Optimal State-Space Estimation of Interferometer Cavity Modes

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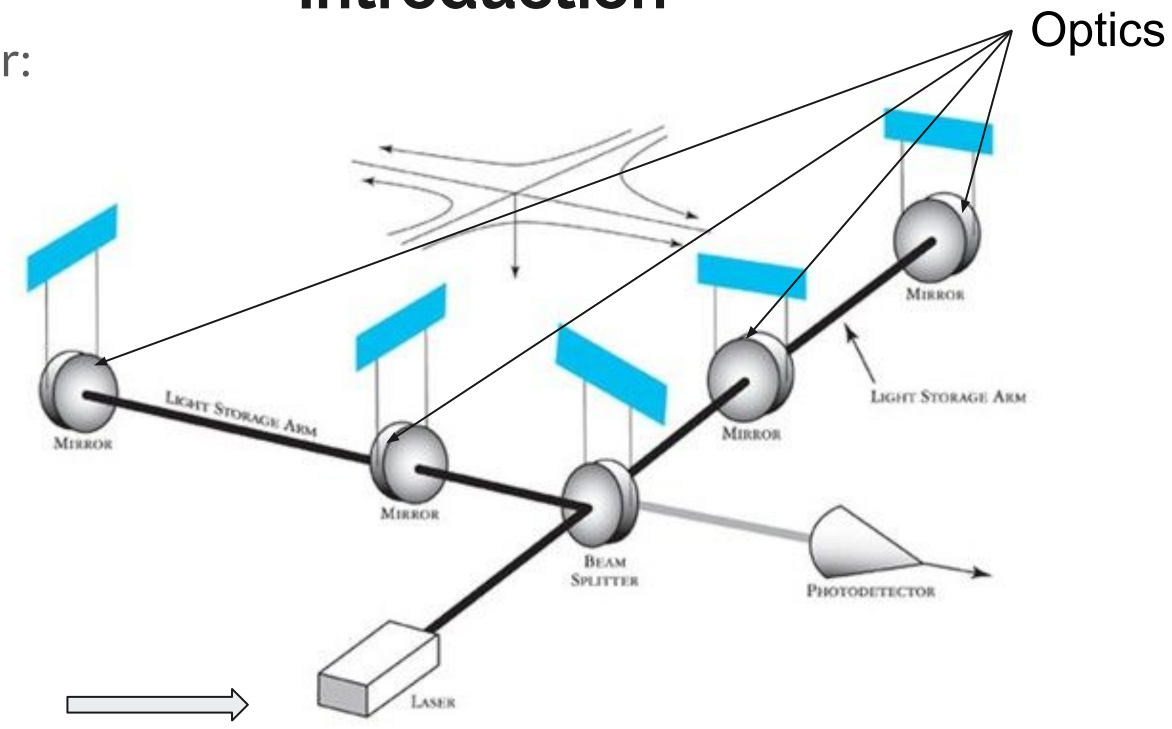
Introduction

- Interferometer:



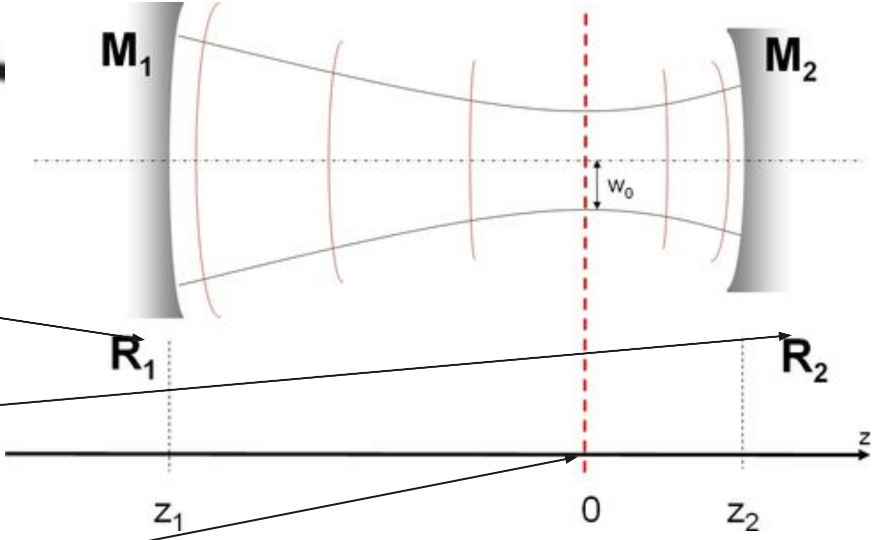
Light Source

Image Credit: https://www.ligo.caltech.edu/page/what-is-interferometer

Problem: Spatial Deviation of Optics

Image Credit: https://www.ligo.caltech.edu/page/what-is-interferometer

- Mirrors 1 and 2 begin to get warped due to thermoelastic expansion
- The mode of the cavity changes



Radius of Curvature M1:
1,935 meters

Radius of Curvature M2:
2,240 meters

Length of Arm Cavity (z2 - z1): 4 kilometers

Image Credits:
http://www.optique-ingenieur.org/en/courses/OPI_ang_M01_C03/co/Contenu_11.html

Adaptive Optics: Thermal Compensation System (TCS)

- Reduce the thermoelastic expansion
- Reduce static deviations of optics
    - How?
        - Ring heater actuators
    - Problem solved right?
        - No, lacks control system
        - No automated, systematic method
        - Require a better method of processing information

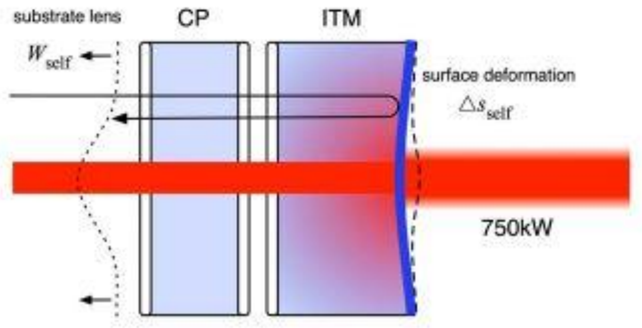


Image Credits: Aidan Brooks et. al Vol. 55, No. 29 / October 10 2016 / Applied Optics

Kalman filter

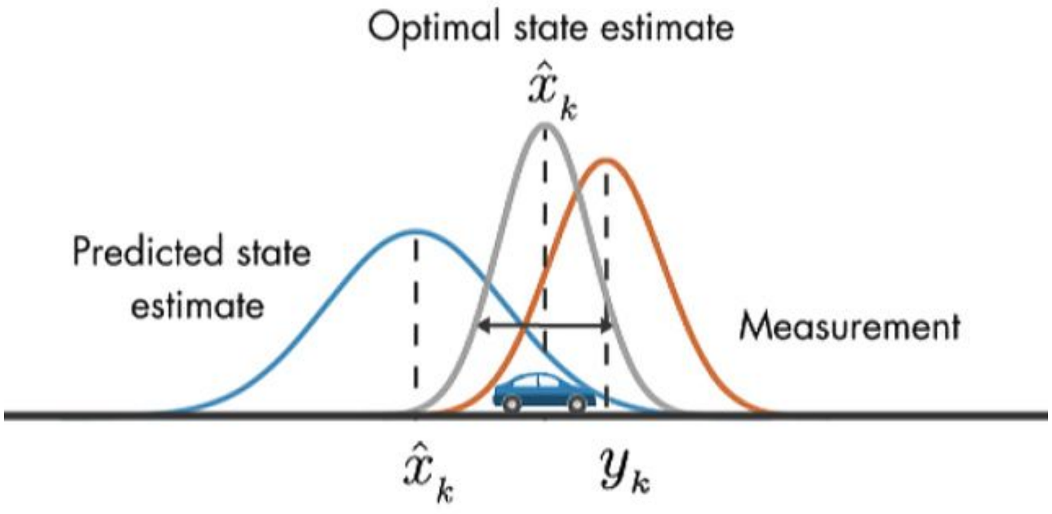


Image Credits: https://www.mathworks.com/videos/understanding-kalman-filters-part-3-optimal-state-estimator--1490710645421.html

Why the Kalman filter?

- GPS, Navigation Systems

- Reusable Rockets

Image Credit: https://www.sciencefocus.com/science/who-really-discovered-gps/

Image credit: https://en.wikipedia.org/wiki/Reusable_launch_system

Goal: Repurpose the Kalman filter in Python for Optical Applications

Step 1: Construct the a priori estimate

Prior Estimate

- Code the true state
  - True Radii of Curvature, true length of arm, true beam size
- State Vector
  - Function of length, radii of curvature, and beam size

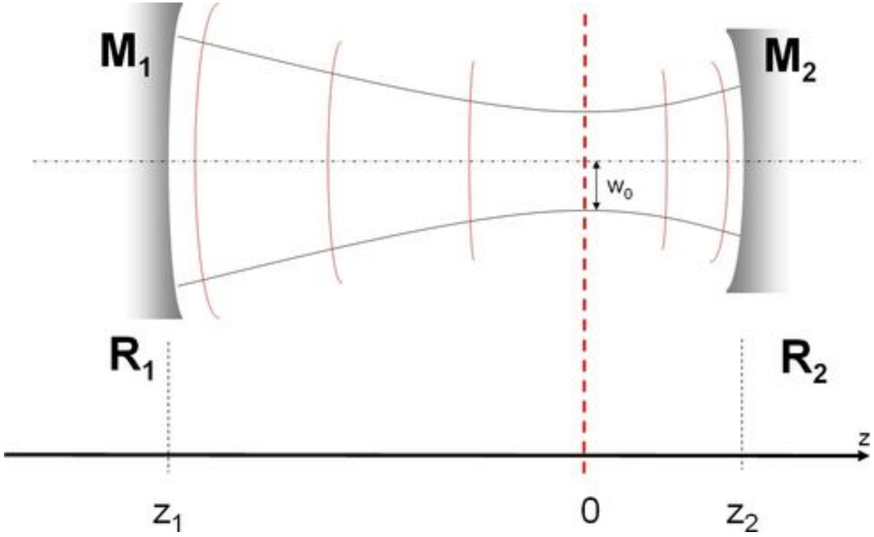
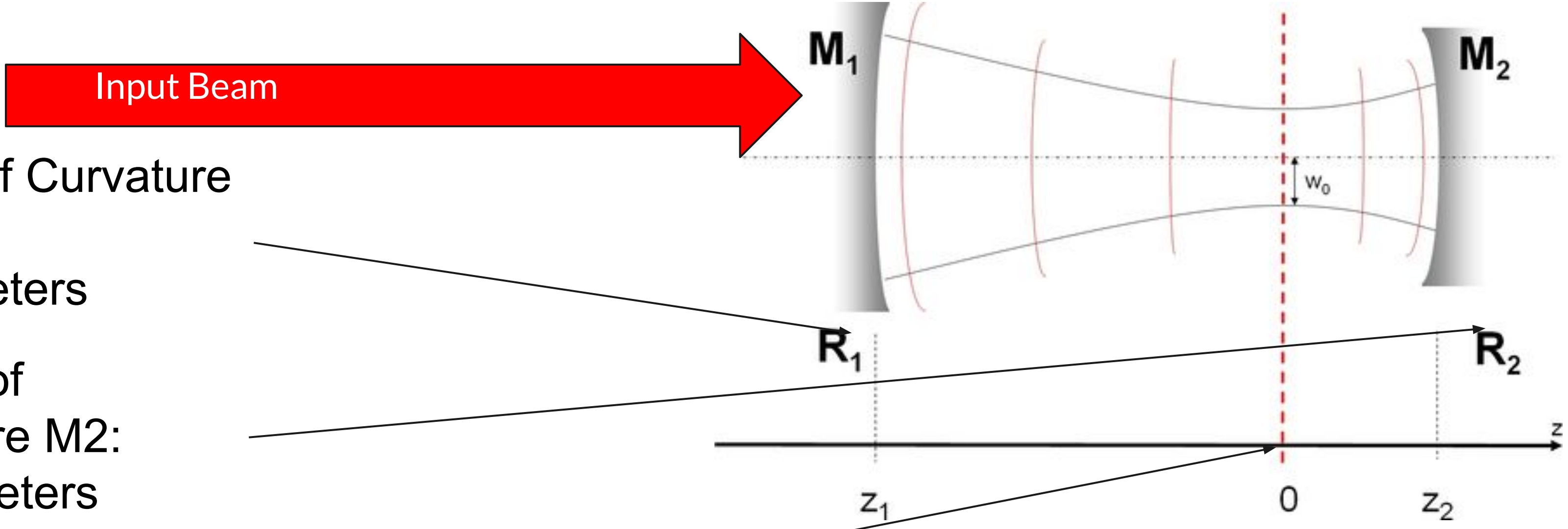


Image Credits: http://www.optique-ingenieur.org/en/courses/OPI_ang_M01_C03/co/Contenu_11.html

Measurement

- How well does the mode match with the shape of the beam?



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Step 2: Construct the a posterior estimate

Posterior Estimate

- Innovation Residual
  - Innovation Covariance
- Optimal Kalman gain
- Updated a posteriori state estimate
  - A posteriori estimate covariance

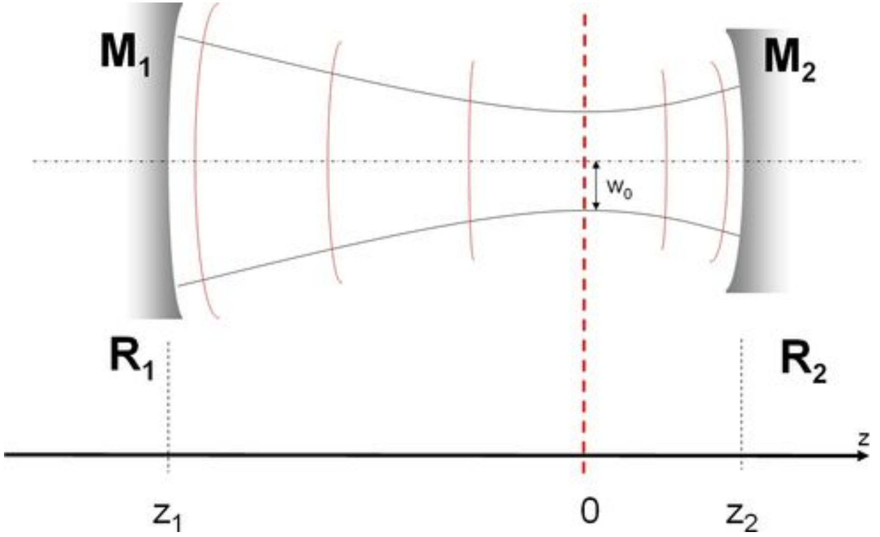

Image Credits: http://www.optique-ingenieur.org/en/courses/OPI_ang_M01_C03/co/Contenu_11.html

Step 4: Plot the prediction and the measurement

Plot of State Estimates

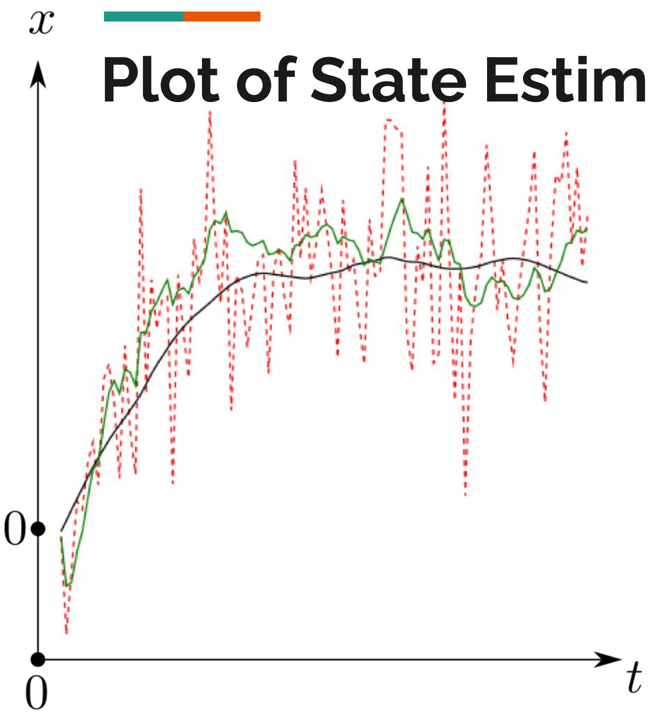

Image Credit: https://en.wikipedia.org/wiki/Kalman_filter

- Black Line:
  - True State
- Red Line:
  - Prior State Estimate
- Green Line:
  - Posterior State Estimate

Preliminary Conclusions and Future Work

- Proof that the Kalman filter is a viable candidate
- Generate a plot depicting the mode matching estimates
- Expand the current code to work on more complex optical systems
- Receive real data from LIGO systems
- Run Kalman filter calculations in real time on LIGO's detectors

Acknowledgement

I would like to thank Dr. Aidan Brooks, Dr. Jon Richardson, Dr. Rana Adhikari who gave me this amazing opportunity and the necessary tools to work on this project.

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Caltec

LIGO

NSF