Upgrading AIR-Spec for the 2019 Eclipse

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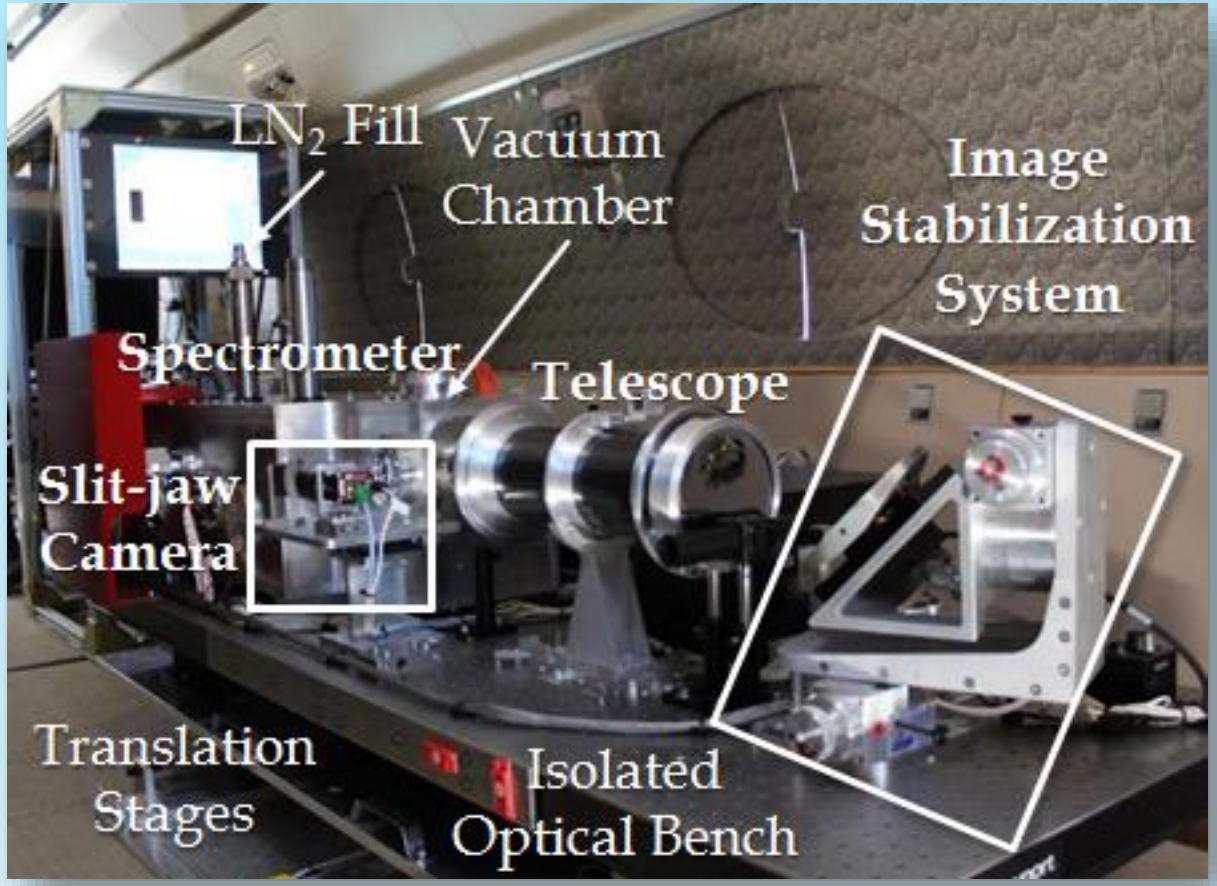
[Predictive Science]

AIR-SPEC: MOTIVATIONS AND GOALS

- AIR-Spec is an Airborne InfraRed Spectrometer that flies on the NSF/NCAR Gulfstream-V above the atmosphere during solar eclipses to make coronal observations.
- Flew in the 2017 Great American Eclipse.
- Upgrade AIR-Spec for the 2019 Solar Eclipse off the coast of South America
- In 2019 it will measure mid-IR spectral lines in the corona:
  - Si X, S XI, Fe IX, Mg VIII
  - 1.4-3 μm

[NOAA, 2013]



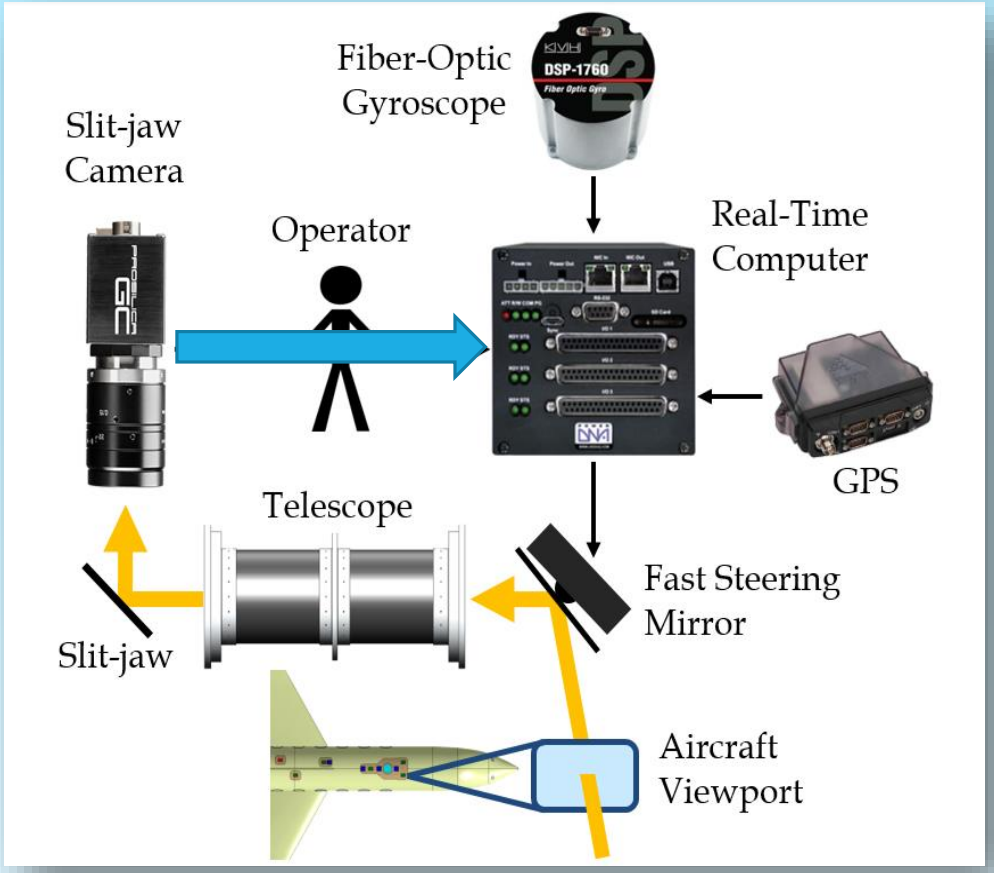
[Samra, 2018]

OUTLINE

- Stabilization Motivation
- Control System
  - Closed Loop
  - PID
- "Fake Sun" Testing Setup
- Modeling
- Lab Testing
- Results
- Conclusion

[Samra, 2018]

2017 STABILIZATION



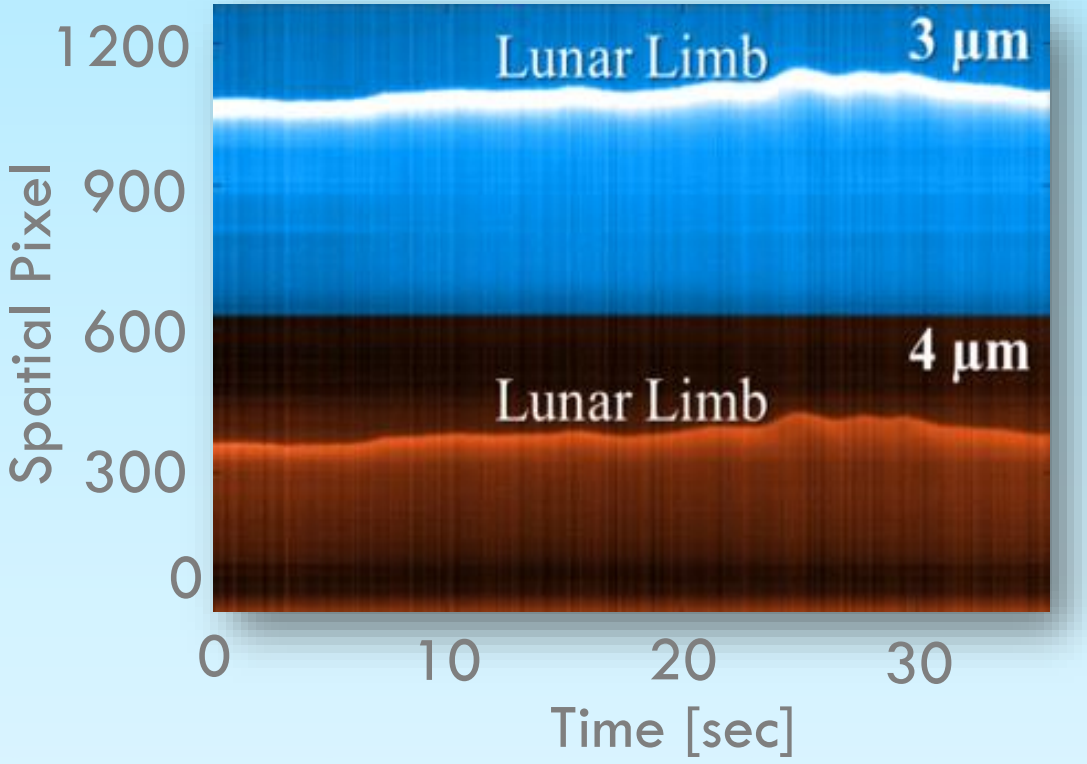
[Samra, 2018]

No Stabilization vs. Open Loop

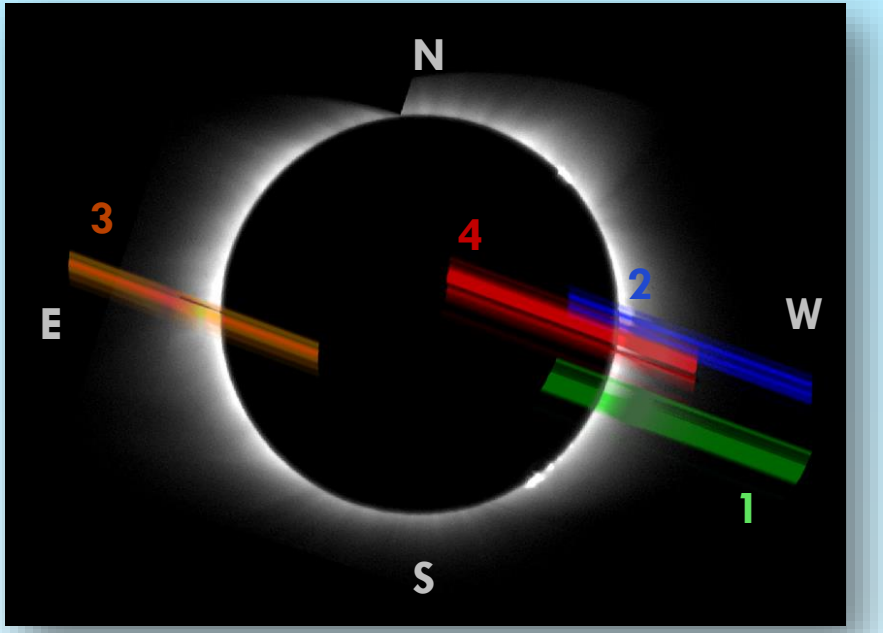
Test Flight: Full Moon Dec 14, 2016

[Samra, 2018]

WHY STABILIZATION NEEDS TO BE IMPROVED



[Samra, 2018]



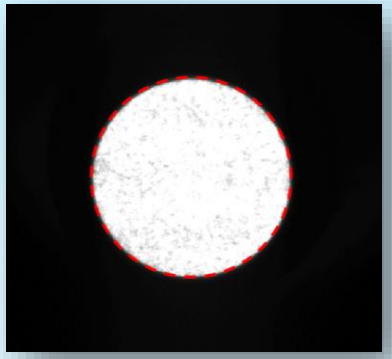
1	West Limb	63.5 sec	953 frames
2	Prominence	41.5 sec	622 frames
3	East Limb	35.7 sec	536 frames
4	Prom./West Limb	52.1 sec	782 frames

OBJECTIVES

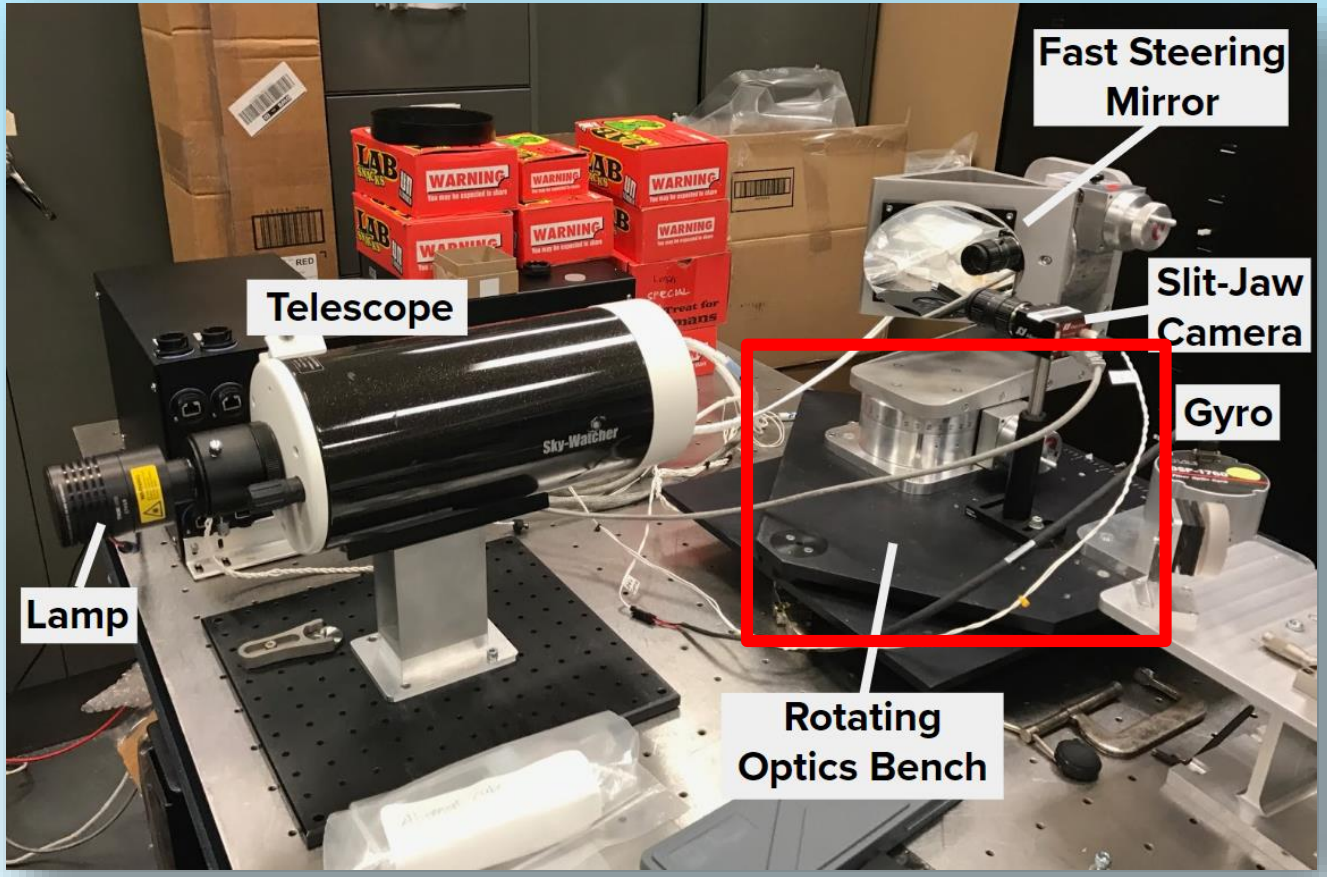
- Develop a proof-of-concept Closed Loop Stabilization System to upgrade AIR-Spec for the 2019 South American Eclipse.
- Find a optimum set of control gains which improve short term stability to under the 4.6 arcsecond Nyquist Limit for a single exposure.
- Increase exposure time from 60 ms to 1 second.
- Assess short and long-term stability for disturbances similar to the airplane's motion during the 2017 solar eclipse.
- Assess and improve response to setpoint changes.

METHODS/ TESTING SETUP

- Hardware Components:
  - Fast Steering Mirror
  - Rotation Optics Bench
  - Fiber Optic Gyroscope
  - Telescope
  - Lamp
  - Slit-Jaw Camera
  - Real Time Computer
- Other
  - Live Plotter
  - C Code
  - Plane Imitator

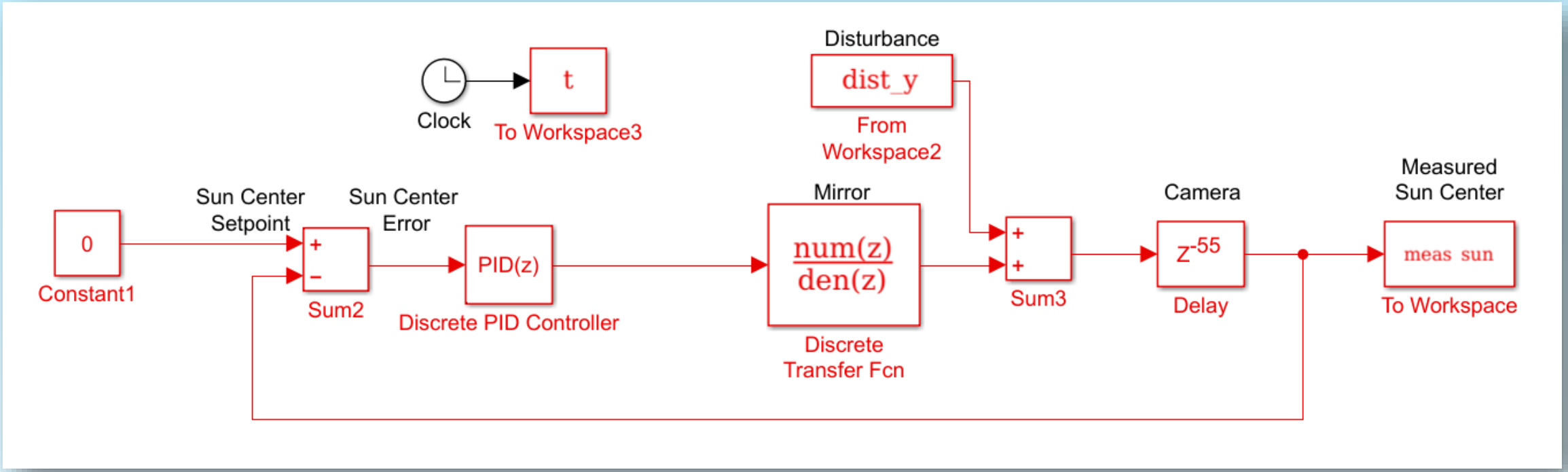


"Fake Sun" Testing Setup



MODELING

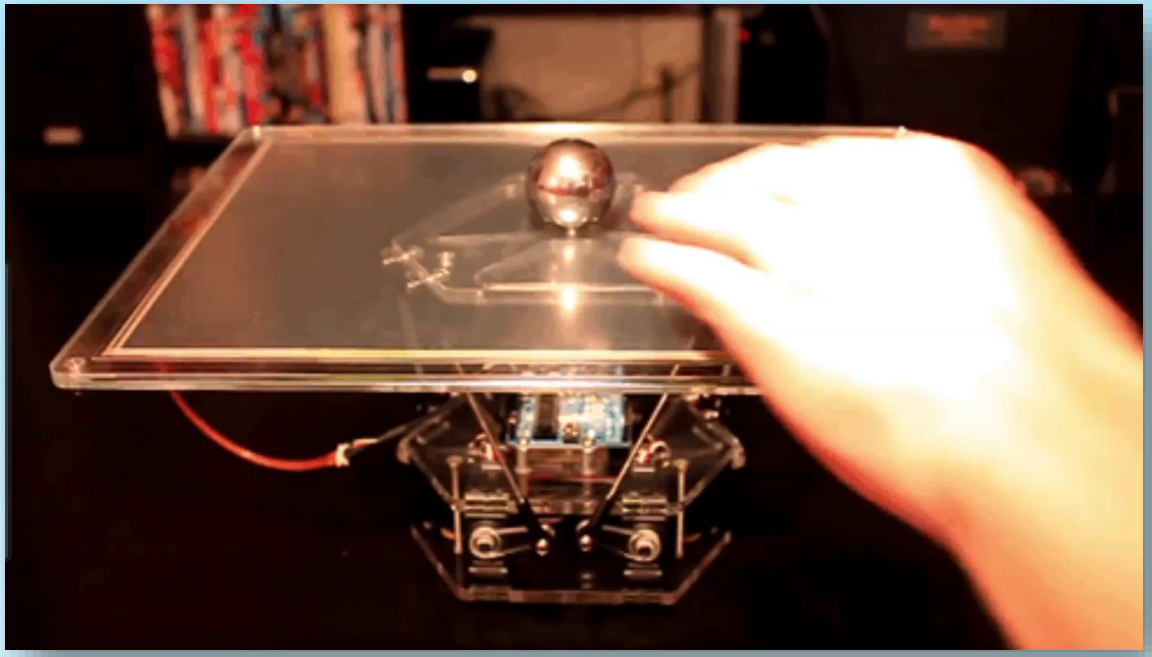
- Simulink Versions
- C



WHAT IS PID? & EXAMPLES

- P – Proportional
- I – Integral
- D – Derivative
- Frequency Equation

$$H(z) = P + IT_S \frac{1}{z-1} + D\frac{1}{T_S}\frac{z-1}{z}$$



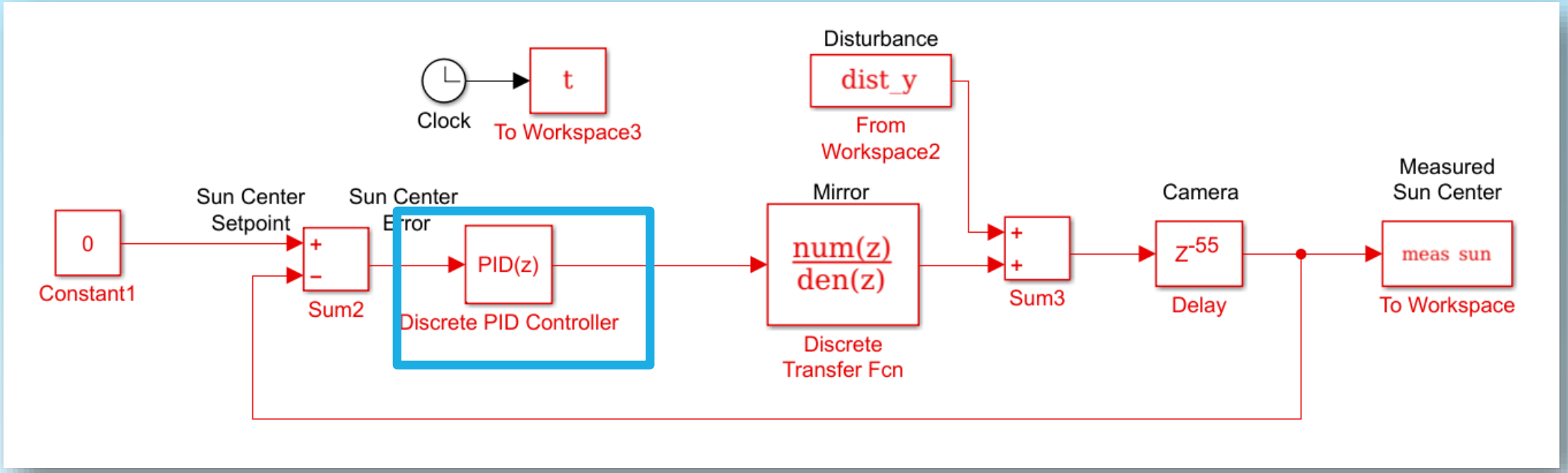
[Shabalin, 2014]

- Second Order Difference Equation

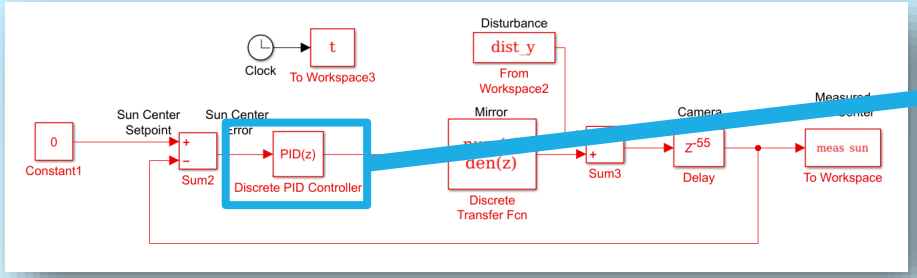
$$x(k) = b_0 e(k) + b_1 e(k-1) + b_2 e(k-2) - a_1 x(k-1) - a_2 x(k-2)$$

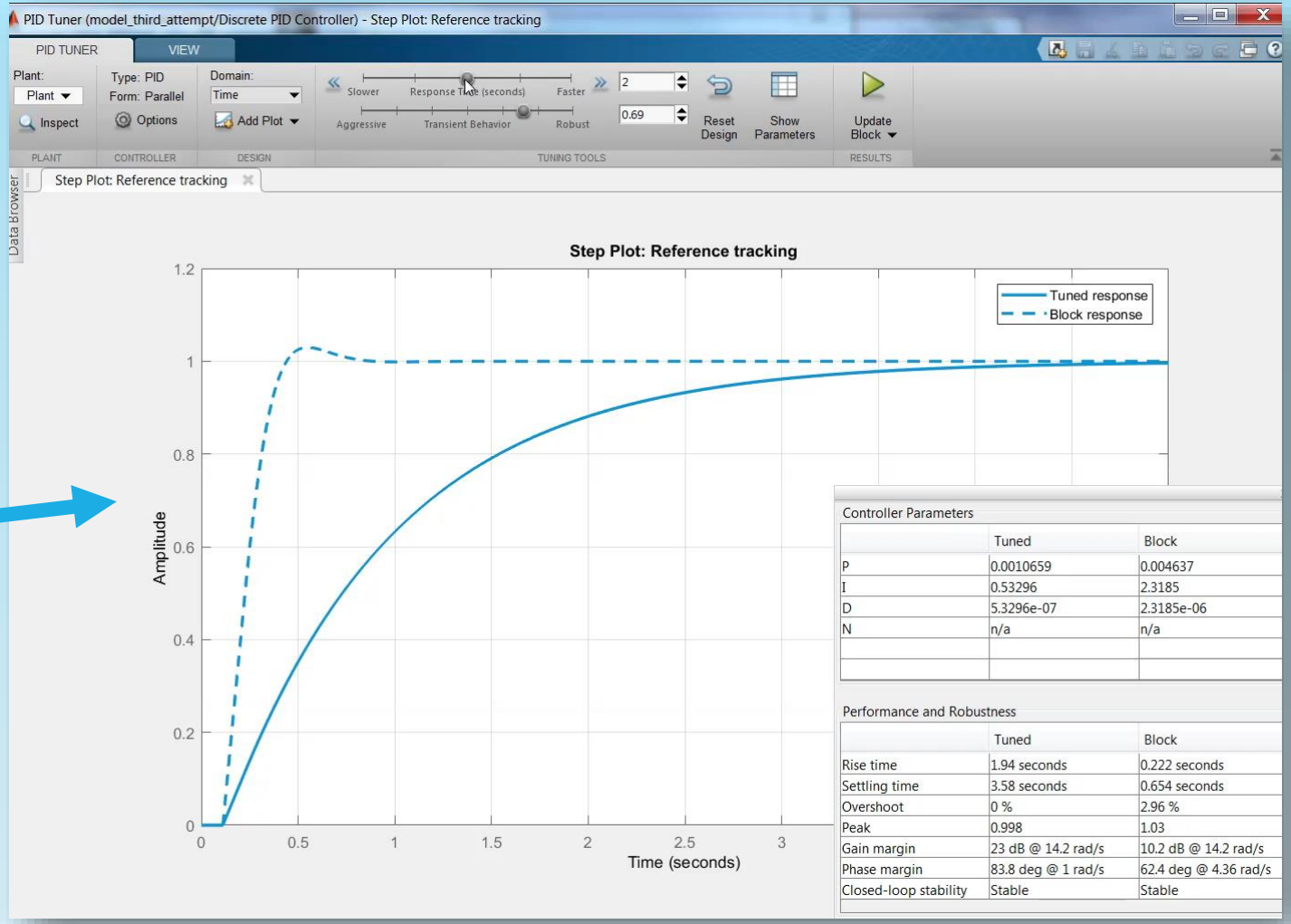
PID TUNING

- Matlab Simulink – 1D Model

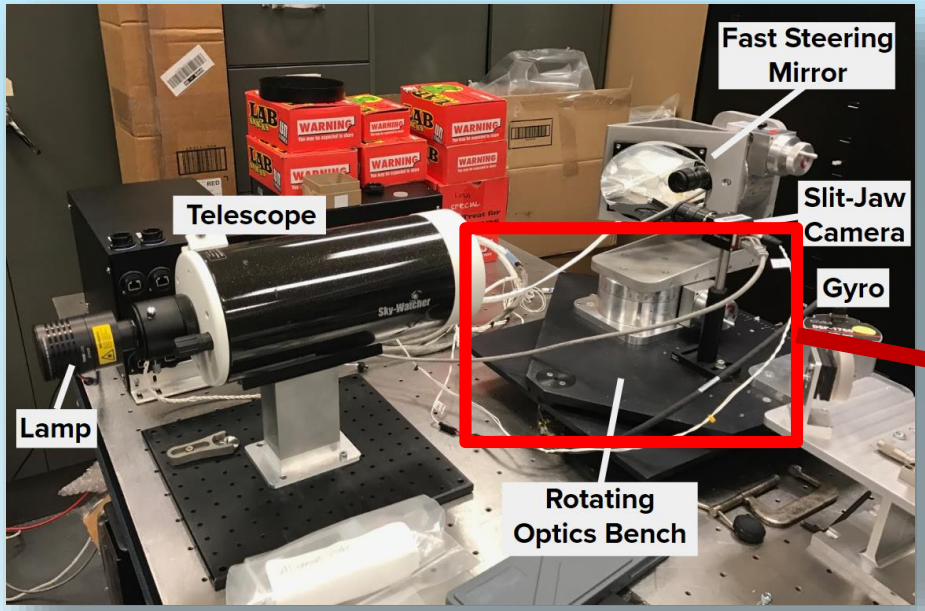


PID TUNING

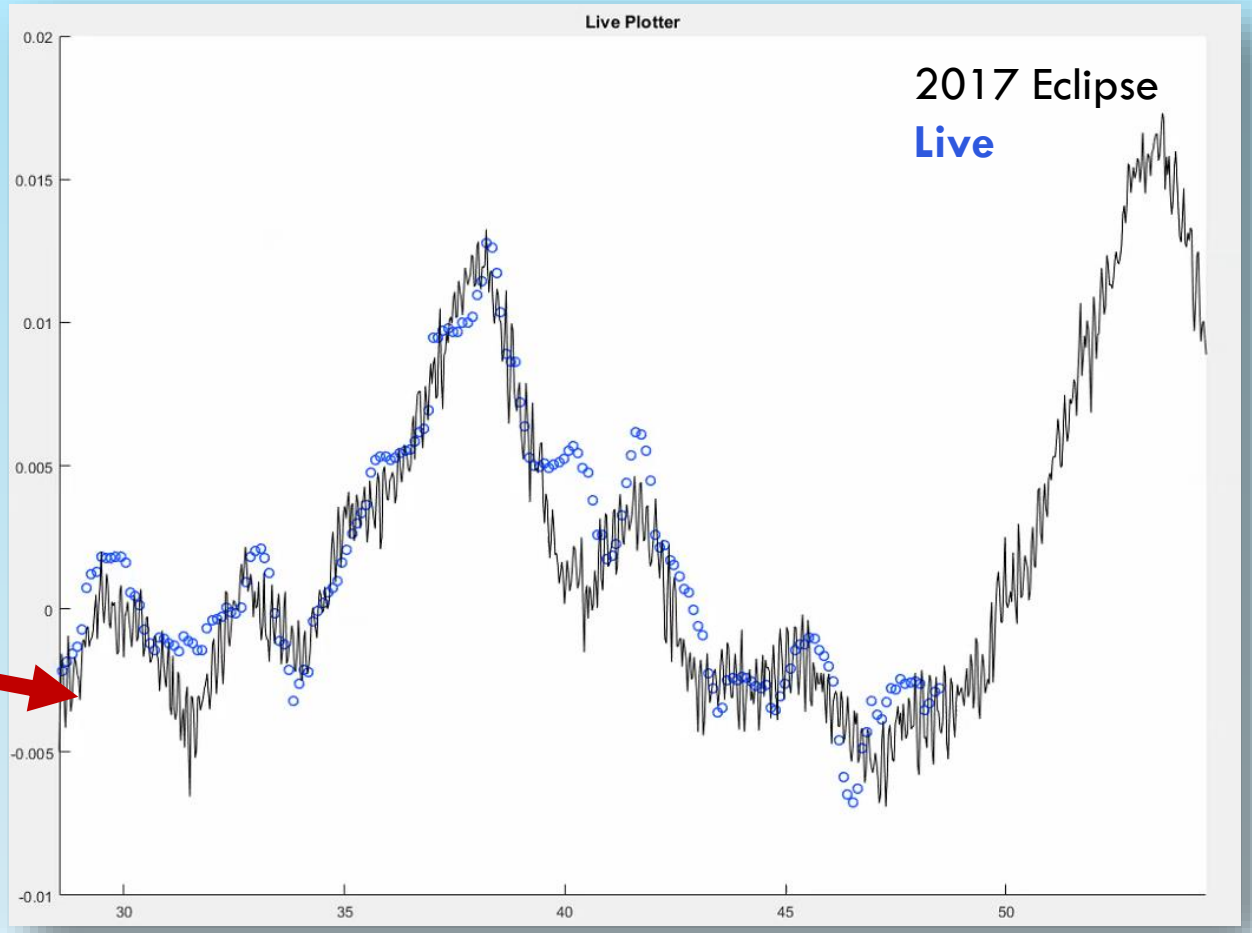

Clock
t
To Workspace3
Disturbance
dist_y
From Workspace2
Sun Center Setpoint
Sun Center Error
Mirror
Camera
Measured
0
Constant1
Sum2
PID(z)
Discrete PID Controller
den(z)
Discrete Transfer Fcn
Sum3
z-55
Delay
meas sun
To Workspace


PID Tuner (model_third_attempt/Discrete PID Controller) - Step Plot: Reference tracking
PID TUNER
VIEW
Plant:
Plant
Inspect
Type: PID
Form: Parallel
Options
Domain:
Time
Add Plot
Slower
Response Time (seconds)
Faster
Aggressive
Transient Behavior
Robust
Reset Design
Show Parameters
Update Block
PLANT
CONTROLLER
DESIGN
TUNING TOOLS
RESULTS
Data Browser
Step Plot: Reference tracking
Step Plot: Reference tracking
Tuned response
Block response
Amplitude
Time (seconds)
Controller Parameters
Tuned
Block
P
0.0010659
0.004637
I
0.53296
2.3185
D
5.3296e-07
2.3185e-06
N
n/a
n/a
Performance and Robustness
Tuned
Block
Rise time
1.94 seconds
0.222 seconds
Settling time
3.58 seconds
0.654 seconds
Overshoot
0 %
2.96 %
Peak
0.998
1.03
Gain margin
23 dB @ 14.2 rad/s
10.2 dB @ 14.2 rad/s
Phase margin
83.8 deg @ 1 rad/s
62.4 deg @ 4.36 rad/s
Closed-loop stability
Stable
Stable

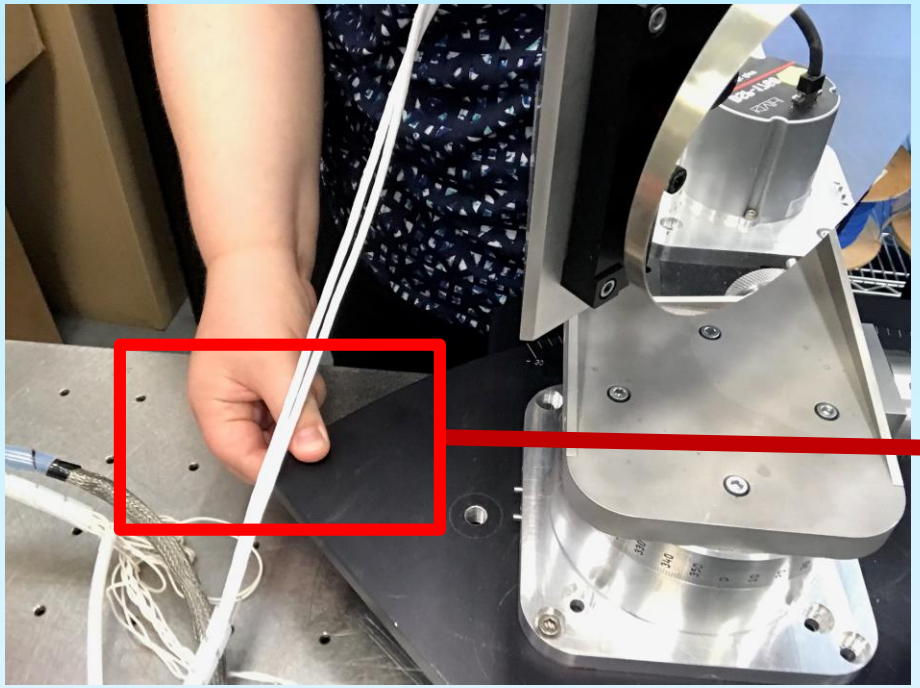
LIVE PLOTTER



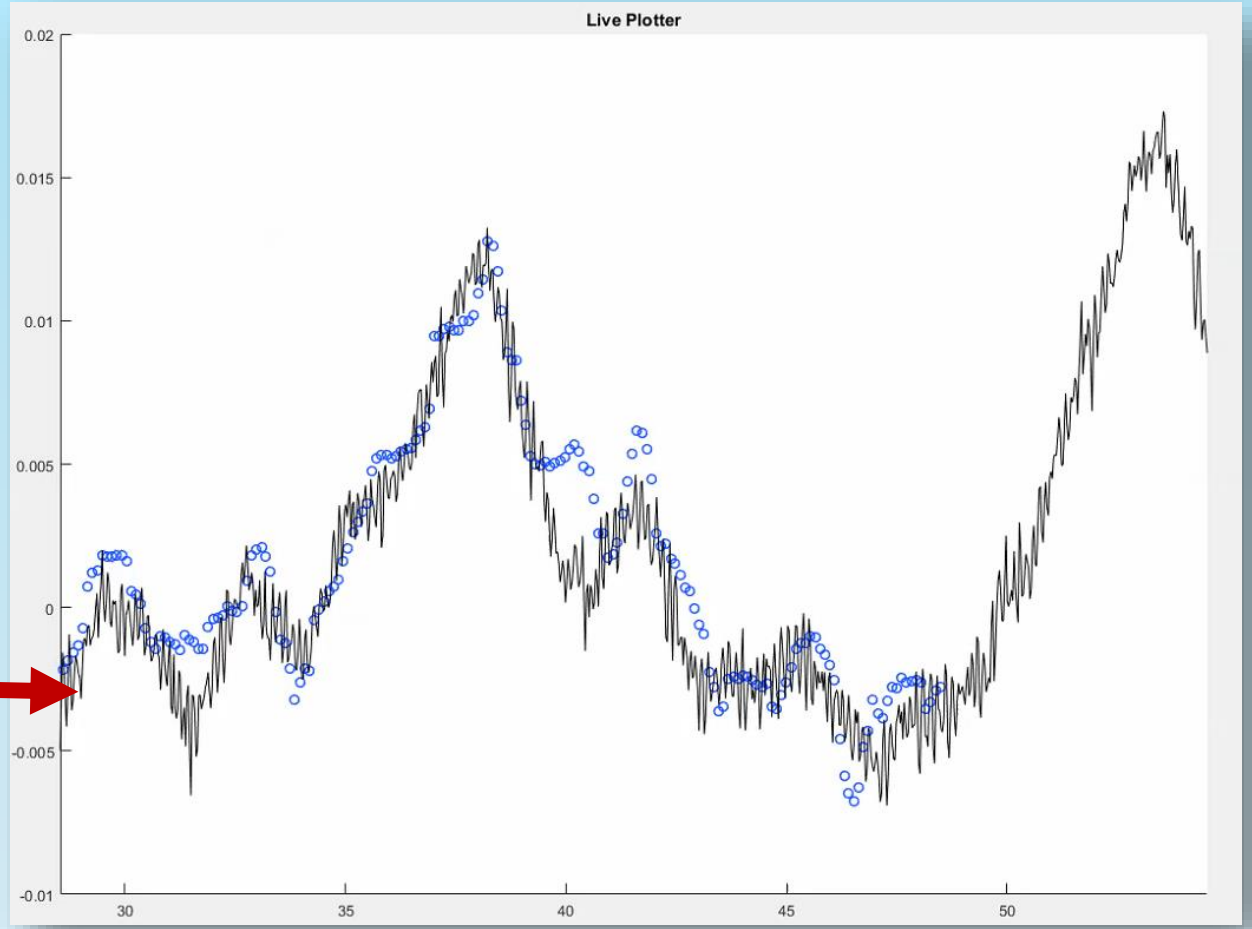
Real Time Motion



LIVE PLOTTER



Real Time Motion

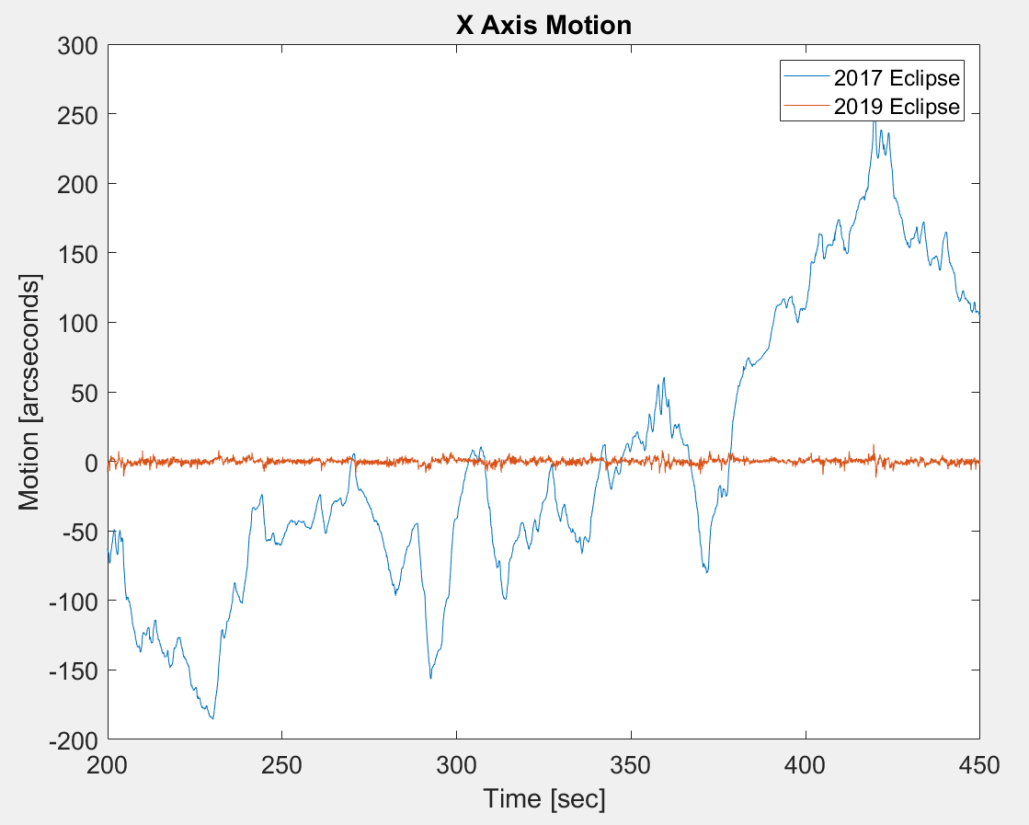


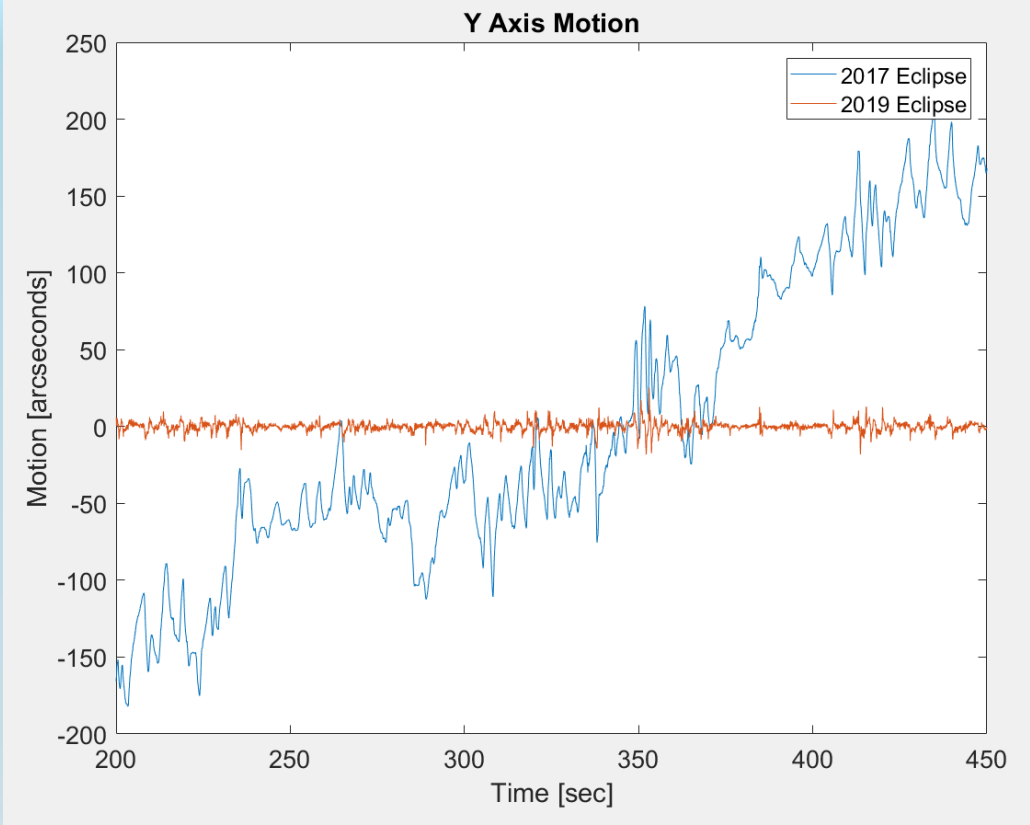
[Druckmuller, 2009]

RESULTS

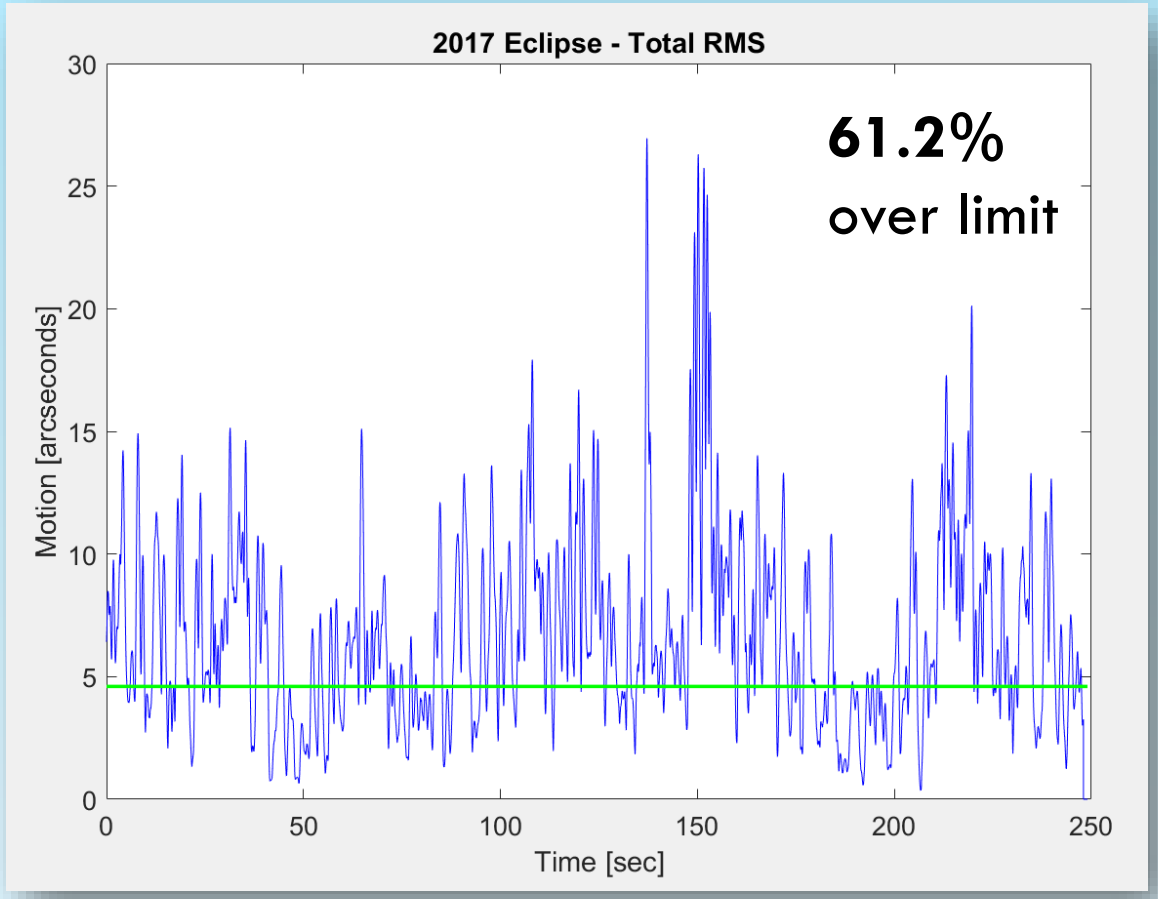
OPTIMIZED PID GAINS

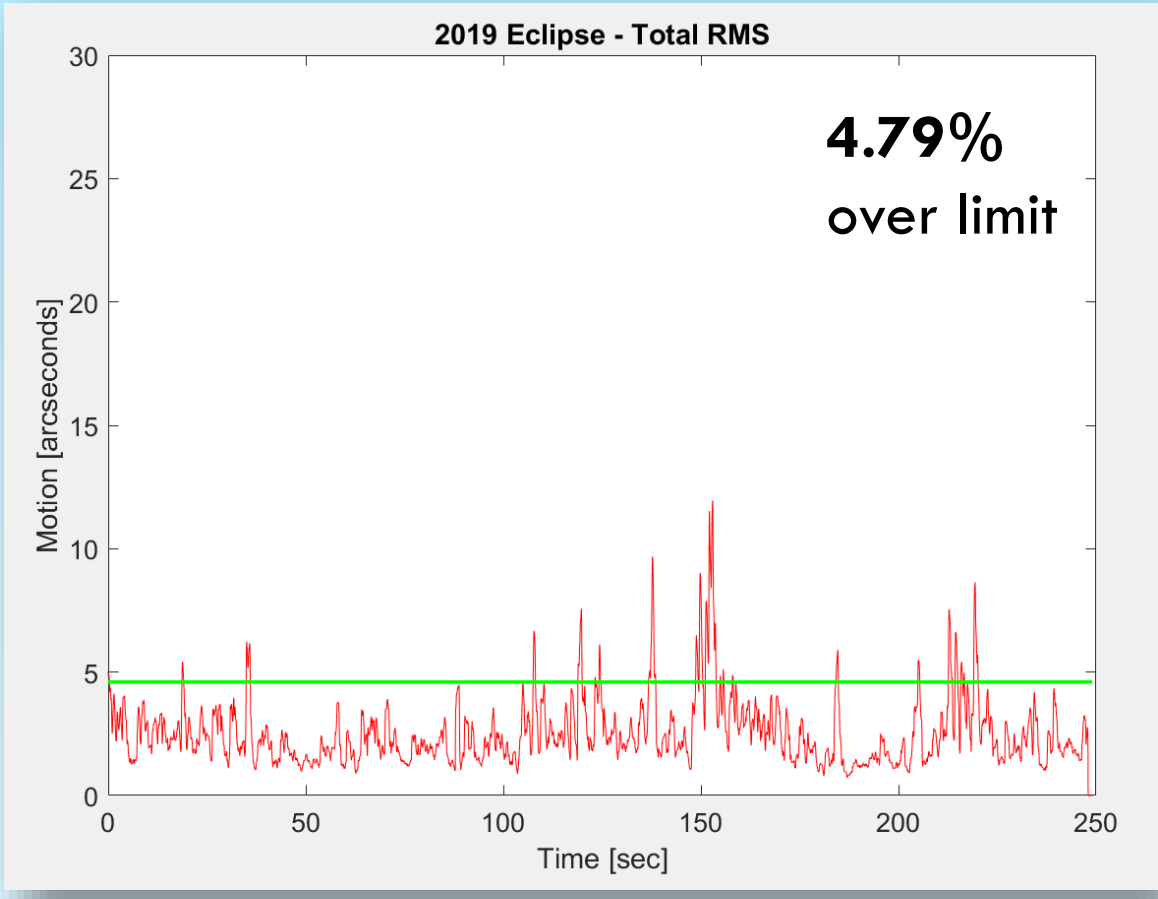
- Max exposure time without smearing.
- Pointing error over an observation.



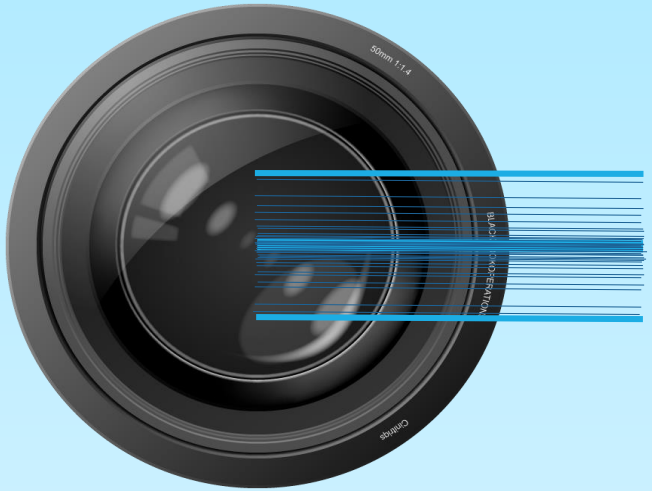


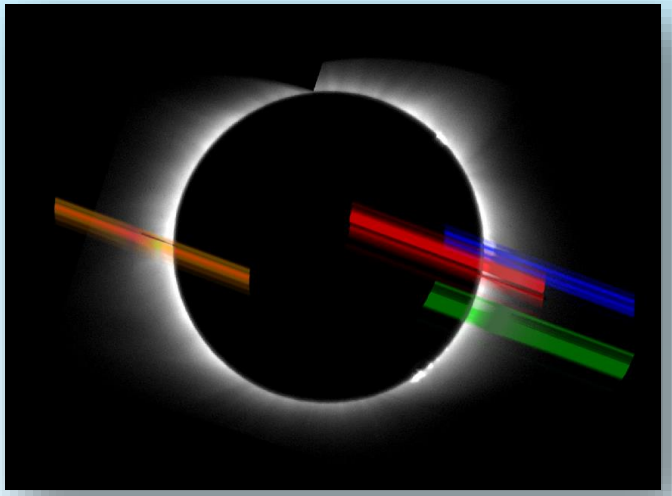
SHORT TERM STABILITY - ONE SEC EXPOSURE RMS





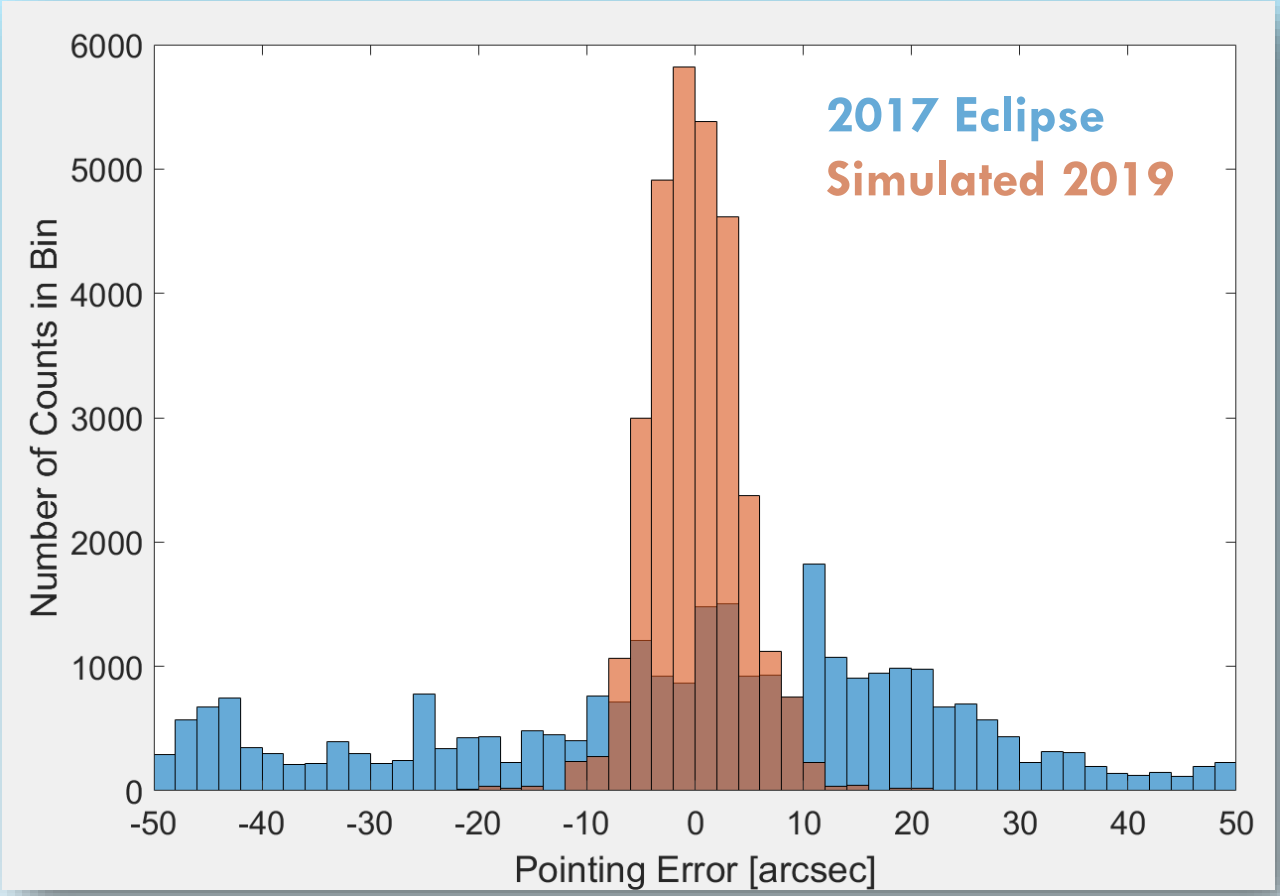
LONG-TERM STABILITY



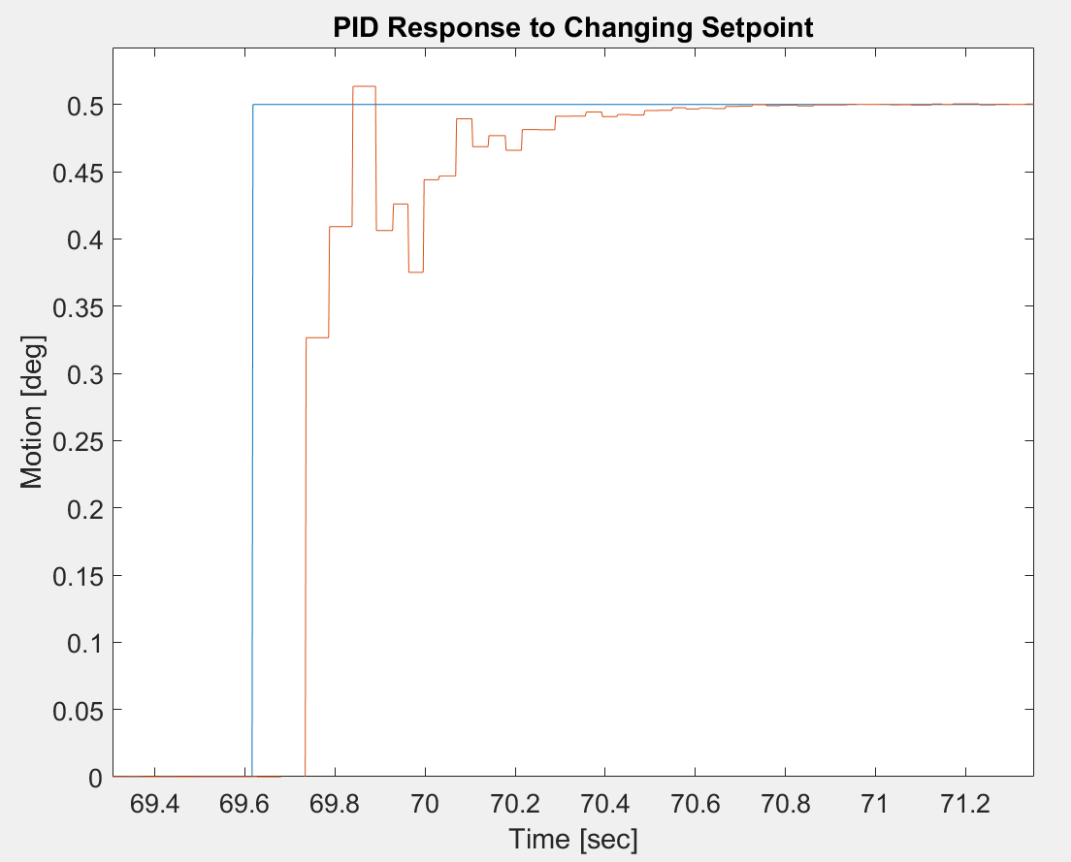


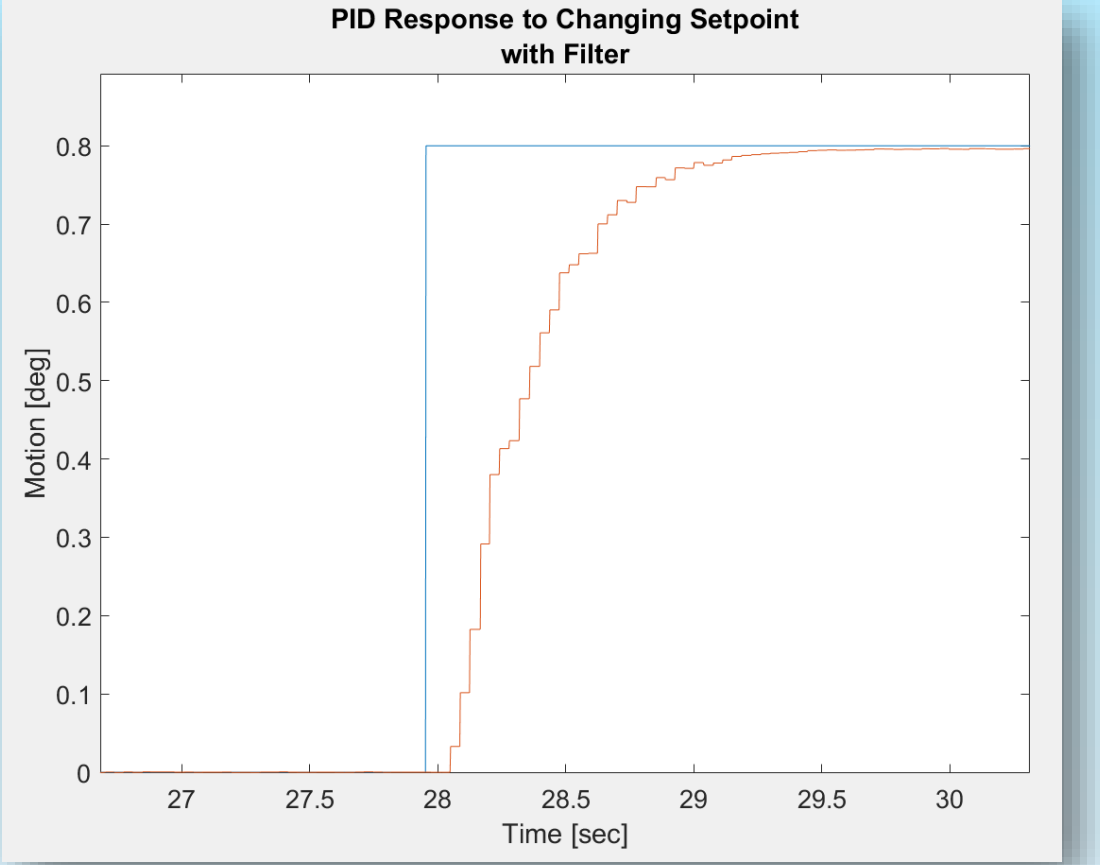
[Samra, 2018]

Perpendicular 60 sec Interval



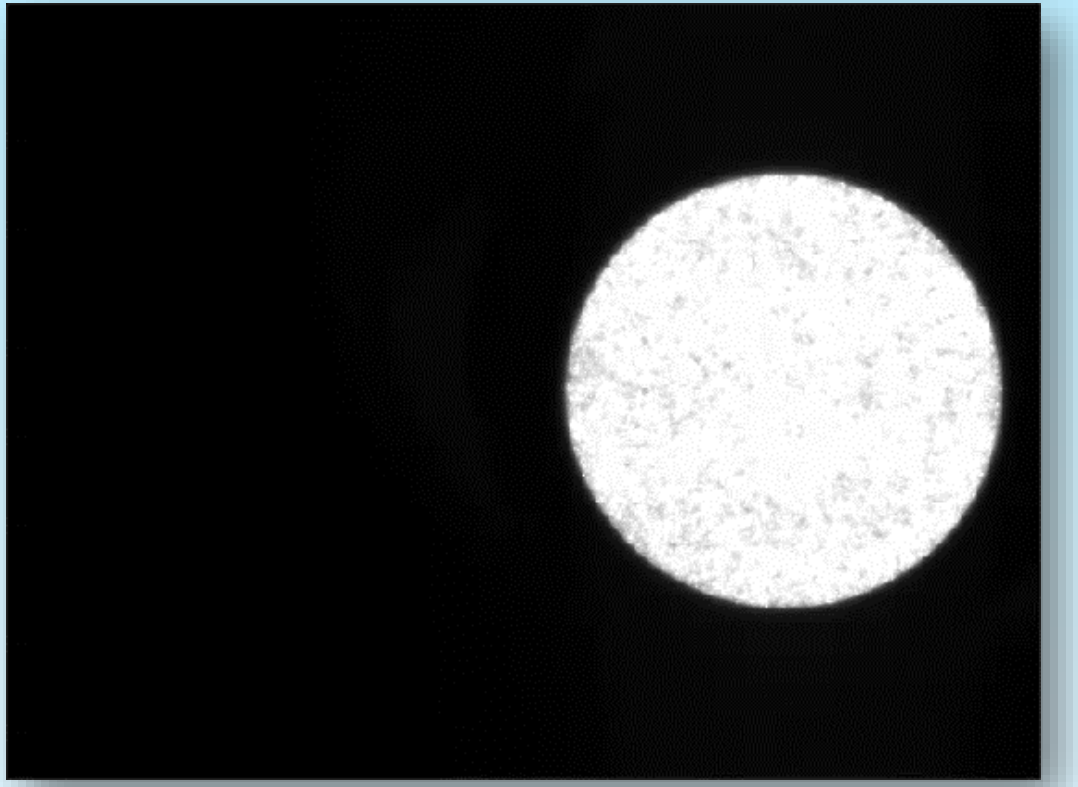
CHANGING SETPOINT RESULTS



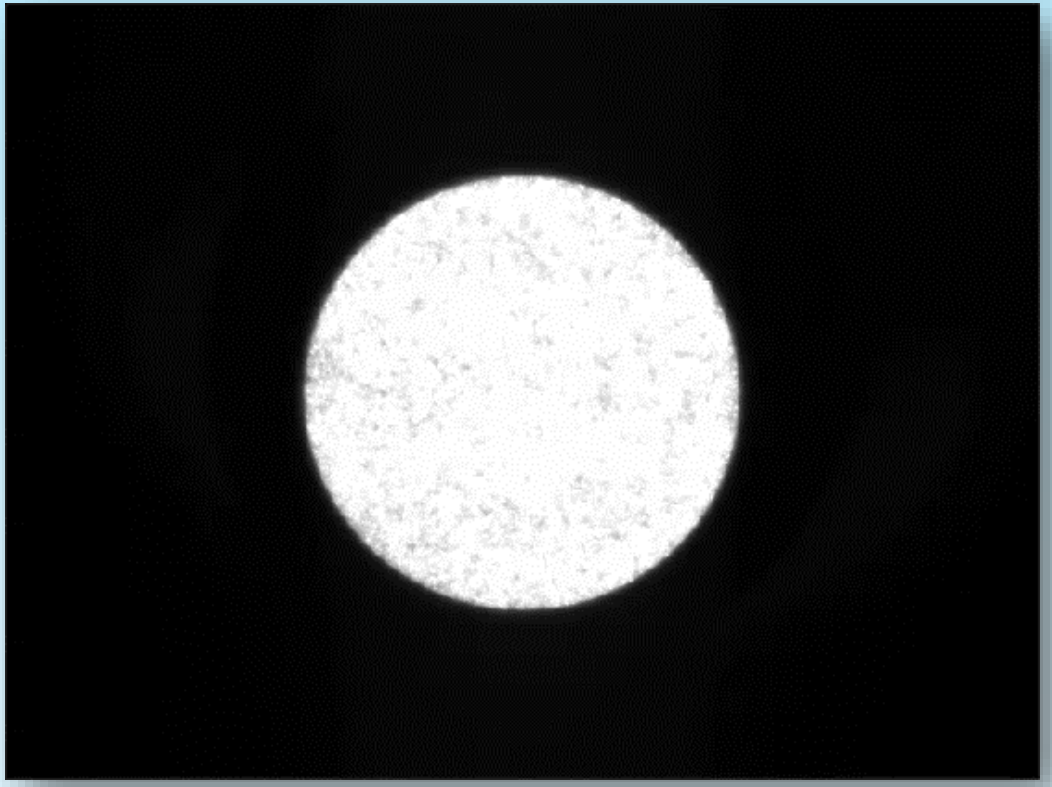


CHANGING SETPOINT RESULTS

No Setpoint Filter

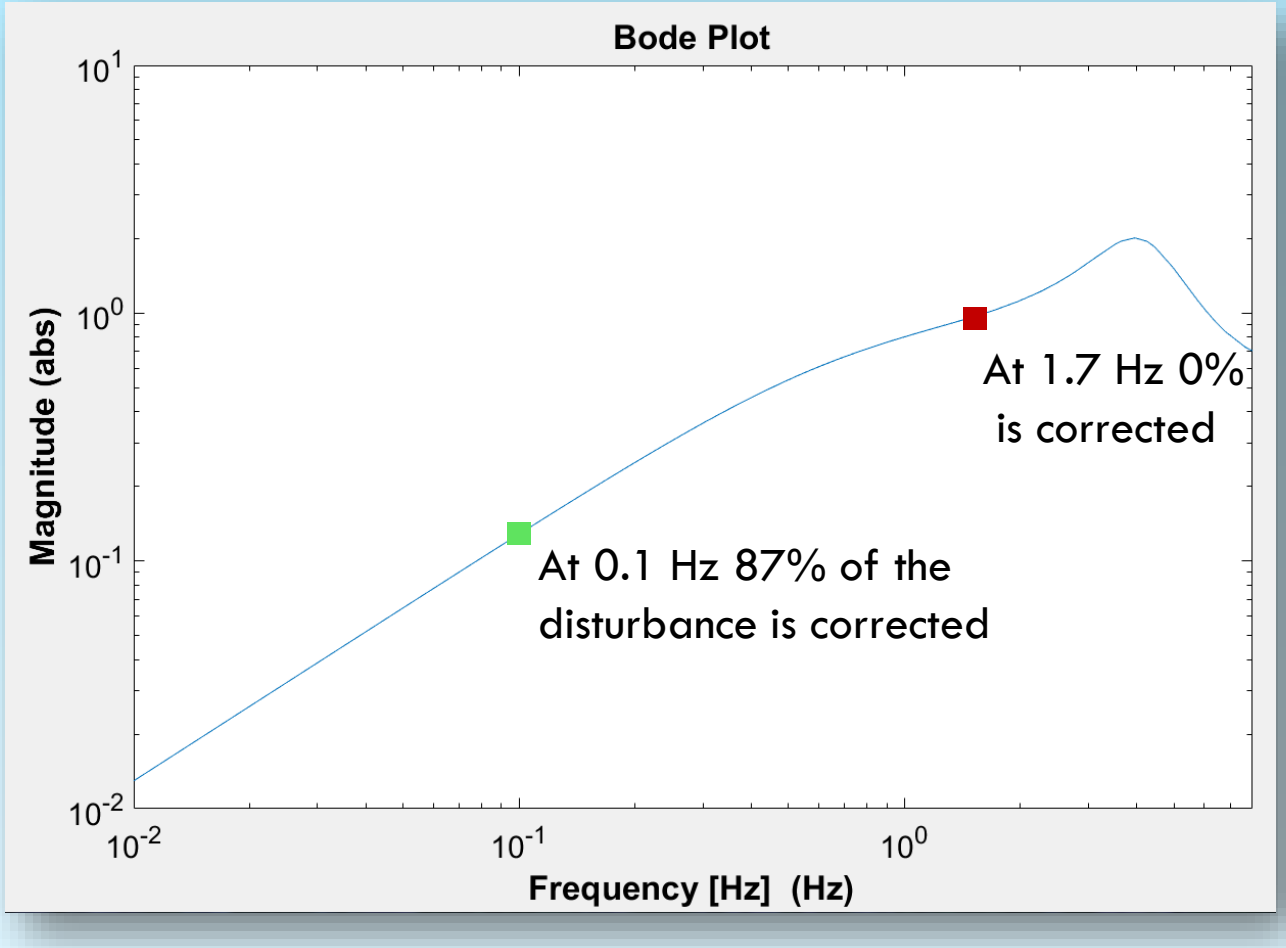


With Setpoint Filter



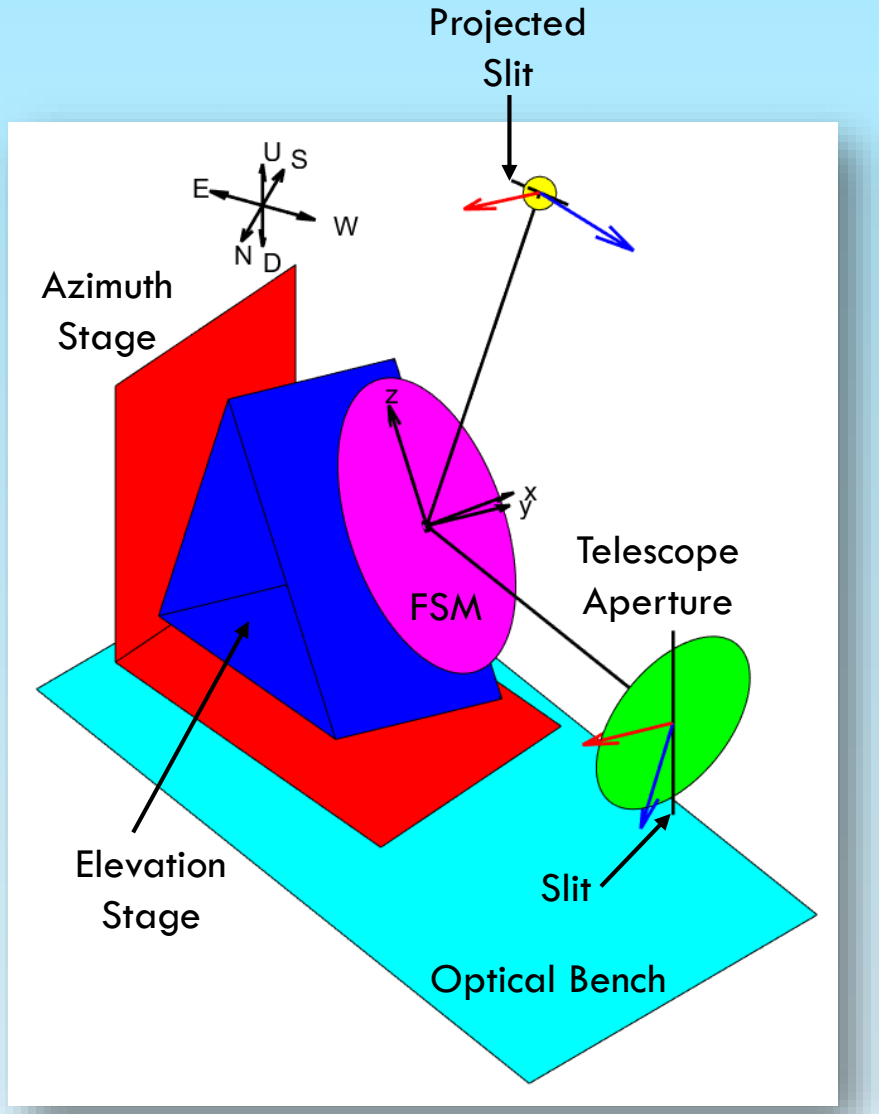
LIMITATIONS OF THE PID CONTROLLER

- There is a 100 ms time delay between the camera and the real-time computer.
- By the time the image error gets to the mirror it's 'stale'.
- This limits the performance at high frequencies.



FUTURE WORK

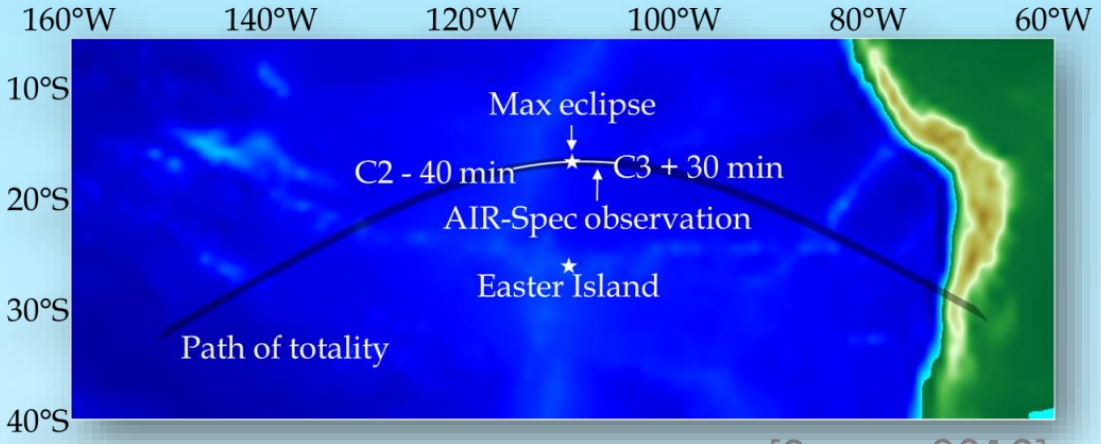
- 2D system model
  - More complicated geometry
  - Motion on three axes
  - More complicated relationship between mirror and image
- Predicting delayed data before it exists
- Minimizing camera delay



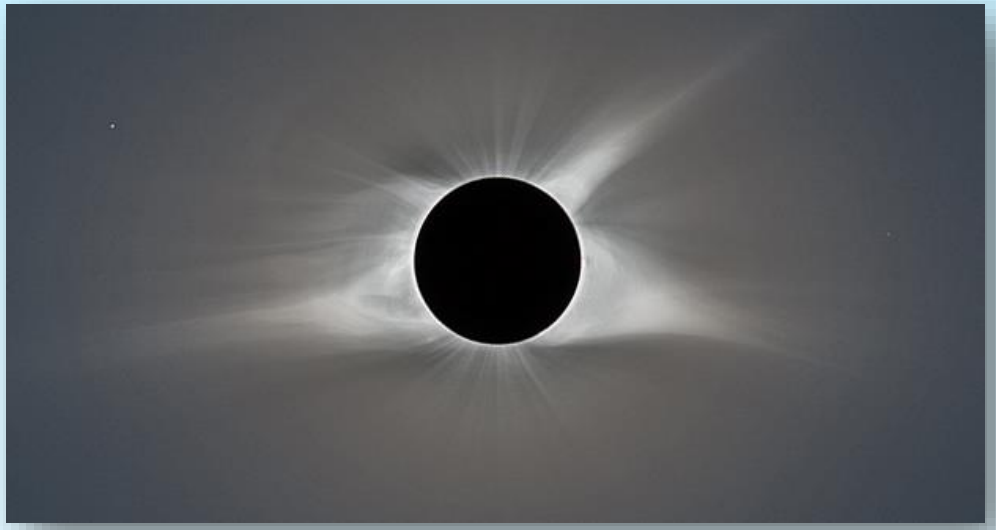
CONCLUSIONS

- A proof-of-concept Closed Loop stabilization system was implemented to upgrade AIR-Spec for the 2019 Eclipse off the coast of South America.
- The best set of PID gains resulted in a total root mean square (RMS) of 94% under the 4.6 arcsecond Nyquist limit for an exposure time of 1 second.
- The PID upgrades will be utilized during the upcoming test flight in order to further refine the controller for the 2019 eclipse.

Flight Path, 2019



[Samra, 2018]



[Schneider, 2018]

ACKNOWLEDGEMENTS

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[Schneider, 2018]

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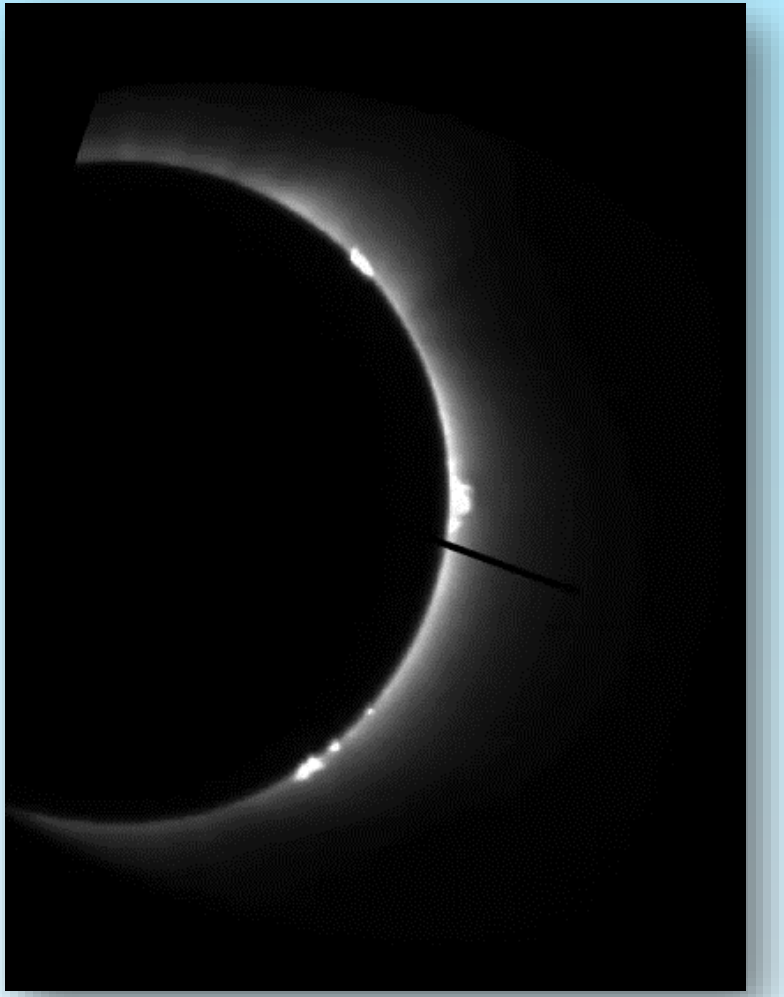
BACKUP

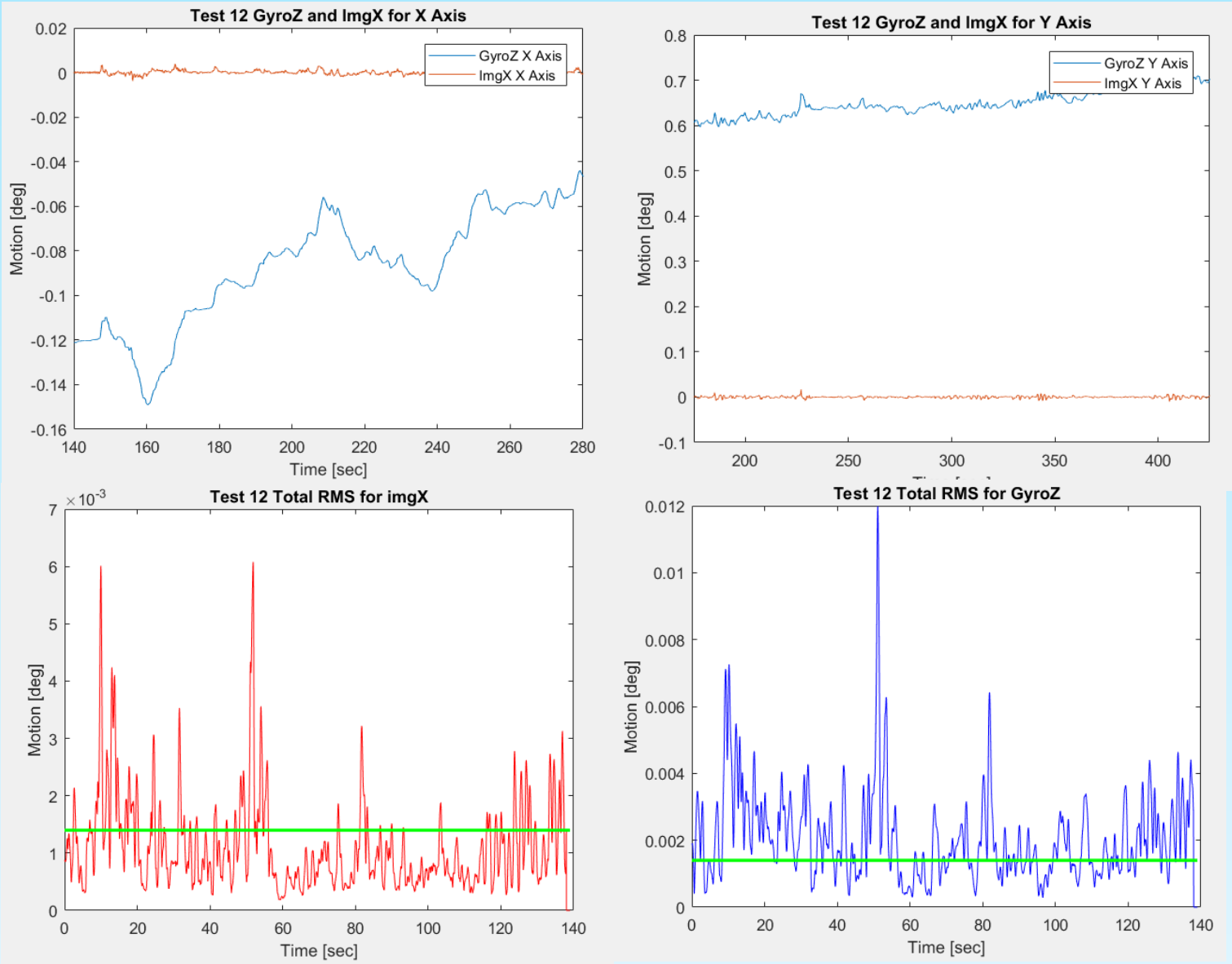
OPEN LOOP VS. CLOSED LOOP



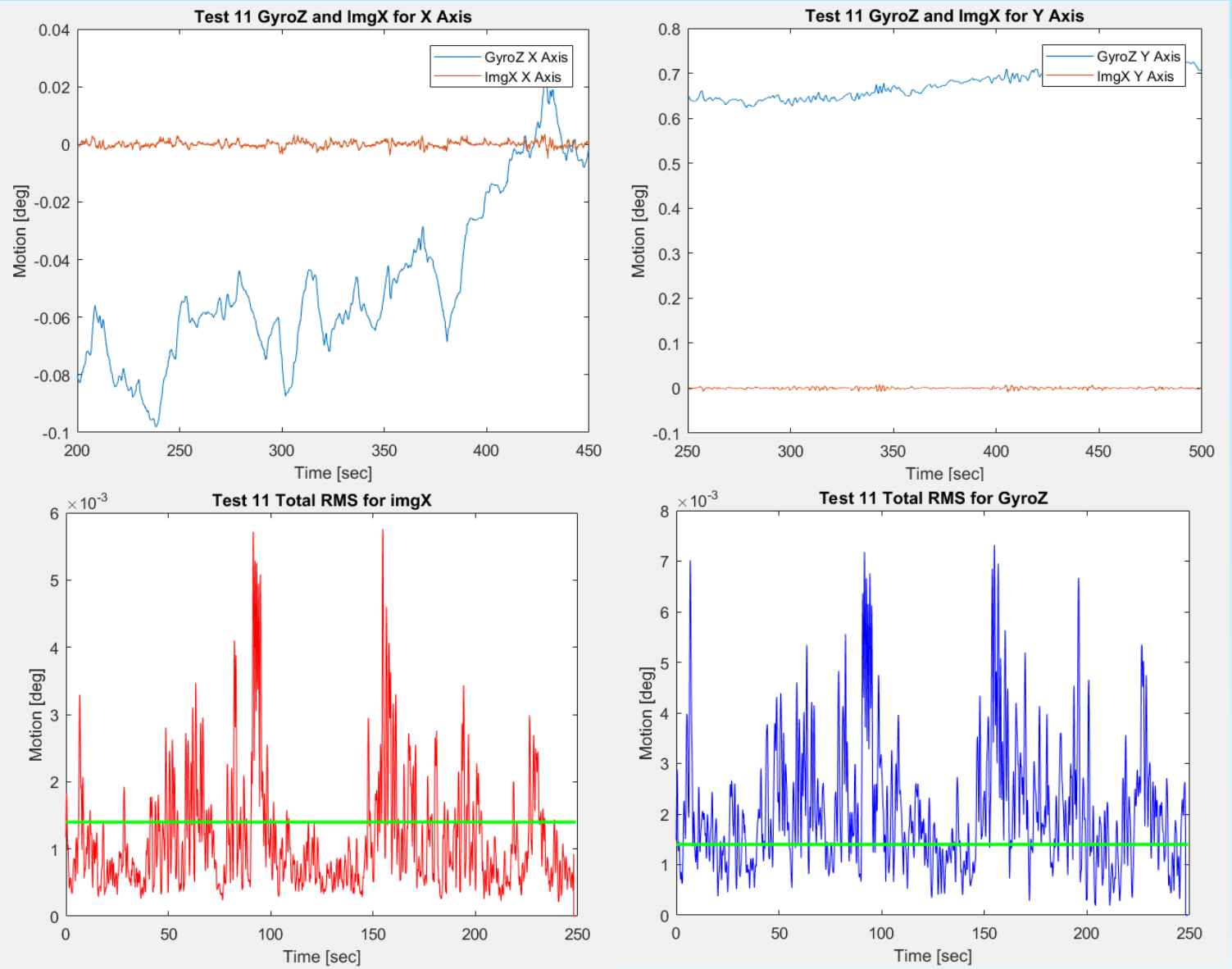
Test 1


Test 1 GyroZ and ImgX for X Axis
GyroZ X Axis
ImgX X Axis
Motion [deg]
Time [sec]
Test 1 GyroZ and ImgX for Y Axis
GyroZ Y Axis
ImgX Y Axis
Motion [deg]
Time [sec]
Test 1 Total RMS for imgX
×10^-3
Motion [deg]
Time [sec]
Test 1 Total RMS for GyroZ
×10^-3
Motion [deg]
Time [sec]

Test 12

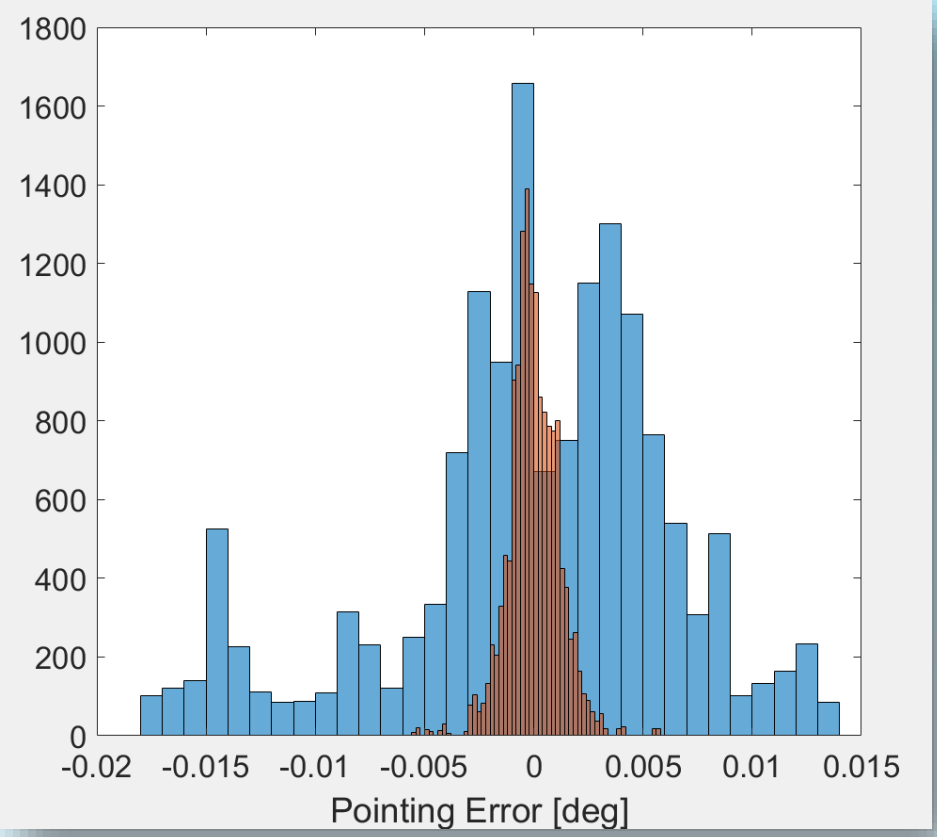

Test 12 GyroZ and ImgX for X Axis
GyroZ X Axis
ImgX X Axis
Motion [deg]
Time [sec]
Test 12 GyroZ and ImgX for Y Axis
GyroZ Y Axis
ImgX Y Axis
Motion [deg]
Test 12 Total RMS for imgX
Motion [deg]
Time [sec]
Test 12 Total RMS for GyroZ
Motion [deg]
Time [sec]

Test 11


Test 11 GyroZ and ImgX for X Axis
GyroZ X Axis
ImgX X Axis
Motion [deg]
Time [sec]
Test 11 GyroZ and ImgX for Y Axis
GyroZ Y Axis
ImgX Y Axis
Motion [deg]
Time [sec]
Test 11 Total RMS for imgX
Motion [deg]
Time [sec]
Test 11 Total RMS for GyroZ
Motion [deg]
Time [sec]

30 SEC AND 1 SEC METRICS

Perpendicular 30 sec Interval



Perpendicular 60 sec Interval