End-to-end EoR data simulations for SKA1-low: Impact of gain errors

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Data-corrupting effects to be included in simulations

- Dipole gain errors
- Ionospheric effects (diffractive, refractive, Faraday rotation)
- RFI
- Sidelobe noise from far-field sources
- Polarization leakage
- Incomplete/incorrect sky model
- Noise

(From Bernardi & Koopmans, NRF-NWO proposal)

First simulated datasets to be created

Start with residual errors and see what we can tolerate in terms of power spectrum

- DATA_REF : Reference data set, sky model + instrumental settings, no errors. This REF model is the reference/comparison data set.
- DATA_GAIN : REF model + receiver and station-based errors.
- DATA_ION : REF model + ionospheric errors.
- DATA_POL : REF model + diffuse polarized foreground.
- DATA_ALL : REF model + all the above effects.

(From Bernardi & Koopmans, NRF-NWO proposal)

Error impact assessment

- Compare dataset with corrupting effects against reference dataset:
  - DATA_GAIN – DATA_REF : Impact of gain errors on observations and analysis
  - DATA_ION – DATA_REF : Impact of ionospheric errors
  - DATA_POL – DATA_REF : Effects of polarization leakage
  - DATA_ALL – DATA_REF : Effects of all the above corrupting effects, and couplings and degeneracies between them

(From Bernardi & Koopmans, NRF-NWO proposal)

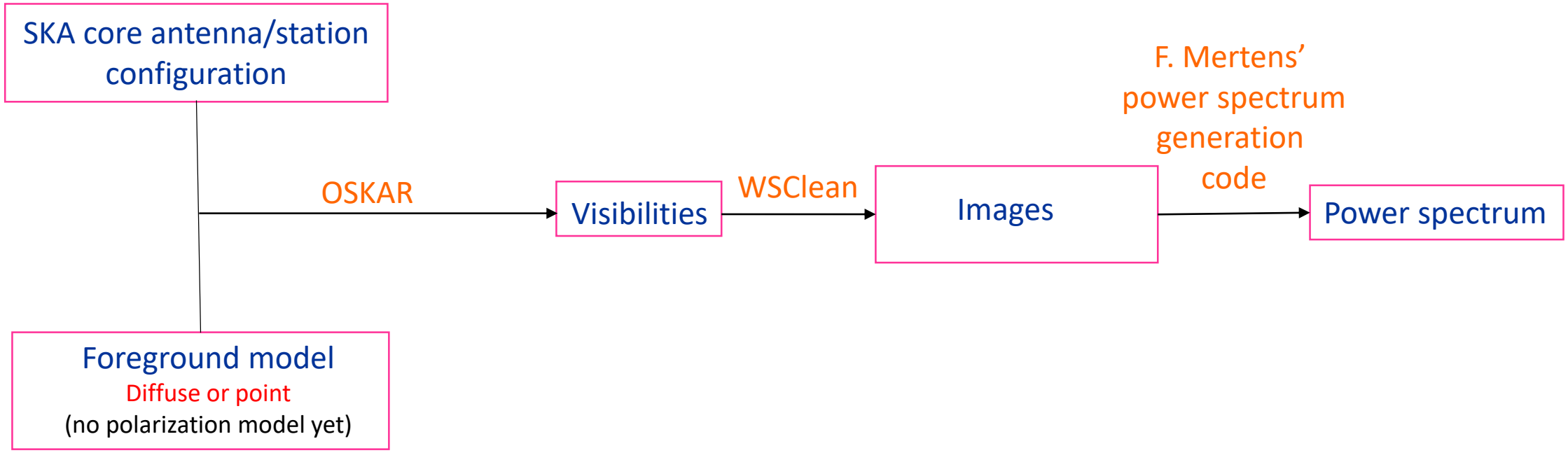
Metric for comparing datasets

Power spectrum

Tools/software for simulations

- OSKAR : Create visibilities from a sky model + antenna/station configuration
- WSClean (A. Offringa) : Imaging
- Power spectrum computation (F. Mertens' code) : Power spectrum from images

Current state of simulations



Steps

- Introduce gain errors to create DATA_GAIN.
- Compare with DATA_REF:
  - Compute power spectrum of DATA_GAIN – DATA_REF
- Study how the power spectrum changes with level of gain errors introduced.

Gain errors

- Beamforming weight:

$$W(\theta_b, \varphi_b, x, y, z, t) = W_0(\theta_b, \varphi_b, x, y, z, t)\underbrace{G e^{i\varphi}}_{\text{Complex gain error}}$$

- Gain errors G, can be:
  - Uncorrelated in time
  - Correlated in time

- The complex gain can be written as:
  - $G e^{i\varphi} = G_{\text{real}} + G_{\text{imag}}$

Uncorrelated gain errors

- $G_{\text{real}} = \text{N}(0, \sigma^2)$
- $G_{\text{imag}} = \text{N}(0, \sigma^2)$

Correlated gain errors

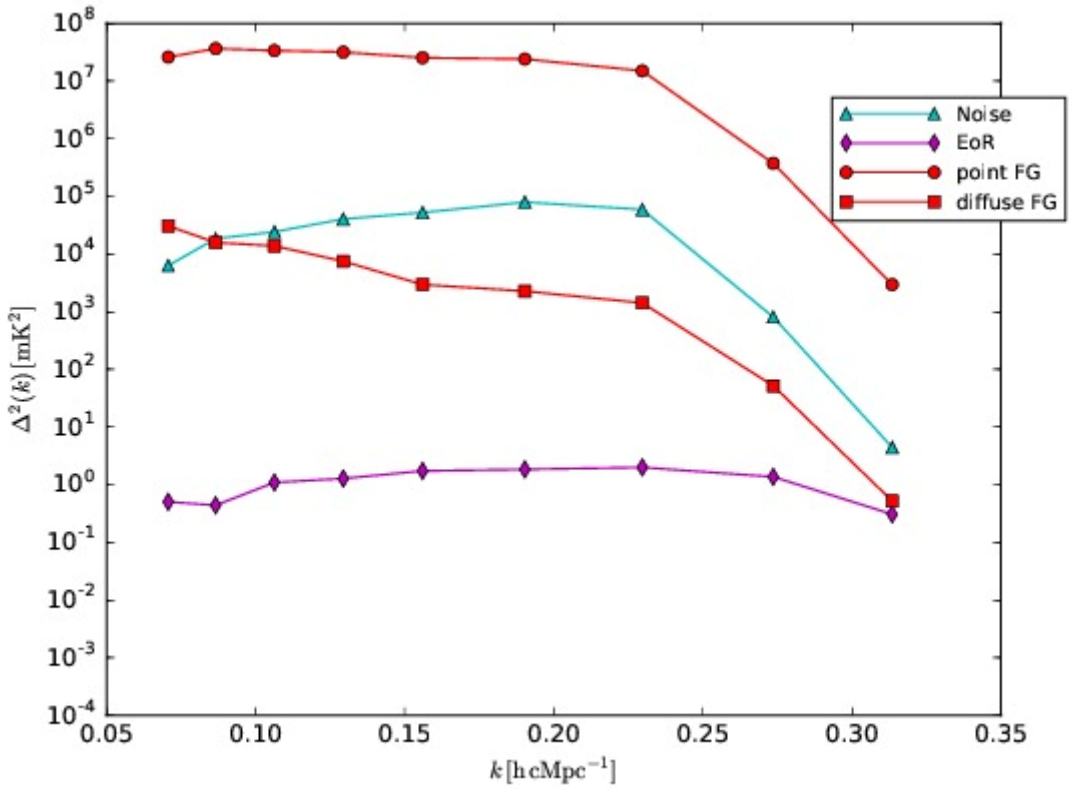
- G_{real} and G_{real} generated via Gaussian Process Regression (GPR), using a Matern Kernel with scale length (l) = coherence time for gain errors, and RMS (σ) = RMS of gain errors.

$$k(x_i, x_j) = \sigma^2 \frac{1}{\Gamma(\nu) 2^{\nu-1}} \left(\gamma \sqrt{2\nu} d(x_i/l, x_j/l) \right)^{\nu} K_{\nu} \left(\gamma \sqrt{2\nu} d(x_i/l, x_j/l) \right),$$

(from http://scikit-learn.org/stable/modules/gaussian_process.html#matern-kernel)

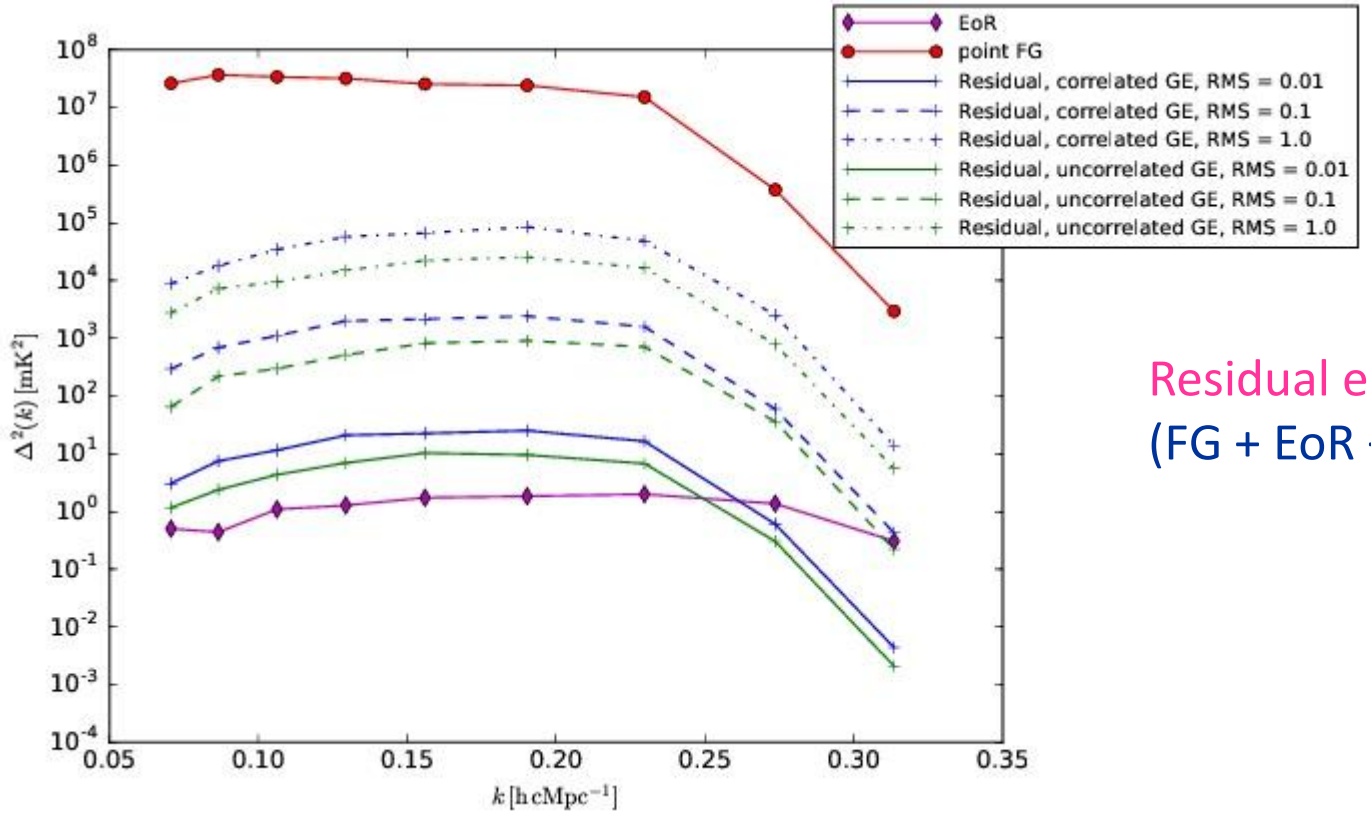
- Coherence time: 1 hour

Power spectrum



Point FG, diffuse FG, EoR, noise

Power spectrum

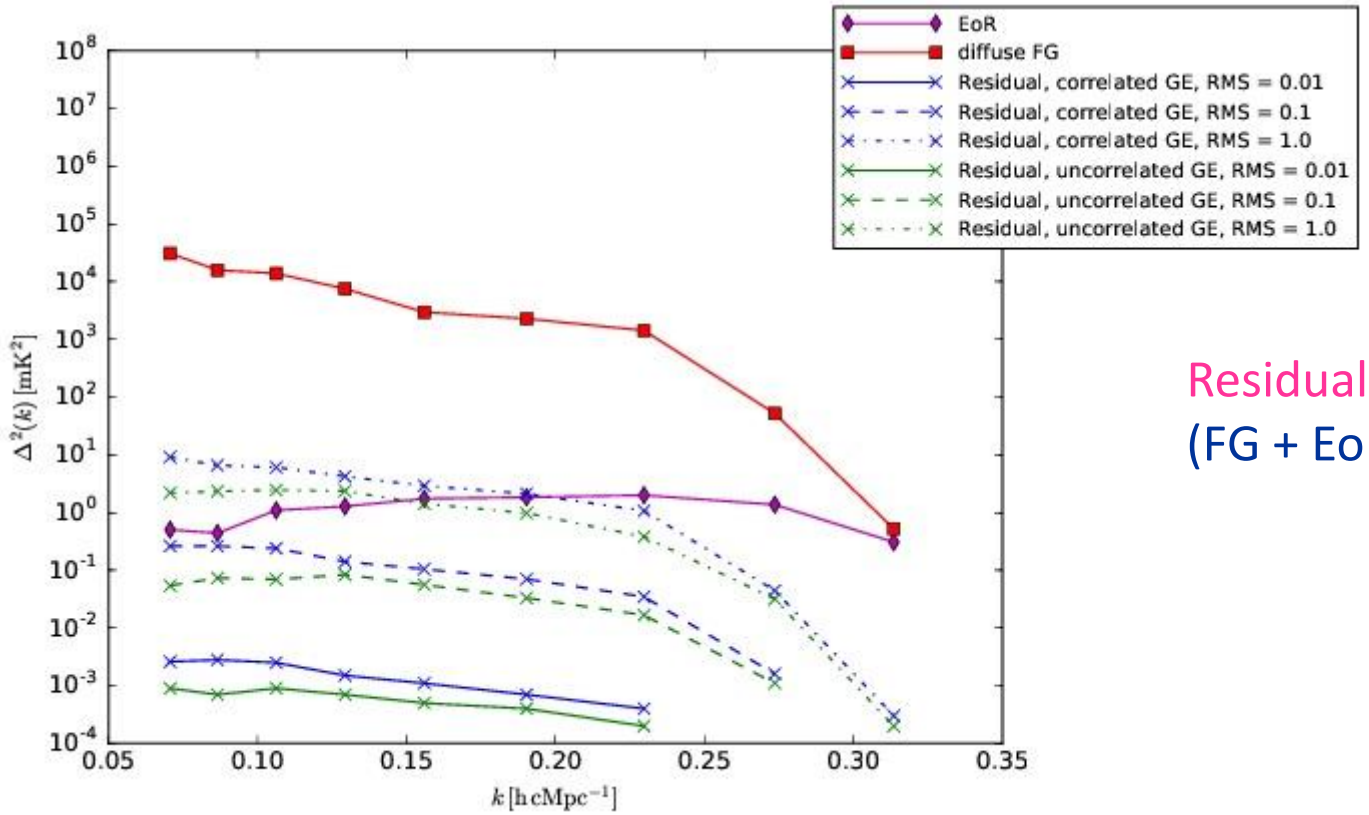


Residual error:

(FG + EoR + GE) – (FG + EoR)

Compact foregrounds and corresponding residuals

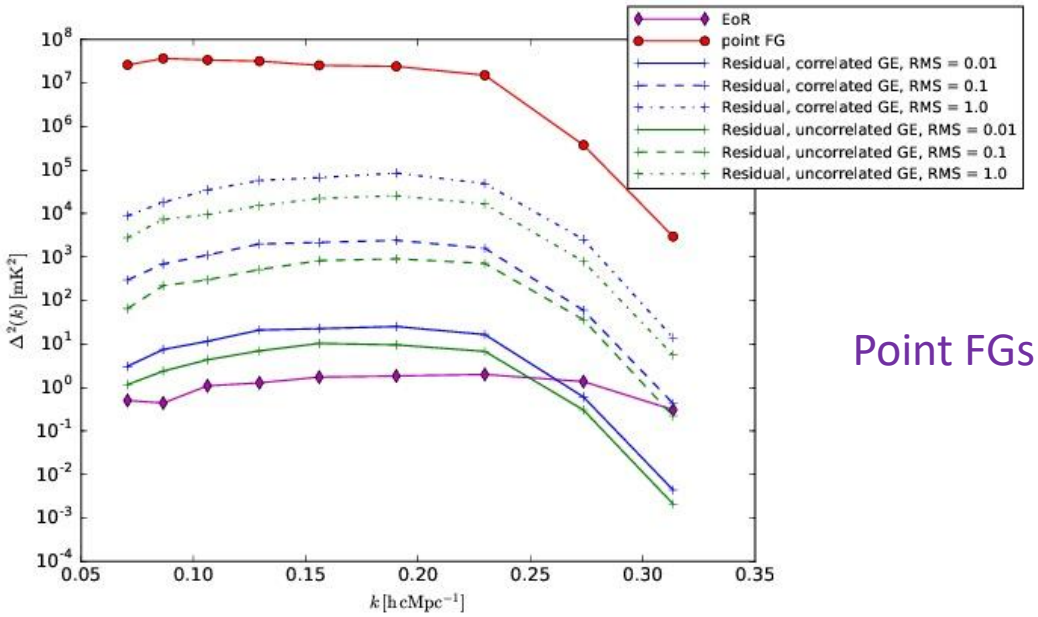
Power spectrum



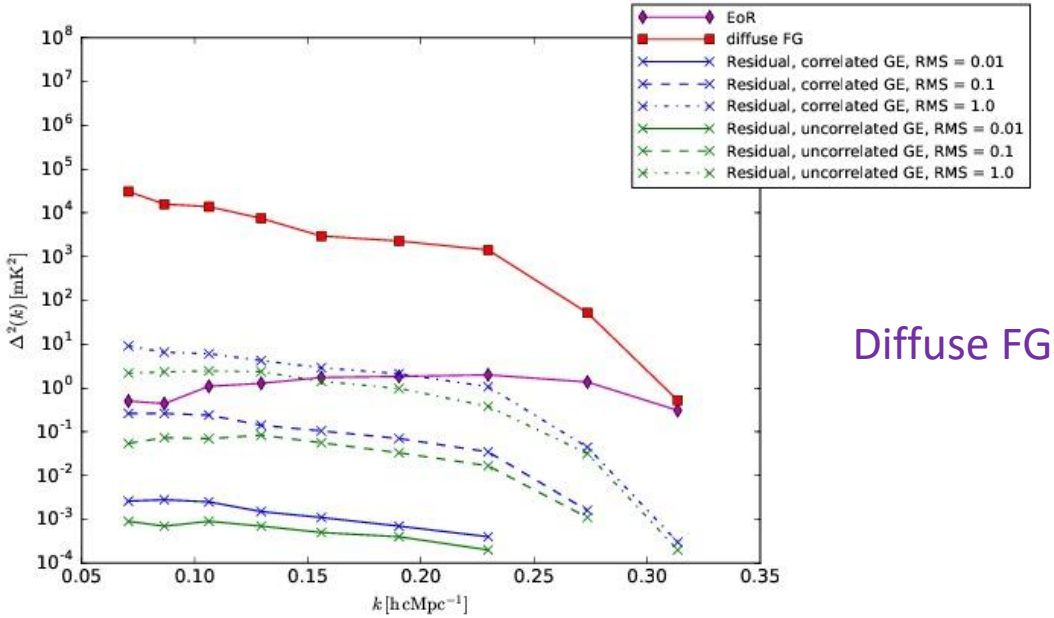
Residual error:
(FG + EoR + GE) – (FG + EoR)

Diffuse foregrounds and corresponding residuals

Power spectrum



Point FGs



Diffuse FGs

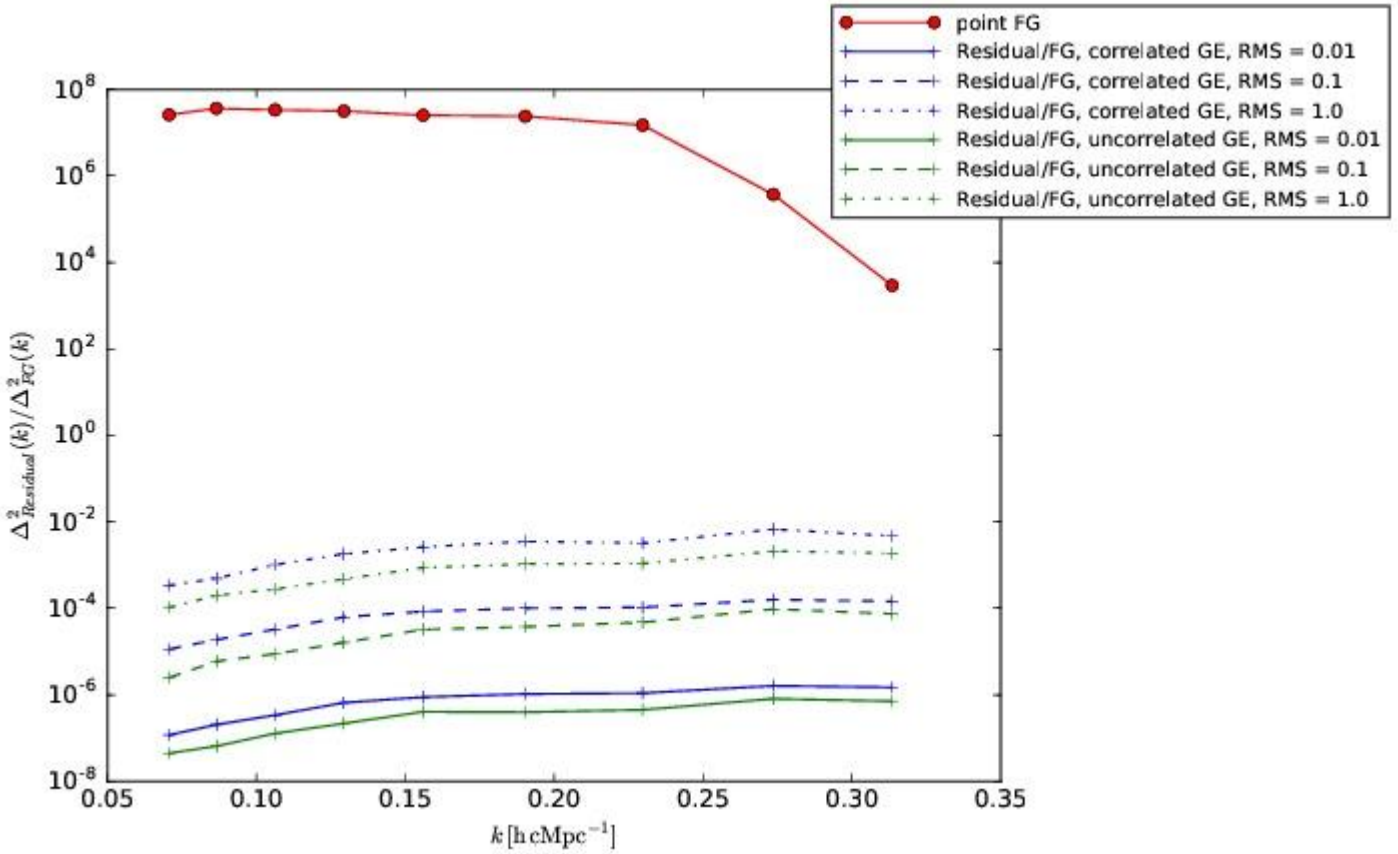
- PS(point sources) ~ 10^3 x PS(diffuse emission)
- PS(gain errors (GEs)) has roughly same shape as associated PS(FG).
- Changing the RMS gain error by a factor f changes PS(GE) by a factor f^2.
- PS(correlated GEs) > PS(uncorrelated GEs).
- This is because the gain errors are averaged down for uncorrelated GEs, but not so for correlated GEs.
- However, gain solutions can be computed over larger solution intervals for correlated GEs.
- Need PS(GE) < PS(EoR) for EoR detection.

Ratio of residual errors to foreground

- Ratio of power spectrum of residual error to power spectrum of foreground:

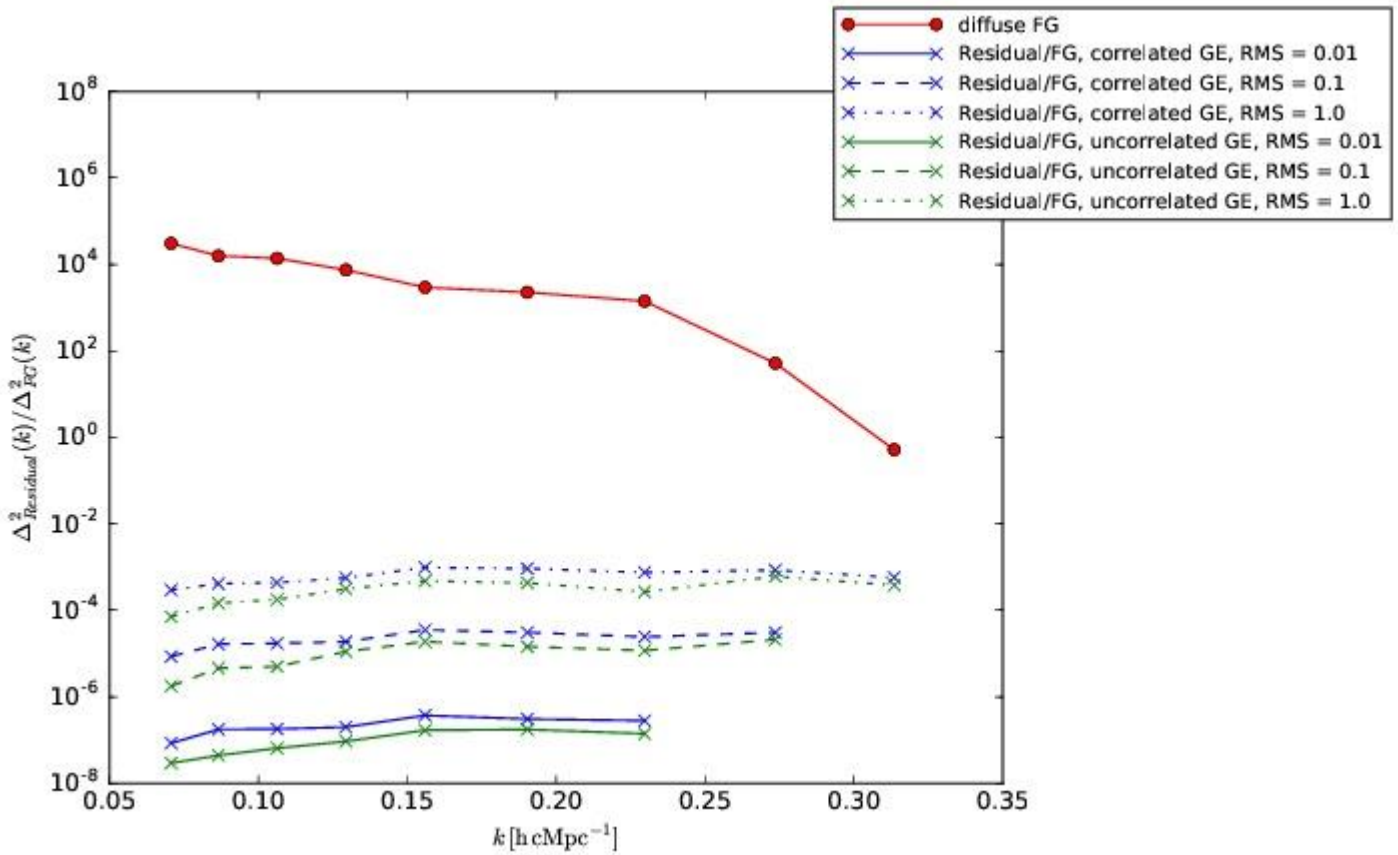
$$\frac{P_{[(\mathrm{FG+EoR+GE})-(\mathrm{EoR+GE})]}}{P_{\mathrm{FG}}}$$

Ratio of residuals to foreground



Compact foregrounds and corresponding residuals

Ratio of residuals to foreground



Diffuse foregrounds and corresponding residuals

Viable combinations of coherence time and gain errors for EoR detection

- For a fixed total observation duration, sampled at least once per coherence time:
  - Coherence time (t_{coh}) ↓ => PS(GE)↓
  - RMS (σ) of gain errors ↓ => PS(GE) ↓
- Need to find region in (t_{coh}, σ) space where PS(GE) < PS(EoR).

Viable region of operation in $(t_{\mathrm{coh}}, \sigma)$ space