

A GP model for shear fields

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Basic premise

We model the 2D lens potential ψ as a Gaussian Process (GP) model,

$$\psi \sim \text{GP}(0, \Sigma),$$

where the GP covariance $\Sigma(\vec{x}, \vec{y})$ is a function of two 2D position vectors to denote the covariance of the realizations of the lens potential at sky positions \vec{x} and \vec{y} .

Observable lensing quantities

- The lensing convergence and shear are 2nd derivatives of the lens potential.
- **Because the derivative of a GP is also a GP**, the vector of $\mathbf{s} \equiv (\kappa, \gamma_1, \gamma_2)$ is GP distributed.
- The covariance of \mathbf{s} is given by 4th derivatives of the covariance of Σ of ψ . That is,

$$\text{Cov}(\psi_{,ij}(\vec{x}), \psi_{,kl}(\vec{y})) = \Sigma_{,x_i x_j y_k y_l}(\vec{x}, \vec{y}).$$

where $i, j, k, l = 1, 2$ denoting the two spatial coordinates

GP covariance parameterizations

Generally, we will write the GP covariance as the product of a precision parameter λ and a ‘kernel’ k ,

$$\Sigma(\vec{x}, \vec{y}) \equiv \lambda^{-1} k(r^2(\vec{x}, \vec{y}, D)),$$

where,

$$r^2 \equiv (\vec{x} - \vec{y})^T D (\vec{x} - \vec{y})$$

for some metric D^{-1} .

GP kernels in george

The [george](#) python package has a number of GP kernels already implemented. Two common interesting ones are:

1. Squared exponential kernel,

$$k(r^2) = \exp(-\frac{1}{2}r^2)$$

2. Matern kernels with parameter ν (only $\nu = (3/2, 5/2)$ implemented in george),

$$k_\nu(r^2) = \frac{1}{\Gamma(\nu)2^{\nu-1}} (2\nu r^2)^{\nu/2} K_\nu(\sqrt{2\nu r^2}),$$

where K_ν is the modified Bessel function of the 2nd kind.

GP covariance derivatives

General relations (1): derivatives of r^2

From before,

$$r^2 \equiv (\vec{x} - \vec{y})^T D (\vec{x} - \vec{y}).$$

Then,

$$\frac{\partial r^2}{\partial x_i} = [D(\vec{x} - \vec{y})]_i \equiv X_i \quad (1)$$

$$\frac{\partial r^2}{\partial y_i} = -X_i \quad (2)$$

$$\text{Hess}_{ij}(r^2) = D_{ij} \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}$$

General relations (2a): derivatives of Σ

The 1st, 2nd, and 4th derivatives of Σ that we need are,

$$\Sigma_{,x_i} = \lambda^{-1} k' r^2_{,x_i}$$

$$\Sigma_{,x_i x_j} = \lambda^{-1} \left[k'' r^2_{,x_j} r^2_{,x_i} + k' r^2_{,x_i x_j} \right]$$

$$\Sigma_{,x_i x_j y_k y_\ell} = \lambda^{-1} [k'''' r^2_{,x_i} r^2_{,x_j} r^2_{,y_k} r^2_{,y_\ell} + k''' (r^2_{,x_i x_j} r^2_{,y_k} r^2_{,y_\ell} + 5\text{perm.}) + k'' (r^2_{,x_i x_j} r^2_{,y_k y_\ell} + 2\text{perm.})]$$

where primes on k denote derivatives with respect to r^2 .

General relations (2b): derivatives of Σ (simplified)

$$\Sigma_{,(x,y)_i} = \pm \lambda^{-1} k' X_i \quad (3)$$

$$\Sigma_{,x_i x_j} = \lambda^{-1} \left[k'' X_i X_j + k' D_{ij} \right] \quad (4)$$

$$\Sigma_{,x_i x_j y_k y_\ell} = \lambda^{-1} [k'''' X_i X_j X_k X_\ell + k''' (D_{ij} X_k X_\ell + 5\text{perm.}) + k'' (D_{ij} D_{k\ell} + 2\text{perm.})] \quad (5)$$

Observations about GP covariances of convergence and shear

- The derivatives of Σ have terms that depend on $X_i \equiv [D(\vec{x} - \vec{y})]_i$, which *increases* in magnitude with increasing separation on the sky. **So, distant points can be highly correlated.**
- In our nominal model, $D_{ij} \propto -\ln(\rho)$ where ρ is the correlation parameter for the GP.
- At small sky separations $X_i \approx 0$ and the covariance of the convergence or shear $\sim D_{ij}^2 \Sigma$. **So, the variance of the convergence and shear is enhanced by a factor $[\ln(\rho)]^2$ over that of the lens potential.**

Derivatives of specific GP kernels

Kernel derivatives: Squared exponential

$$k(r^2) \equiv \exp(-\frac{1}{2}r^2)$$

Because there's just the exponential term, the n th derivatives are trivial,

$$k^{(n)} = \left(-\frac{1}{2}\right)^n k$$

Final GP covariance derivatives: Squared exponential

$$\Sigma_{,(x,y)_i} = \mp \frac{1}{2} X_i \Sigma \quad (6)$$

$$\Sigma_{,x_i x_j} = \left[\frac{1}{4} X_i X_j - \frac{1}{2} D_{ij} \right] \Sigma \quad (7)$$

$$\Sigma_{,x_i x_j y_k y_\ell} = \left[\frac{1}{16} X_i X_j X_k X_\ell - \frac{1}{8} (D_{ij} X_k X_\ell + 5 \text{perm.}) + \frac{1}{4} (D_{ij} D_{k\ell} + 2 \text{perm.}) \right] \Sigma \quad (8)$$

Kernel derivatives: Matern (1)

$$k_\nu(r^2) = \frac{1}{\Gamma(\nu) 2^{\nu-1}} (2\nu r^2)^{\nu/2} K_\nu(\sqrt{2\nu r^2}),$$

The n th derivatives of the modified Bessel function of the 2nd kind [can be represented by the Meijer G function](#). But, george only implements the cases $\nu = 3/2, 5/2$ and the kernel has a simpler form for these cases,

$$k_\nu(r^2) = p_\nu(r) \exp\left(-\sqrt{2\nu r^2}\right)$$

where p_ν is a polynomial in $\sqrt{r^2}$.

We'll consider the 1st-4th derivatives of this expression next.

Lensing parameters

Convergence and shear from lens potential

Note the subscripts correspond to derivatives w.r.t. spatial coords

$$\kappa = \frac{1}{2} (\psi_{,11} + \psi_{,22})$$

$$\gamma_1 = \frac{1}{2} (\psi_{,11} - \psi_{,22})$$

$$\gamma_2 = \frac{1}{2} (\psi_{,12} + \psi_{,21})$$

Convergence and shear GP covariances

$$\text{Cov}(\kappa) = \frac{1}{4} (\Sigma_{,1111} + \Sigma_{,1122} + \Sigma_{,2211} + \Sigma_{,2222}) \quad (9)$$

$$\text{Cov}(\gamma_1) = \frac{1}{4} (\Sigma_{,1111} - \Sigma_{,1122} - \Sigma_{,2211} + \Sigma_{,2222}) \quad (10)$$

$$\text{Cov}(\gamma_2) = \frac{1}{4} (\Sigma_{,1212} + \Sigma_{,1221} + \Sigma_{,2112} + \Sigma_{,2121}) \quad (11)$$