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Mitigating systematics by mapmaking

Extensions of the destriping principle

Definitions

- *Mapmaking*: Projecting Time-Ordered Data (TOD) into maps.
- *Destriping*: Solving and subtracting long and intermediate time scale (seconds to hours) noise fluctuations from the TOD.
- *Filtering* or *deprojection*: Removing or suppressing modes in the TOD that are contaminated by systematics.
- *Extended destriping*: Combines noise offsets with systematics templates to optimally clean the TOD.
- *Systematics*: Any component of the TOD that is not sky signal nor noise. The boundary between noise and systematics is fluid.

Linear regression

- Standard tool in data analysis toolbox that all mapmaking can be traced back to:

$$\vec{y} = X\vec{\beta} + \vec{\varepsilon}$$

- Ordinary least squares:

$$\left(X^T X\right)\vec{\beta} = X^T\vec{y}$$

- Generalized least squares:

$$\left(X^T\Omega^{-1}X\right)\vec{\beta} = X^T\Omega^{-1}\vec{y}, \quad \Omega = \langle\vec{\varepsilon}\vec{\varepsilon}^T\rangle$$

Mapmaking

- Mapmaking can be cast as a linear regression problem where the pixel values are the template coefficients

$$\vec{d} = \mathrm{P}\vec{m} + \vec{n}$$

- And the maximum likelihood map follows from generalized least squares:

$$\left(\mathrm{P}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{P}\right)\vec{m} = \mathrm{P}^{\mathrm{T}}\mathrm{N}^{-1}\vec{d}, \quad \mathrm{N} = \langle \vec{n}\vec{n}^{\mathrm{T}} \rangle$$

Destriping

- Destriping adds another set of templates and template coefficients we call *baseline offsets*:

$$\vec{d} = \mathrm{P}\vec{m} + \mathrm{F}\vec{a} + \vec{n}$$

- If the residual noise is white, it is possible to solve exclusively for these additional templates:

$$\left(\mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{Z}\mathrm{F}\right)\vec{a} = \mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{Z}\vec{d}$$

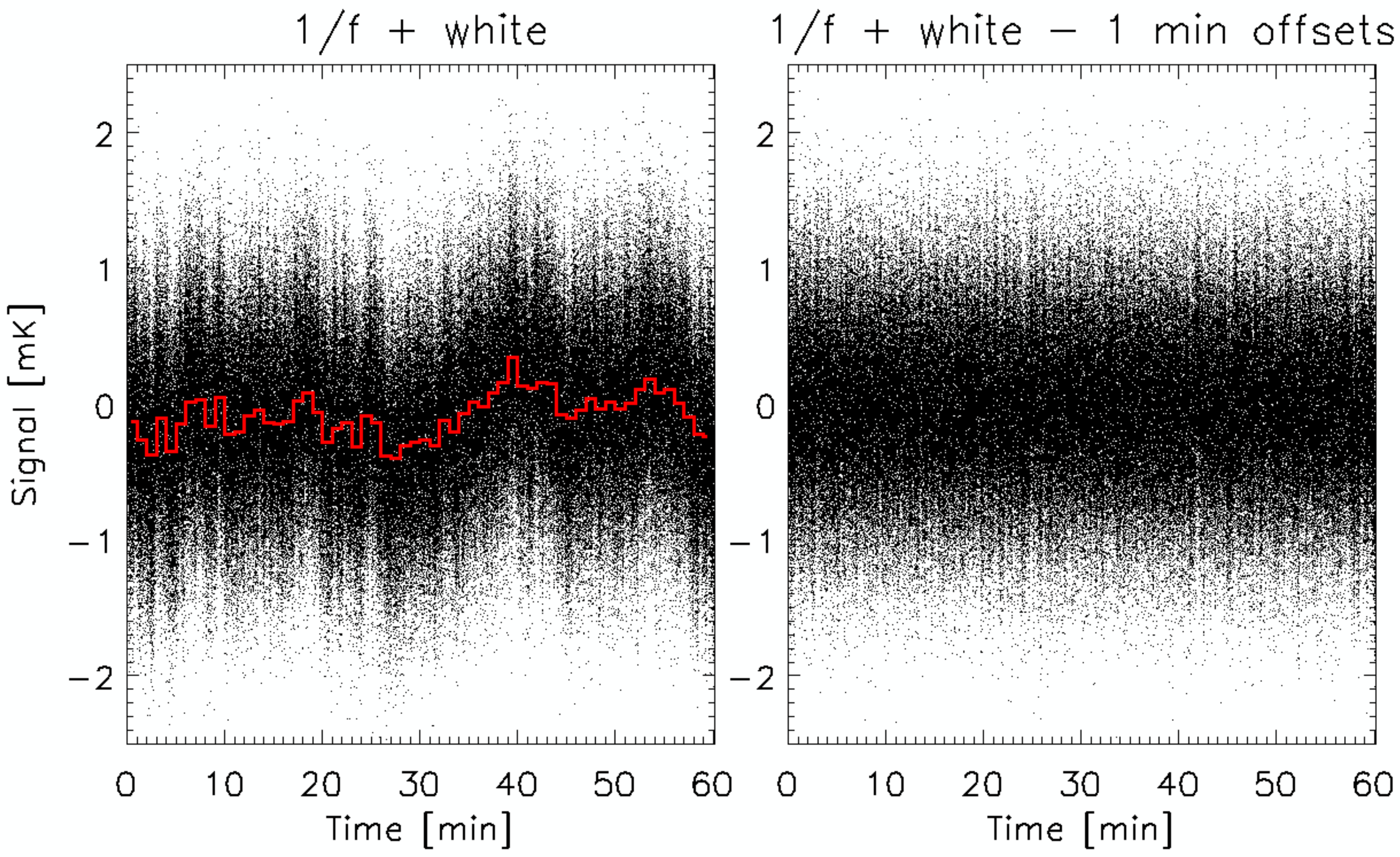
where

$$\mathrm{Z} = \mathrm{I} - \mathrm{P}\left(\mathrm{P}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{P}\right)^{-1}\mathrm{P}^{\mathrm{T}}\mathrm{N}^{-1}$$

Keihänen et al (2004, 2005, 2010)

Destriping (continued)

$$\left(\mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{Z}\mathrm{F}\right)\vec{a} = \mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{Z}\vec{d}$$



$$\left(\mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{Z}\mathrm{F} + \mathrm{C}_a^{-1}\right)\vec{a} = \mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{Z}\vec{d}$$

Keihänen et al (2004, 2005, 2010)

Filtering

- Ground experiments typically *filter* or *deproject* compromised modes out of the TOD. This is pure linear regression.
- Filtering enables batch processing so only a fraction of the data are kept in memory at a time.
- Filtering suppresses signal and systematics alike and reduces S/N. Further analysis is complicated by introduced biases.

Extended destriping

- There is no formal restriction for the shape of destriping templates.

$$\vec{d} = \mathrm{P}\vec{m} + \mathrm{F}\vec{a} + \vec{n}$$

- A deprojection template makes a great destriping template!

$$\left(\mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{Z}\mathrm{F}\right)\vec{a} = \mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{Z}\vec{d}$$

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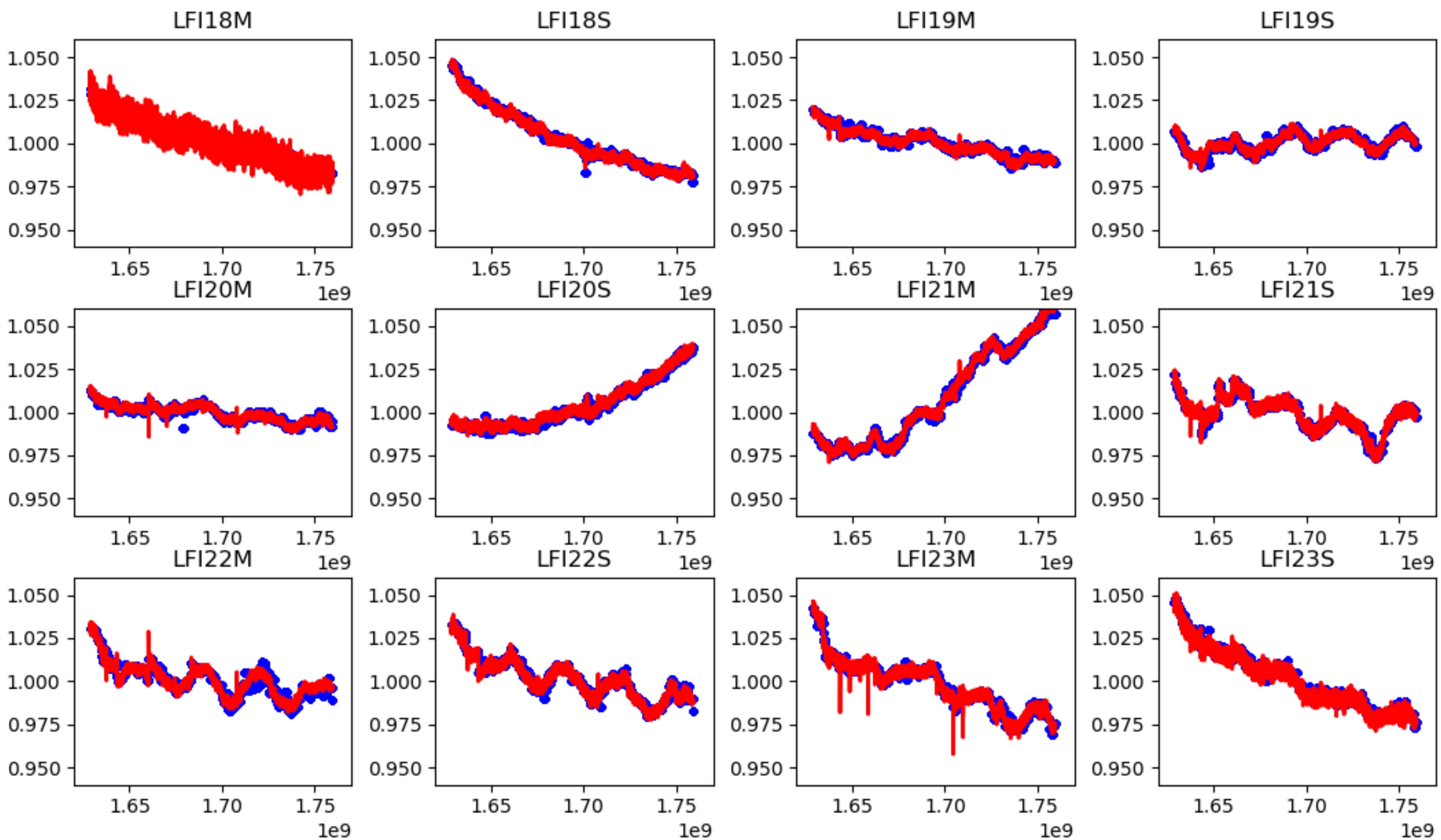
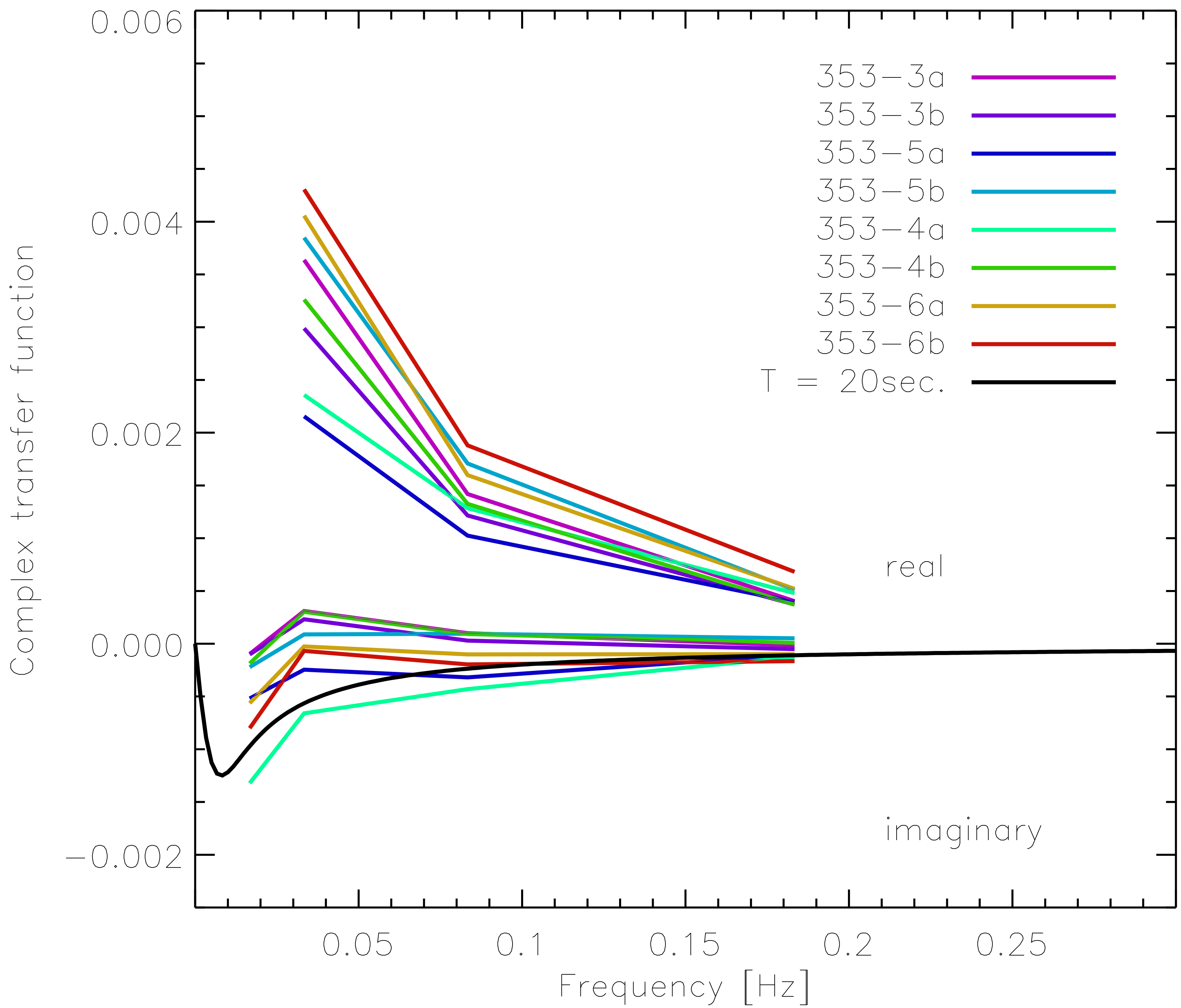
Extended destriping (continued)



Extended destriping (continued)



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Systematics

- Orbital dipole
- Gain fluctuations
- Bandpass mismatch
- Far side lobe pickup
- Transfer function residuals
- Zodiacal light
- Crosstalk
- Errors in pointing, beams and polarization efficiency
- HWP synchronous signal

To conclude

- It is possible to *cast the mapmaking* problem in the very familiar *language of linear regression*.
- It is possible to *solve* for *general systematics* templates using the mapmaking formalism and *in map-orthogonal subspaces* of the full TOD domain.
- It is more than likely that extended mapmaking methods will couple with filtering to reach the ultimate sensitivity.

Pixel-pixel noise covariance

$$\mathrm{N}_{pp\prime} = \langle \delta m \delta m^{\mathrm{T}} \rangle = \left(\mathrm{P}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{P}\right)^{-1}$$

$$\mathrm{N}_{aa\prime} = \langle \delta a \delta a^{\mathrm{T}} \rangle = \left(\mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{Z}\mathrm{F}\right)^{-1}$$

$$\mathrm{N}_{pp\prime} = \mathrm{N}^{\mathrm{wn}}_{pp\prime} + \mathrm{N}^{\mathrm{wn}}_{pp\prime}\mathrm{P}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{F}\,\mathrm{N}_{aa\prime}\,\mathrm{F}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{P}\mathrm{N}^{\mathrm{wn}}_{pp\prime}$$

Tristram et al (2011)

$$\mathrm{N}^{\mathrm{tot}}_{pp\prime} = \mathrm{N}_{pp\prime} + \mathrm{B}\mathscr{N}\mathrm{B}^{\mathrm{T}}$$

$$\mathscr{N} = \langle \delta y \delta y^{\mathrm{T}} \rangle, \quad \mathrm{B} = \left(\mathrm{P}^{\mathrm{T}}\mathrm{N}^{-1}\mathrm{P}\right)^{-1}\mathrm{P}^{\mathrm{T}}\mathrm{N}^{-1}$$