_{\tau,\ell}(k)}{\partial \theta_i} \left[\mathbf{C}_{\tau\tau'}^{\ell\ell'}(k) \right]^{-1} \frac{\partial \boldsymbol{P}_{\tau',\ell'}(k)}{\partial \theta_j} \tag{34}$$

but we are now implicitly integrating over the contributions within $\tau = \{\alpha, \beta, \mathrm{X}\}$ i.e. the different different generic tracers α and β, plus their cross-correlation X. For the combination of HI intensity mapping and a galaxy survey, we would have $\alpha \equiv \mathrm{HI}$ and $\beta \equiv \mathrm{g}$. The data vector $\boldsymbol{P}_{\tau,\ell}$ represents the "non-observed" power spectra (i.e. without noise) containing each tracer combination and multipole i.e.

$$\boldsymbol{P}_{\tau,\ell}(k) = \{\boldsymbol{P}_{\alpha,\ell}(k), \boldsymbol{P}_{\beta,\ell}(k), \boldsymbol{P}_{\mathrm{X},\ell}(k)\} \tag{35}$$

with each element its own $n_\ell \times n_k$ vector. For the multipoles analysis, the covariance is given by

$$\mathbf{C}_{\tau\tau'}^{\ell\ell'}(k) = \begin{pmatrix} C_{\alpha\alpha}^{\ell\ell'} & C_{\alpha\beta}^{\ell\ell'} & C_{\alpha\mathrm{X}}^{\ell\ell'} \\ & C_{\beta\beta}^{\ell\ell'} & C_{\beta\mathrm{X}}^{\ell\ell'} \\ & & C_{\mathrm{XX}}^{\ell\ell'} \end{pmatrix} \,, \tag{36}$$

where each element represents the reduced covariance as before, given by the below;

$$C_{\alpha\alpha}^{\ell\ell'}(k) = (2\ell + 1)(2\ell' + 1) \int_0^1 \mathrm{d}\mu \mathcal{L}_\ell(\mu) \mathcal{L}_{\ell'}(\mu) P_\alpha^{\mathrm{obs}}(k, \mu)^2 \,, \tag{37}$$

$$C_{\alpha\beta}^{\ell\ell'}(k) = (2\ell + 1)(2\ell' + 1) \int_0^1 \mathrm{d}\mu \mathcal{L}_\ell(\mu) \mathcal{L}_{\ell'}(\mu) P_\alpha(k, \mu) P_\beta(k, \mu) \,, \tag{38}$$

$$C_{\alpha\mathrm{X}}^{\ell\ell'}(k) = (2\ell + 1)(2\ell' + 1) \int_0^1 \mathrm{d}\mu \mathcal{L}_\ell(\mu) \mathcal{L}_{\ell'}(\mu) P_\alpha^{\mathrm{obs}}(k, \mu) P_\mathrm{X}(k, \mu) \,, \tag{39}$$

$$C_{\mathrm{XX}}^{\ell\ell'}(k) = \frac{(2\ell + 1)(2\ell' + 1)}{2} \int_0^1 \mathrm{d}\mu \mathcal{L}_\ell(\mu) \mathcal{L}_{\ell'}(\mu) \left[P_\mathrm{X}^2(k, \mu) + P_\alpha^{\mathrm{obs}}(k, \mu) P_\beta^{\mathrm{obs}}(k, \mu) \right] \,. \tag{40}$$

Each element is its own sub-matrix of size $n_\ell \times n_k$. We assume no mode coupling between k, thus the only non-zero off-diagonal components in the matrix come from multipole $(\ell\ell')$ and tracer $(\tau\tau')$ covariance.

For further reading and related works on Fisher forecasting in the context of HI intensity mapping, we recommend Camera et al. (2013); Bull et al. (2015); Fonseca et al. (2015); Alonso and Ferreira (2015); Alonso et al. (2015); Pourtsidou et al. (2017); Bernal et al. (2019).

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