Optimal Kalman Filtering for Tip-Tilt Correction

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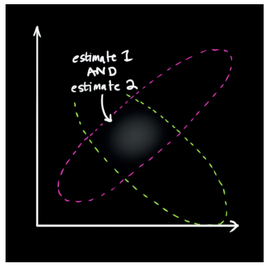
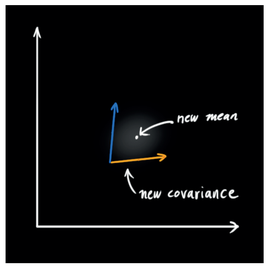
Abstract

I aim to greatly improve tip and tilt filtering and correction for the Keck telescopes. This can be optimally done using a Kalman filter with a physics model conditioned by the expected tip/tilt power spectrum and vibration peaks. The effects of measurement noise, loop delays, and the response of the control hardware are also considered.

Kalman Filtering

- Kalman filter overlaps physics-model expectations, actual measurements
- Useful to reduce measurement error and make predictions for TT control
- Provides optimal linear state observer for Linear-Quadratic-Gaussian control
- Depends heavily on accurate physics model: have to learn online and fit

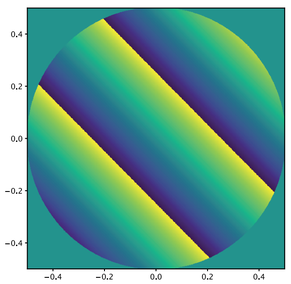


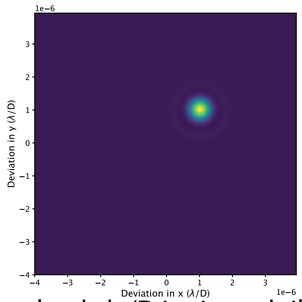


Source: "How a Kalman filter works, in pictures" (see references section)

Tip-Tilt Mode Behaviour

- Tip-tilt is measured as a sequence of x-y positions: image across 4 pixels and find center of mass.
- Dynamics can be predicted for turbulence and vibrations by fitting to openloop data: construct a state and transition rule that gives dynamics for all times

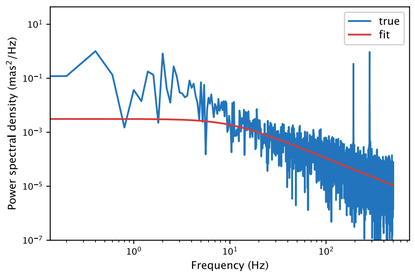




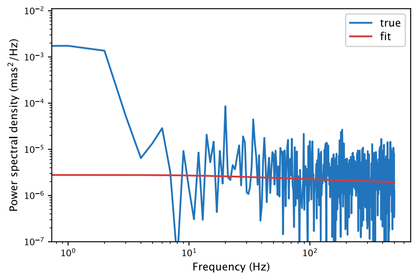
Phase screen and intensity for one lambda/D in tip and tilt

Turbulence Fitting

- Tip-tilt turbulence has a known power spectrum ($f^{-1/3}$ transitioning to f^{-2})
- Can invert this to build an impulse response
- Use this as coefficients for moving-average model
- Integrator also helps with measurement noise
- In practice, model is built off fit coefficients because real-life data doesn't always match this power law (real Keck data here has almost zero slope!)



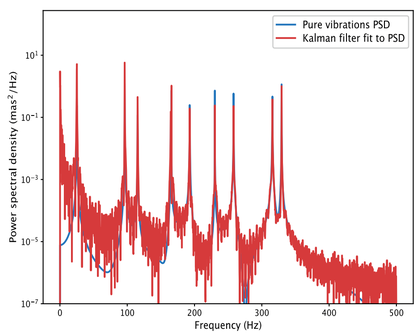
Theoretical power-law



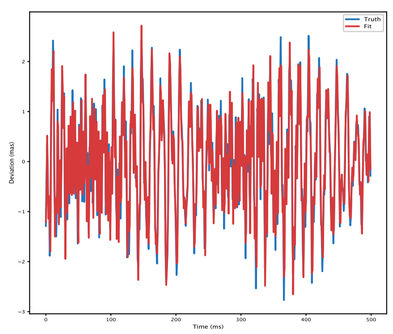
Observed data from Keck

Vibration Fitting

- Vibrations show up as peaks on a power spectrum
- Can fit autoregressive model to each peak
  - maximum likelihood estimation
  - get frequency from position, damping ratio from spread
  - MLE fit standard deviation gives covariance for Kalman filter
- Batch identification: look at PSD every 1000 timesteps
- Can check/adjust in closed loop whether vibrations are being completely controlled



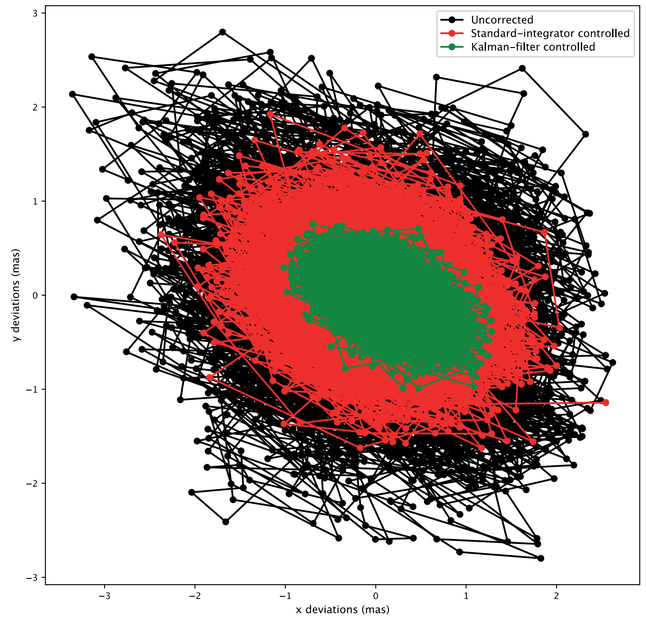
Fit in frequency space



Pure vibrations being fitted

Results and Next Steps

- Filtering shows performance improvements!
- Can further improve by:
  - tuning noise model - specific to a telescope
  - tuning LQR cost parameters
  - tighter/more expensive fit to turbulence
- Can test against standard integrator on-sky
- Can also incorporate control action error in filter



Acknowledgements and References

Thanks to Dr. Donald Gavel, Dr. Lisa Poyneer, Dr. Alexander Rudy and Emiel Por for their advice. Simulation and results at https://github.com/aditya-sengupta/adaptive-optics/control/!

This research made use of HCIPy, an open-source object-oriented framework written in Python for performing end-to-end simulations of high-contrast imaging instruments (Por et al. 2018).

"Tip–tilt disturbance model identification for Kalman-based control scheme: application to XAO and ELT systems", Meimon et al., 2016

"Kalman filtering to suppress spurious signals in adaptive optics control", Poyneer & Veran, 2010

"A laboratory demonstration of an LQG technique for correcting frozen flow turbulence in adaptive optics systems", Rudy et al., 2015

"How a Kalman filter works, in pictures": https://www.bzarg.com/p/how-a-kalman-filter-works-in-pictures