First sub-picometer wavefront control demonstration using a 20-bit DM controller and the Zernike wavefront sensor at HCIT

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Controller development motivation

The DM controller defines key DM performance such as resolution and stability.

1) **Actuator resolution:** HabEx allocation for resolution is 2.5 pm and 1.9 pm for LUVOIR Mennesson et al, table 2. CGI Requirement is 15 pm resolution

1) **Actuator stability:** We assumed 10 pm/hrHabEx report: “expected contrast performance” is 1.45x10^-11 @ 0.45um would imply 5 pm stability. Input for from CTR is 10 pm /15 min

Requirement	Current state of the art	CGI requirement	Expected Habex / HWO	2k HiRes requirement
Resolution	~10 pm (@DST2)	~15 pm	2.5 pm	< 2 pm
Stability	TBD	< 50	< 5	< 10 pm/hr
Actuator count	50 x 50	48 x 48	> 64x64	48x48

2k DM Controller overview

Designed at JPL (E. Bendek PI + Teilch Contractor, Funded by HCIT)

Performance (as tested)

- 2040 channels
- 100% channel yield
- Maximum voltage 125 V
- 20-bit resolution
  ⇒ For 125V, we electrically measured 119μV

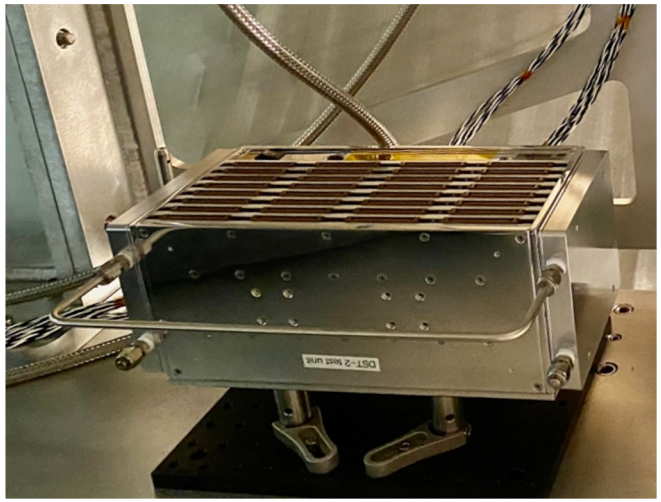
Features

- Vacuum compatible
- USB input
- 24V power supply
- Voltage telemetry and closed loop control
- Thermal, power and pressure telemetry
- Vacuum sensor with interlock
- Water cooled
- 3M 68-pin output connectors

Volume mass and power

- Volume: 12.5” x 6.5” x 5.5”
- Mass: 7 kg
- Power: 33 W in operation

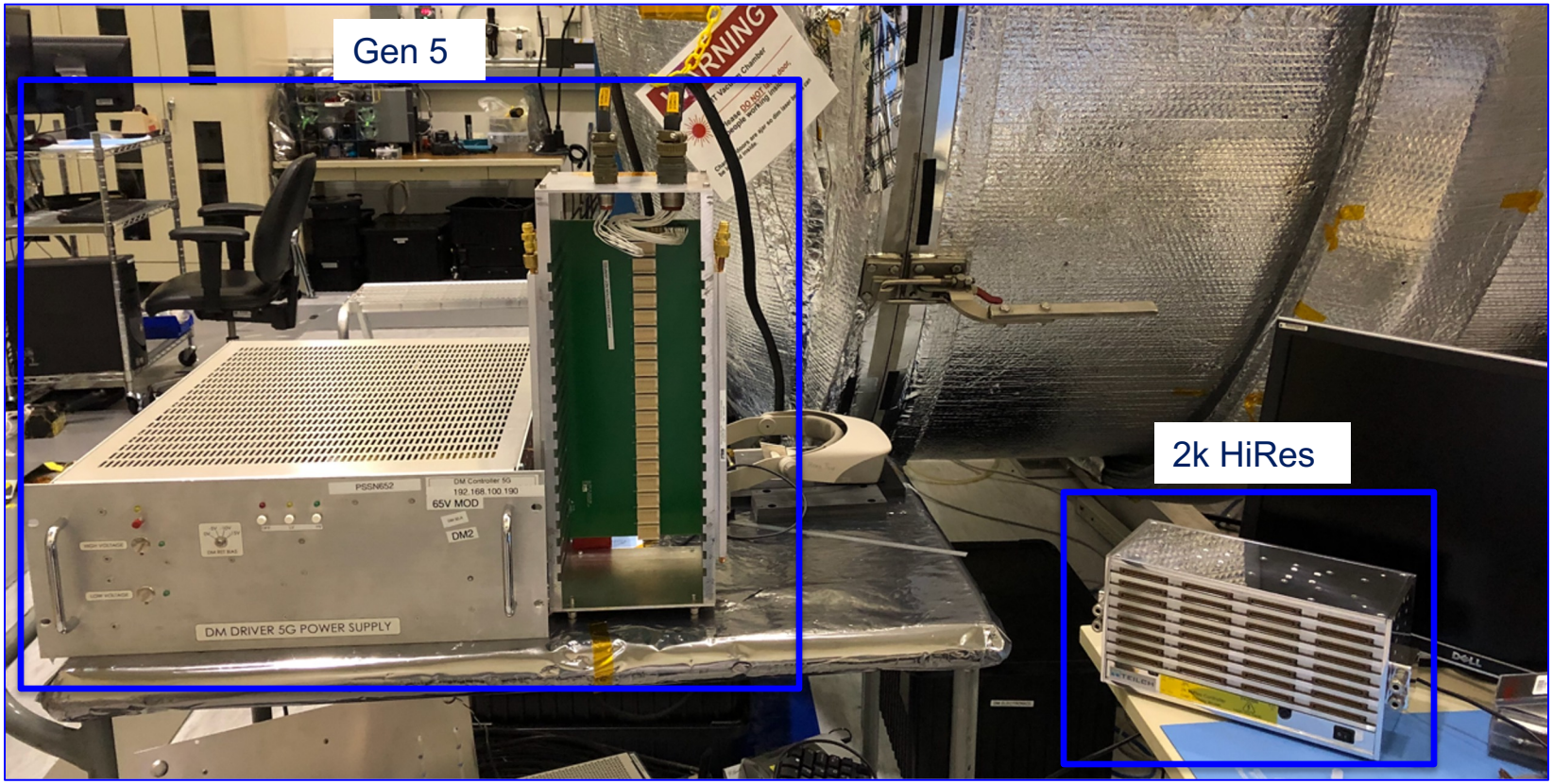
2k DM Controller



2k DM Controller installed in DST 2

2k DM HiRes DM

Dimensional comparison with Gen 5



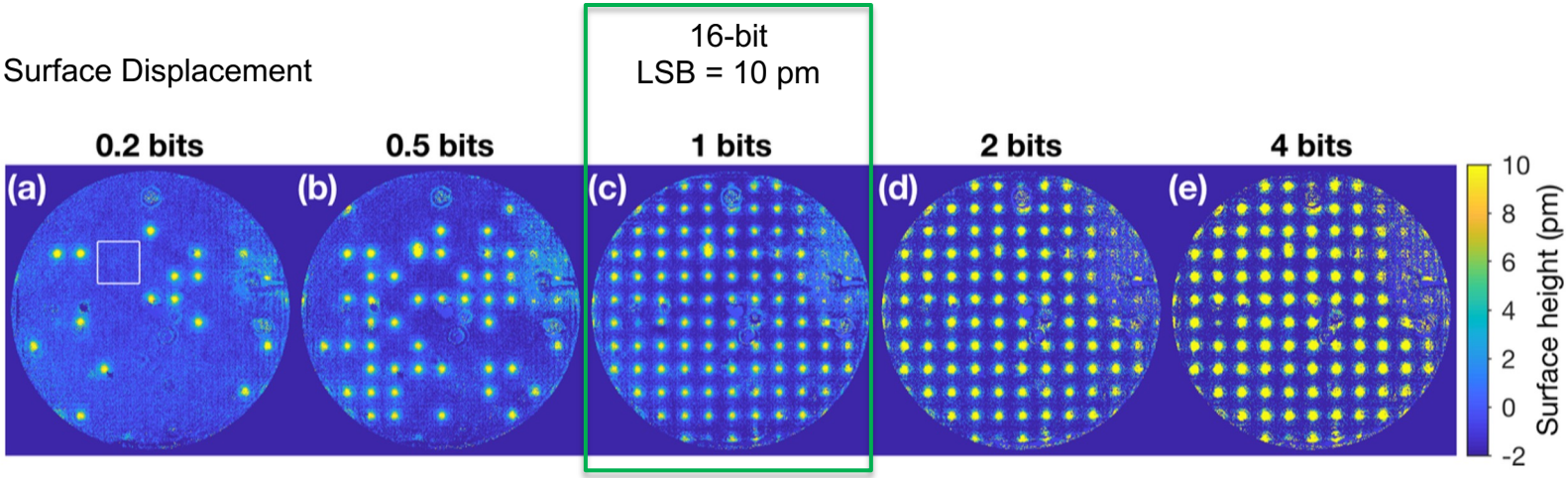
Resolution Gen5: previous state-of-the-art

Gen 5 is the workhorse 16-bit controller at HCIT

- Measured pokes of 92 actuators on a BMC 2K DM
- Poke amplitude of least significant bit @16 bit is about 10 pm
- Attempting to command less than that the LSB results in rounding and randome actuator moving 10 pm

Gen 5: Does not meet Habex / HWO requirements

Poke amplitude	
Mean surface motion:	10 pm
Estimated resolution	**10 pm**



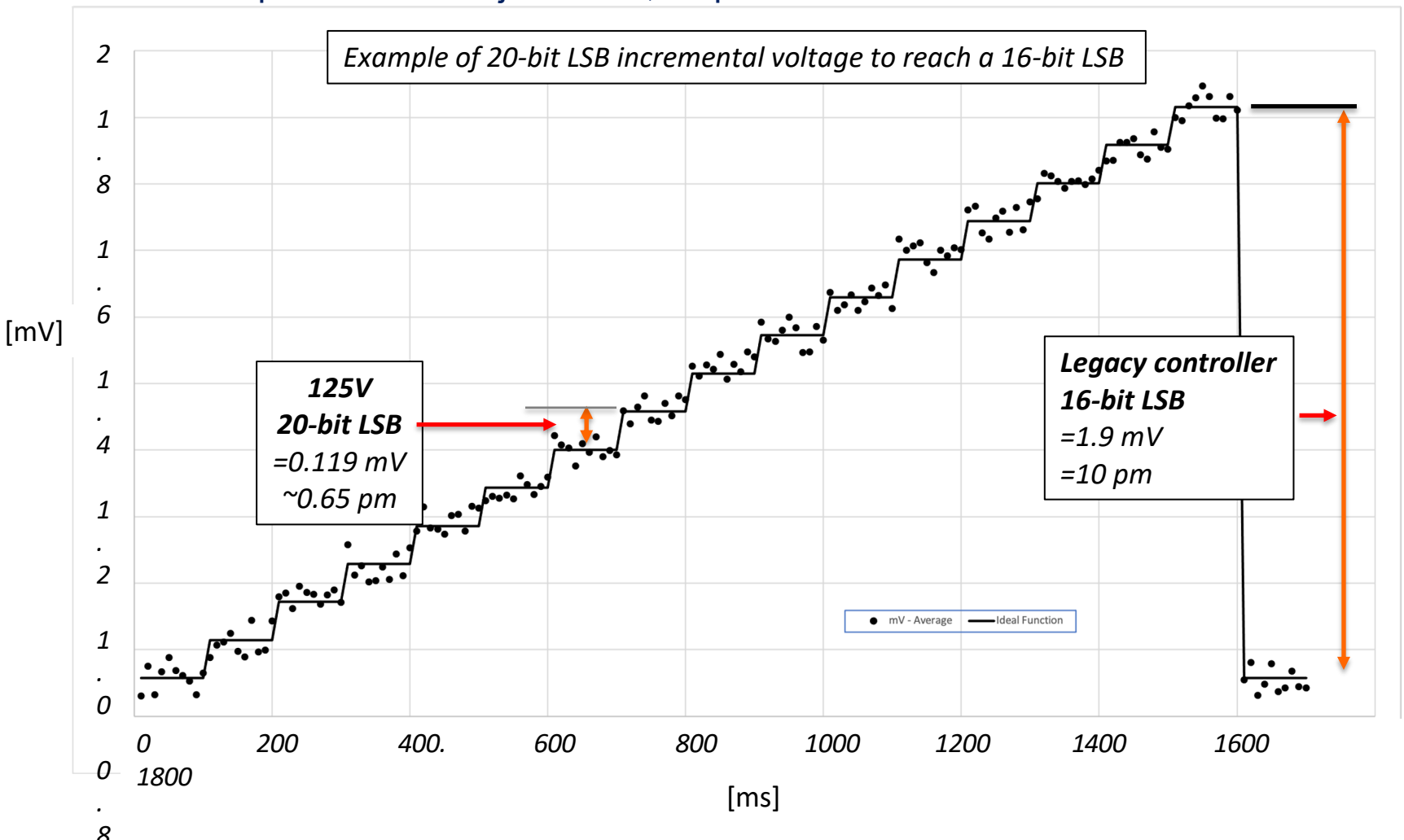
From Ruane et al 2020.

Measured DM surface height difference after changing the voltage of a grid of actuators by (a) 0.2, (b) 0.5, (c) 1, (d) 2, and (e) 4 bits. (a) and (b) show that a proportional number of actuators respond when the command is less than 1 bit, which confirms that the DM actuators were moving by the minimum possible height change (~10 pm) corresponding to the least significant bit of the DM electronics

2k DM 20-bit implementation

Resolution is key to meet HWO requirements

- High-speed Duty Cycle (or dithering) enables 20-bit resolution
- RC filters implemented to reject noise, response to 90% is < 70 ms

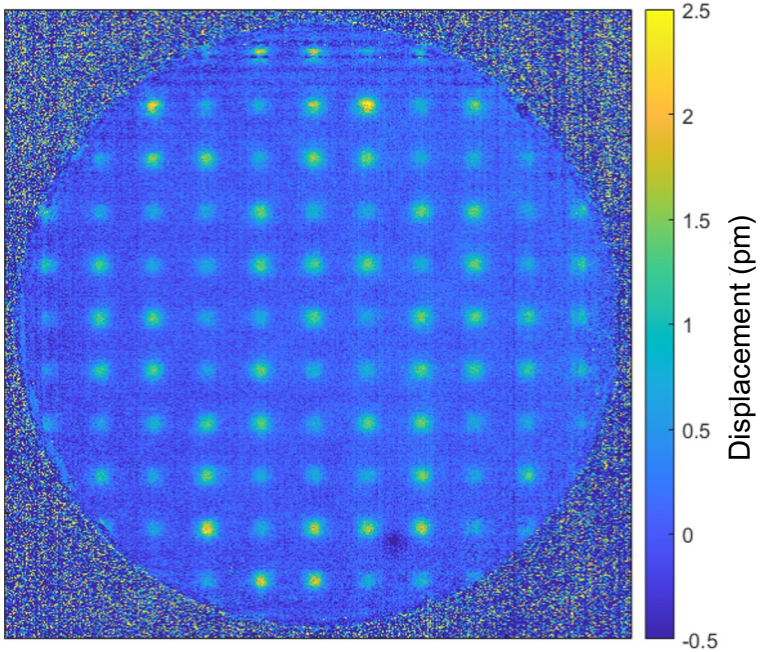


New 20-bit hi-resolution DM Controller

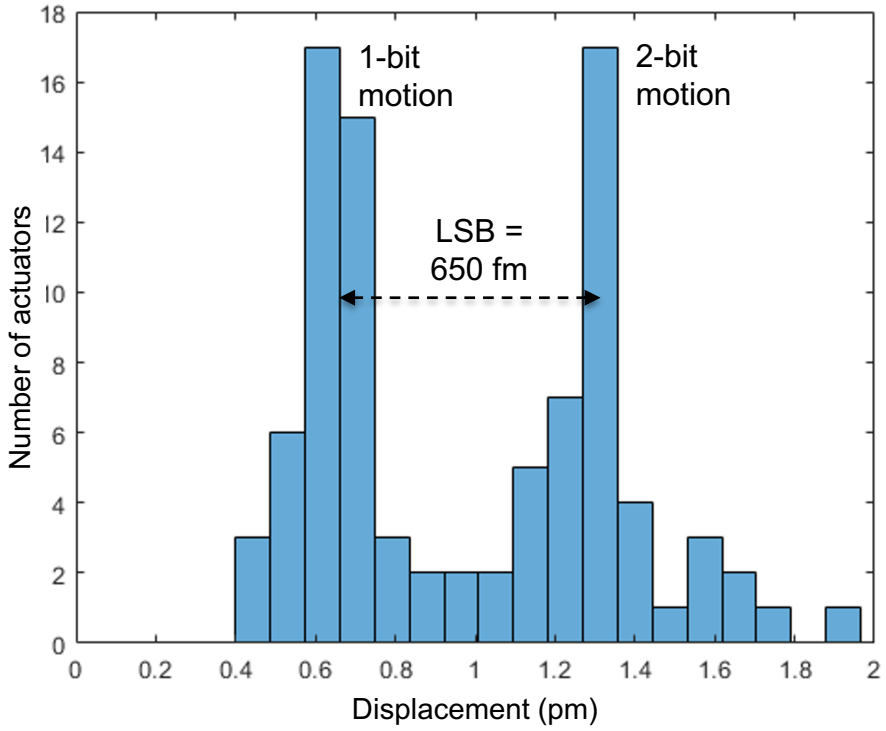
- Measured pokes of 92 actuators on a BMC 2K DM
- Poke amplitude of approximately 1 pm
- 10000 frames, ~14 hrs integration time
- **Measured resolution of 650 fm**
- **2kHi Res meets Habex / HWO requirements with ample margin.**

Poke amplitude applied	
Mean surface motion:	996 fm
	650 fm
Uncertainty	71 fm (11%)

Surface Displacement



Actuator displacement histogram

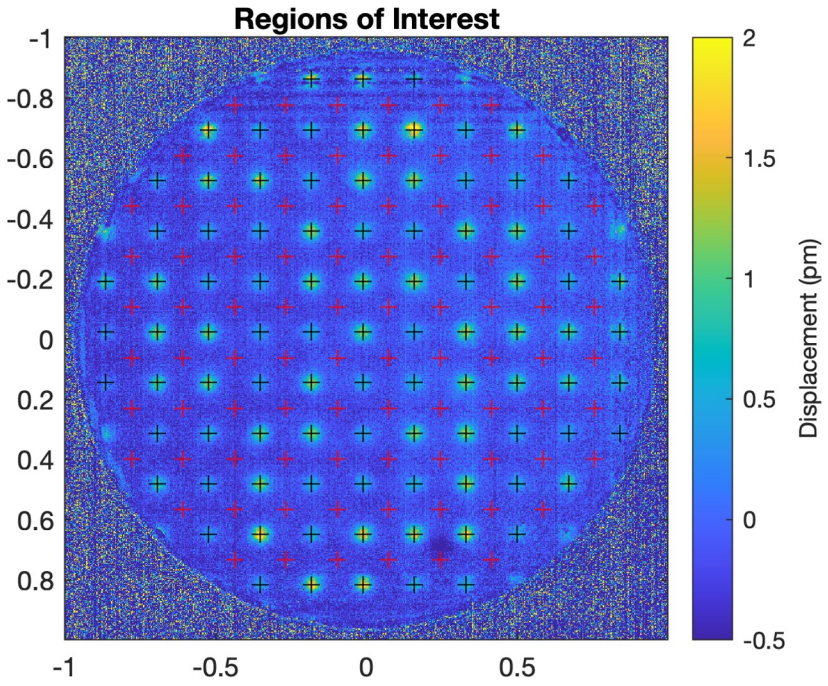


Bendek, Allen, Ruane, in prep 2023

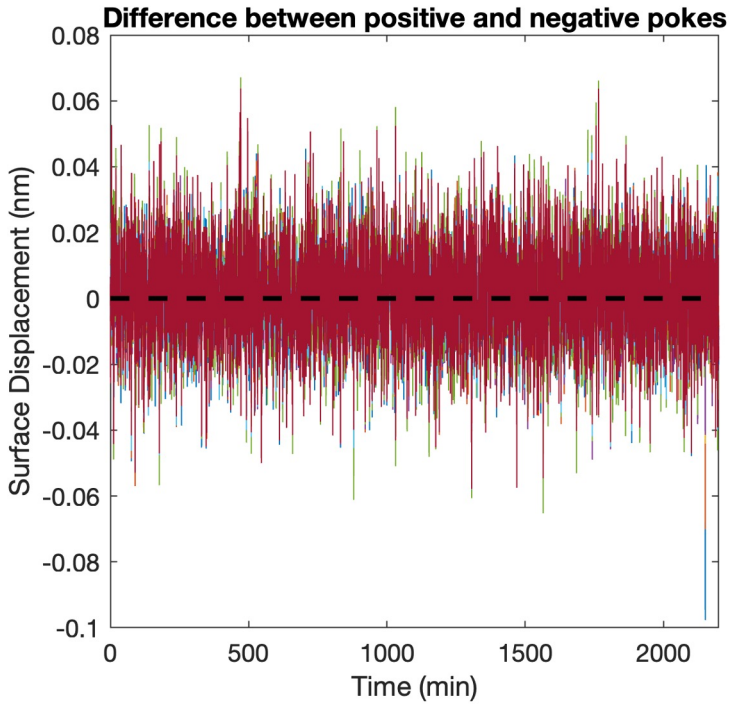
Stability test 1: Relative

Stability of the DM surface is a key requirement

- Requirement is < 10 pm/hr
- We measured the **relative** difference between poked and flat areas which showed to be stable below measurable levels of 1 pm/hr



Relative stability is measured as the difference between the areas marked by black and red crosses

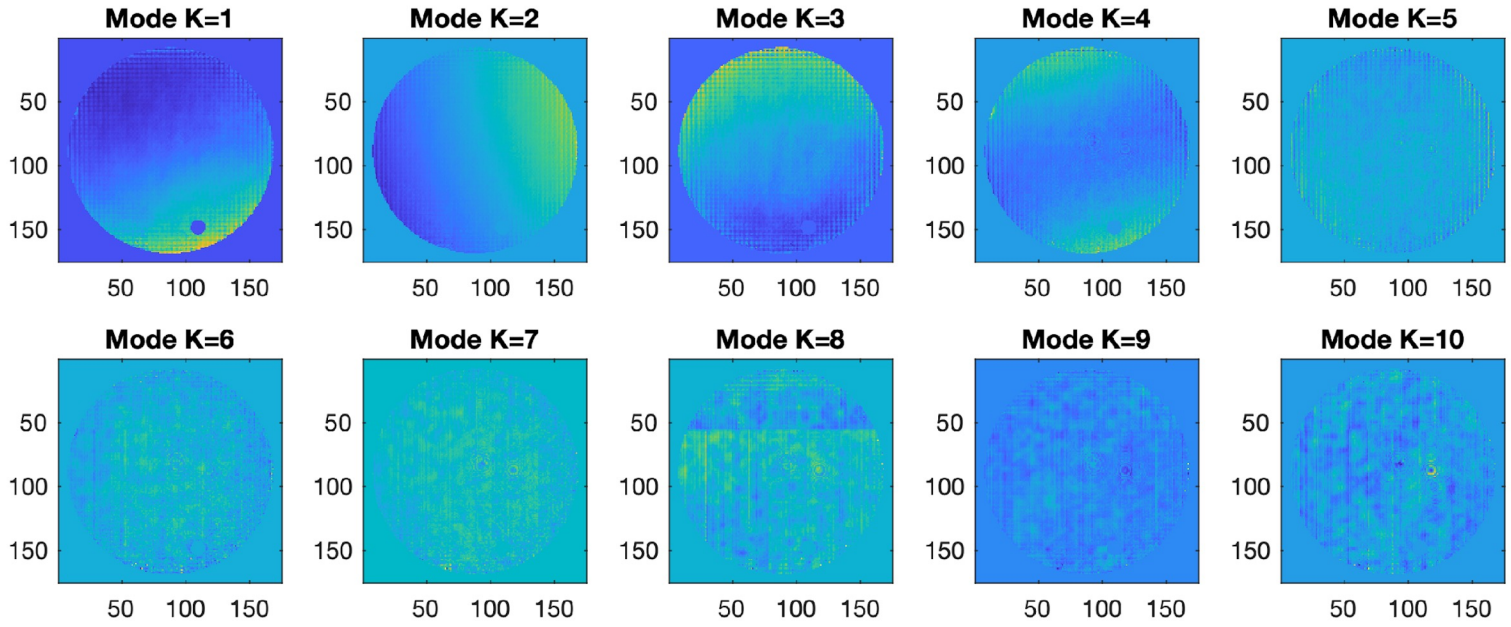


RMS=17 pm mostly due to measurement noise
Linear fit return a slope of 3.5e-16 m

Stability test 2: total drift

Principal Component Analysis of the wavefront

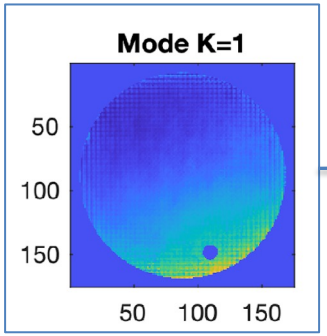
- We decomposed in 10 modes
- The morphology of modes 1, 2, and 3 corresponds to drifts in the testbed including ZWFS mask pointing (Can we model this?)
- Higher orders, could have a component arising from the electronics. However, none of them match the electronics boards mapping to the DM. Thus, it is unlikely that the drift is caused by the electronics.

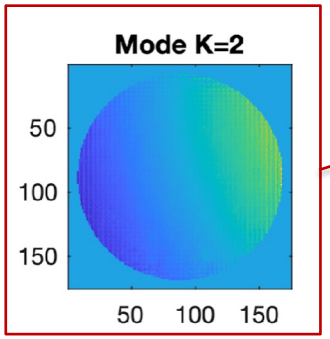


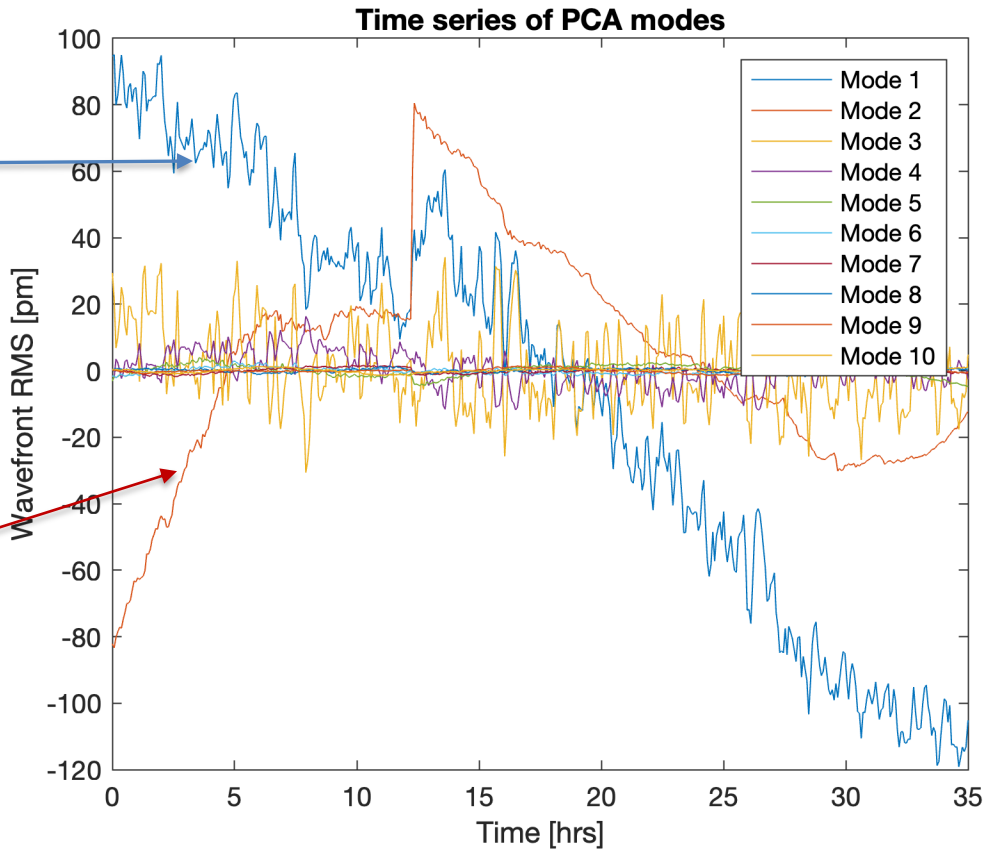
Stability test 2: total drift

Principal Component Analysis of the wavefront time series

- The first two modes dominate the wavefront changes with a maximum of rate of 5 pm/hr
- The third mode rapidly reduces to about 1 pm/hr



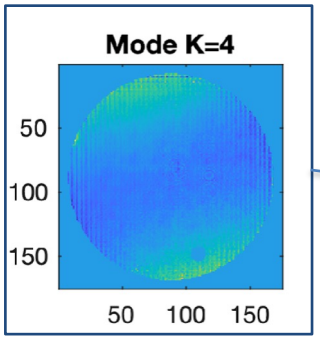


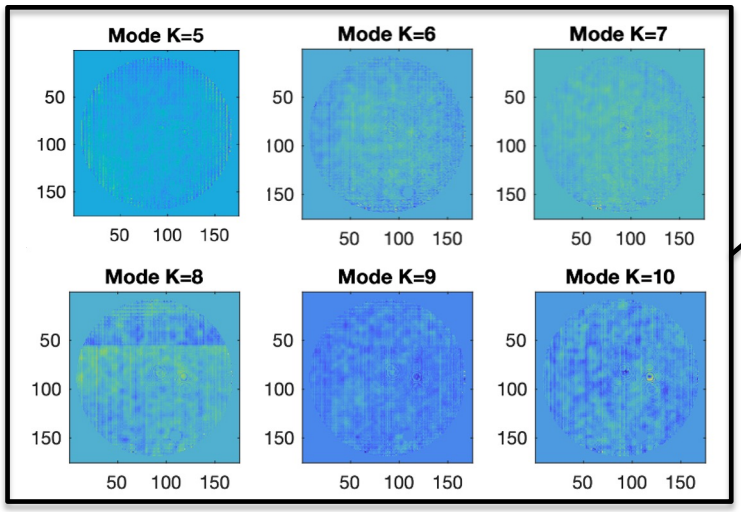


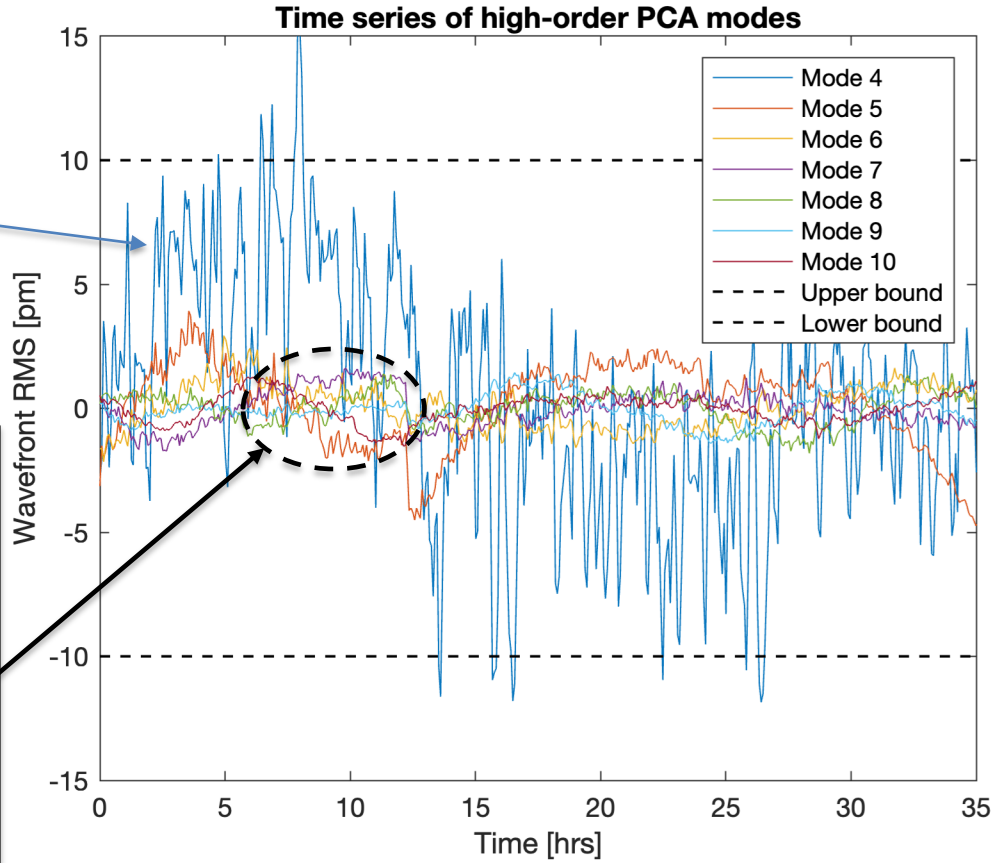
Stability test 2: total drift

Principal Component Analysis of the wavefront time series

- Higher order terms are bounded to variations of less than 1 pm/hr



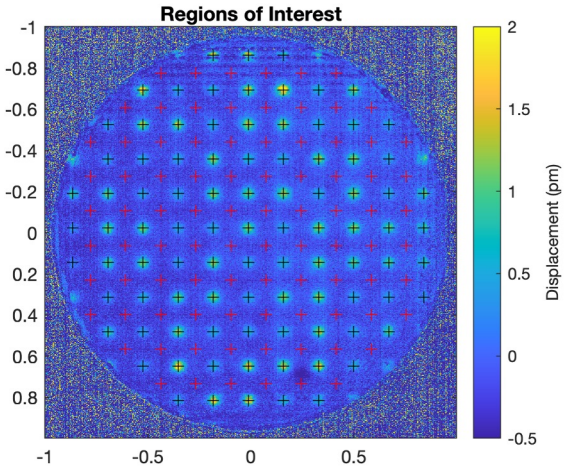




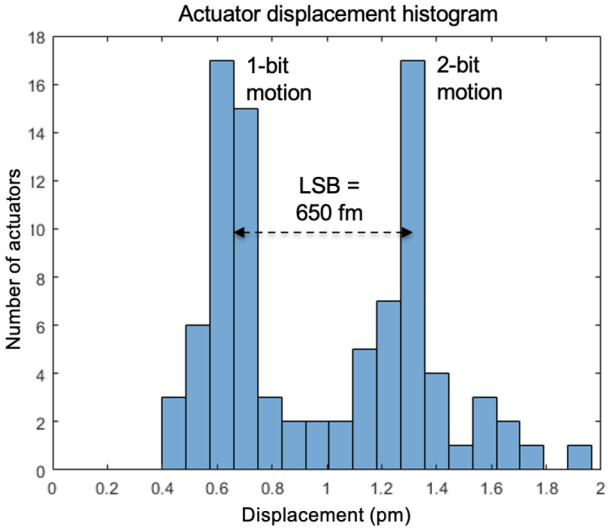
2k DM controller performance summary

- 20-bit electrical resolution (0.119 mV)
- Measured 0.65 pm optical resolution
- Meets Habex / HWO requirements (2 pm)
- Stability bounded within 1 pm/hr
- Designed at JPL (E. Bendek PI + Teilch Contractor, Funded by HCIT)

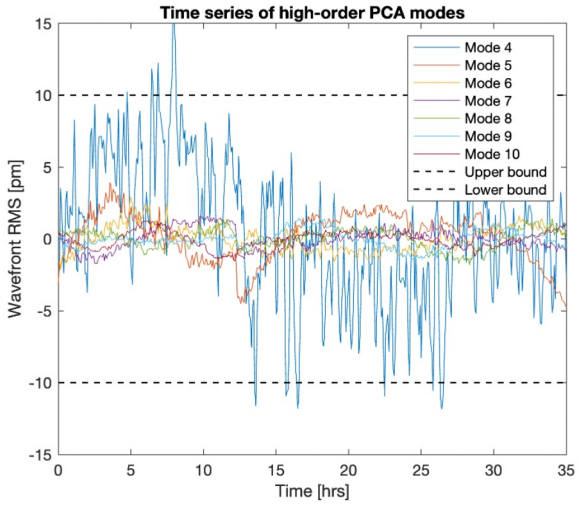
2k DM Controller



Wavefront showing 1 pm pokes



Histogram showing resolution 1 and 2-bit pokes



Time series of the PCA modes showing that the drift is bounded to 1 pm/hr