M1CS Sensor System Preliminary Design Review

Pasadena
March 29 - 30, 2012

P02: Sensor System Design Overview

Mark Colavita
M1CS Sensor System Preliminary Design Review
Pasadena
March 29 - 30, 2012

Objective

- Outline the baseline sensor system implementation, which is responsive to the requirements to be described next, in order to provide context for requirements and to introduce the other presentations

Outline

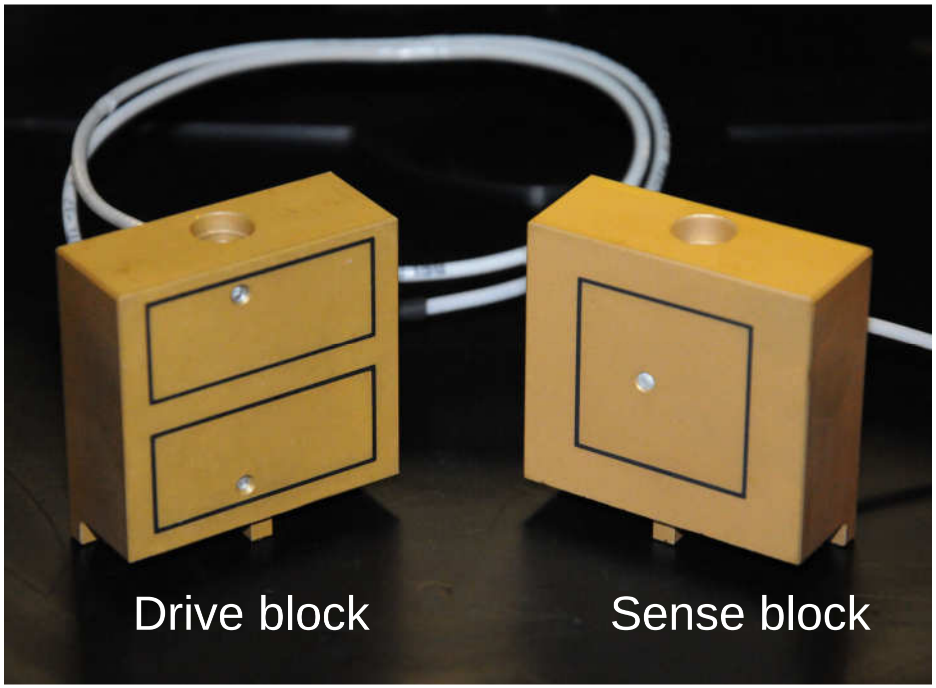
- Sensor overview: blocks/coatings, dust boot, & electronics
- Sensor interface to the telescope & M1CS
- M1CS global control using the edge sensors
- The sensor equation, in-plane motion, and sensor calibration
- TMT vs. Keck sensors
- Operational issues
- Summary

THIRTY METER TELESCOPE

Jet Propulsion Laboratory
California Institute of Technology

Sensor components

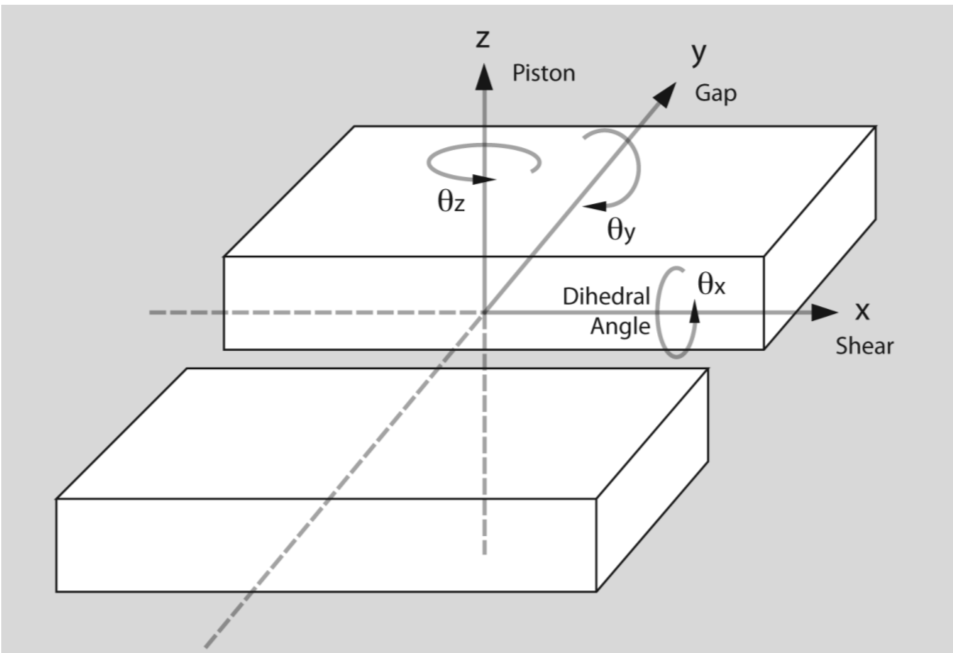
Capacitive position sensor



These are the prior 52 mm high blocks, for which most of the testing was done. The current blocks are 67 mm high with an updated foot geometry.

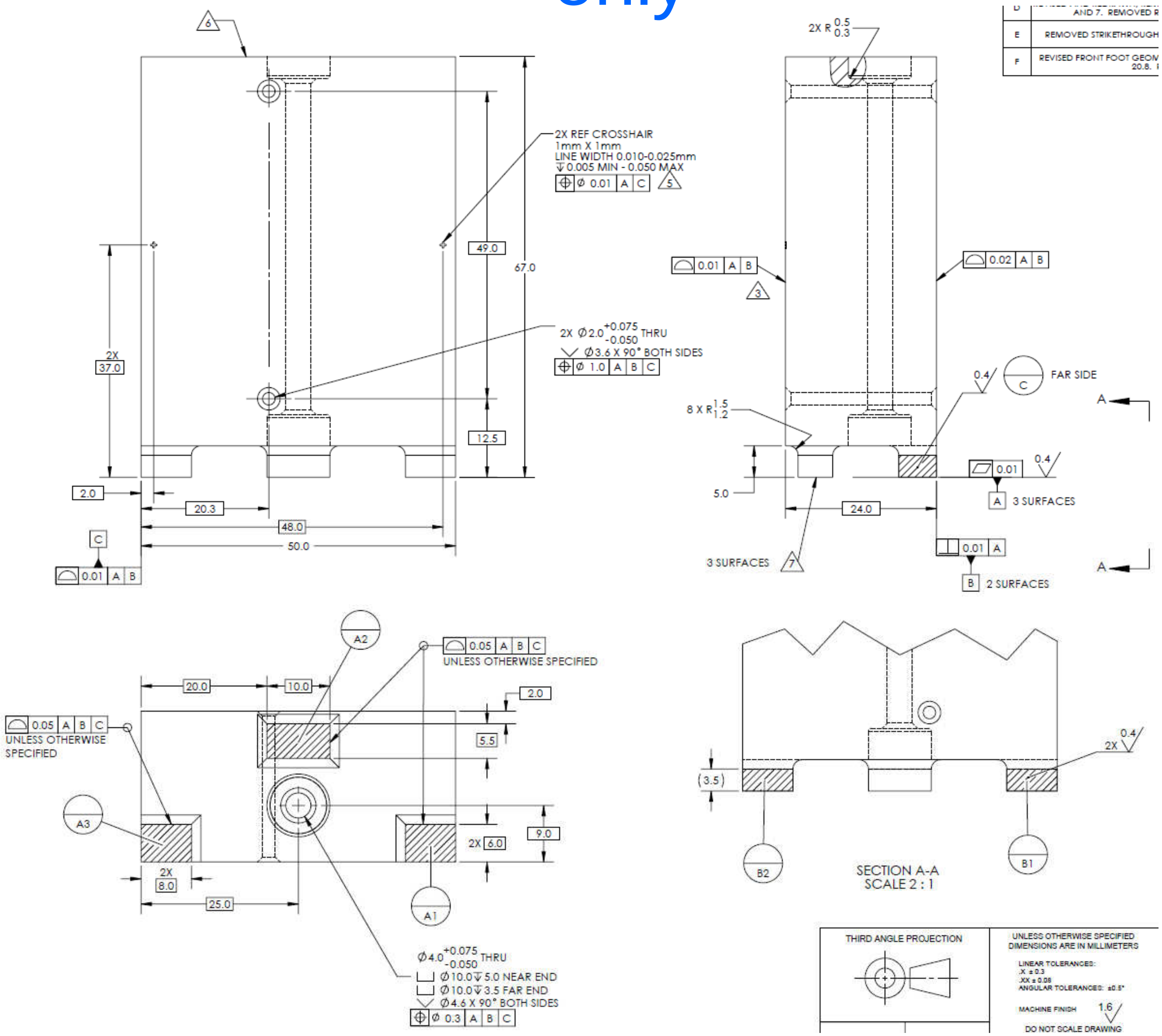
- Face-on capacitive position sensor
- Two drive electrodes
- One sense electrode
- Blocks are Zerodur, 67 mm tall by 24 mm deep
- Gold electrode coating
- Electronics measure the mutual capacitance between the drive and sense plates to extract piston, dihedral angle, and gap

Geometry and sensing

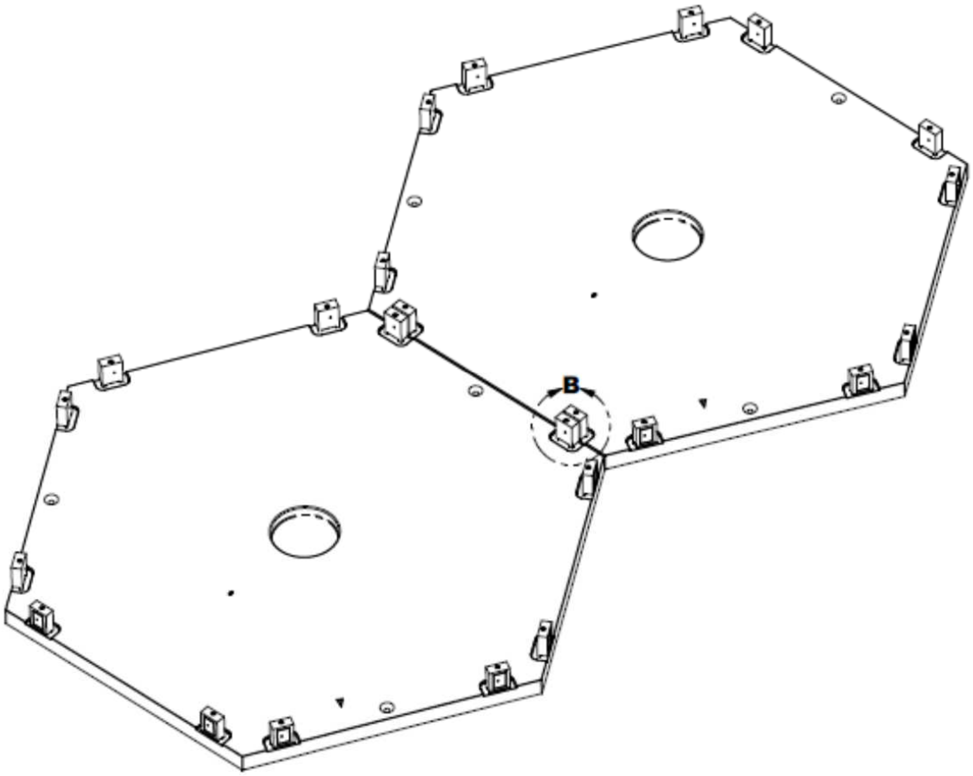


- Sensors provide two outputs
  - A “height” output which sums
    - Relative piston z between segments, *and*
    - Relative angle θ_x between segments $\times$ L_{eff}
      - θ_x = the dihedral angle
      - L_{eff} = the effective lever arm
  - A “gap” output which measures the separation between sensors
    - Necessary for calibration

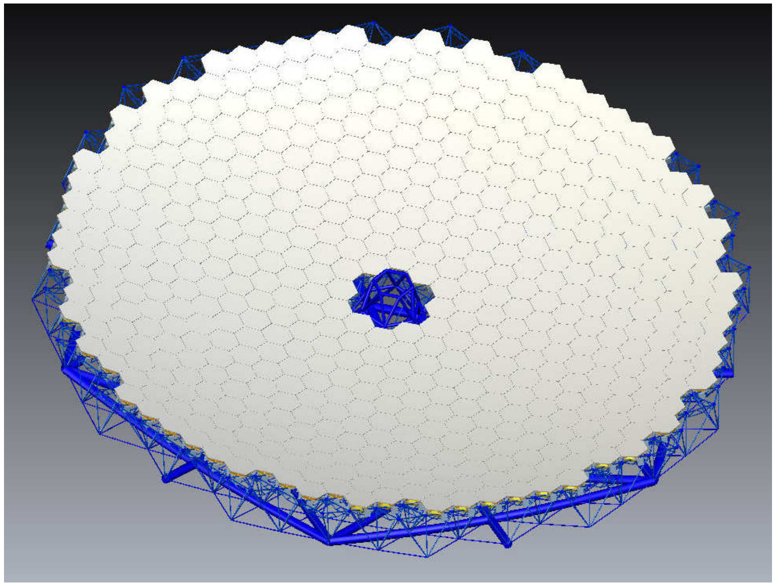
67 mm sensors – reference only



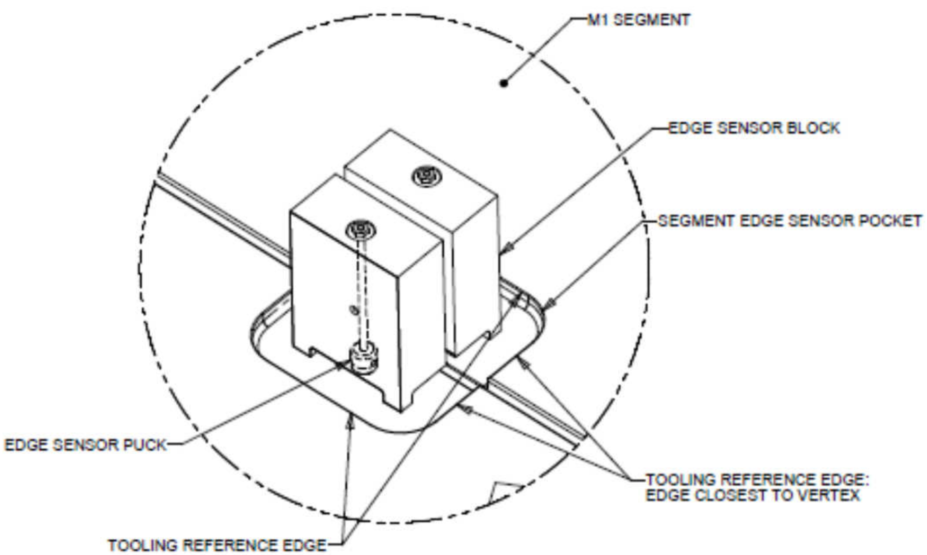
Mounting, 1

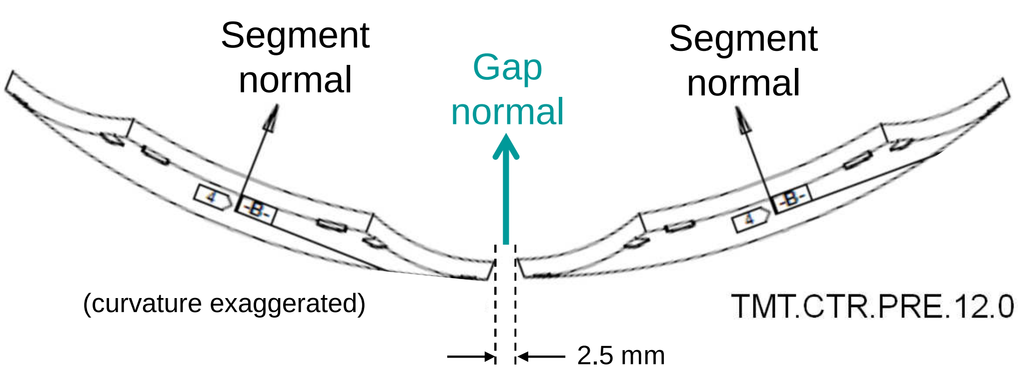


- Two sensor pairs mount to the underside of the segments along each shared intersegment edge
  - 2772 total sensors for 492 segments
  - Plus sensors for the segments of the spare sector



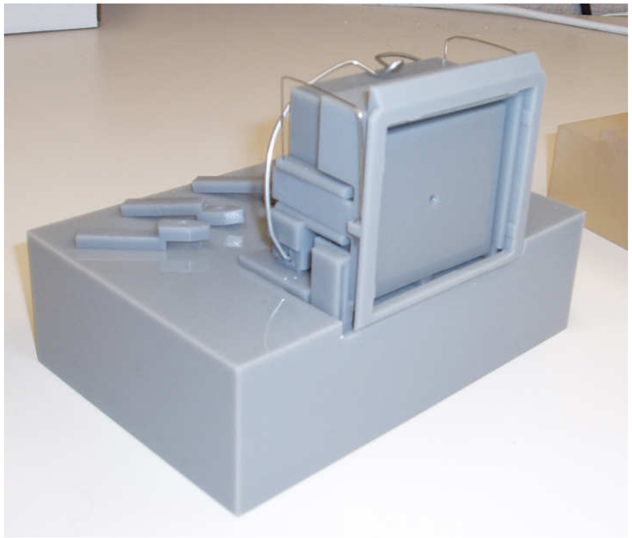
Mounting, 2

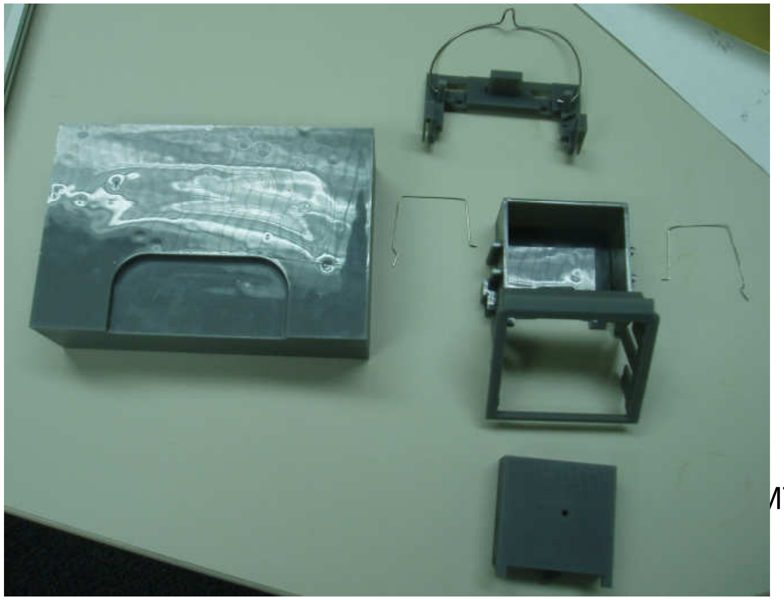




- Sensors mount in pockets machined into the underside of segments
  - All sensors mount identically, referenced to pocket features
- Sensors are mounted parallel to the "gap normal" 4.8 mm apart
- The extra setback relative to the 2.5 mm segment gap allows safe segment removal, which is along the "segment normal"

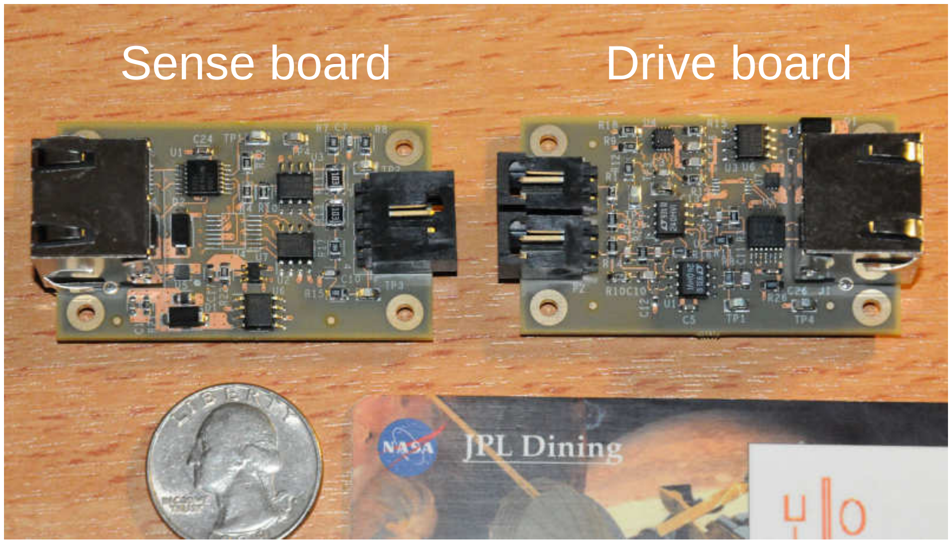
Dust cover and purge system

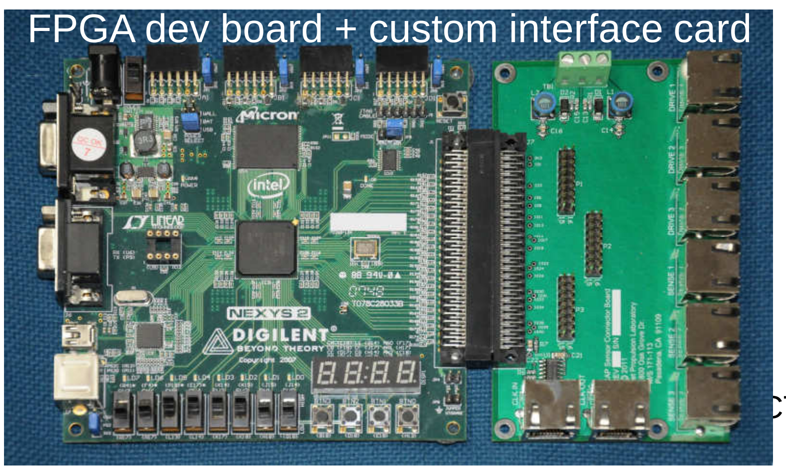




- A dust cover is required to keep the sensor clean, and to provide a purgable volume
  - Capacitive sensor are sensitive to humidity above ~50%
  - A purge system provides dry gas to each boot to keep the humidity low
- Design uses a fixed backshell with a sliding mate
  - Ideally, no handling needed on segment exchange
- Separable base sets location of spacers for locating sensor block

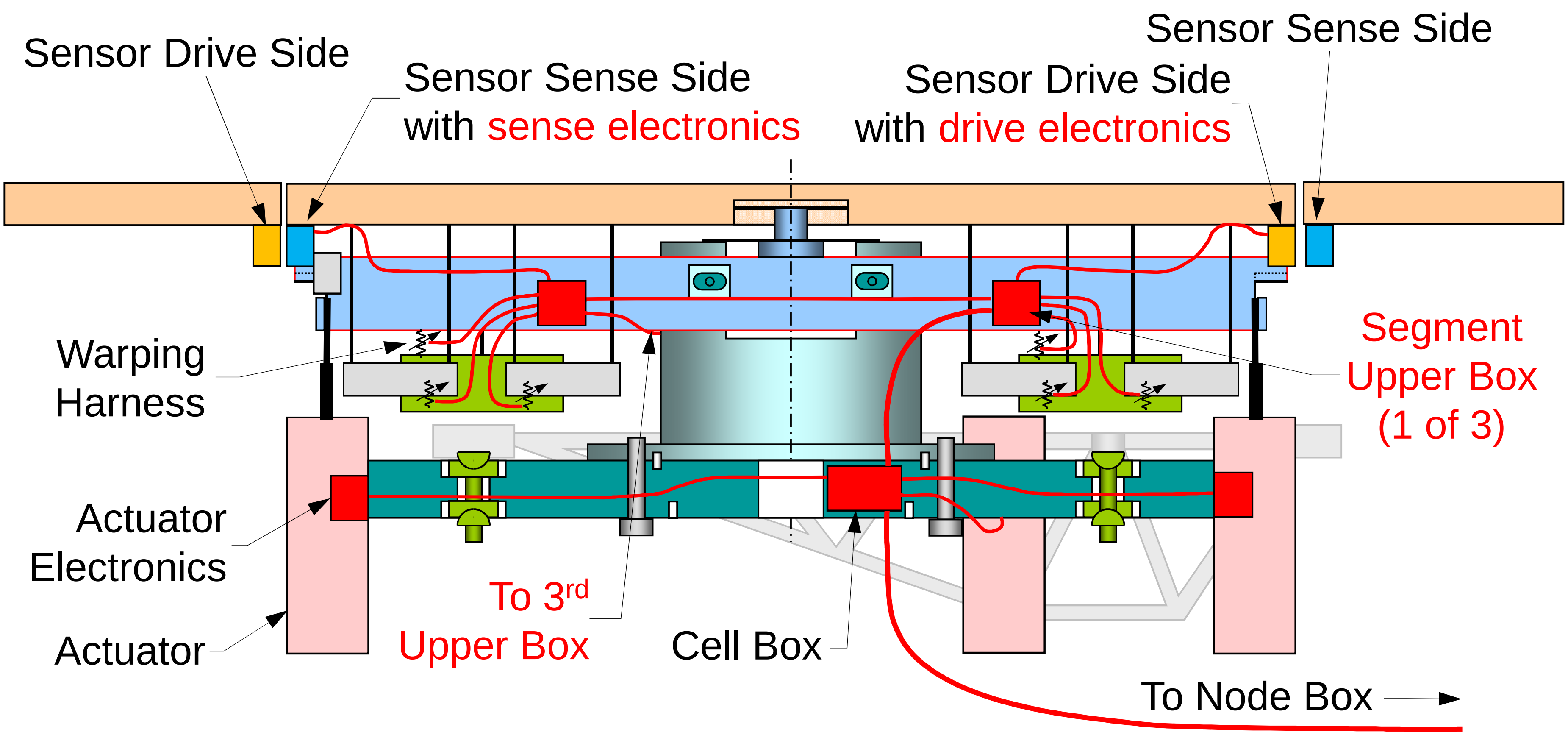
Sensor electronics



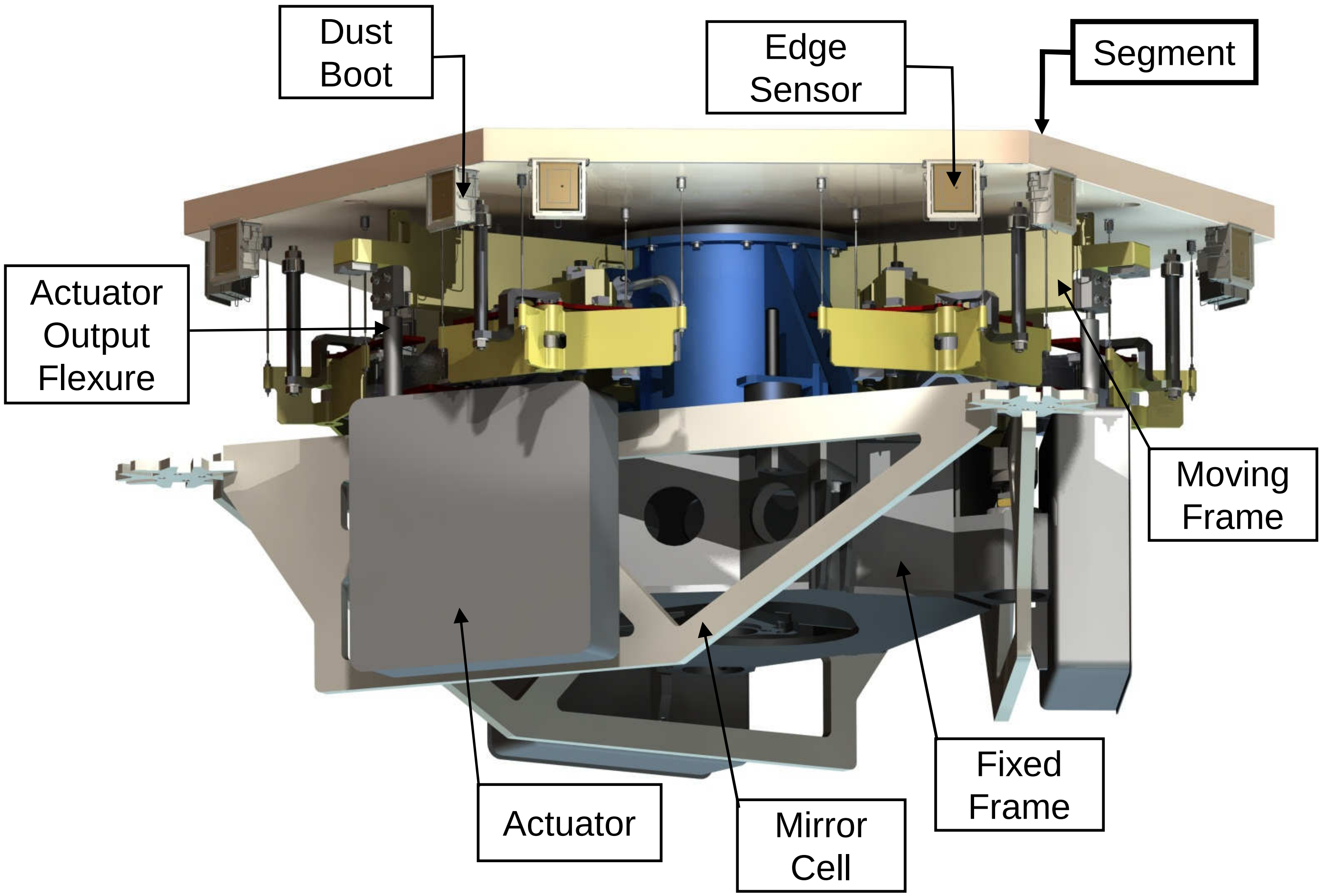


- Approach: sine excitation at 50 & 100 kHz for height and gap with coherent demodulation
- Local electronics at each sensor block
- Drive board
  - Serial digital in
  - DACs for differential & common-mode waveforms
  - Sum/diff amplifiers for the two electrodes
- Sense board
  - Low noise amplifier and filter
  - 18 bit ADC
  - Serial digital out
- Drive waveform generation and coherent demodulation implemented digitally in an FPGA on a commercial development card with a custom interface (for prototyping)

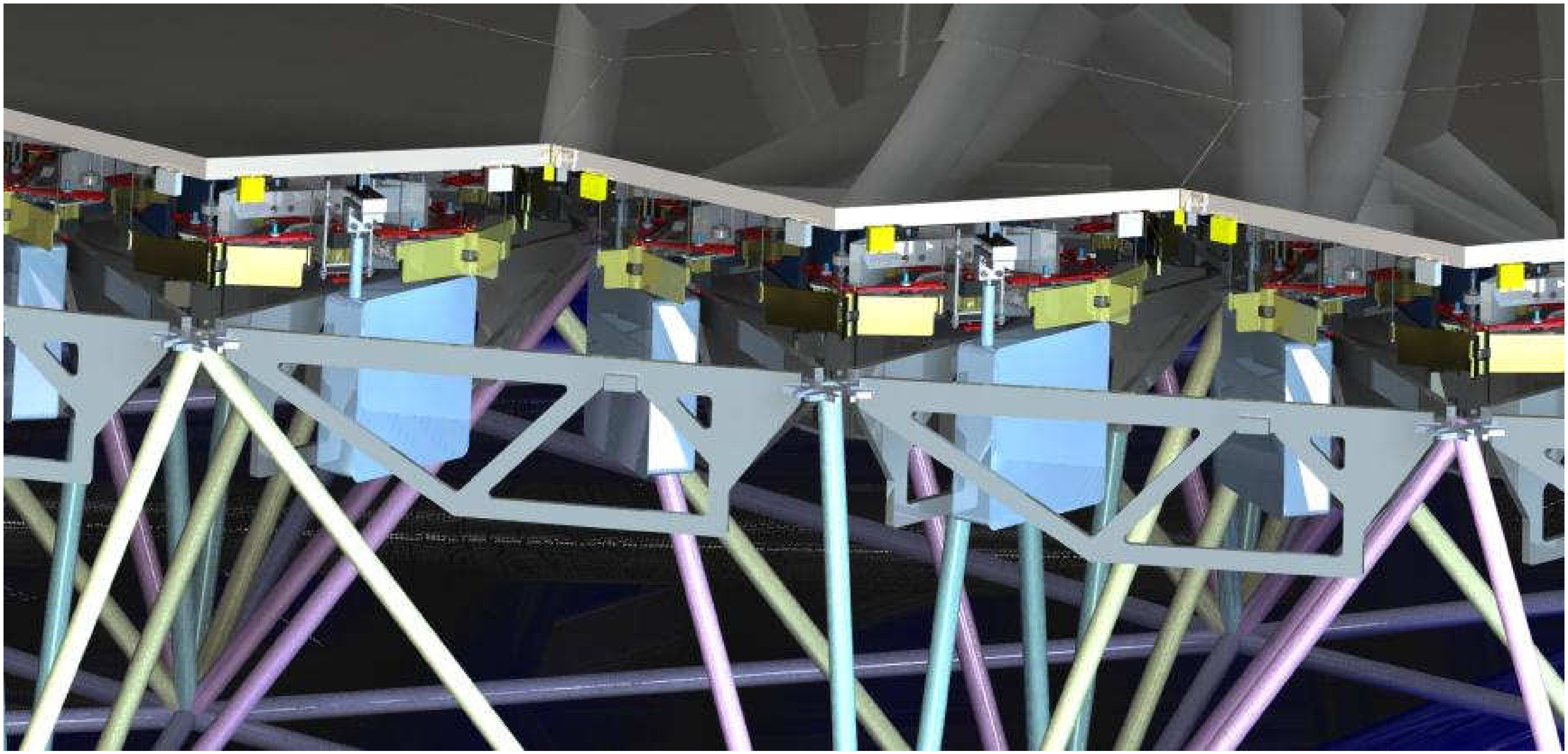
Sensor electronics on the telescope



Sensors and actuators on the Segment Support Assembly (SSA)



Segment Supports Assemblies on the mirror cell



THIRTY METER TELESCOPE

Jet Propulsion Laboratory
California Institute of Technology

M1CS control

Sensor modes

- There are 1476 controllable mirror modes, i.e., equal to the number of actuators
- Global piston, tip, and tilt are not sensed with the edge sensors
  - These modes are estimated from the actuator positions
- The remaining modes are estimated using the pseudo-inverse of the “A” matrix that relates actuator positions to sensor outputs
  - Focus mode is the first of these modes

More on focus mode

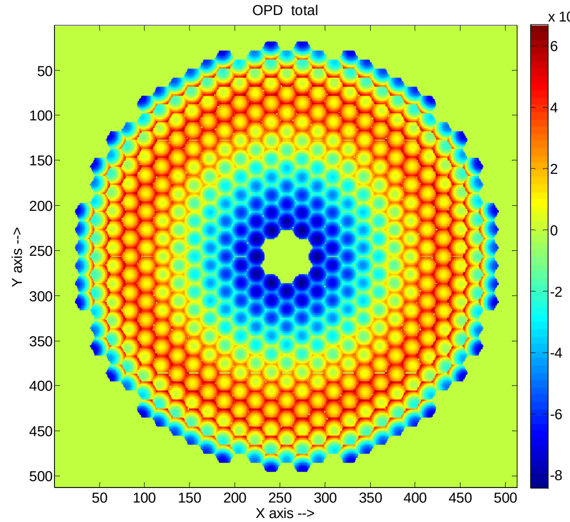
- It's just the change in the overall power of the primary
  - For slow drifts, focus mode is mostly compensated by refocusing (moving M2)
  - However, because the telescope is segmented, if the overall power of M1 doesn't match the individual power of the segments, there will be a high-spatial-frequency "scalloping" residual
- Focus mode is the lowest order mode that can be practically reconstructed from the segment edge sensors
  - It's approximately proportional to the average value of the 2772 edge sensors values (for a sensor sensitive to height and dihedral angle)
- Total focus mode OPD rms is ~850 × ⟨sensors⟩ for cap sensor with Leff = 52 mm – our current baseline
  - 8 um focus mode OPD, after refocusing, gives a PSSN of 0.990
  - Focus mode is sensitive to correlated drifts in the sensor mean, more so than for Keck, and this drives the desired value of L_{eff}

Example: OPD for M1 Focus Mode corrected with M2 Piston

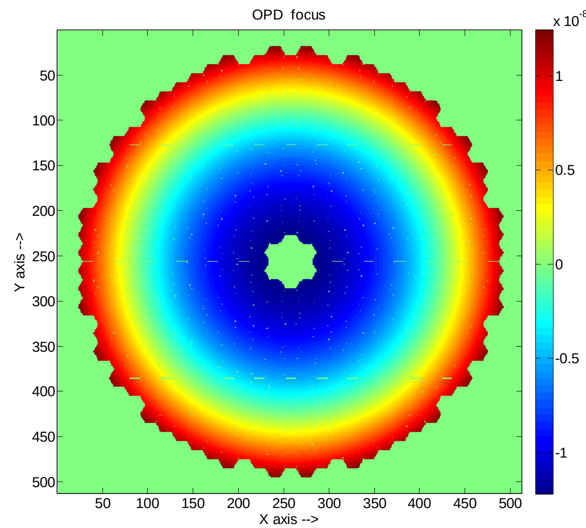
TMT THIRTY METER TELESCOPE

JPL Jet Propulsion Laboratory California Institute of Technology

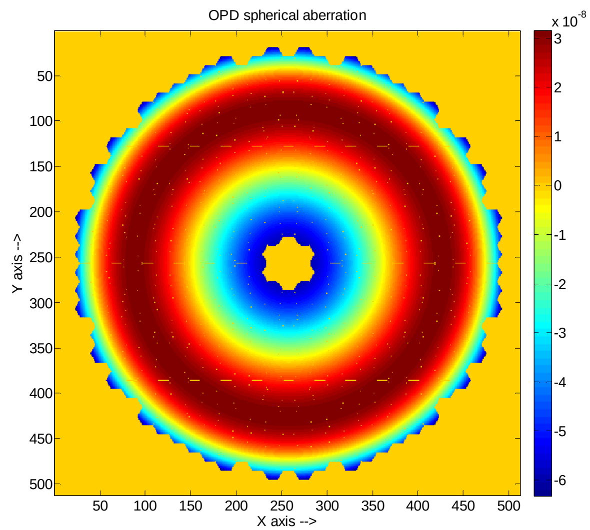
Total OPD 140 nm p-v



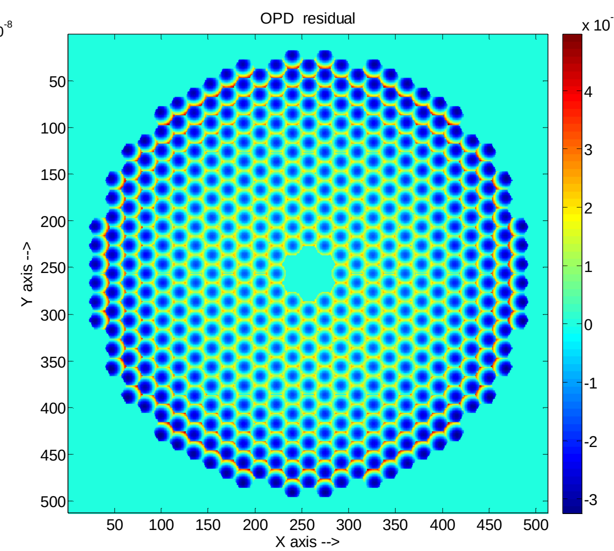
Focus OPD 24 nm p-v



Spherical Aberration OPD 90 nm p-v



Residual OPD, mostly focus-mode scalloping 75 nm p-v



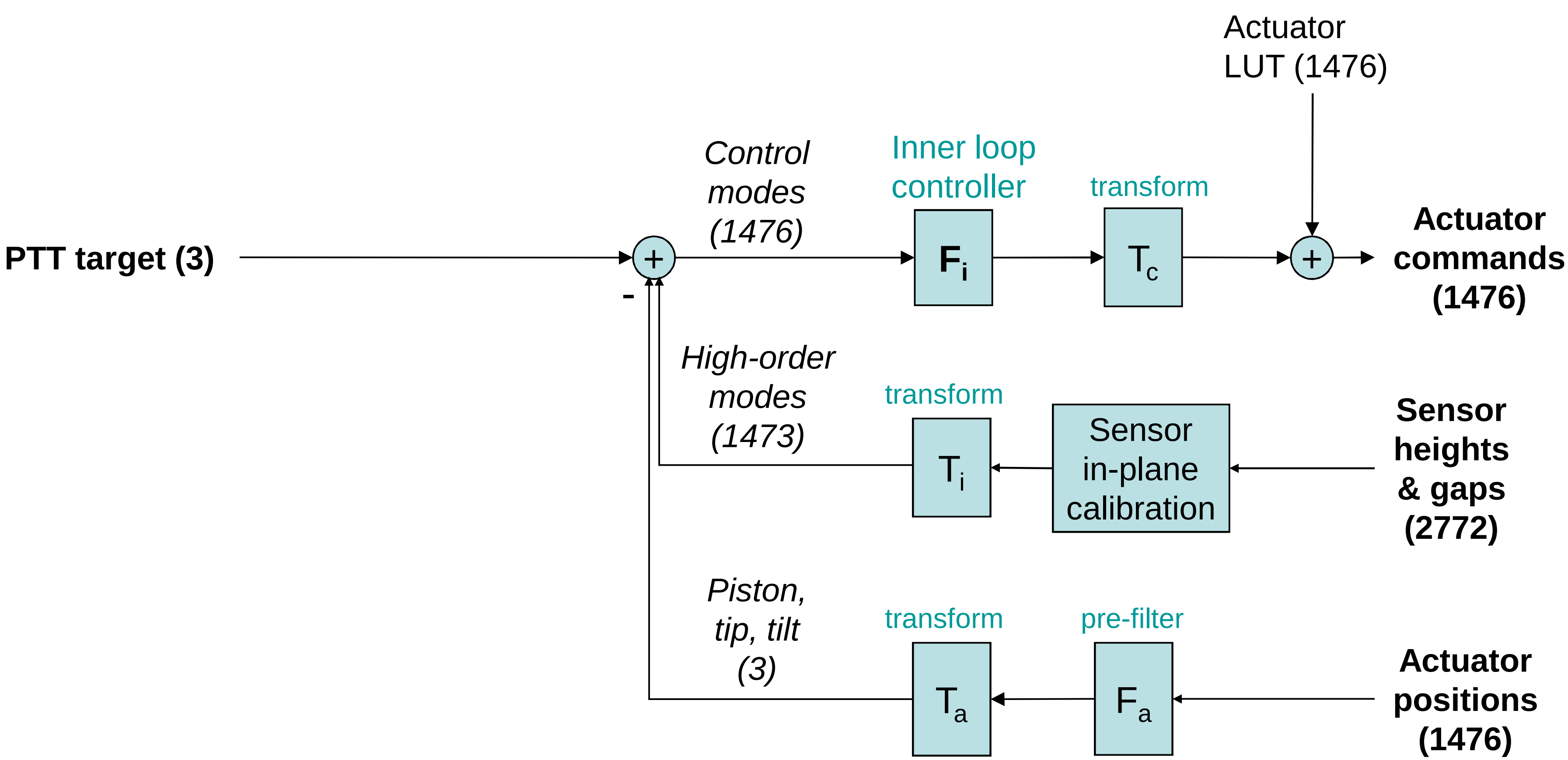
M1CS control strategy

- Higher-order modes controlled by M1CS at 1-2 Hz
  - These modes are well observed by the edge sensors
- Focus-mode controlled by M1CS at 0.1-0.2 Hz
  - Lower bandwidth accounts for poorer noise propagation, and stability issues associated with the accuracy of the pseudo-inverse of "A"
- Optical feedback from AGWFS or AO to M1CS to correct for systematic errors or drifts
  - Low-order Zernikes used in outer loop around M1CS controller
  - AO can also sense the residual scalloping of focus mode
- Assumes telescope focus control from AGWFS or AO, via TCS, which drives M2
  - Tracking telescope focus at moderate bandwidth is essential to maintain the PSSN budget (so that we can use the focus-corrected PSSN expression for focus mode errors due to sensor drifts)

Global controller

inner loop

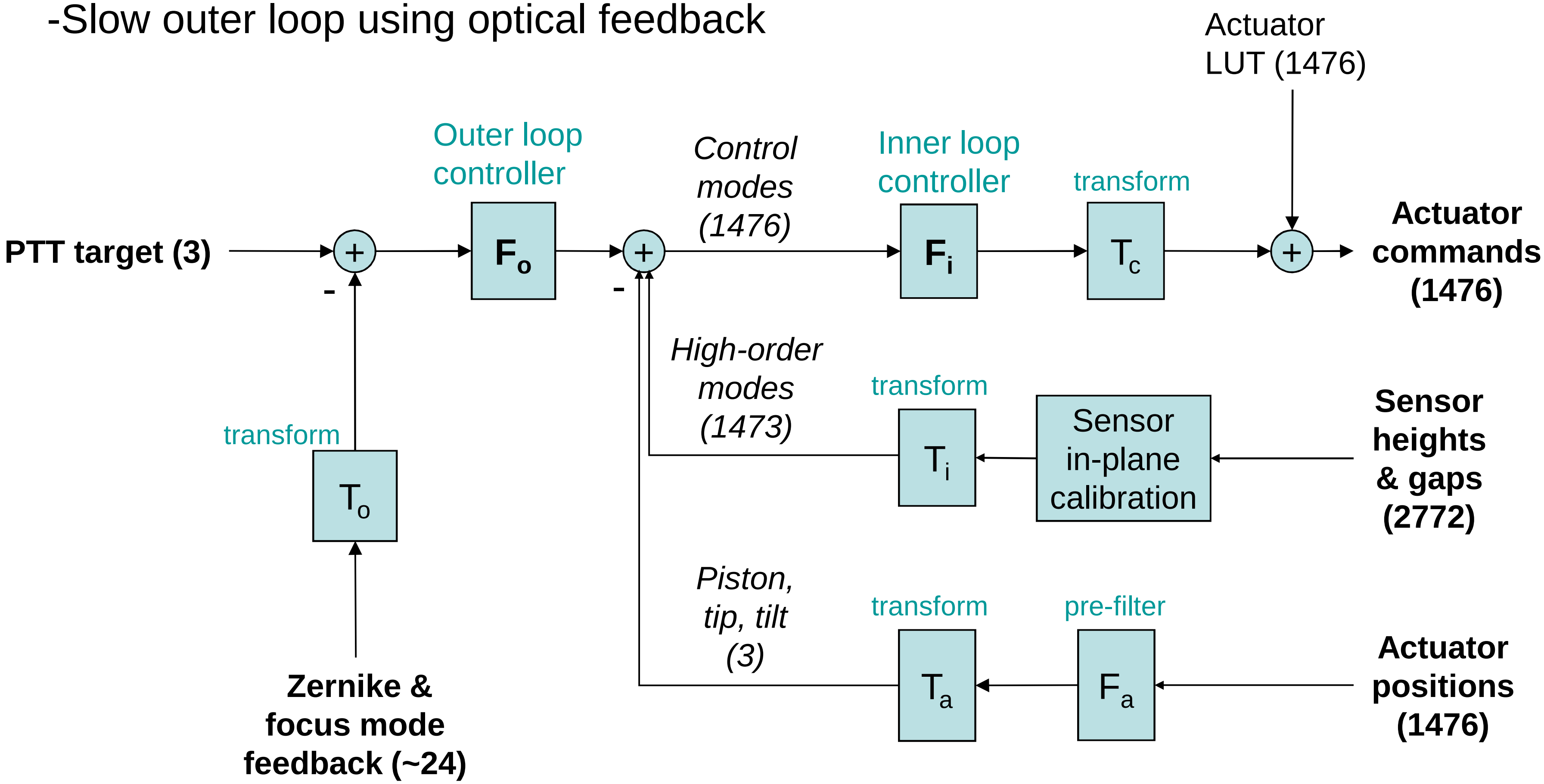
-Fast inner loop using edge sensors and actuator positions



Global controller

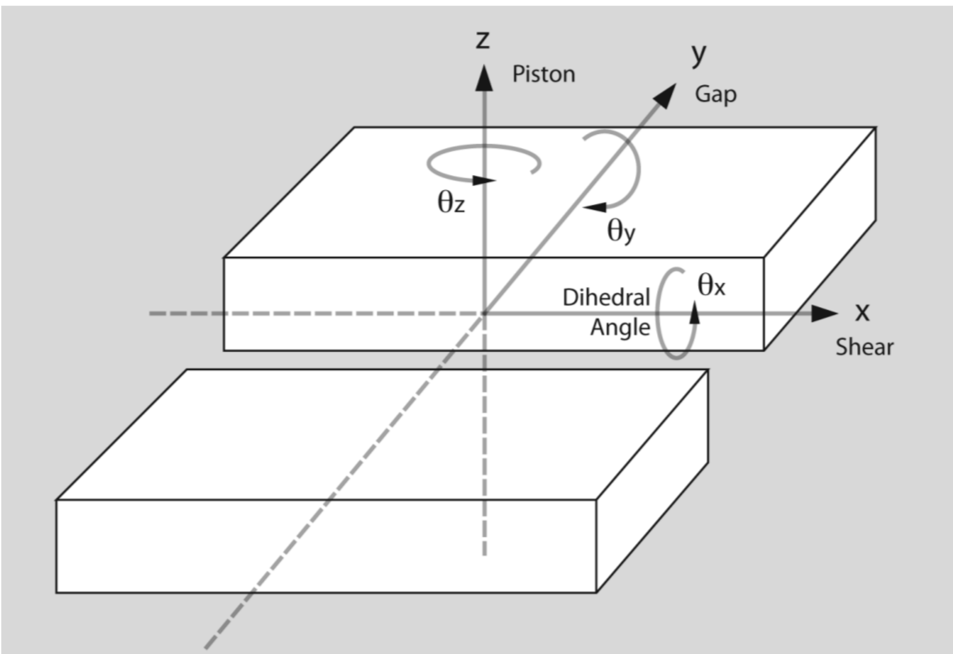
inner & outer loop

-Fast inner loop using edge sensors and actuator positions
-Slow outer loop using optical feedback



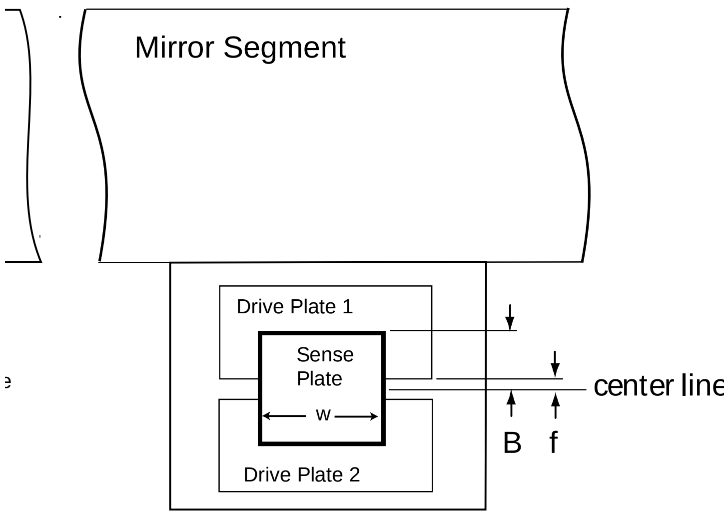
Sensor calibration

Geometry and sensing



- Sensors provide two outputs
  - A "height" output which sums
    - Relative piston z between segments, *and*
    - Relative angle θ_x between segments $\times$ L_{eff}
      - θ_x = the dihedral angle
      - L_{eff} = the effective lever arm
  - A "gap" output which measures the separation between sensors
    - Necessary for calibration

Sensor equation



$$V_{height} \propto \frac{1}{\text{gap}}\left(\text{piston} + \text{L}_{\text{eff}} \times \text{dihedral angle}\right)$$

$$where\ L_{eff} = \frac{\text{const.}}{\text{gap}}$$

$$V_{\text{gap}} \propto \frac{1}{\text{gap}}$$

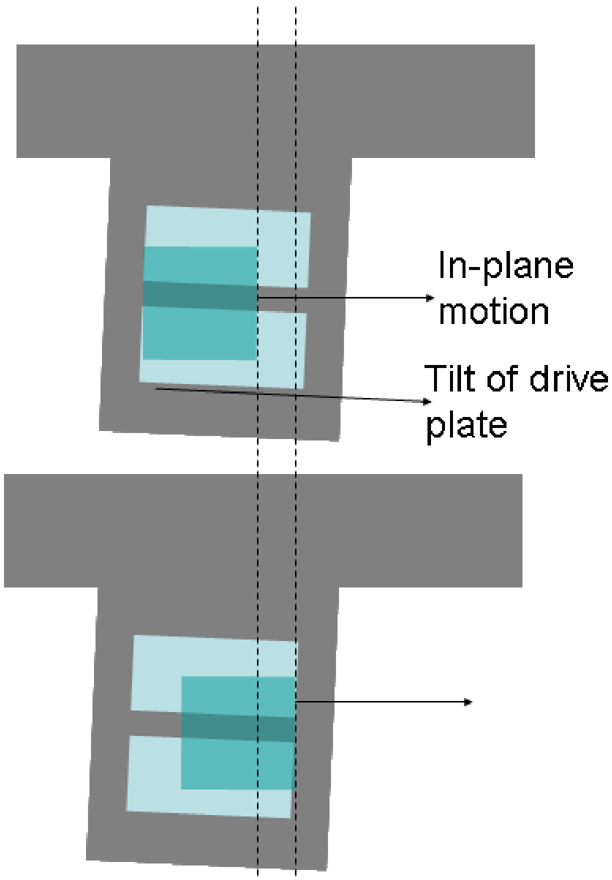
- The sensor outputs follow a simple equation, whose coefficients depend on the sensor electrode geometry
- Gap between sensors is measured from the voltage on the sense plate when the drive plates are driven in-phase – an absolute measurement
- Height is measured from the voltage on the sense plate when the drive plates are driven out-of-phase – a differential measurement
- L_{eff} (the effective lever) is the coefficient that multiplies dihedral angle before summing it with piston
- L_{eff} is inversely proportional to gap
- The overall height signal is also inversely proportion to gap
  - “Gap compensation” is essential for proper interpretation of the signals

TMT vs. Keck sensors

The face-on geometry of the TMT sensors makes them more challenging

		Keck	TMT	
		interlocking	face-on	
		168 sensors	2772 sensors	
Sensitivity				
plate width		30	30	mm
plate height		30	20	mm
gap btwn plates		4	4.8	mm
capacitance between plates (C)		2.0	1.1	pF
sensitive axis for mirror piston z		gap	height	
$\partial C / \partial z$ (one electrode)		C / gap = 0.5	C / height = 0.06	pF/mm
Leff				
value		55	52	mm
properties		physical	$\propto$ 1/gap	
Sensitivity to in-plane motion (no mounting errors)				
segment X		none	none	
segment Y		none	$\propto$ 1/gap	
Second output		none	"gap output" $\propto$ 1/gap	
		no self cal for in-plane effects	allows for self cal of in-plane effects	

In-plane motion & sensor calibration, I



Example of an imperfectly-mounted drive block. In-plane (i.e., in the plane of the segment) motion of the sense block causes an apparent height change

- In the presence of segment in-plane motion, imperfectly mounted sensors see apparent height changes
  – For 100 um in-plane motion, sensors would need to be mounted to 10's urad accuracy for negligible coupling: not practical

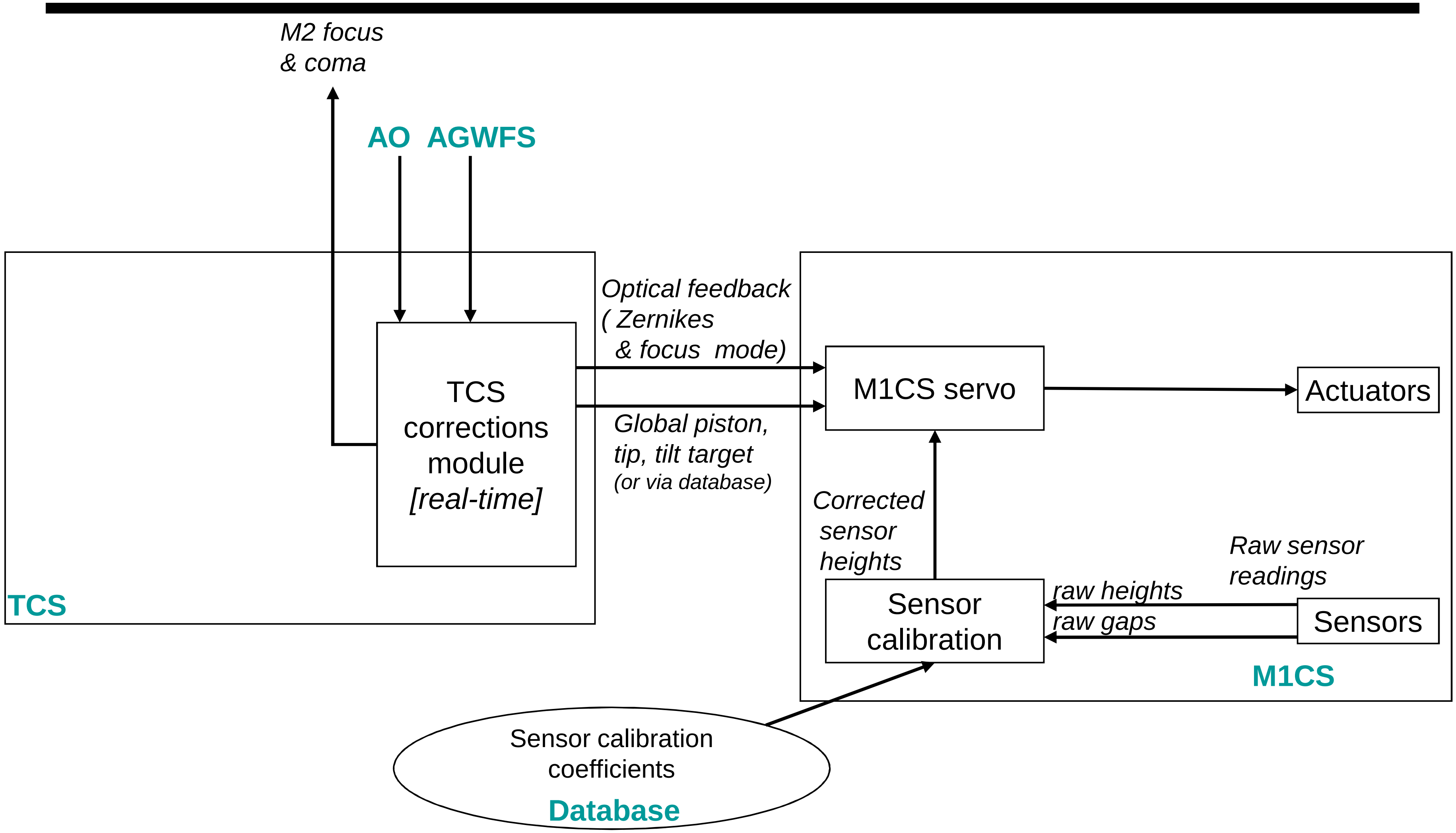
In-plane motion & sensor calibration, II

- Instead of requiring near perfect sensor installation, sensor calibration uses measurements from multiple APS runs at different zenith angles (ZA) and temperatures (which have different amounts of in-plane motion) to solve for this dependency
- This is done on a sensor-by-sensor basis using the set of all gap readings, which can be used for solve for local gap and local shear
- Sensor calibration solves for the coefficients of functions of local gap and shear to calibrate each sensor
  - Sensor calibration also accounts for the gap dependency of the height signal and L_{eff} discussed earlier
- This is a powerful technique, as many systematic effects (sensor flexure, sensor thermal drift, etc.) are well correlated with local gap and shear, and are corrected in the sensor calibration process
- In-calibration does not eliminate all requirements on sensor mounting – the performance degrades with large installation errors: this will be parameterized in the calibration talk

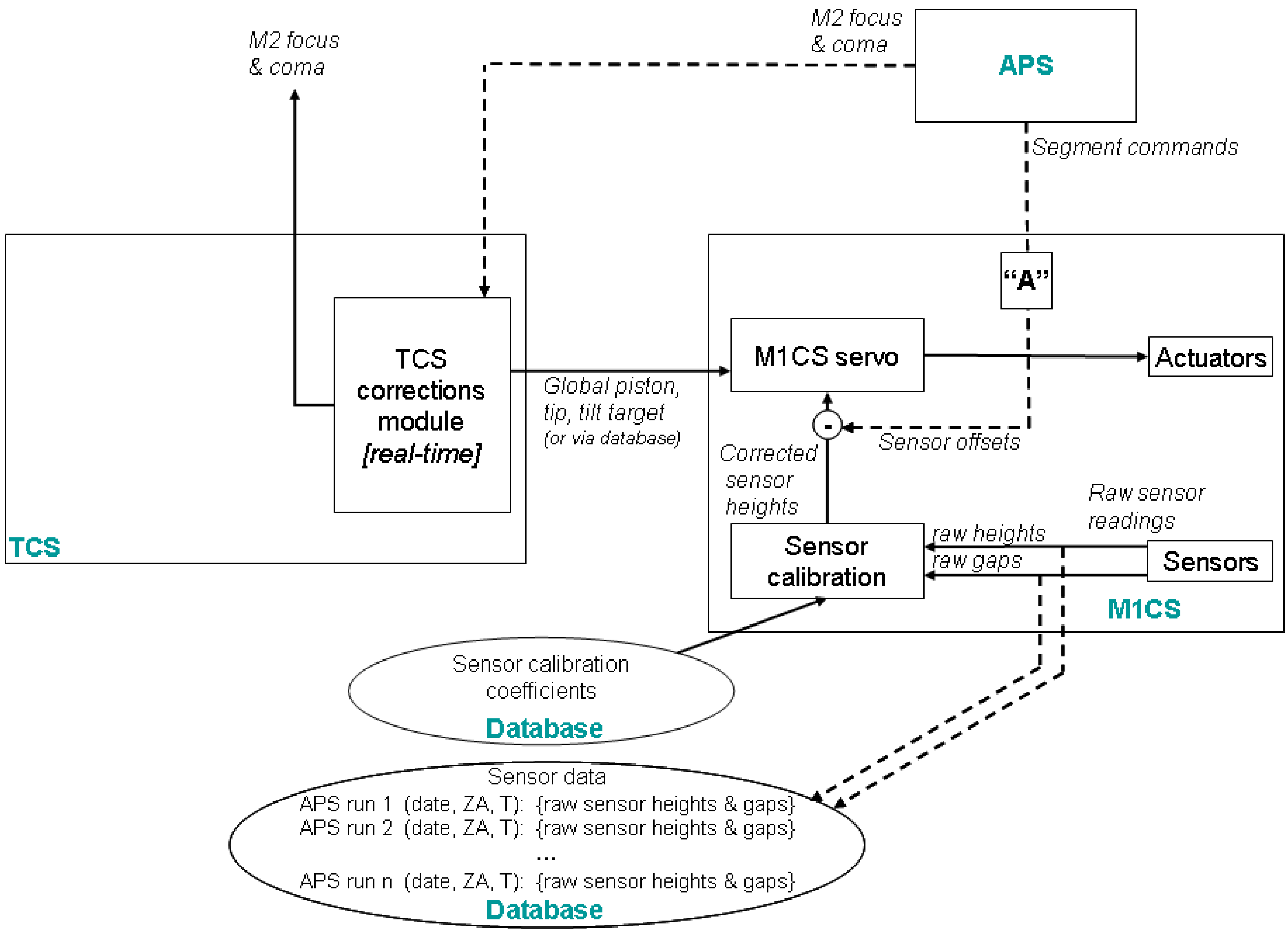
Operational considerations

- Steady state
  - Four or more APS runs at different zenith angles and temperatures are used to solve for the in-plane coefficients of each sensor pair
- Segment replacement
  - To recoat all segments every 2 years, 10 segments must be replaced every two weeks
    - Although for spec'ing the sensor, we assume a four-week interval (but require recalibration after that time even if no segments are replaced)
- Sensors and collocated electronics stay on the segments
  - We assume spare segments include their own sensors and electronics
- Sensors associated with replaced segments will require new calibration coefficients; however we want to retain the calibration of the other sensors
  - Initial APS runs at several ZA's will allow for an initial set of sensor calibration coefficients for the new sensors, and updates to the other sensors
  - Additional APS runs needed when the temperature changes to improve the fits of the newly replaced sensors
- Sensor maintenance ideally occurs only when the segments are removed for recoating, and ideally consists of only inspection and minor cleaning

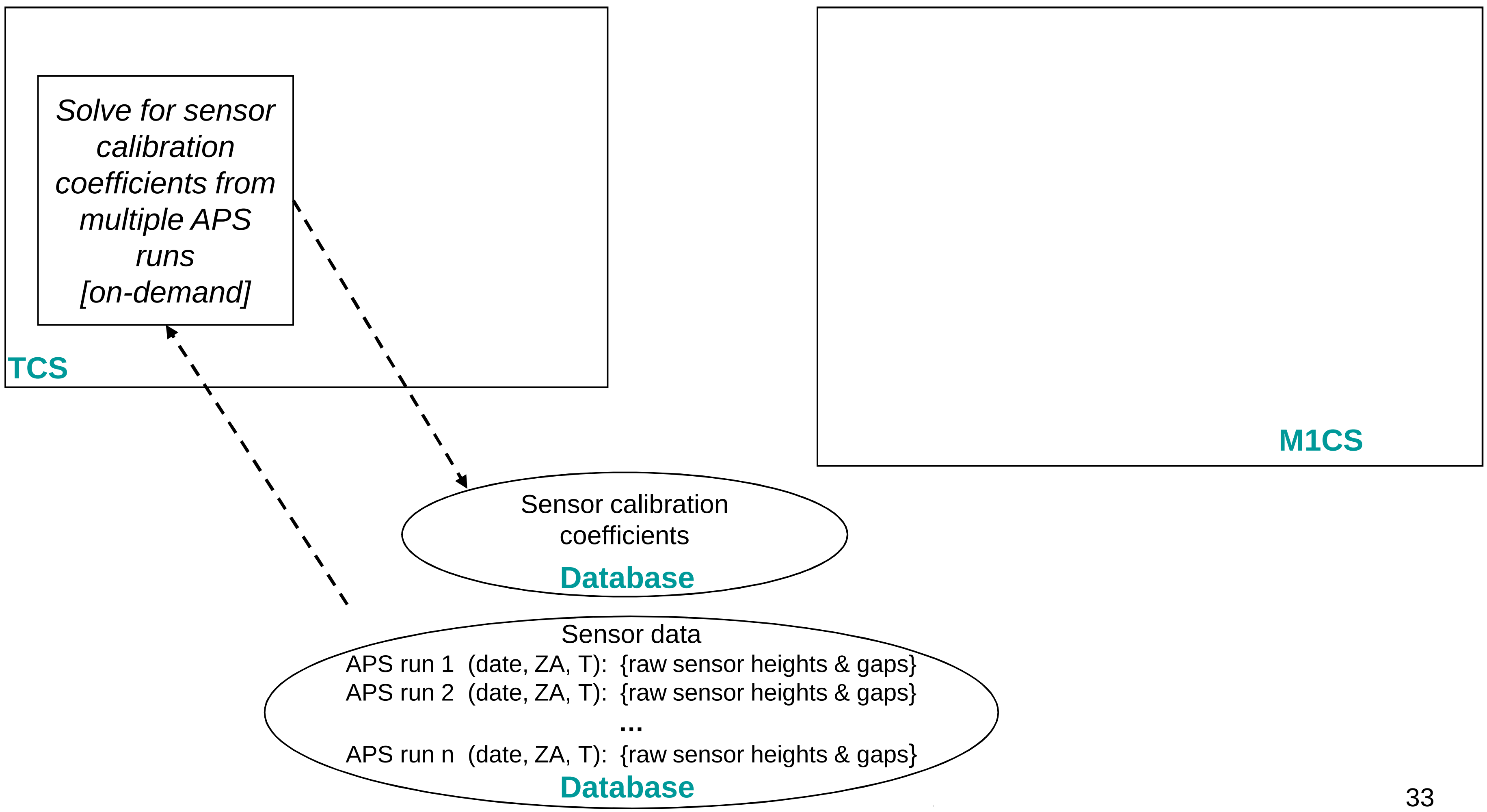
M1CS: Normal ops



M1CS: Under APS control



M1CS: Solving for sensor coefficients



Summary

- Keck heritage, but significant differences to accommodate TMT requirements and incorporate new technology
  - Lots of sensors
  - Face-on non-interlocking design
  - Dust boots and dry-gas purge system for good performance under all conditions
  - Collocated electronics with digital i/o
  - More complicated sensor equation
  - Gap output used to linearize sensor response and as input to in-plane calibration approach
  - Operational considerations, esp. frequency of segment replacement, drives requirements

TMT
THIRTY METER TELESCOPE

JPL
Jet Propulsion Laboratory
California Institute of Technology

P03: Requirements & Error Budgets

Mark Colavita
M1CS Sensor System Preliminary Design Review
Pasadena
March 29 - 30, 2012

Introduction

- This presentation gives the design requirements from the edge sensor Design Requirement Document (DRD)
  - Level 3: REQ-3-M1CS.SEN-xxxx
- These flow down from the M1CS System DRD, which in turn flows down requirements from the parent documents
  - TMT Observatory Requirements Document (ORD)
  - TMT Observatory Architecture Document (OAD)
  - and also tries to be consistent with the text of the TMT Operations Concept Document (OCD)
- We include key error budgets that allocate high-level PSSN requirements among sensor error terms
- We also include key requirements from the sensor-to-segment ICD

Outline

- High-level requirements
- Environmental & survival
- Compatibility with recoating process
- Power dissipation, sampling rate
- Required range of motion

- PSSN allocations
- Height error budget
- Focus mode error budget
- Gap error budget
- Sensor gain stability

- Boot and purge system requirements

- A few requirements from the MICD
- System attributes
- Summary

Overall requirements

High-level requirements

- Sensor are to be non-interlocking [0480*]
  - Driving requirement for ease of segment replacement
  - This is the major difference between the Keck and TMT capacitive sensors
- Sensor shall provide two outputs: height + dihedral angle, and gap [1020]
  - Formalizes M1CS approach to focus-mode control
  - Keck also had combined height output, but no gap output
- Leff > 45 mm [1330]
  - Design decision at M1CS level affecting the focus-mode error budget
  - Similar to Keck value, but error propagation different because of larger number of segments
- Gap readings to be used to correct the sensor height readings in the presence of in-plane motion [1040]
  - Formalizes M1CS approach to calibration of in-plane effects

* Requirement number in the sensor DRD

Environmental – Temperature, Humidity, Pressure

- TMT standard performance, functional ranges [0110,0115,0120,0140]
  - (survival requirements discussed later)

(A)	(B)	(C)	(D)
	Observing Performance Conditions	**Component Functional Conditions**	**Survival Conditions**
Ambient air temperature	-5C to +9C	-13C to +25C	-16C to +30C
Ambient air relative humidity	All non-condensing	All non-condensing	Condensing (0 to 100% RH)
Ambient air pressure	0.6 atm	0.6 to 1 atm	0.6 to 1 atm

  - Humidity is a driving requirement: requires humidity control at sensor head

Environmental – Dust

- Accommodate the dust environment in the enclosure; no cleaning/maintenance required except during biennial segment replacement [0160]
  - Environment not formally spec'd: however, we know from Keck that domes are dirty
  - Cleanliness is driving req't: requires dust boot around sensor
- High-level boot requirements [0162]
  - Any dust boot must not affect sensor readings
- Boot cleanliness: generate no particulates [0290]

Environmental – EMI/RFI

- Perform in presence of TBD EMI/RFI environment [0180]
  - Environment not formally quantified
  - However, sensors are susceptible to electronic pickup
    - Driving requirement: drives aspects of electronics design and requirement for ground continuity across gap

- And conversely…
  - The sensors shall not emit electromagnetic radiation that would interfere with or degrade the performance of systems or subsystems at the observatory [7410]
    - Not well defined…

Environment: earthquake

- 10 year return period earthquake: no damage [0240]
  - Expect no recalibration needed so long as no segment-to-segment contact occurs
- 200 year return period earthquake: two week recovery [0242]
  - Full recalibration assumed; some sensors may need remounting if have shifted due to segment-to-segment contact
    - Expect that these sensors can be identified during the initial phase of the recalibration process
- 1000 year return period earthquake: no damage to telescope optics [0244]
  - Not driving: sensors are not in the optics' load paths
- Power loss: no damage to telescope optics [0244]
  - Not driving
- Temperature and humidity survival range (e.g. condensing) [0220, 0230]
  - 0220 – allows for repeated exposures
  - 0230 – allows for 6 hour inspection
  - Note: if sensors indeed get wet, likely that new calibrations will be needed

Compatibility with recoating process

- Vacuum compatible: sensor and boot [0282, 0283]
  - Adopt some limits on allowable outgassing, but with assumed differential pumping in coating chamber, don't need to be UHV compatible
- Compatible with 50°C soaks [0296]
  - If required for segment coating/cleaning
- Compatible with cleaning/stripping/coating chemicals [0298]
  - There's a list in the DRD
  - While gold on Zerodur is pretty resistant, dust boots and PCBs are not:
    - *"Compatibility means that the sensors should ideally be insensitive to exposure to these chemicals, though some sort of cover or mask could also be an acceptable way to protect edge sensors during the stripping and recoating process"*

Power dissipation

- Average power dissipated to air by each sensor transmit and receive pair and local electronics shall be less than 200 mW [0440]
  - This is only the power dissipated directly at the segment – not at lower levels of the primary segment assembly (PSA)
  - Value comes from aero-thermal modeling
  - This is a driving requirement on the electronics

Electronics & control

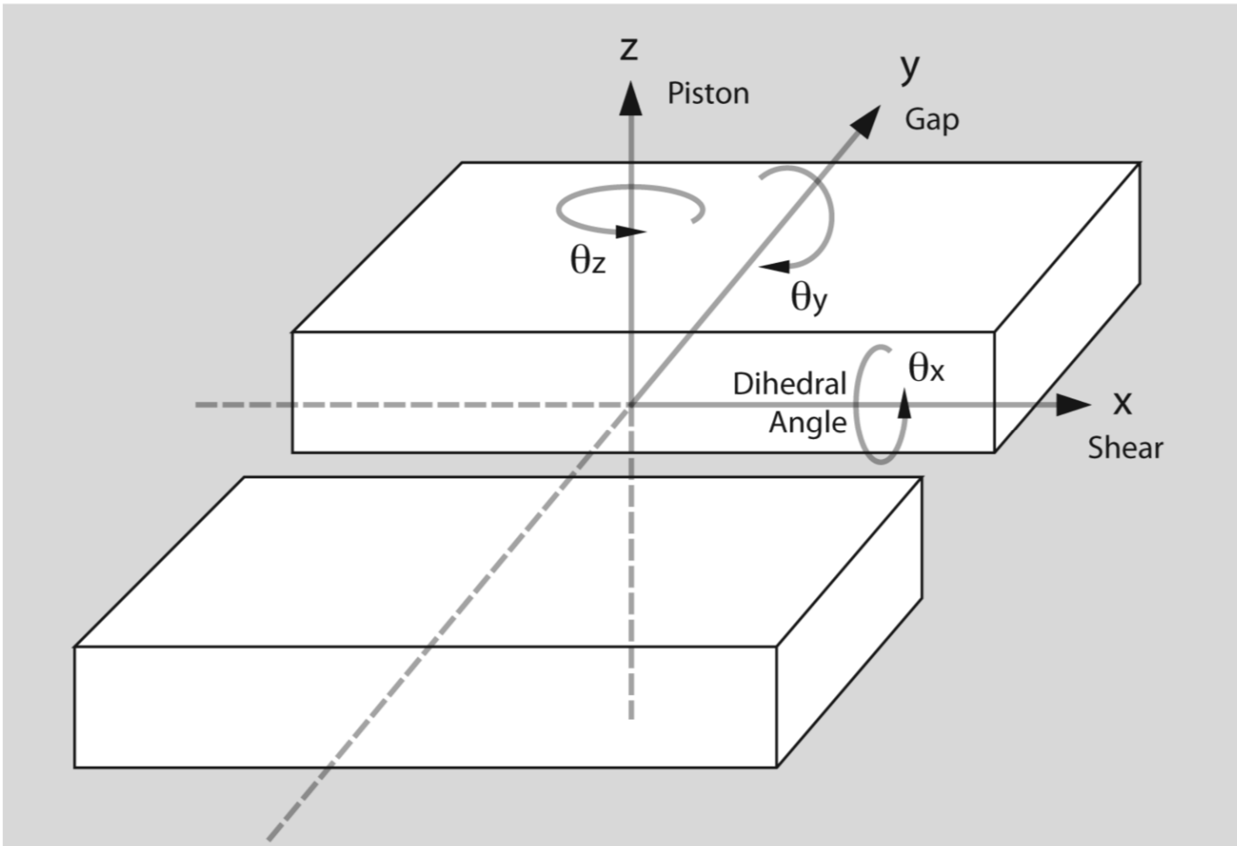
- Support up to a 40 Hz sampling rate for closed-loop operation [1600]
  - To support up to 2 Hz global bandwidths on high-order modes with minimal sampling delay
- Support up to a 400 Hz sampling rate for diagnostics [1620]
  - To support system identification (sys-ID) and other functions

- 60 minute (TBC) warm-up time to performance level [1060]
- Electronics are to be interchangeable [1080]
  - Although we assume recalibration is required if electronics or blocks are swapped or remounted

Range of motion for full performance

- The performance range for the sensors must accommodate [1100-1200]
  – Sensor (block and coating) fabrication errors
  – Pocket fabrication errors
  – Sensor installation errors
  – Segment installation errors
  – In-plane motion from thermal deflection
  – In-plane motion from gravity deflection
    - 0-80 degree range, i.e., 0-65 deg ZA plus mirror curvature [0140]

Sensor geometry



Performance range estimate

		Sensor fab (rms ea)	Pocket fab (rms ea)	Sensor install (rms ea)	Segment install (rms ea)	Thermal deflection (rms ea)	Gravity deflection (rms ea)	RSS (rms ea)	2 sigma, relative (max, pair)	Req't (max, pair)
thetaX (dha)	(mrad)	0.1	**0.5**	0.1	0.0	0.0	0.0	0.5	**1.4**	**1.5**
thetaY	(mrad)	0.0	**0.3**	0.1	0.0	0.0	0.0	0.3	**0.7**	**1.0**
thetaZ	(mrad)	0.1	**1.0**	0.4	0.3	0.0	0.1	1.1	**3.2**	**3.5**
X (shear)	(um)	40	25	35	**287**	24	57	299	**845**	**1000**
Y (gap)	(um)	**150**	25	35	**200**	36	85	270	**763**	**1000**
Z* (height)	(um)	10	0	1	0	0	0	10	**28**	**30**
*Pocket offsets (25 um rms) will be measured										

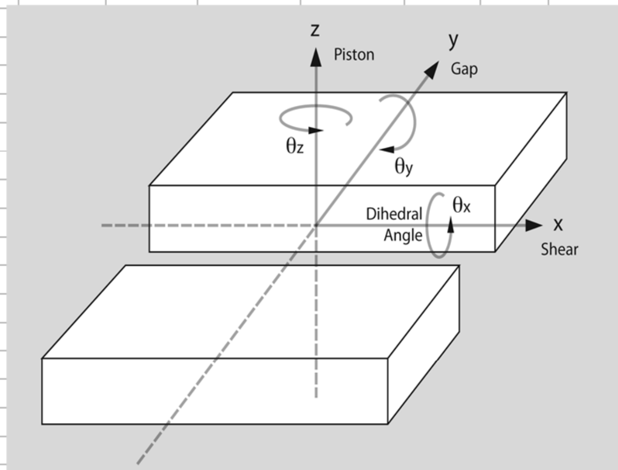
- These are reqs 1100-1200
- Pocket fabrication errors drive the angular ranges
- Sensor fabrication and segment install errors drive the linear ranges
- Z is a special case, and will be measured to meet APS requirement

Full spreadsheet with notes

			a	b	c	d	e	f	g	h	i	j	k	l	m			
0			Sensor block (max)	Sensor coating (max)	Segment pocket (max)	Installation allocation (max)	**Subtotal sensor install (rms)**	*Req't (rms)*	Segment install error (rms)	**Subtotal: sensor & segment install (rms)**	Relative error [x 1.41] (rms, rel)	Thermal (rms, rel)	Gravity (rms, rel)	Relative total install & ops (rms, rel)	**Relative total install & ops (max, rel)**			
1	thetaX	(mrad)	0.15	-	1	0.1	**0.5**	*1*		**0.5**	0.7			0.7	**1.4**	thetaX	(mrad)	dihedral angle
2	thetaY	(mrad)	-	0.08	0.5	0.1	**0.3**	*1*		**0.3**	0.4			0.4	**0.7**	thetaY	(mrad)	
3	thetaZ	(mrad)	0.20	-	2	0.8	**1.1**	*2.5*	0.285	**1.1**	1.6		0.08	1.6	**3.2**	thetaZ	(mrad)	
4	X	(um)	-	80	50	70	**59**	*500*	287	**293**	414	34.3	80	423	**845**	X	(um)	shear
5	Y	(um)	300	-	50	70	**156**	*350*	200	**254**	359	50.3	120	382	**763**	Y	(um)	gap
6	Z	(um)	-	20	50	1	**27**	*15 (max)*		**27**	38			38	**76**	Z	(um)	height

Notes

a1	0.01 profile tolerance on front of sensor with respect to the three feet; 67 mm sensor height[R1]
a3	0.01 profile tolerance of back surface with respect to front surface; 50 mm sensor width [R1]
a5	1 decimal thickness tolerance: 0.3 per title block [R3]
b2	0.003 profile tolerance wrt feet over 39 mm coating width [R1]
b4	2 decimal dimension: 0.08 per title block [R1]
b6	0.02 position tolerance with respect to feet [R1]
c1	See R2, note 10.
c2	See R2, note 10.
c3	See R2, note 10.
c4	0.01 profile tolerance wrt ideal surface (i.e., +/0.005) [R2]
c4	0.01 profile tolerance wrt ideal surface (i.e., +/0.005) [R2]
c6	40.000±0.050 from front surface [R2]
e0	Interpret max values as 2-sigma
g3	285 urad [R3, #4302]
g4	rss of 200 um [R3, #4304] and 1.44/2 x 285 urad [R3, #4302]
g5	200 um rms [R3, #4304]
i0	Assume independent contributions
j4	thermal clocking 6.8 urad/C, for 3.5C (1/4 of performance range) * 1.44/2 * 2 [R4]
j5	1.24m face to face * 3.5 deg [1/4 of performance range] * 11.6 ppm
k3	Adopt half of the variance of relative x motion as due to relative rotation
k4	1/2 of max X from [R5]
k5	1/2 of max Y from [R5]



References

R1 P2 Sensor 67 mm Drawing Set (TMT.CTR.DWG.11.012.REL02)
R2 M1S SEGMENT - M1CS EDGE SENSOR INTERFACE CONTROL DRAWING (TMT.SEN.DWG.09.007)
R3 M1 Optics System Design Requirements Document (TMT.0PT.DRD.07.007) (req 4302, 4304)
R4 Analysis: relaxation of segment clocking tolerance(TMT.OPT.TEC.07.033.DRF02)
R5 M1CS Calibration Analysis II (TMT.CTR.TEC.09.064)

Special requirements on the performance range for height

- The performance range for height shall be no less than ±100 micron prior to the application of any electronic offset [1140]
  - Accommodates Z installation errors
  - We expect a single sensor gain will suffice for this range
- The sensor shall meet all requirements over a relative height range of ±0.25 microns anywhere within the performance range [1142]
  - Accommodates apparent height change from in-plane motion
- The sensor shall provide an offset capability to the height output with a resolution of at least 0.5 micron [1145]
  - Allows the sensor to work close to null during observations, reducing requirements on integral linearity and gain stability

Operational range of motion

- Require smooth degradation outside of performance range [1220]
- For height, we require that the sign be correct over ±5 mm to accommodate the max difference between segments [1222, 1228]
- For the other degrees of freedom, we use twice the previous performance values [1224-1234]
- Max ZA = 105 deg to allow sensing with telescope at horizon [0150]

PSSN allocations and error budgets

PSSN allocations from the OAD/PSSN error budget

(a) Edge sensor noise	**0.9977**	Suballocation of M1-G: Segment Dynamic Displacement Residuals REQ-1-OAD-0420
(b) Edge sensor thermal drift	**0.9976**	Suballocation of M1-F: Segment Out-of-Plane Displacement REQ-1-OAD-0418
(c) Edge sensor calibration	**0.9980**	Suballocation of M1-F: Segment Out-of-Plane Displacement REQ-1-OAD-0418

- These are the three allocations ("Estimated Performance") for the edge sensors in the PSSN budget V15

PSSn (Point Source Sensitivity, normalized) is an image quality metric used for quantifying TMT's performance for seeing-limited observing.
PSSn = 1 is a perfect telescope. Deviations from unit PSSn quantify performance degradation.

Converting sensor noise to PSSN

- For higher order mirror modes (excluding focus mode)
  - **17 nm rms *uncorrelated*** noise on each sensor in the servo bandwidth
    - $\times$ 17 $\rightarrow$ 290 nm rms higher-order-mode OPD
    - **PSSN: 0.99**
- For focus mode
  - **9 nm rms *correlated*** drift on each sensor (Leff = 52 mm)
    - $\times$ 850 $\rightarrow$ 8 um rms focus mode OPD
    - **PSSN after refocus: 0.99**
  - Uncorrelated sensor noise has only a small effect on focus mode for the current sensor and the low focus-mode bandwidth [28 nm for 0.99]

Error budget allocations

- We adopt (a) Edge sensor noise: PSSN = 0.9977 for all random sensor height errors
  - In sensor space, it's 8.2 nm rms
- We adopt (b) Edge sensor thermal drift: PSSN = 0.9976 for all correlated sensor height errors (i.e., focus mode)
  - In sensor space, it's 4.4 nm rms

- These two values are the key sensor driving requirements

PSSN allocations - discussion

- The error budget allocates 0.998 for edge sensor calibration
- However, as will be seen tomorrow, the calibration modeling includes APS noise (which has a separate PSSN allocation) as required for proper error propagation
    - APS PSSN: 0.9955 (CBE from APS team)
- The calibration modeling also includes, using the FEM output and a thermal model, the optical consequences of segment in-plane motion (which have separate PSSN allocations)
    - Thermal clocking: 0.99984 (dT = 4K)
    - Decenter: 0.99956 (30→60 deg ZA)
- These various terms will need to be reconciled / reallocated at some point after this review
    - In addition, should decide if current allocations are appropriate
    - Also, should probably reassign sensor allocations to reflect how they're actually used

PSS Budget V15 M1-E (Segment In-Plane Displacement)

DRD.07.026.REL15													
						Estimated performan							
in-plane displacement (SIPD)		**0.99978**	**M1-E**			***Segment in-plane displacement (S***					**0.99988**		
Gravity induced	0.99990						*Gravity induced*			*0.99996*			*gravity mirror cell deformation*
Thermal induced	0.99988						*Thermal induced*			*0.99992*			*includes SSA clocking only -*
							Total NOT ESTIMATED			*1*			
**Not included in the Standard Year*		*1*								*1*			

PSS Budget V15 M1-F
Segment Out-of-Plane Displacement

TMT.SEN.DRD.07.026.REL15							
				Estimated performance			
Segment out-of-plane displacement (SOPD)		**0.99101**	**M1-F**	***Segment out-of-plane displacement (SOPD)***		**0.99304**	
APS measurement error - uncorrela	0.99700			*APS measurement error - uncorrelated*	*0.99714*		*WFS noise influencing APS interferomet*
APS measurement error - correlate	0.99500			*APS measurement error - correlated*	*0.99589*		*Atmospheric residual on high order APS*
Actuator repeatability	0.99999			*Actuator repeatability**	*0.99999*		*NOT ESTIMATED*
Edge sensor calibration	0.99950			*Edge sensor calibration**	*0.99800*		*Residual after calibration*
Other M1CS loop errors	0.99950			*Other M1CS loop errors**	*0.99950*		*NOT ESTIMATED (may include A-matrix*
				*Edge sensor thermal drift**	*0.99760*		*Assumes 2 nm correlated sensor drift (d*
				Total NOT ESTIMATED	*0.99949*		
**Not included in the Standard Year*		*0.99899*			*0.99510*		

PSS Budget V15 M1-G Segment Dynamic Displacement Residuals

TMT.SEN.DRD.07.026.REL15								
					Estimated performance			
Segment dynamic displacement residua			**0.98936**	**M1-G**	***Segment dynamic displacement residuals (S***		**0.99142**	
	Edge sensor noise	0.99600			*Edge sensor noise**	*0.99770*		
	Actuator noise	0.99990			*Actuator noise**	*0.99800*		*corresponds to ~4.4 nm*
	Segment wind buffeting	0.99400			*Segment wind buffeting*	*0.99700*		*mean over the Standard Year (*
	Segment micro-seizmic vibration	0.99993			*Segment micro-seizmic vibration**	*0.99999*		*based on site testing results a*
	Segment equipment vibration	0.99950			*Segment equipment vibration**	*0.99870*		
					Total NOT ESTIMATED	*1.00000*		
	**Not included in the Standard Year*		0.99533			*0.99440*		

Height error budget – intro

- The random sensor noise of 8.2 nm is allocated among the following terms

random terms		allocation		8.2 nm
req-1240	**Sensor noise**			
req-1500	**Temperature**			
req-1520	**Drift**			
req-1582	**Humidity**			
req-1400	**Linearity**			
req-1460	**Flexure**			
	Cross terms			

- These all apply after calibration, so that in general, these represent the unmodelable effects

Height budget – 1/4

random terms				**allocation**	**8.2 nm rms**		
				total	**7.4 nm rms**		
req-1240	**Sensor noise**	5	*nm rms*		5.0	*nm rms*	Noise in $\pi/2$ * 2 Hz bandwidth (2.8 nm/rHz)
req-1500	**Temperature**	1	*nm/K*		2.5	*nm rms*	adopt +/- 2.5 K range to approximate standard year; this is after calibration

- Random sensor noise is the largest term
  - 2 Hz is the max control bandwidth anticipated
  - This required value should be readily achieved by the electronics (at least with final cable lengths)
- The temperature term applies after calibration
  - We use $\pm$ 2.5 K to approximate the standard year
  - “After calibration” is important: even with ideal electronics, CTE mismatches among the sensor and segments contribute 2 nm rms

TMT
THIRTY METER TELESCOPE

Detail on non-electronic temperature coefficients

Jet Propulsion Laboratory
California Institute of Technology

- Segment tempco
  - Mean of all segments: a number between -40 and +40 ppb
  - rms difference of individual segments about that number: 25 ppb rms (50 ppb max)
  - For 40 mm pocket offset: 1.0 nm/K rms per pocket
    - » 1.4 nm/K rms effect on sensor (two uncorrelated pockets)
- Sensor block tempco
  - Expansion Class 1 Zerodur ($0 \pm 0.05\times10^{-6}$ K^{-1}) has similar properties as segments
  - For 37 mm effective sensor height: 0.9 nm/K rms per block
    - » 1.3 nm/K rms for sensor pair
- Total segment & sensor tempco
  - 1.9 nm/K rms
  - There is also a temperature effect from the CTE of the block hold-down rod and the finite compliance of the hold-down springs of 1.3 nm/K
    - » This should be common-mode, affecting all blocks
    - » The rod is also centered so that there should not be a dihedral-angle change with temperature

Height budget – 2/4

random terms				**allocation**	**8.2**	**nm rms**	
				total	**7.4**	**nm rms**	
req-1520	**Drift**	5	*nm rms @ 30days*		3.5	*nm rms*	adopt 1/2 variance for average over interval
req-1582	**Humidity**	2	*nm rms*		2.0	*nm rms*	

- For drift, the requirement is 5 nm rms after 30 days, i.e., applies to an ensemble of sensors
  - To accommodate standard year weighting, we adopt half the variance as the average over the interval; in reality, depends on the underlying statistics
  - Applies after a 24 settling time for newly installed sensors
- Humidity will be controlled by the boot: expect this term to be small

Height budget – 3/4

random terms				**allocation**	**8.2 nm rms**		
				total	**7.4 nm rms**		
req-1400	**Linearity**	0.10%			0.8	*nm rms*	applies over +/- 0.75 um closed-loop range
req-1460	**Flexure**	2	nm rms		2		see DRD: this represents unmodeled terms

- Linearity applies after application of the electronic offset
  - The offset to set the sensor near null allows for a fairly loose tolerance
- Sensor flexure represents unmodeled deviations from the sensor flexure model – not the calibration residual
  - This is a large effect before calibration. Even with an optimized block, the shear change of a single block is ~20 nm from zenith to horizon
  - This effect, slightly different for each sensor, is incorporated into the physical sensor model used in the calibration analysis

Height budget 4/4

random terms				**allocation**	**8.2 nm rms**			
				total	**7.4 nm rms**			
	Cross terms				1.6	*nm rms*	see DRD: this represents unmodeled terms	

Cross terms to height												
							(dist. subtotals)					
	Cross terms				**Disturbances**			thermal	gravity		**Product**	
Req 1300	X -> Z	**17**	*nm/mm*		X	**0.05**	*mm rms*	0.02	0.04		**0.8**	*nm rms*
Req 1320	Y -> Z	**17**	*nm/mm*		Y	**0.07**	*mm rms*	0.04	0.06		**1.2**	*nm rms*
Req 1360	thetaY -> Z	**20**	*nm/mrad*		thetaY	**0.00**	*mrad rms*	0	0		**0.0**	*nm rms*
Req 1335	thetaZ -> Z	**20**	*nm/mrad*		thetaZ	**0.04**	*mrad rms*	0.0	0.04		**0.8**	*nm rms*
									total		**1.6**	**nm rms**

- Cross terms represent unmodeled deviations from the sensor model
- We use deformations from the 2009 telescope FEM to approximate a standard year weighting
- The shear to height cross term, req 1300, is driving: it levies requirements on the straightness of the coating edges

Focus mode budget – intro

- As note above, the allocation for correlated sensor noise is 4.4 nm. This is allocated among the following terms

			allocation	4.4 nm rms
req-1502	**Temperature**			
req-1522	**Drift**			
req-1580	**Humidity**			

- These all apply after calibration, so that in general, these represent the unmodelable effects

Focus mode budget

				allocation	4.4 nm rms			
				total	4.3 nm rms			
req-1502	**Temperature**	1	*nm/K*			2.5	*nm rms*	adopt +/- 2.5 K range to approximate standard year; this is after calibration
req-1522	**Drift**	4	*nm @ 30days*			2.8	*nm rms*	adopt 1/2 variance for average over interval
req-1580	**Humidity**	2	*nm rms*			2.0	*nm rms*	should be small with boot

- The allocation for correlated errors is for control of focus mode
  - The larger Leff (52 mm) of the current sensor makes this budget more tractable than with the older value
- Temperature stability applies after calibration

Height and focus mode budgets – discussion

- Note that all of these terms, with the exception of random electronic noise, can be improved by optical feedback
- Note also that the focus mode control scheme is predicated on real-time sensing and control of focus (M2 position)
  - Focus mode from correlated sensor drifts has untenable error propagation without refocus

Gap error budget - intro

- The allowed noise on the gap does not flow directly from the PSSN error budgets
  - Rather, gap noise affects the accuracy of the calibration for in-plane motion
  - Based on calibration modeling results, the process is not strongly dependent on gap noise, and we levy a total requirement of 1 um rms in the same way as for the random height noise
  - The calibration process appears robust to correlated gap noise, and we do not levy a requirement for it

Gap error budget

Gap noise				total	0.9 um rms		
req-1280	**Sensor noise**	0.5	*um rms*		0.5	*um rms*	This is in 1 Hz bandwidth - probably much more than needed given rates of in-plane motion
req-1515	**Temperature**	0.25	*um/K*		0.6	*um rms*	adopt +/- 2.5 K range to approximate standard year; applies after calibration
req-1560	**Drift**	0.5	*um rms @ 30days*		0.4	*um rms*	adopt 1/2 variance for average over interval
req-1440	**Linearity**	0.10%			0.1	*um rms*	applies over 70 um rms range to approximate std year (see cross-terms tab)
	Cross terms				0.3	*um rms*	

Gap cross terms

Cross terms to gap												
Values of the cross terms in the DRD					**Disturbances**			(dist. subtotals)			**Product**	
						total		thermal	gravity			
Req 1340	X -> Y	**3**	*um/mm*		X	**0.05**	*mm rms*	0.02	0.04		0.2	um rms
Req 1350	thetaX -> Y	**5**	*um/mrad*		thetaX	**0.00**	*mrad rms*	0	0		0.0	um rms
Req 1355	thetaY -> Y	**5**	*um/mrad*		thetaY	**0.00**	*mrad rms*	0	0		0.0	um rms
Req 1380	thetaZ -> Y	**5**	*um/mrad*		thetaZ	**0.04**	*mrad rms*	0.0	0.04		0.2	um rms
										total	**0.3**	**um rms**

Additional stability requirements: Sensor gain stability

- Based on modeling results looking at the stability of the global control loop to A-matrix uncertainty, we adopt a total 0.1% sensor gain stability requirement, allocated as
  - Temperature sensitivity of 0 ± 0.01%/C after calibration [1518]
  - Temporal drift of 0 ± 0.05% in 30 days after calibration [1570]

Boot and Purge System (BPS) Requirements

Boot and purge system (BPS) requirements,1

- Driving requirements
  - The boot and purge system (BPS) shall maintain the local environment in the sensor gap, including the drive and sense surfaces, at less than 40% relative humidity in the performance range [0500]
    - Relatively humidity levels less than this value have only small effects on the sensors.
  - The boot and purge system (BPS) shall maintain the local environment in the sensor gap, including the drive and sense surfaces, at less than TBD dust level [0504]
    - Subject to TBD dust environment

Max allowed intersegment forces

- Max allowed intersegment forces from Optics Group [0163-0165]

Z (height)	0.05 N
Y (gap)	0.10 N
X (shear)	0.15 N

BPS requirements, 2

- The BPS shall not have a negative impact on mirror seeing [0510]
- The BPS shall provide gas to the dust boots at a temperature that is in equilibrium with the segment where the gas is being provided [0520]
- The BPS shall be designed to minimize the time required to mate/demate BPS components during segment removal and installation [0530]
  - Ideally the dust boots will require no handling at all during segment exchange (sliding interface).
- A local ground connection between members of each drive/sense pair shall be provided across the gap [0610]
  - The loop from drive to sense provides a large area for pickup of magnetic interference.
  - Ideally, the boot should provide a conducting path for grounding from one side of the gap to the other. However, this may difficult given the low allowed forces and the need for low interface friction between the boot halves (see previous slide)
  - Alternatively, and probably more reliably, an easily attachable/detachable ground wire could be used, similar to Keck

BPS requirements, 3

- BPS performance range of motion is same as that of sensor [0550-0570]
- BPS operational range of motion is same as that of sensor, except that up to +/- 10 mm can be accommodated [0580-0600]

- Particulates and outgassing
  – The BPS shall not produce particulate or chemical contamination [0640]
  – The BPS shall have less than 1% TML (TBC) and less than 0.1% CVCM (TBC) measured according to the ASTM-E595 standard test for outgassing (TBC) [0650]

BPS requirements, 4

- The BPS shall survive 200,000 (TBC) cycles of the full performance range of motion without loss of performance [0620]
- The BPS shall survive 200,000 (TBC) cycles of the full operational range of motion without loss of performance [0630]
  - 200k cycles corresponds to 10 cycles per night for 50 years. In reality, however, the instantaneous motion per night will likely include more cycles but a much smaller range. This will need to be refined later, but should not be hard to meet.

-Key MICD Requirements
-System Attributes
-Summary

Selected Requirements from the MICD (more discussion in the interfaces presentation, later)

- [INT-SEN-M1-0130] The maximum mass of the sensor block shall be 200 g [TBC]
- [INT-SEN-M1-0140] The mass of the sensor block shall be measured to +/-1 g prior to delivery.
  - The CBE as of Feb 2012 is 180 g for the block
  - The mass of the sensor affects the optimization of the M1 segment support
- [REQ-3-M1CS.SEN-0660] Components of the BPS attached to the segment glass shall have a mass of less than 100 g per sensor half (TBC)
  - The CBE as of Feb 2012 is 70 g for the 3-piece boot
- [REQ-3-M1CS.SEN-0665] Components of the BPS attached to the segment at each sensor edge shall have masses that are consistent from unit to unit within 5 g (TBC) per sensor half
  - These last two requirements are currently in the DRD, but should probably be moved to the ICD

Boot and Mass Budget, ref.

Draft sensor & boot mass budget			
	mass (g)	uncertainty (g)	basis
Single block (drive or sense)	180	5	SolidWorks model, scaled from Al (2.7 g/cm3) to Zerodur (2.53 g/cm3); consistent with mass scaled from measured shorter sensor
Drive cables	2	1	measured Cooner CW2040-3675-SR silicone jacketed 75 ohm coax: 0.13g/in; two 6" cables on drive, one 6" on sense: use avg of 9" for each; est. 0.5 g for connector
Puck	3	1	measured
Bellevilles (4)	1	0	McMaster PN 9713K58 0.375" OD x 0.19" ID x 0.015"
Flat washer	0	0	McMaster PN 90107A010 0.375" OD x 0.17" ID x 0.02-0.04"
Nut	0	0	measured zinc plated steel, Bossard BN40132 M2.5 nut, scaled to stainless
Threaded rod	2	1	measured brass rod, scaled to stainless
Boot 3 pieces + springs	70	23	Measured 2 boots: 53 g and 56 g. Slight differences in springs and bases account for most of difference. Significant uncertainty due to final design and material. Using 1.21 g/cc for Accura 50 SLA material for measured boots (http://www.proto3000.com/uploads/Accura50.pdf). Scale to Delrin 570 (glass filled, 1.56 g/cc). [Note other Delrins: Delrin 100: 1.42 g/cc, Delrin 500AF: 1.53 g/cc).
Effective mass of purge tube and connector	6	3	wag. Will be either PTFE or Polyprop. - neither is very heavy.
Sensor PCB	11	3	measured 10.5 g drive, 10.9 g sense. Board will change for final design
Sensor elex packaging: conformal coating, shielding	3	2	wag - 30% of board mass
Effective mass of digital cable and connector	6	3	Shielded cat6 1g/in; estimate 6" effective non-relieved mass - likely to change
	284	**42**	15%

Reliability, 1

- **[REQ-3-M1CS.SEN-6100]** The edge sensor system shall be designed for a 50 year operational lifetime
- **[REQ-3-M1CS.SEN-6200]** The sensor system shall comply with the TBD sensor allocation of the downtime budget
  - This is the current OAD downtime budget

[REQ-1-OAD-0328]	M1 Control System (M1CS)	0.73%	
[REQ-1-OAD-0330]	Sensors		0.17%
[REQ-1-OAD-0332]	Actuators		0.48%
[REQ-1-OAD-0334]	Control & misc		0.08%

  - We assume that reallocations are acceptable so long as the top level number is maintained
  - We expect reliability to be a matter of electronics and interconnects

Reliability, 2

- **[REQ-3-M1CS.SEN-6220]** The sensor system shall comply with the TBD sensor reduced-performance budget
  - This is a known open item
  - The GLC controller has almost 2× redundancy between edge sensors (2772) and actuators (1476 [-ptt])
    - Thus a large number of non-clustered bad sensors can be accommodated so long as their locations are known and the controller updated
    - Keck usually operates without a full sensor complement
- **[REQ-3-M1CS.SEN-6240]** Line-replaceable units of the sensor system shall be replaceable in less than 10 minutes (TBC) by a trained technician
  - Given the above discussion, except for clustered failures, failed sensors would likely only be replaced during segment removal/recoating; TBC needs refinement based on this

Maintainability

- As a goal the sensors will require no regular scheduled maintenance. It shall not be necessary to remove, release, or otherwise "manage" the sensors in order to remove a primary mirror segment from the telescope. It is acceptable to disconnect electrical cables. [8000]
  - The first item is a goal: probably should have been written more clearly as no regular scheduled maintenance except during segment replacements
  - Electrical cables would include the ground cable previously discussed
  - We expect there to be only a single power/signal umbilical per PSA.
- All the tasks necessary to fully service a sensor during its scheduled servicing shall take no longer than 20 minutes per sensor (TBC) [8105]
  - This would likely include inspection and dry-gas or CO2 cleaning
    - The actual servicing operations and procedures would be defined in the sensor maintenance plan

Summary

- The sensor requirements are very demanding
  - Tight error budgets
  - Face-on geometry drives various sensitivities
- Key driving requirements
  - Non interlocking
  - Accommodate humidity and dust
  - Thermal and temporal stability
  - EMI (operation at low signal levels)
  - Low power dissipation
  - Edge lithography requirements

P04_Sensor Downselect Overview

Chris Lindensmith

M1CS Sensor System Preliminary Design Review

Pasadena

March 29 - 30, 2012

Outline

- Sensor Development History
- Sensors Evaluated
  - Capacitive
    - Without dry purge
    - With dry purge
  - Inductive
    - “Flex” coils on polymer substrate
    - Direct deposit on glass
- Sensor Evaluation Comparison
- Summary

Sensor Development History

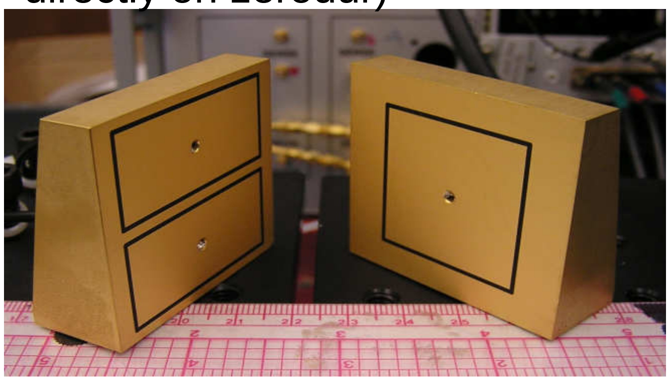
- Started with P1 Cap sensor developed at LBNL
- Later split into two paths
  - Continuation of capacitive development at JPL
  - New development of inductive sensor by Fogale Nanotech (France)
    - Several different implementations of the inductive sensors were investigated to various degrees.
- Also looked at other sensors in less depth:
  - Optical sensors from Heidenhain
  - Inductive sensors from Micro-epsilon
- Led to a downselect between capacitive (designed by JPL, build anywhere) vs. inductive (Fogale)
- Recommendation at downselect was to continue with capacitive sensors
  - Inductive sensor was promising but additional development required resulted in higher risk.
  - Inductive sensor was also effectively only available from a sole-source (Fogale)

Sensors Evaluated

- Used predicted Prototype 2 (P2) performance of sensors for baseline scores
- Cap sensor
  - Used predicted P2 performance with and without purge (using measured performance with improved front end electronics)
  - Worst case used humidity sensitivity shifted to onset at lower RH
- Inductive sensor – flex technology: prototype developed
  - Based on measured performance from prototype development with two improvements
    - Block thickness increased by 20%
    - Dummy sensor glued to back to compensate for bimorph
    - Assumed a factor of 2.8x improvement for the two changes
  - Worst case assumed performance of current sensor
- Inductive sensor – Direct Deposit on Glass (DDG) – design only, no prototype
  - Assumed it has no humidity sensitivity
  - Assumed same temperature sensitivity as flex inductive sensor
  - Higher risk because it’s in very early development

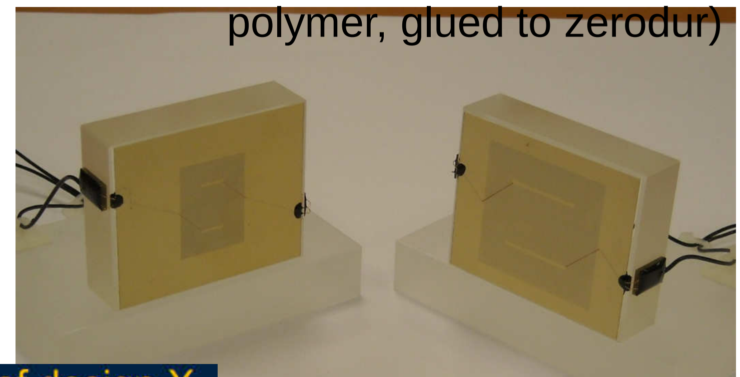
Sensors Evaluated

LBNL Capacitive Sensor (Thin gold electrodes deposited directly on zerodur)

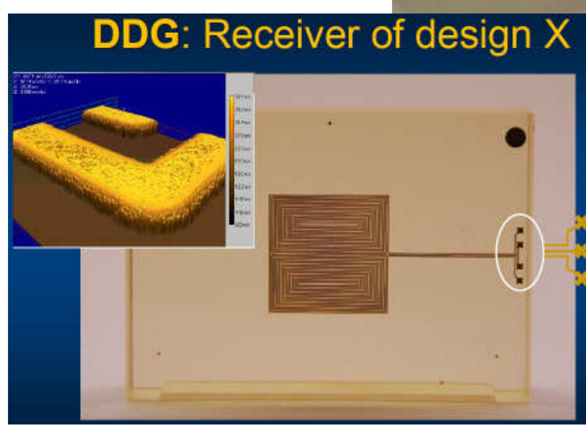


Both types of sensor were evaluated in a variety of configurations

Fogale Inductive Sensor Baseline (Coils on flexible polymer, glued to zerodur)



Fogale's alternative design, "Direct Deposit on Glass" was promising but at the time of selection there were difficulties in getting sufficiently thick precision coils at Fogale and in parallel development at JPL.



PSSN comparison
All Sensors Considered

- Numbers the table have quasi-static focus mode errors removed, i.e., all sensor errors are assumed to be uncorrelated
- Contributions to error from various sources are shown
  - Inductive sensor "worst case" column is the performance achieved as of the downselect
    - Highlighted column performance depended on improvements with some high risks, as well as unvalidated models of humidity performance
    - Adding a purge boot to the flex sensor would have negated the perceived advantages that led to its consideration
  - Cap sensor values assumes electronics redesign to improve temperature coefficients

	Cap Sensor Worst Case Humidity	Cap Sensor (no purge)	Cap Sensor (purge)	Perfect Cap Sensor	Perfect Inductive Sensor	Flex Inductive Sensor	Flex Inductive Worst Case humidity and temp
Piston Measurement Noise	0.9998	0.9998	0.9998	1.0000	1.0000	1.0000	1.0000
Piston Measurement Drift (30 days)	0.9983	0.9983	0.9983	1.0000	1.0000	0.9999	0.9999
humidity effect	0.9629	0.9956	1.0000	1.0000	1.0000	0.9999	0.9999
temperature effect head	0.9999	0.9999	0.9999	1.0000	1.0000	0.9998	0.9925
temperature effect electronics	0.9997	0.9997	0.9997	1.0000	1.0000	0.9998	0.9998
Mounting Misalignment	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980	0.9980
Total Sensor PSSN	**0.9588**	**0.9914**	**0.9957**	**0.9980**	**0.9980**	**0.9973**	**0.9901**

Quasi-Static Focus Mode Budget

- Correlated sensor errors with non-zero mean can lead to large quasi-static focus mode errors
- Numbers in the table show allowable quasi-static focus mode errors after subtracting all non-QSFM errors from the sensor PSSN allocation.
- Allowable sensor errors are computed assuming that all QSFM is due to correlated sensor errors with non-zero mean, and focus is corrected by the OIWFS.
- This led to increasing the height of the sensors (described later).

Allowable quasi-static focu	Cap Sensor Worst Case Humidity	Cap Sensor (no purge)	Cap Sensor (purge)	Perfect Cap Sensor	Perfect Inductive Sensor	Flex Inductive Sensor	Flex Inductive Worst Case humidity and temp
Remainder available for QSFM (PSSN)	1.0000	1.0000	0.9998	0.9975	0.9975	0.9982	1.0000
Allowed QSFM sensor error (nm)	**0.0**	**0.0**	**0.76**	**2.55**	**1.80**	**1.54**	**0.0**

PSSN Comparison
Summary of High Order Performance

	Cap Sensor	Inductive Sensor
Perfect Sensor	**0.9980**	**0.9980**
Nominal Sensor no Purge	**0.9914**	**0.9973**
Nominal Sensor with Purge	**0.9957**	**0.9974**
Worst Case RH and T no Purge	**0.9588**	**0.9901**
Worst Case RH and T with Purge	**0.9914**	**0.9901**

Sensor PSSN Allocation=0.9955

- "Perfect Sensor" is limited by segment mounting accuracy in both cases and has no other errors.
- PSSN shown for all sensor cases does not include quasi-static focus mode errors
- Purged Cap Sensor and Unpurged Inductive Sensor achieve similar performance within model uncertainty.
- Strengths and Weaknesses tipped evaluation in favor of Purged Cap Sensor

Major Strengths

Cap Sensor with Purge	Flex Inductive Sensor
• No significant memory effect • TMT owns design • Cap sensor head is very simple mechanically robust construction (gold on Zerodur) • Based on 15 years of Keck experience	• Less sensitive to RH without purge • Less sensitive to contamination • Not sensitive to molecular contamination • Better min/max performance (can't give errors of 1000 nm)

Major Weaknesses

Cap Sensor	Flex Inductive Sensor
With purge system ⬣Requires a dust boot and purge system ⬣Purge system may apply only extremely small force across segment gap **Without purge system** ⬣Has high humidity sensitivity ⬣Requires a dust boot ⬣Risk of extrapolating Keck performance to a TMT sensor ⬣No way to know if it's clean enough without putting in RH chamber ⬣Cap sensor is subject to unpredictable contamination effects having a very large effect	⬣Humidity effect depends on a model that isn't fully validated ⬣Truly a sole source, no second vendor ⬣Additional development is needed to reduce RH and T sensitivity (~ factor of 3 to 5 needed) ⬣Water memory in the epoxy layer ⬣Not demonstrated in an operational system (never used so far as we know)

Minor Strengths

Cap Sensor with Purge	Flex Inductive Sensor
• Geometry is defined by lithography • Error multiplier is smaller than for inductive • Sensor head design is mature • Less sensitive to EMI (built in faraday shield) • TMT can build new components if vendors disappear • Surface scratch is just an offset in piston calibration	• May not require a dust boot • Electronics is nearly plug and play • Turnkey vendor is identified • Potential Electroplated sensor head as a backup for mitigating some risks • Lower power • Remote electronics (no electronics on PSA) • Noise is lower for both gap and height • Smaller height dependence with gap

Minor Weaknesses

Cap Sensor	Flex Inductive Sensor
⬣Dihedral sensitivity is more gap dependent ⬣High impedance designs more subject to contamination ⬣Prototype electronics have high T sensitivity: requires electronics redesign during P2 ⬣Probably requires periodic cleaning ⬣Requires on-segment pre-amp ⬣Don't have a turnkey vendor identified	⬣Sensitive to changes in nearby metal components (e.g. mounting screw) ⬣Coils are potentially susceptible to minor damage causing sensor failure (dig through LCP can destroy coil turns) ⬣Less physical intuition into function (model isn't simple analytic model) ⬣EMI management requires more planning and bookkeeping ⬣Multi-layer structure (LCP, epoxy, metal) remains a lifetime concern (e.g. temp cycling in vacuum chamber) ⬣Cost is sensitive to exchange rate ⬣Future support for spares and replacements given that Fogale is small company ⬣Management issue of an overseas contract including language/communication

THIRTY METER TELESCOPE

Jet Propulsion Laboratory
California Institute of Technology

Summary

- Both sensors needed additional development work
- Cap sensor needed:
  - Redesign of electronics
  - Development of a purged boot system
- Inductive sensor needed:
  - Improvements in temperature and RH performance that were complicated by the multi-layer structure that included epoxies
- Capacitive sensor was overall preferable over inductive sensor
  - Has additional advantage of being a TMT-owned technology, allowing more vendor choice.

Sensor Selection Statement

- Selection committee recommended a "Capacitive sensor, with a purge system…"
- Additionally, the committee recommended investigation of alternative methods of controlling quasi-static focus mode error due to the small correlated-error budgets of the edge sensors.

Selection Statement:
"The M1CS Sensor Down-Select committee recommends that the TMT Project Office adopt the LBNL capacitive sensor, with a purge system, as the baseline edge sensor for the M1CS and for future development work leading to design for manufacturability efforts and eventual full scale production. The committee emphasizes that this recommendation is contingent on the development and inclusion of a purge system to minimize humidity effects."

TMT
THIRTY METER TELESCOPE

JPL
Jet Propulsion Laboratory
California Institute of Technology

P05_Detailed Description and Performance I Blocks, Coatings, Interconnects

Chris Lindensmith

M1CS Sensor System Preliminary Design Review
Pasadena
March 29 - 30, 2012

Outline

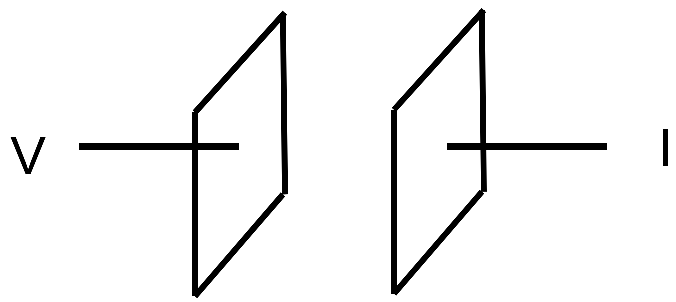
- How the capacitive sensor works
  - Cap sensor physics
  - Principles behind the TMT cap sensor
  - Brief TMT sensor development history (mechanical)
- Error Budget and Design
- Mechanical Design
- Coating Design
  - Requirements
  - Capability
- Interconnect and Cable Design

Objective

- Describe how the sensor works
- Show that edge sensor detailed design was driven by performance requirements
  - Mechanical fabrication
  - Mechanical stability
  - Environmental stability
- Show that the detailed design meets the requirements

Physics of Capacitive Sensors

- A change of voltage in one metal plate induces a charge flow (a current) in another metal plate
- The proportionality constant is "capacitance"
- MKS units are meters, volts, coulombs, farads



$$C\Delta V = \Delta Q$$

$$C = \varepsilon_0 \frac{Area}{Gap}$$

$$\varepsilon_0 = 8.854\,10^{-12}\,(MKS)$$

- A capacitive sensor has one or more drive plates excited with AC voltages, which induce AC currents in one or more sense plates
- There is significant freedom of expression, in shape, spacing and number of drive and sense plates, and in excitation waveforms

Practical Rules of Thumb for Parallel Plate Cap Design

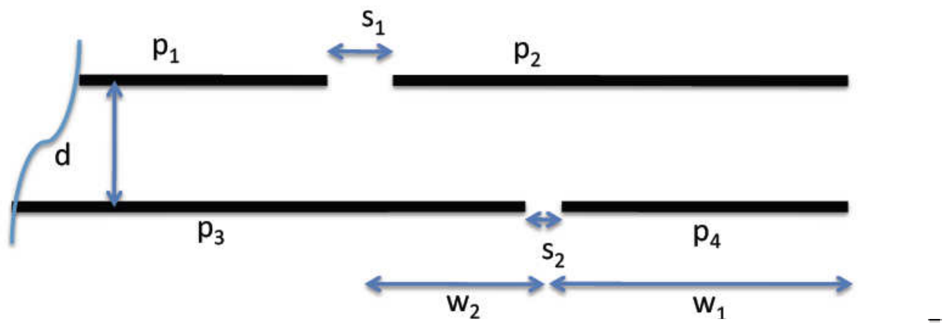


Figure 1 Example of two electrodes p_1 and p_3 with guard bands p_2 and p_4 and the dimensions for describing the capacitive sensor design rules. The electrodes p_1 and p_3 extend infinitely t the left.

Analytic solutions to Laplace's equation for useful cap sensors can be difficult (or impossible) to solve analytically, but if the following rules are followed then the simple parallel plate equation ($C=\varepsilon A/d$) is good to 1 ppm

- Rule 1: If $d/s_1 > 4.5$, then we can treat s_1 as infinitesimal and the boundaries of p_1 and p_2 are at the center of the separation
  - Our design complies with this rule
- Rule 2: If rule 1 is true, then we can also ignore fringe effects at the edges if $w_1, w_2 > 4.5d$
  - Our design complies with this in some dimensions and not others (due to space constraints). In the worst case, the deviation from parallel plate is 1/1000, with a very stable environment so that fringe effects will be stable and consistent.

We can thus treat the sensor as a pair of parallel plate capacitors.

TMT Capacitive Edge Sensor Concept

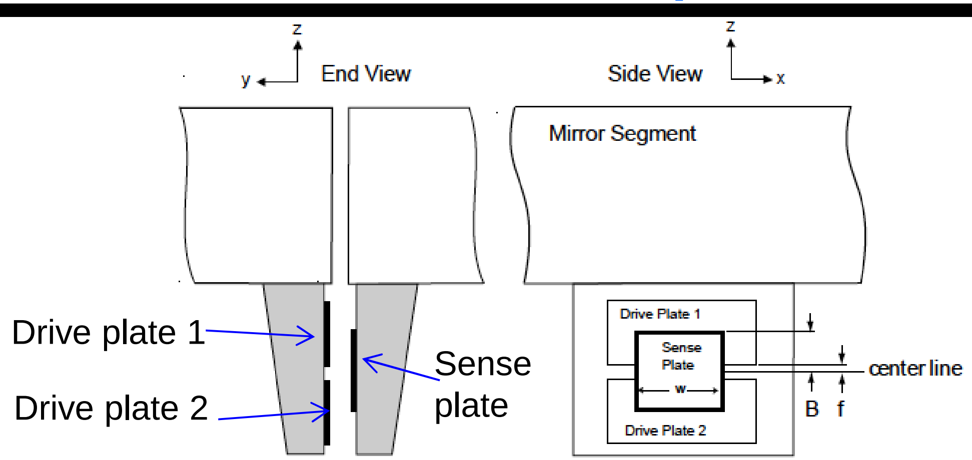
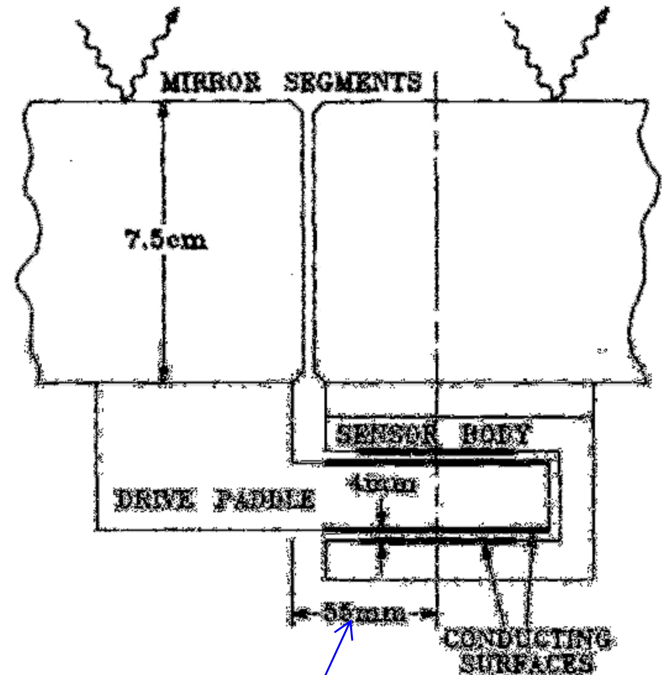


Figure 3-1 TMT Capacitive Sensor Geometry

- For Height Measurement
  - The drive plates are driven out of phase with each other
  - Height signal is proportional to (sense-to-drive1 overlap area) - (sense-to-drive2 overlap area).
  - Tilt signal (for measuring focus mode) is proportional to 1/(sense-to-drive1 gap) - 1/(sense-to-drive2 gap).
- For Gap Measurement
  - The drive plates are driven in phase with each other
  - Gap signal is proportional to the sum (vs. difference) of the currents induced by drive1 and drive2, and is proportional to 1/gap.

Keck Capacitive Edge Sensor

- Height signal is proportional to:
  1/(upper gap) – 1/(lower gap)
- Dihedral angle (tilt) sensitivity is provided by the 55 mm physical lever arm.
- The ratio of height to tilt sensitivity is called the effective lever arm, or *L*.
- **This parameter is important for controlling "focus mode" errors**



$$Sensor\_reading = z + L\theta_x$$

L=55 mm

"L effective"

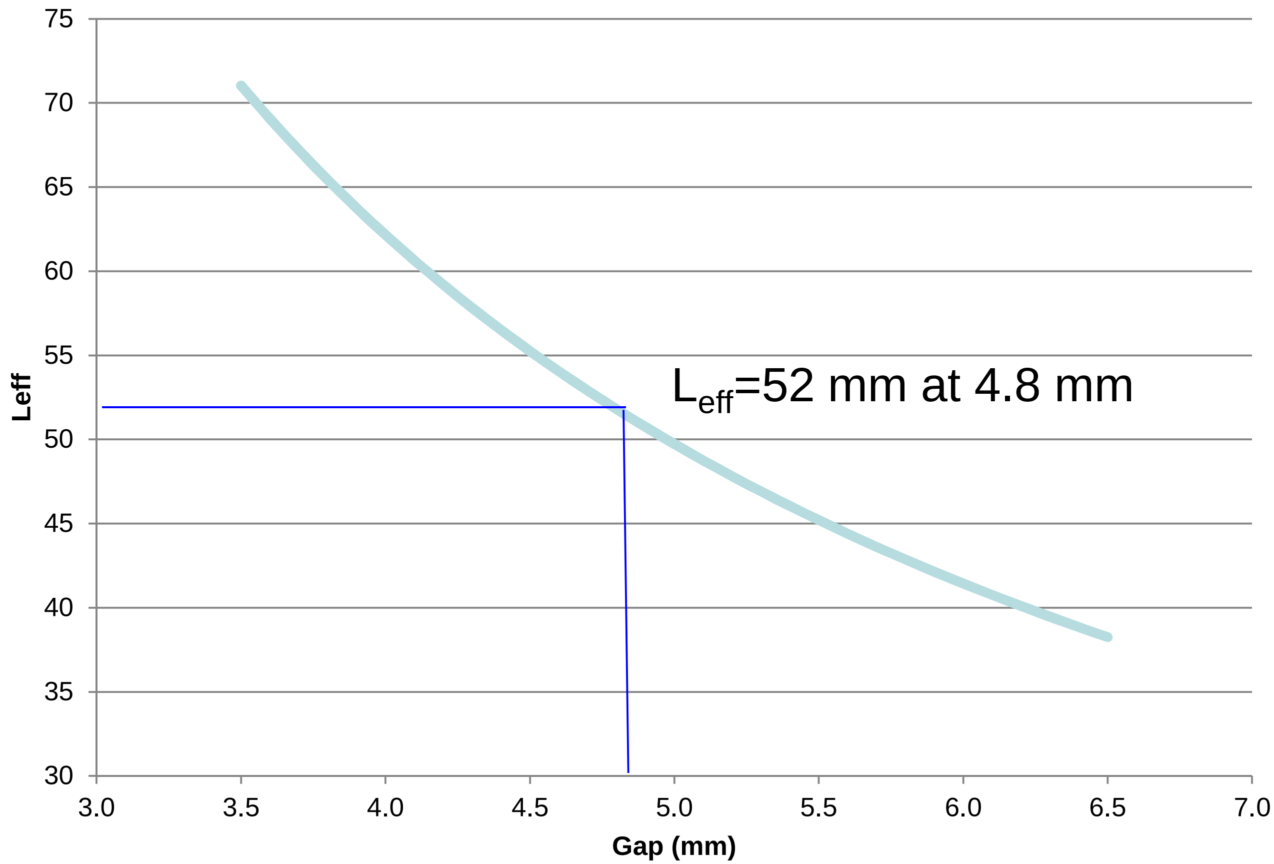
The TMT sensor doesn't have a real lever arm like the Keck sensor, but has an equivalent parameter: the output sensitivity to θ_x. We call this parameter L_{eff}.

- $L_{eff} = dV_z/d\theta_x$
  - Z output and θx output are combined into a single output:

$$V_z = z + L_{eff}\theta_x$$

- For a Keck style sensor, $L_{eff}=L$
- For a face-on style sensor, L_{eff} is set by the geometry of the drive and sense electrodes
  - Achieving high L_{eff} depends on height of sensor and is constrained by segment exchange requirement
- L_{eff} is gap dependent for the face-on sensor.

L_{eff} vs. Gap for TMT Cap sensor



TMT nominal sensor gap is 4.8 mm

P1 Capacitive Sensor Analytic Model (Height)

$$R = \frac{2\pi f_s \varepsilon_0 w V}{y'}\left(k(B-f) - z' - x'\theta'_y + L_{eff}\theta'_x\right)$$

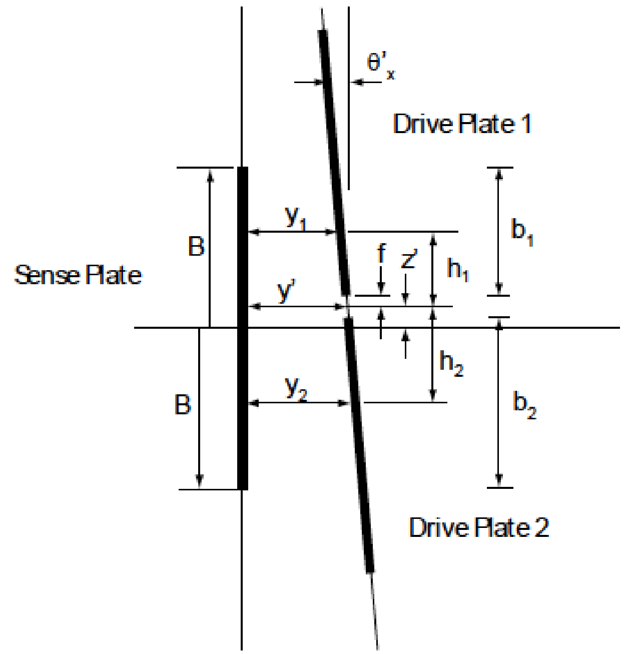
Gap (y')

Height Offset Trim (k)

Height (z')

Shear to Height Crossterm ($x'\theta'_y$)

Dihedral Angle ($L_{eff}\theta'_x$)

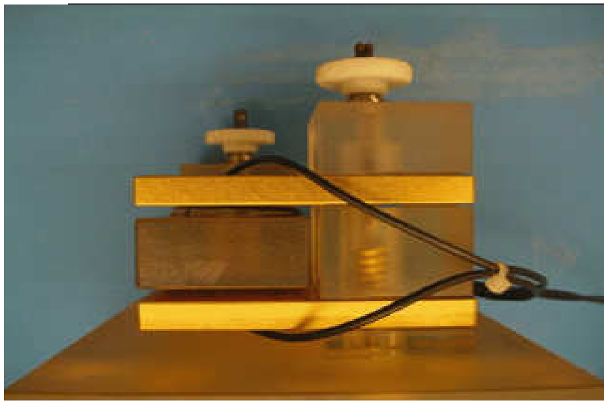


R	Sensor reading per drive edge (coulombs)
ε_0	8.854 × 10^{-12} farads / meter
f_s	Drive frequency (50 kHz)
w	Sense plate width (30 mm)
V	Drive amplitude (8.192 V_{pp} max, 4.8 V_{pp} typ)
2B	Sense plate height (45 mm)
2f	Spacing between drive plates (6 mm)
y	Gap from drive to sense (4.8 +/- 1.2 mm)
k	Height offset parameter supplied through the electronics
$\theta'_x\ \theta'_y$	Relative angles of the sensor halves about the *x* and *y* axes

$$L_{eff} = \frac{B^2 - f^2}{2y'}$$

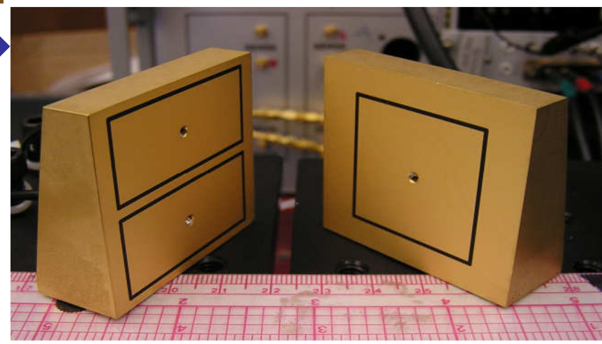
Full derivation is in TMT.CTR.TEC.11.003

TMT Capacitive Sensor Evolution



Keck Sensor
- 9 pieces of glass per sensor
- L_{eff} = 55 mm
- Glass spans the intersegment gap
- Significant handling during segment exchange
- Measures only height
- Requires custom shim for each sensor

TMT Sensor (LBL)
- 2 pieces of glass per sensor
- 45 x 50 x 20 mm wedge
- L_{eff} = 24 mm (at 4.5 mm sensor gap)
- Nothing spans segment gap
- No handling during segment exchange
- Measures height and gap
- Glue-down mounting



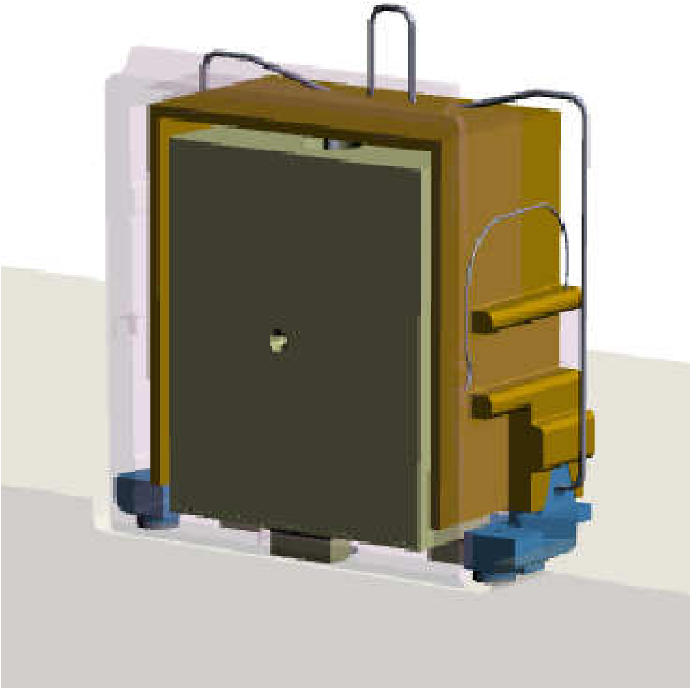
TMT Prototype Sensor (JPL)
- Added feet for glass-glass mounting, and pocket on segment side
- 52 x 50 x 20 mm (height increase due to feet)
- Mount with bonded puck + threaded rod through sensor
- Increased drive plate separation and moved connection holes to reduce effect of connection points on measurement
- Mounts to machined segment pocket
- Foot setback accommodates purged boot

Prototype Summary

- LBNL prototype
- JPL Prototypes
  - 52 mm tall
    - First Mindrum unit
    - 15 Pairs from Mindrum
      - 5 micron ground surface finish
        - Mechanically masked coating – edge quality not acceptable
          - Parylene coated (for RH testing)
          - AMCX-18 coated (for RH testing)
        - Photolithographic coating (from Williams/TFT) – edge quality limited by surface finish
      - Polished (60/40 scratch/dig) surface finish
        - Photolithographic coating (from Williams/TFT) – good edge quality
  - 67 mm tall
    - No coated version yet

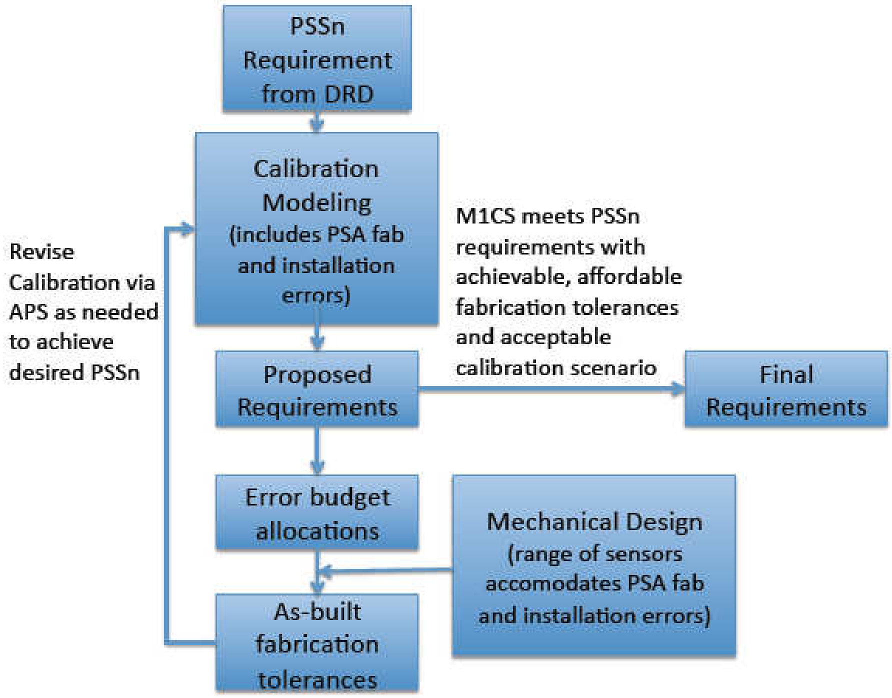
Current Sensor Design

- Increased height to 67 mm to get L_{eff} > 45 mm to provide margin against correlated errors
- Reduced gravity sag with increased foot size.
- Mounting hole location set to prevent tilt from mounting force change (from installation or thermal effects)
- New coax cable is more flexible and has lower capacitance (lower shunt capacitance leads to lower noise)
- Foot locations adjusted and width increased to 24 mm accommodate increased clearance for etching and bonding of puck (relaxed tolerance on etching location lowers cost)
- Includes purged dust boot with no handling required for segment exchange
- Electrode hole locations and tolerances adjusted to reduce manufacturing cost



Error Budget Development

The details of the error budget (shown in P03 and repeated on the next slide) were developed iteratively, integrating the in situ calibration process with the mechanical design and fabrication.



The error budget drives the tolerances of many of the fabricated parts of the edge sensor system.

Error Budget

This presentation covers block and coating fab.

		Sensor fab (rms ea)	Pocket fab (rms ea)	Sensor install (rms ea)	Segment install (rms ea)	Thermal deflection (rms ea)	Gravity deflection (rms ea)	RSS (rms ea)	**2 sigma, relative (max, pair)**	**Req't (max, pair)**
thetaX (dha)	(mrad)	0.1	**0.5**	0.1	0.0	0.0	0.0	0.5	**1.4**	**1.5**
thetaY	(mrad)	0.0	**0.3**	0.1	0.0	0.0	0.0	0.3	**0.7**	**1.0**
thetaZ	(mrad)	0.1	**1.0**	0.4	0.3	0.0	0.1	1.1	**3.2**	**3.5**
X (shear)	(um)	40	25	35	**287**	24	57	299	**845**	**1000**
Y (gap)	(um)	**150**	25	35	**200**	36	85	270	**763**	**1000**
Z* (height)	(um)	10	0	1	0	0	0	10	**28**	**30**
*Pocket offsets (25 um rms) will be measured										

- ❑x and ❑y are the most critical tolerances for calibratibility.
- Sensor fabrication and segment install errors drive the linear ranges
- Z is a special case, and will be measured at installation to meet APS requirement

Sensor Blocks and Coatings

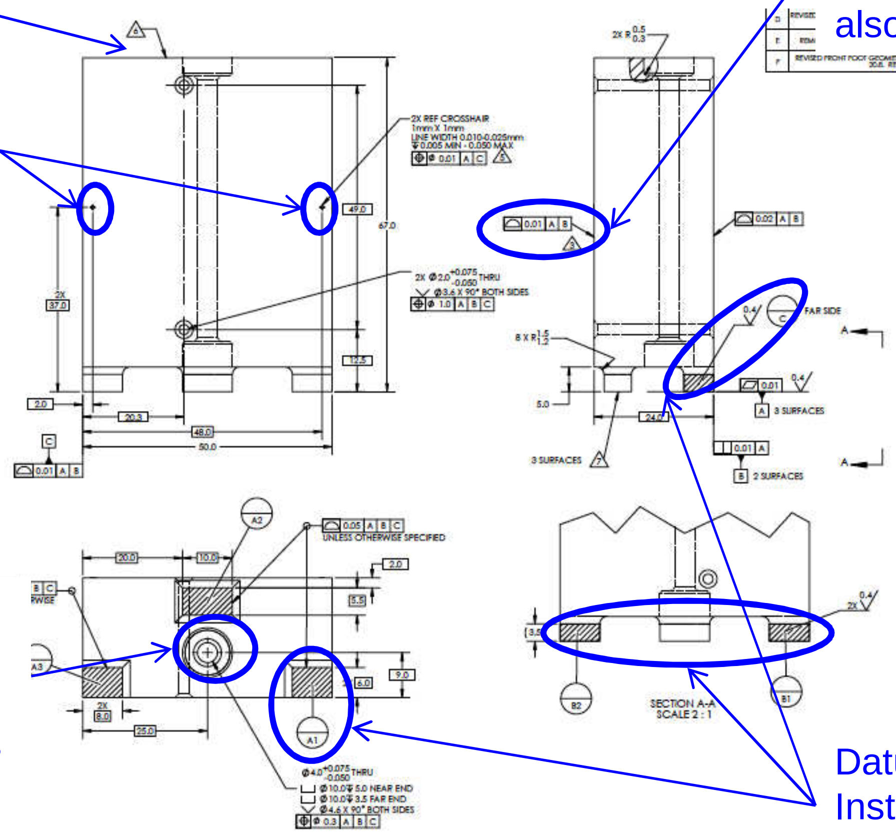
- The edge sensor blocks and coatings were designed in combination with the mounting system and interface to produce a complete system that complies with the error budget after installation.
- The edge sensor blocks (prior to coating) are nearly identical (except the feedthrough holes) for the drive and sense sides so that as much fabrication and QA as possible is common to both.
- Both block drawings are shown in the next two slides, with key features highlighted. **All key features are common to both blocks.**
- Tolerances on the blocks and coatings are all well within fabrication and measurement capability for a typical precision fabrication and inspection shops.

Drive Side Block Drawing

Material is Expansion Class 1 Zerodur for low CTE

Front face profile controls θ_x error relative to foot surface; also controls y error

Crosshairs are reference points for the coating process



Mounting hole is located so that all feet have equal pressure to prevent tilt change due to mounting force changes

Datums are matched to Installation Reference Points

Full drawing is at [TMT.CTR.DWG.11.008](TMT.CTR.DWG.11.008)

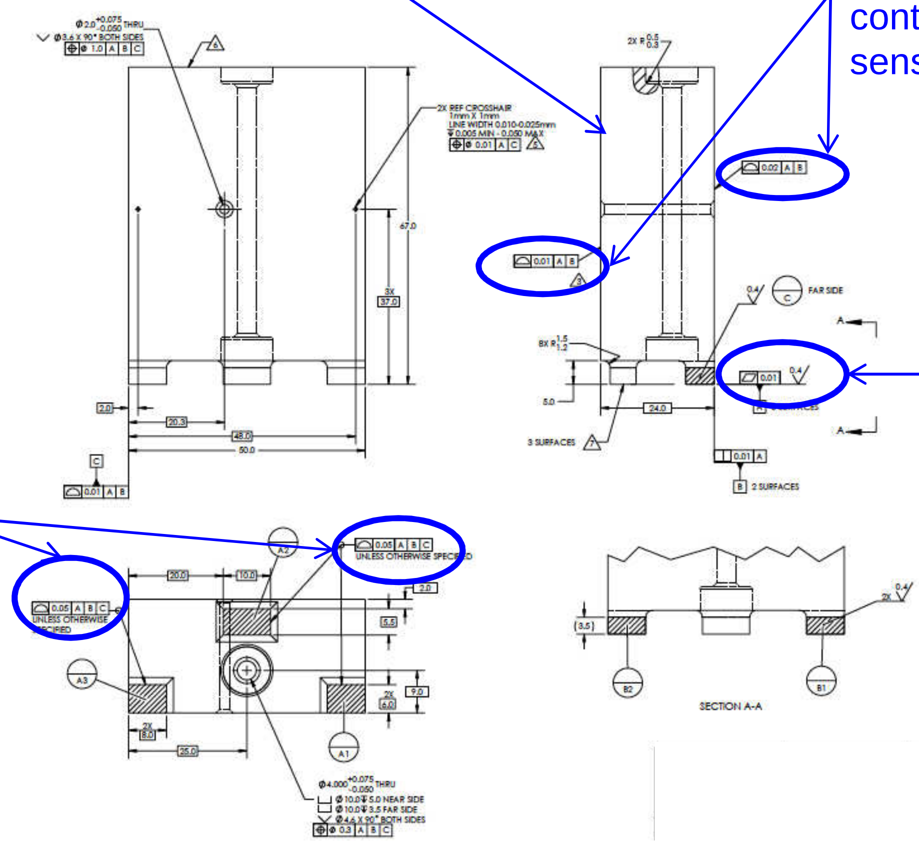
Sense Side Block Drawing

Front face is polished to mirror finish so coating edges can be made smooth

Front and back face profiles control θ_z contribution from sensors

Planarity and finish of bottoms of feet ensure accurate mounting angles

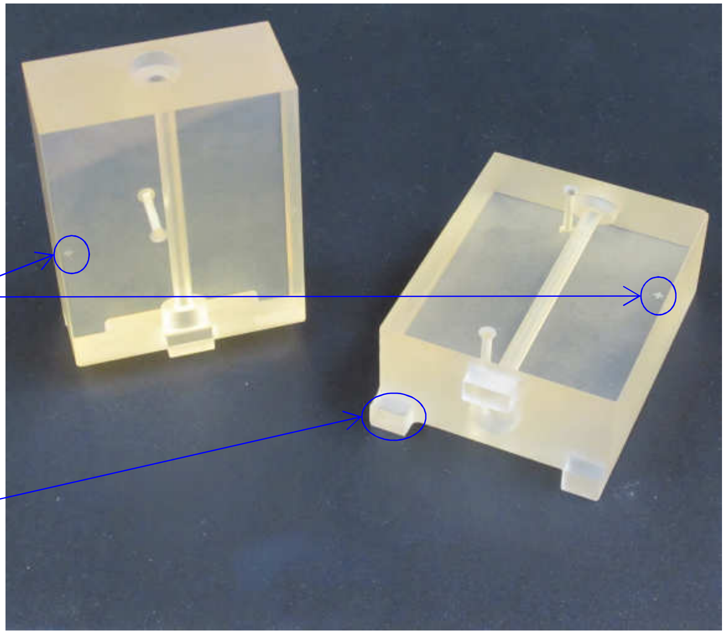
Foot size tolerance ensures consistent mounting pressure from sensor to sensor, and consistent gravity sag



Full drawing is at TMT.CTR.DWG.11.009

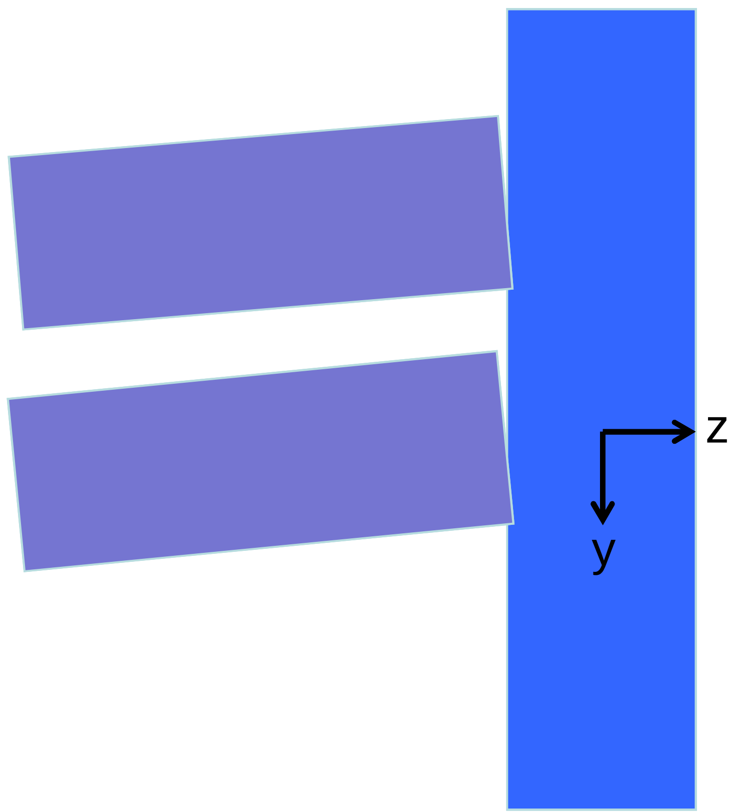
67 mm Prototype Blocks

- One set of prototype blocks was built to 67 mm drawings and measured for compliance by an outside QA measurement shop
- Blocks comply with drawing with 2 exceptions:
  - Crosshair accuracy and location was on a "best effort" basis- the as-drawn requirement is based on the vendor using a laser-etch system, which was not cost-effective to procure for one sensor.
    - The crosshairs are also not required for sensor performance- they are there for the convenience of the gold coater
  - Bottom edges of the feet required 0.15 edge break instead of 0.1 to remove chips. This is acceptable based on sensor calibration models that include gravity sag that weren't complete at the time the drawings were made.
    - Drawing tolerance can be relaxed without any sensor performance penalty
- Sets of the 52 mm blocks built earlier were measured by JPL receiving inspection and also in full compliance to drawings.



Effect of Gravity Sag

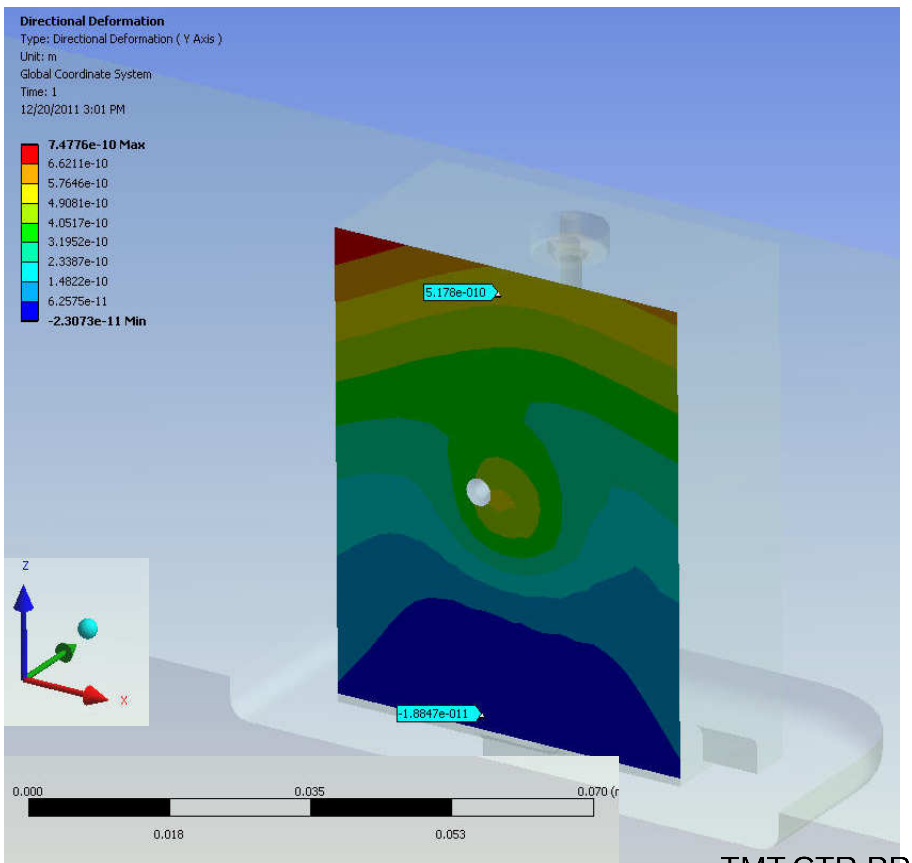
- When sensor is rotated about X axis, gravity sag will appear as piston error (δz) due to relative shear of the sensor faces.
- Tilt (δy) due to sag is shown exaggerated.
- The observed shear is twice the shear of a single sensor half.
- Gravity Sag can be calibrated out if it's repeatable for each sensor
    - Gravity sag is incorporated into the sensor model used in the calibration algorithm development, and even with sensor to sensor variability calibrates out.
    - The sensor feet have been designed to minimize total gravity sag for each sensor.
- More detailed analysis is at TMT.CTR.PRE.11.071

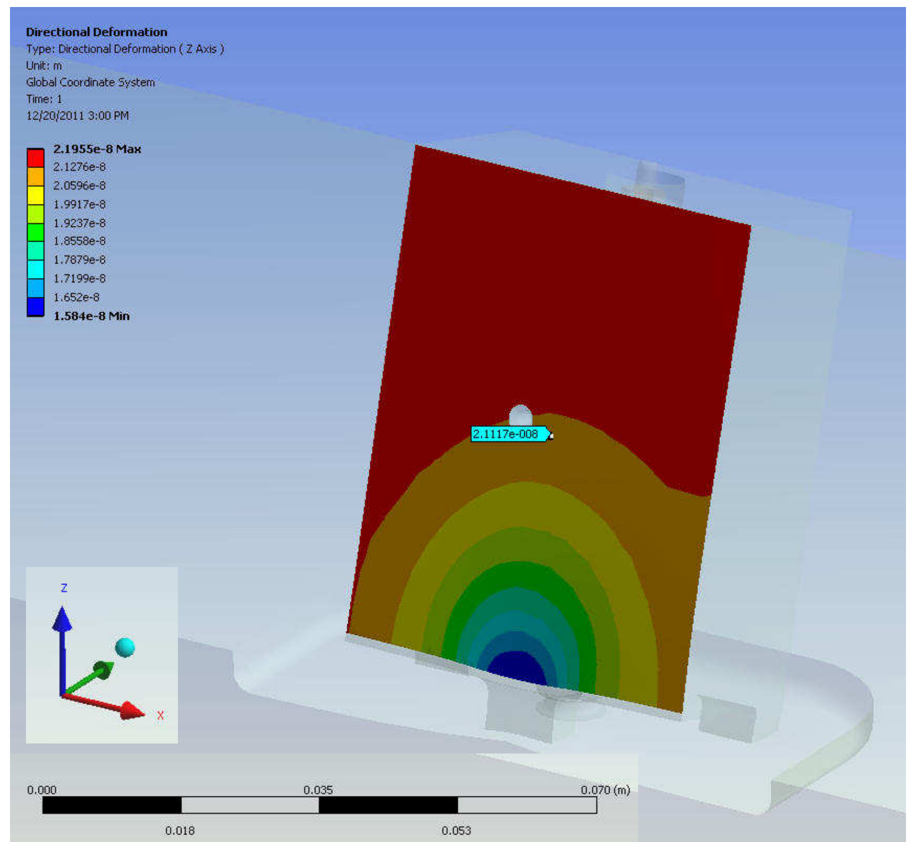


Modeled Effects of Preload and Gravity

- Central hole location is optimized so there's no tilt with variations in preload(at the 5×10^{-10} nm level)

- 21 nm shear per block from gravity, zenith to horizon





Coating Requirements

- Coating requirements are derived from the effects of fabrication errors on the capacitance as the sensor halves move relative to each other.
- The sensors must be sensitive to dC/C of ~0.1 ppm, so very small imperfections must be considered
  - Effects were estimated analytically assuming a parallel plate model for capacitance
  - Effects were modeled using Maxwell (E&M finite element modeling software)
  - Results were used to define coating tolerances in critical areas
  - Drawings are shown first, followed by explanation of the coating analysis
  - Details of coating requirement analysis are given in: TMT.CTR.TEC.096 and TMT.CTR.PRE.056

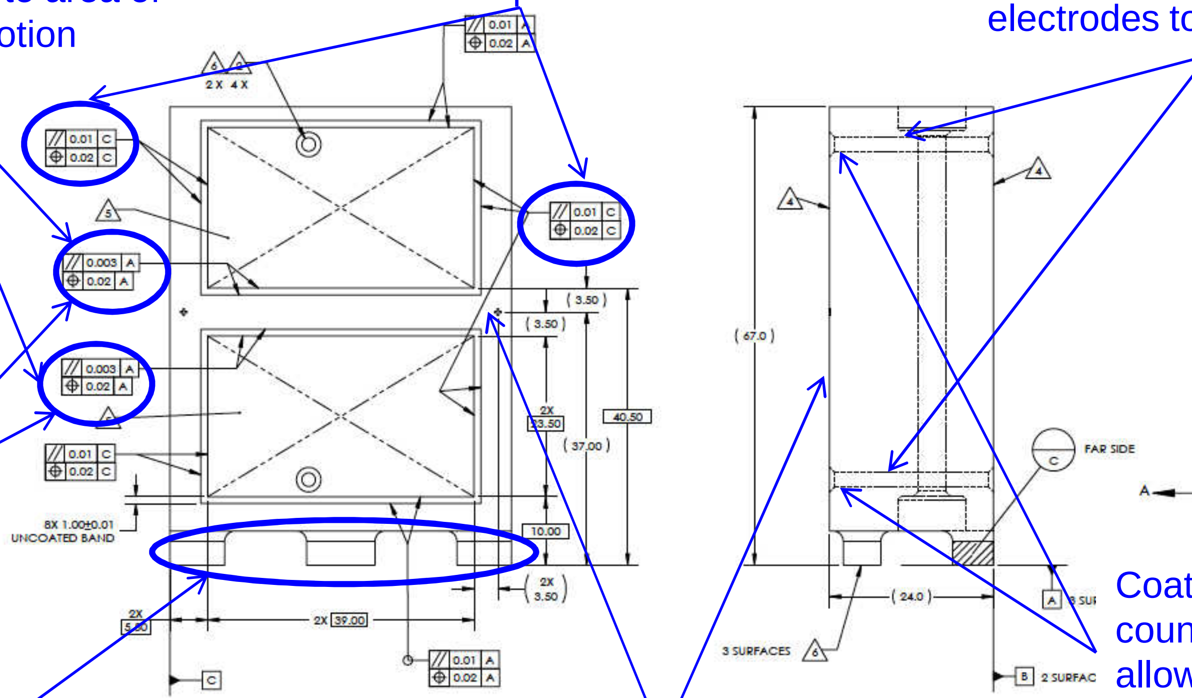
Drive Side Coating Pattern

Tight edge tolerances to prevent erroneous signals due to area of cap changing with x motion

Looser tolerances where drive and sense electrodes don't overlap

No coating through holes to prevent contact from drive electrodes to ground

Parallelism tolerance controls θ_y error, position tolerance controls z error



Coating into countersinks to allow soldering of leads in place

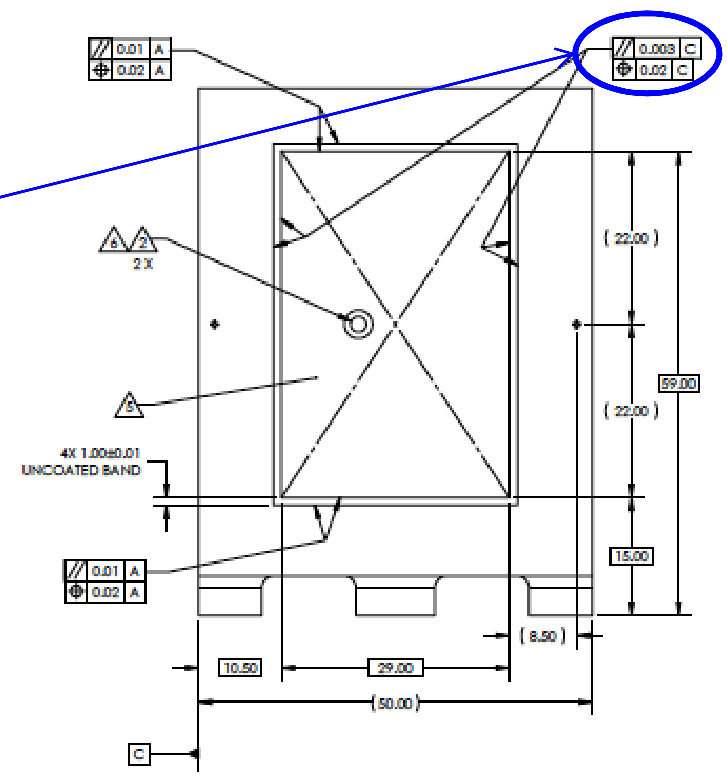
No coating on bottom of feet so contact is glass to glass

Block coated all around with grounded "guard ring" to get parallel plate behavior and prevent crosstalk

Full drawing is at TMT.CTR.DWG.11.010

Sense Side Coating Pattern

- Most features are the same as on the drive side
- Tolerances are tighter on the vertical edges, rather than the horizontal, so that height changes aren't affected by edge roughness. Position tolerance constrains x error



Also note:

- Max temperature of blocks is limited to 130 C during coating to prevent changes in Zerodur CTE
- Coating is 0.5 micron gold (0.9999 pure or better) over 0.05 micron chrome
- Parallelism requirements on the critical lines are currently tighter than needed in order to control the edge smoothness.

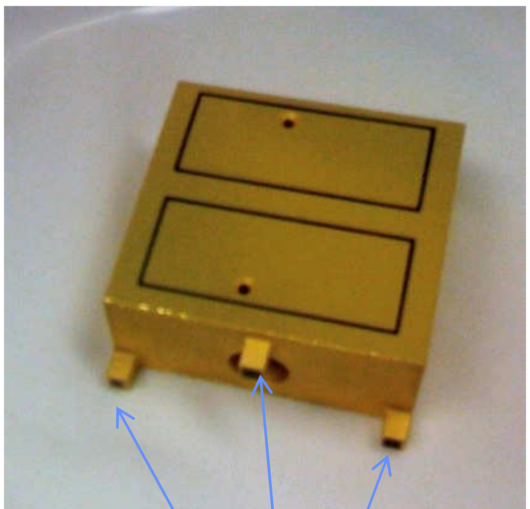
Full drawing is at TMT.CTR.DWG.11.011

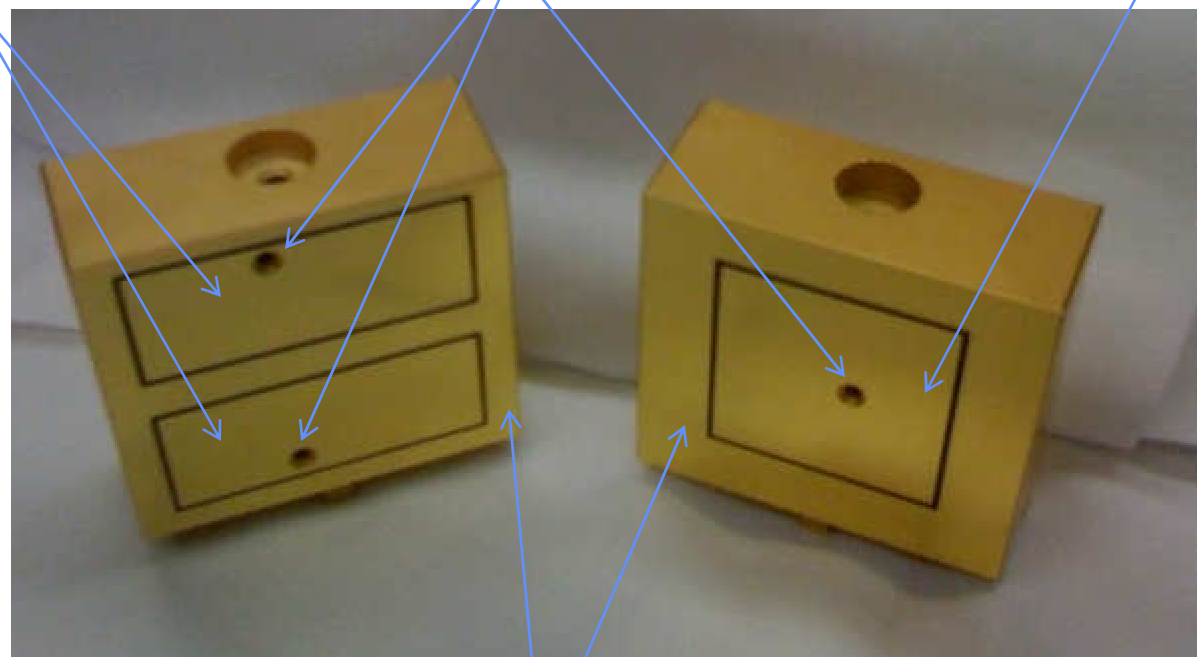
Coated 52 mm Tall Sensors (not yet cabled)

Drive Electrodes

Feedthrough holes

Sense Electrode





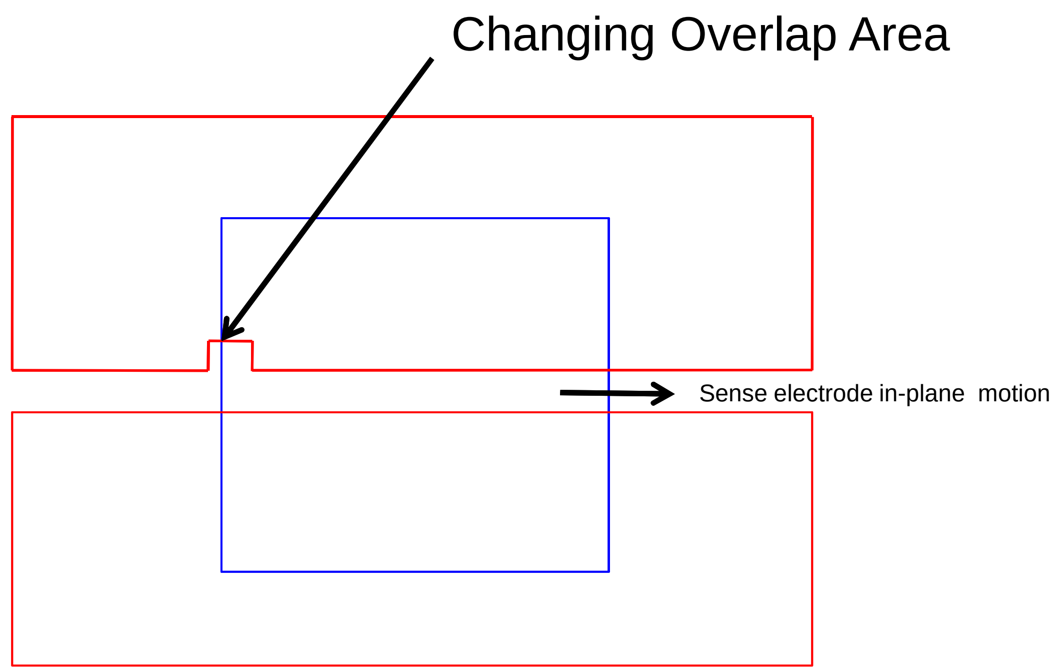
Feet

Guard electrodes (coating on all sides except bottoms of feet)

Electrode Edge Requirements

In the presence of in-plane motion, deviations from a straight line where the edges of the opposing electrodes cross can lead to errors in the edge sensor measurements

Example: As the sense electrode moves to the right due to in-plane motion, the overlap area of the sense electrode and upper drive electrode changes, leading to an apparent (erroneous) relative vertical motion.

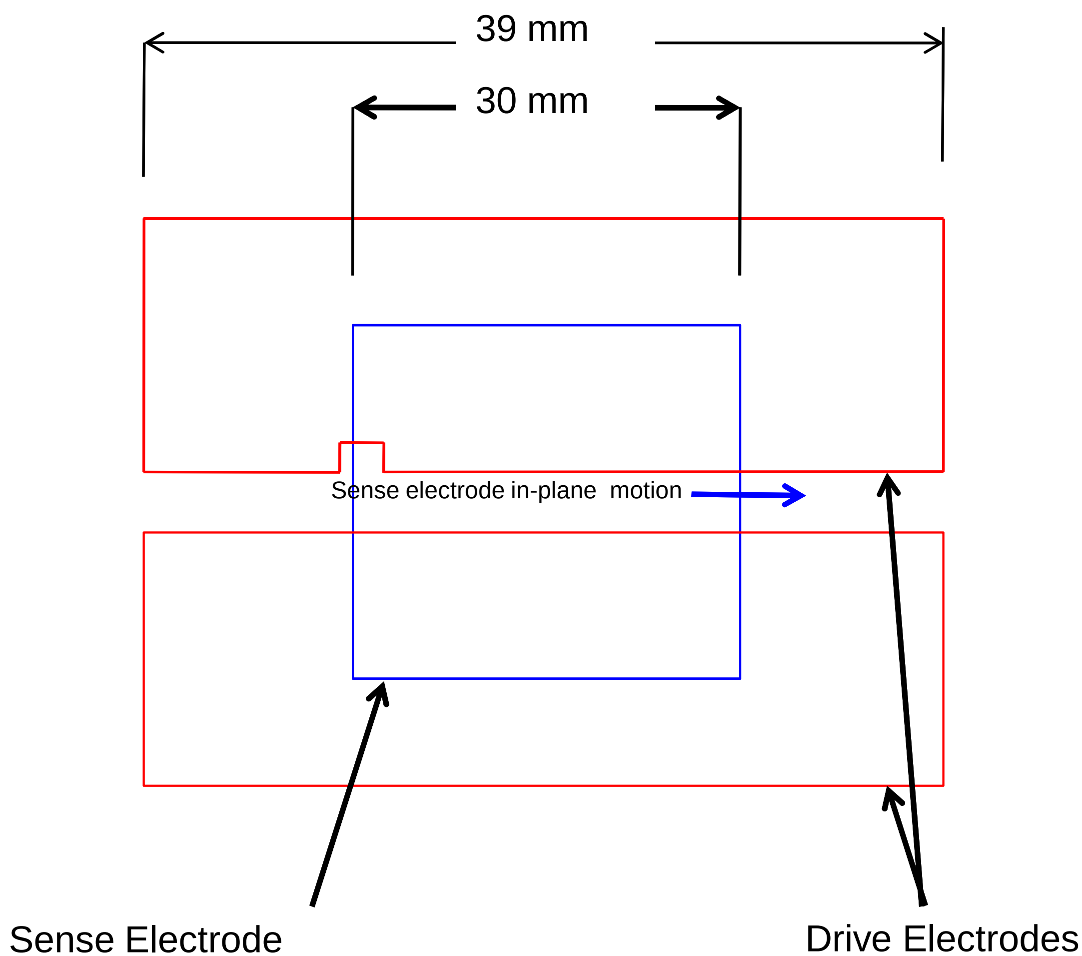


Electrode Edge Requirements

•1 nm of measured piston corresponds to 1 nm increase in the overlap of the sense electrode with one drive electrode, and a corresponding decrease in the other drive electrode

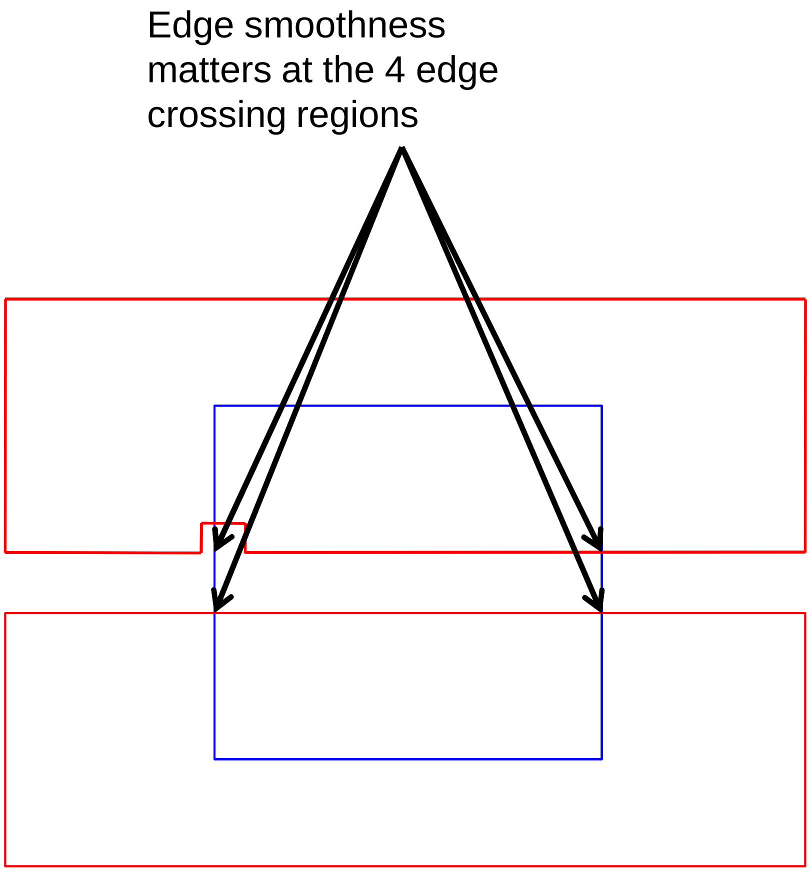
•1 nm displacement of upper electrode gives a change in overlapped area of
30 mm * 1 nm = 30 µm^2.
If there is no corresponding change in the overlap of the lower electrode it will appear as ~0.5 nm height change

•30 µm^2 corresponds to moving the sense electrode in-plane past a 5.5 µm square patch of missing drive electrode.



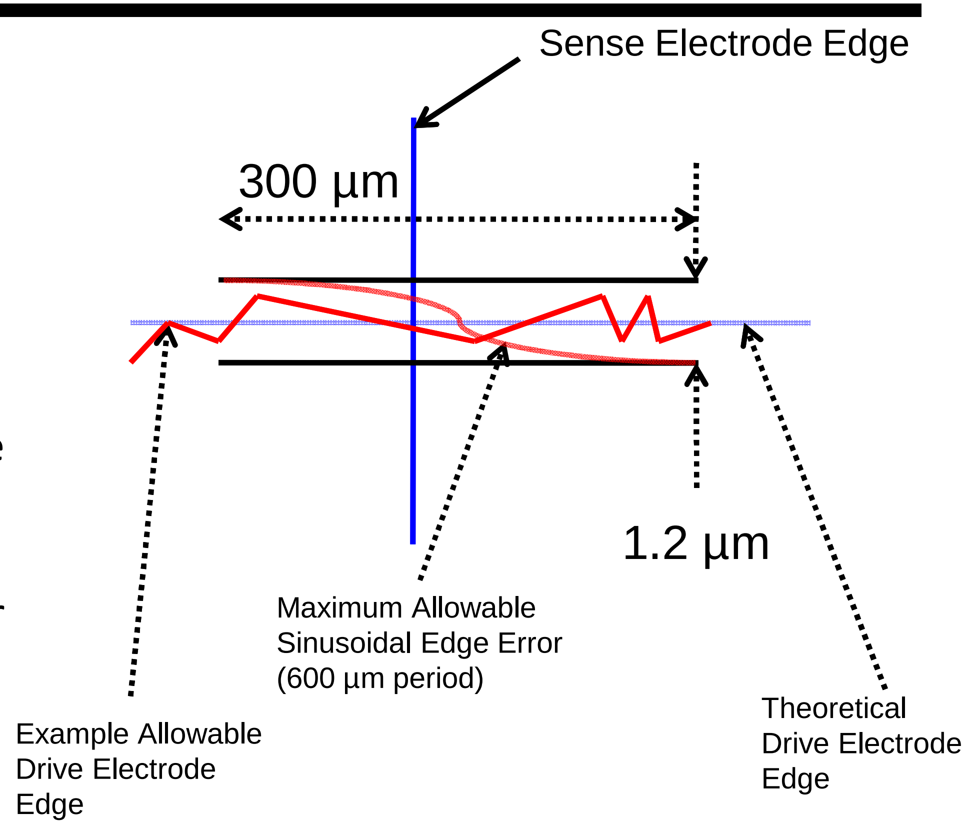
Electrode Edge Requirements

- To determine the edge requirements we need to:
  - Determine our allowable limits for dz/dx (height crosstalk due to in-plane motion) due to sensor error
  - Determine the sensor error introduced for a given size flaw in the electrode edge
- Note that the tolerances on the drive electrodes will be different than on the sense electrodes due to the differing ranges of motion during operation
  - In plane performance range is 2.0 mm max (+-1 mm)
  - Out of plane performance range is 0.1 mm, but is centered about a zero that may vary from sensor to sensor with installation tolerances



Electrode Edge Requirements

- The DRD requirement for unmodeled sensor dz/dx error is 5 nm per 300 micron
- This leads to the requirement that each edge should be inside a 1.2 µm wide band in any 300 µm wide window
- Global rotations of the pattern appear the same as installation errors and can be calibrated out within the limits of the in situ calibration process.
- Long period variations should also appear as linear calibration errors plus a non-linear residual if they are significantly longer scale than the in-plane displacement between calibration points (0.3 to 0.5 mm)
- Linear offsets of the pattern can be removed via the sensor electronics zero offset.



Maxwell Model of a Notch at the Edge Crossing

- We also used Maxwell to do a finite element electrostatic model to validate the approach
- The model used reduced size electrodes in order to solve in a finite time at the resolution needed
- The model compared the capacitance of one notched and one perfect drive electrode as the notch moved past the sense electrode edge.
- Various size notches were modeled, from 0.1 mm up to 3 mm. Smaller notches were not practical due to computation times.

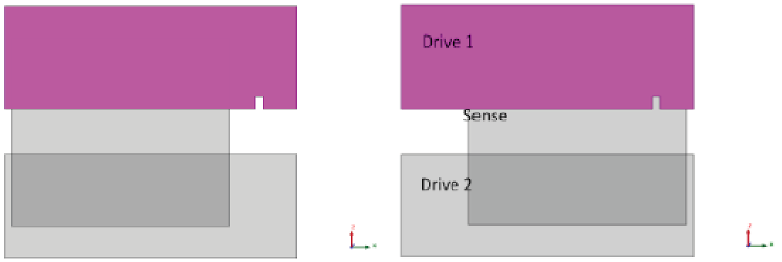


Figure 2 The drive and sense plates at the two extremes of motion in the model -2 mm and +2 mm. The guard electrodes are not shown for clarity. But cover all spaces around the electrodes except for 0.5 mm insulating gaps.

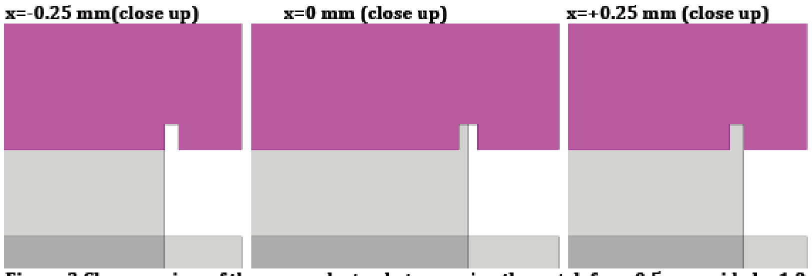
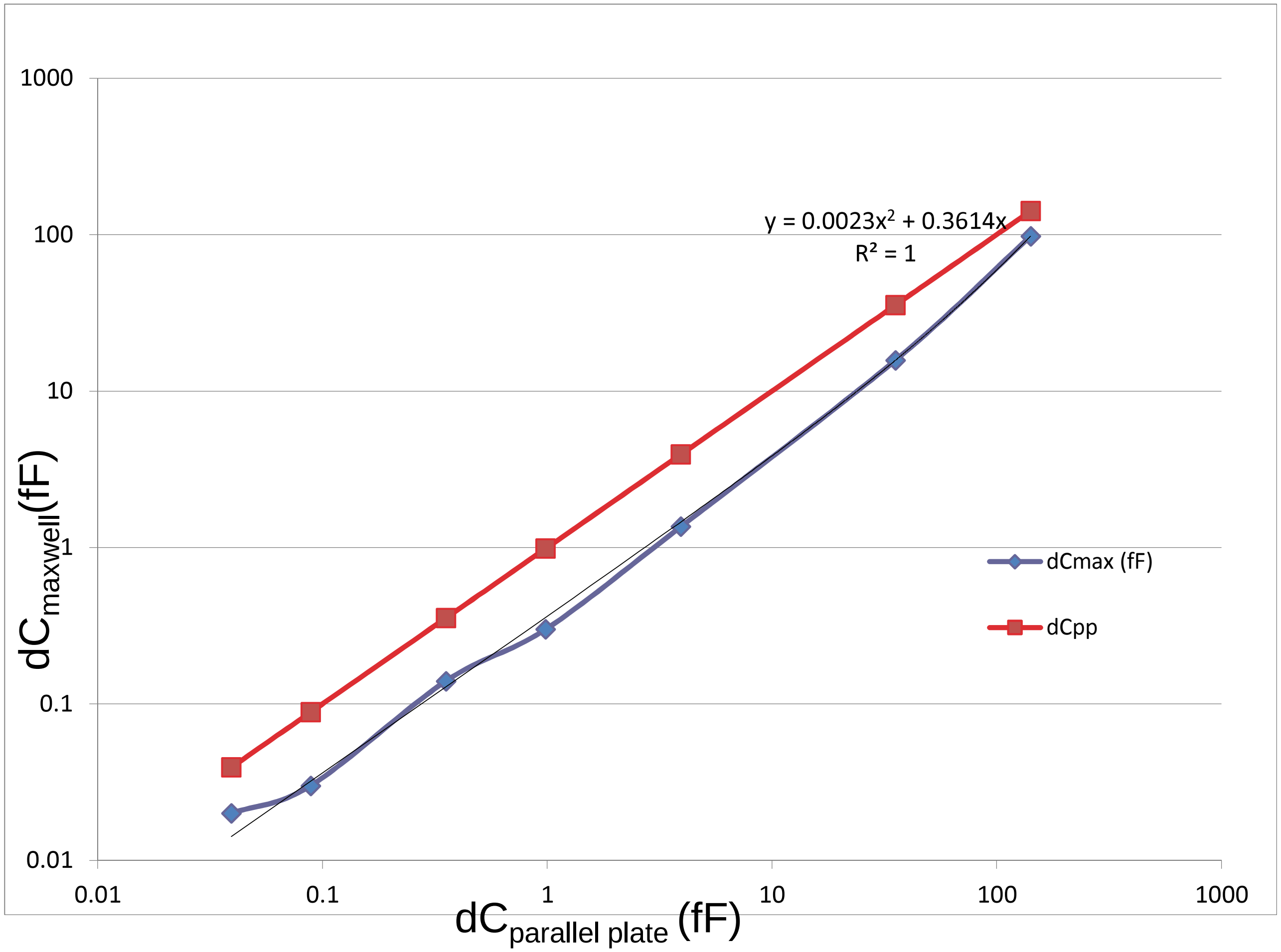


Figure 3 Close up view of the sense electrode traversing the notch for a 0.5 mm wide by 1.0 mm high notch.

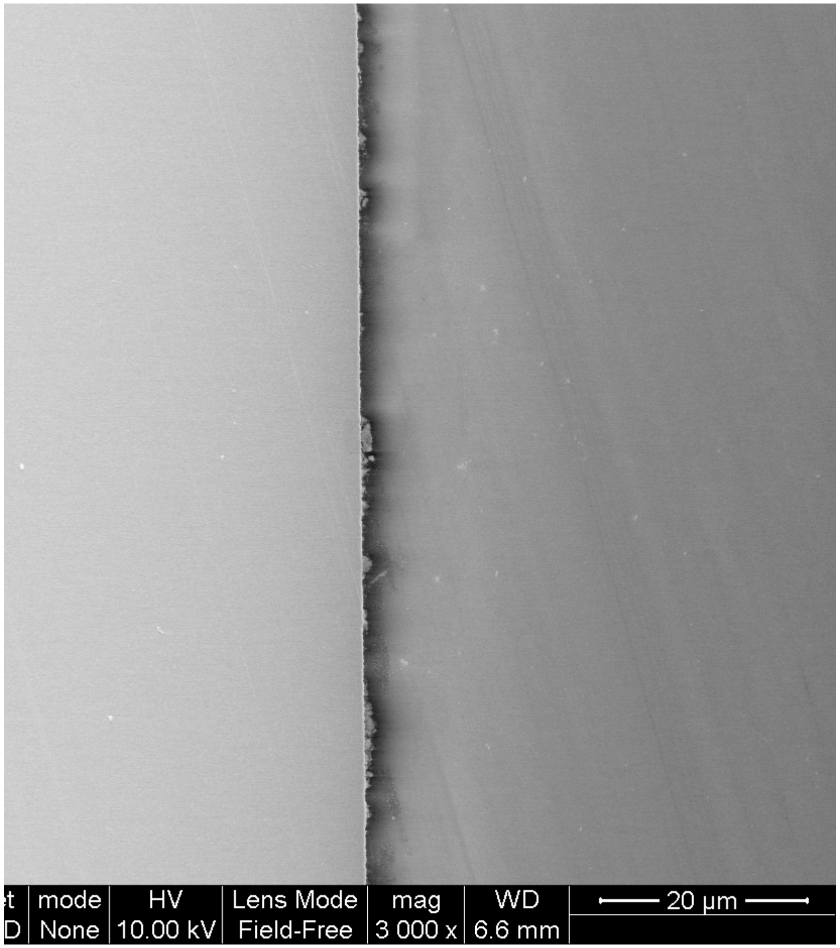
Maxwell model programming was done by Rosemary Diaz

Comparison to Parallel Plate Estimate

- Plot of Maxwell results vs Parallel Plate results validates model over a large range, with a consistent 3x difference.
- The difference is likely due to edge effects– the decreased area is partly compensated by a increased capacitance due to fringe fields at a longer perimeter
- We relax the edge smoothness requirement (relative to the 1.2 micron of parallel plate model) to 3.6 micron as a result

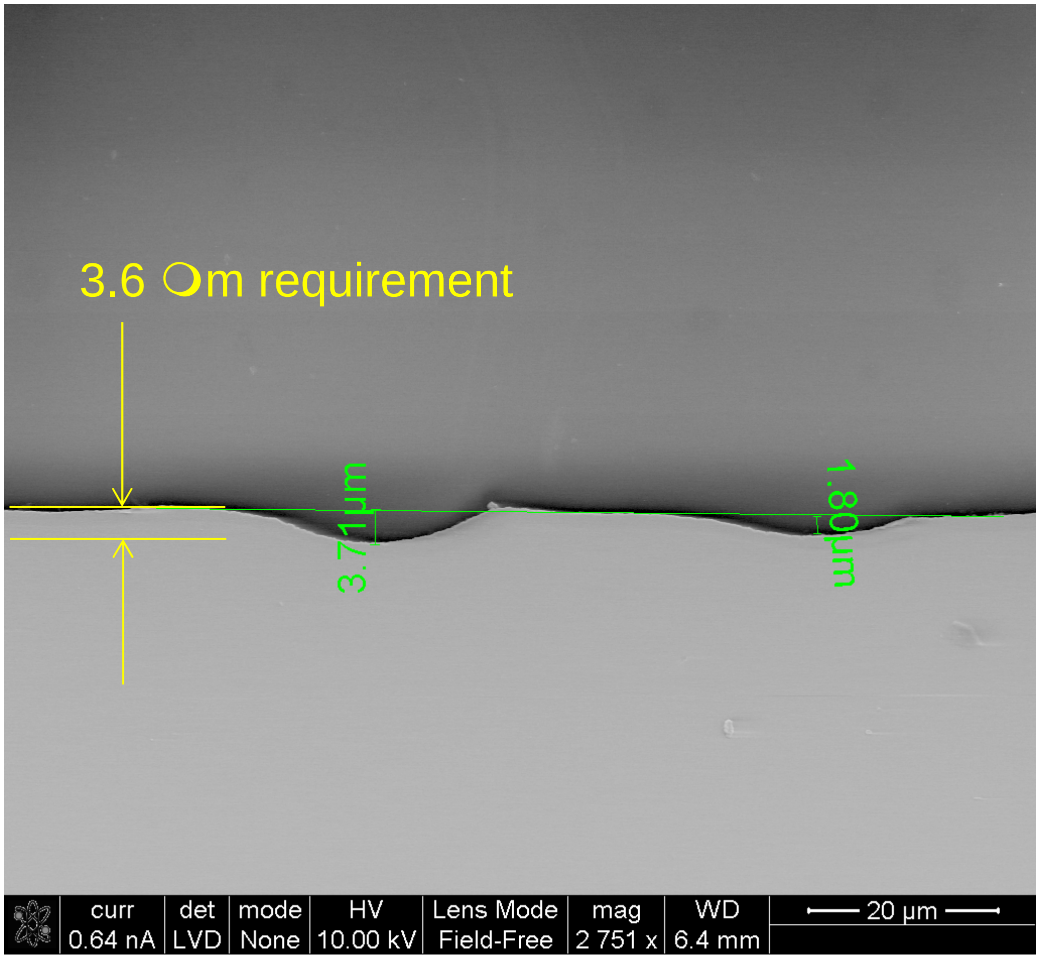


Example of Fabricated Electrode Edge



- This is an SEM photo of the edge of an electrode made fabricated by Materion (Barr/TFT)
- The substrate is 60/40 (scratch dig) polished
- Deviations from the smooth line are a few microns (requirement is 3.6 micron edge width
- This was done on a 52 x 52 mm block
- These are compliant with the requirement on edge linearity

Example of Fabricated Electrode Edge



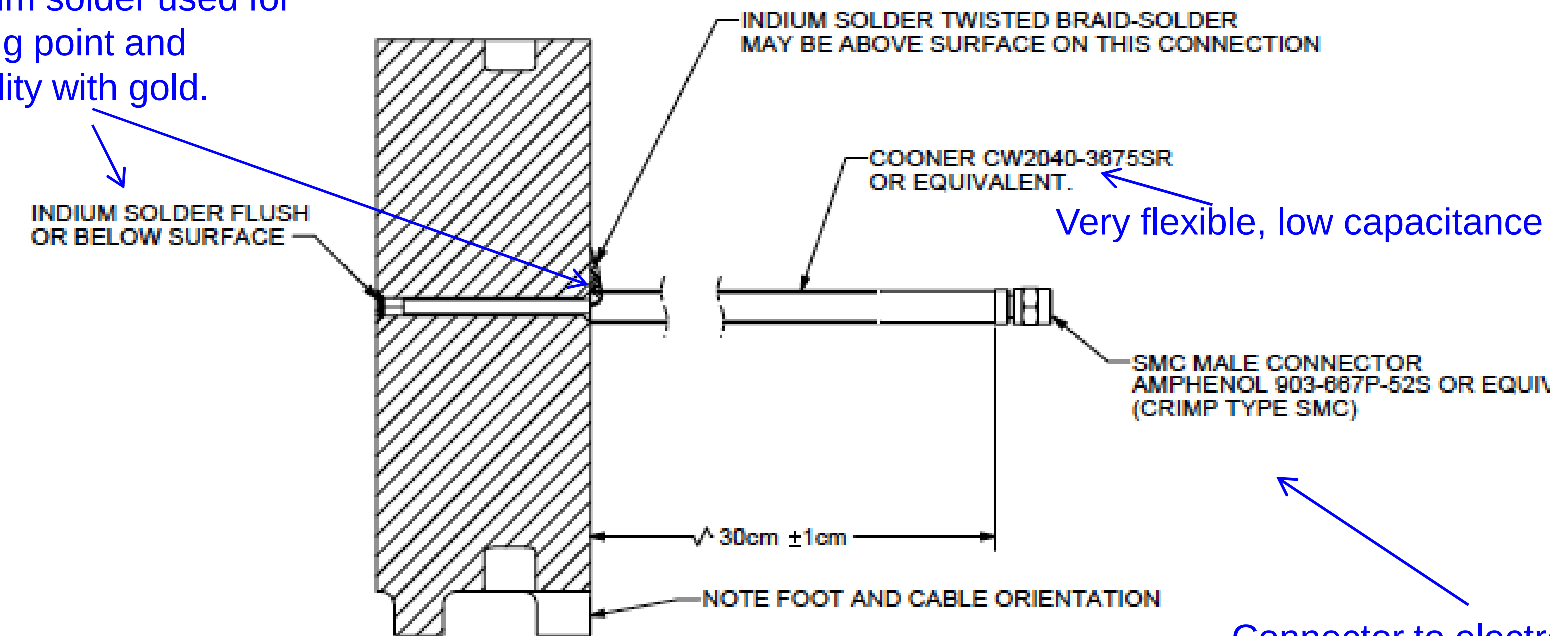
- SEM photo showing depths of deviations from smooth.
- These are typical examples from the prototypes.
- Small, high spatial frequency errors larger than 3.6 mm are acceptable, as the edge is driven by the low spatial frequency requirement
- We're constrained partly by mechanical drawing and fab standards that don't lend themselves to a spectral distribution of errors

Coating Fabrication Results

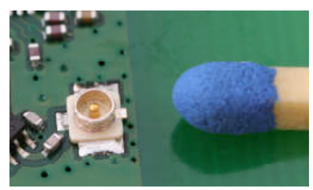
- Coatings were inspected with Scanning Electron Microscope for detailed edge quality and JPL's TESA video inspection system for position and orientation
- Coating requirements have been partially demonstrated, limited by lack of fiducials on early blocks
  - Edge smoothness requirement is met on a polished block surface
    - High spatial frequency deviations on order 3.6 micron or less
    - No low spatial frequency deviations (which drive the 3.6 micron requirement)
  - Pattern rotation requirement relative to datum is consistently met (♦ = 0.128 mrad)
    - The current drawing sets this tolerance tighter than needed
  - Position offset errors on prototype blocks were not well demonstrated (offsets of 50-150 micron from nominal locations)
    - Lack of fiducials on the surface combined with limited focus depth for photolithography machine led to using corner of beveled front face as a reference, rather than the plane of the feet.
    - Repeatability was high- edge locations were consistent to better than 10 microns.
    - Position tolerance of pattern is least critical, and is already planned to be calibrated out during installation. High repeatability can reduce installation-time calibration, even if offset it large.
  - Fiducials were added to surface in new drawings at the request of the optical coater to simplify pattern location.

Sensor Cabling

Pure indium solder used for low melting point and compatibility with gold.



Very flexible, low capacitance cable



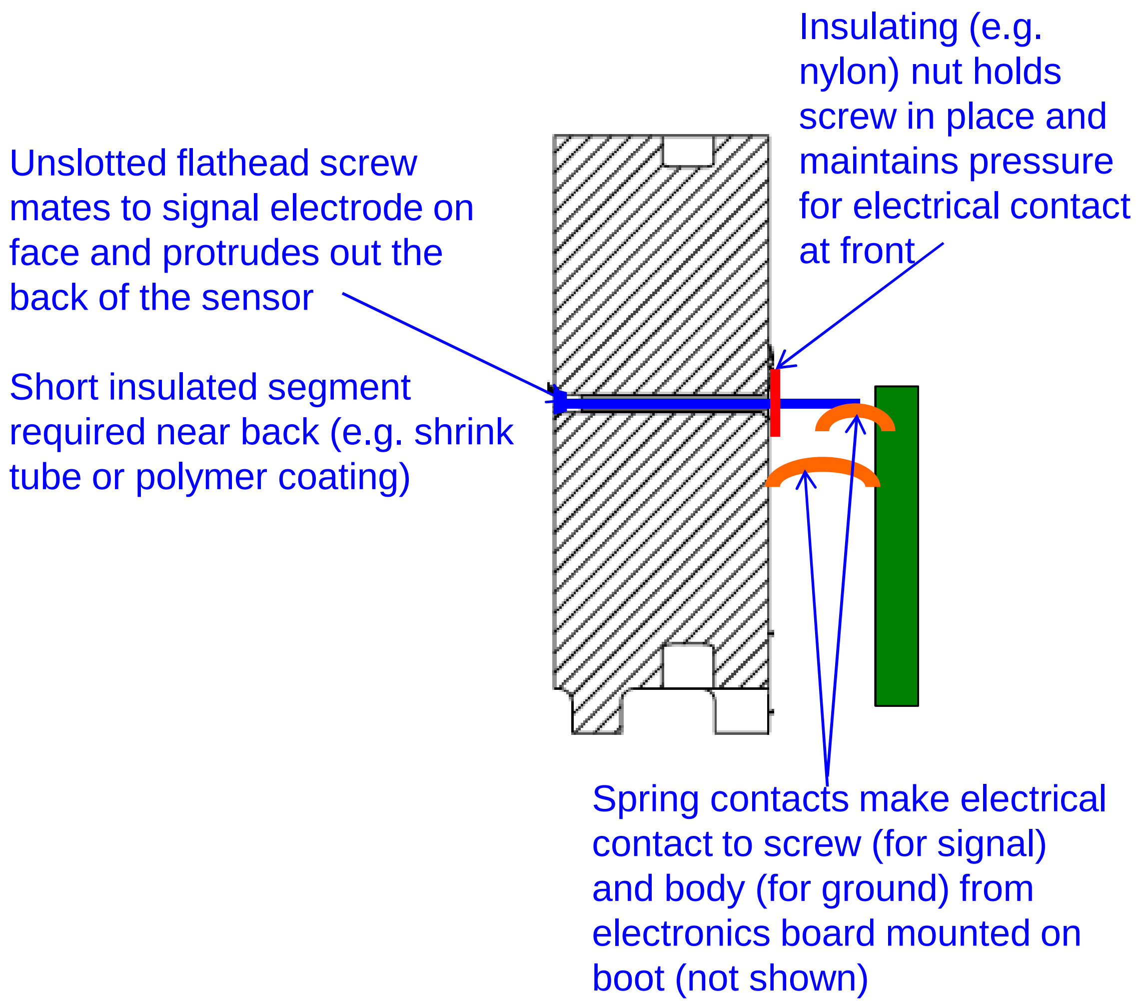
Connector to electronics is TBD– the SMC connector is larger and heavier than required
(U.FL connectors appear suitable)

Full drawing is at TMT.CTR.DWG.11.007

Alternative Interconnect Concepts (not baselined)

The current interconnect concept (solder and cable) works, but an alternative concept (shown at right) might offer several improvements:

- simplify assembly and reduce cost
- Reduce temperature coefficient
- Reduce shunt capacitance, which will reduce noise



Blocks and Coatings Summary

- The block and coating design tolerances are based on the error budget allocations
- Tight tolerances are applied only where needed to meet the error budget requirements– tolerances are looser in other areas
- We’ve built blocks and coatings that comply with the requirements.
- The compliance of the blocks and coatings can be verified by the normal inspection techniques used in mechanical and coating fabrication

P06 Sensor Electronics

Chris Shelton

M1CS Sensor System Preliminary Design Review

Pasadena

March 29 - 30, 2012

Edge Sensor Electronics Outline

- Overview
- Physical Description
- Design Approach and Functional Description
- Height Offset Adjustment and Quadrature Nulling
- SPICE Modeling
- Performance Summary
- Future Work
- Conclusions
- Backup Slides

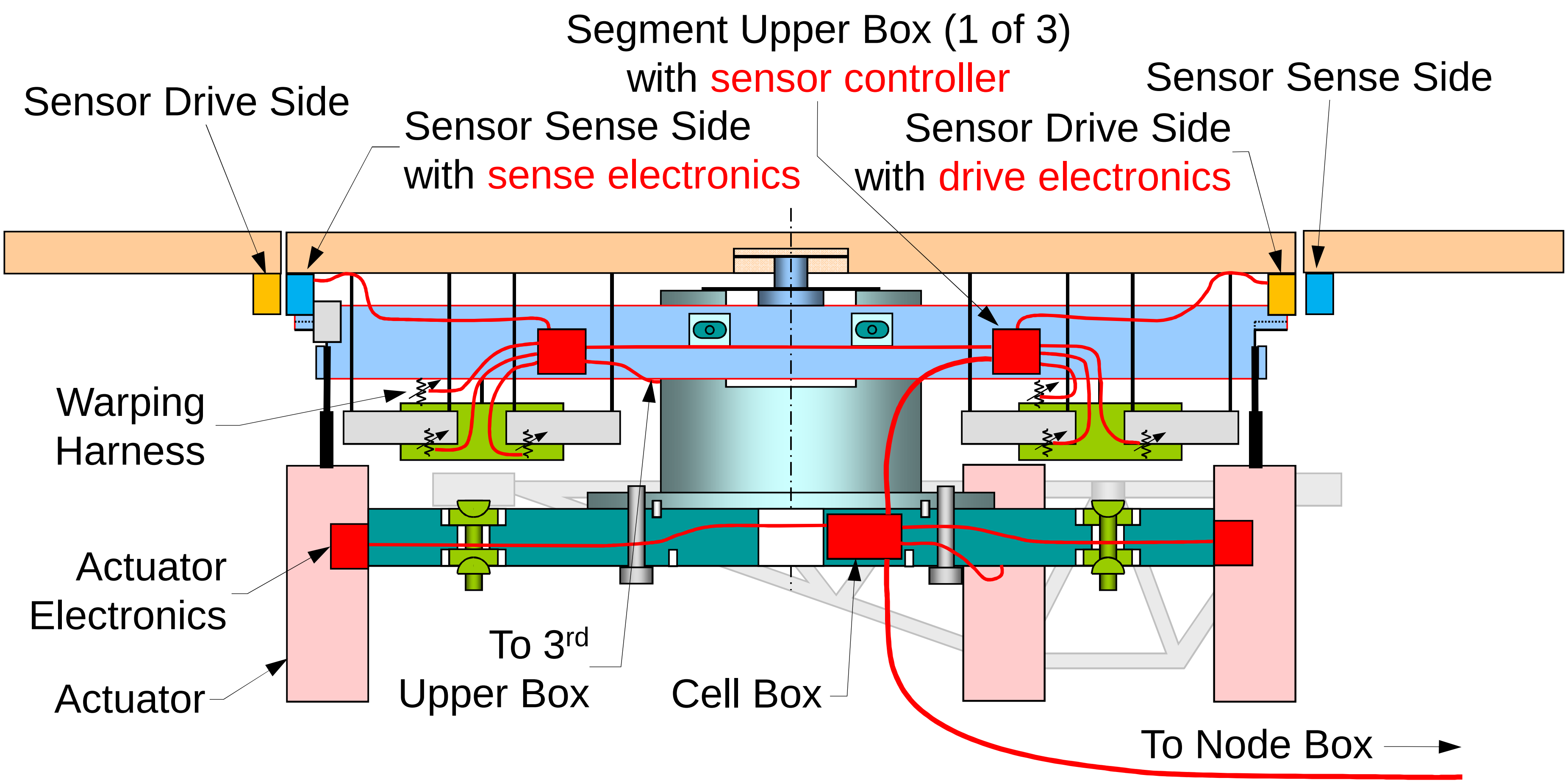
Edge Sensor Electronics Overview

- The challenge for sensor electronics is to meet the sensor noise, temperature coefficient, drift, and power requirements described earlier, and to do so economically.
- This presentation will describe a design approach and a board set that answers this challenge.
- The presentation after this will fully describe the performance testing in the lab of complete sensors. Some performance results are presented here; they are from that report.

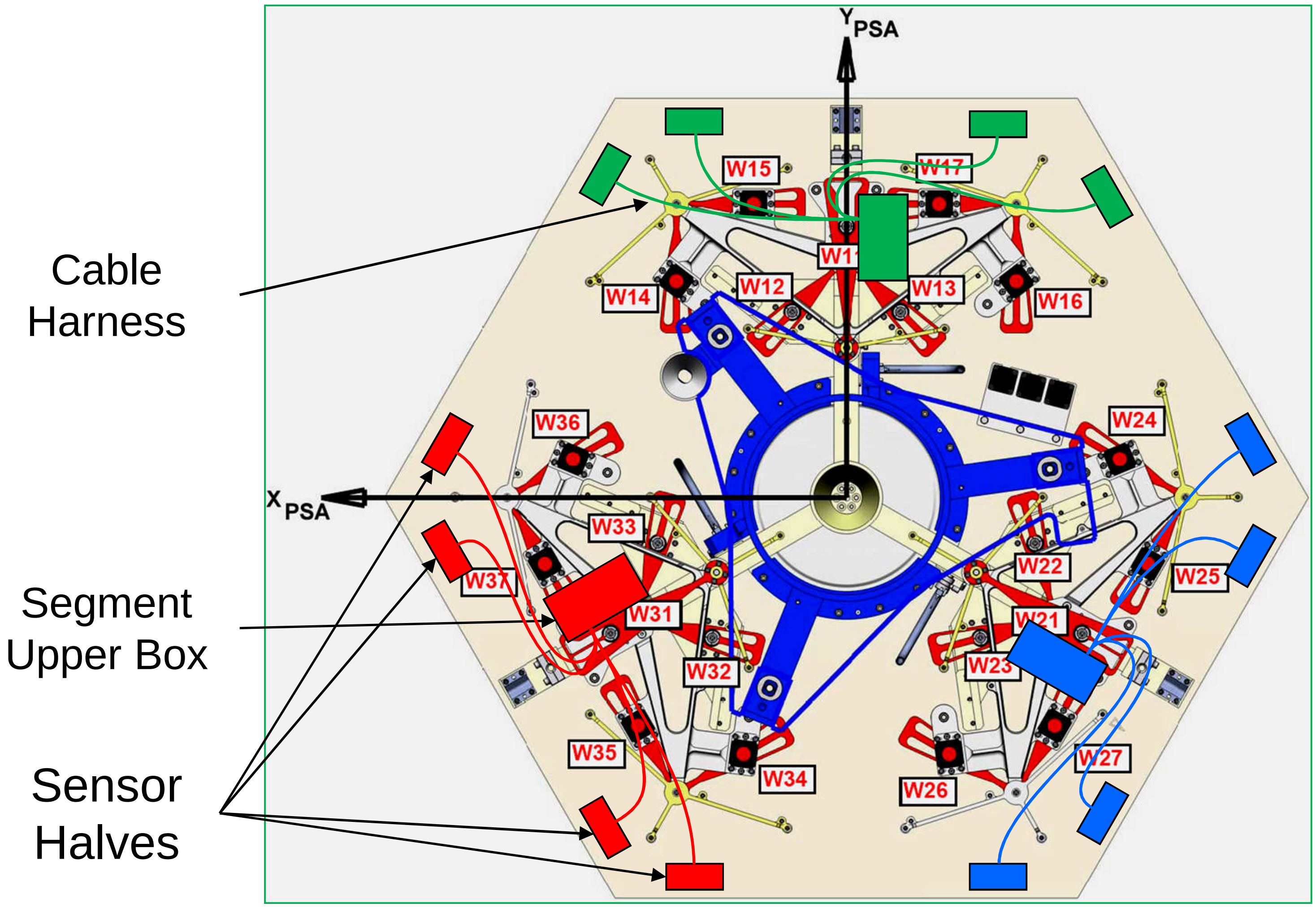
Edge Sensor Electronics Physical Description

- The edge sensor electronics consist of a small “drive board” and a small “sense board” that are both local to the sensor blocks, and a “controller board”.
- The drive and sense boards contain all analog electronics, and the all-digital controller board interfaces multiple sensor pairs to the rest of M1CS.
- The emphasis in the current phase of sensor development is on performance, stability and meeting all requirements, that is, analog design.
- The digital interface is provisional, and will be refined when the Segment Cabling and Controller (SCC) design is refined.
- The next several slides illustrate how these electronics will be located on a mirror segment, and show some pictures of the hardware.

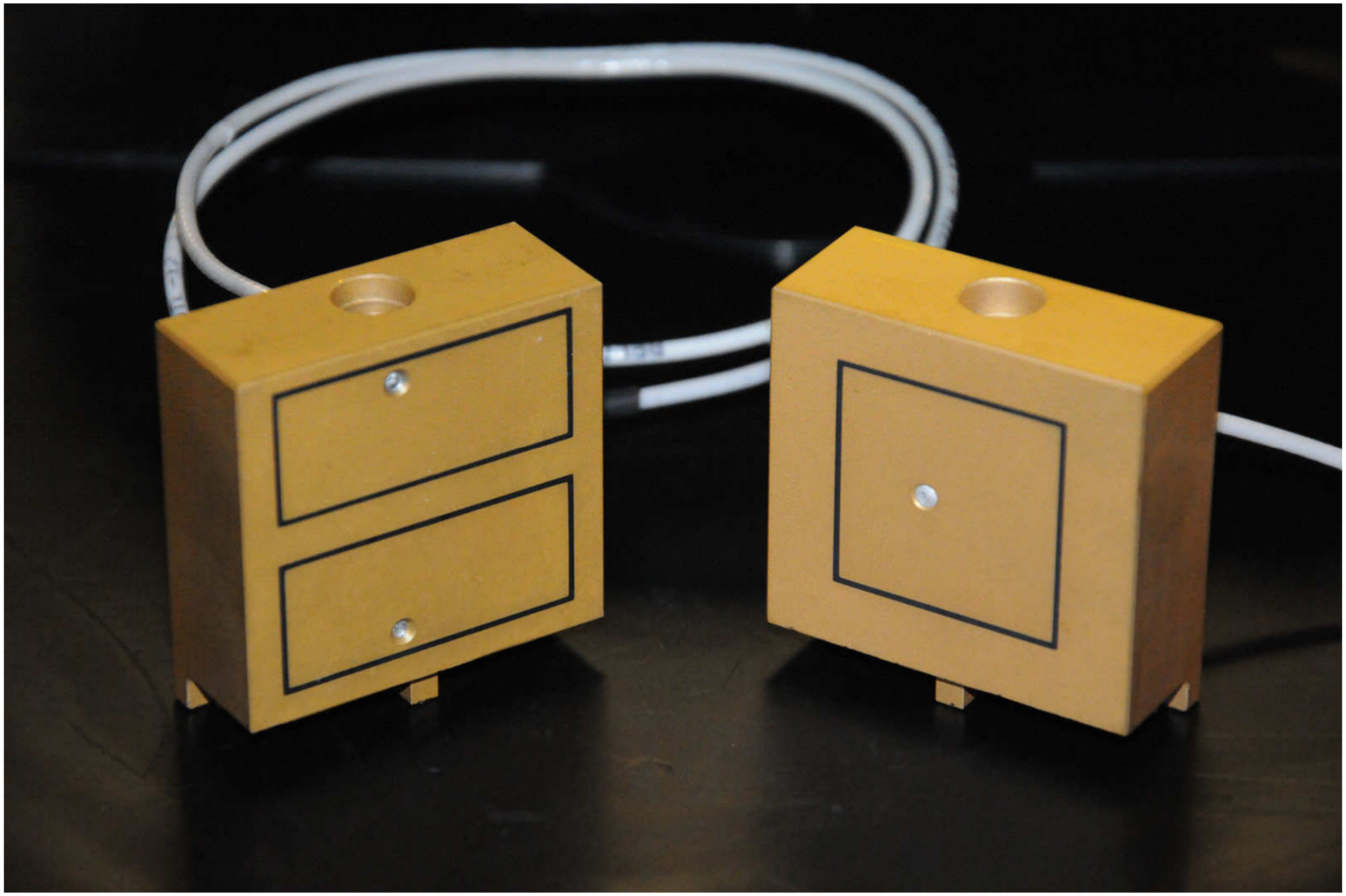
Edge Sensor Electronics on the Telescope



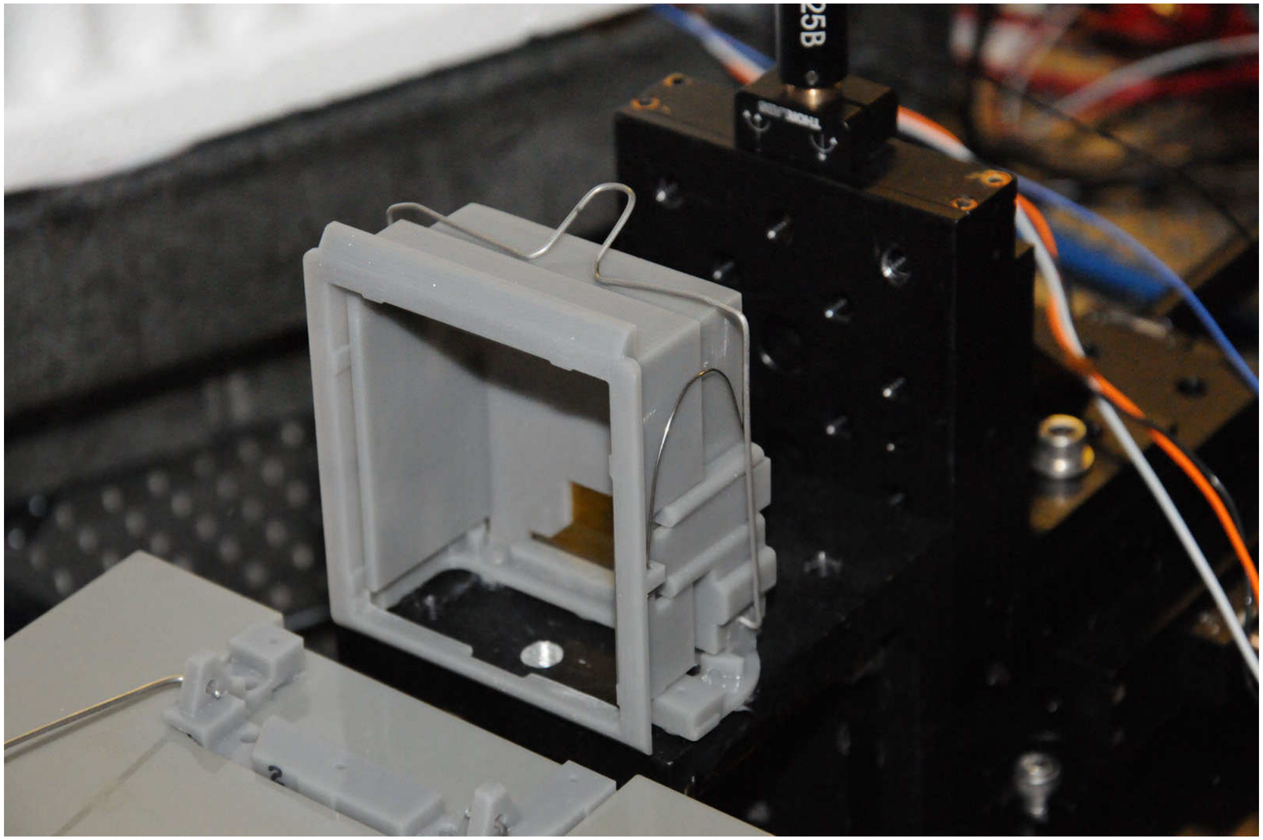
Edge Sensor Cabling



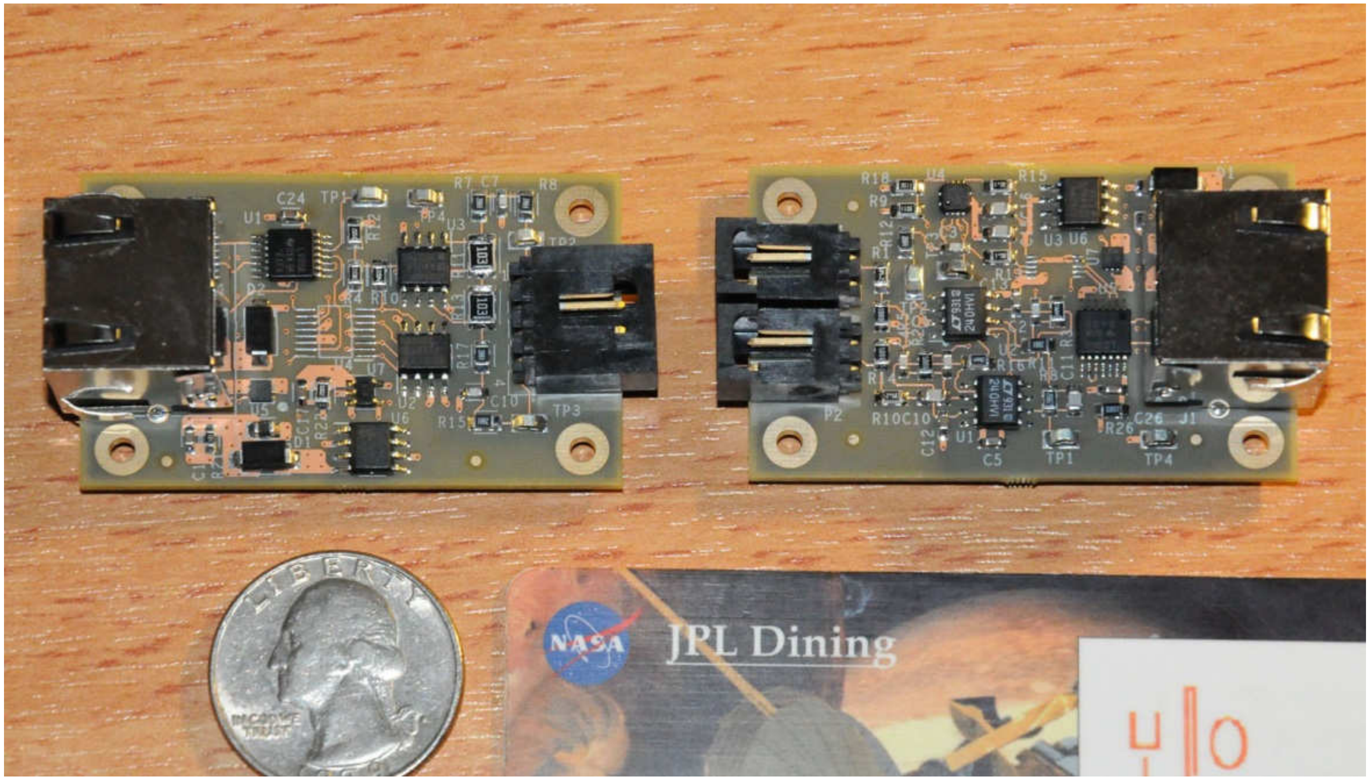
Sensor Drive and Sense Blocks



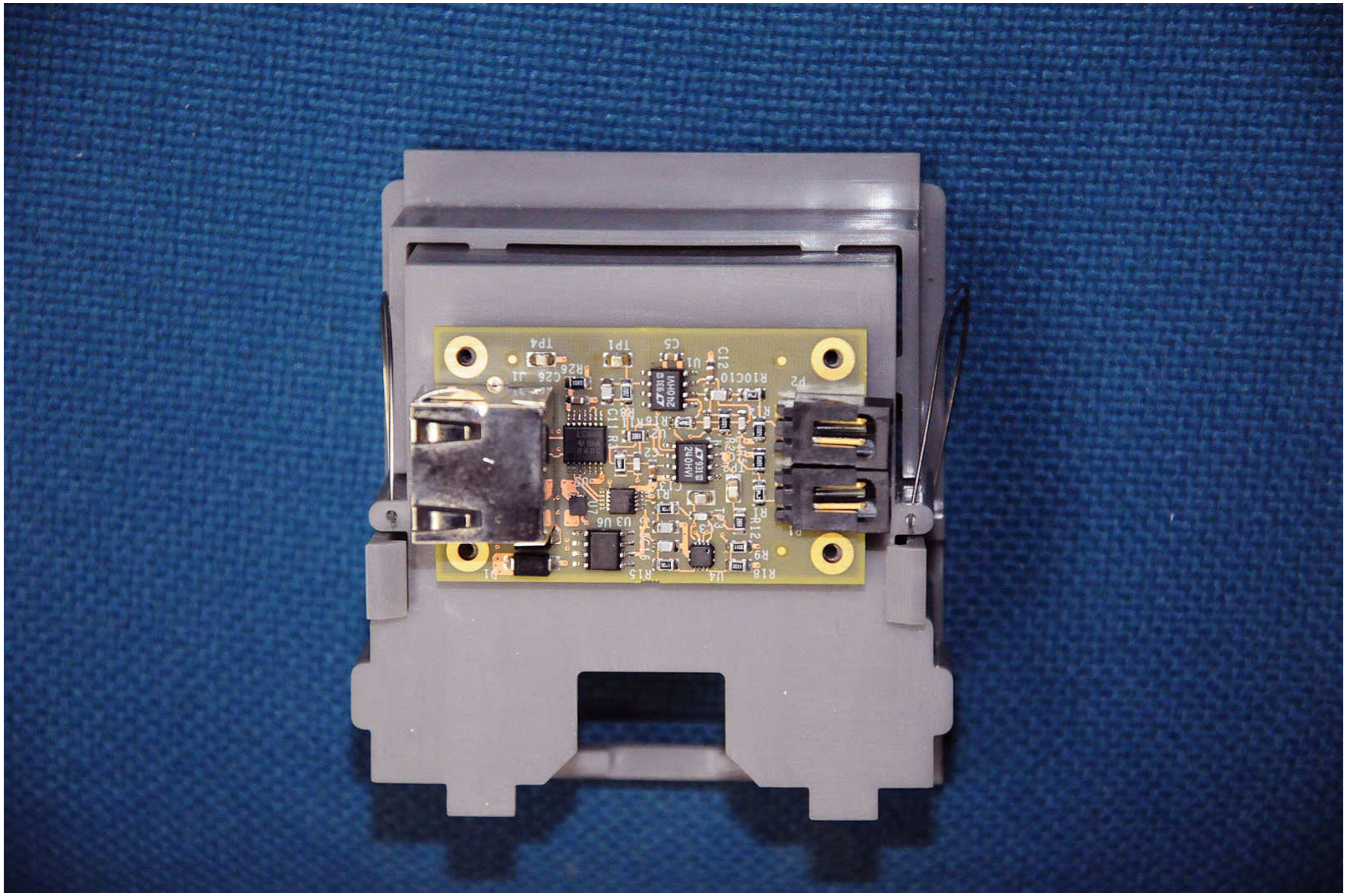
Sensor Protective Boot



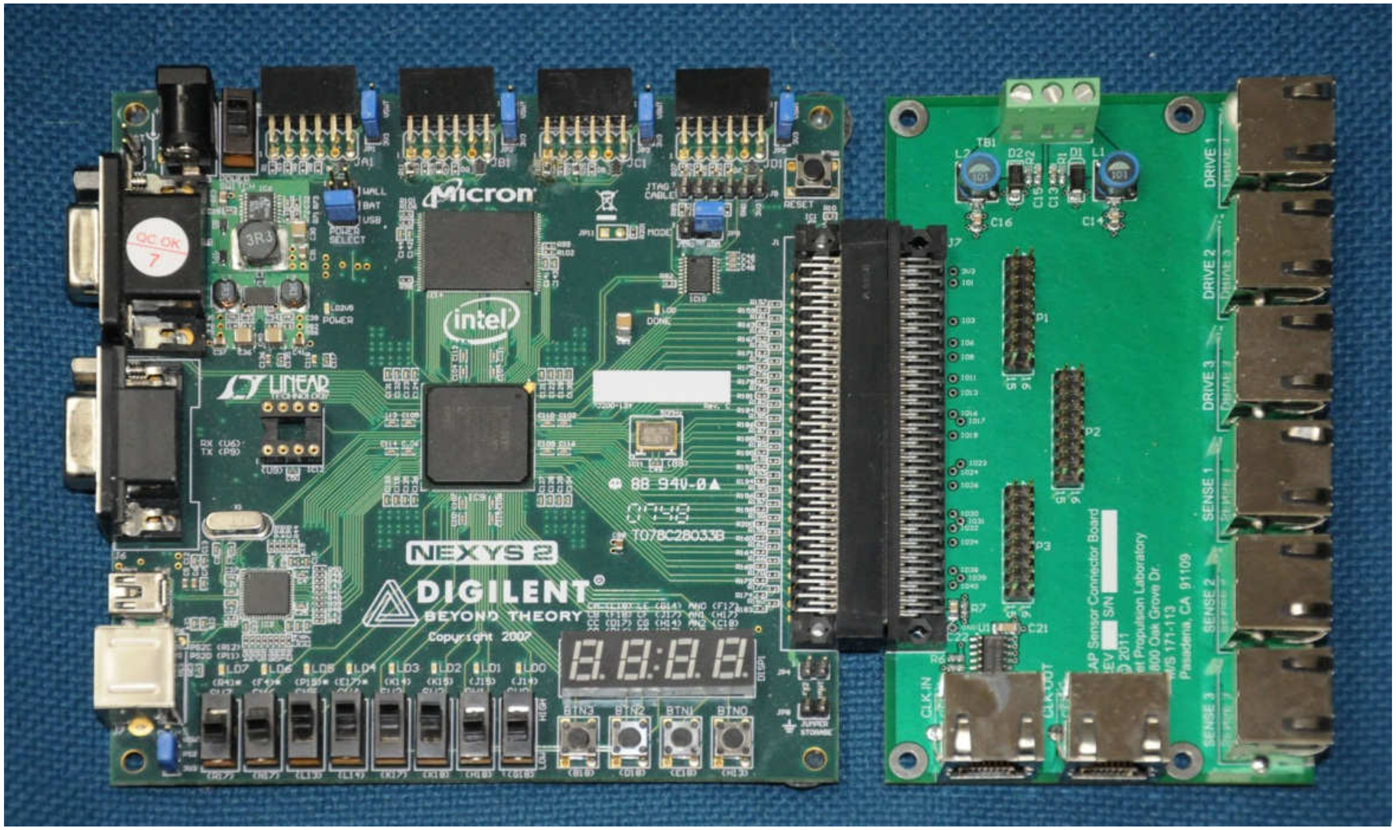
Drive and Sense Boards



Boot with Board Showing Mounting



Sensor Controller for Development



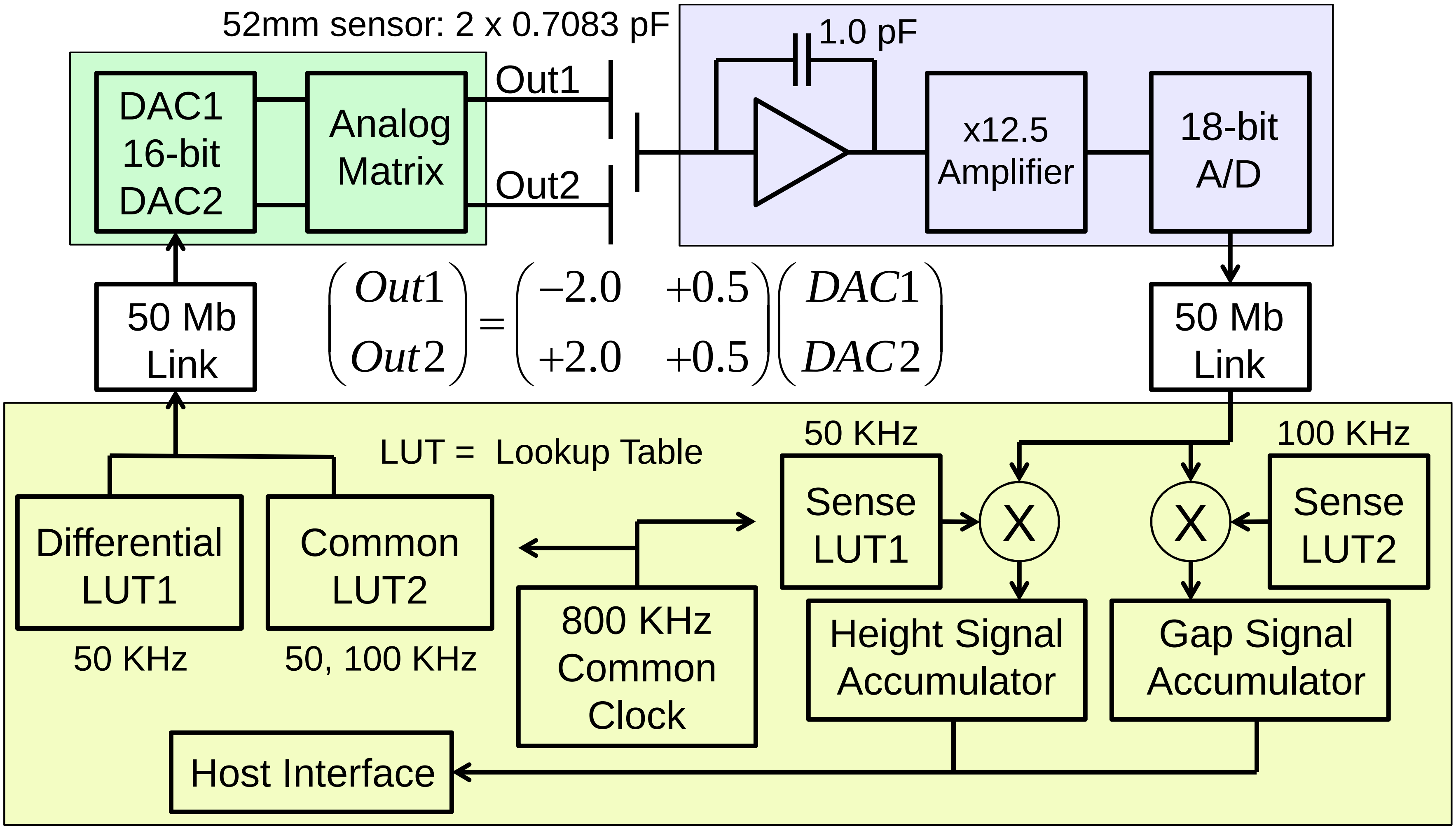
Design Approach and Functional Description

- The requirement for concurrent height and gap outputs is met by using sine wave excitation at 50 KHz for the height signal and 100 KHz for the gap signal, with a single A/D converter on the sense side. Synchronous demodulation in firmware separates the two signals.
- The drive side electronics has a dual 16 bit DAC, a resistor matrix and two +/-5V output amplifiers for each of the two drive-side electrodes. The first DAC is used to create opposing signals in the two electrode outputs, and the second DAC is used to create common-mode signals in the two electrode outputs. This is done with the resistor matrix and a precision inverter.
- The block diagram on slide 14 illustrates the organization graphically. Simplified schematics appear in the section on SPICE modeling, and full schematics are in the backup slides.

Functional Description II

- DAC1, driving the drive plates differentially, creates a 50 KHz sine wave sampled at 800 KHz. This is for height measurement. DAC2, driving the drive plates in common mode, generates a 100 KHz sine wave, also sampled at 800 KHz. This is for gap measurement.
- The second DAC also outputs a small 50 KHz sine wave, with separately adjustable in-phase and quadrature components. This gives a height offset adjustment and quadrature nulling (to be described).
- The sense electronics starts with a transimpedance amplifier with 1.0 pF capacitive feedback. The feedback capacitor, C1, acts as a reference part, and sets the absolute scaling of the sensor.
- The rest of the sense board is a gain stage, an A/D driver and an 18 bit A/D which samples at 800 KHz.

Functional Block Diagram



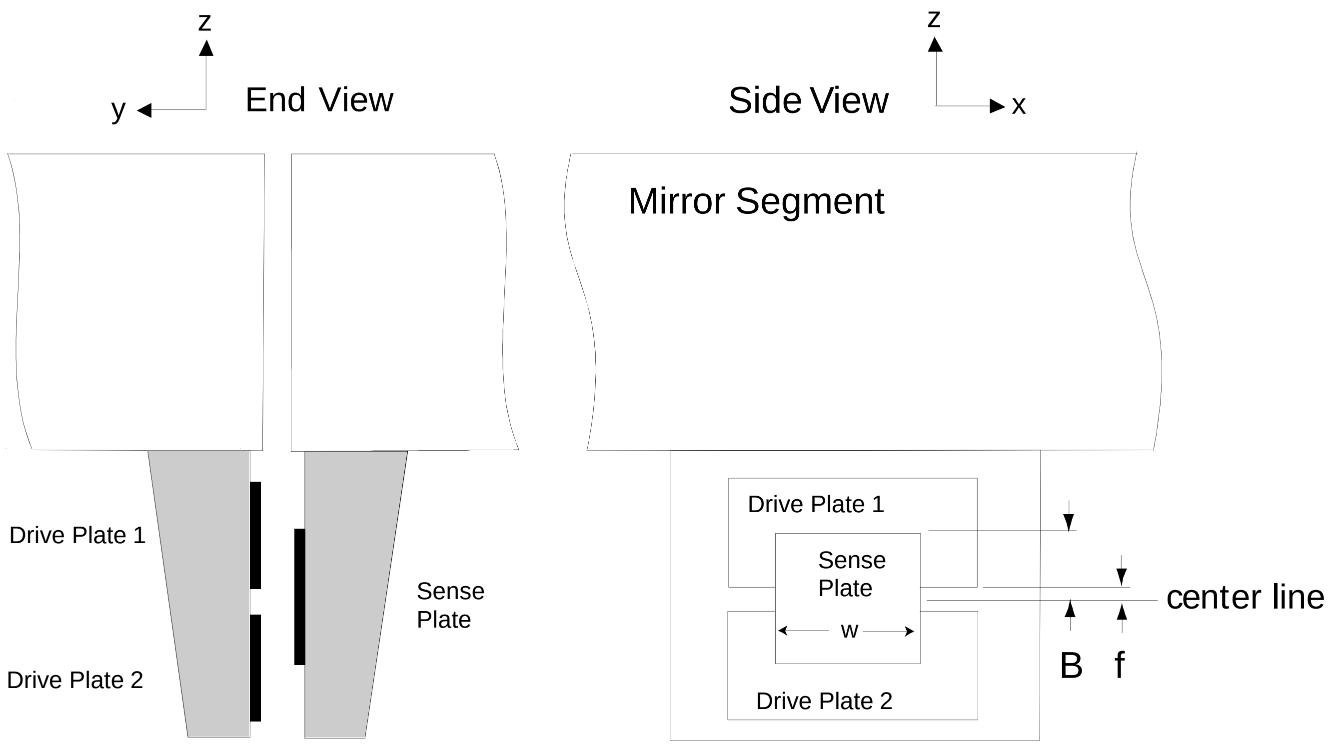
$$\begin{pmatrix} Out1 \\ Out2 \end{pmatrix} = \begin{pmatrix} -2.0 & +0.5 \\ +2.0 & +0.5 \end{pmatrix} \begin{pmatrix} DAC1 \\ DAC2 \end{pmatrix}$$

Signal Processing in Firmware

- The firmware sends 16-bit digital waveforms from two lookup tables to the dual DAC on the drive side, and receives 18-bit data from the A/D on the sense side, both at an 800KHz sample rate, and both over a 50 Mbaud SPI link.
- The sense signal is demodulated concurrently at 50 and 100 KHz, using 18x18 bit hardware multipliers and 40 bit accumulation. Reference sine waves are generated by lookup table and accumulation is over whole sine wave periods This gives height and gap readings at an internal rate of 50 KHz.
- These are averaged to provide height and gap outputs at a selectable rate, typically 400 or 20 Hz, then are sent as two 40-bit integers via a 57 or 460 Kbaud serial link to a desktop computer for visualization and data recording under LabView.
- A block diagram of the firmware is in the backup slides.

TMT Edge Sensor

Dimensions are for current 67 mm sensor



w	Sense plate effective width (30 mm)
2B	Sense plate effective height (45 mm)
2f	Effective spacing between drive plates (6 mm)
V	Drive amplitude (0 to 8.192 V_{pp})

Capacitive Sensor Analytic Model

$$R = \frac{A}{y}\left(k(B - f) - z - x\theta_y + \frac{B^2 - f^2}{2y}\theta_x \right)$$

$A = \varepsilon_0 wV$ Square wave excitation

$A = 2\pi f_S \varepsilon_0 wV$ Sine wave excitation

$$L_{eff} = \frac{B^2 - f^2}{2y}$$

R	Sensor reading (coulombs for square wave, amperes for sine wave)
ε_0	8.854 10^{-12} farads / meter
w	Sense plate effective width (30 mm)
2B	Sense plate effective height (45 mm)
2f	Effective spacing between drive plates (6 mm)
y	Gap from drive to sense (4.8 +/- 1.0 mm)
V	Drive amplitude (0 to 8.192 V_{pp})
f_s	Drive frequency
θ_X,θ_Y	Drive-side tip and tilt as seen from sense side
x,y,z	Coordinates of drive side as seen from sense side
k	= (Common-mode drive amplitude) / (Differential drive amplitude)

Dimensions are for current 67 mm sensor

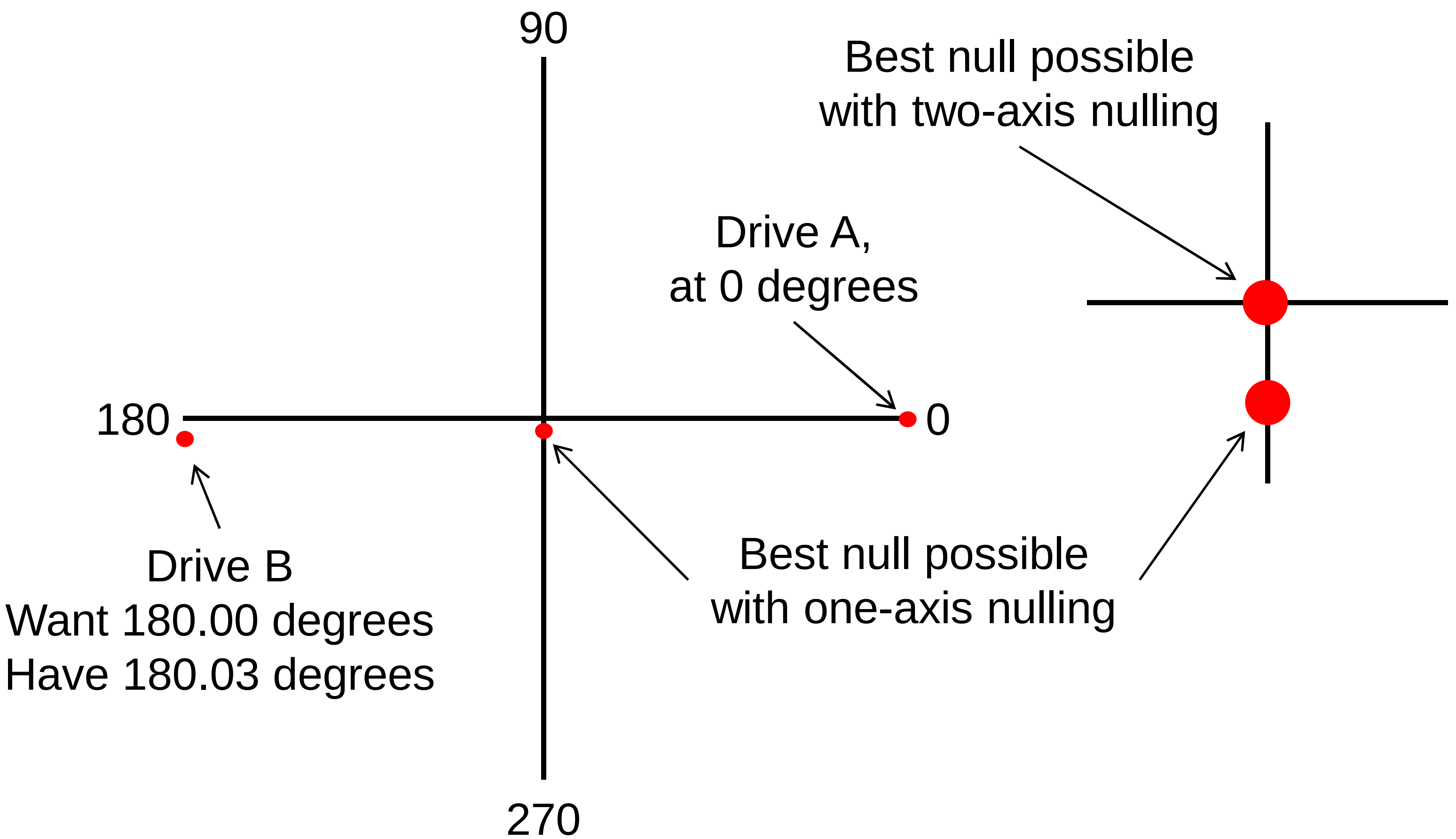
TMT
THIRTY METER TELESCOPE

Height Offset Adjustment

Jet Propulsion Laboratory
California Institute of Technology

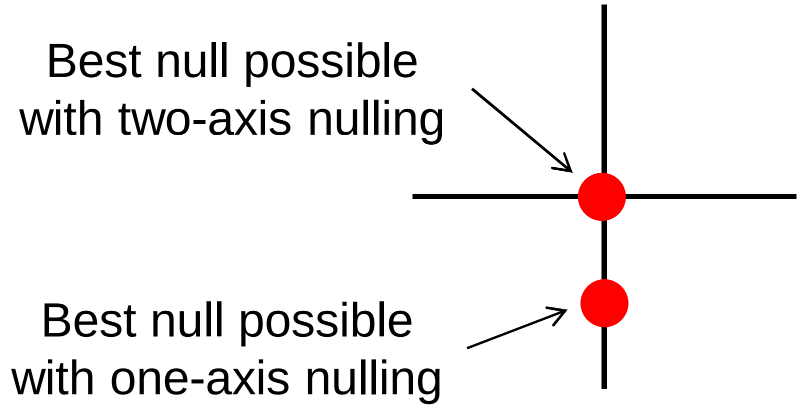
- The term k(B-f) in the sensor analytic model is a height offset term that that comes from adjusting the balance of drive voltages on the two drive plates. It is used to offset the linear height span over a wide range.
  - Both B and f are dimensions of a gold electrode deposited onto Zerodur. The ratio k is set by a 16-bit DAC and precision resistors, and is not a function of reference voltage.
  - Thus the offset is stable and absolute. It is also independent of gap, with or without gap compensation.
- With B=22.5 mm and f=3mm, and k ranging from -0.25 to +0.25, the zero offset range currently is +/-4.88 mm, with a granularity of 149 nm. This can be scaled down if desired.
- A quick check in the lab verified the offset equation to 1.4%.

Quadrature Nulling



Quadrature Nulling II

- One nanometer of height corresponds to 0.051 ppm drive plate unbalance.
- With current electronics, the best possible 1-axis null is 500 ppm, 10,000x bigger than the 1 nm signal.



- We added a quadrature offset in the LabView GUI, meaning both sine and cosine component of the common-mode DAC 50 KHz can be trimmed. There were no changes to hardware or firmware.
- The result was more than 3x reduction in tempco.

SPICE Modeling

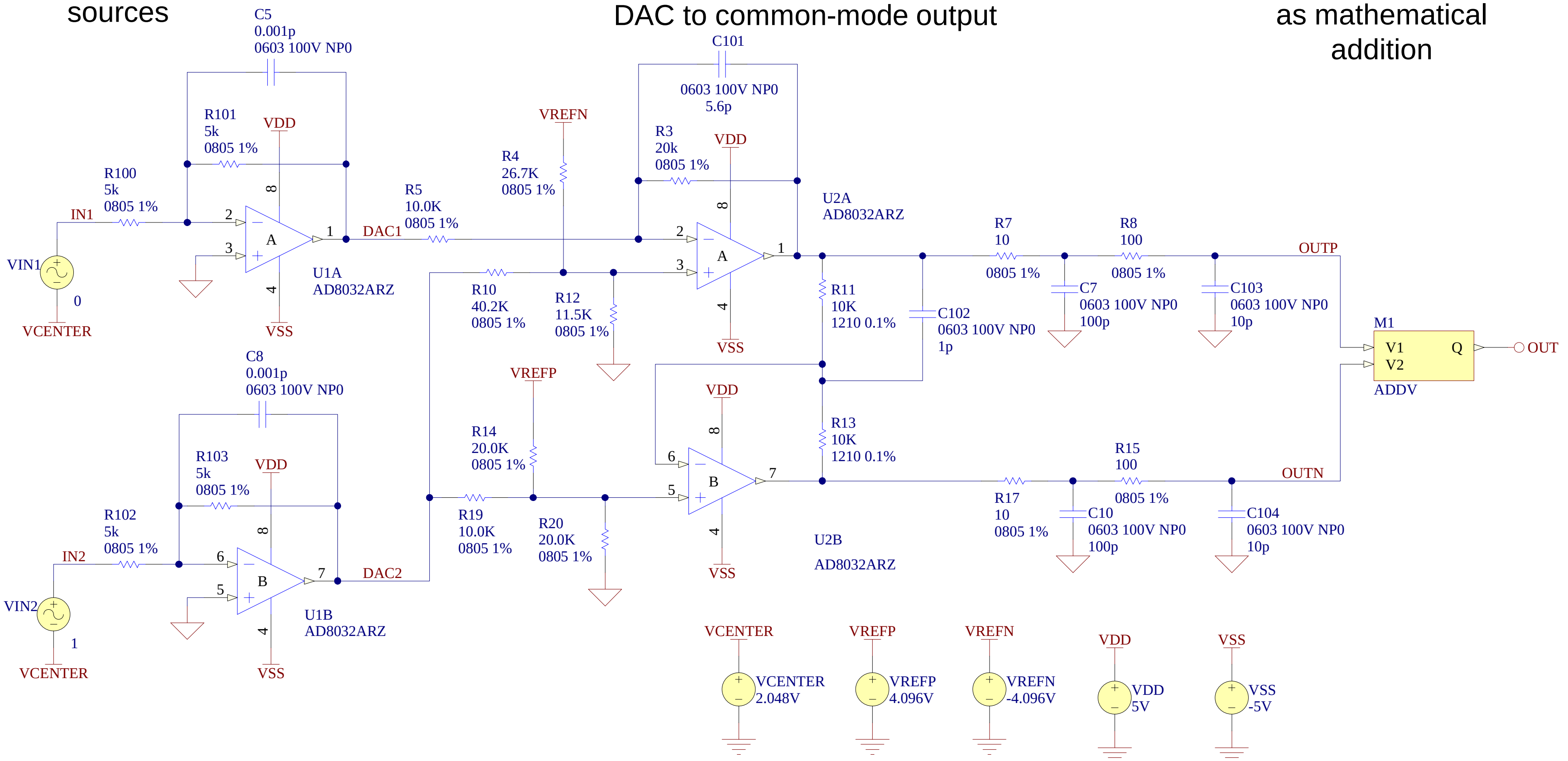
- Full SPICE models of drive and sense boards was implemented to guide improvements in tempco and noise, and to verify calibration.
- An end-to-end model of drive board, blocks at a gap of 4.5 mm, and sense board gave observed gap A/D counts lower than predicted gap A/D counts by 11.6%. The difference is likely dominated by circuit board stray capacity adding to the 1.0 pF reference capacitor.
- The formula for offset DAC count vs measured height offset was verified to 1.4%.
- Noise and tempco were improved considerably by part substitutions guided by modeling.

Spice Model of Drive Board

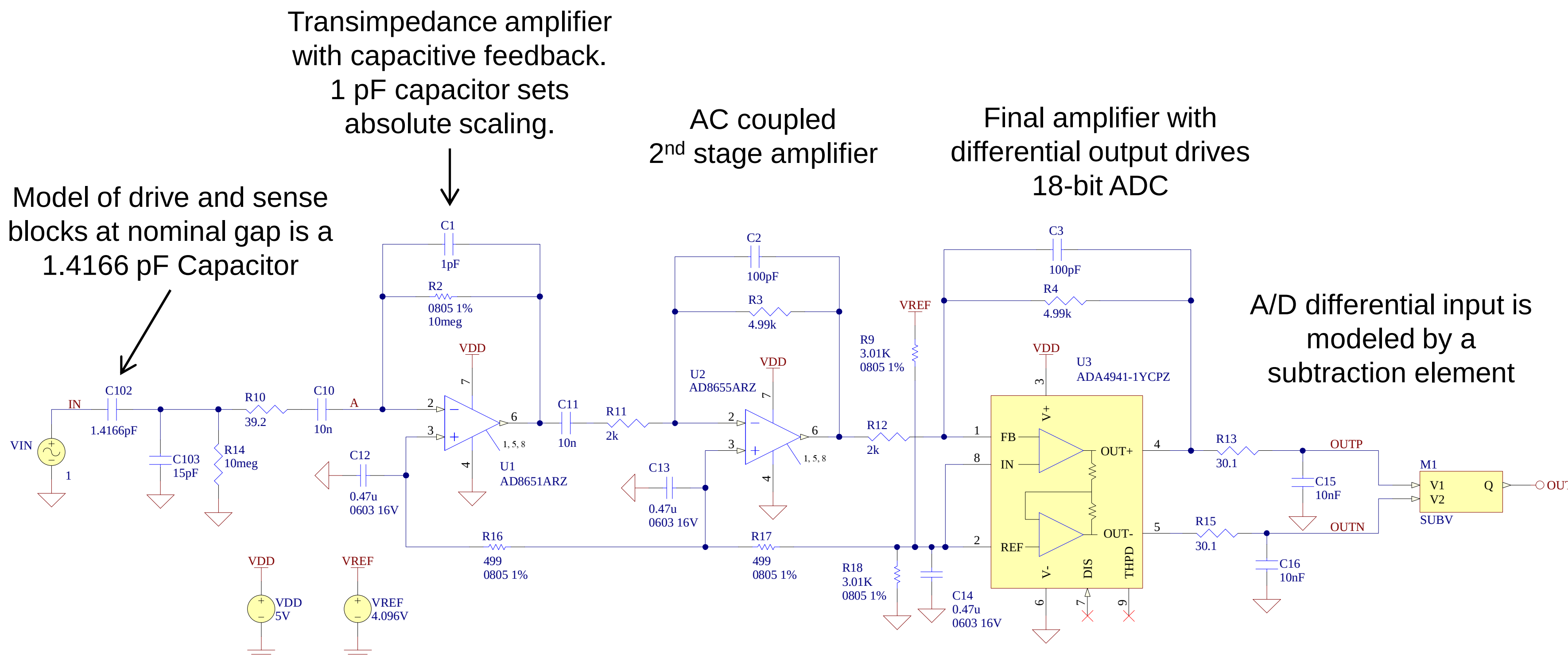
16-bit dual DAC is modeled as two voltage sources

A resistor matrix and precision inverter map upper DAC to differential output, and lower DAC to common-mode output

The effect of the two drive plates is modeled as mathematical addition



Spice Model of Sense Board



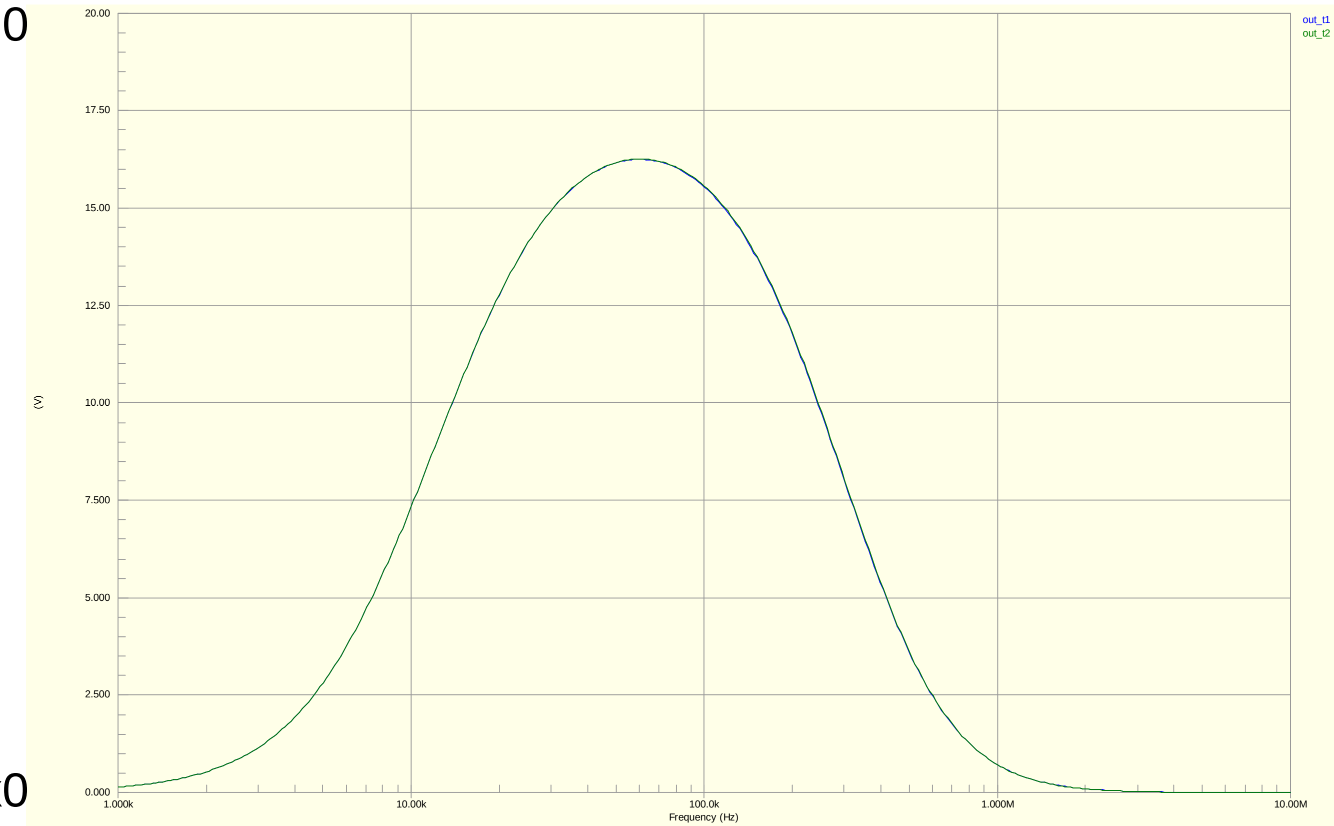
Sense Board Frequency Response

A/D volts per gap drive volts at nominal gap

x20

x10

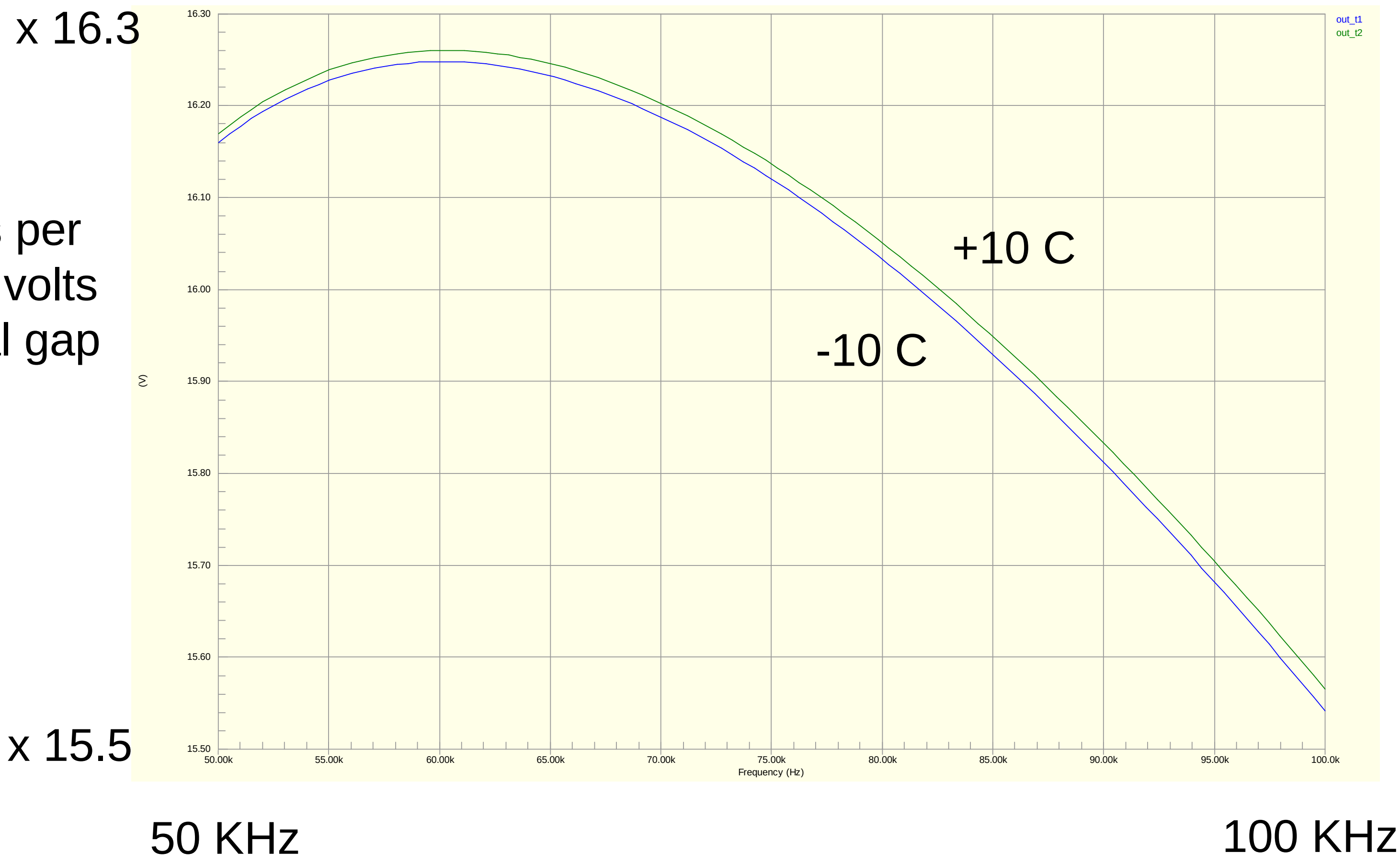
x0



1 KHz 100 KHz 10 MHz

Sense Board Detailed Frequency Response

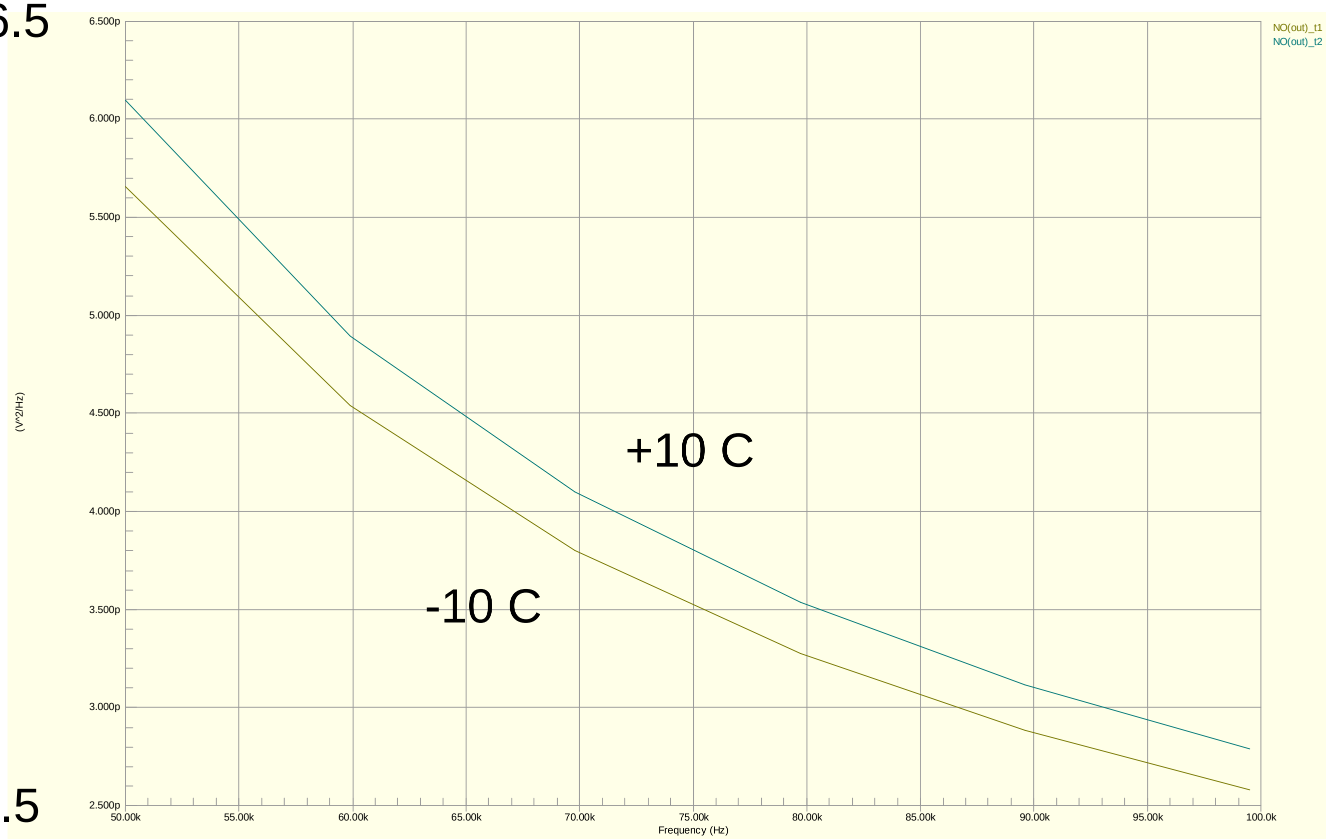
A/D volts per gap drive volts at nominal gap



Sense Board Noise Performance

10^{-12} V^2/Hz at A/D input

6.5



2.5

50 KHz

100 KHz

Lessons Learned

- Knowledge of end-to-end scaling is dominated by imperfect knowledge of the effective capacitance of C1, which acts as a capacitance reference. It is a 1.0 pF capacitor; circuit board stray capacitance of 0.11 pF can explain the reduced signal.
- Tempco in nm/C is dominated by the performance of precision inverter in the drive board, which is dominated by the gain-bandwidth of its amplifier.
- On drive board, adding quadrature nulling reduced tempco by more than 3x (see next two slides).
- The sense board contributes no observable offset with temperature.
- The interface cables (data/power) can contribute capricious offsets and crosstalk between sensors unless well shielded.
- On sense board, thermal noise from the two 10 Meg resistors which constrain DC operating point (R2 and R14) is a major contributor to total noise.

Summary of Current Performance

- These are a preview of the next presentation's data. They are a snapshot at the current development level.
- Height noise density: Requirement is 2.8 nm/√Hz, measured is 2.2 nm/√Hz.
- Height temperature coefficient: Requirement is 1 nm/C after calibration. Measured is 12 nm/C before calibration; a study in the calibration presentation shows this is reduced to the requirement level, but with little margin.
- Power dissipation: Requirement is 200 mW or less. Actual drive board power is 99.2 mW, sense board is 90.5 mW, total is 190 mW.

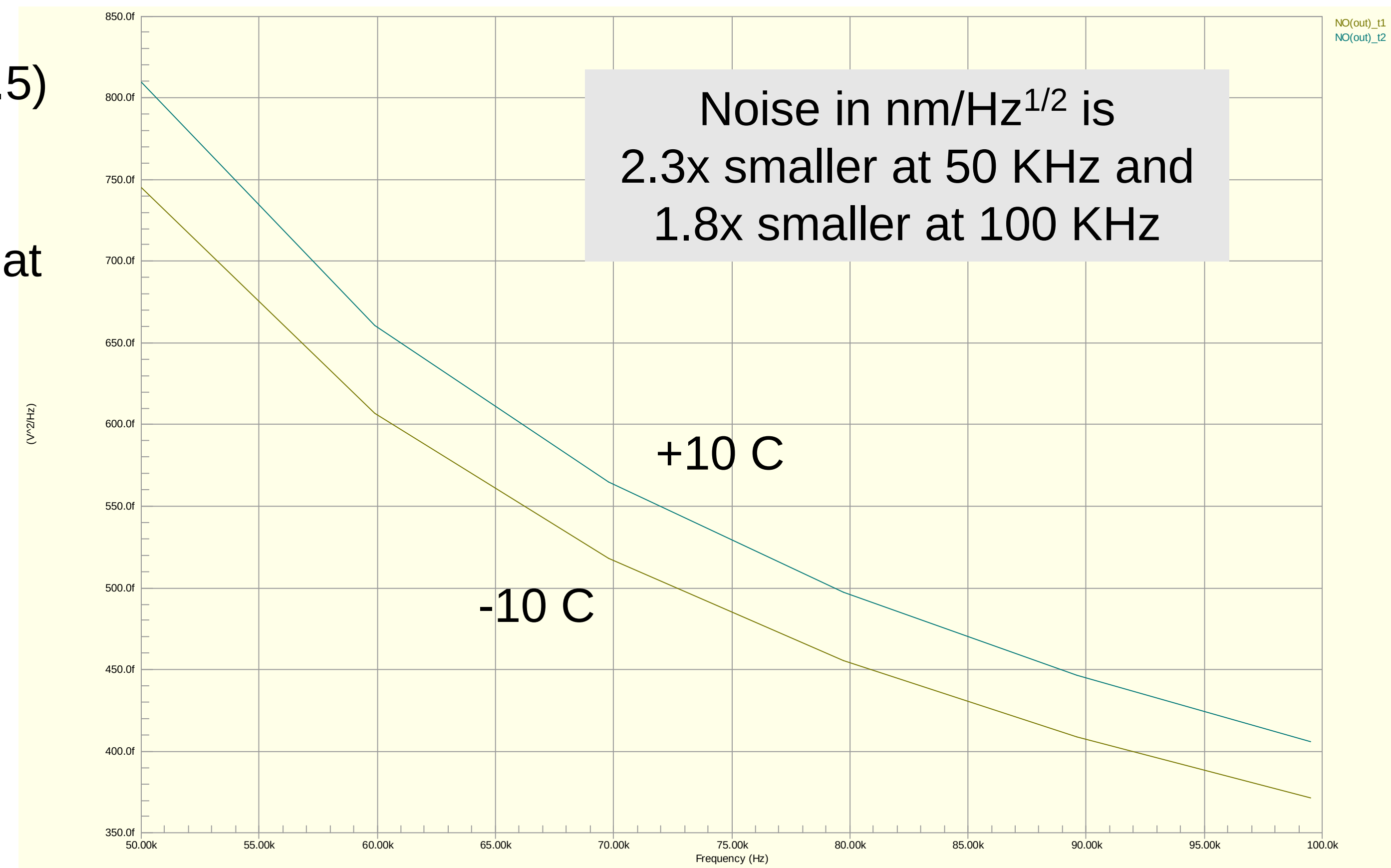
Near-Term (PCP-phase) Improvements

- On sense board, replacing 10 Meg resistors R2 and R14 with 100 Meg resistors and replacing AD8651 with AD8655 will improve noise and tempco.
- The projected improvement is a 2.3x reduction in height noise, 1.8x reduction in gap noise, a reduction in tempco from 12 nm/C to 8 nm/C.
- These changes do not require a board respin. They may be adequate to meet all requirements.
- Another iteration with a new board layout will be desirable in the PCP phase to accommodate lower tempco parts and smaller connectors.

Improved Sense Board Noise Performance

0.85
(was 6.5)

10^{-12} V^2/Hz at A/D input



0.35
(was 2.5)

50 KHz

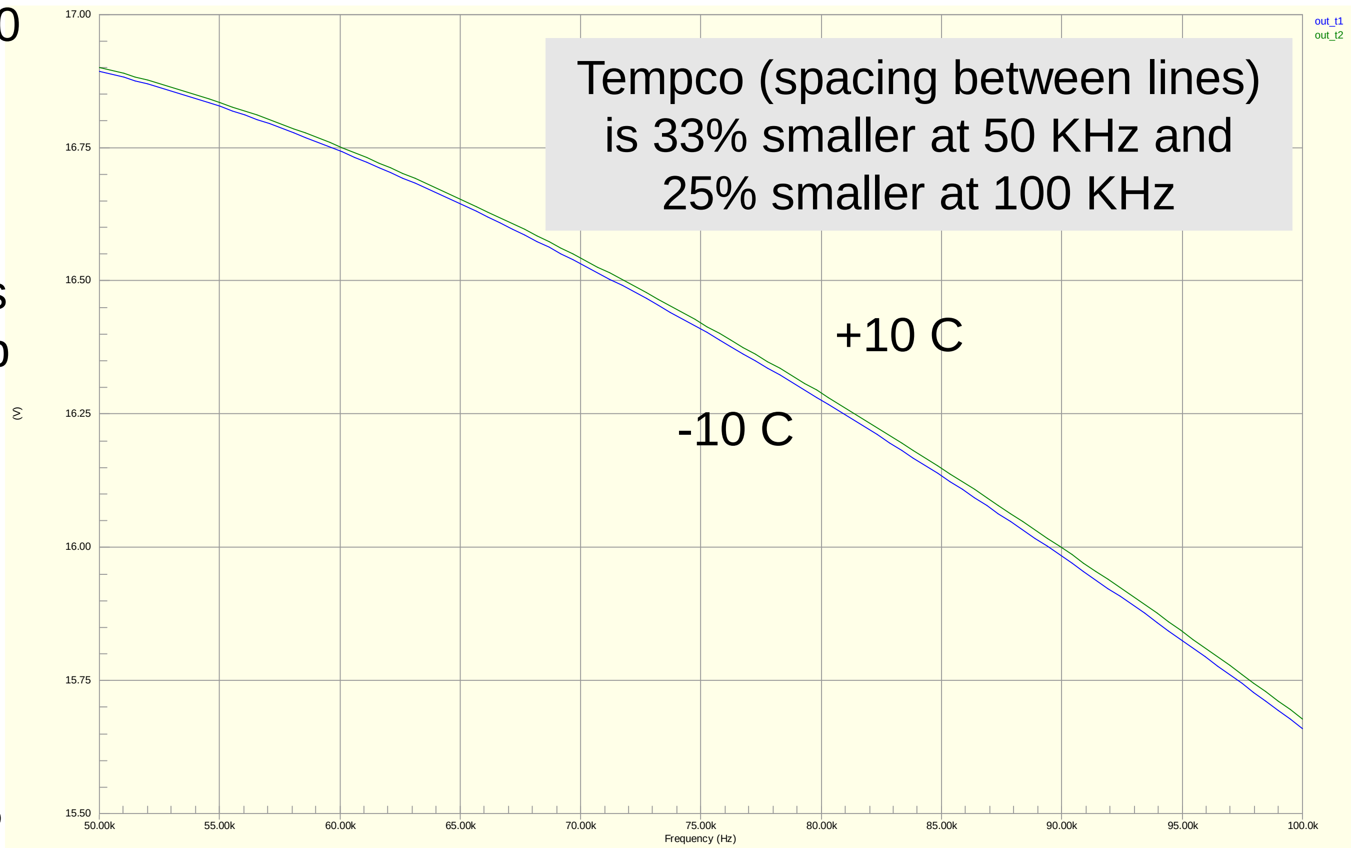
100 KHz

Improved Sense Board Detailed Frequency Response

x 17.0

A/D volts per
gap drive volts
at nominal gap

x 15.5



50 KHz

100 KHz

Integration with SCC during Construction Phase

- Sense, drive and the connector boards will all need redesign as the digital interface, connectors and cabling are fully defined as part of future SCC development.
- The last sensor electronics design task will be to create the deliverable controller/interface board, which will reside in the Upper Segment Box.

Conclusions

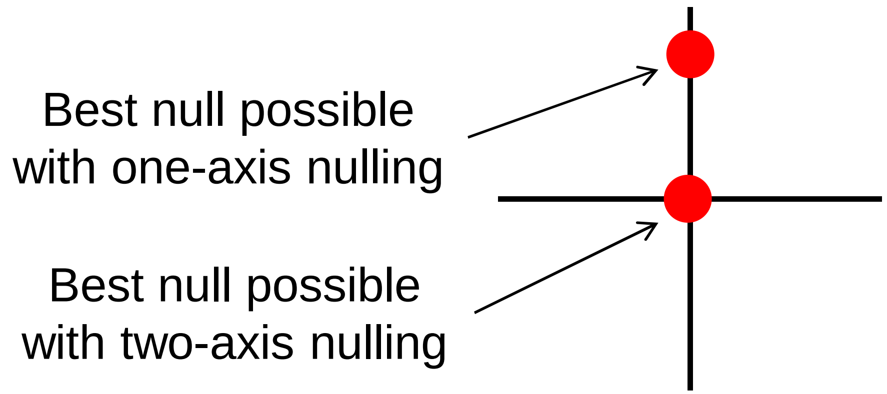
- The current electronics are close to achieving the performance requirements.
  - The current electronics have a 12 nm/C temperature coefficient. Reducing this to 6 nm/C is desirable so that the PSSN impact drops below 0.001 after calibration (see calibration presentation).
  - The measured temporal drift of 4.4 nm rms over 24 days is slightly greater than the 3.5 nm over 30 days requirement.
- Both near-term and longer-term improvements are planned to further reduce temperature coefficient and drift with time.

Backup Slides

- Quadrature nulling detail
- Preview of Performance Measurements
- Comparison of Keck and TMT edge sensors
- Drive board full schematic
- Sense board full schematic
- Firmware functional block diagram
- References

Quadrature Nulling - backup

- One nanometer of height corresponds to 0.051 ppm drive plate unbalance.
- The best possible 1-axis null with no C102 is 5500 ppm, 100K bigger than the 1 nm signal. This is right at the 18-bit A/D theoretical limit.



- The best possible 1-axis null with C102 = 1.0 pF is 500 ppm, 10K bigger than the 1 nm signal.
- We added a quadrature offset in the LabView GUI, meaning both sine and cosine component of the common-mode DAC 50 KHz can be trimmed. Besides adding C102, there were no changes to hardware or firmware.
- The result was more than 3x reduction in tempco.

Requirements and Performance I

Requirement	Value	Sensor DRD Req	Current Performance	Notes
Piston Noise	5 nm in 2 Hz bandwidth (2.8 nm/√Hz).	1240	<2.2 nm rms/√Hz	For each sensor
Piston Offset Drift	5 nm rms @ 30 days [3.5 nm avg over interval]	1520	4.4 nm rms over 24 days interval, single sensor	For the ensemble of sensors
Piston Offset Drift	+- 4 nm avg	1522	<5 nm/24 days for a single sensor after 1 day settling, some variations outside 5 nm during that period	For the ensemble of sensors
Piston Offset Temp. Sensitivity	+-1 nm/C after calibration	1500	~12 nm/C before calibration	For each sensor
Avg. Piston Offset Temp. Sensitivity	+- 1 nm/C after calibration	1502	Is met if 1500 is met	For the ensemble of sensors
Gap Noise	0.5 micron rms in a 1 Hz bandwidth	1280	<0.13 micron rms/√Hz	For each sensor. Is 0.026 um/√Hz for drive level of 0.05x -larger than currently used
Gap Drift	+-0.5 micron/30 days	1560	0.2 micron rms/24 days	For each sensor
Gap Temperature Sensitivity	± 0.25 micron/C after calibration	1515	0.18 micron/C before calibration	For each sensor

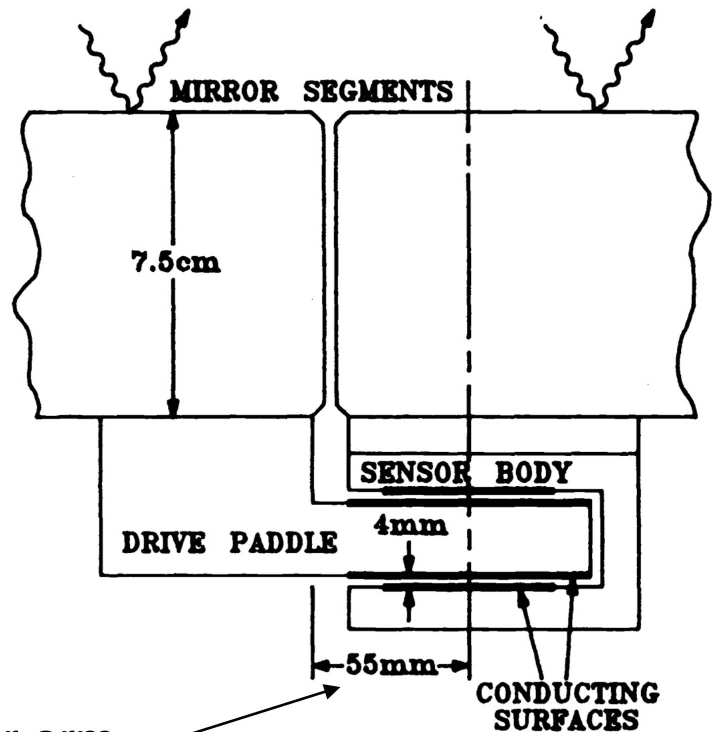
Requirements and Performance II

Requirement	Value	Requirement Number	Current Performance	Notes
Sampling Rate	40 Hz	1600	40 Hz	Sampling rates from 2 Hz to 400 Hz settable with two firmware registers. Rates above and below that range not tested.
Sampling Rate	400 Hz	1620	400 Hz	Higher speeds than 400 Hz not well tested
Piston Monotonicity		1222	Meets requirement	
Zero offset adjustment range	+-100 micron	1140	+-5 mm	Will be reduced to +-0.5 mm with resistor change to improve resolution of zero offset.
Zero offset adjustment resolution	0.5 micron	1145	<0.1 micron	
Non-interlocking	--	480	Require ground across gap	Per sensor
No external initialization proc at power up		1060	Next level of assembly, but tuning process is worked out.	Sensor tuning process worked out at individual level
Interchangeability		1080	Requires tracking piston offset of each pocket.	Sensor halves can be tracked for higher precision offset adjustment.

Keck Edge Sensor

Dihedral angle sensitivity is provided by the 55 mm lever arm shown.
This is the ratio of height to tilt sensitivity.
By analogy to Keck, for TMT sensors this ratio is called the effective lever arm, or Leff.

$$\text{Sensor Reading} = z + L\theta_x$$
$$L = L_{eff} = 55mm$$

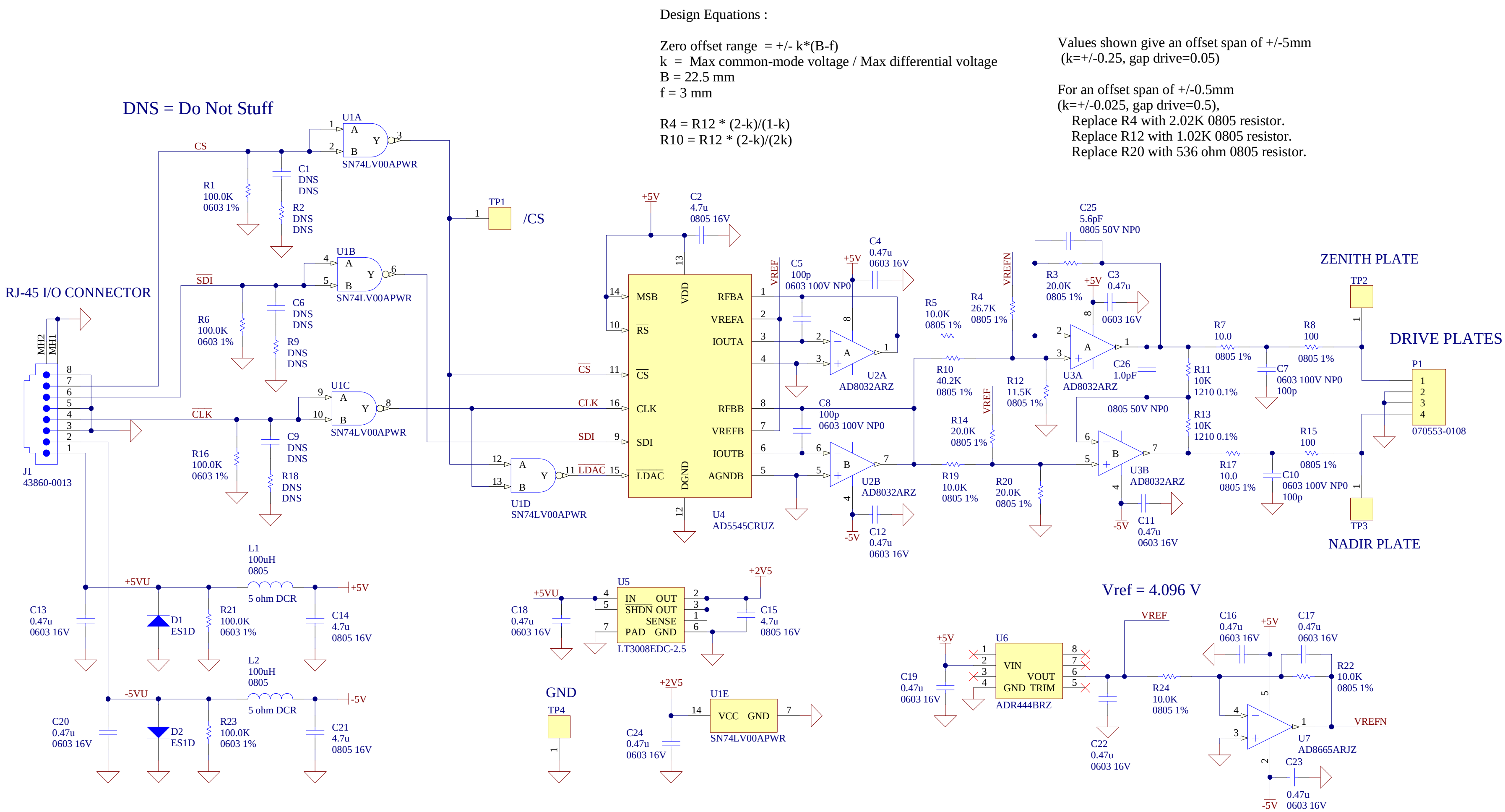


55 mm physical lever arm gives sensitivity to segment dihedral angle

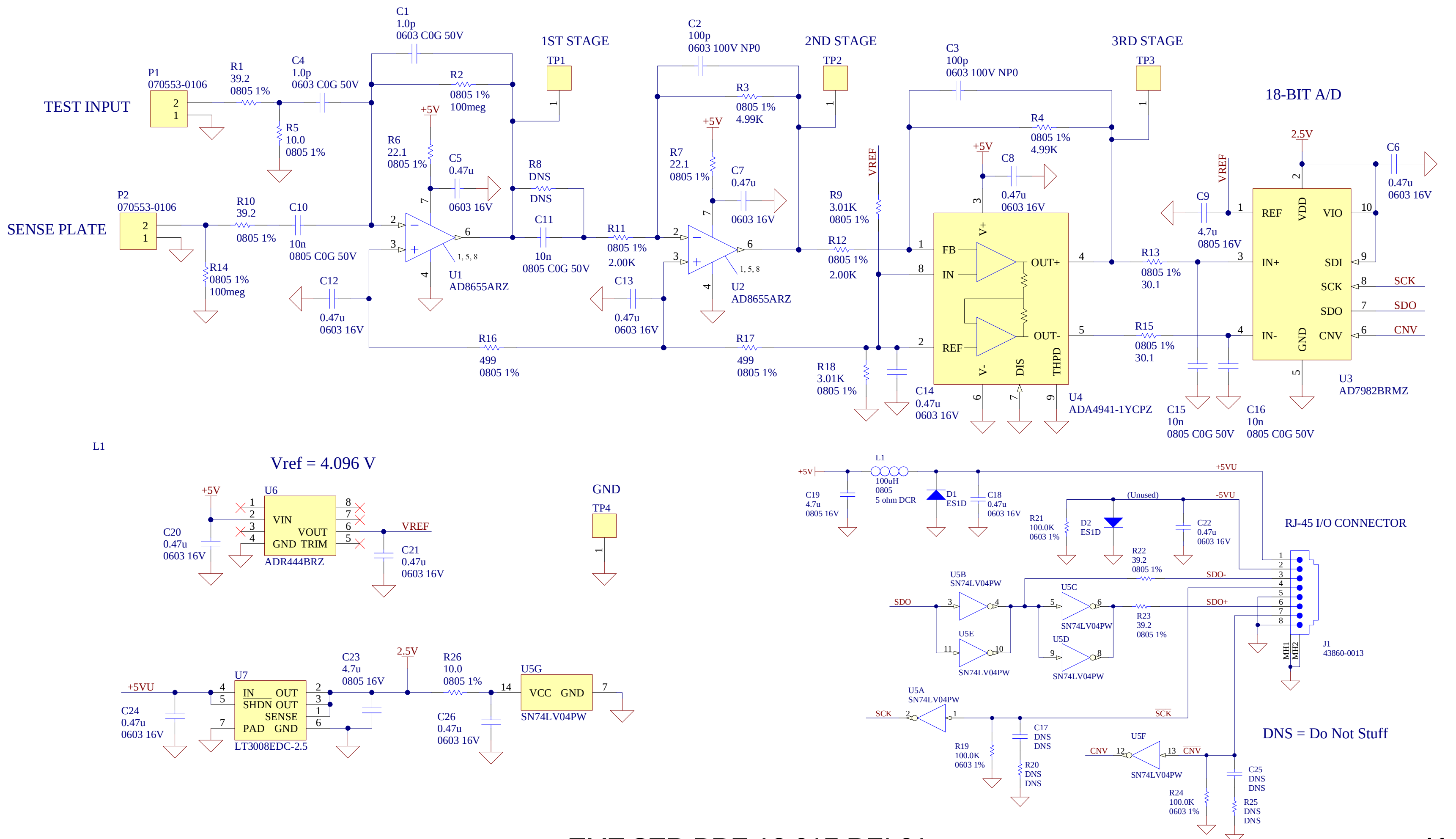
Keck and TMT Edge Sensors

KECK	TMT
Arm must swing out of the way for segment replacement.	Face-on design simplifies segment replacement.
Dihedral angle sensitivity not a function of gap.	Dihedral angle sensitivity proportional to 1/gap.
Output is a non-linear function of height difference.	Output is linear function of height difference.
Geometry gives relatively benign electrical noise, tempco and drift requirement.	Face-on design needs ~8x smaller electrical noise, tempco and drift for same spec in nm.
Uses square-wave drive at 10KHz, with charge-sensitive preamp.	Uses sine wave drive at 50KHz and 100KHz, with capacitive transimpedance preamp.

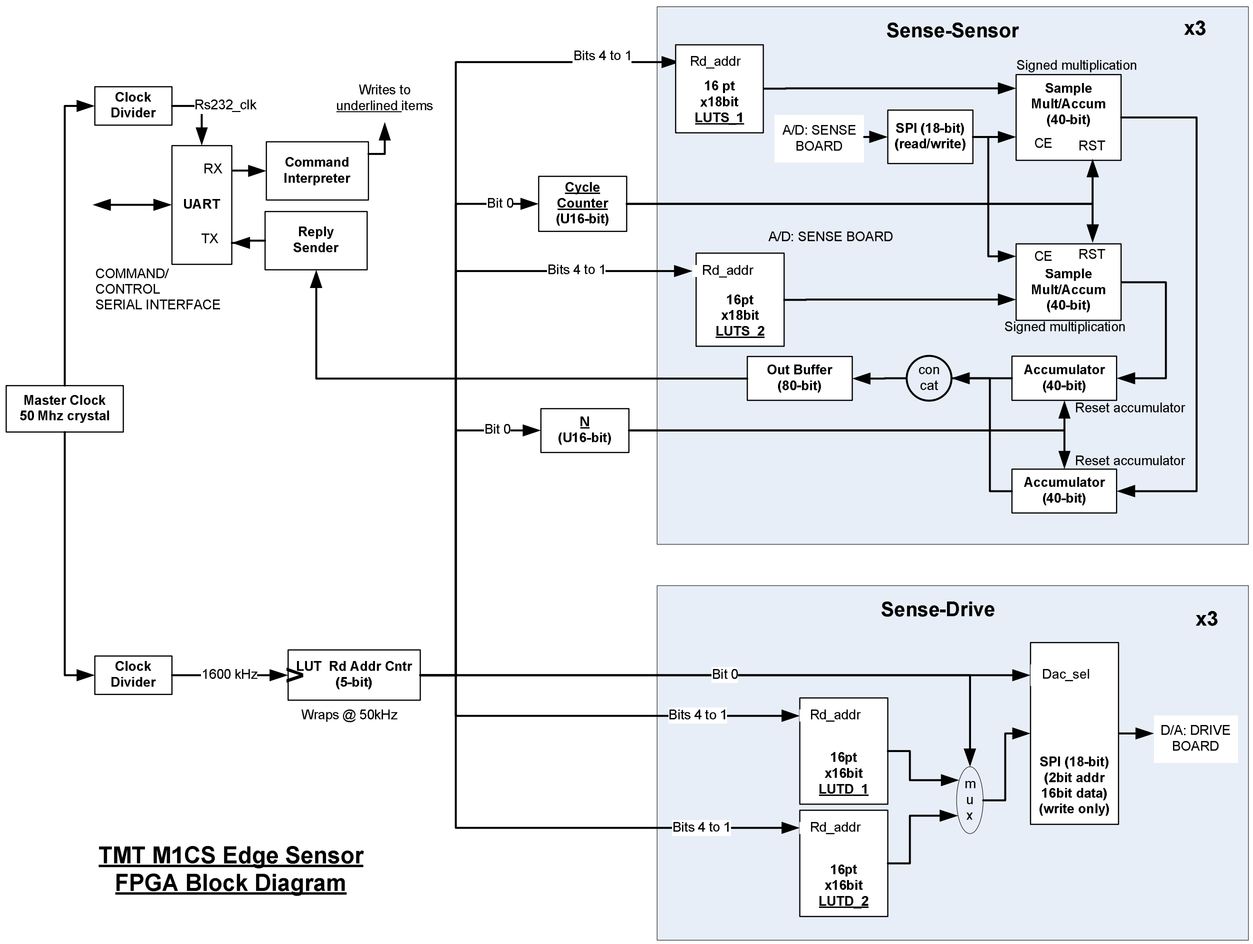
Drive Board Full Schematic



Sense Board
Full Schematic



Firmware
Functional Block Diagram



TMT M1CS Edge Sensor
FPGA Block Diagram

References

- “Sensor Electronics Description”, TMT.CTR.TEC.11.063.REL01

P07_Detailed Description and Performance II
Boots, Purge, System Testing

Chris Lindensmith, Chris Shelton
M1CS Sensor System Preliminary Design Review
Pasadena
March 29 - 30, 2012

Outline

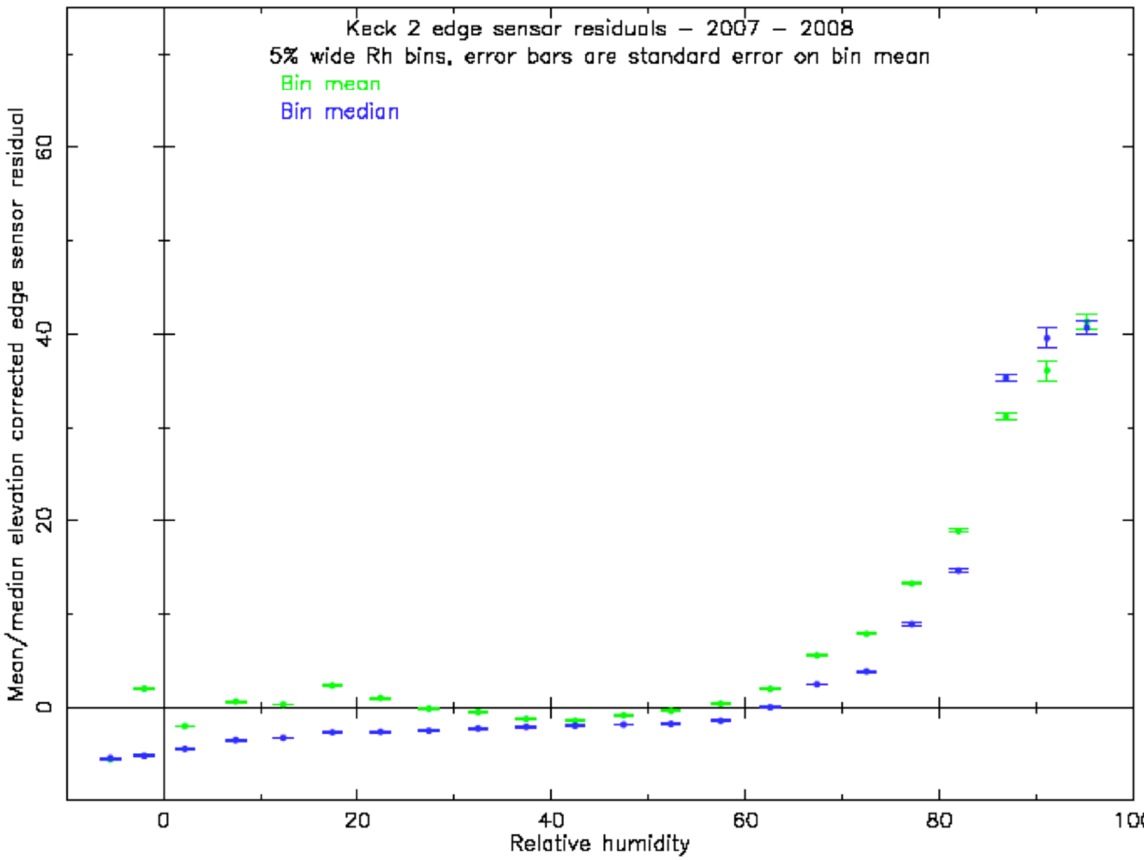
- Purged dust boot
  - Motivation & key requirements
  - Concept development
  - Current boot design and test results
- Purge system conceptual design
- [Sensor electronics presentation – Chris Shelton, P06]
- Sensor system test results
  - Noise, stability, and drift and compliance with requirements
- Mechanical stability and repeatability

Purged Dust Boot

Need For Dust Boot

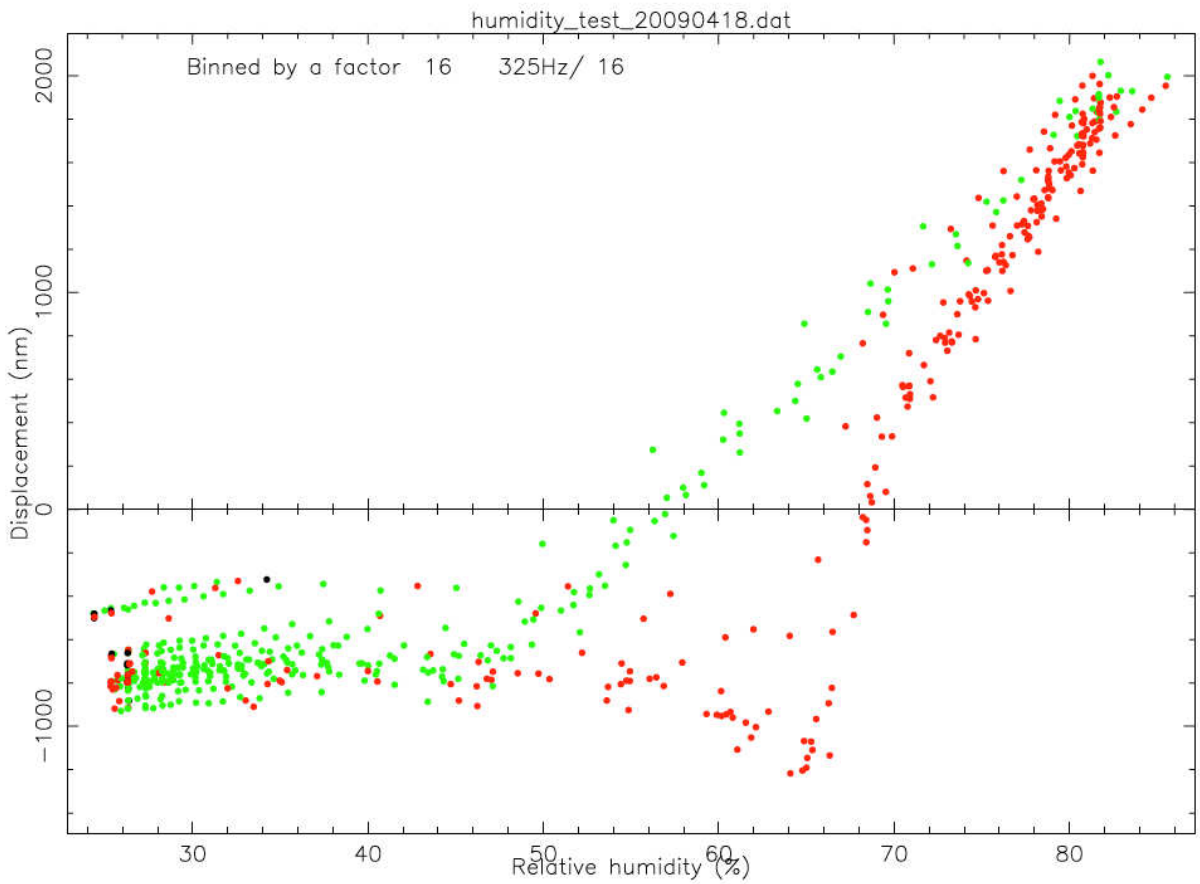
- Capacitive edge sensors are sensitive to dust deposits and humidity variations
  - The edge sensor selection board specifically identified a dry-gas purged boot as part of the selection.
  - TMT edge sensors show sensitivity to RH above about 40-50%
  - Some fraction of telescope operation will be at (non-condensing) RH > 50%
  - Low surface energy dielectric coatings do not prevent adsorption of water onto the sensor surface.
- Keck sensors have a non-hermetic dust boot
  - Works well to keep dust off sensors
  - Sensors do show sensitivity to variations in humidity that are sufficiently large to be a concern for TMT
- For more detail see: TMT.CTR.TEC.09.042

Keck RH Observations



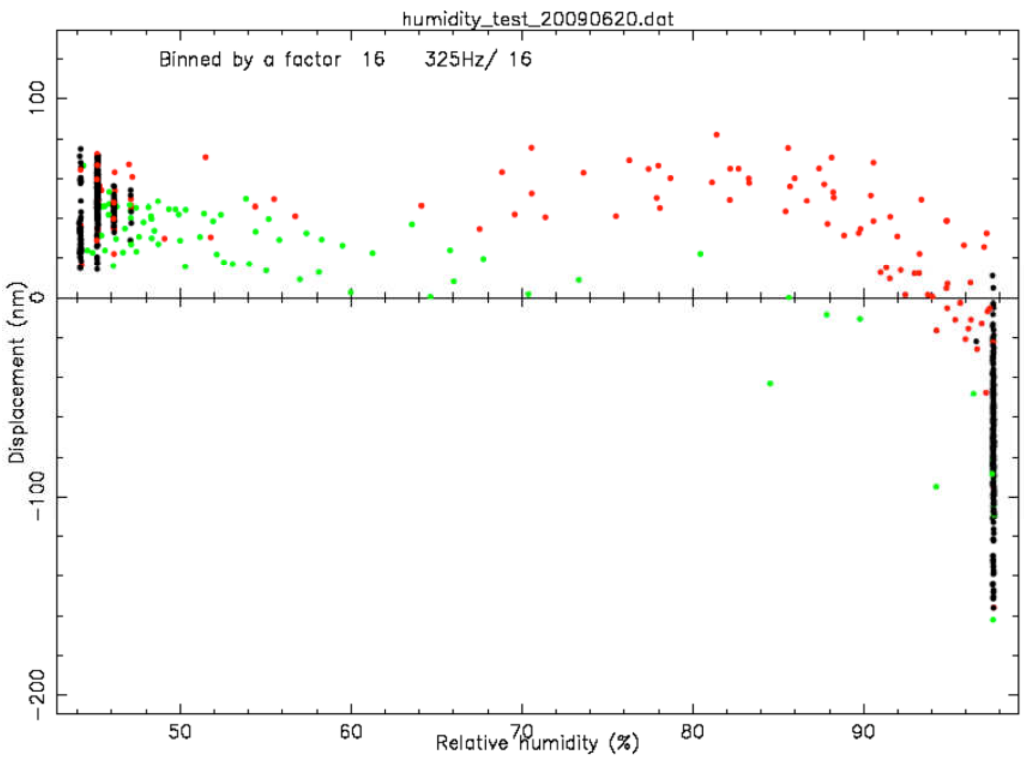
- Keck sensors show an increase in residuals at RH > 60%
  - Assumes that at a given RH, all sensors have same magnitude error with random sign, and that the sensor error is 1.64* the residual (Chanan)

Humidity Sensitivity – “Dirty” TMT Cap Sensor Measured at JPL



- Red is increasing RH, Green is decreasing RH
- Shows large errors, with onset around 50% RH
- Sign of error depends on asymmetry of water adsorbed onto sensors

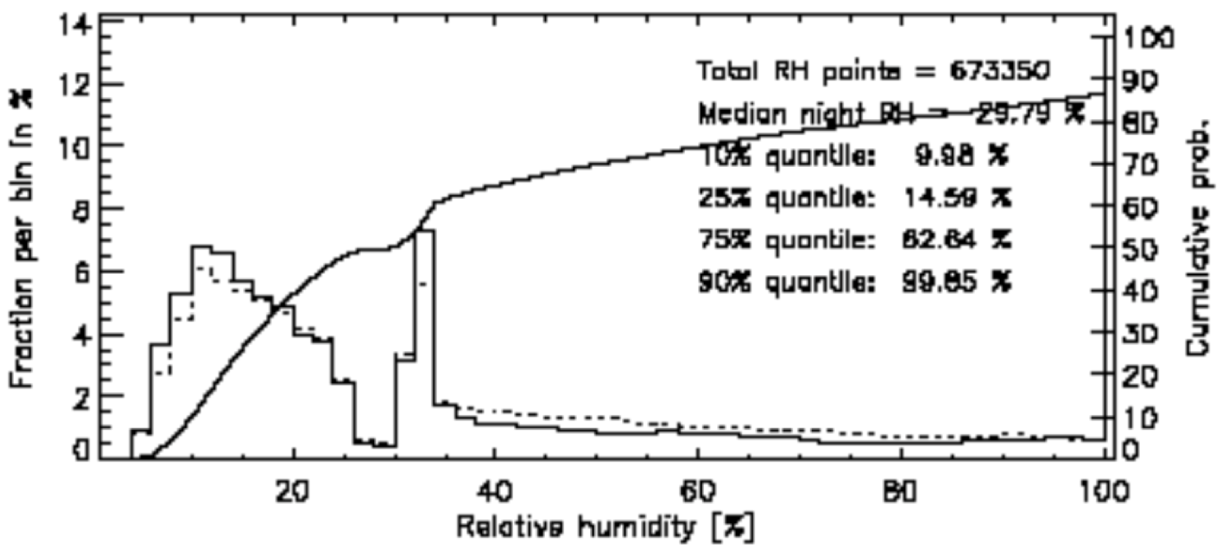
Humidity Sensitivity – “Precision Cleaned” TMT Cap Sensor



- Same sensor as previous slide, but cleaned in ultrasonic baths of DI water and Alcohol
- No change in shunt resistance before and after cleaning
- Red is increasing RH, green is decreasing RH
- Shows significantly smaller RH effect, with later onset.
- **Leaving sensor untouched in air it will return to “dirty” state in weeks to months.**

Cleaning sensors may result in acceptable short term humidity performance, but is not practical for long term stable operation.

Humidity – Mauna Kea environment



- Chart shows site-survey data from Mauna Kea.
- We assume statistics will be consistent, and also that the dome will be closed if RH≥90%

Observing Impact of Relative Humidity

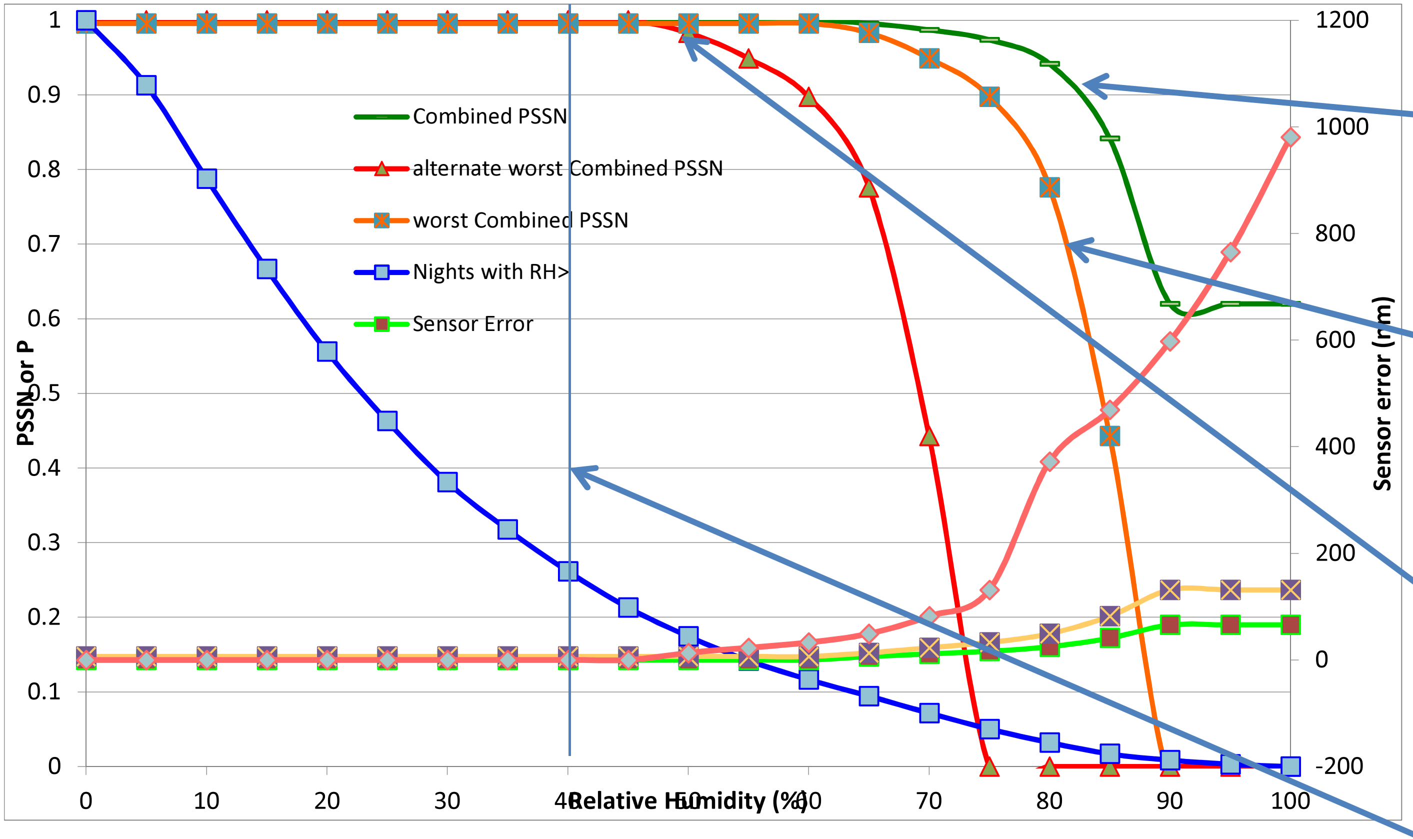


Chart from sensor downselect review, incorporating a pessimistic humidity model, showing PSSN vs.. humidity under different scenarios (R,O,G), and a cumulative distribution of RH (B)

Combined PSSN is the total PSSN effect (high order + focus mode) of the same RH effect as at Keck II.

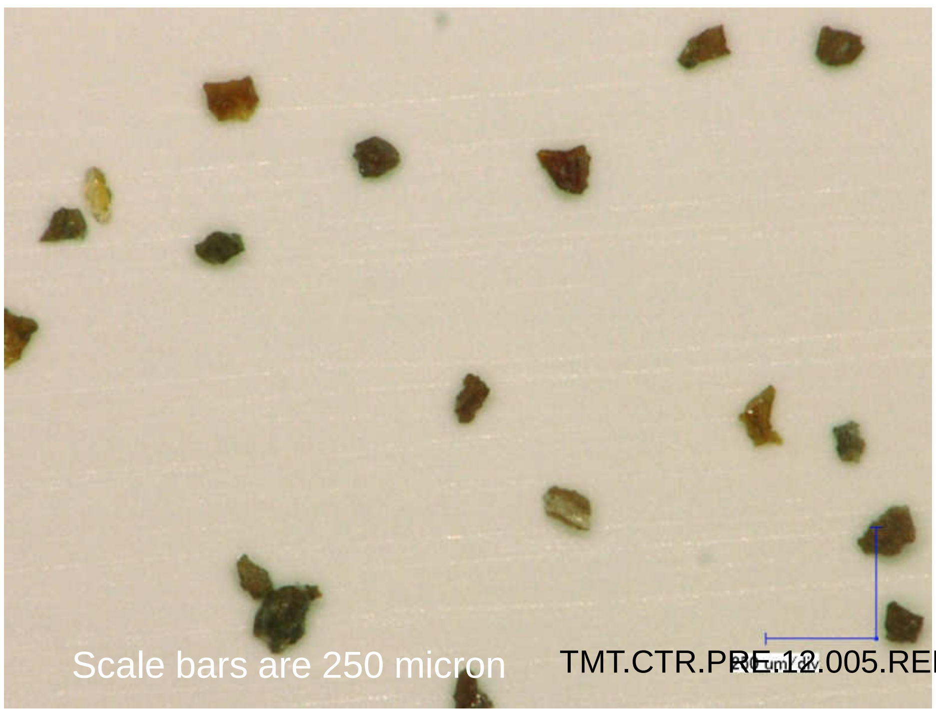
For a "worst case" model, RH effect is twice as bad as observed at Keck II.

For an "alternate worst case" humidity model, performance starts to degrade at RH~50%, and RH is twice as bad as observed at Keck II

Setting the purge design at 40% provides safety margin at little or no additional cost - dry air is cheap

Typical Dust at Keck

- Significant dust accumulates on the dust boot of the Keck sensors
- Dust sampled from vertical edge gap (using a cotton swab) at Keck shows particles 50-100 µm
- We expect a similar dust environment at TMT, and a similar need to keep the sensors clean



Scale bars are 250 micron

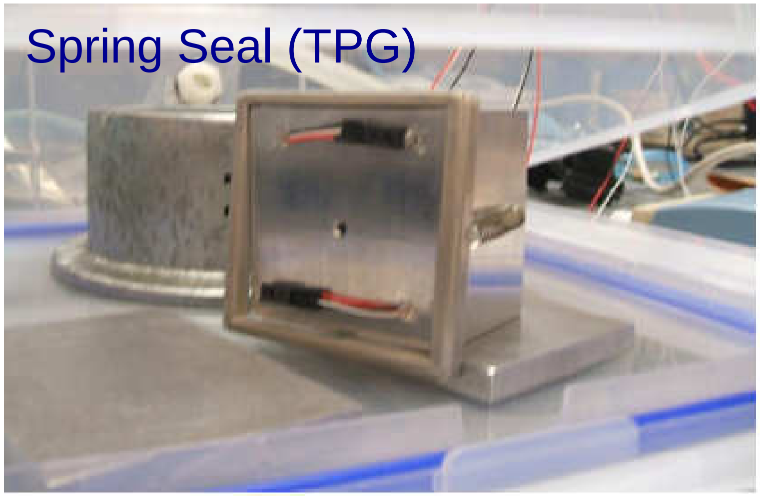
Key Requirements on Purged Dust Boots

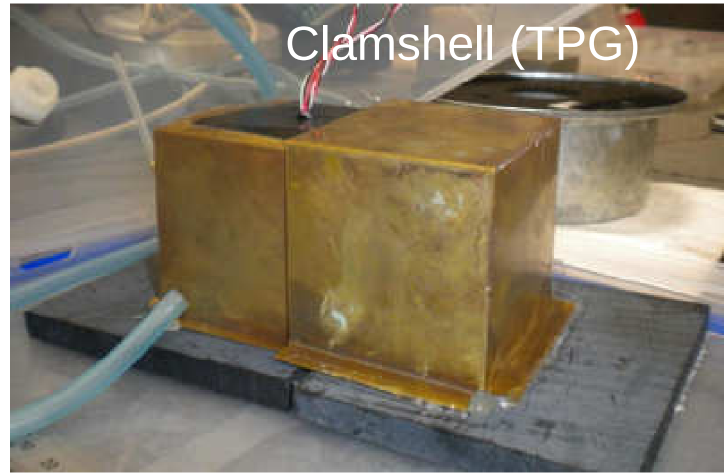
- Maintain RH<40% with ~5 cc/s dry purge gas
  - There is some flexibility in the allowed flow rate, but 5 cc/s allows for a very large leak around the seal edge. 10-15 cc/s could also be provided with minimal effect on gas supply design.
- Protect sensor from dust on face
- Limit on inter-segment forces contributed by boots
  - Fx<150 mN over +-1 mm motion (shear)
  - Fy<100 mN over +-1 mm motion (gap)
  - Fz<50 mN over +-0.5 mm motion (height)
  - Larger forces are acceptable during non-observing operations when segments may move greater distances.
  - Dynamic changes during operation are smaller (~0.3 mm)
- Boots should require no additional handling/service during segment exchange operations
- Desired features
  - Can tolerate 50° C temperature soak
  - 50 year operational life
  - Materials compatible with cleaning, stripping and recoating process

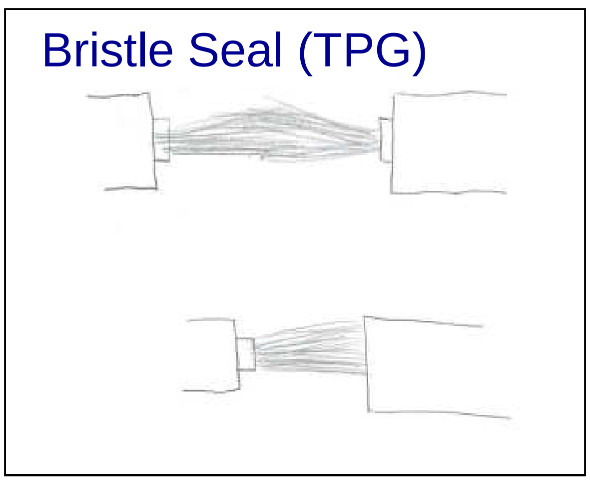
Development Program

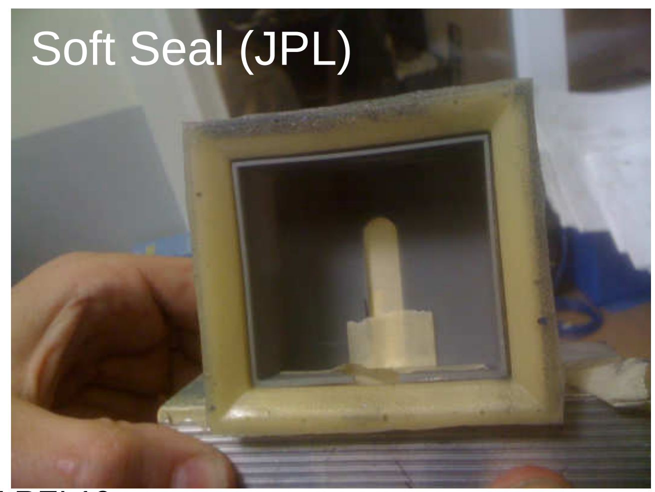
- Developed several proof of concept boots at JPL and TPG
- Tested each for dust and RH performance
- Measured or calculated intersegment forces
- Selected a concept for detailed design and qualification
- Developed detailed design that is near-final
  - Included environmental and motion-life tests
  - Motion-life test will be in FDR with correct materials

Boot Concept Development

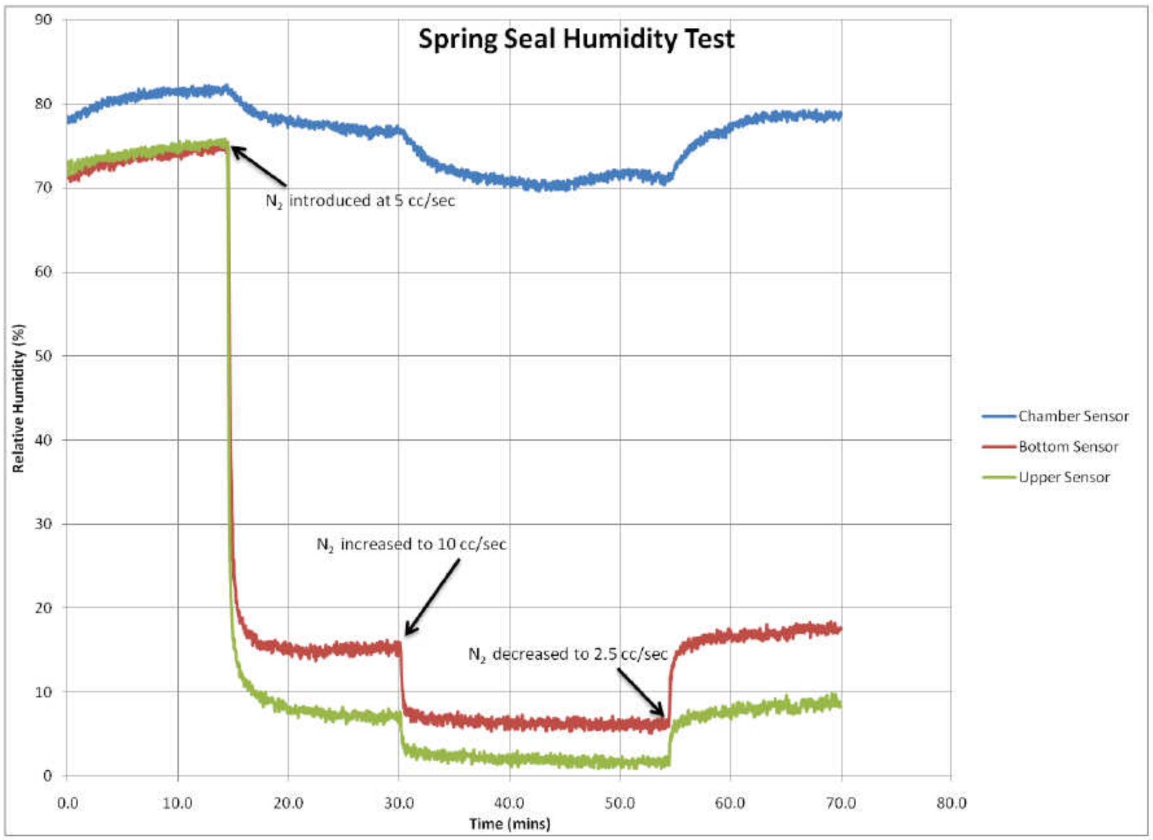








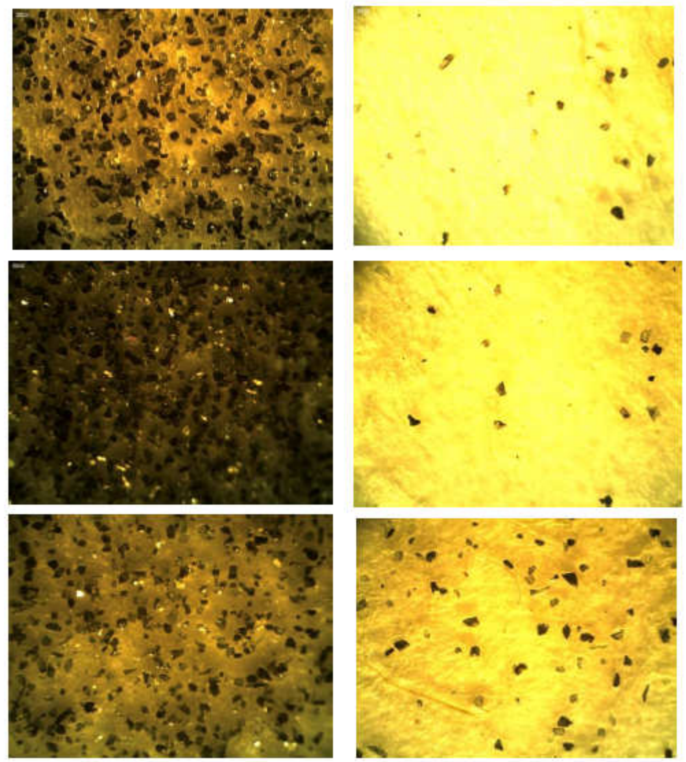
Example Humidity Performance Measurement



Example Dust Attenuation Measurement

The Pilot Group

Dust Test



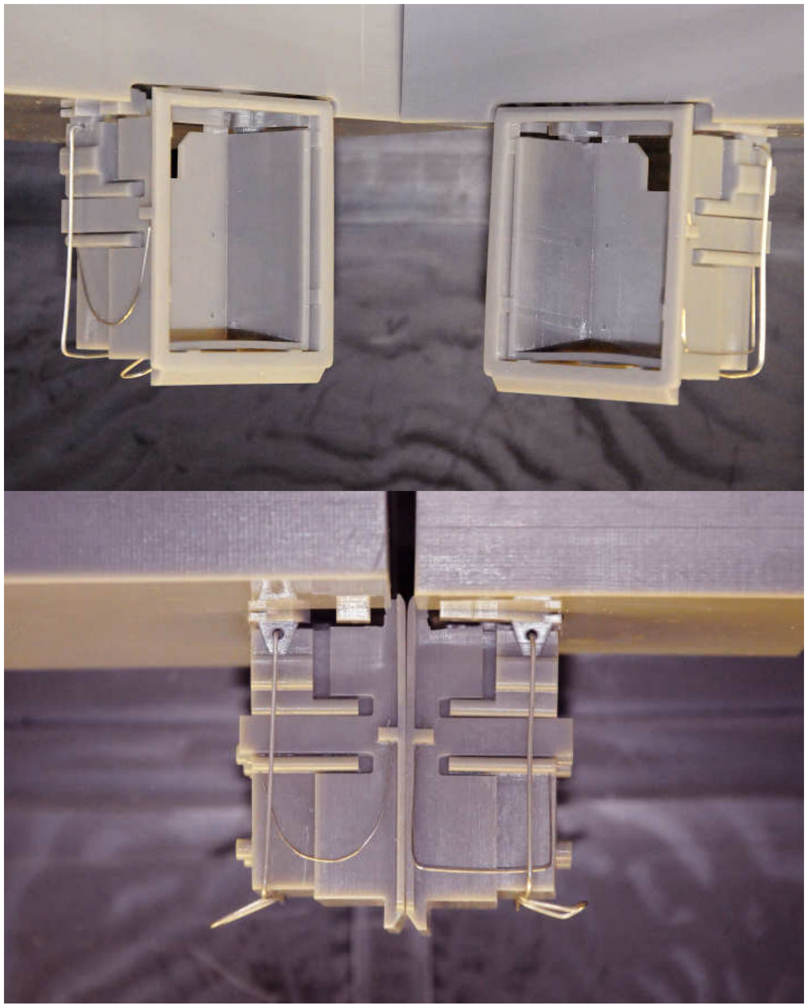
Type	Ratio (Out/In)
Spring Seal	36.76
ClamShell R1	44.81
Bristle Seal	7.93

Comparison of All 4 Concepts

Test:	Spring Seal	Clamshell	Bristle Seal	JPL Boot
Moisture (5cc/sec)	11.045 %RH	30.105 %RH	28.955 %RH	20% RH inside
Dust Attenuation Ratio	37	45	8	136
Performance Range Forces (Actual/Req'd) (mN)	X = 4/150 Y = 107/100 Z = 4/50	No Contact	X = 93.5/150 Y = 170/100 Z = 93.5/50	X= (200-300)/150 Y= 166/100 Z= (200-300)/50
Operation Range Ease of Use	No Management	Flip Up 1 Segment	No Management (?)	Minimal management/TBD (edge redesign required)

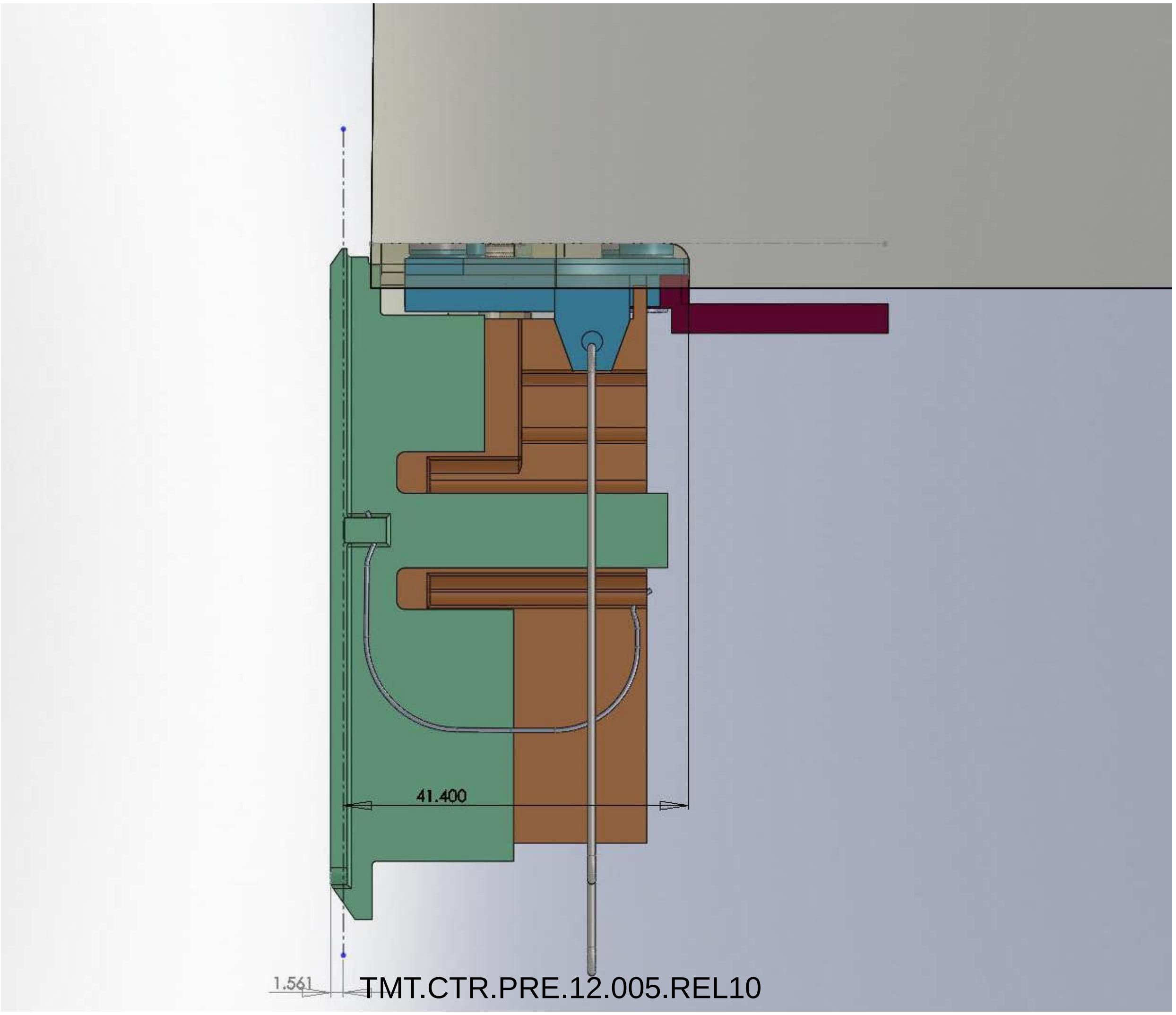
Production costs for all will be roughly comparable, assuming injection molding.
Selected Spring Seal for further design at JPL.

Selected Dust cover and purge-system interface



- Dust cover required to keep sensor clean, and provide a volume for the purge system to keep dry at high humidity
- Design uses a fixed backshell with a sliding mate – no handling required during segment exchange
- Separable base sets location of spacers for sensor block location
  - Backshell can be removed to check sensor location after transport or disturbance
- Small forces (F_x, F_z< 50 mN, F_y<100 mN) in all three axes to avoid distorting segment edge

Dust boot model on the segment



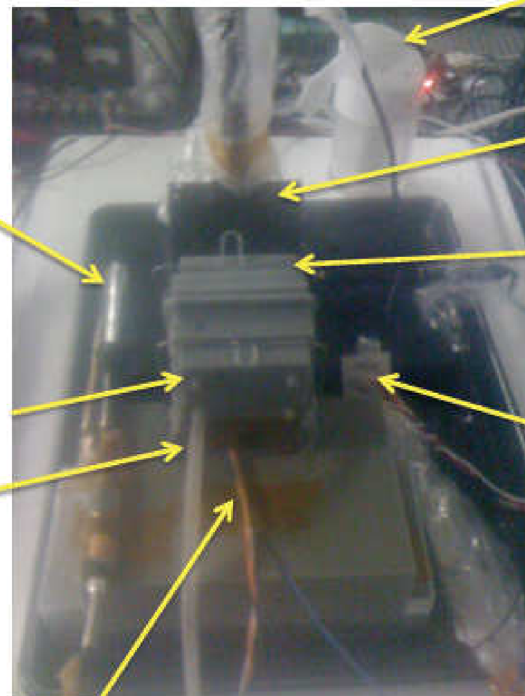
Dust Boot Manufacturing

- Prototype dust boots are made by inexpensive stereolithography
  - Provides accurate parts but is low volume.
  - Cost is low relative to machining, but not low enough when you're making ~7000 parts for production
  - Plastic for prototypes is Accura 50 SLA plastic, slightly lower density, higher friction than Delrin
- Production parts will be made by injection molding
  - Mold making is about half the cost
  - Cost per unit is low (a few $).
  - Production parts will be low friction Delrin AF or Delrin 570
  - Final design requires adjusting part features for mold release
- Current Boot Model is in DCC in Collection-6001

Force Measurements and Expected Wear

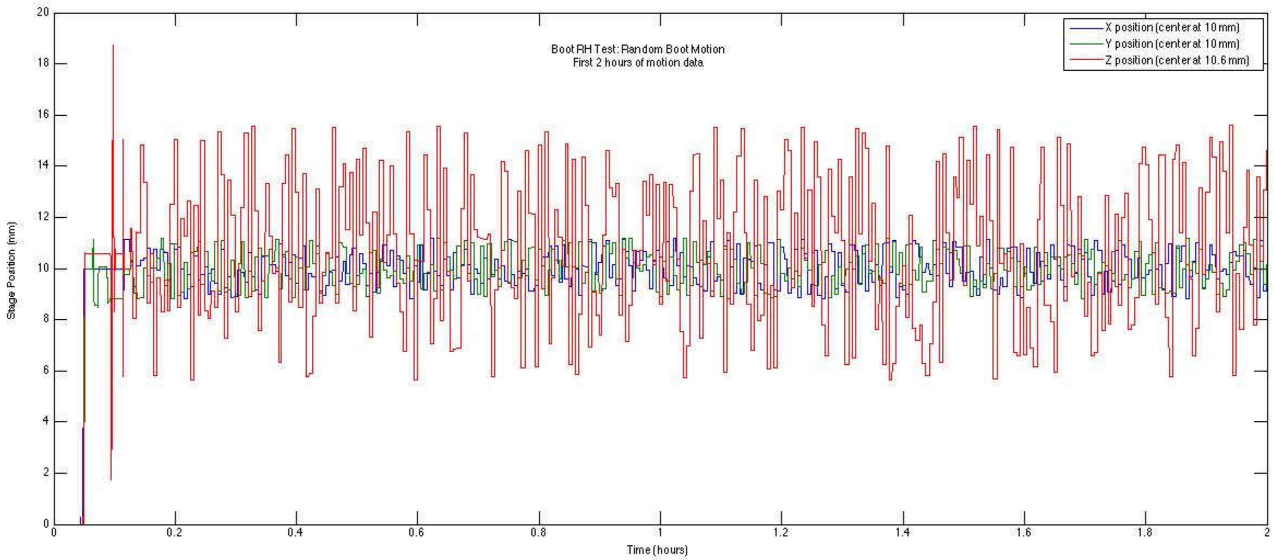
- Y force
  - 14 grams of force will compress the springs by 3.3 mm
    - Spring constant is 41 mN/mm
  - If springs are compressed 2.2 mm in operation, F_y=91 mN
    - Meets requirement to be less than 100 mN
- X and Z force
  - F_x and F_z are obtained from F_y and the friction coefficient of Delrin (0.25)
  - Estimate $F_x = F_z = 23$ mN
    - Meets requirement to be less than 150 mN & 50 mN, resp.
- The boot lifetime spec is 200k cycles over the full +/- 1 mm performance range
- The proposed design should be compliant
  - Because of the low required forces between boots, there is negligible wear of the sliding surfaces
  - Stress in the weak springs should also be below the fatigue limit

Boot RH Performance Measurement Setup



Boot performance detail in: TMT.CTR.PRE.12.002

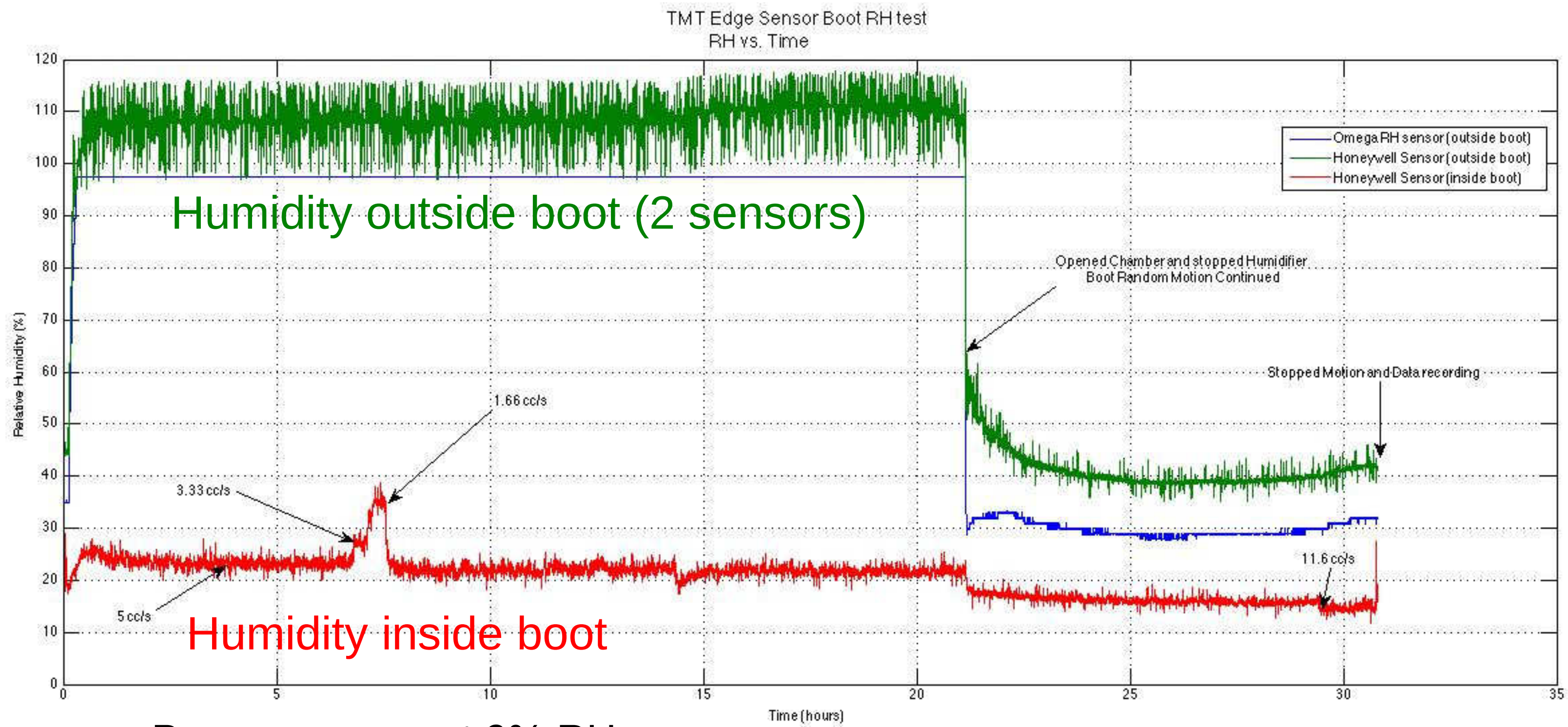
Boot Motion vs.. Time



-X, Y, Z boot positions
-First 2 or 30 h shown
-Vertical divisions are 2 mm

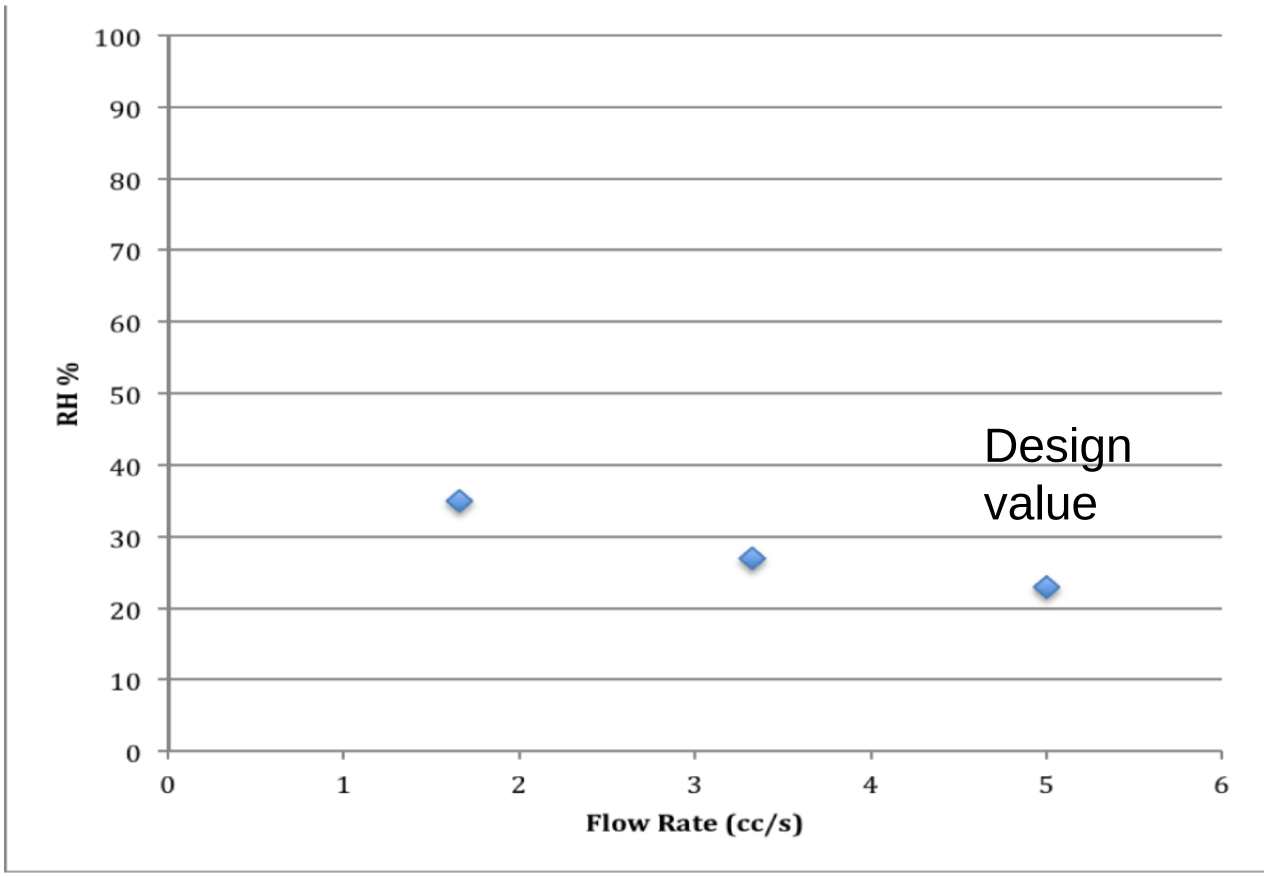
- Randomly generated motion, 30 hours
- Z motion: +- 5 mm
- X, Y motion: +-1.2 mm
- Time between moves: 20 s (including move time)

RH vs. Time During Boot Motion



- Purge gas was at 9% RH
- Purge rate changed for short periods at around 7 hours into test
- Boot maintains low RH, over the full range of motion with 100% RH external
- More detail available at: TMT.CTR.TEC.12.002

RH vs. Flow Rate from Boot Test



External RH= 100%
Gas supply RH=10%

System is very tolerant of reduced flow rate:
1.7 cc/sec still meets requirements.

Purge system is also designed to support higher flow rates for added margin

Boot Mating Movie

- Movie shows proper boot mating with overlap up to 2.3 mm past normal position to simulate behavior during segment exchange without additional handling
- Movie is in DCC as: TMT.CTR.TEC.12.004

Summary: Boot

- Boot requirements driven by need to control humidity and keep sensor clean
- Downselected, prototyped, and tested a concept that meets sensor requirements
  - Is also compliant with requirements on max force and support of segment exchange
- Approach for low-cost volume production identified.

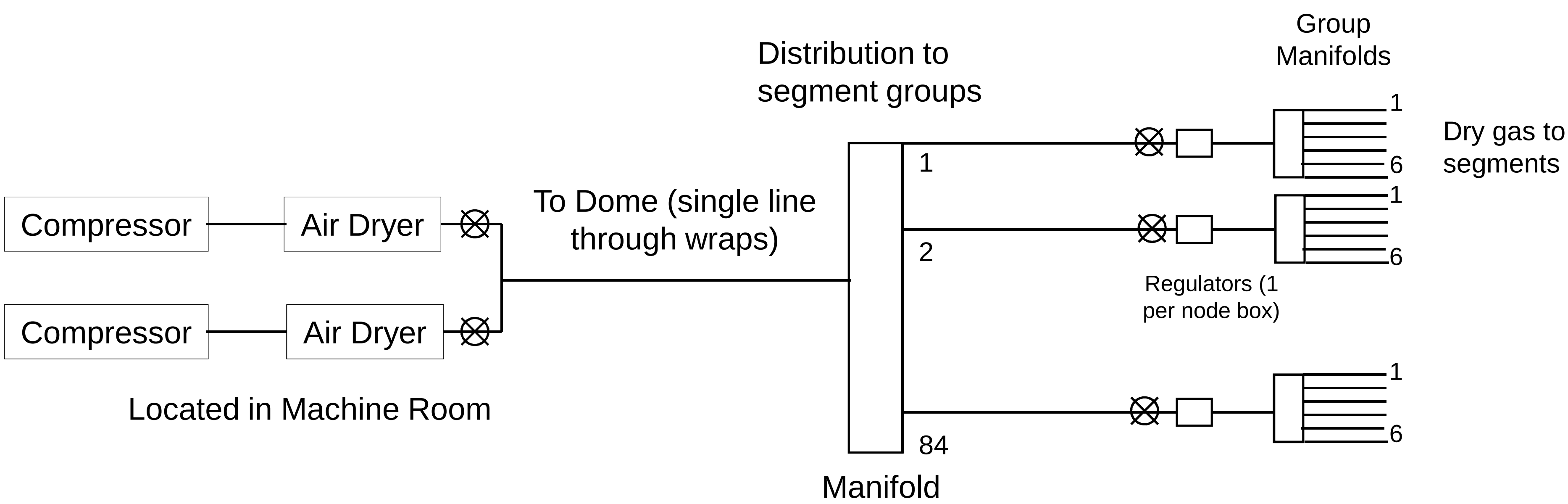
Purge system

Purge System Requirements

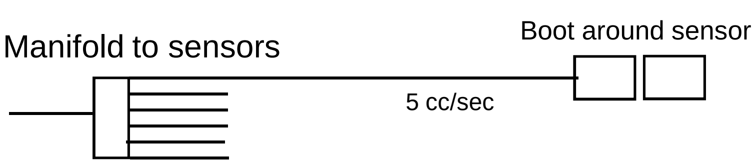
- Provide 5 cc/s per boot: 28 scfm* total for the system
- Provide 28 scfm capacity, at 40 psi at orifices, plus design margin to accommodate uncertainties in final boot design
- Provide <5% RH @ -5C inlet temperature
- Trap oil and dust
- Provide redundant system to allow servicing, extra capacity

(* scfm =“standard cubic feet per minute”, defined as 1 atm, room temperature, where there’s some variation among manufacturers in exact values of P and T used. The TMT system is oversized so that these small differences don’t affect design)

Purge System Concept



At each Segment:



RH Estimates

- Delivering dry air at <5% RH can't increase RH by more than 5% relative to delivering it at 0%
- Air dryers are usually specified in terms of dewpoint, but we're interested in RH:
  - Saturated Vapor Pressure of water (using Goff-Gratch equation for SVP)
    - At -60 C: 1.86 Pa
    - At -40 C: 18.6 Pa
    - At -5 C: 416.4 Pa
  - If we supply gas with a dewpoint of -40 C and a temperature of -5 C, the RH will be
    - RH = 18.6/416.4 = 4.5%
  - If we supply gas with a dewpoint of -60 C and a temperature of -5 C, the RH will be
    - RH = 1.86/416.4 = 0.45%

Baseline Approach

- 5 cc/s to 2772 sensors is 28 scfm (10.5 cfm at 40 psi; orifices are typically specified for flow at 40 psi)
  - Champion VR7F-8-230/1 Advantage Reciprocating Air Compressor
    - Provides 23 cfm at 120 psi (~60 cfm at 40 psi, or ~160 scfm at 15 psi)
  - Deltech HCT-40 desiccant gas dryer
    - Maintains dewpoint at -40 C, which is less than 5% RH at -5 C ambient
  - Lines to telescope (through wrap) are reinforced flex hose
  - Lines on telescope are flexible TFE and polypropylene tubing with push-to-connect fittings up to segment, and barbed fittings at boots.

Proposed Purge System Components for Mechanical Room

	Make	Qty	Wid (in)	Len (in)	Ht (in)	Wt (lbs)	Power	Voltage	Notes
Compressor	Champion VRF7F-8-230	2	33	24	77	545	7.5 HP	230V 1- and 3- phase versions, 208 3-phase	This is significantly oversized, but lower capacity compressors don't have significantly smaller footprints.
Coalescing Filter	Aircel ACFH65D	2	4.5	4.5	10.5	4.5	0	n/a	Removes particles down to 0.01 micron and reduces oil to 0.003 ppm - extends life of the dessicant in the dessicant air dryer
Gas Dryer	Deltech HCT-40	2	32	32	46	365	not stated- heatless dryers use power for only for control and switching	available in 100 thru 240 V, 1-phase versions	
Total effective footprint:	6 ft x 6 ft + workspace or 3 ft x 12 ft + workspace 8 ft ceiling ok								

Electronics Design

Chris Shelton

Electronics Testing

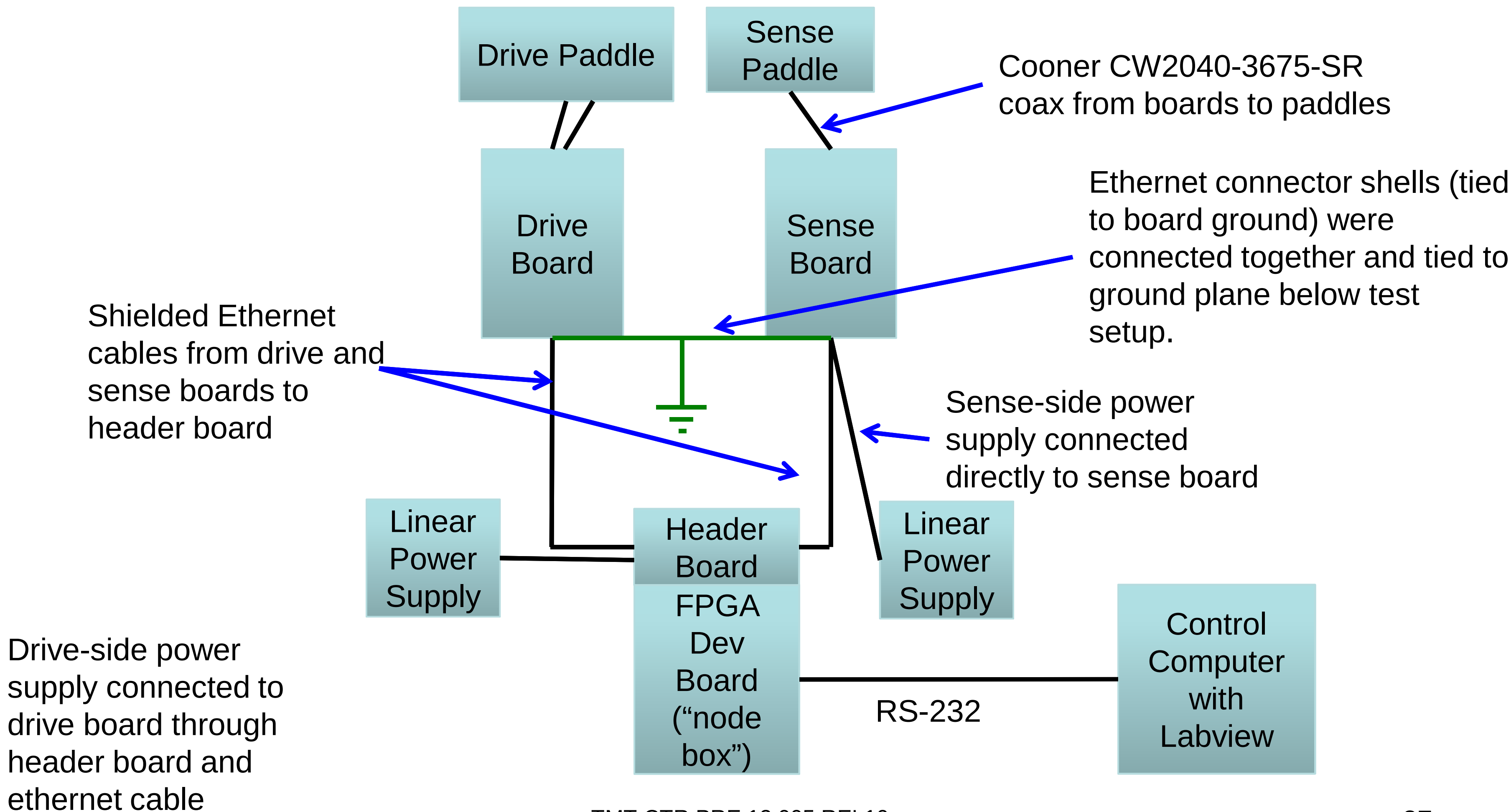
Electronics Testing

- Scale factors
  - Height scale factor
  - Gap scale factor
- Noise
  - Height noise (short term)
  - Gap noise (short term)
- Temperature coefficients
  - Height
    - Sensor blocks
    - Electronics
  - Gap
- Drift
  - Height
  - Gap
- See TMT.CTR.TEC.12.007 for more detail

General Test Details

- Two test setups
- All sensors mounted with 8 in-oz torque (100 N)
- All tests on 52 mm tall sensor with 4x4 mm feet at a gap of 4.5 mm
  - 50 mm wide x 20 mm thick
  - Final block design is larger, but tests on these blocks should characterize performance
- All data from the same, latest rev of electronics
  - Drive and sensor boards up to latest rev
  - Cooner 75-ohm micro-coax with silicone outer jacket, FEP dielectric
  - Drive boards powered with linear power supply through breakout board
  - Sense boards powered directly with separate linear power supply
  - Connections from FPGA dev board to drive/sense boards through shielded Ethernet cables
- Piston measurement has offset adjusted to near null output, quadrature-trim also applied to achieve null at quadrature
- Piston measurement at 50 kHz
- Gap measurement at 100 kHz
- Measured piston scale factor 2.7 nm/ADC unit

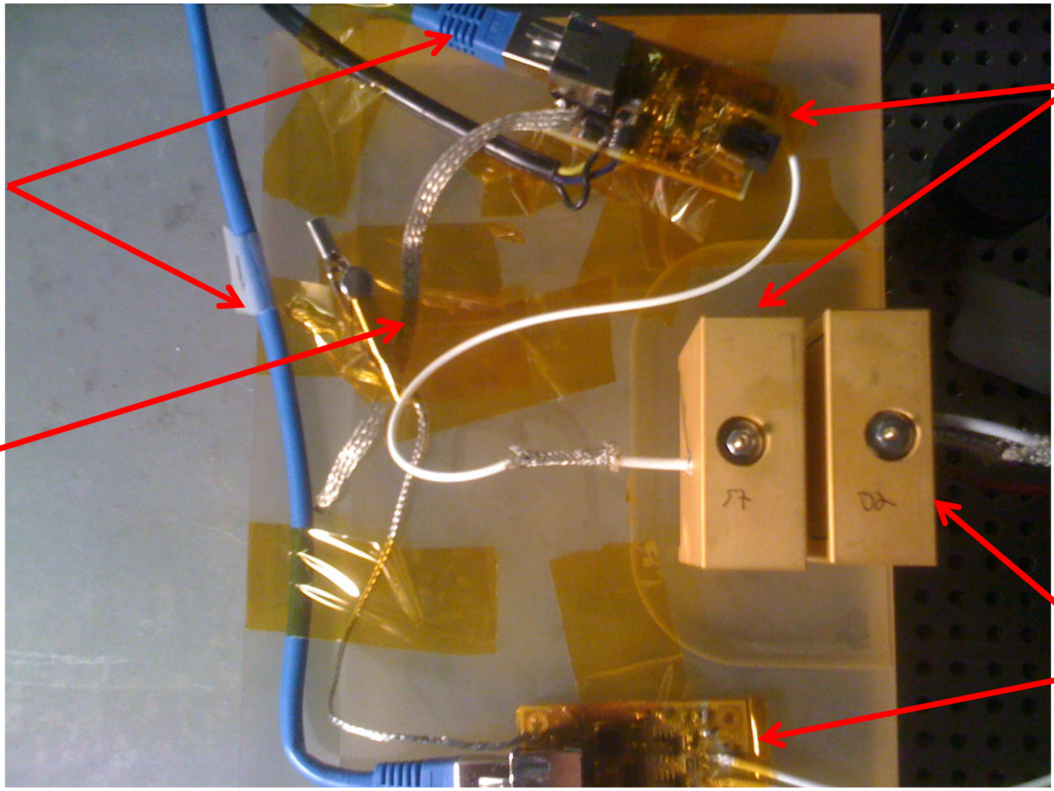
Electronics Test Setup



Test Setup 1 on Coupon
(used for drift and settling)

Digital and Power

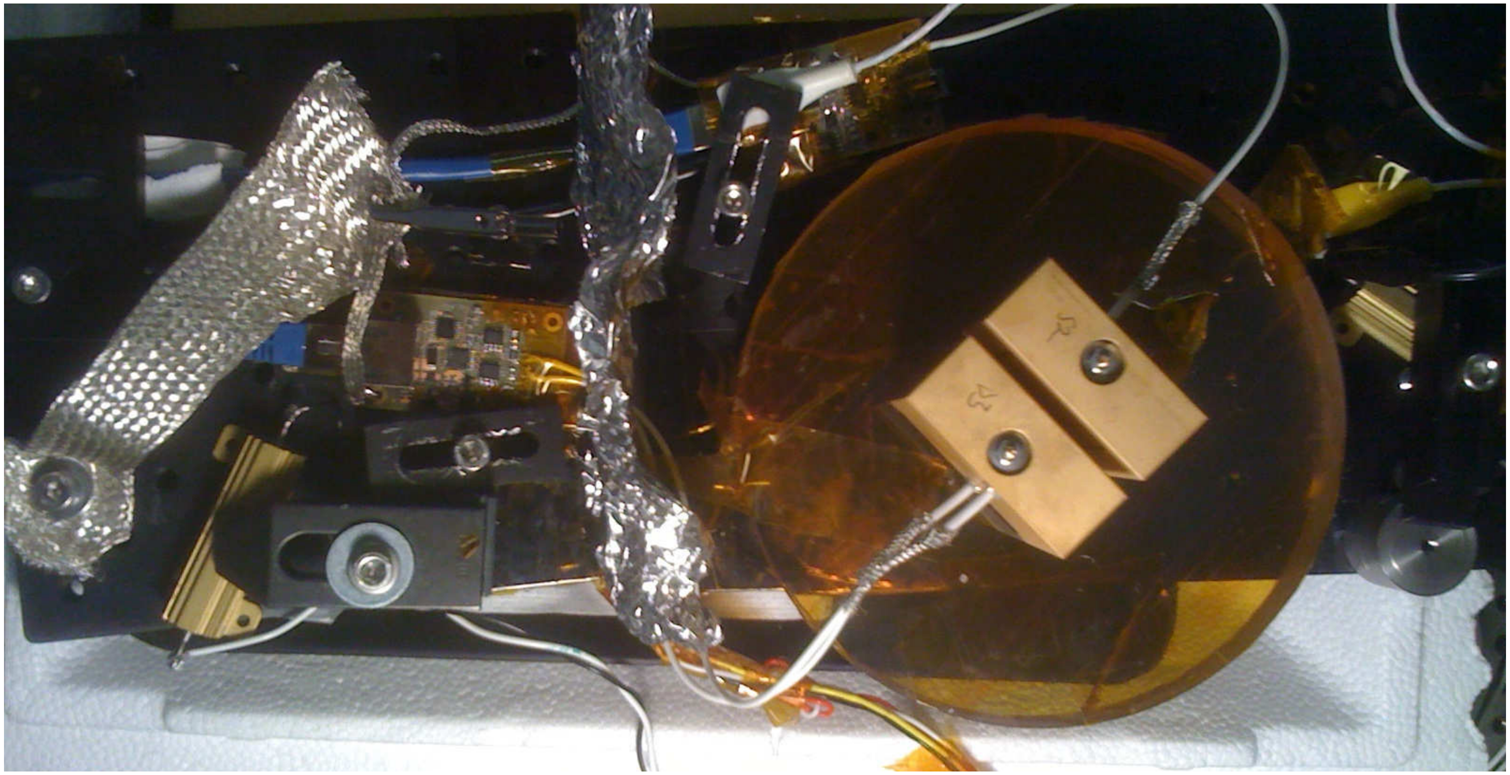
Intersegment Ground



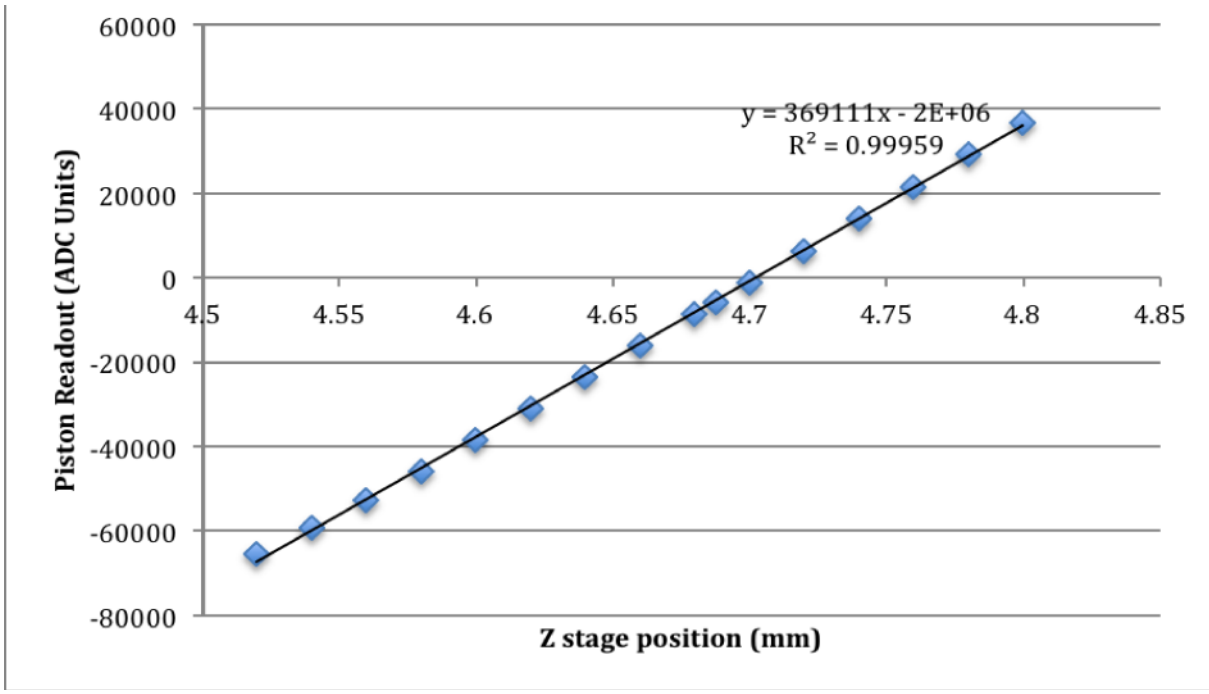
Sense

Drive

Test Setup 2 on Polished Surface
(used for tempco)

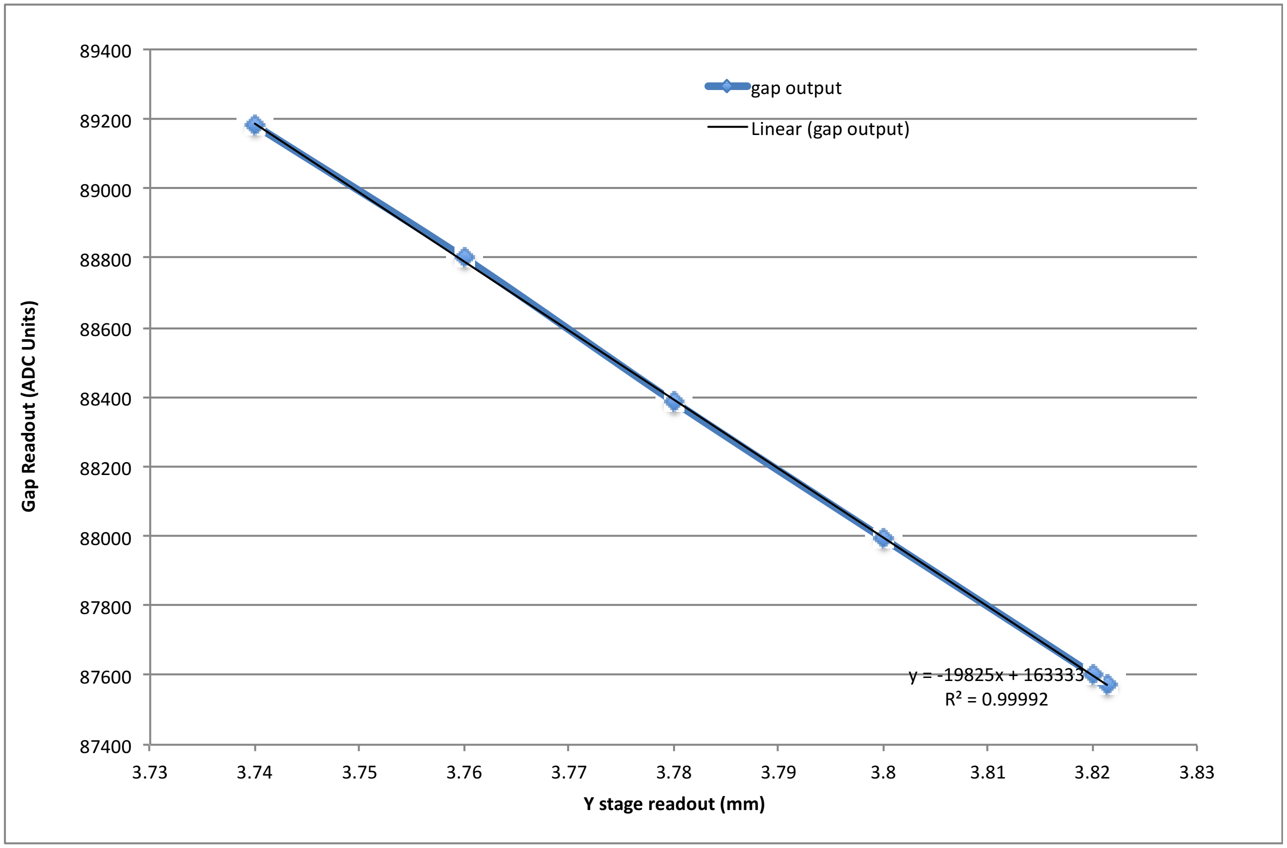


Height Output Scale Factor



- Measured using Thorlabs XYZ stage with ~50 nm resolution
- 2.7 nm/count at 0.6 height drive (standard test setting)
- ***[Height drive: 0 – 1, refers to the relative amplitude of the drive paddle excitation: the sum of the height and gap drives must be <1 to avoid saturation]***
- Drive can be adjusted to get lower noise, e.g. 1.8 nm/count at 0.9 height drive

Gap Output Scale Factor



- 50 nm/count at 0.05 gap drive
- 250 nm/count at 0.01 gap drive
- The gap data are properly fit by a 1/gap function, but over short ranges can be well approximated by a linear fit

Noise Performance

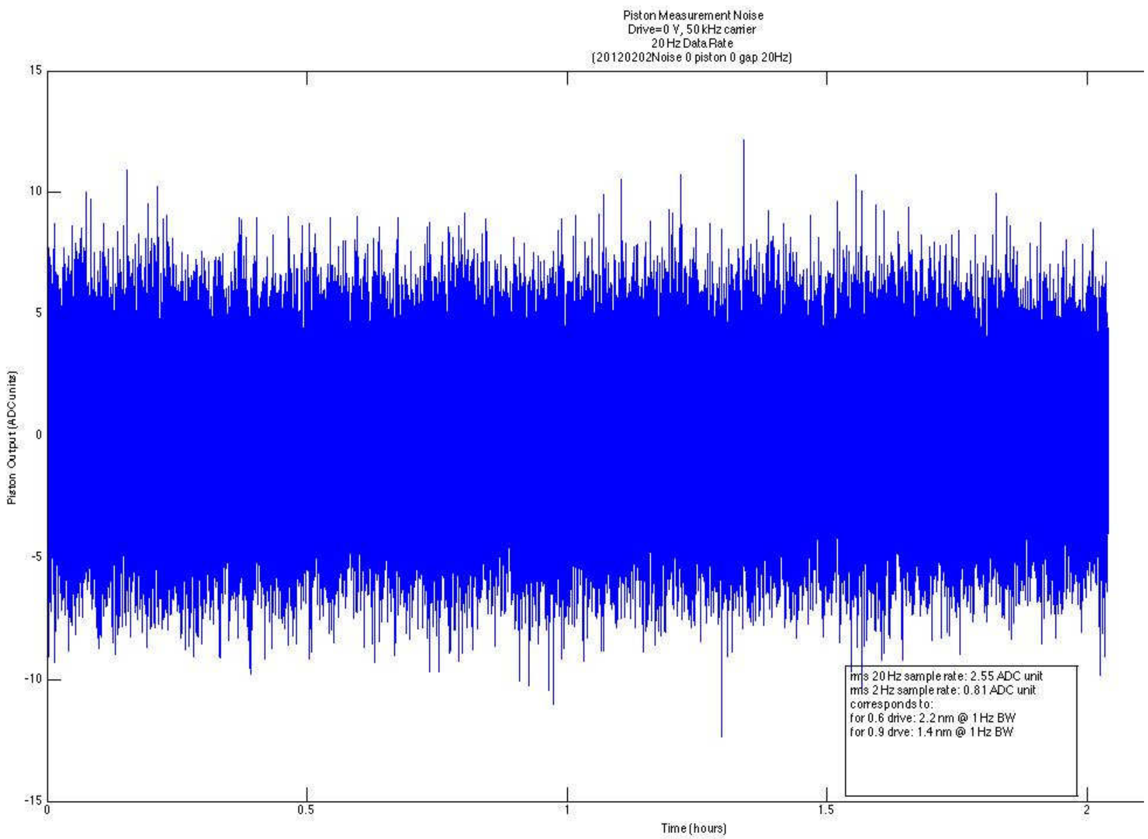
Requirement	Value	Sensor DRD Req	Current Performance	Notes
Piston Noise	5 nm in 2 Hz bandwidth (2.8 nm/√Hz).	1240	<2.2 nm rms/√Hz	For each sensor
Gap Noise	0.5 micron rms in a 1 Hz bandwidth	1280	<0.13 micron rms/√Hz	For each sensor. Is 0.026 um/√Hz for drive level of 0.05x -larger than currently used

- Piston and Gap noise were both measured with and without drive (to identify separate contributions from drive side and sense side).
- Noise levels were the same for both with and without drive.

THIRTY METER TELESCOPE

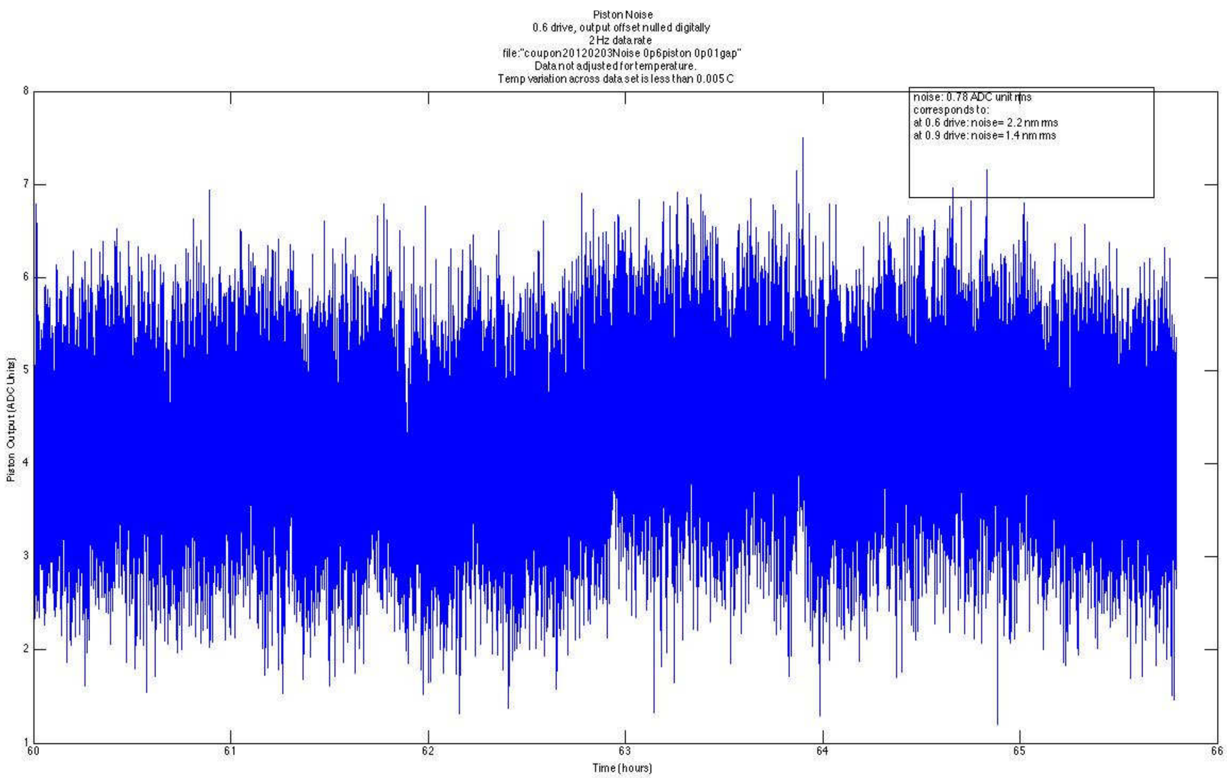
Sense Side Noise Measurement

Jet Propulsion Laboratory
California Institute of Technology



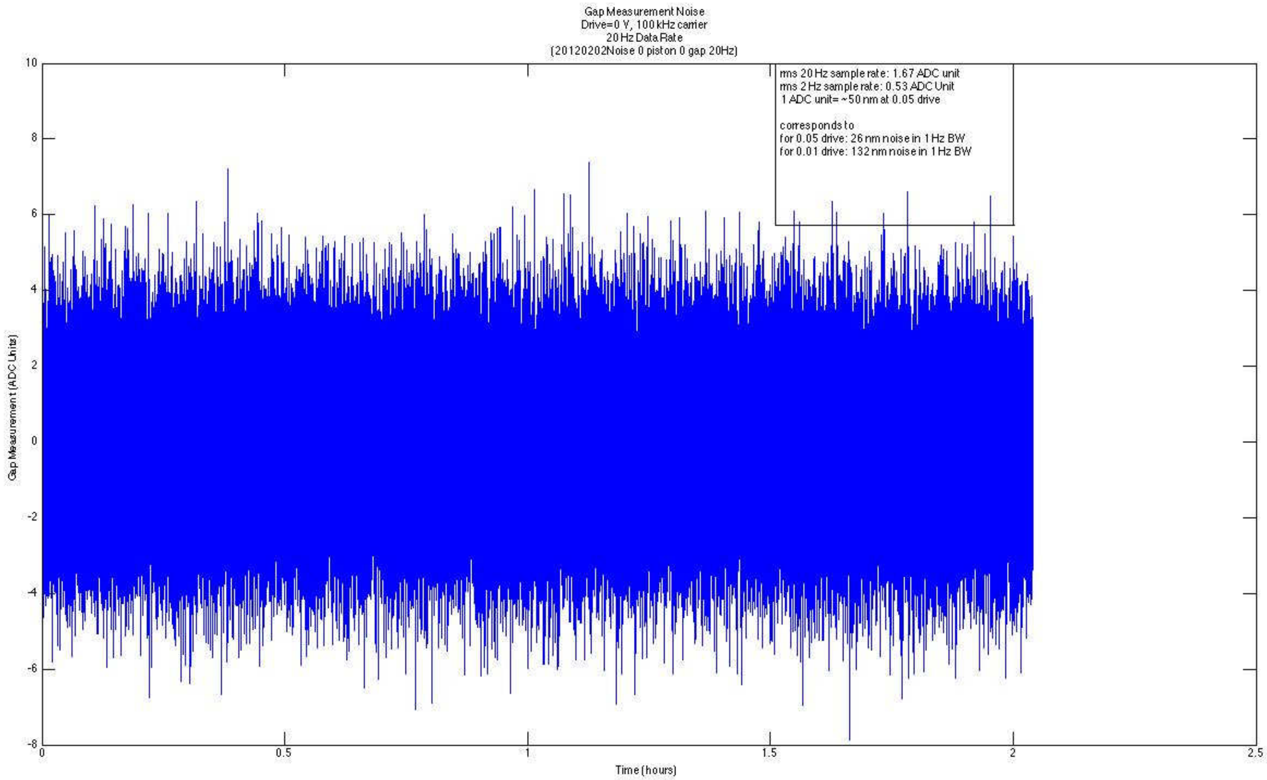
- These data are zero height drive, and reflect the sense-side noise level only.
- Sampling rate 20 Hz
- RMS is 2.55 ADC unit.
- For a height drive level of 0.6, this is 2.2 nm/√Hz, and about 1.5 nm/√Hz at a drive of 0.9

Height Noise, with 0.6 Drive



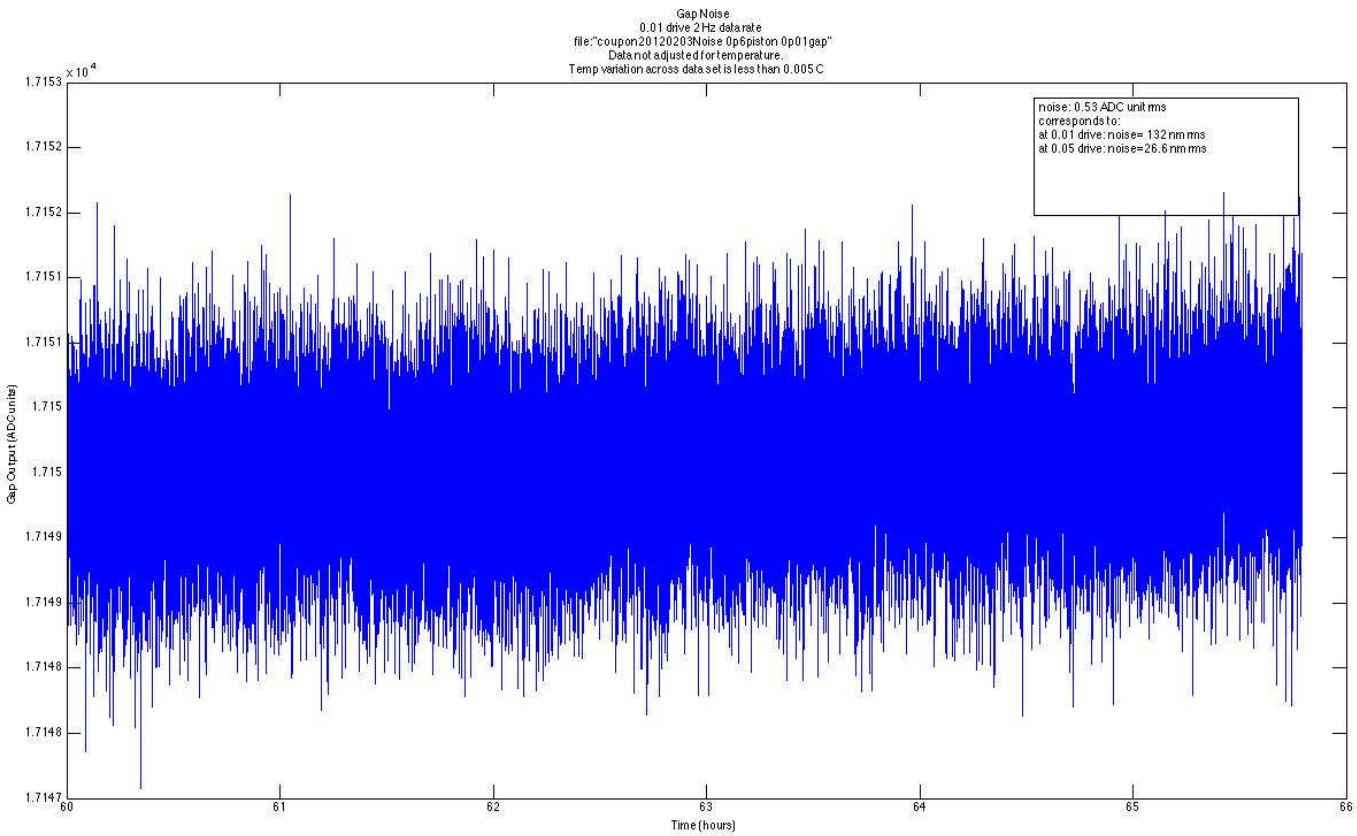
- These data are 0.6 height drive, and reflect noise of the whole sensor system.
- Sampling rate 20 Hz
- RMS is 2.55 ADC unit.
- For a height drive level of 0.6, this shows the same 2.2 nm/√Hz (1.5 nm/√Hz at a drive of 0.9)

Gap Noise, Sense Side



- These data are zero gap drive, and reflect the sense-side noise level only.
- Sampling rate 20 Hz
- RMS is 1.67 ADC unit.
- For a gap drive level of 0.05, this is 26 nm/√Hz (132 nm/√Hz at a gap drive of 0.01)

Gap Noise, 0.01 Drive



- These data are for 0.01 gap drive, and reflect the gap noise of the whole system.

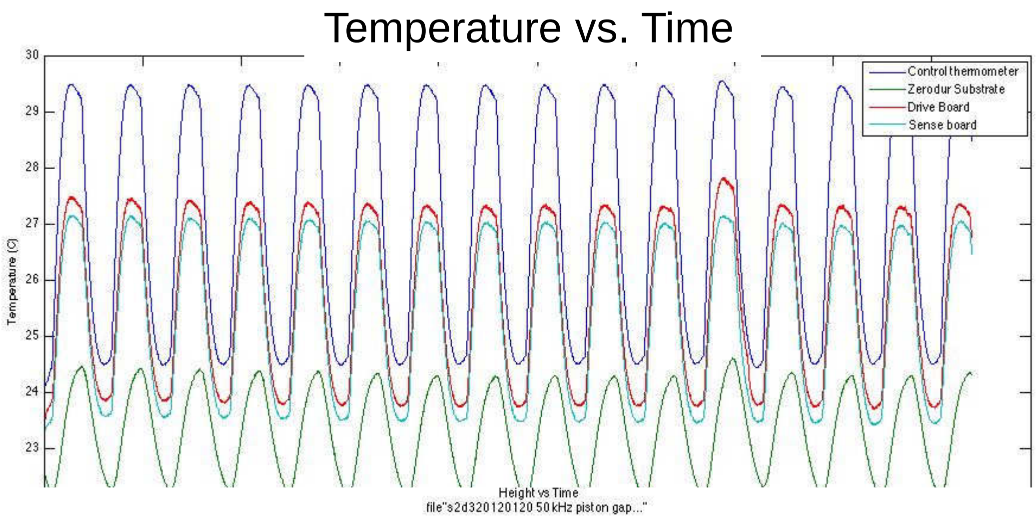
- Sampling rate 20 Hz
- RMS is 0.53 ADC unit.

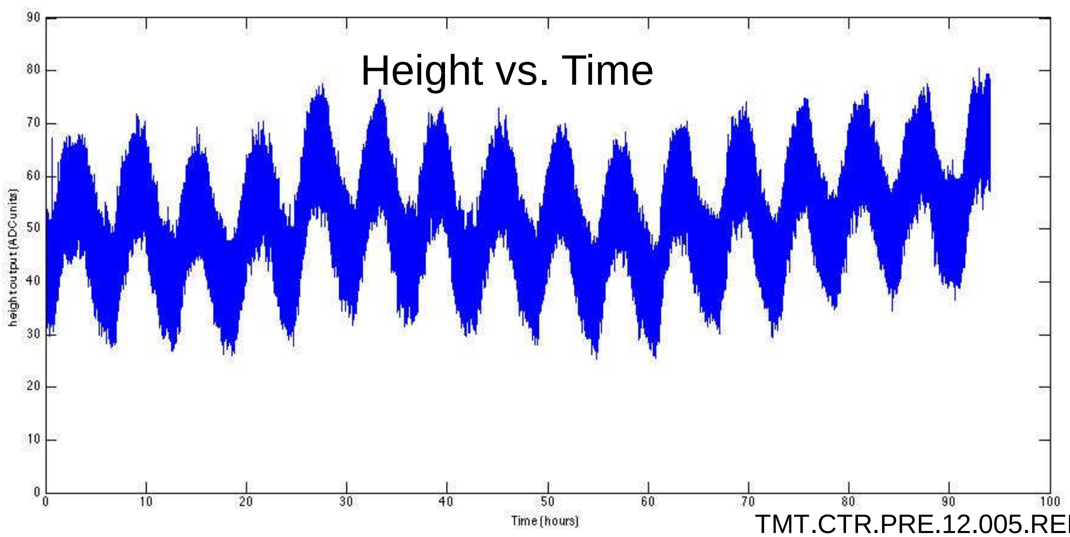
- For a the drive level of 0.01, this is 132 nm/√Hz (26.5 nm/√Hz at a drive of 0.05)

Temperature Sensitivity

Requirement	Value	Sensor DRD Req	Current Performance	Notes
Piston Offset Temp. Sensitivity	+-1 nm/C after calibration	1500	~12 nm/C before calibration	For each sensor
Avg. Piston Offset Temp. Sensitivity	+- 1 nm/C after calibration	1502	Is met if 1500 is met	For the ensemble of sensors
Gap Temperature Sensitivity	± 0.25 micron/C after calibration	1515	0.18 micron/C before calibration	For each sensor

Temperature Coefficient Measurement

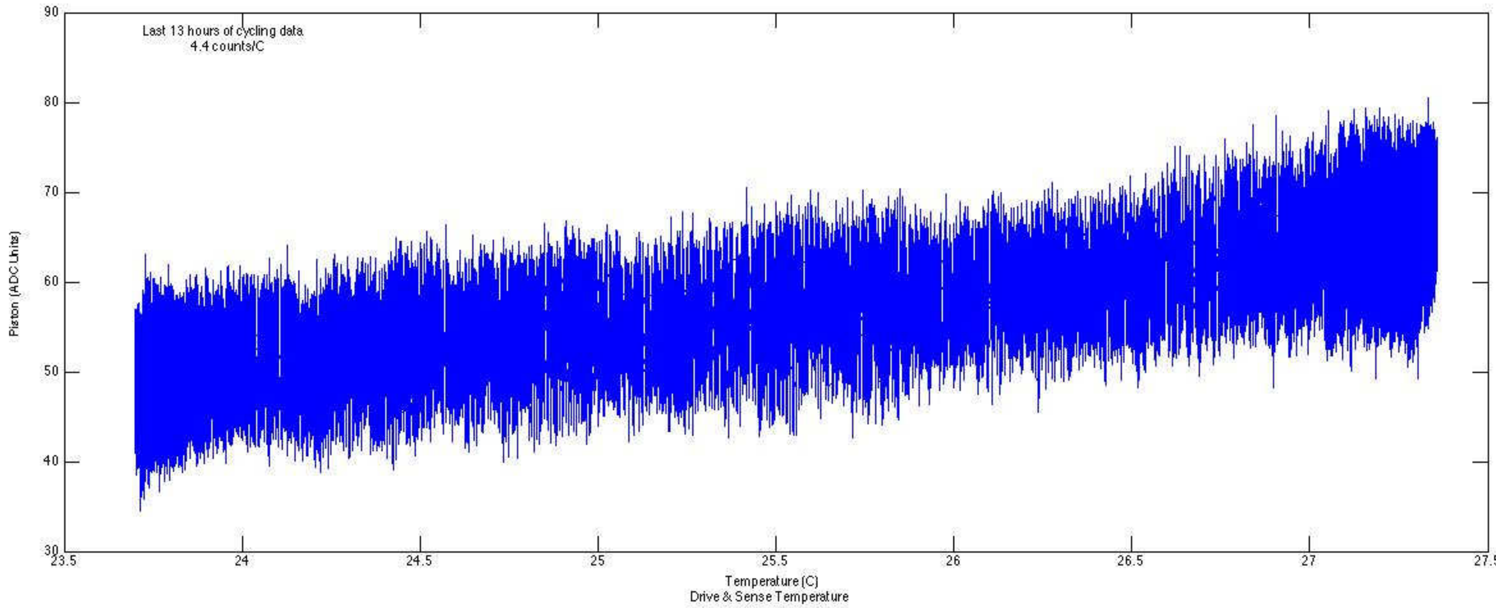




• The sensor temperature coefficient was measured by driving the system (or selected portions of it) with a controlled heater while measuring the sensor response on height and gap.

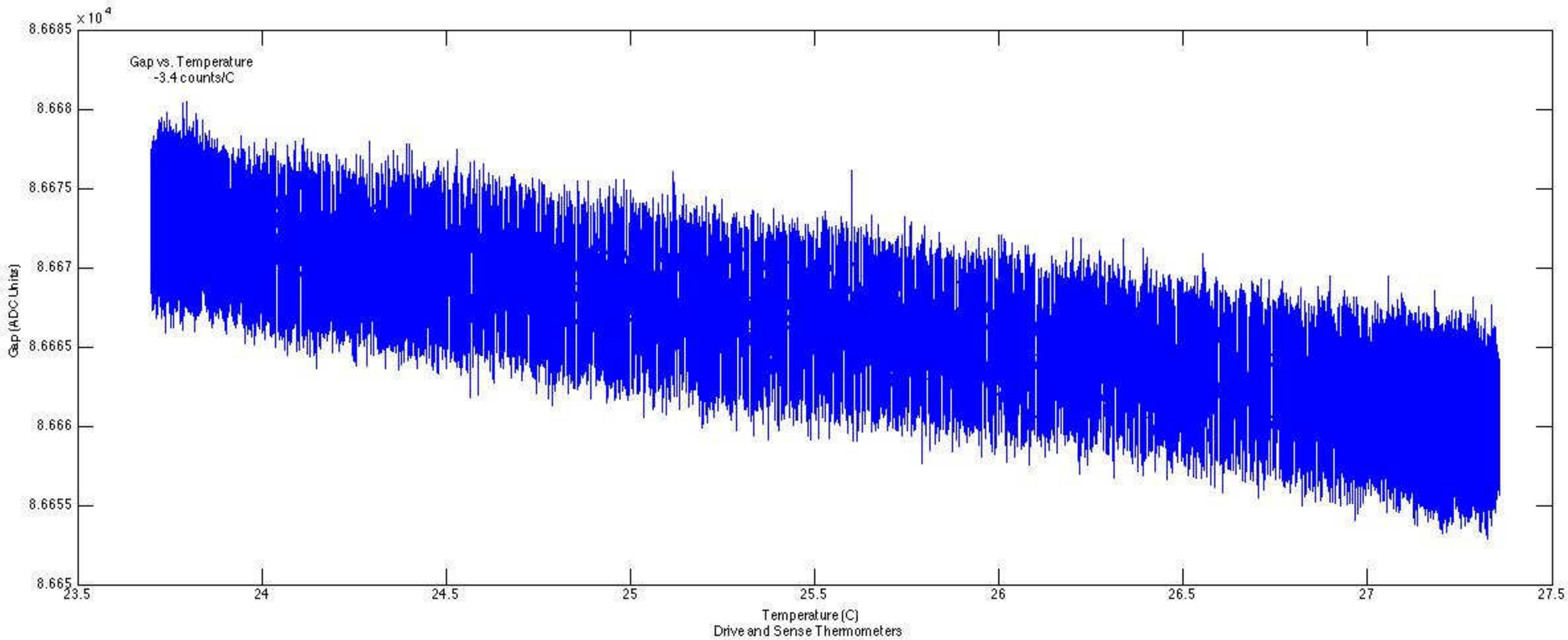
• The data at left are typical - the different parts of the system follow the heater at different rates (top) and the sensor output responds at the drive frequency (bottom).

Temperature Coefficient, Height



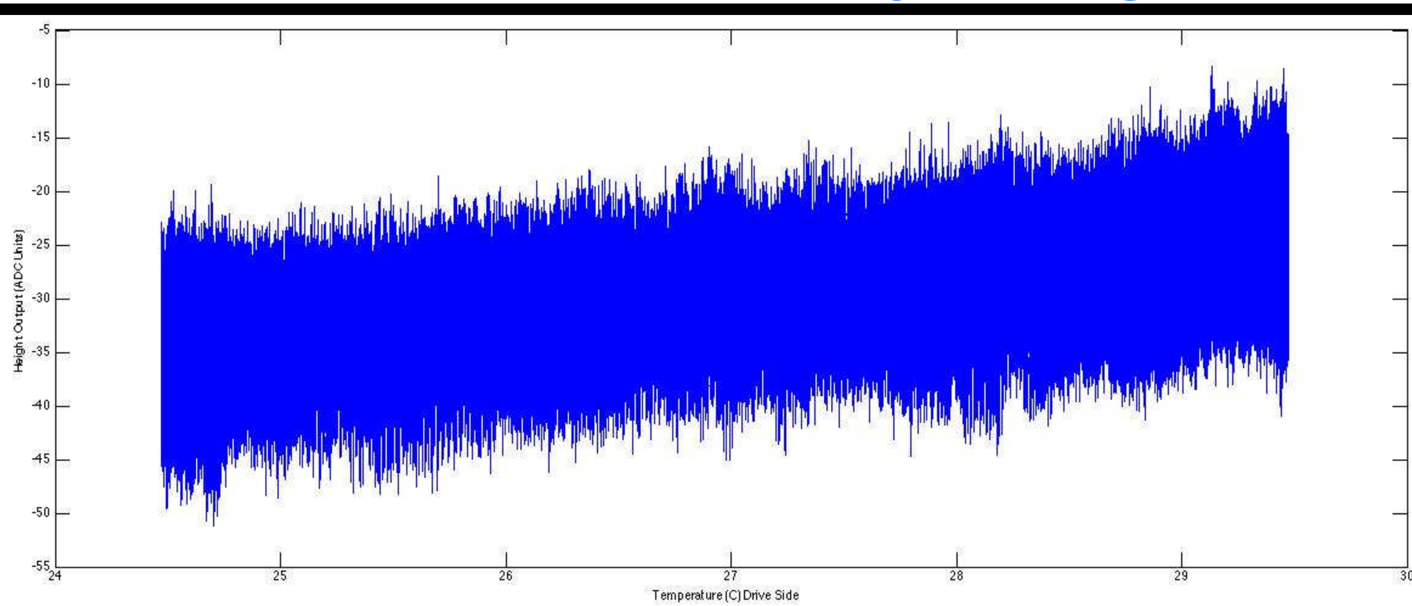
- The height temperature coefficient was determined by plotting the height output vs.. temperature.
- The data above are the last 13.5 hours of data from the previous chart, using the temperature measured at the electronics boards.
- The temperature coefficient is 4.4 ADC units/C (12 nm/C for the standard 0.6 drive level used in this test)

Temperature Coefficient: Gap



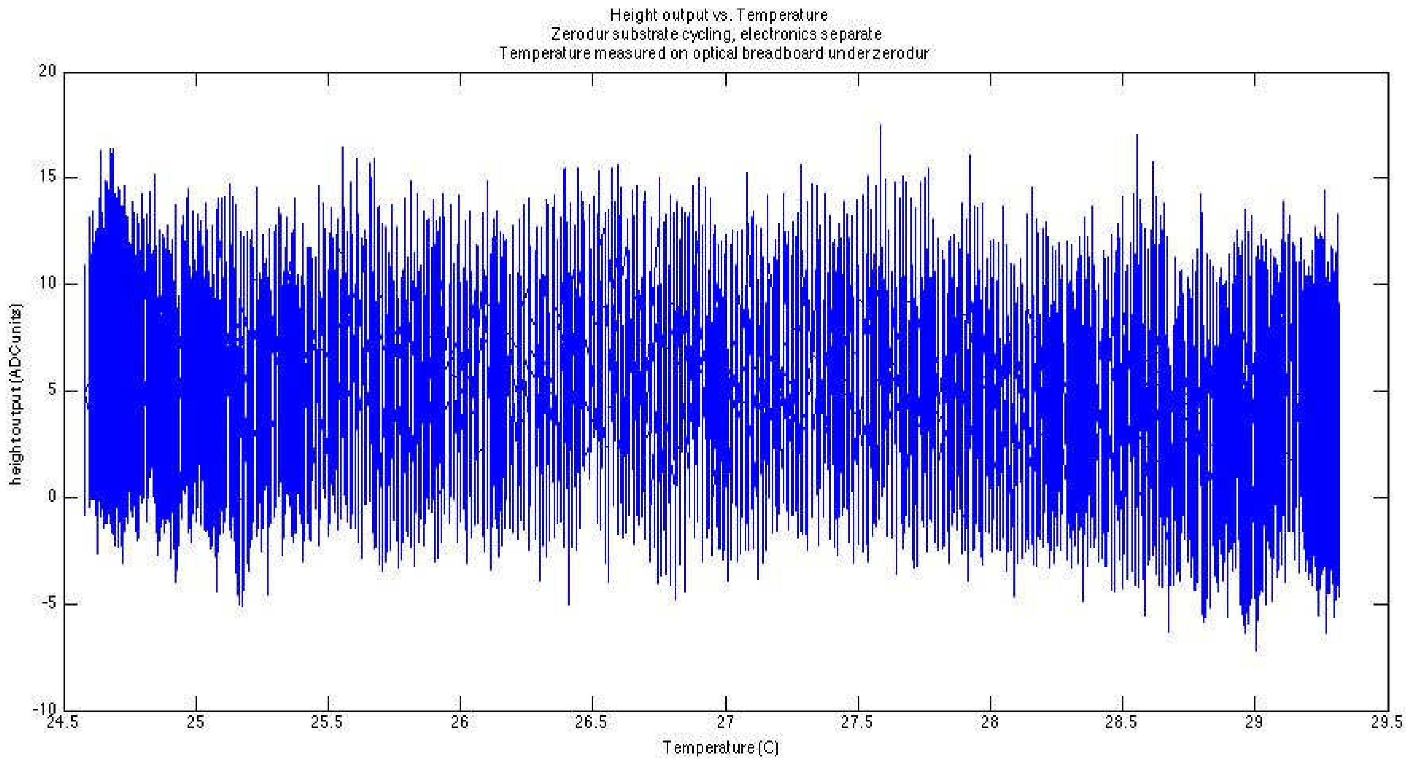
- The gap temperature coefficient was determined by plotting the gap output vs.. temperature.
- The data above are the from the same 13.5 hours as the height tempco data.
- The temperature coefficient is 3.4 ADC units/C (180 nm/C for the 0.05 drive level used in this test)

Temperature Coefficient: Drive Board Only, Height



- The drive board was isolated from the rest of the system and cycled over the temperature range shown.
- Temperature coefficient is 2.24 ADC units/C (6 nm/C at 0.6 height drive).
- Sense side electronics were monitored and varied over a 1 C range, while the Zerodur components varied over a 0.25 C range
- Data indicate that a significant amount of the tempco comes from the drive side

Temperature Coefficient: Zerodur Components



- Height output vs. temperature for heating the Zerodur components only
- The height output shows a temperature sensitivity of -0.57 ADC units/C (-1.6 nm/C)
- Suggests drifts are dominated by electronics, as expected

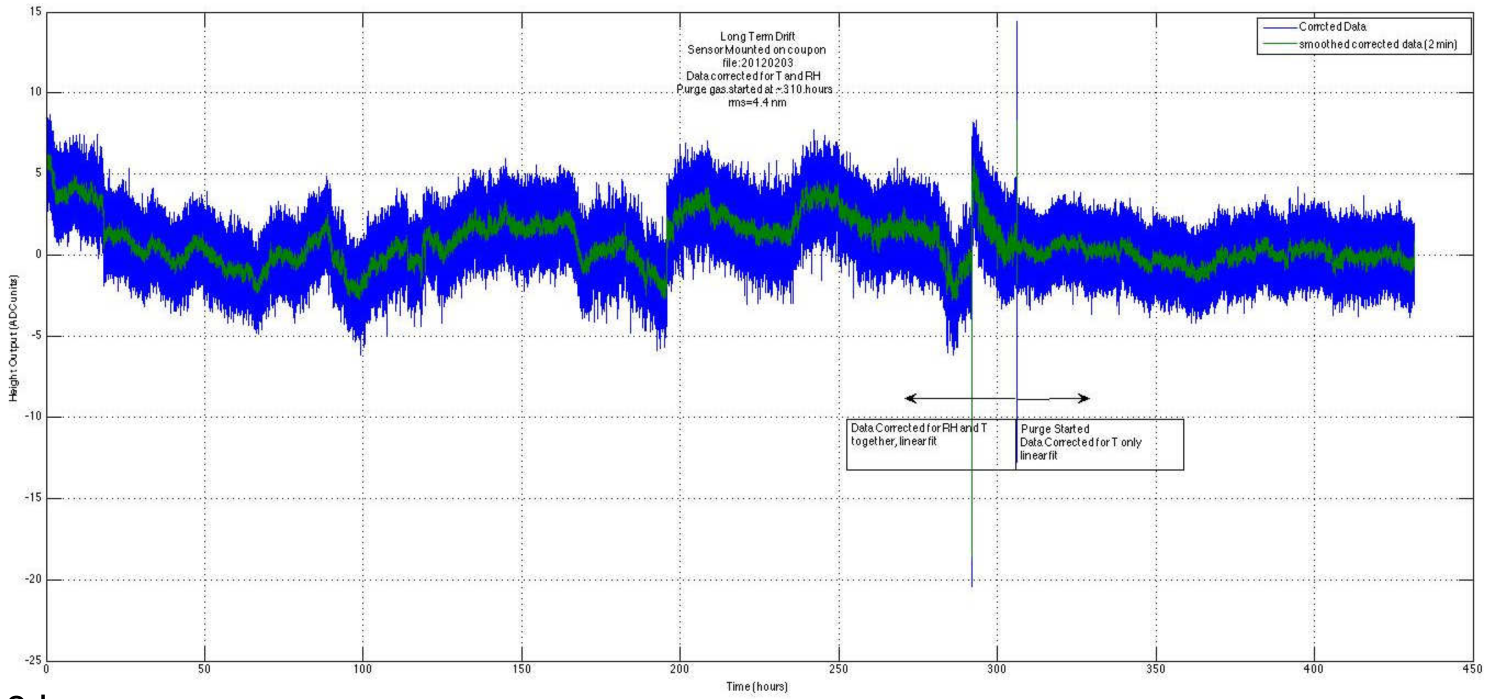
Long term drift tests

- These tests were done only on the coupon test set over 430 h (some unresolved issues with the second setup)
- Humidity was uncontrolled for the first 310 h; at 310 h, the purge system was enabled for the rest of test
- NB: long term drift is specified as an rms for the ensemble of sensors; here, we test a representative sensor only

Drift Performance

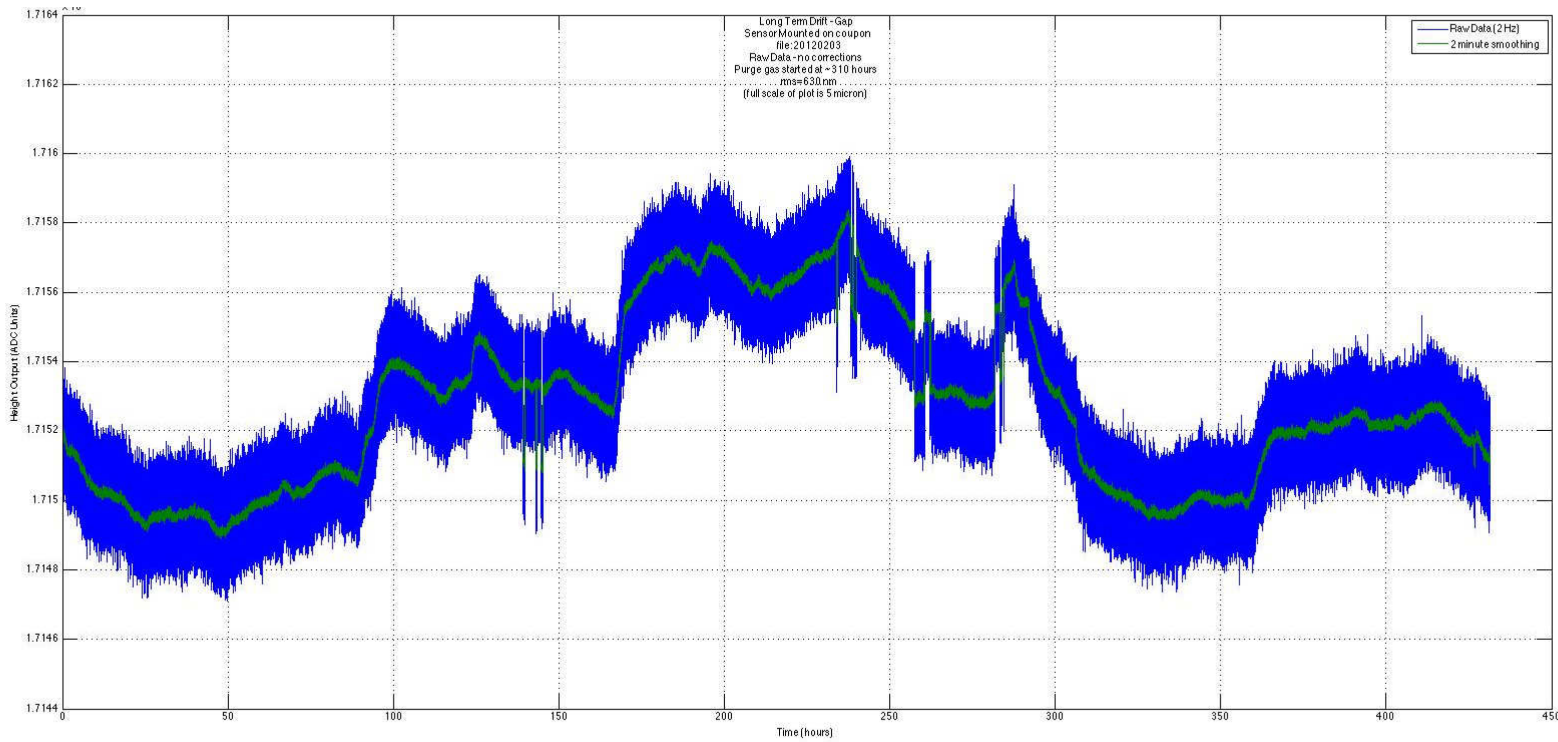
Requirement	Value	Sensor DRD Req	Current Performance	Notes
Piston Offset Drift	5 nm rms @ 30 days [3.5 nm avg over interval]	1520	4.4 nm rms over 24 days interval, single sensor	For the ensemble of sensors
Piston Offset Drift	+- 4 nm avg	1522	<5 nm/24 days for a single sensor after 1 day settling, some variations outside 5 nm during that period	For the ensemble of sensors
Gap Drift	+-0.5 micron/30 days	1560	0.2 micron rms/24 days	For each sensor

Long Term Drift: Corrected Height



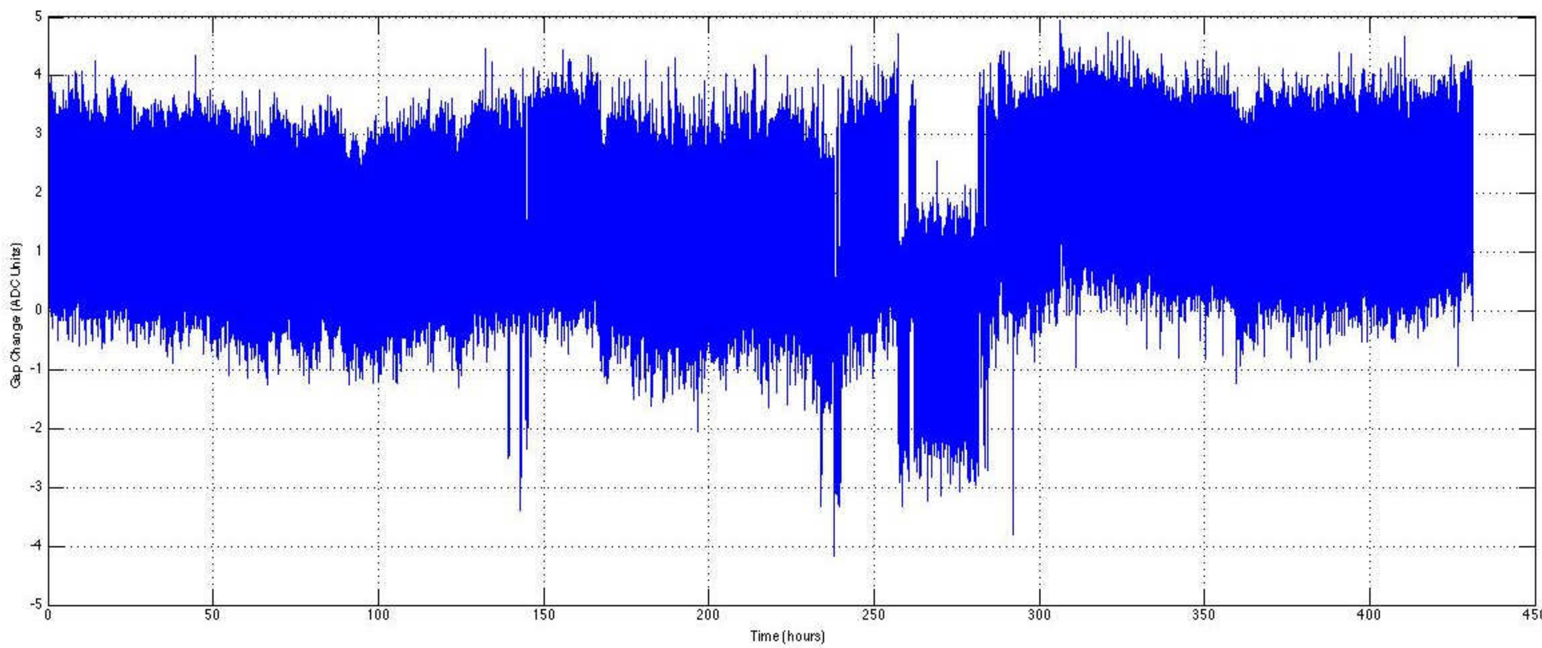
- 0 - 310 h
  - Data without purge, corrected using RH data as Temp and RH combined correction (linear fit)
- 310-450 h
  - Purge gas supplied to chamber, height corrected with Temp only (linear fit)
- RMS variation over the full 450 h duration is 4.4 nm rms
  - There are some missing data (see notes) in the last 10 days, but this wouldn't significantly affect the rms

Long Term Drift: Gap



Uncorrected gap data, green line shows 2 minute averaging.

Long Term Drift: Gap Temp, RH Adjusted Data



- First 310 hours of data without purge,
- Corrected full set using RH data as Temp and RH combined correction, based on fit of first 200K points to RH data.
- Noise for full duration is 205 nm rms

Performance Summary

Requirement	Value	Sensor DRD Req	Current Performance	Notes
Piston Noise	5 nm in 2 Hz bandwidth (2.8 nm/√Hz).	1240	<2.2 nm rms/√Hz	For each sensor
Piston Offset Drift	5 nm rms @ 30 days [3.5 nm avg over interval]	1520	4.4 nm rms over 24 days interval, single sensor	For the ensemble of sensors
Piston Offset Drift	+- 4 nm avg	1522	<5 nm/24 days for a single sensor after 1 day settling, some variations outside 5 nm during that period	For the ensemble of sensors
Piston Offset Temp. Sensitivity	+-1 nm/C after calibration	1500	~12 nm/C before calibration	For each sensor
Avg. Piston Offset Temp. Sensitivity	+- 1 nm/C after calibration	1502	Is met if 1500 is met	For the ensemble of sensors
Gap Noise	0.5 micron rms in a 1 Hz bandwidth	1280	<0.13 micron rms/√Hz	For each sensor. Is 0.026 um/√Hz for drive level of 0.05x -larger than currently used
Gap Drift	+-0.5 micron/30 days	1560	0.2 micron rms/24 days	For each sensor
Gap Temperature Sensitivity	± 0.25 micron/C after calibration	1515	0.18 micron/C before calibration	For each sensor

Performance Summary

Requirement	Value	Requirement #	Current Performance	Notes
Sampling Rate	40 Hz	1600	40 Hz	Sampling rates from 2 Hz to 400 Hz settable with two firmware registers. Rates above and below that range not tested.
Sampling Rate	400 Hz	1620	400 Hz	Higher speeds than 400 Hz not well tested
Piston Monotonicity		1222	Meets requirement	
Zero offset adjustment range	+-100 micron	1140	+-5 mm	Will be reduced to +-0.5 mm with resistor change to improve resolution of zero offset.
Zero offset adjustment resolution	0.5 micron	1145	<0.1 micron	
Non-interlocking	--	480	Require ground across gap	Per sensor
No external initialization proc at power up		1060	Next level of assembly, but tuning process is worked out.	Sensor tuning process worked out at individual level
Interchangeability		1080	Requires tracking piston offset of each pocket.	Sensor halves can be tracked for higher precision offset adjustment.

Summary: Noise, Temperature, and Drift

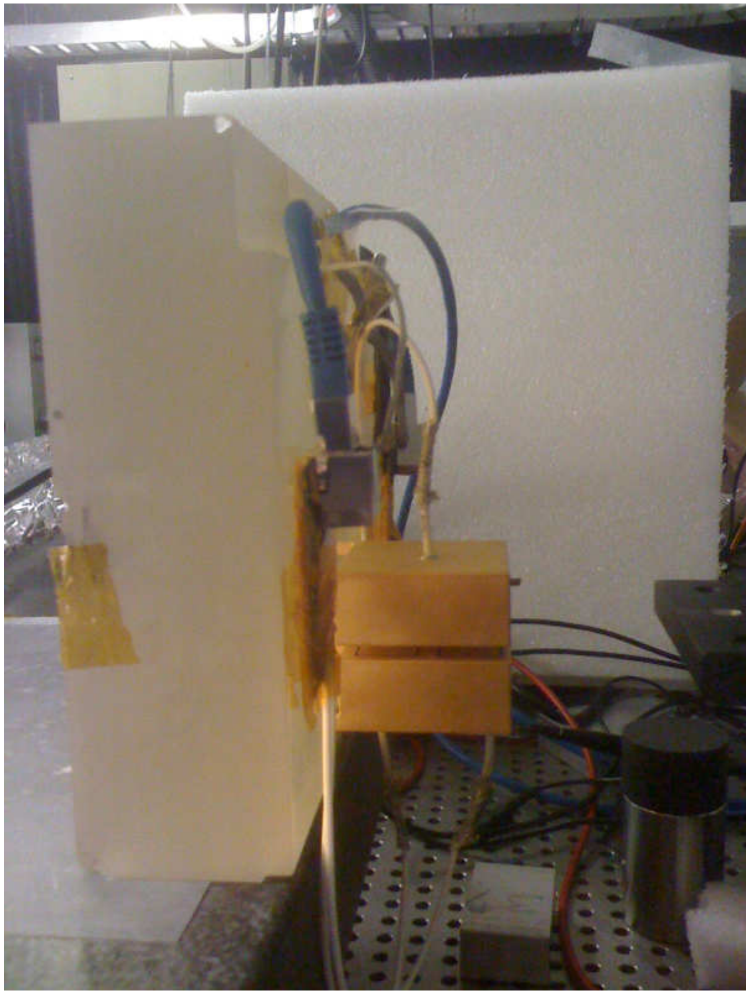
- The electronics meet the noise requirements for height and gap
- The temperature coefficients are acceptable and can be removed by the calibration process (see calibration presentation)
- The height and gap long term drift for a single sample are close to system requirements, but can be made more robust by a few design changes (along with the tempco)
- Design changes have been identified that should improve both the temperature coefficient and long term drift performance
  - Electronics update to improve drive-side stability
  - Improve coaxial cable stability
  - Install and test with coax connector at board end
- Additional testing should be done:
  - Check for crosstalk among sensors
  - Verify long term drift performance on multiple units after planned improvements

Mechanical stability and repeatability

Edge Sensor Tilt and Settling Tests

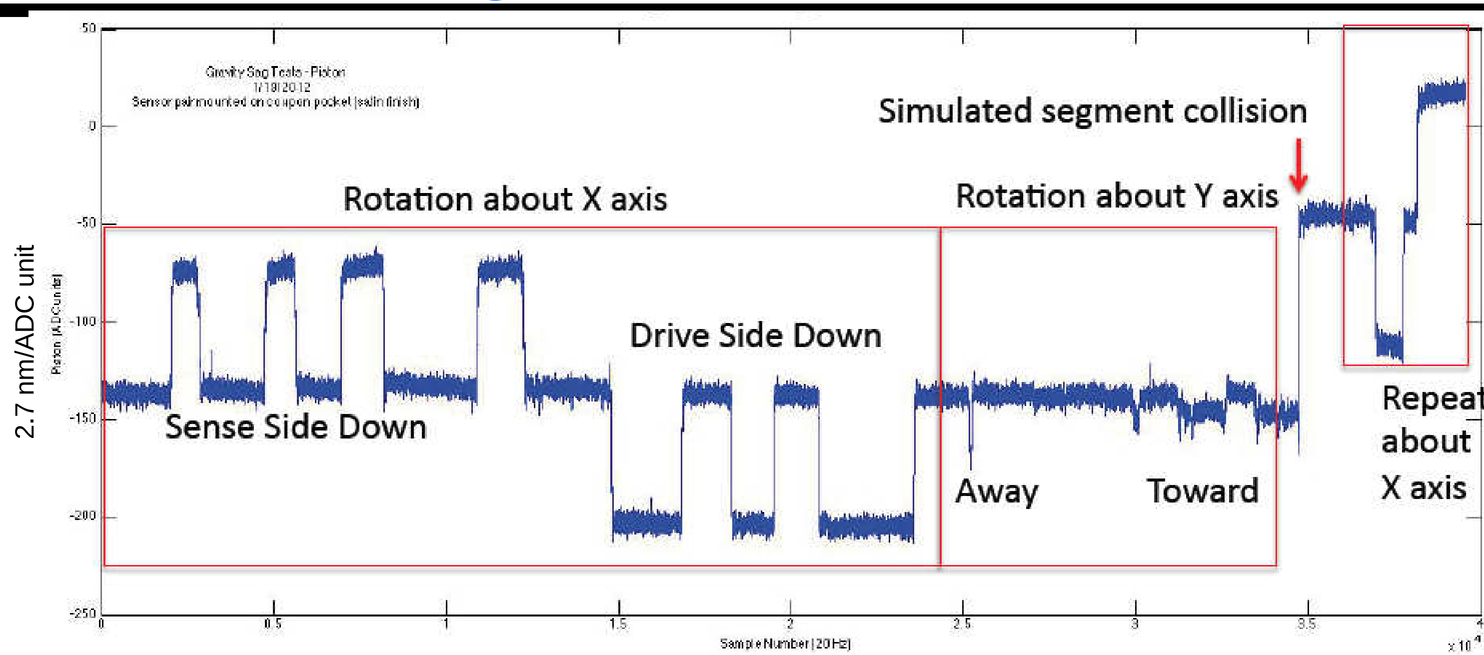
- Testing to determine
  - The repeatability of gravity sag on the sensors
  - Whether the sensors "settle" mechanically after installation, and if so, characterize settling time
  - Whether the sensors settle when rotated to a different orientation
- For settling tests a 0.5 g peak 60 Hz vibration was applied to the substrate for extended periods to accelerate any settling effects
- Test first with baseline machined interface. If significant drifts observed, repeat with polished interface.
- See TMT.CTR.TEC.12.018 for more details.

Tilting and Settling Tests



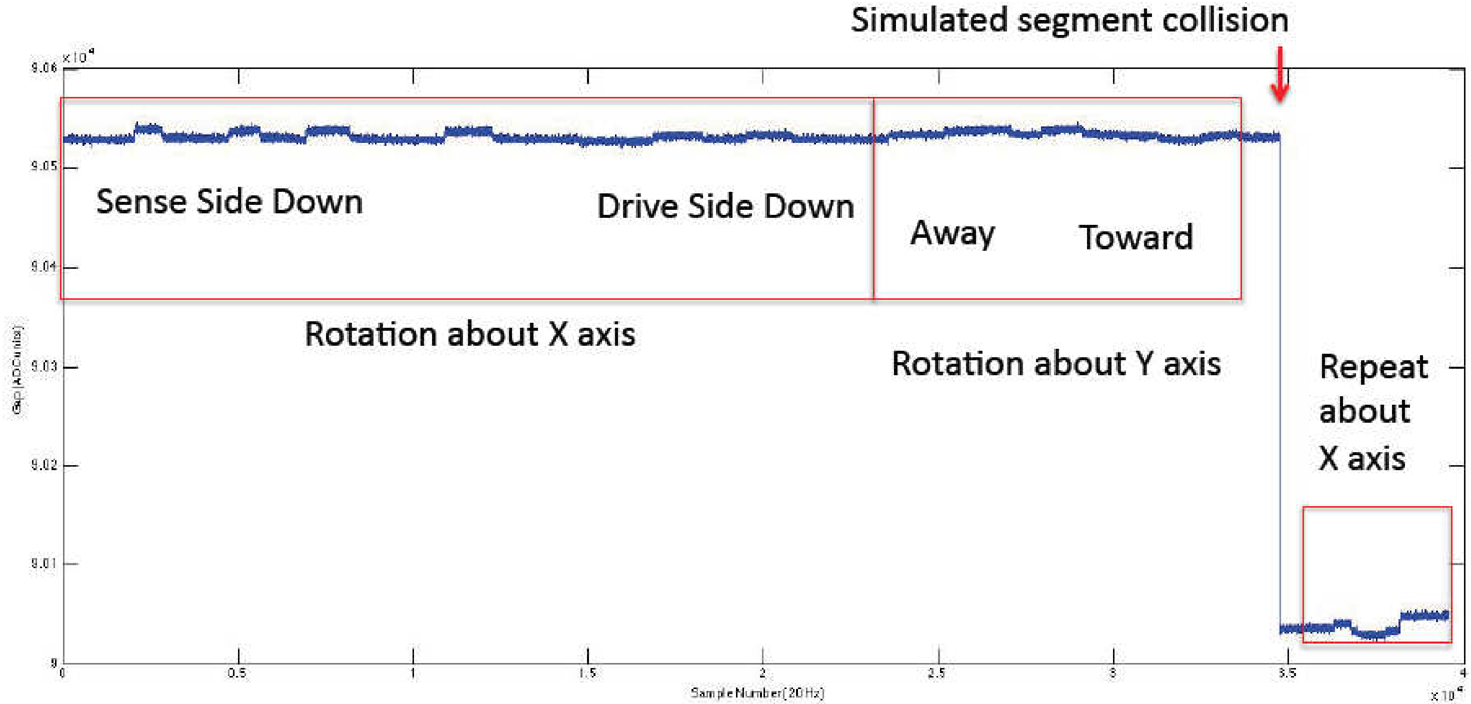
Sensor shown tilted drive-side down. Four orientations were measured (90 degree rotations from level)

Gravity Sag: Height Measurement



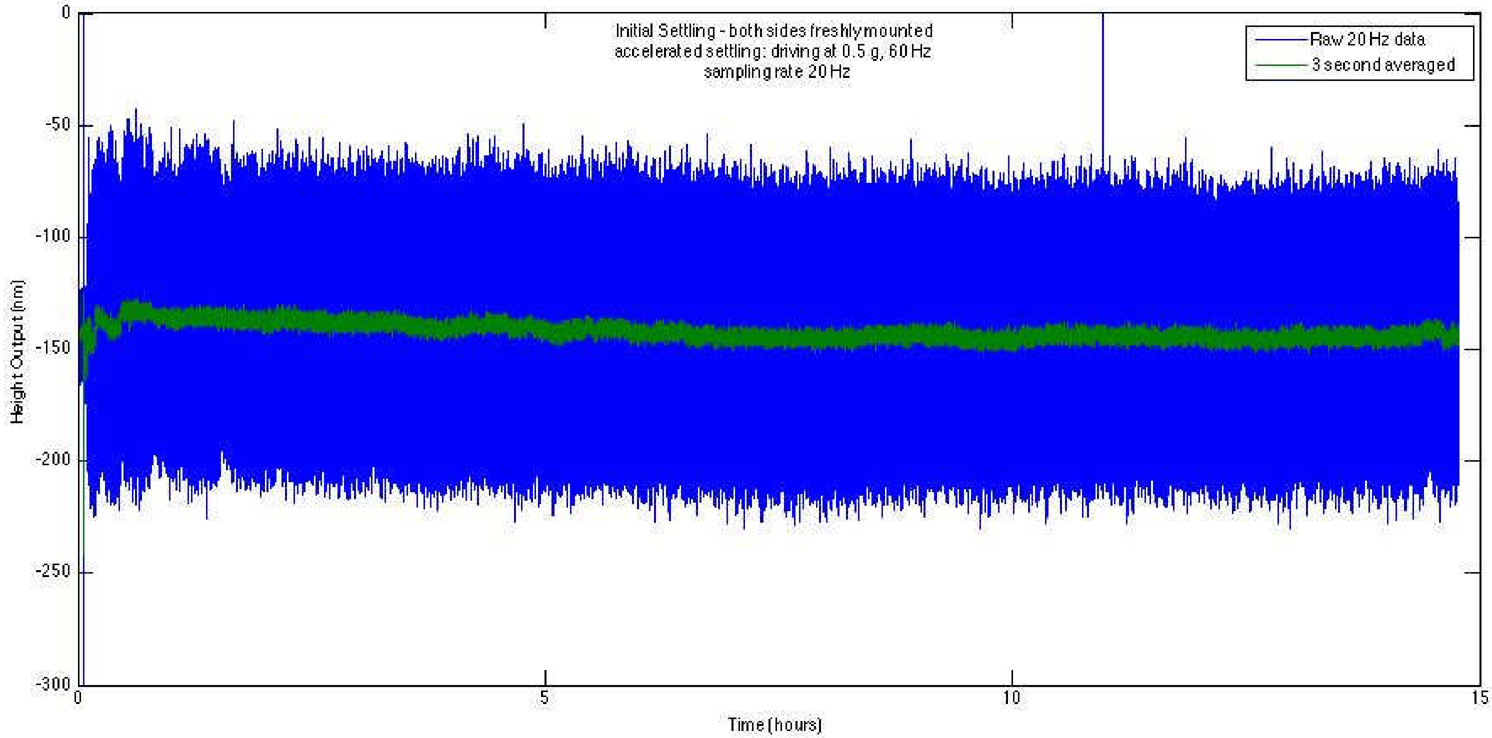
- Both sensor halves mounted less than 1 hour before start of test
- Repeatability to 1 ADC unit or less (2.7 nm)
- Observed effect from rotation "toward" is probably due to substrate flexing
- "Segment Collision" was from setting the substrate down hard on the granite block table, producing a shock. It produced a measureable offset, but the sensor remains repeatable at the new position
- <u>Note that these tests are with the 52 mm tall sensor: The gravity sag of the baselined 67 mm block with improved foot geometry will be much smaller: ~20 nm per block from the model</u>

Gravity Sag: Gap Measurement



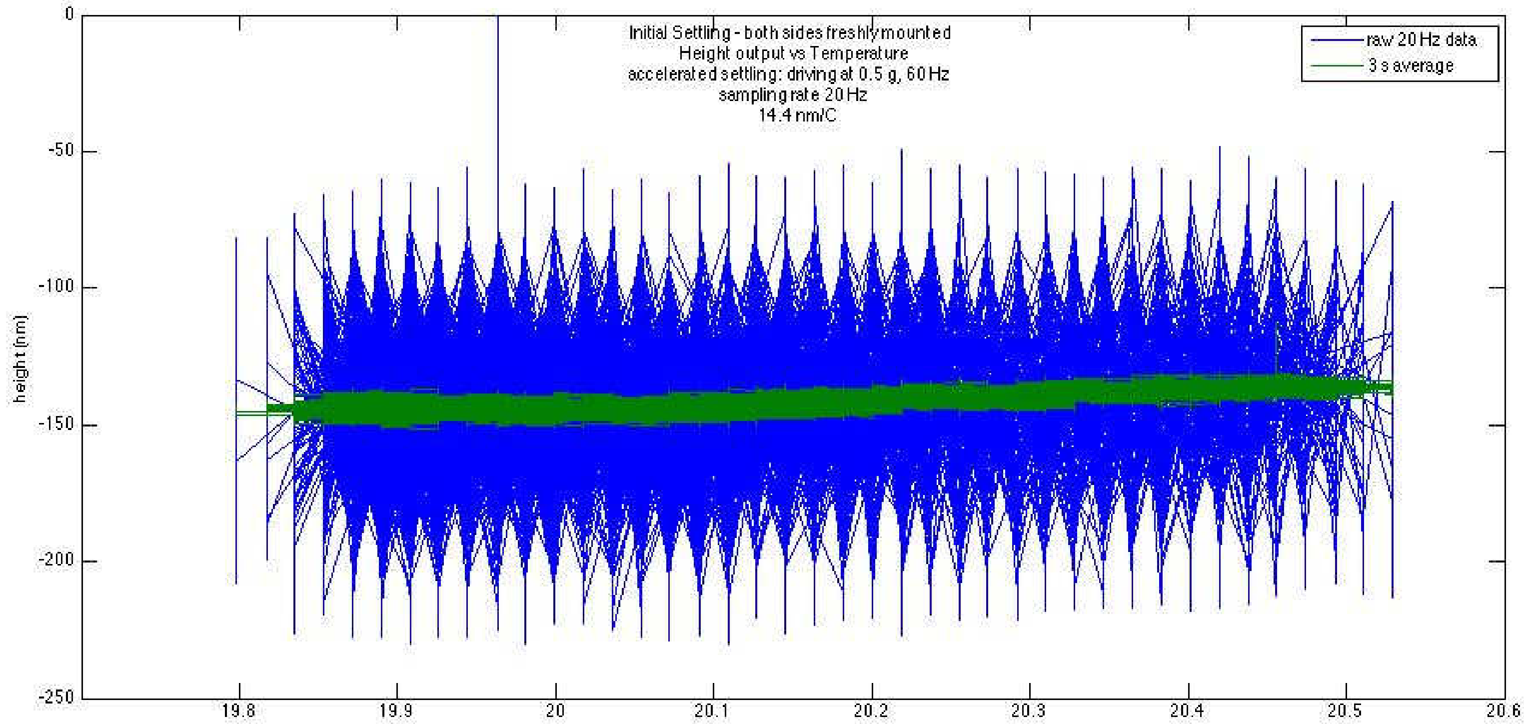
- Both sensor halves mounted less than 1 hour before start of test
- Repeatability to 1 ADC unit or less (2.7 nm)
- Observed effect from rotation "toward" is probably due to substrate flexing
- "Segment Collision" was from setting the substrate down hard on the granite block table, producing a shock. It produced a measureable offset, but the sensor remains repeatable at the new position

Accelerated settling
Height vs.. Time



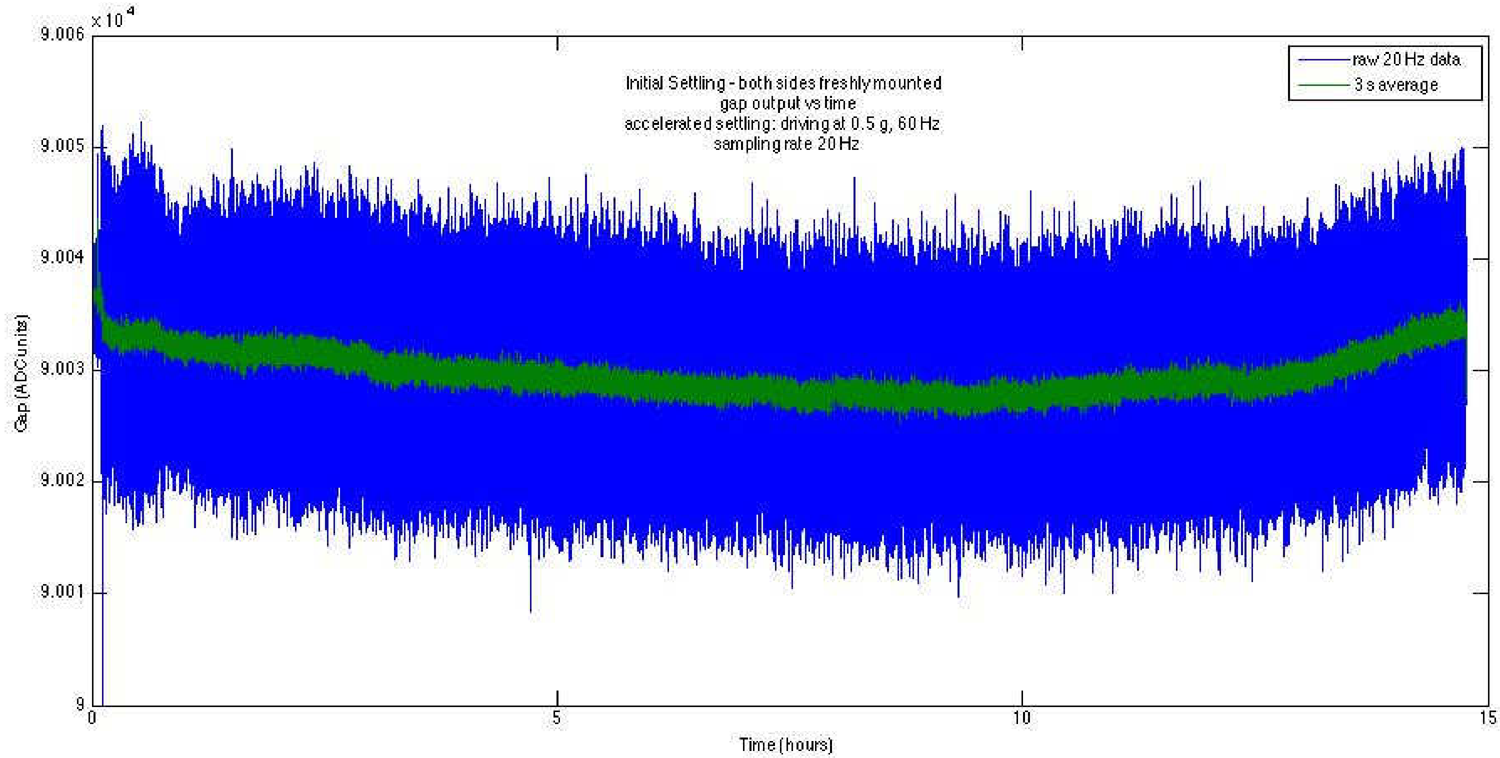
- Height (nm) vs.. Time (hours) with edge sensors level and 60 Hz, 0.5 g mechanical drive. Blue trace is the raw 20 Hz data and green is a 3 second running average.
- The small change correlates well with temperature (next slide)

Accelerated settling Height vs. Temperature



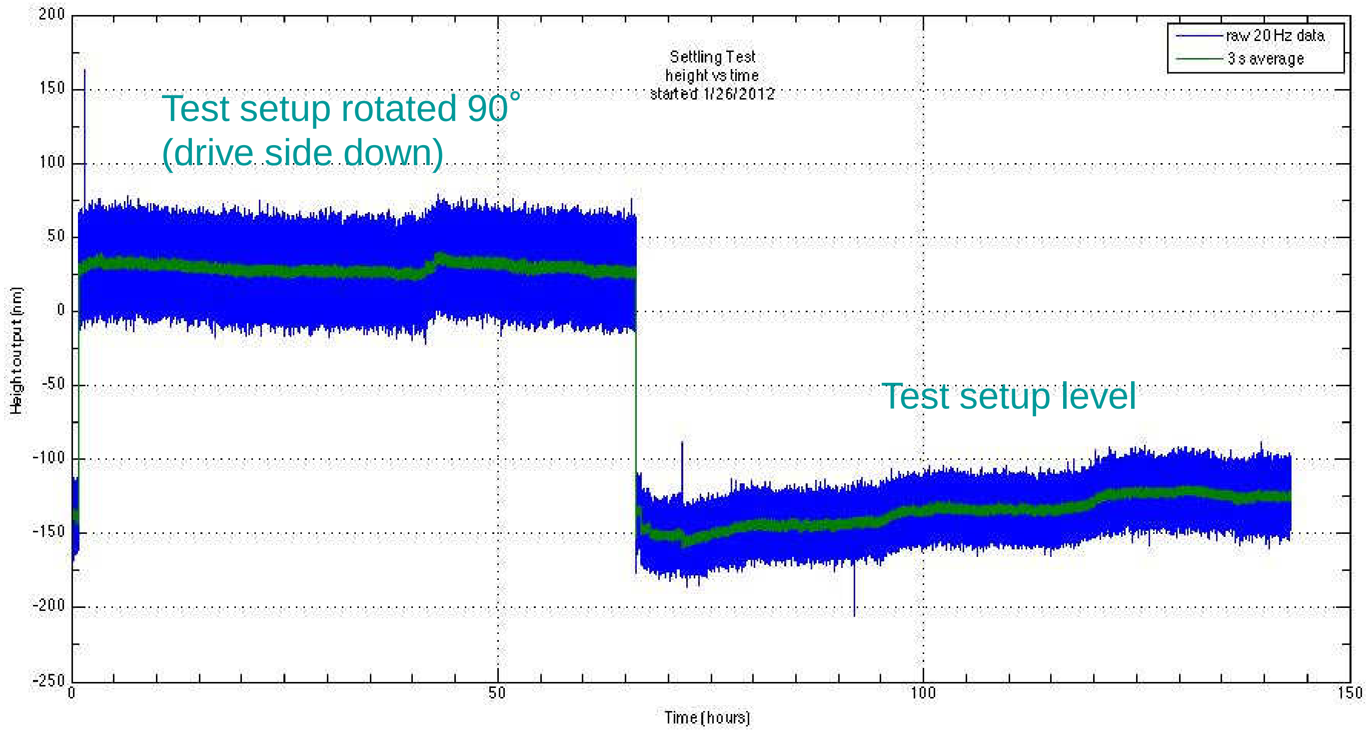
- Height (ADC units) vs.. Temperature for the data from the previous two slides
- A linear fit gives ~14.4 nm/C, which is consistent with the temperature coefficients shown earlier
- The good fit to temperature implies that variations during the test are dominated by temperature fluctuations

Accelerated Settling
Gap vs. Time



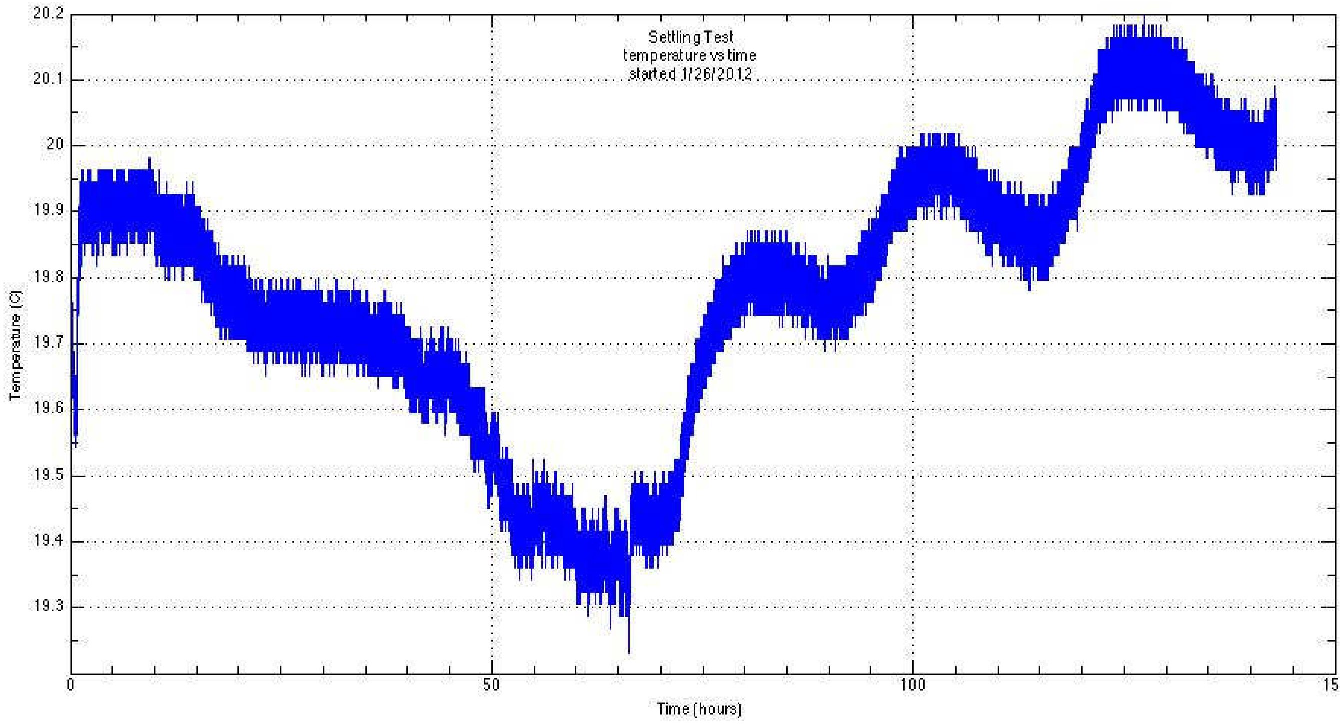
- Gap (ADC units) vs. Time (hours) from the same run as the height data just shown. Blue trace is the raw 20 Hz data and green is a 3 second running average. 1 ADC unit= 50 nm
- The correlation with temperature is not as consistent as for height
  - This may indicate some possible settling, or else some crosstalk between height and gap in the demodulation (we have not had time to fully explore this)

Long term settling
Height vs. Time

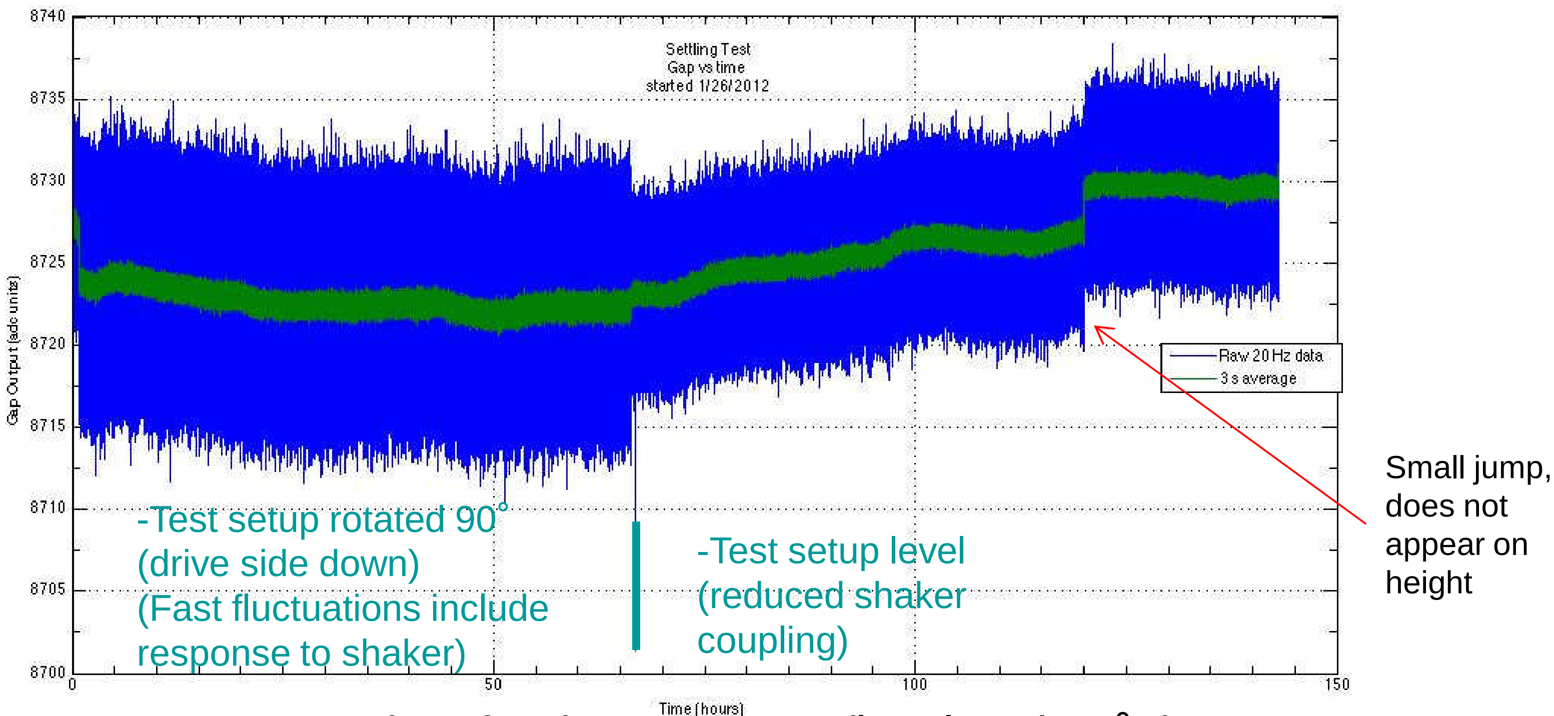


- Accelerated settling test with sensor rotated to look for orientation sensitivity to settling
- Height data follow temperature as before: there is no evidence of settling at the accuracy of this test

Long term settling
Temperature vs. Time



Long term settling
Gap vs. Time



- Gap vs. Time for the same run (level and 90°)
- Gap data appear to follow temperature, but do show a small discontinuity that does not appear on the height data.
  - Jump is likely a non-mechanical disturbance, but not fully understood

Gravity Sag and Settling Conclusions

- Height and gap show very repeatable behavior with changes in gravity
- Time dependent changes correlate well with temperature, as expected
- Height shows little or no settling, even with 0.5 g applied to accelerate any settling effects
  - This was with machined interface. With these good results, we did not test using the more expensive polished interface.
- Gap shows settling of up to a few microns with shaker applied (not fully understood: may not be mechanical)
- Long term drift data (with no shaker) does not show gap settling

P08_Installation- Requirements, Tolerances, Process, and Test Results

Chris Lindensmith, Eric Williams

M1CS Sensor System Preliminary Design Review

Pasadena

March 29 - 30, 2012

Outline

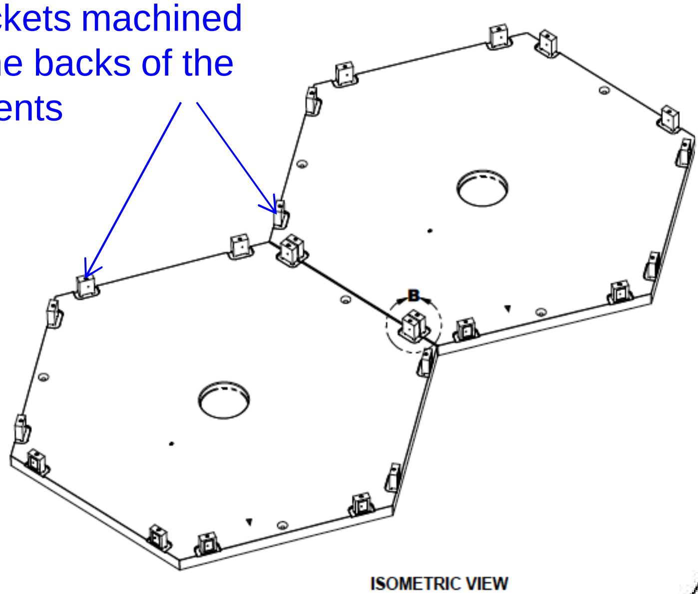
- Installation Error Budget
- Sensor Mounting Errors and Calibration
- Sensor Mounting Process
  - Pre-mounting measurements
  - Mounting and Installation details
  - Repeatability
  - Print-through on Segments
- Stability
  - Vibration test
  - Drift Tests (see presentation P07)

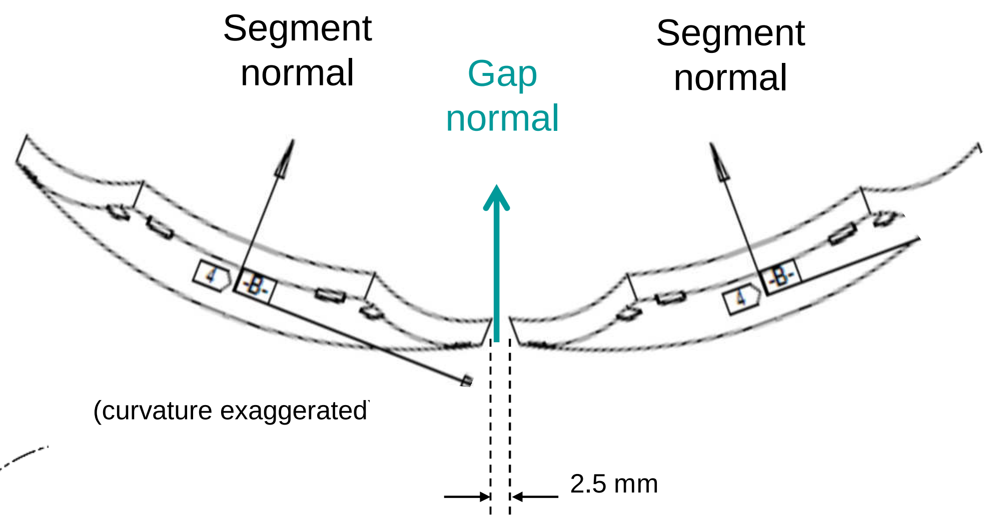
Objective

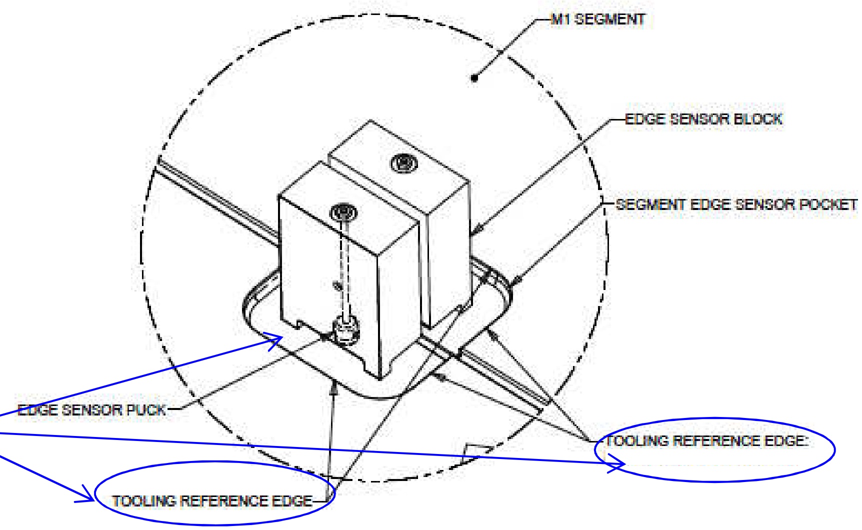
- Show that the installation tolerances are based on requirements derived from calibration and performance requirements
- Show that the required installation tolerances are readily achievable
- Show that the installation process is straightforward and economical
- Show that the installed sensors are stable against environmental disturbances (e.g. earthquakes)

Sensor Mounting

Edge Sensors mount to pockets machined into the backs of the segments

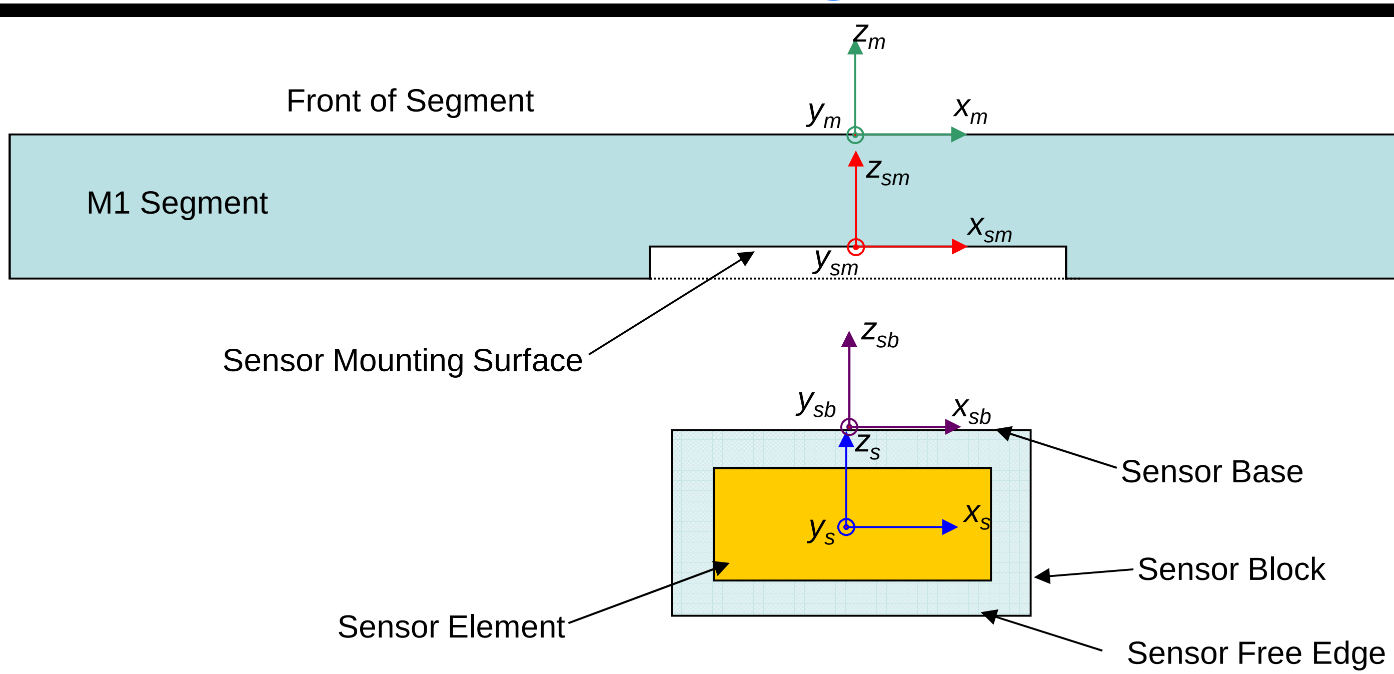






The pocket mounting surface and two edges are used as references for controlling the sensor position and orientation

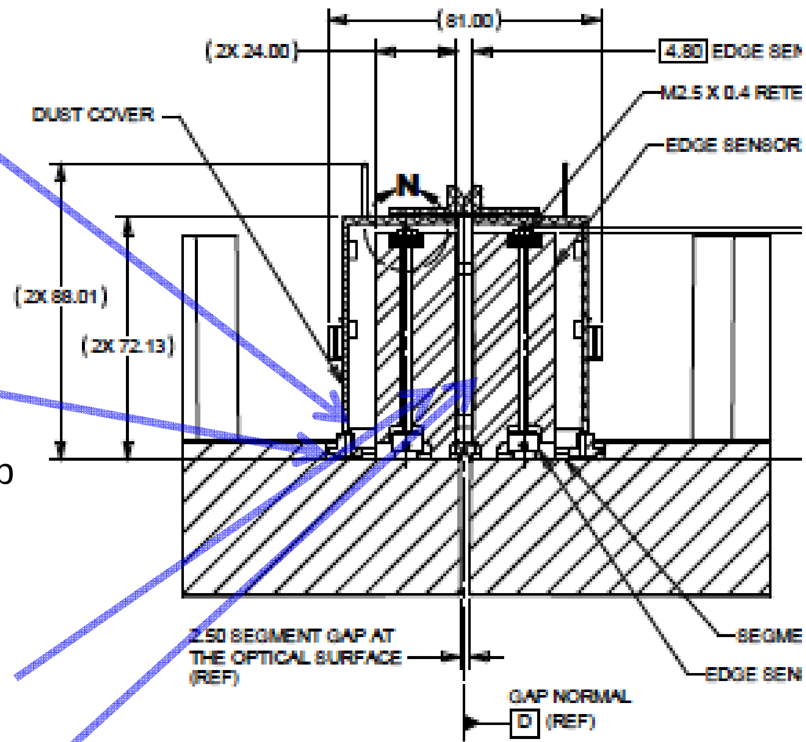
Edge Sensor and Segment Mating



- The overall requirements are on the location and orientation of the coating pattern (subscript s) relative to the local optical surface (subscript m) using the "gap normal" at each sensor location as a datum.
- The mounting surface for each sensor is machined to be perpendicular to the gap normal.
- The sensor mounting process adds errors at the interface from the sensor base (subscript sb) to the sensor mounting surface (subscript sm)

Installation Error Sources

- Errors are introduced in 4 places
  - Installation capability
    - Accuracy of installation relative to fiducials Introduces errors in X,Y,❑$_z$
    - Parameters measureable at fabrication or installation time that can be used to provide initial calibration (e.g. height offsets)
  - Segment Manufacturing capability
    - Orientation and height of sensor mounting surface relative to local optical surface as defined by the gap normal (Z, θ_x and θ_y)
    - Pocket fiducial edges for locating in X and Y (less critical)
  - Edge sensor block manufacturing capability (P05)
    - Block thickness and width, tilt of the sensor face (Y, θ_x, θ_z)
  - Edge Sensor Coating Capability (P05)
    - Orientation and location of the pattern on the faces of the sensor blocks. (X,Z, θ_y)

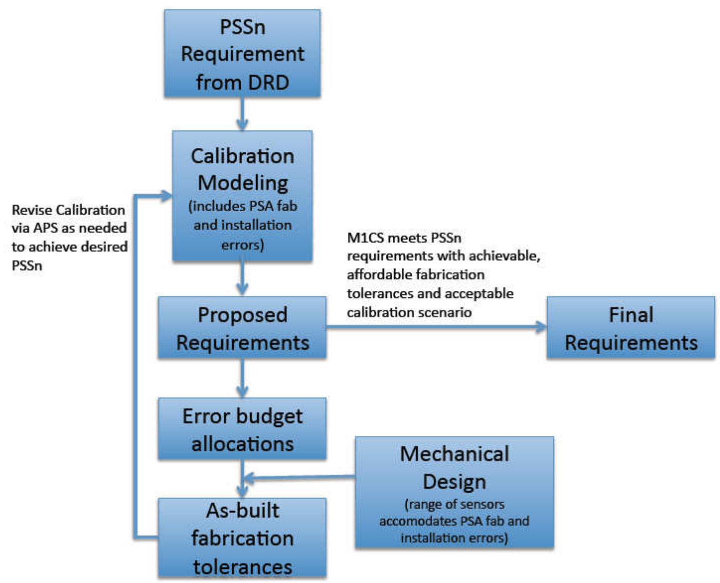


Drivers on the Installation Tolerances

- Edge sensor top level mounting tolerances are driven by multiple factors:
  - Height-offset is a critical requirement and can be measured at installation time (height, or z_s-z_m)
    - The M1CS needs to be able to bring segment surfaces within the APS capture range (+-30 micron) without on-sky information.
    - Offsets due to segment and sensor errors can be measured at fabrication/installation and used in the APS acquisition.
  - Other requirements are driven by on-sky calibration of sensors
    - These critical requirements are absolute alignment relative to the local optical surface (θ_x and θ_y)
    - θ_x and θ_y need to be controlled to relative to the local optical surface (actual fabrication tolerance- these can't be corrected in the calibration process)
    - The limits are determined by the performance of the on-sky calibration process.

Error Budget Development

The details of the error budget (shown in P03 and repeated on the next slide) were developed iteratively, integrating the in situ calibration process with the mechanical design and fabrication.



The error budget also drives the installation requirements and process.

Pocket Definition and MICD

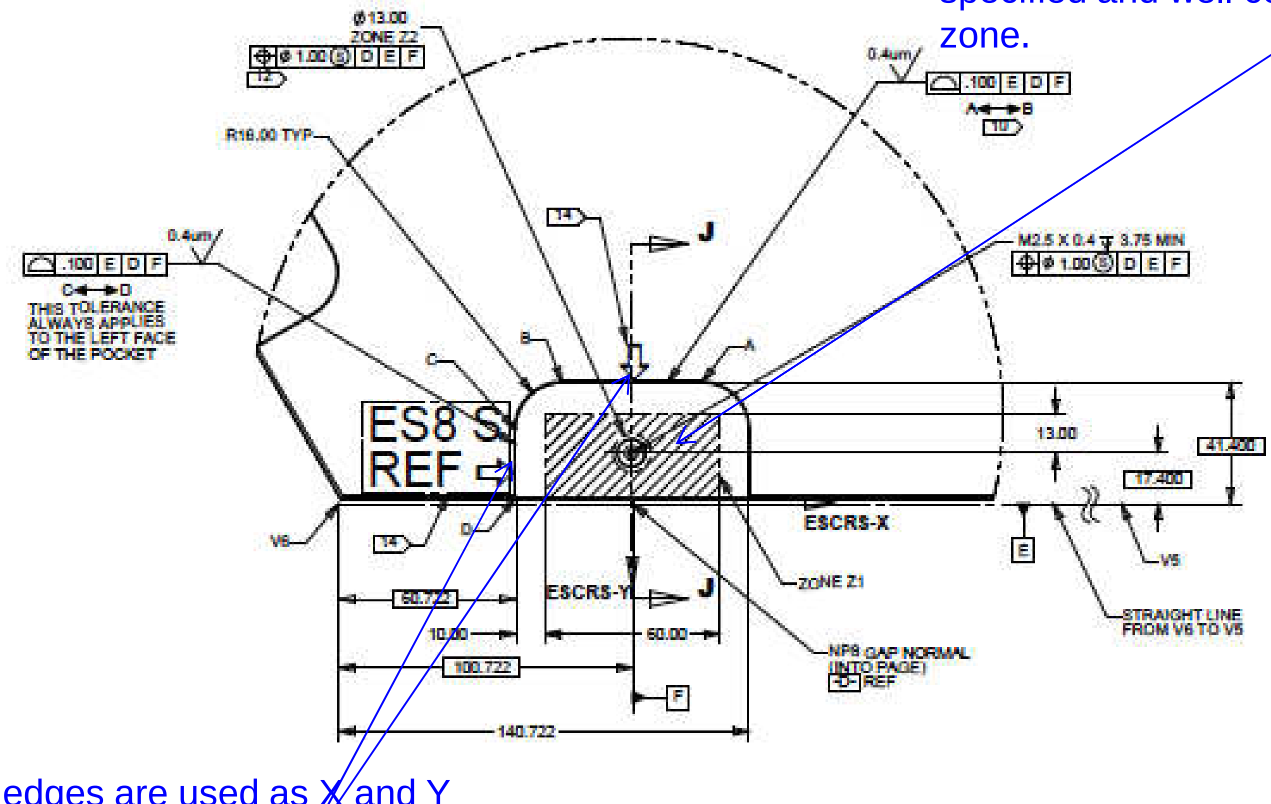
This column is determined by segment fab and defined in MICD.

		Sensor fab (rms ea)	Pocket fab (rms ea)	Sensor install (rms ea)	Segment install (rms ea)	Thermal deflection (rms ea)	Gravity deflection (rms ea)	RSS (rms ea)	2 sigma, relative (max, pair)	Req't (max, pair)
thetaX (dha)	(mrad)	0.1	**0.5**	0.1	0.0	0.0	0.0	0.5	**1.4**	**1.5**
thetaY	(mrad)	0.0	**0.3**	0.1	0.0	0.0	0.0	0.3	**0.7**	**1.0**
thetaZ	(mrad)	0.1	**1.0**	0.4	0.3	0.0	0.1	1.1	**3.2**	**3.5**
X (shear)	(um)	40	25	35	**287**	24	57	299	**845**	**1000**
Y (gap)	(um)	**150**	25	35	**200**	36	85	270	**763**	**1000**
Z* (height)	(um)	10	0	1	0	0	0	10	**28**	**30**
*Pocket offsets (25 um rms) will be measured										

- These are reqs 1100-1200
- Pocket fabrication errors drive the angular ranges
- Sensor fabrication and segment install errors drive the linear ranges
- Z is a special case, and will be measured to meet APS requirement

Segment MICD Detail

Zone Z1 is the sensor mounting surface and the perpendicularity and flatness are specified and well controlled within the zone.



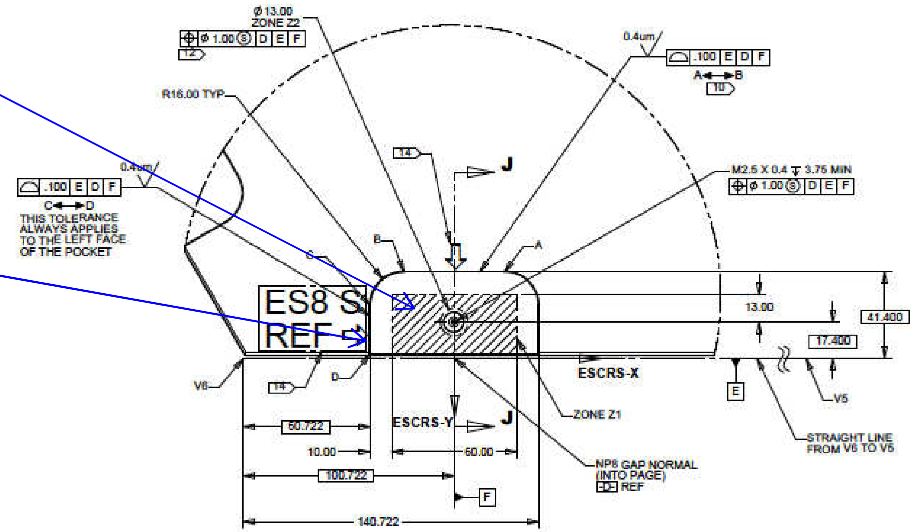
Two pocket edges are used as X and Y fiducials for sensor mounting

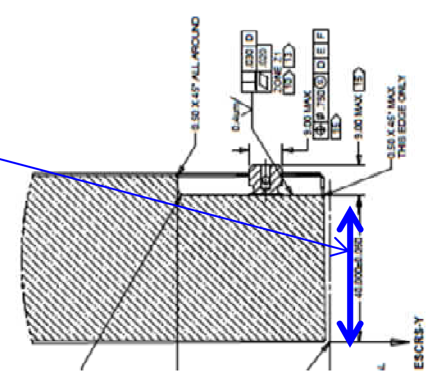
DETAIL H
SHEET 4, ZONE B3

From MICD: TMT.M1.M1CS-INT-001

Interface to M1 Segments
Pocket Definition and Error Budget

- The segment pocket surface profile and finish dominate the errors in $\square_x$ and $\square_y$.
  - The values used were set based on demonstration coupons built by ITT
- The segment pocket edges (marked with arrows) provide references for X and Y location of the sensor blocks
- The segment thickness at the pocket determines the z offset for the sensor halves.
  - Because APS capture needs height accuracy to +-30 microns, we measure the segment pocket at sensor installation time to determine the offset. This is less expensive than trying to manufacture the segments with the thickness controlled to a fraction of the 30 microns.



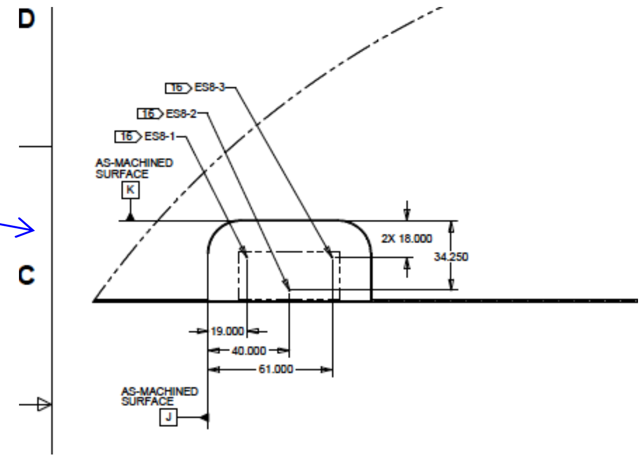


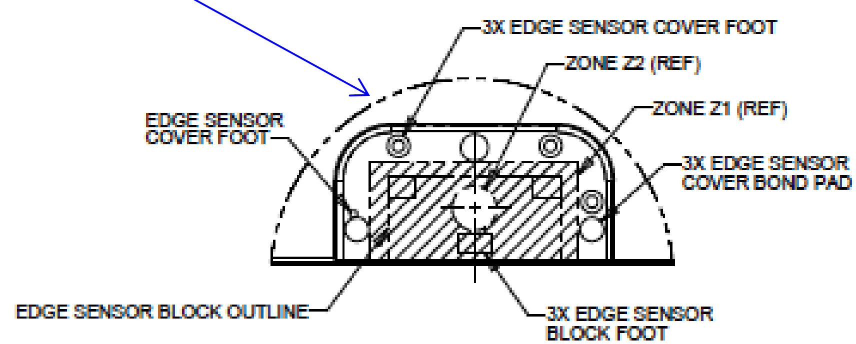
Interface to M1 Segments Sensor to Segment Detail II

TMT THIRTY METER TELESCOPE

Jet Propulsion Laboratory
California Institute of Technology

- Recently updated to include measurement locations for segment thickness to determine sensor z-offset
- Boot base glue pads





Installation Error Budget

This column is determined by sensor installation

		Sensor fab (rms ea)	Pocket fab (rms ea)	Sensor install (rms ea)	Segment install (rms ea)	Thermal deflection (rms ea)	Gravity deflection (rms ea)	RSS (rms ea)	2 sigma, relative (max, pair)	Req't (max, pair)
thetaX (dha)	(mrad)	0.1	**0.5**	0.1	0.0	0.0	0.0	0.5	**1.4**	**1.5**
thetaY	(mrad)	0.0	**0.3**	0.1	0.0	0.0	0.0	0.3	**0.7**	**1.0**
thetaZ	(mrad)	0.1	**1.0**	0.4	0.3	0.0	0.1	1.1	**3.2**	**3.5**
X (shear)	(um)	40	25	35	**287**	24	57	299	**845**	**1000**
Y (gap)	(um)	**150**	25	35	**200**	36	85	270	**763**	**1000**
Z* (height)	(um)	10	0	1	0	0	0	10	**28**	**30**
*Pocket offsets (25 um rms) will be measured										

- These are reqs 1100-1200
- Pocket fabrication errors drive the angular ranges
- Sensor fabrication and segment install errors drive the linear ranges
- Z is a special case, and will be measured to meet APS requirement

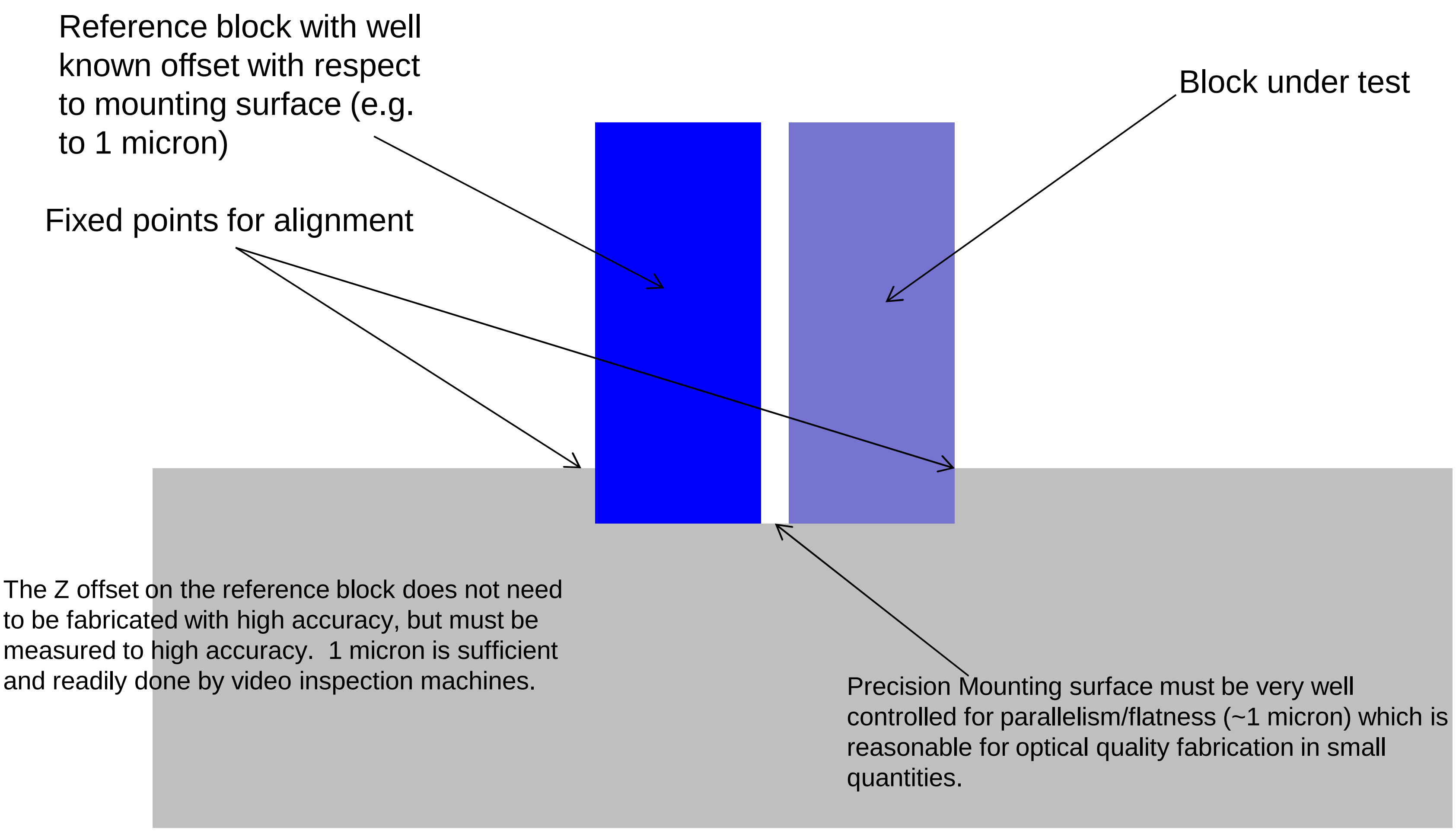
Piston Offset Measurement Sensor Side

- The piston offset requirement is met more cost effectively by measuring the offset for later use in the APS setup.
  - There are two available approaches to measuring pattern offsets:

    A) The sensor pattern offsets relative to the block feet can be measured accurately to ~1 micron accuracy with automated video inspection machines (e.g JPL's Tesa inspection machine) in a few minutes per sensor.

    B) Relatively low cost set of fixtures can be made with "reference" drive and sense blocks mounted on them and offsets of production sensors can be measured in an "as-installed" type of fixture.
  - It may be possible to apply the coating patterns to 5 micron or better accuracy, but this is difficult to verify with the current as-manufactured blocks due to lack of fiducials.
    - Current drawings include fiducials and we expect to be able to verify accuracy and consistency on all future sensor blocks

Sensor Offset Measurement Fixture Concept



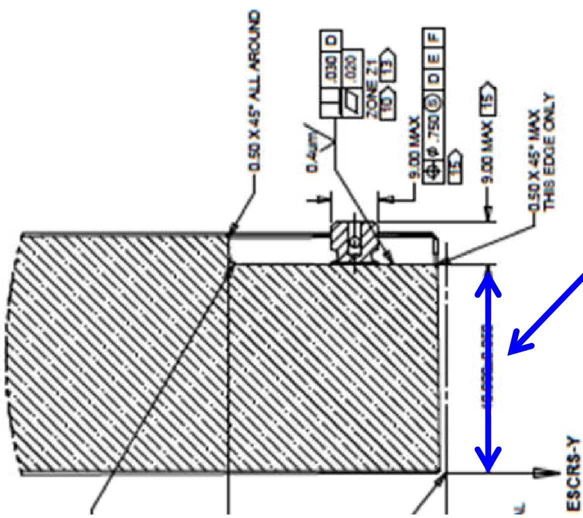
Piston Offset Measurement Segment Side

- The current requirement for the accuracy of the segment-side piston offset comes from the expected accuracy of the machine ITT used for demonstrating segment-back machining.
  - A higher accuracy requirement would increase the cost of machining.
  - The offset can be readily measured at sensor installation time with a micrometer. A simple plate (included in current costing) that mates to the sensor pocket and has micrometers mounted to it can measure the piston offset at the sensor-mounting location quickly and accurately
  - Standard shop micrometers (e.g. costing a few hundred dollars from Starrett, B&S, or Mitutoyo) have 2 micron accuracy.
  - Practical micrometer accuracy may be limited by clutch repeatability to about 5 microns (tested on a new Mitutoyo micrometer).
- Note that this measurement must be done for the mounting pockets on both the drive and the sense sides.

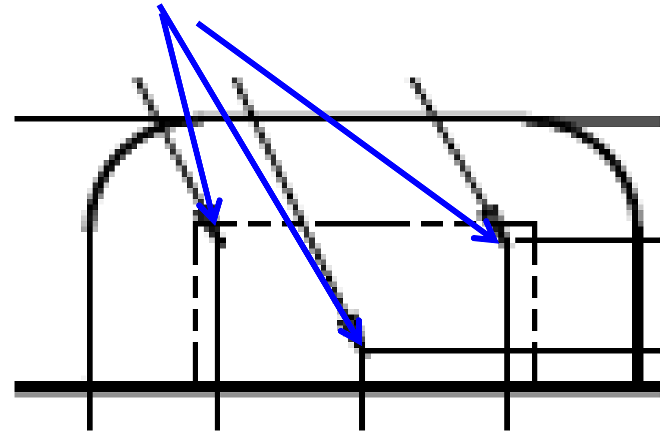
THIRTY METER TELESCOPE

Piston Offset Measurement – Segment Side

Jet Propulsion Laboratory
California Institute of Technology

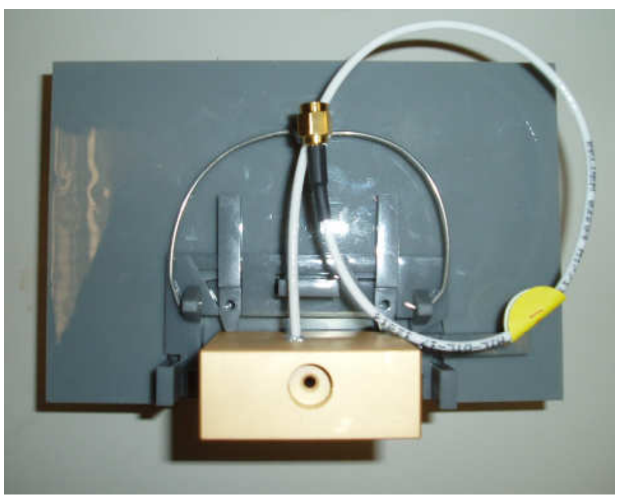


Micrometer Measurement of Segment thickness at the locations of the three feet



- COTS (e.g. Starrett, Mitutoyo) micrometers are typically 2 micron accuracy and available with inexpensive digital outputs.
- Jig will include plate for alignment of micrometers in pocket and 3 micrometers

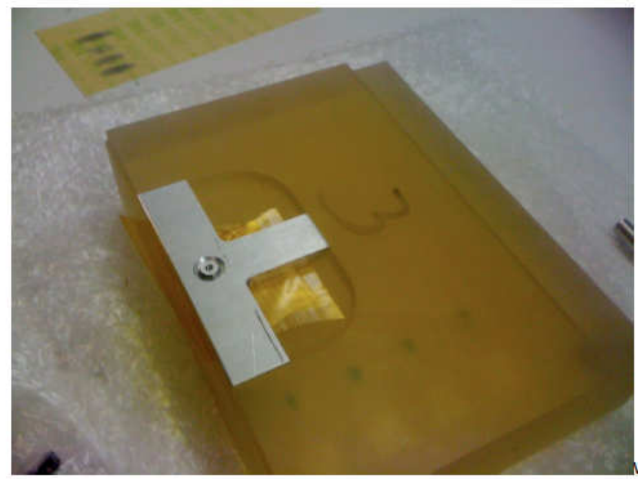
Sensor mounting



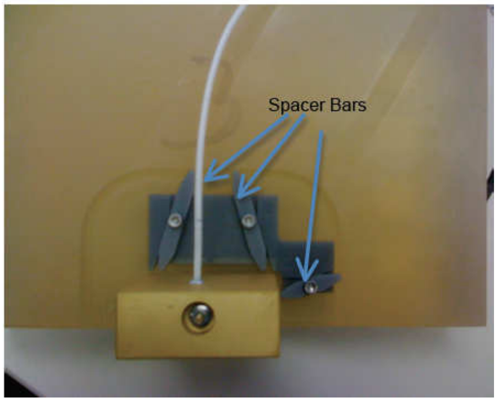
- Sensors mount in machined pockets on underside of segments
  - Held down by threaded rod to bonded puck
- Mounting tolerances maintained via reference to precision tolerances on pocket reference surfaces
- Separate jig measures distance from pocket to optical surface
- Three identical spacer bars contact glass on pocket edge and on sensor block, base is low-precision
- Prototype mounting fixture shown with real sensor (note: glass block has oversized pocket – plastic block shows correct fit)
- Force is maintained by spring-washers.
- Base stays in place as dust cover base. Spacer bars are removed. Cover can then be removed to check sensor location
- Step by step details are shown in: TMT.CTR.TEC.11.011 and TMT.CTR.TEC.12.005

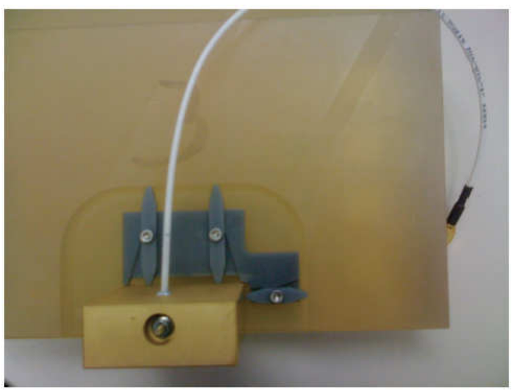
Location and Gluing of Puck

The Puck is installed at the segment manufacturer using a simple alignment tool that references the puck location to the pocket edges.



Sensor Installation with Spacing Tools



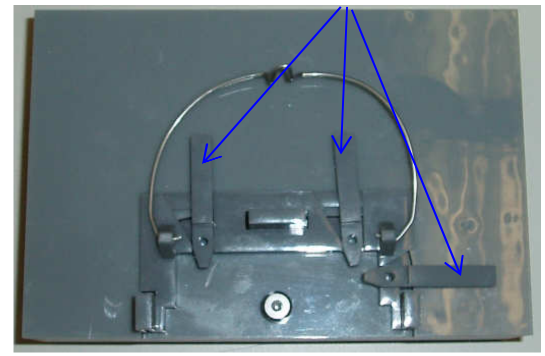


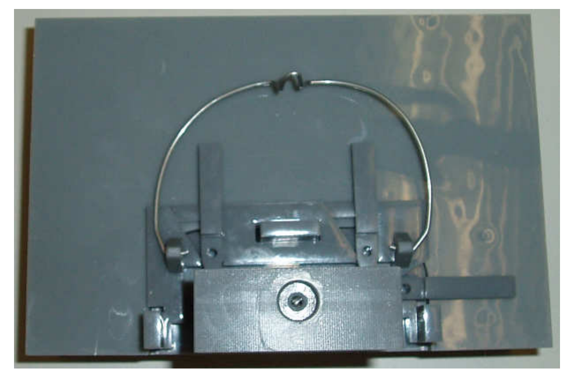
11 Installation setup with the spacer bars set to the "spacing" positions.

The photos on the left show the sensor installation jig used before development of the boot base as the alignment jig. The photos at the right show installation using the boot base and plastic models.

In both cases, the spacer bars contact the glass pocket edge and the back and sides of the sensor. The solid base (on the left) and boot base (on the right) are only used to locate the bars.

Spacer Bars

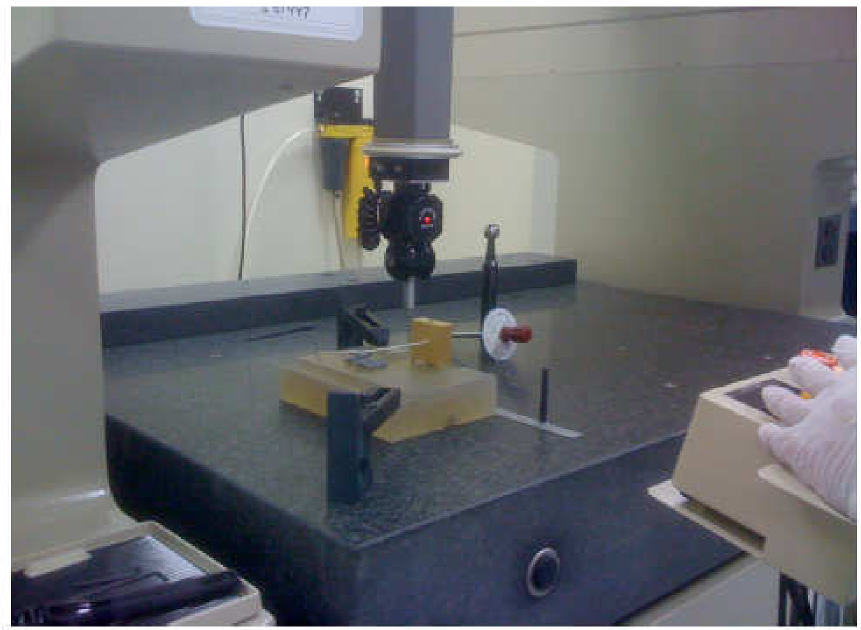




Installation Repeatability Setup

- Installation repeatability was tested by mounting a sensor repeatedly on the coupon and measuring its location relative to the pocket with a CMM (0.5 micron accuracy)
- Measurements were taken at locations contacted by the alignment jig to obtain x position, two y positions, and determine the angle ❑$_z$ relative to the pocket edge
- Separate measurements were done to determine z position repeatability. Z position was repeatable to 0.5 micron (the limit of the machine)
- Alignment of the sensor and torquing the nut takes only a few minutes.

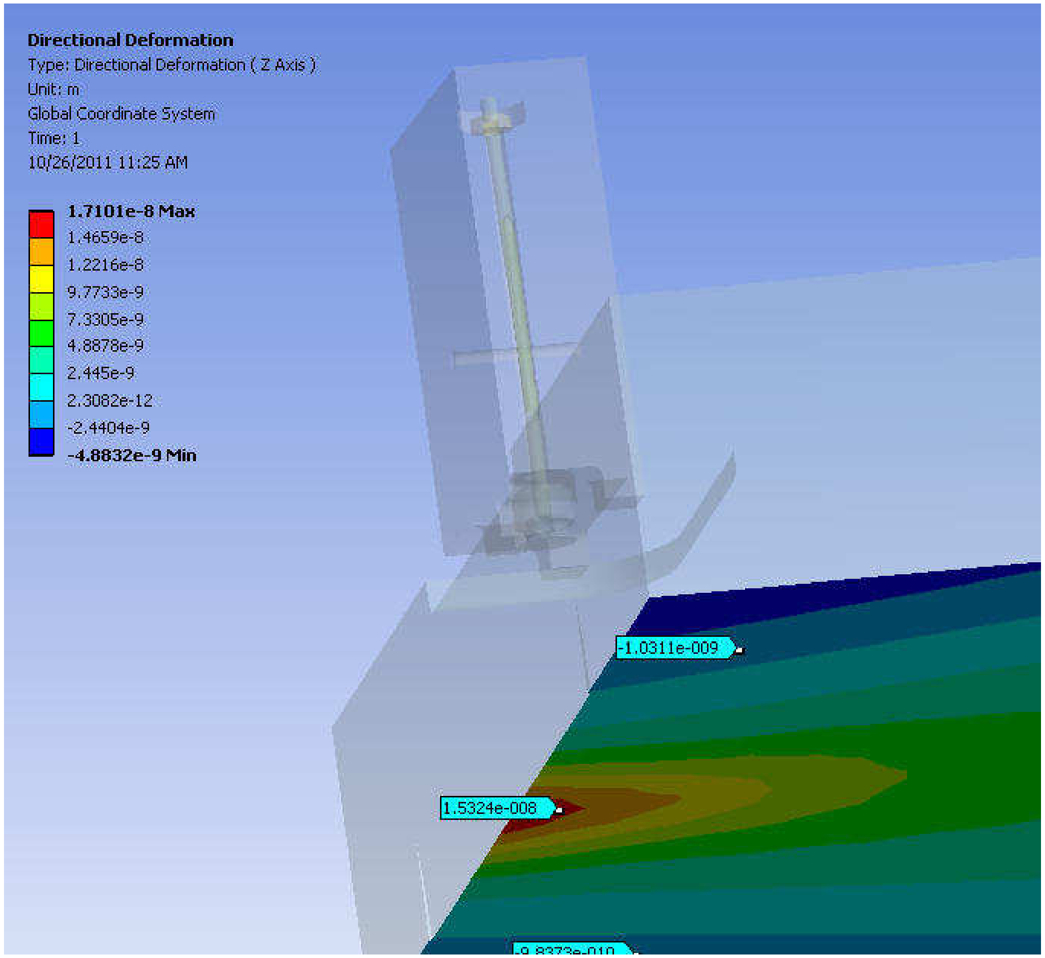
Coordinate	1♦
X	16 micron
Y_1	4 micron
Y_2	3 micron
Z	0.5 micron or better
❑$_{x,}$	0.025 mrad
❑$_y$	0.01 mrad
❑$_z$	0.13 mrad



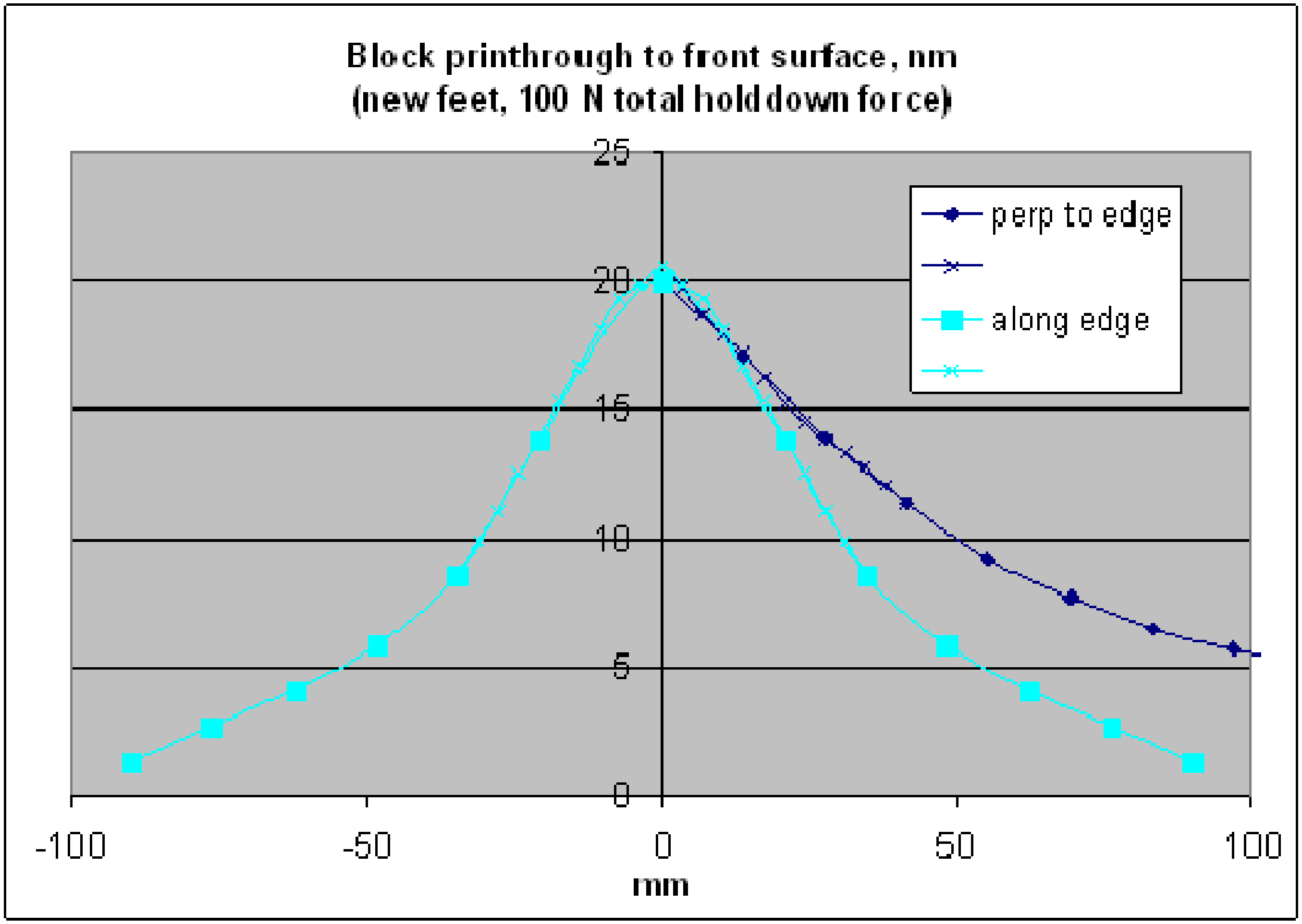
Details described in: TMT.CTR.TEC.11.011

Print Through on Segment

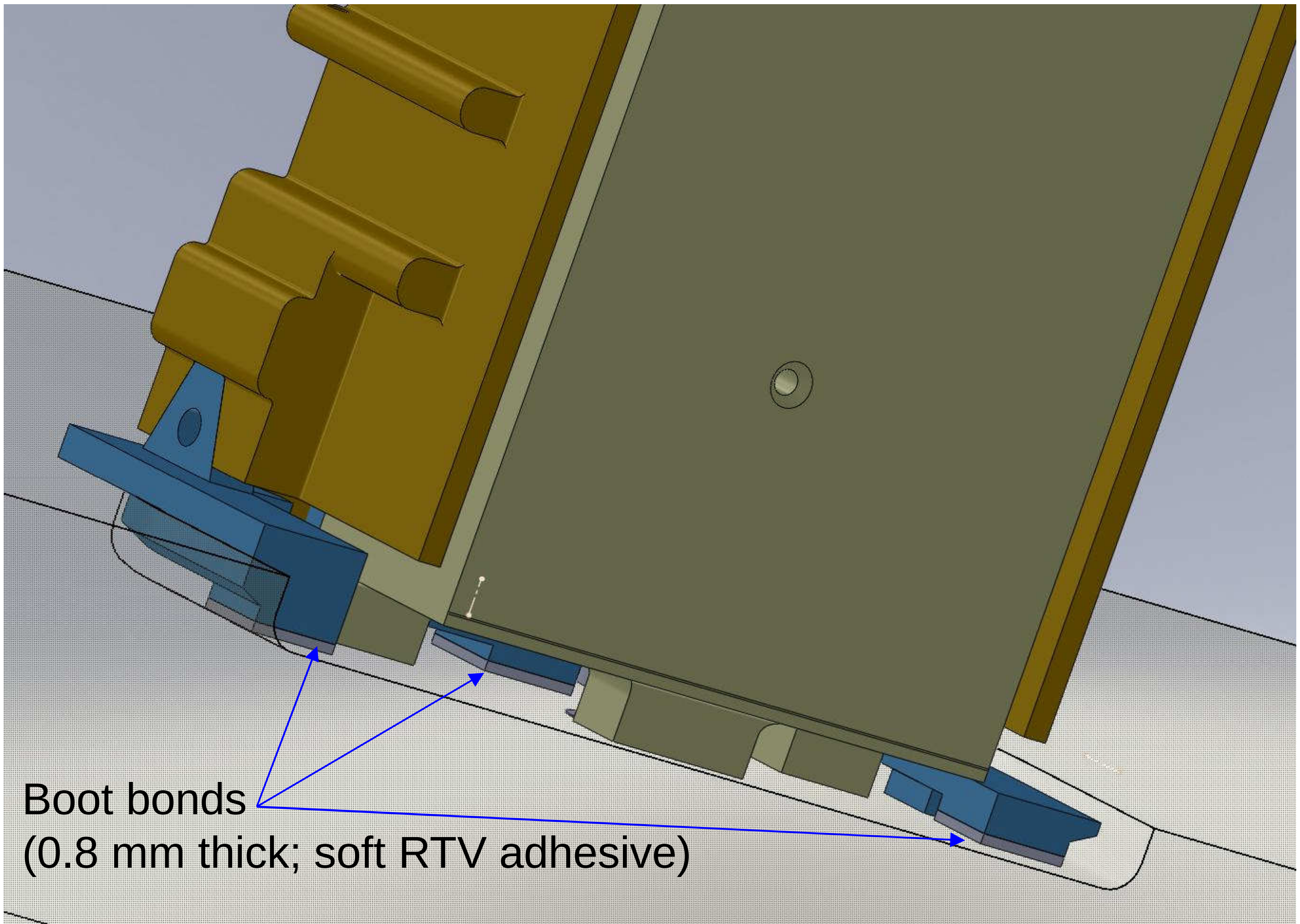
- 100 N preload gives about 15 nm of deformation on segment, 93 psi on feet
- Dummy sensors will be installed during polishing so that this deformation is polished out
- Details presented in: TMT.CTR.PRE.11.071



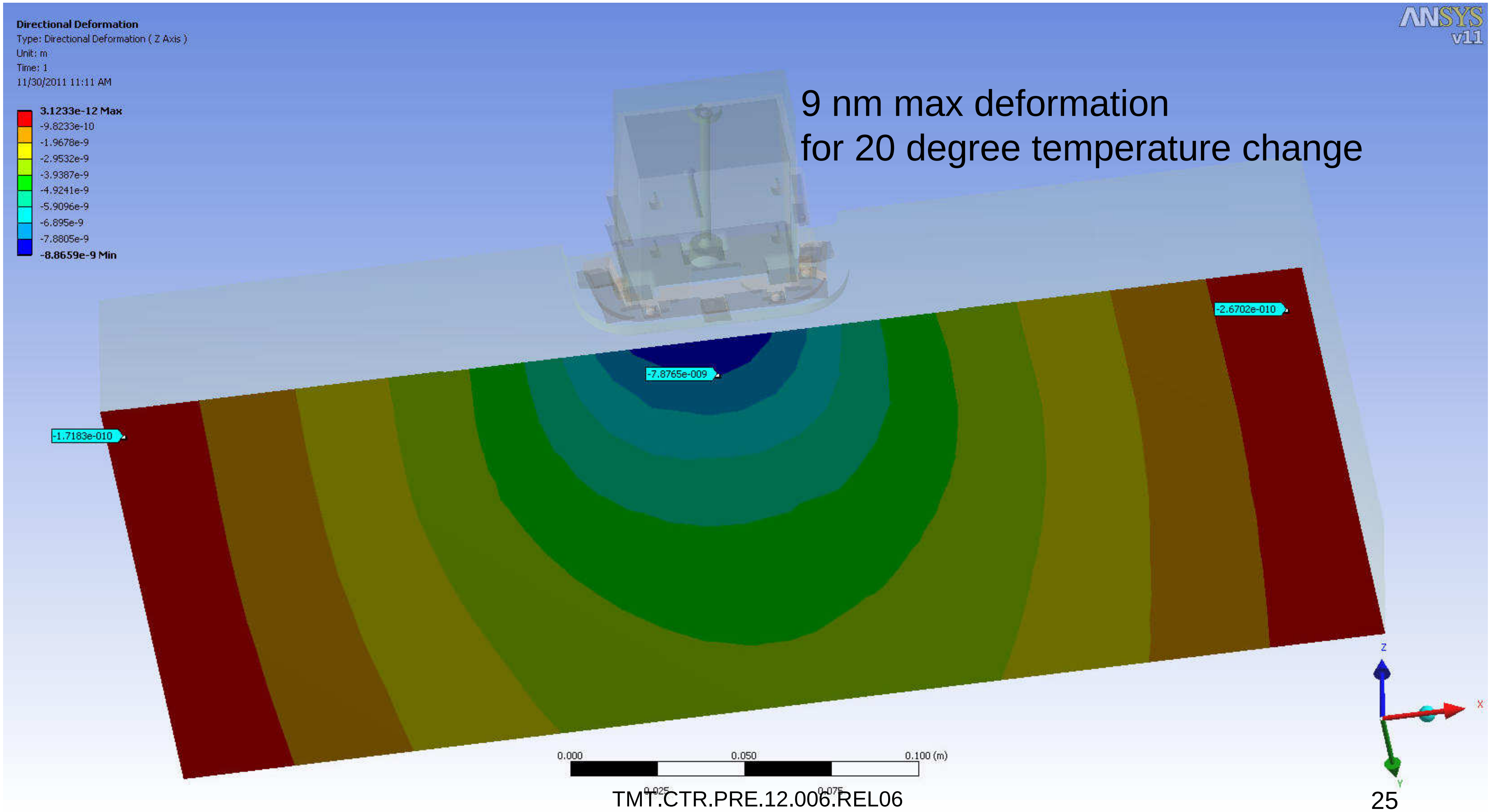
Block Print-through spatial scale



Boot footprint on glass



Boot print-through to optical surface

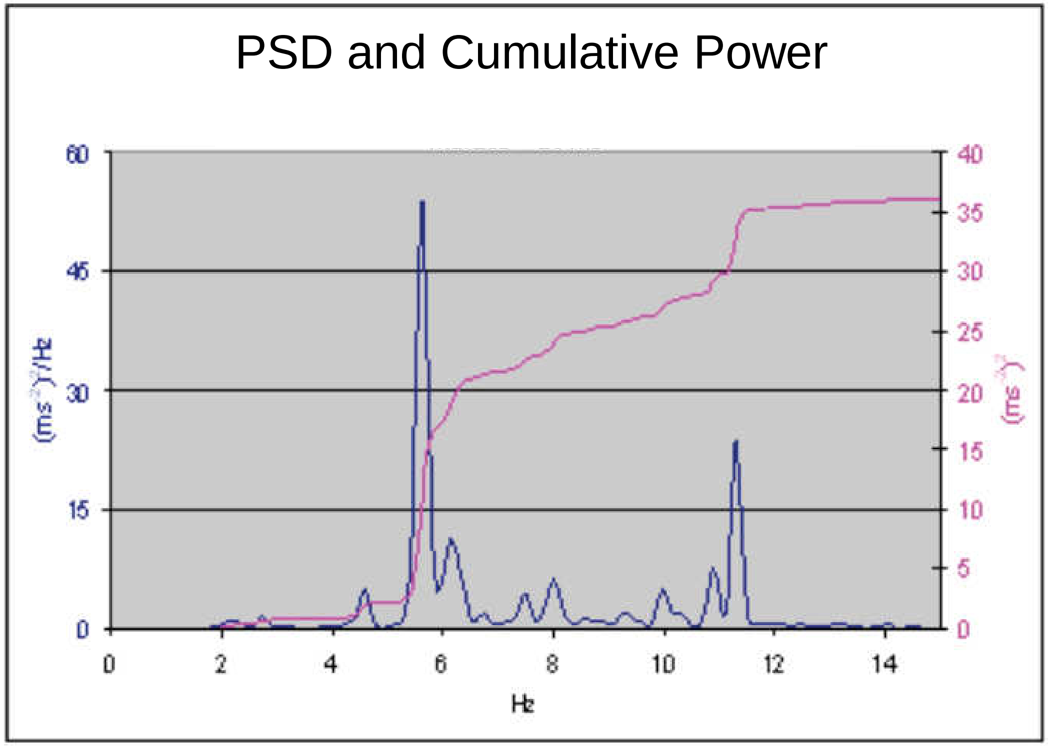


Vibration Test for Environment: earthquake

- Earthquake Requirement:
  - 10 year return period earthquake: no damage [0240]
    - Expect no recalibration needed as long as no segment-to-segment contact
  - 200 year return period earthquake: two week recovery [0242]
    - Full recalibration assumed; some sensors may need remounting if have shifted due to segment-to-segment contact
    - Expect that these sensors can be identified during the initial part of the recalibration process
  - 1000 year return period earthquake: no damage to telescope optics [0244]
    - Not driving – sensor are not in the optics' load paths
- Test against Earthquake requirement with vibration
  - Low cost test done in lab with a 60 Hz shaker
  - Recommend that the test be repeated with Final Design hardware, complete with boot in place.
- More detail in: TMT.CTR.TEC.11.010

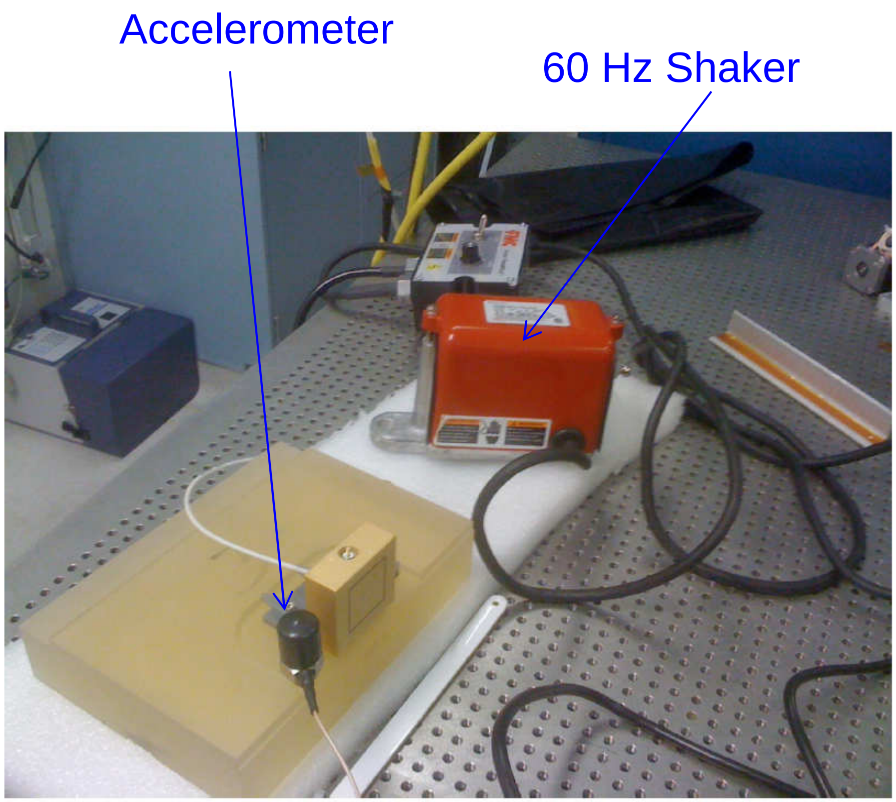
Vibration Test Requirement

- Vibration environment is not well specified in the parent requirement documents.
- Kei Szeto from TMT provided the PSD and cumulative power chart at the right for the accelerations at the top surface of the mirror cell
- The power in the earthquake is dominated by peaks near 6 and 12 Hz, with peak accelerations of 3g and 0.6 grms.
- Testing was done at 60 Hz with a 3g peak.



Vibration Test Setup

- The sensor was mounted to the coupon using the mounting procedure described earlier, but with 4 inch-oz torque (50 N force), which was an earlier spec for the holddown force.
- The vibration test setup is shown at the right. The assembly is resting on foam to allow it to slip under the force of the shaker. The restoring force was provided manually.
- Acceleration was measured with an accelerometer held in place with wax.
- The 3g peak drive was supplied for at least 20 seconds on each axis.



Vibration Test Verification and Conclusions

- Position of the sensor relative to the pocket was measured before and after vibration using a CMM with 0.5 micron accuracy.
- The position of the sensor before and after was the same to within 3 microns on the x and y axes. This is probably due to the difficulty of measuring exactly the same spot on the sensor and pocket after moving the assembly.
- The 3 microns is well within the installation tolerances, suggesting that even in the case of a design-maximum earthquake the sensor will require only a repeat of the normal *in situ* calibration process.
- Recommend repeating test with final assembly including all components (e.g Sensor, boot, and electronics) made from production materials.

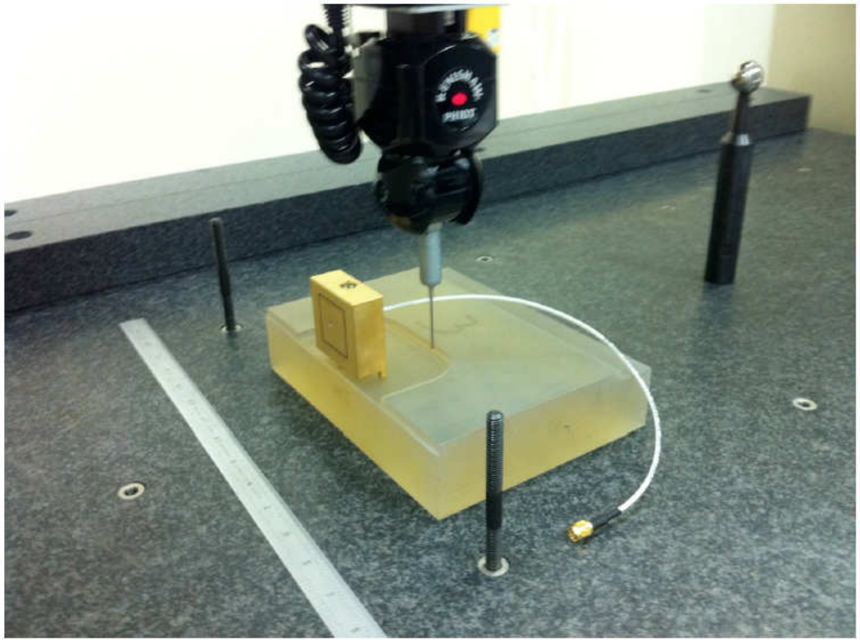


Figure 4 Test coupon and edge sensor block on the CMM machine for location measurement.

Conclusions

- The sensor mounting approach is well developed and has been experimentally verified.
- The interface definition is critical to the installation process, and both sides of the interface are well defined.
- The mounting approach repeatably meets the error budget allocations for sensor alignment.
- The labor time required to install each sensor half (after puck installation) is minimal.
- The mounting approach is stable against the maximum required earthquake load.

P09_Interfaces

Chris Lindensmith

M1CS Sensor System Preliminary Design Review

Pasadena

March 29 - 30, 2012

Outline

- Interfaces External to M1CS
  - Optics (TMT.TEL.OPT)
    - M1 Segments (TMT.TEL.OPT.M1)
    - Segment Handling carts (TMT.TEL.OPT.HNDL)
    - Optics cleaning (TMT.TEL.OPT.CLN)
    - Optics coating (TMT.TEL.OPT.COAT)
  - Telescope Structure (TMT.TEL.STR)
  - Facilities
- Interfaces Internal to M1CS
  - Segment Controller and Cables (electronics)

Objective

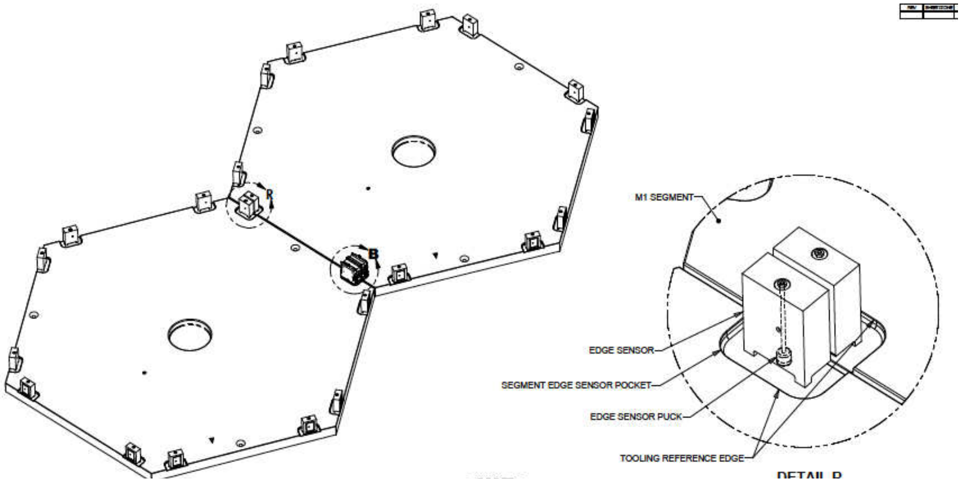
- Show the external interfaces (from SEN to outside M1CS)
  - Show that they're well defined
  - Show that they're met (particularly critical ones) or that there's a straightforward way to meet them (less critical ones)
- Show interfaces internal to M1CS and their status
  - SCC (sensor electronics)

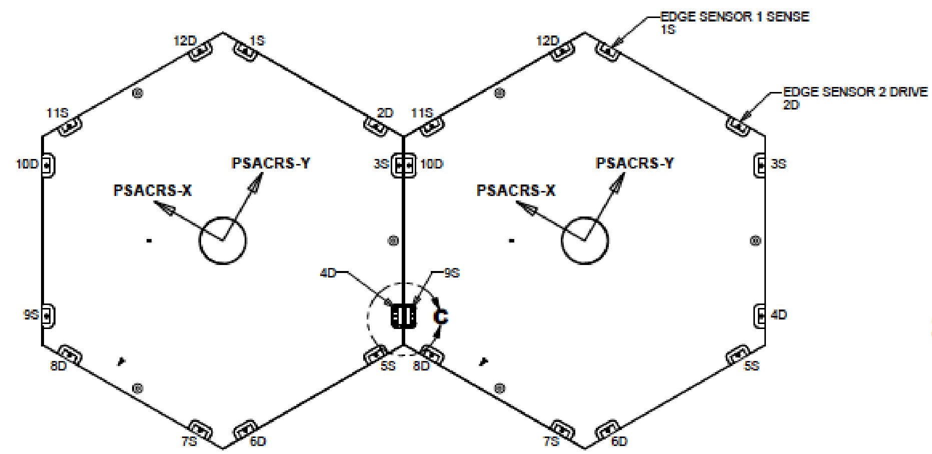
M1CS Sensor External Interfaces

		M1 Control System				
		Purge System	Global Loop Controller	Segment Controller and Cables	Sensors and Boots	Actuators
Summit Facilities	**Computer Room**		x			
	Mechanical Room	x				
Telescope Structure	**Mirror Cell**	x		x		
	Cable Wrap	x		x		
M1 Optics System	**Segment**				X	
	Primary Segment Assembly	x		x	x	
	Mounted Segment Assembly					x
Telescope Control System			x			
Observatory Safety System			x			

Interface to M1 Segments Overview

- Sensor to Segment MICD is well developed. First release version signed December 2010 (TMT.M1.M1CS-INT-001)
  - Most critical details shown in previous presentation (P08 – Installation)
- Includes the coordinate transformations to map sensor geometry back to mirror surface
- ICD is released and includes the non-mechanical interface requirements (TMT.CTR.ICD.08.001). An updated version (excerpts shown in this review) is nearing release in the coming week.





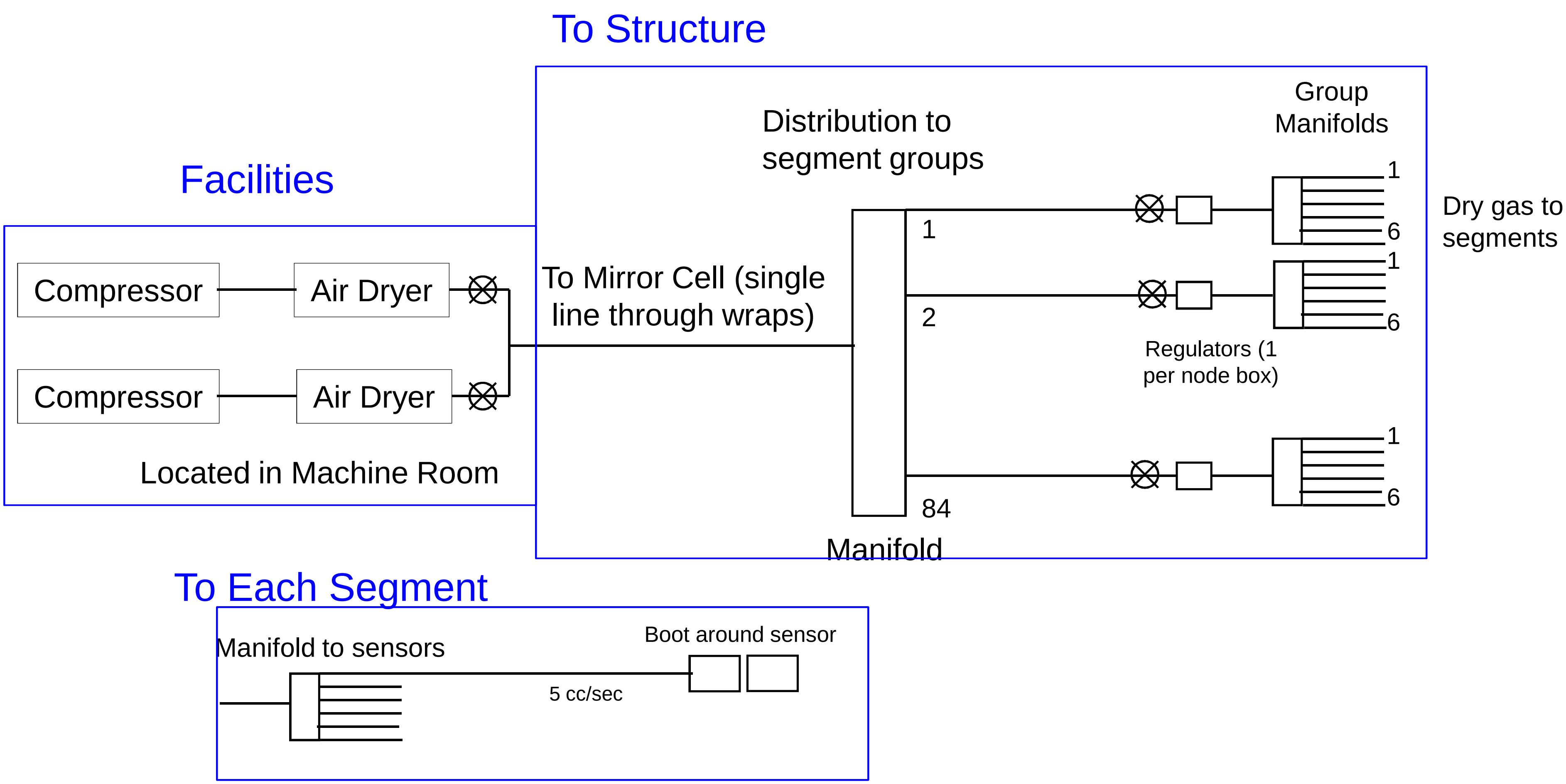
Interface to Optics Cleaning, Coating, and Handling

- Interfaces to optics cleaning and coating are handled through requirements in the Edge Sensor DRD
- Interfaces to the segment handling system are not yet developed. This is a minimal interface, as the sensors do not protrude significantly from the back of the segment.

Interface to structure

- The purge system plumbing interfaces to the telescope structure
  - Single large (1” dia) line through the cable wrap
  - Manifold on the telescope structure to deliver gas to regulators that serve groups of 6 segments
  - Regulator mounts
  - Smaller manifolds to deliver gas to the segments
  - Tubing routing to the manifolds and segments
- The required equipment and material is identified
- Detailed design of the interface will be done later as part of detailed cable routing design.

Purge System Interfaces

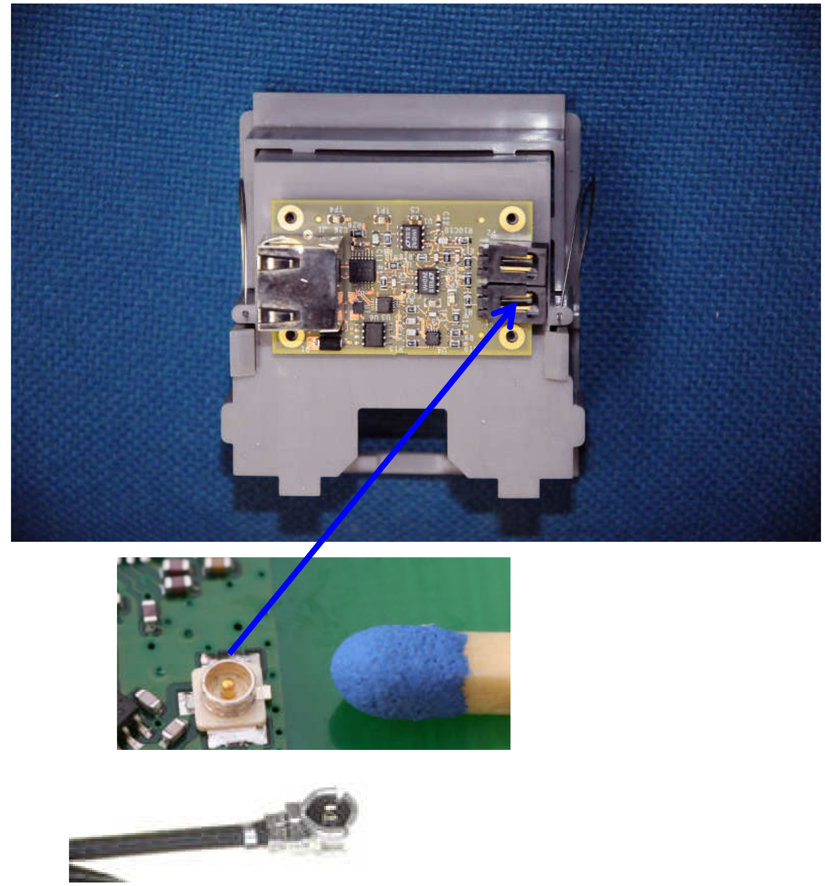


Interface to Facilities
Dry Purge Gas System
Footprint and Power:

	Make	Qty	Wid (in)	Len (in)	Ht (in)	Wt (lbs)	Power	Voltage	Notes
Compressor	Champion VRF7F-8-230	2	33	24	77	545	7.5 HP	230V 1- and 3- phase versions, 208 3-phase	This is significantly oversized, but lower capacity compressors don't have significantly smaller footprints.
Coalescing Filter	Aircel ACFH65D	2	4.5	4.5	10.5	4.5	0	n/a	Removes particles down to 0.01 micron and reduces oil to 0.003 ppm - extends life of the dessicant in the dessicant air dryer
Gas Dryer	Deltech HCT-40	2	32	32	46	365	not stated- heatless dryers use power for only for control and switching	available in 100 thru 240 V, 1-phase versions	
Total effective footprint:	6 ft x 6 ft + workspace or 3 ft x 12 ft + workspace 8 ft ceiling ok								

Interface to SCC

- The sensor interface to the Segment Controller and Cables is internal to M1CS (SCC is an element of M1CS)
- The interface occurs at the connections to the A/D and D/A electronics
- The interface is currently defined with the electronics boards attaching to bosses on the boots, and a small coaxial connector attaching to the boards
  - The connectors (both digital and analog) will be replaced with smaller connectors in a forthcoming design update.
  - The orientation of the board may be changed when the board size is reduced.
  - Changes to this interface will have minimal effect outside the M1CS (small change in mass of the boards)



Summary

- The critical external interface for the Sensor system to the M1 Segments is very well defined and controlled.
- The interface of the purge system is identified and a concept is defined.
  - The details of the interface will wait until the cable routing interfaces through the structure is being designed.
  - This will likely occur in tandem with SCC cable routing interface definition
- Other interfaces outside of the M1CS have been identified and developed as needed by the external systems.
- The interface to the SCC is identified and in development, and will be refined as the SCC is revised.

P10_Calibration: Algorithm, Performance, and Use Cases

Chris Shelton, Lewis Roberts

M1CS Sensor System Preliminary Design Review

Pasadena

March 29 - 30, 2012

Outline I

- Overview of Calibration
- Calibration Methodology
- Errors Corrected by Calibration
- The 6 Degree-of-Freedom A-Matrix
- Computing Shears from Gaps
- Simulation of M1CS and Calibration
- Parametric Studies
  - Default Values of Parameters
  - Standard Year Weighting
  - Calibration Error vs Number of APS Runs
  - Calibration Error vs Installation Error
- Break

Outline II

- The PSSN Impact of Sensor Temperature Coefficient
- The PSSN Impact of Sensor Flexure
- Calibration and Correlated Sensor Drift
  - Height Drift
  - Gap Drift
- Modeling Segment Replacement
- Conclusions
- Future Work
- Acknowledgements
- Backup Material
- References

Overview of Calibration

What is Edge Sensor Calibration?

- The TMT M1 edge sensors need to resolve 5 nm height differences in the presence of “in-plane” motions spanning a millimeter.
- If this is taken at face value, the sensors must be installed with an angular accuracy of 5 nm / 0.5 mm, or 10 µrad. This is difficult and costly when installing 5544 sensor halves.
- In 2007, Terry Mast, Jerry Nelson and Gary Chanan proposed using edge sensor gap readings to measure in-plane motions, and using this knowledge plus telescope phasing (APS) runs on bright stars to “calibrate” the as-installed sensors.
- “Calibration” means the sensor readings are corrected for in-plane motions, with relaxed sensor installation tolerances.
- Basing sensor corrections on in-plane motions should give a more fundamental and drift-free result than basing sensor corrections on zenith angle and temperature.
- Temperature gradients and extra flexure due to added loads or aging should generate no errors with this procedure.

Status of Calibration

- The calibration procedure and its simulated operation with M1CS are now fully fleshed out, and we have shown that M1CS can meet its requirements with attainable sensor installation errors.
- As other error sources have been identified, such as sensor sag with gravity, and sensor drift with temperature, the procedure has proven robust against these too, without modification.

M1 Active Control Geometry

Three actuators move each segment as a rigid body, in tip, tilt and piston.

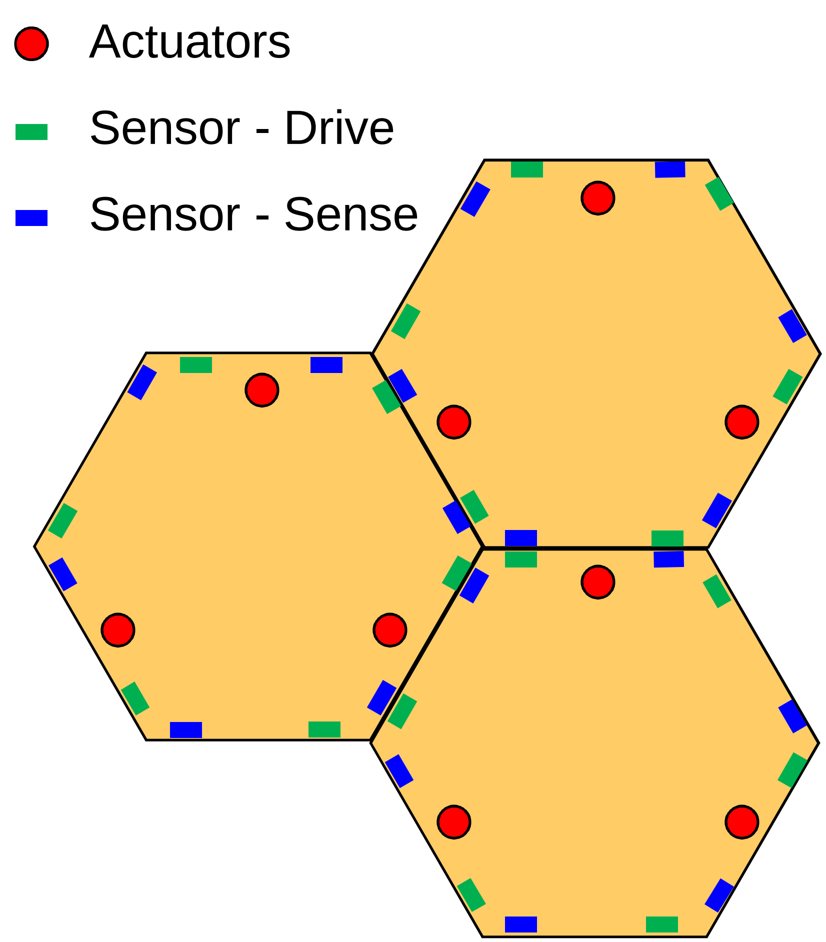
Edge sensors report on the relative position of neighboring segments.

A sensor has a drive half on one segment and a sense half on the other side of the gap between segments.

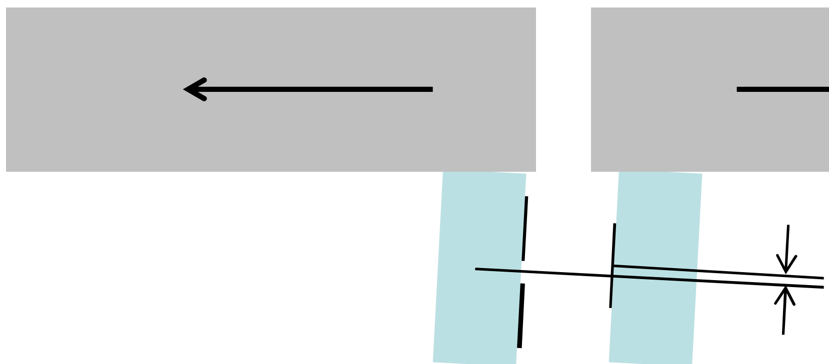
Each sensor has two output signals.

A “height” output is proportional to a combination of height and dihedral angle. The ratio of height to angle sensitivity is called the effective lever arm, or Leff.

A “gap” output measures the gap between the sensor halves.



An Example of the Need for Calibration

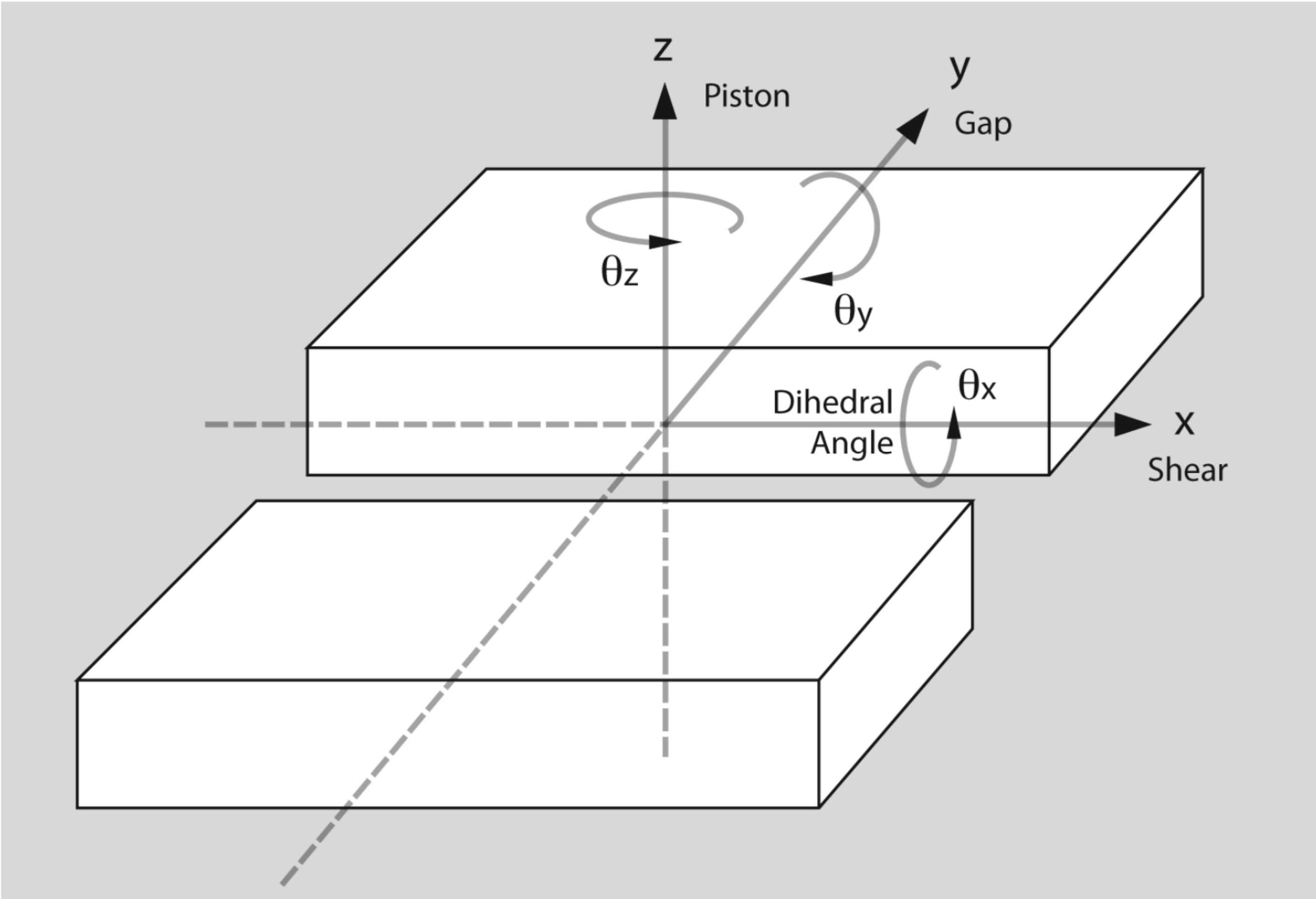


Thermal expansion of mirror cell moves segments apart

A sensor tilted because of installation errors gives a height reading with an offset that changes as the segments move apart

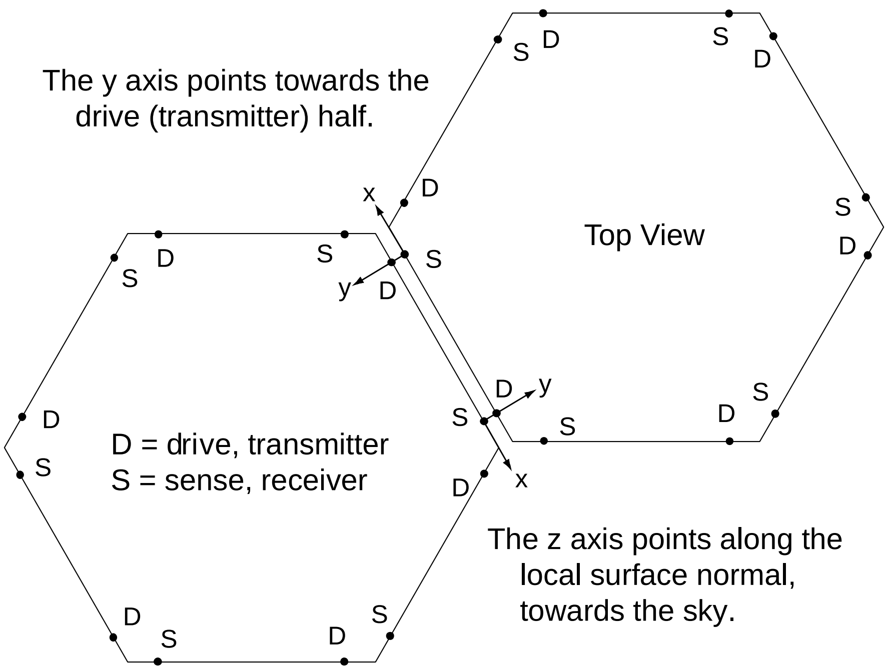
- Consider ordinary thermal expansion of the steel M1 support structure vs that of the zerodur mirror segments. By itself this gives a change in the gap between segments of 14.4 µm/C.
- If an edge sensor is mounted onto the mirror segments with a 1 mrad tilt, that edge sensor now has a 14.4 nm/C height error, but the need is for 1 nm/C or less, after calibration.

Segment to Segment Coordinate Definitions



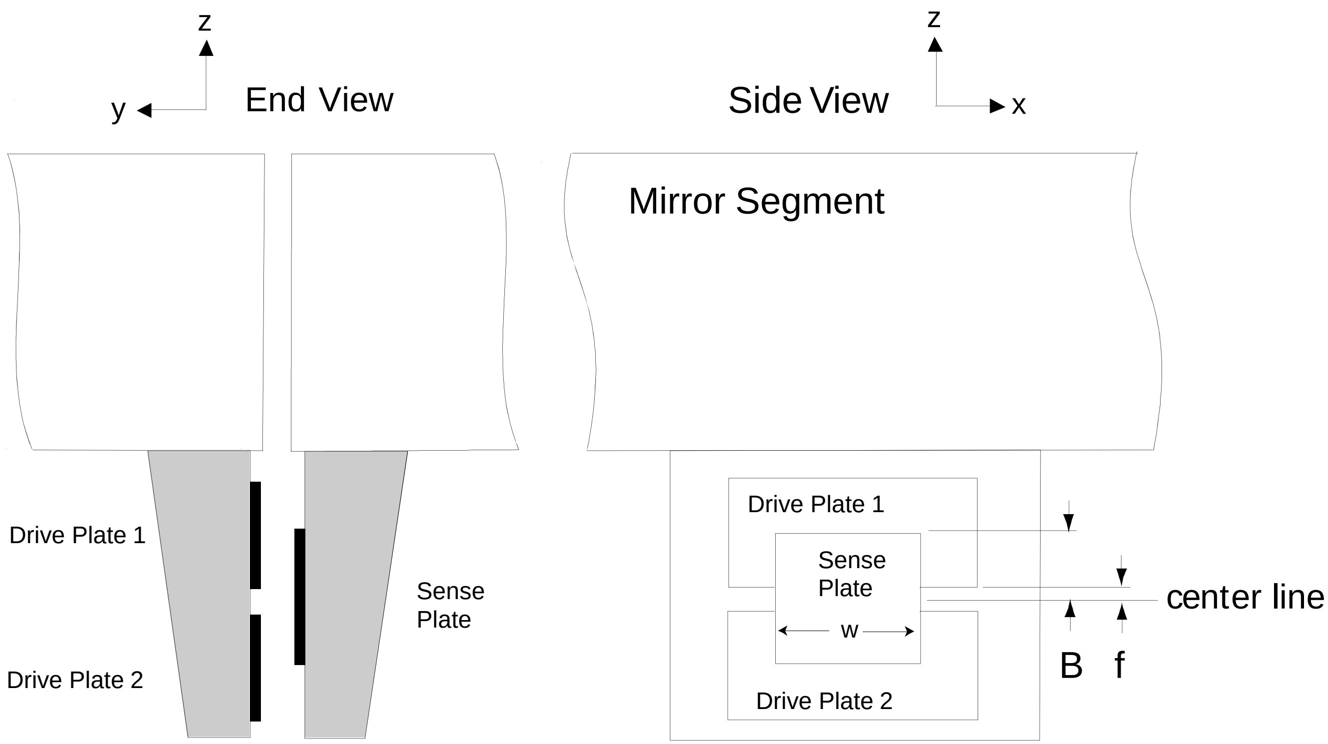
Sensor Coordinates, Piston, Gap and Shear

- Sensor-y points across the gap, from sense-side to drive-side. Sensor-x points along the segment edge. Sensor-z is the surface normal in the center of the gap, towards the sky.
- The distance from drive-side to sense-side along sensor-y is “gap”, and the mismatch along sensor-x is “shear”. The z difference is “piston” or “height”.
- Flexure, temperature and installation tolerances combine to make a sensor gap range of 4.8 +/- 1.0 mm.



TMT Capacitive Edge Sensor

Dimensions are for current 67 mm sensor



w	Sense plate effective width (30 mm)
2B	Sense plate effective height (45 mm)
2f	Effective spacing between drive plates (6 mm)
V	Drive amplitude (0 to 8.192 Vpp)

Capacitive Sensor Analytic Model

$$R = \frac{A}{y}\left(k(B - f) - z - x\theta_y + \frac{B^2 - f^2}{2y}\theta_x \right)$$

$A = \varepsilon_0 wV$ Square wave excitation

$A = 2\pi f_S \varepsilon_0 wV$ Sine wave excitation

$$L_{eff} = \frac{B^2 - f^2}{2y}$$

R	Sensor reading (coulombs for square wave, amperes for sine wave)
ε_0	8.854 10-12 farads / meter
w	Sense plate effective width (30 mm)
2B	Sense plate effective height (45 mm)
2f	Effective spacing between drive plates (6 mm)
y	Gap from drive to sense (4.8 +/- 1.0 mm)
V	Drive amplitude (0 to 8.192 Vpp)
fs	Drive frequency
θ_x, θ_y	Drive-side tip and tilt as seen from sense side
x,y,z	Coordinates of drive side as seen from sense side
k	= (Common-mode drive amplitude)/(Differential drive amplitude)

Dimensions are for current 67 mm sensor

Gap Compensation

- The edge sensor “height” output mixes height and dihedral angle sensitivity.
- Height and dihedral angle sensitivities have different dependencies on gap:

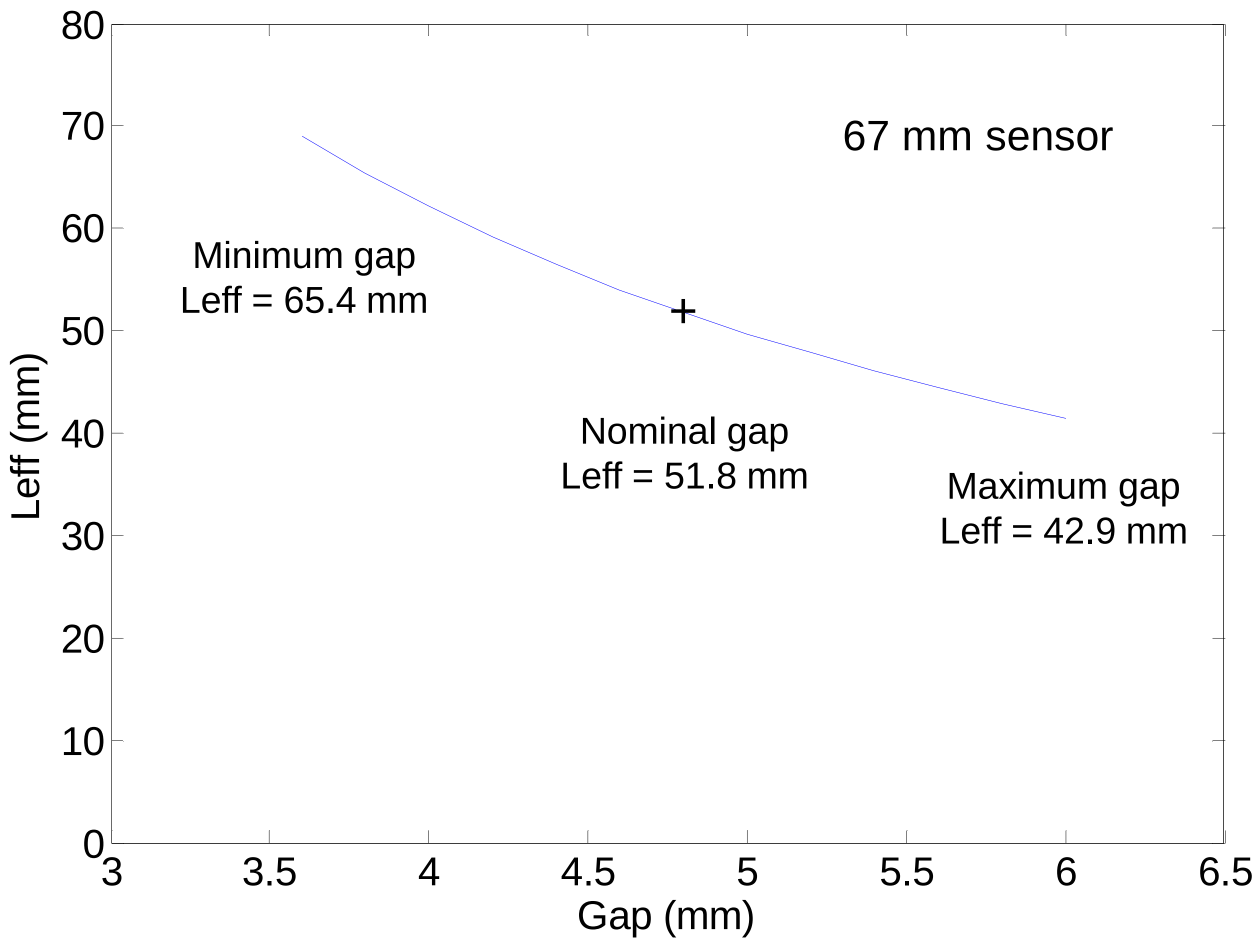
$$R = \frac{A}{gap} z + \frac{B}{gap^2} \theta_x$$

- “Gap compensation” means to use the gap reading to partially remove the gap dependence of the height reading.

$$R = \frac{gap^p}{A} \left(\frac{A}{gap} z + \frac{B}{gap^2} \theta_x \right)$$

- Setting the power p to 1 is the baseline gap compensation and is presented here.
- Setting p to 1.5 gives indication of improving calibration by about 30%. This and other proposed gap compensation concepts may in the future improve calibration performance.

Dihedral Angle Sensitivity vs Gap for Capacitive Edge Sensor



Calibration Methodology

Calibration Procedure Overview

- APS runs are performed at different zenith angles and telescope temperatures. This is to get diversity of gap and shear.
- When processing APS runs:
  - Each APS run gives a set of “desired sensor readings” and sensor gap readings, which are saved to a calibration database.
  - In the calibration database, sensor shear and segment in-plane positions are calculated from the gap readings and also saved.
  - The coefficients in a fitting equation are fit to the collection of desired sensor readings, gaps and shears from all APS runs, and saved.
- During observing:
  - Sensor shear is calculated from sensor gap readings.
  - The gap and shear data are put into the fitting equation with the saved calibration coefficients.
  - The resulting corrections are applied to sensor height readings.

Fitting Functions

- A fitting function computes a correction to sensor readings from fit coefficients times observables such as a gap, shear, 1/gap, gap_mean, zenith_angle.
- The basic fitting function, used when fitting four or more APS runs, has a constant, a gap term and a shear term for each sensor:

$$Reading\ correction = C_0 + C_1 * gap + C_2 * shear$$

- With one APS run, there is nothing to fit – the reading correction from the single APS run becomes the constant term, which is the only term.
- For two and three APS runs, specialized fit equations have been devised. These and the full set of fit types that have been tested are discussed in backup slides.
- Better fit functions may be developed in future work.

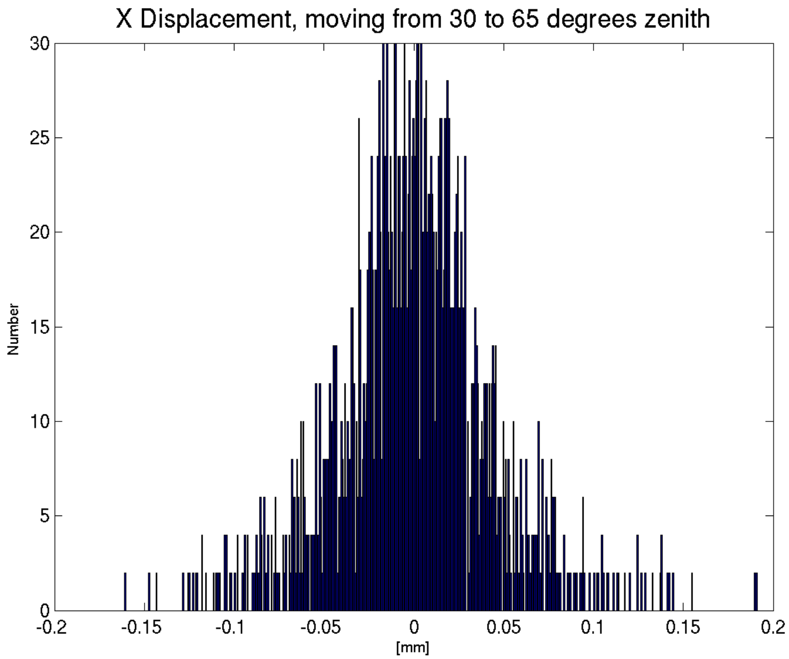
Errors Corrected by Calibration

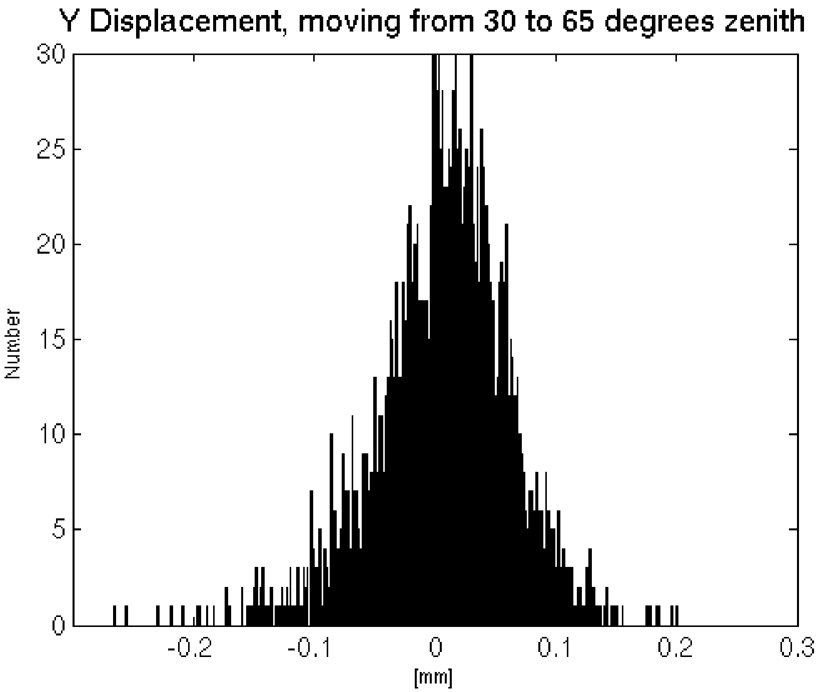
The Magnitude of Errors Corrected

- Sensor installation errors are dominant
  - These interact with segment installation errors, structure thermal expansion, and structure deformation from gravity.
  - The current expected theta_x installation error is 0.5 mrad rms.
  - In-plane motions with zenith angle are 50 µm rms, 270 µm peak
  - The combination gives height reading errors of 25 nm rms, 135 nm peak, which translates to an OPD error of 425 nm rms, 2300 nm peak.
- Sensor temperature coefficients up to 12 nm/C is modeled and corrected.
- Sensor flexure with gravity can give up to 12 nm pv of OPD, if not corrected. This small effect is essentially eliminated in calibration.
- Non-spherical segments which are clocked or translated give a figure error, and an edge height difference of up to 150 nm.
  - A simple model of warping is included in the simulation to account for the interaction this has with calibration.

Shear and Gap In-plane Motions Changing Zenith from 30 to 65 Deg.

When changing zenith angle from 30 to 65 degrees, in-plane motions due to gravity are +/- 270 microns peak, 35-55 microns RMS. Motions from 30 to 0 degrees are of similar magnitude.





Motions due to temperature are another +/- 150 microns, are mostly in gap. Segment installation tolerances can contribute up to a millimeter of static offsets.

Modeling Temperature

- The current temperature model is simple:
  - Global thermal expansion of segment locations at the temperature coefficient of expansion of steel, 11.6 ppm/C.
  - Items fixed to the zerodur segments move with the segments.
  - Segments undergo thermal clocking at 6.8 µrad/C, in a direction that depends on sector. The segments in sectors A,C,E clock in positive θ_z, where z is the segment center skyward normal. The segments in sectors B,D,F clock in negative θ_z.
- Future extensions of the temperature model to include gradients will occur in the FEA model, and the results imported into this simulation just as the current gravity-only FEA results.

Modeling Sensor Gravity Deformation

- Locate a pivot point on pocket surface of block
- Define a surface normal **n**
- Model a rigid body rotation of 2.25 µrad zenith to horizon, i.e.,

  $\theta = 2.25\ \mu\text{rad} \times \mathbf{n \cdot g}$

- This gives the same height change as a SolidWorks model of deformation

  $\delta z = 38\ \text{mm} \times 2.25\ \mu\text{rad} \times \sin(15)$

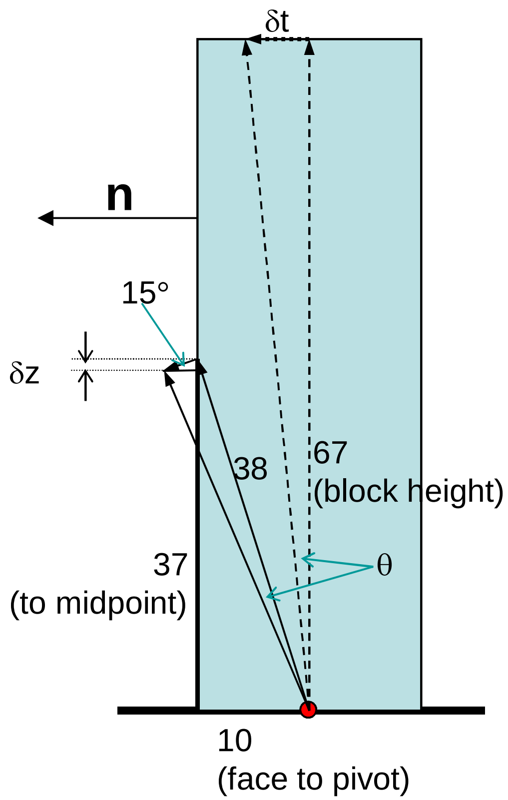
  $\delta z = 22\ \text{nm}$

- And is also very close on the motion of the top of the block:

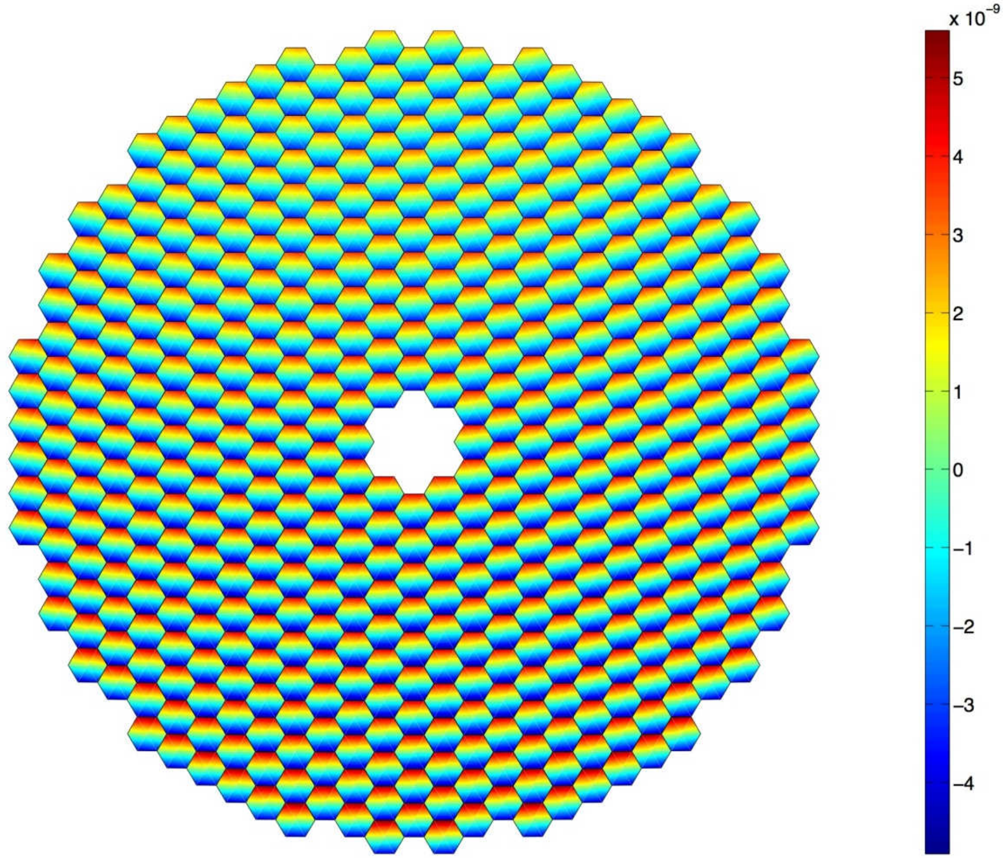
  $\delta t = 67\ \text{mm} \times 2.25\ \mu\text{rad} = 150\ \text{nm}$

- The change in sensor reading is

  $\delta R = 2 * 22\text{nm} + \theta \times \text{gap} = 55\ \text{nm}$

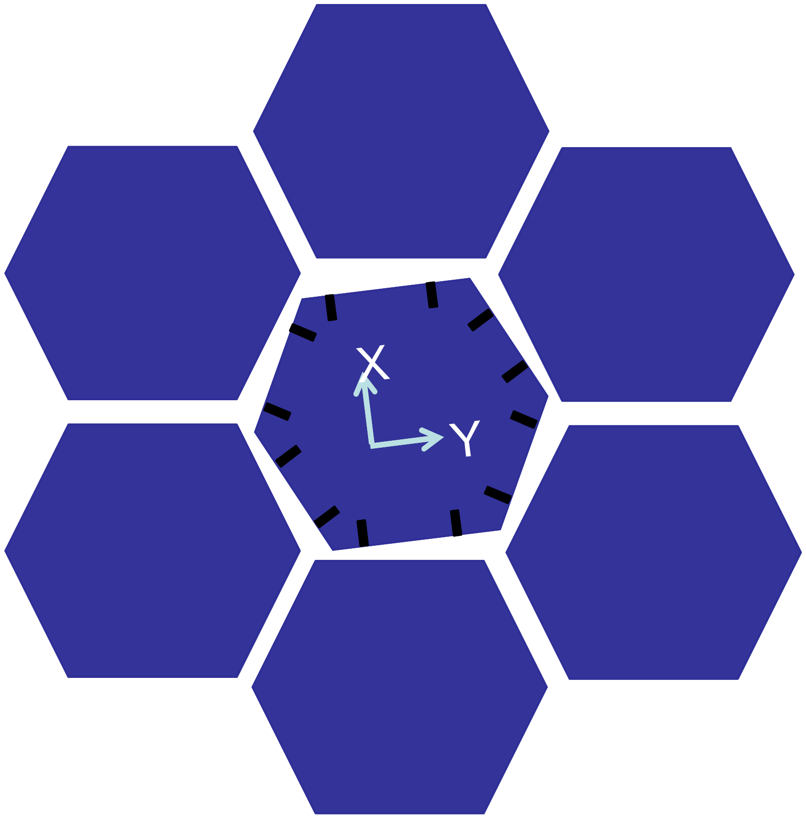


OPD from Sensor Flexure

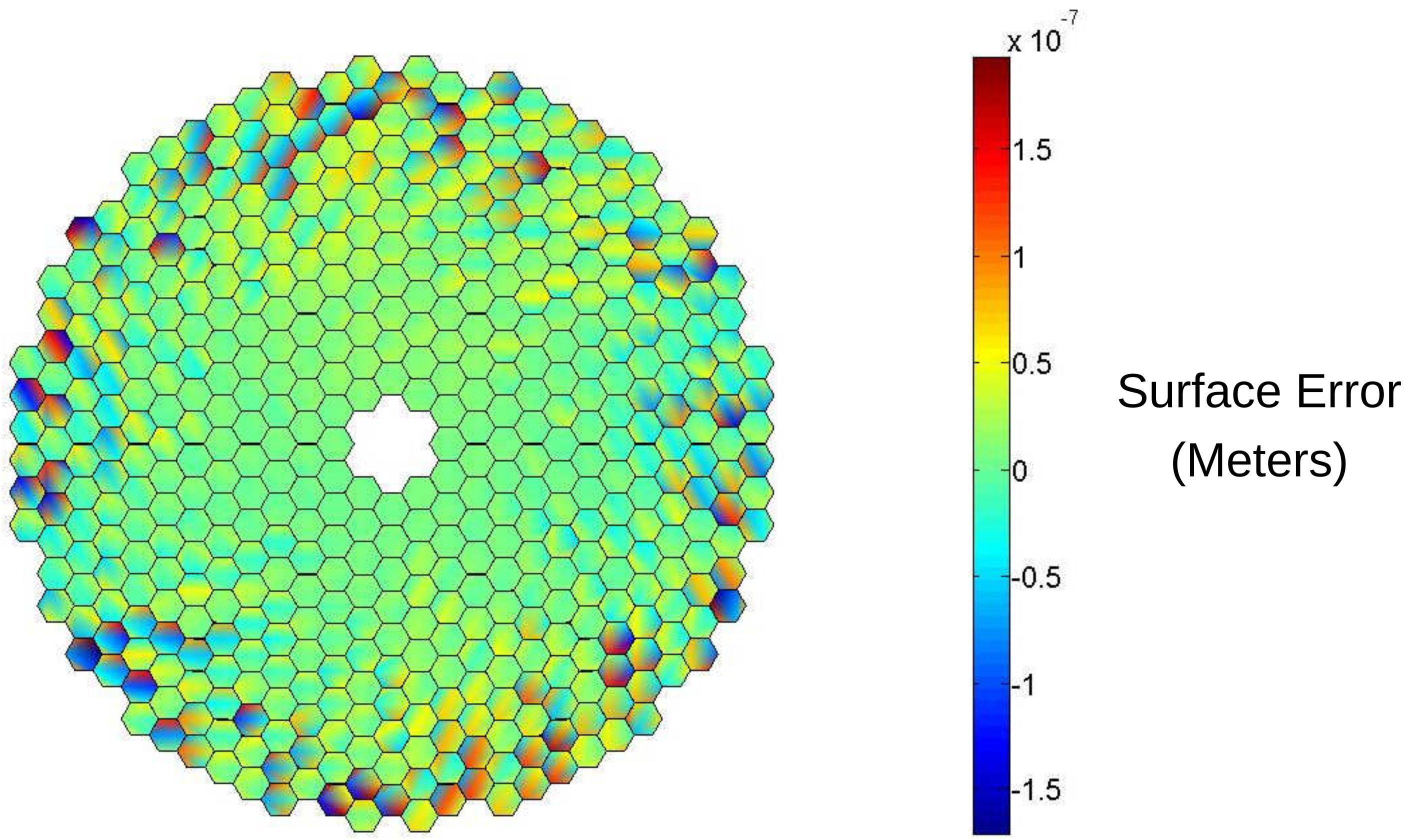


- An OPD of 12 nm pv results from going from 30 deg to 65 deg zenith, on an otherwise perfect mirror.

- Segment clocking of outer segments creates astigmatism which is corrected by warping the segment at one zenith angle and temperature.
- Calibration then improves performance at other zenith angles and temperatures.
- Since sensors move when the segment warps, re-warping implies re-calibrating.



Effect of Segment Clocking-- Surface Error before Warping



Includes segment in-plane installation errors, but segments are assumed to be perfect

The 6 Degree-of-Freedom A-Matrix

The 6 Degree-of-Freedom A-matrix

- The 6DOF A-matrix express how segment motions in all six degrees of freedom affect edge sensor height, gap and shear.
- Segment out-of-plane motions are tip, tilt and piston. These are controlled by actuators.
- Segment in-plane motions are inplane_X, inplane_Y and clocking. These are caused by gravity deformation and temperature changes, plus initial in-plane positions are subject to segment installation errors.

$$\begin{pmatrix} height \\ gap \\ shear \end{pmatrix} = A_{6DOF} \begin{pmatrix} tip \\ tilt \\ piston \\ inplane\_X \\ inplane\_Y \\ clocking \end{pmatrix}$$

The Need for the 6DOF A-matrix

- The 6 DOF A-matrix plays a major role in analyzing calibration, control stability and focus mode, in comparing TMT and ESO methodology, and is necessary for the gap-to-shear transformation.
- The 6 DOF A-matrix provides a rigorous 3-D model of the M1 geometry for controls analysis.
- It has a full set of inputs:
  - Ideal M1 geometry
  - Merit-Function-generated segment, vertex, sensor and actuator locations and orientations
  - Gravity deformations
  - Temperature expansion
  - Segment installation error
  - Sensor installation error
  - Sensor gravity flexure
  - Sensor temperature coefficient

The Parts of the 6DOF A-Matrix

Standard 3D A-Matrix → (first cell)

Height per actuator stroke	Height per inplane X, Y	Height per segment clocking
Gap per actuator stroke	Gap per inplane X, Y	Gap per segment clocking
Shear per actuator stroke	Shear per inplane X, Y	Shear per segment clocking

← G Matrix (Gap per inplane X, Y; Gap per segment clocking)

← H Matrix (Shear per inplane X, Y; Shear per segment clocking)

The 6 DOF A-matrix is created by moving each segment slightly in each of its 6 degrees of freedom, while observing the effect on sensor height, gap and shear readings.

Computing Shears from Gaps

Obtaining Shear Data

- Calibration requires a knowledge both of gap and shear aspects of the in-plane segment motions. The TMT baseline sensor provides a gap output, but not a shear output.
- Shear data can be measured with shear sensing (ESO approach), or computed from gap data (TMT approach).
- The procedure for computing shears from gaps [Ref 15] is summarized in the next slide. It uses the G and H matrices just defined.
- The procedure works well, and has the side benefit of filtering out the unphysical part of gap noise. In simulation, the measured noise multiplier agrees with the theoretical value.

Computing Shears from Gaps

- Gap readings, called here $y_{measured}$, can be turned into best-fit sensor x (shear) and y (gap) offsets as follows --

$$x_{calculated} = HG^{\dagger} y_{measured}$$

$$y_{calculated} = GG^{\dagger} y_{measured}$$

- G is a constant matrix connecting segment coordinates to sensor-y coordinates. $G^{\dagger}$ is the pseudo-inverse of G. H connects segment coordinates to sensor-x coordinates.
- For details, see Gary Chanan, “Segment In-Plane Position Sensing”, TMT.CTR.PRE.07.019.REL01 (2007).

Torsion Mode

- There is one unobservable mode, “torsion mode”, which is lost in computing shear from gap [Ref 7]. It is the mean clocking of all segments.
- Because of its symmetry, the complete M1 shows very low mean clocking of segments. However, with one dead segment, for example, there is mean clocking of (6.8/492) µrad/C. Estimating the consequences of this is future work.
- If torsion mode does need to be observed, a single or a very few shear sensors are sufficient to bring the torsion mode noise multiplier in line with other modes.
- Adding shear sensing to the current design would require modifying the drive side and firmware only. The resulting shear-capable drive-side assembly would be a drop-in replacement. There would be no sense-side or cabling changes.
- The added cost to do this for one or a few edge sensors is low.

Simulation of M1CS and Calibration

Simulation Overview

- The M1CS Simulation unifies previously separate calibration and A-matrix codes, and connects tightly with TMT databases and FEA modeling.
- It is a time-domain simulation, capable of modeling non-linear effects such as sensor and actuator saturation.
- The positions and orientations of all M1CS elements are tracked, with rigorous handling of all rotations and translations.
- The intent is that these routines evolve into the deliverable Matlab routines to the GLC effort. Some pieces will become actual GLC code, and some pieces will become telescope simulation stubs for GLC code

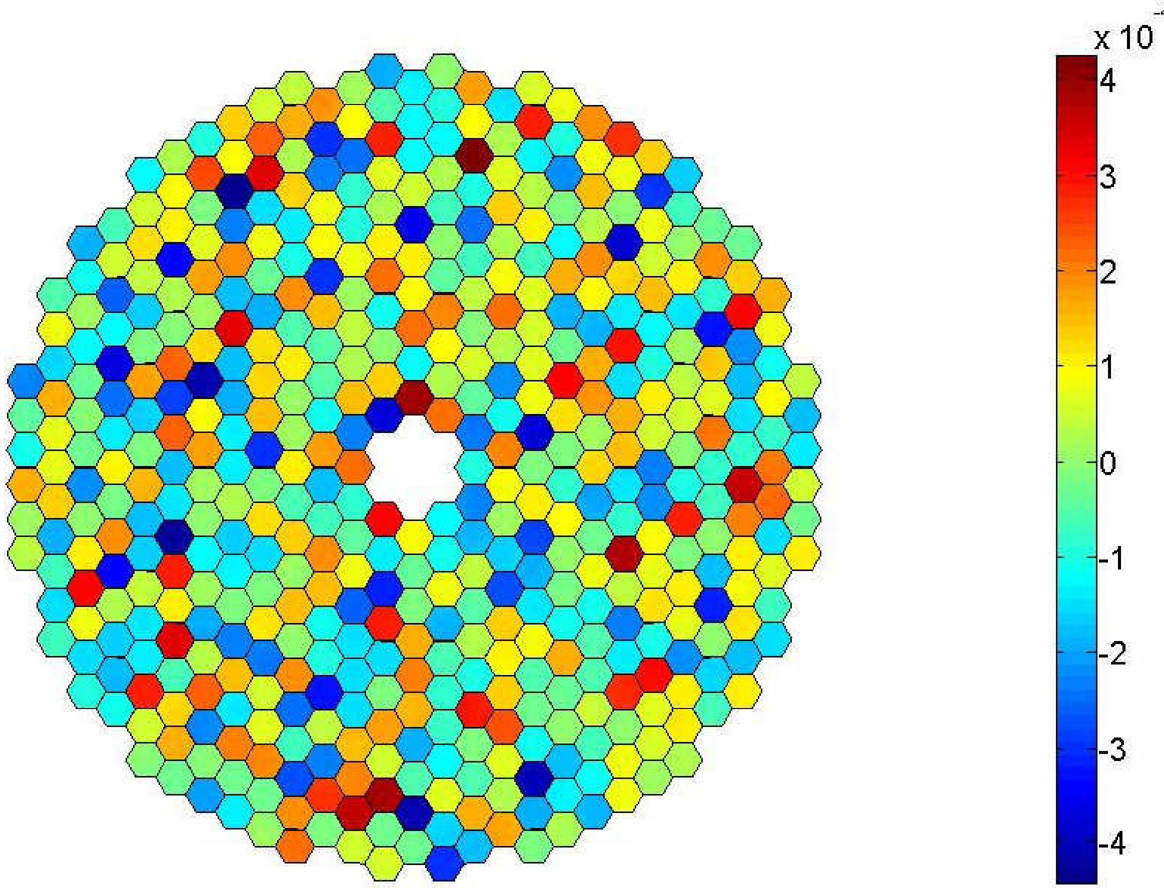
Calibration and Simulation Features

- The M1CS simulation model imports irregular segments from the TMT Segmentation Database. Sensor and actuator locations are also imported, in 3D, rather than calculated.
- All math is fully general, with no small angle approximations. Full 3x3 rotation matrices are used.
- The full 6DOF A-matrix is evaluated.
  - Enables computing shears from gaps for the 3D mirror with irregular hexagons.
  - Allows comparison with E-ELT control techniques.
- For modeling gravity deformations, 2010/10/22 FEA data imported in a true 3D format can be selected, or 2008 FEA data imported in a 2D projection.

Calibration and Simulation More Features

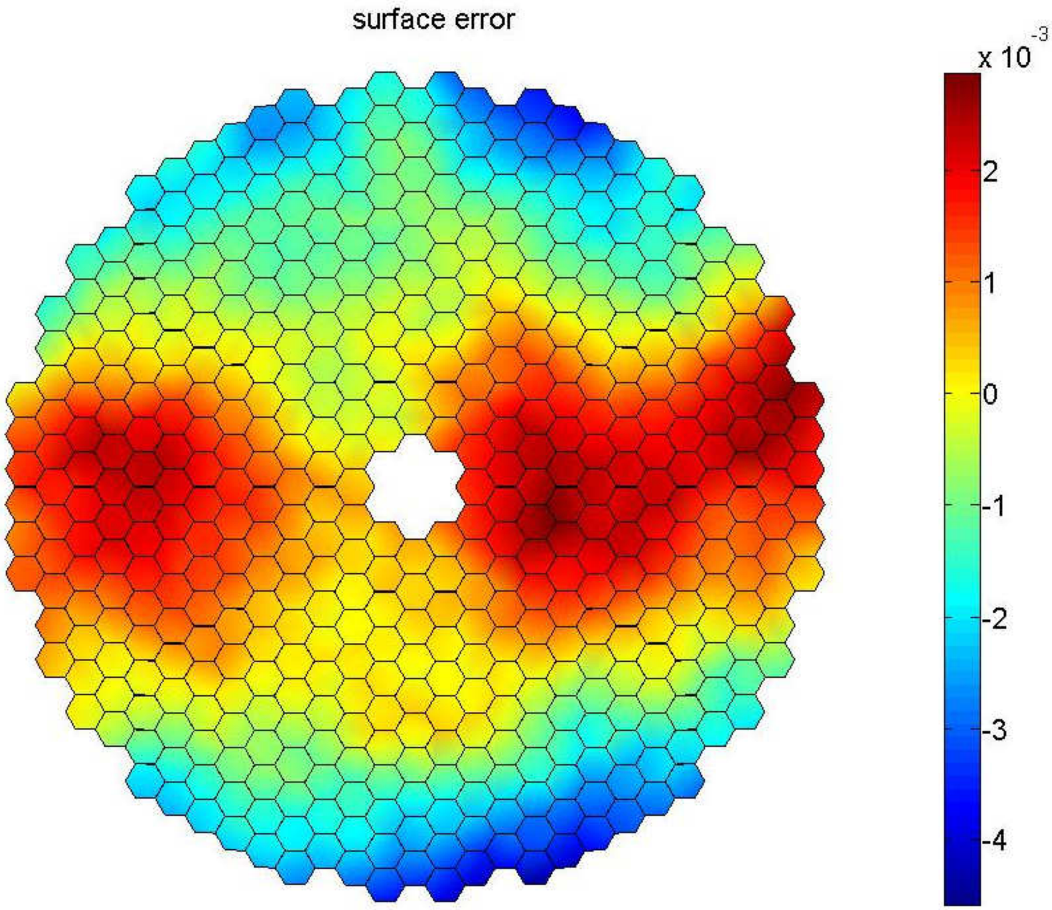
- Closed loop feedback from an AGWFS
  - This corrects a selectable number of zernike aberrations, starting with focus.
  - For this presentation, all PSSN results include correction of Zernike/Noll modes 4 through 11 unless stated otherwise.
- Thermal clocking of segments
- Sensor flexure and sensor temperature coefficient
- Various schemes for fitting calibration parameters to APS data have been evaluated.
- Closed Loop Simulation of M1CS
  - On-the-fly changes in the system response (A-matrix) with zenith/temperature are accurately modeled.
  - Allows investigation of how often control matrix and calibration changes need be applied.
  - Allows study of M1CS behavior with non-linear effects, such as sensor and actuator saturation.

Surface Error at Initial Segment Installation



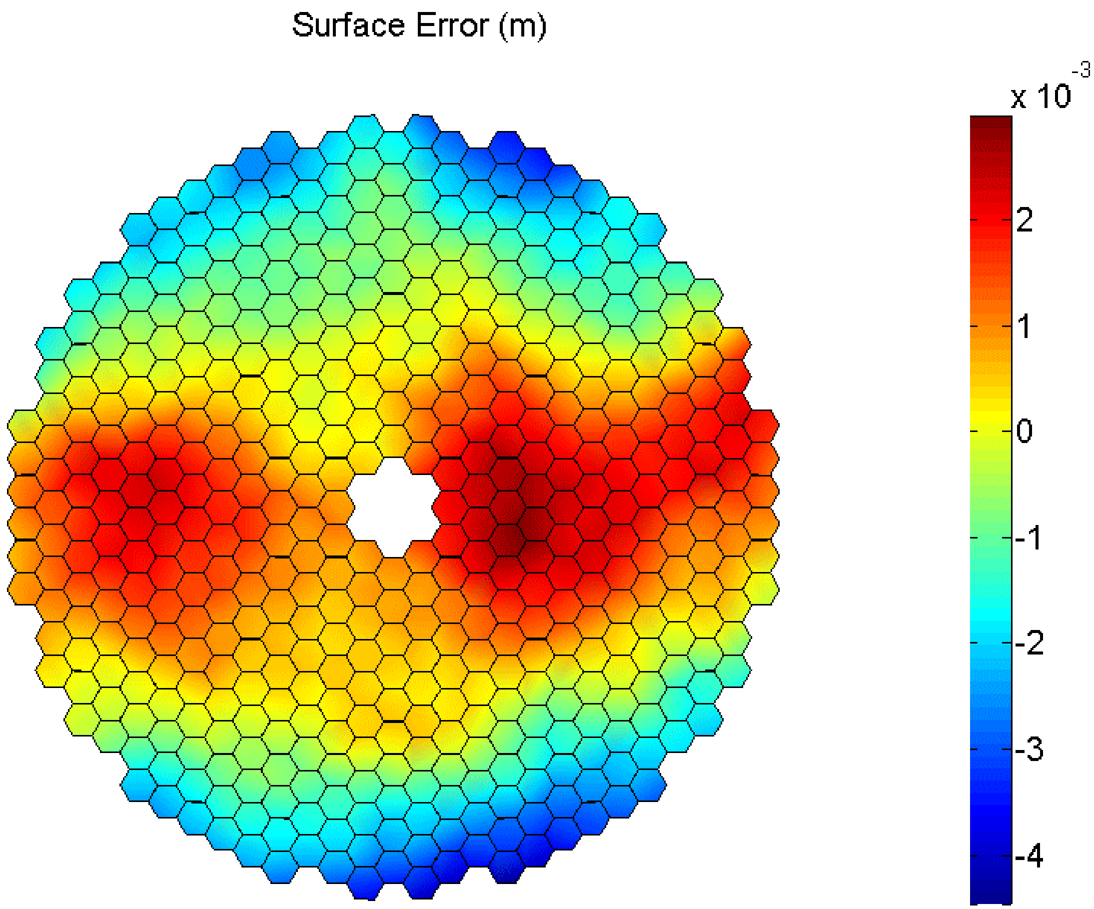
Surface Error (Meters)

Surface Error, M1CS on, with no APS or Calibration



Surface Error (Meters)

APS Movie



Parametric Studies –
Default Values of Parameters

Default Values for Parametric Studies I

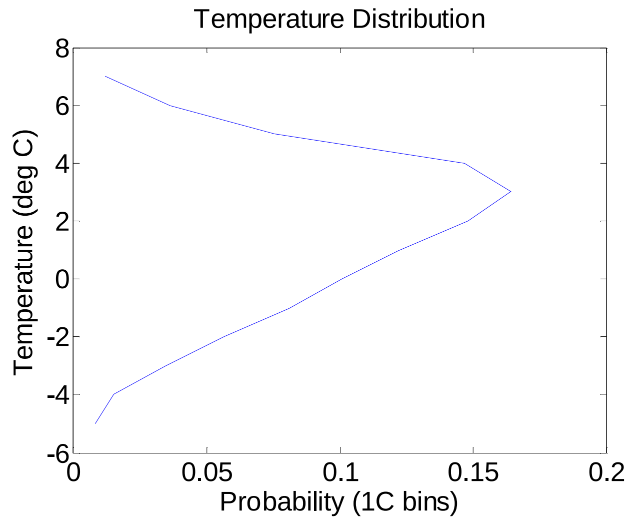
Parameters	Value	Source
Segment Install Errors	σ_x = 200 µm σ_y= 200 µm σ_z= 200 µm $\sigma_{clocking}$ = 285 µrad	TMT.OPT.DRD.07.007.DRF06 Current all-inclusive estimate.
Sensor Install errors	Nominals: $\sigma_{\theta x}$= 0.5 mrad $\sigma_{\theta y}$= 0.3 mrad Parametric scan: $\sigma_{\theta x}$= $\sigma_{\theta y}$= 0.2, 0.5, 1.0, 2, 3 mrad	TMT.CTR.PRE.11.042.DRF05 Drive and Sense errors are the same. These numbers are 1 sigma. They are approximately half of the not-to-exceed requirements.
Sensor Noise for Calibration Purposes	σ_h= 1 nm rms σ_g= 300 nm rms	These include several seconds of averaging.
APS Noise	Modeled as 10.4 nm rms random error in desired sensor readings.	The error magnitude was adjusted to match the PSSN of the APS model.

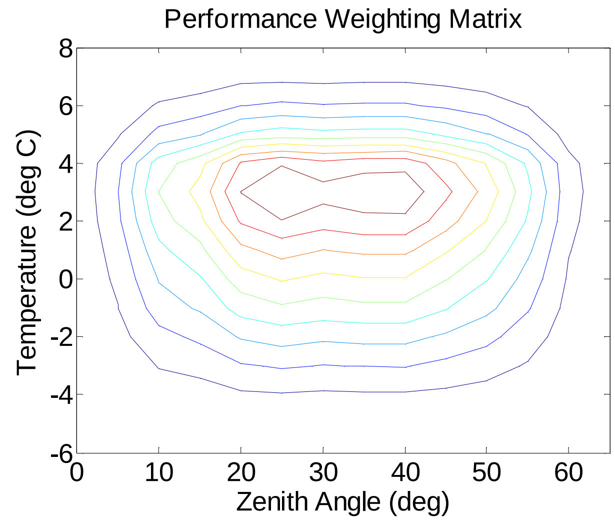
Default Values for Parametric Studies II

Parameters	Value	Source
Finite Element Model	2010 10 22 FEA	TMT.SEN.TEC.11.002.REL01
Sensor flexure magnitude	2.25 µrad zenith to horizon	FEM modeling
Sensor flexure effective pivot location	10 mm behind sensor face in contact plane with segment	FEM modeling
Zernike modes corrected by optical feedback from AGWFS	4 through 11 in Noll numbering	Placeholder
Sensor type	67 mm tall sensor	
Sensor temperature coefficient	0 nm/C	
Gap compensation exponent “p”	1.0	
Fitting equation	Fit type 13: constant, gap, shear	

Parametric Studies –
Standard Year Weighting

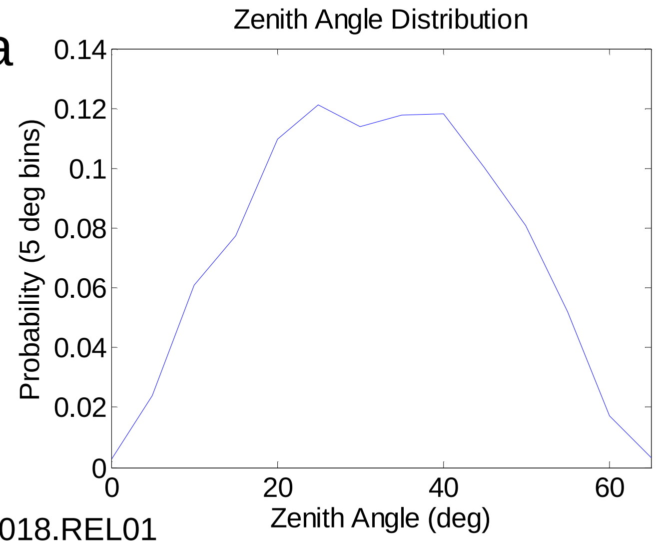
Performance Metrics are Weighted by Standard Year Experience



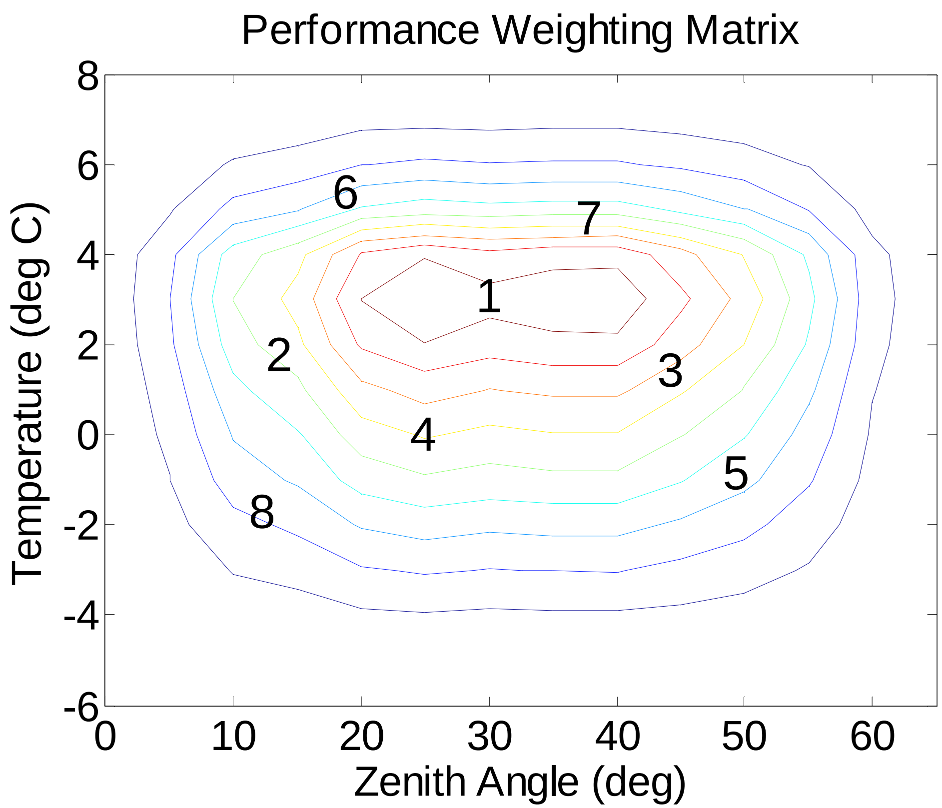


The TMT Standard Year [Ref 16] is a record of Mauna Kea temperatures and Gemini North pointing from 6/29/2006 to 6/1/2008.

These probability distributions were computed from this record.



Use Cases: APS Runs for Evaluating Performance



Each use case adds one APS run at a time in the above sequence. These cases are the assumed zenith angles and temperatures in evaluating candidate calibration procedures.

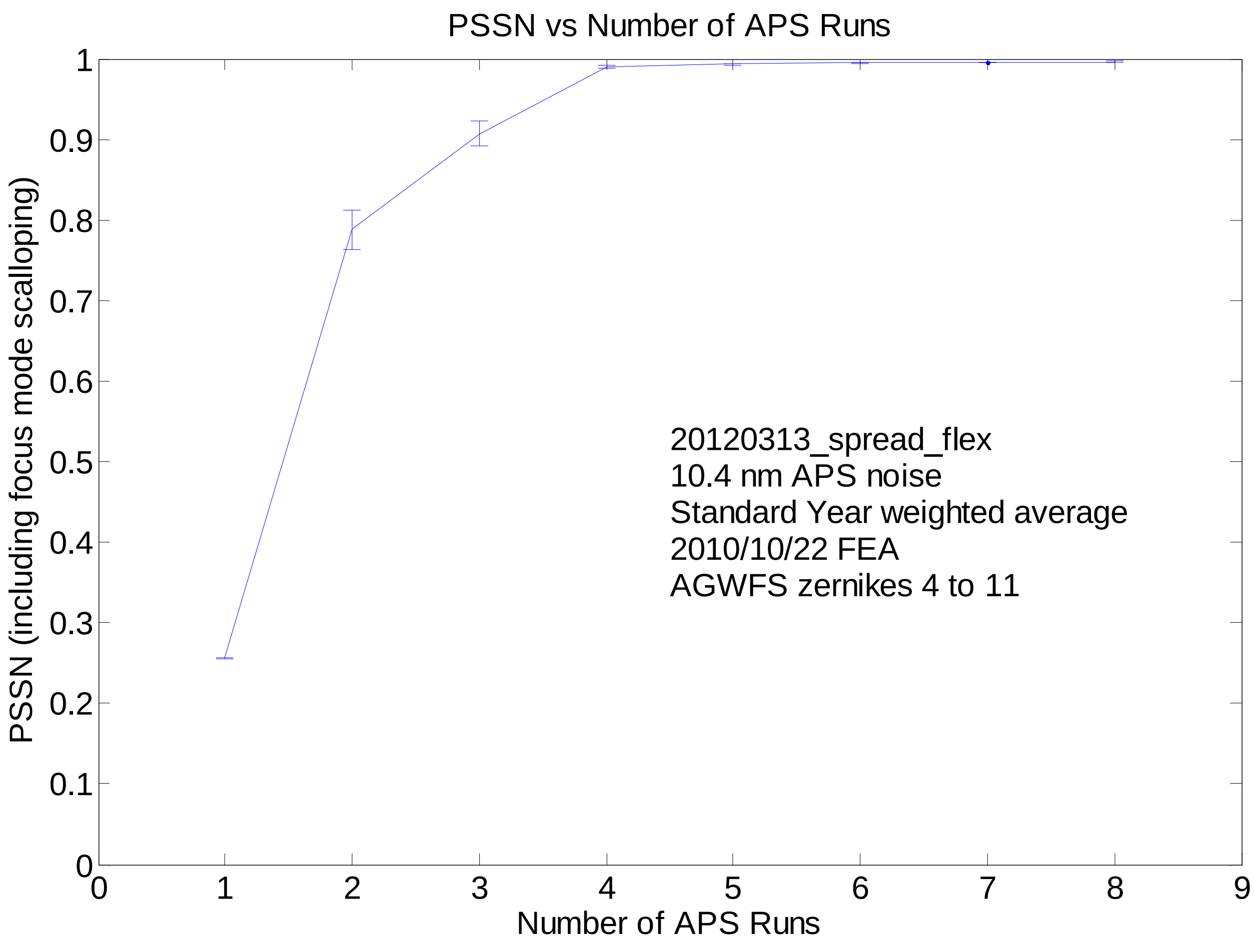
Parametric Studies –

Calibration Error vs Number of APS Runs

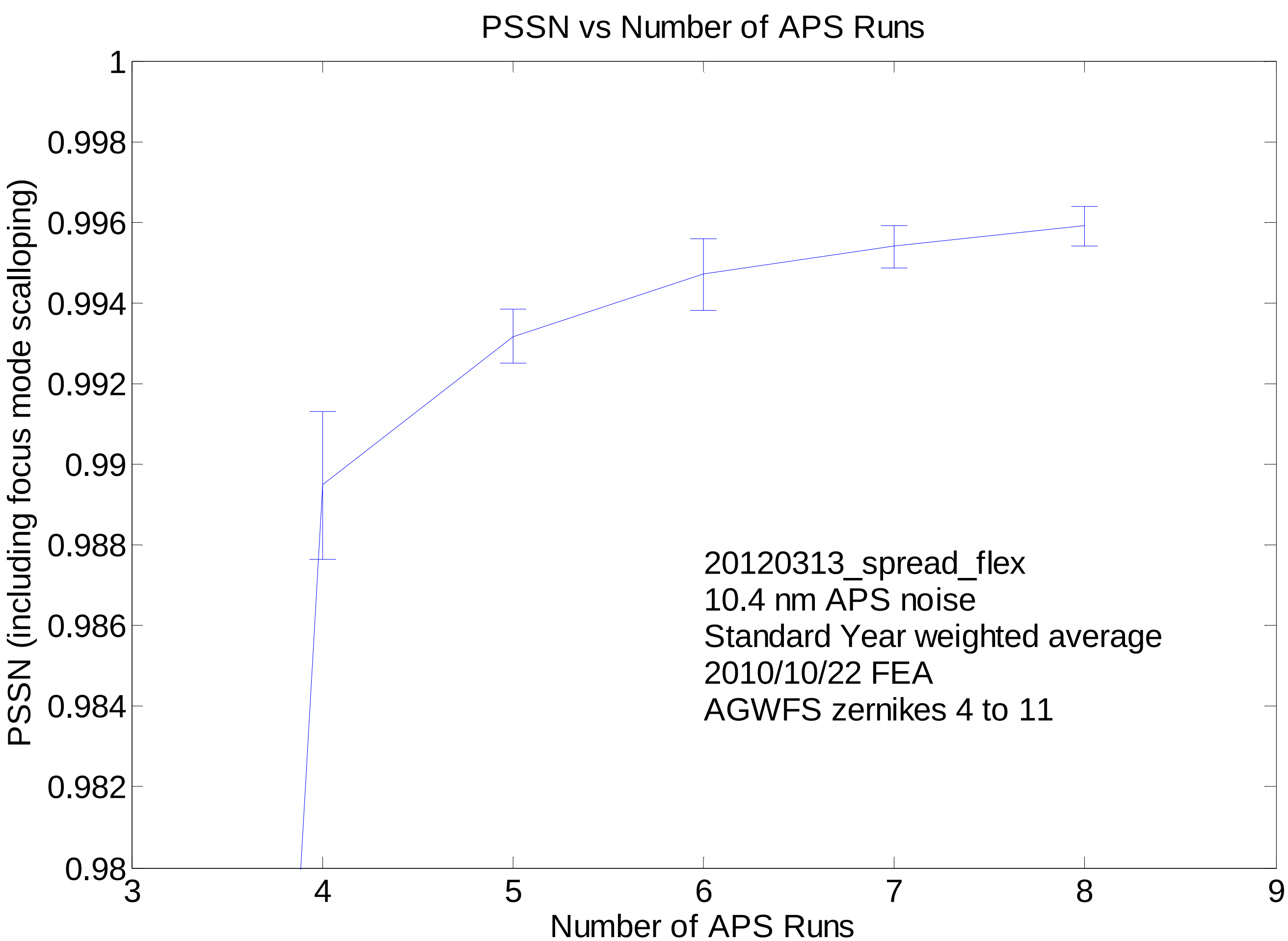
Calibration Error vs Number of APS Runs

- "Calibration Error" is the PSSN impact of having less-than-ideal desired sensor readings.
- Calibration PSSN incorporates four effects, with these current allocations in error budget
  - APS noise 0.9955
  - "Sensor Calibration" 0.998
  - Thermal clocking: 0.99984 (dT = 4K)
  - Decenter: 0.99956 (30→60 deg ZA)
- The product of these is PSSN = 0.9929
  - This is the "good enough" level for the simulations to follow.
- The vertical bars show the spread in results when different random seeds are used in the simulation.
- Any parameter values not annotated have their default values.

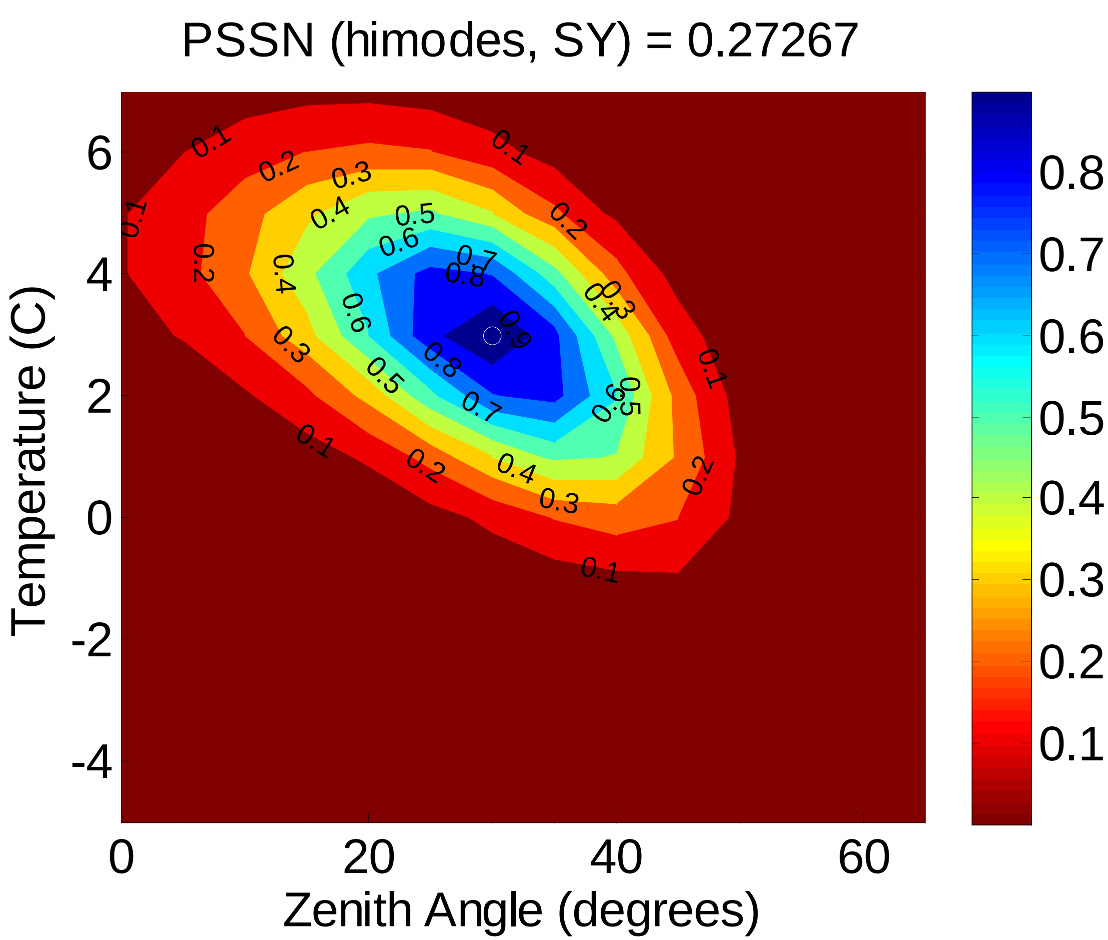
Calibration PSSN vs Number of APS Runs



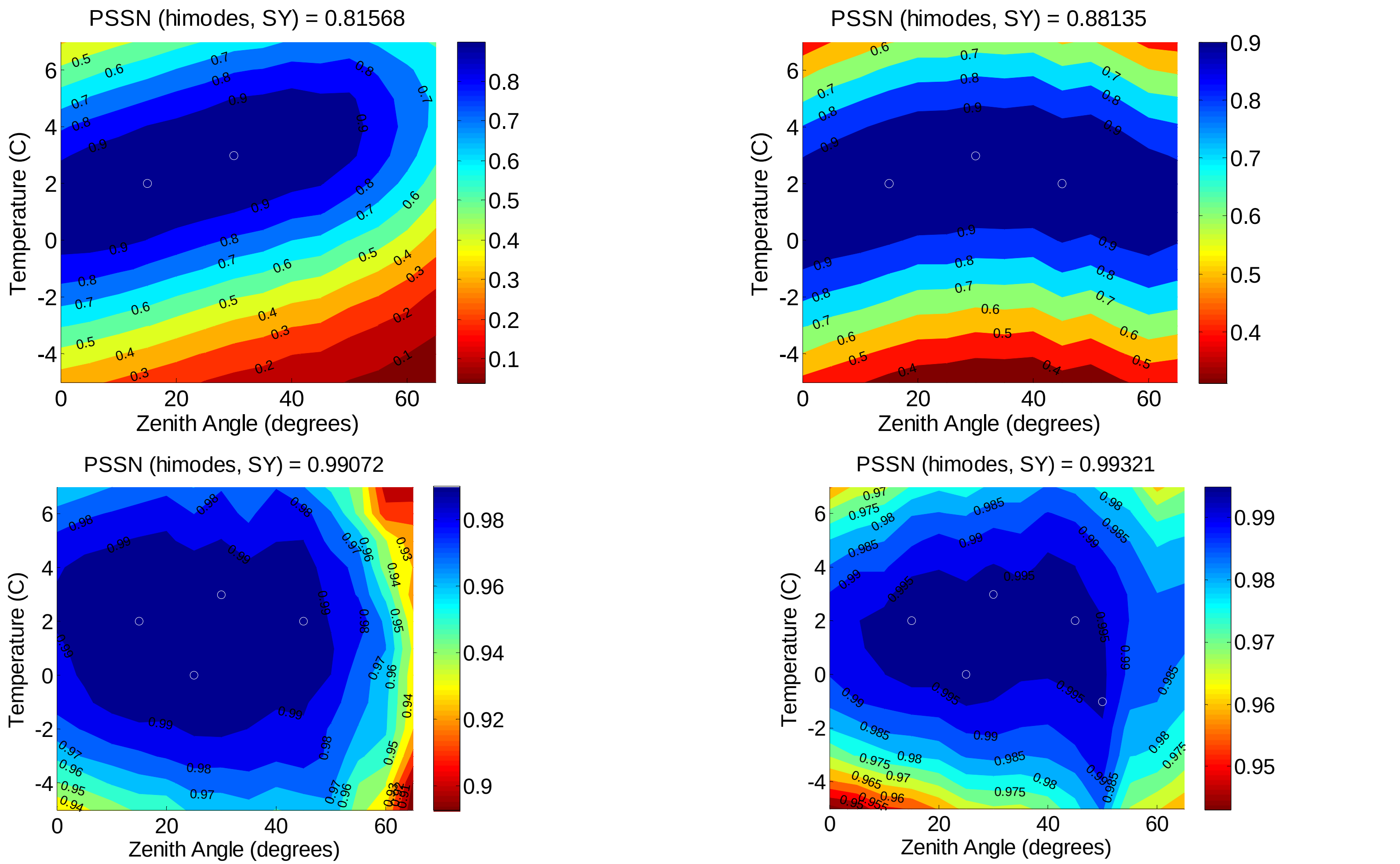
Calibration PSSN vs Number of APS Runs - Detail



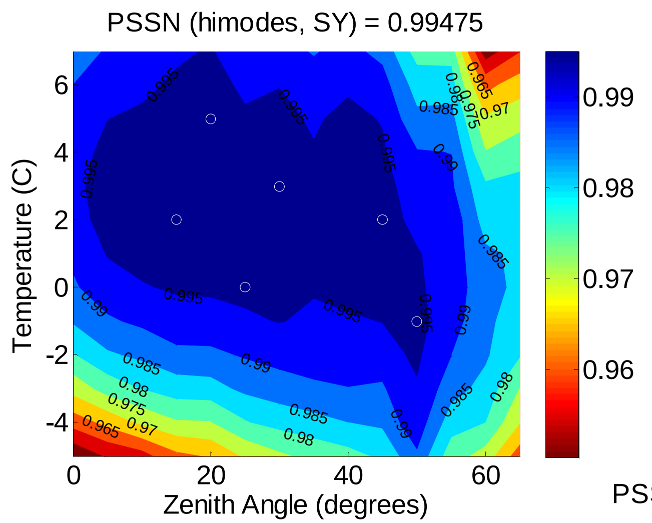
PSSN vs Zenith Angle and Temperature for 1 APS Run

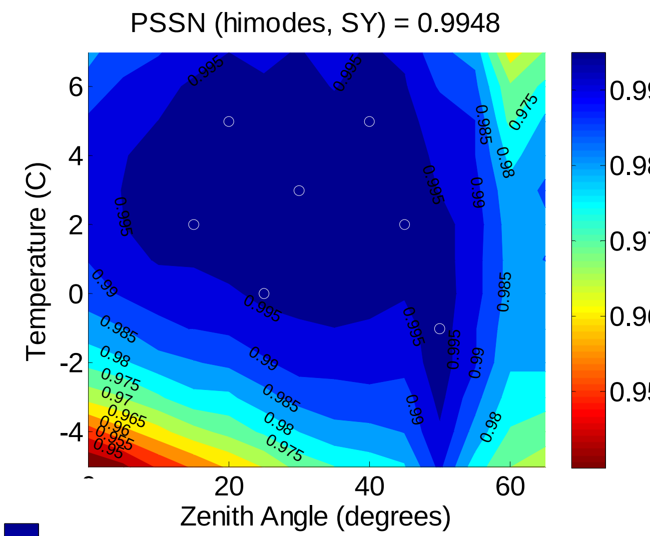


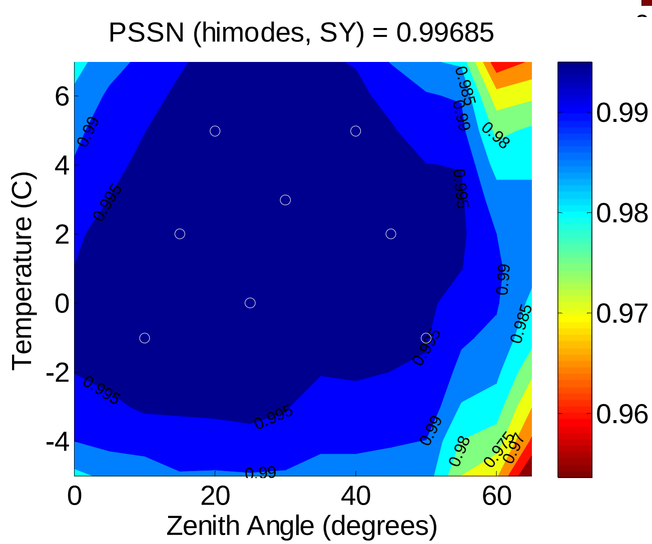
PSSN vs Zenith Angle and Temperature for 2-5 APS Runs



PSSN vs Zenith Angle and Temperature for 6-8 APS Runs





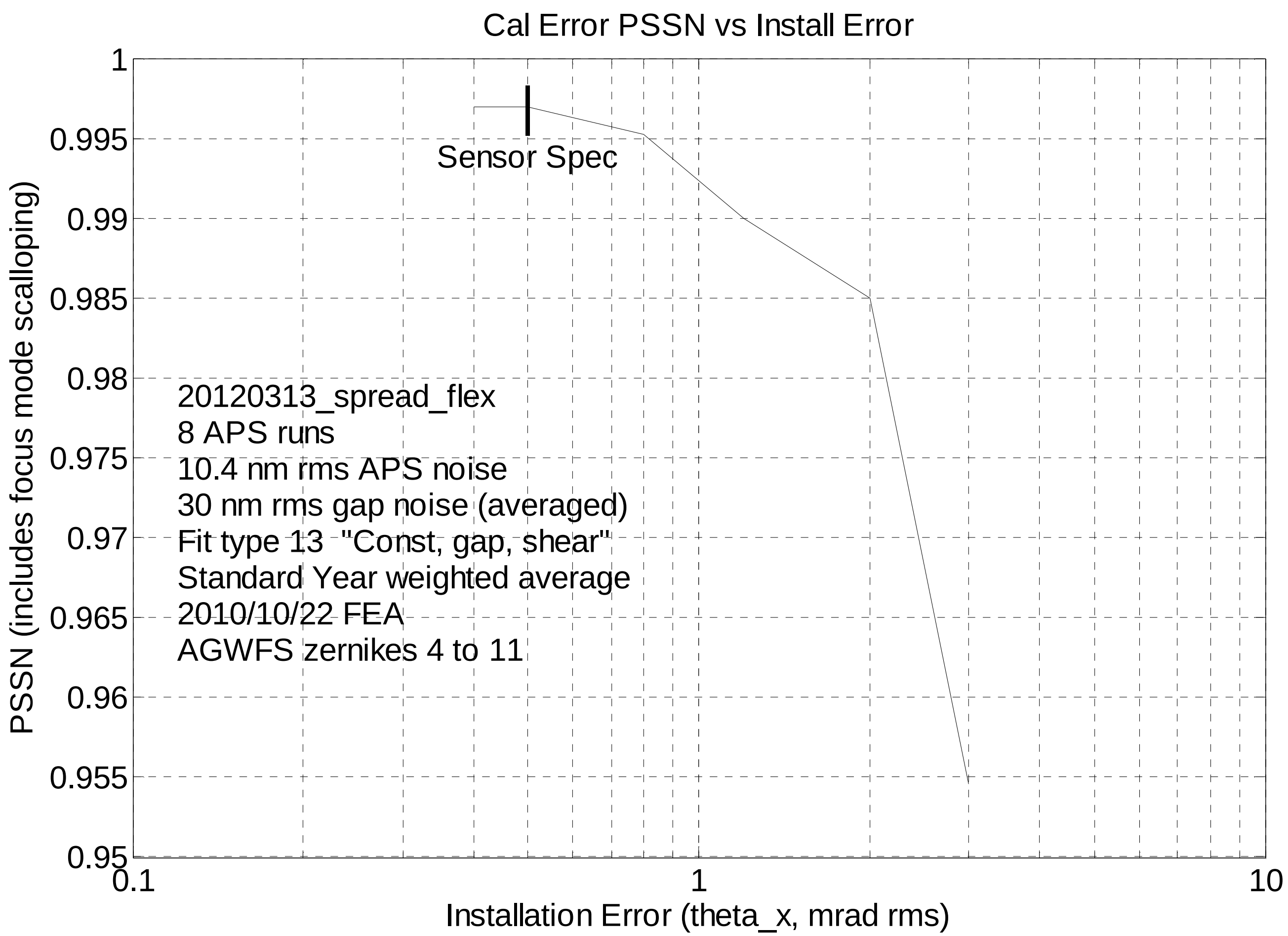


Parametric Studies –
Calibration Error vs Installation Error

Calibration Error vs Installation Error

- The installation error in the graph is the theta_x value.
  - The theta_y and theta_z values are scaled along with theta_x.
- The calibration PSSN asymptotes to a value set by APS noise for small installation errors.
- It degrades less than 0.002 from the APS asymptote for expected installation errors, consistent with requirement.

Calibration PSSN vs Installation Error

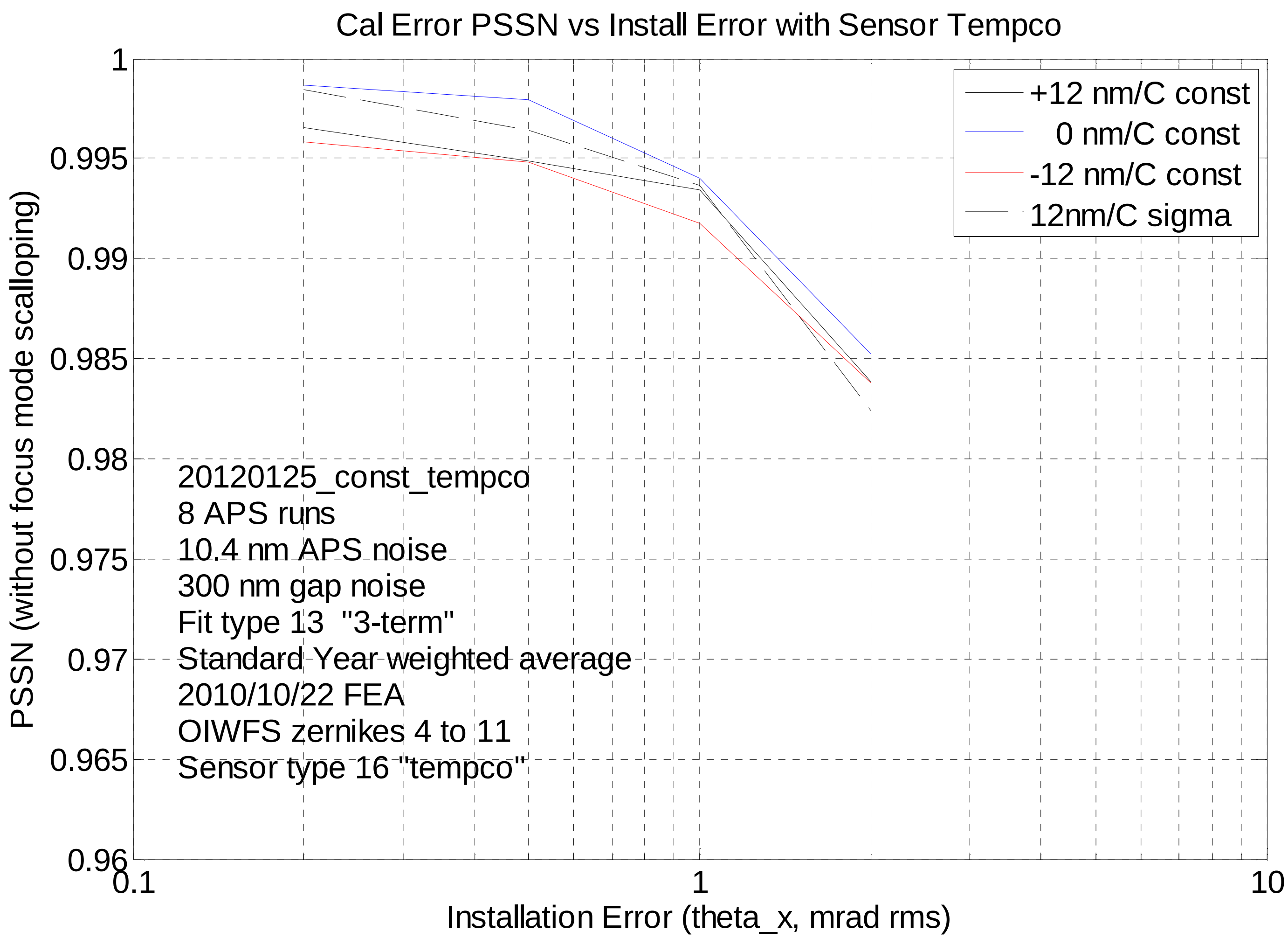


The PSSN Impact of Sensor Temperature Coefficient

The PSSN Impact of Sensor Temperature Coefficient

- The default value of sensor temperature coefficient in the simulation is zero.
- We have evaluated the impact on PSSN of the edge sensors having a non-zero temperature coefficient (tempco).
- A temperature coefficient was added to the standard sensor model, and PSSN vs installation error was evaluated for four cases.
- The four cases run were
  - All sensors with +12 nm/C tempco
  - All sensors with zero tempco
  - All sensors with -12 nm/C tempco
  - Random sensor tempcos with sigma 12 nm/C, zero mean.
- Results are on the next slide.

PSSN vs Installation Error with Sensor Temperature Coefficient



Sensor Temperature Coefficient Conclusions

- At an installation error of 0.5 mrad and with 8 APS runs, the PSSN impact of sensor temperature coefficient was

  0.9969 for +12 nm/C

  0.9968 for -12 nm/C

  0.9984 for the random tempcos with 12 nm/C sigma
- PSSN impact is the reduction in PSSN (a ratio) from sensors with zero tempco to sensors with non-zero tempco.
- Using 0.997 for the PSSN impact of sensor tempco, and multiplying by the 8-APS run PSSN of 0.996 yields a composite PSSN of 0.993. This is our best estimate of current sensor and calibration performance.
- The PSSN impact is quadratic with the magnitude of the tempco. For example, 0.9969 for +12 nm/C scales to 0.9992 at +6 nm/C, which would increase the composite value above to 0.995
- The conclusion is that the calibration procedure is robust without modification against sensor tempcos, and that keeping the impact of sensor correlated tempco at 0.999 or better requires that the combined mechanical and electronic tempco be below 6 nm/C.

The PSSN Impact of Sensor Flexure

The PSSN Impact of Sensor Flexure

- Sensor flexure is included in the baseline model.
- The PSSN impact of sensor flexure is very small, about 0.0001.

Calibration and Correlated Sensor Drift

Height Drift

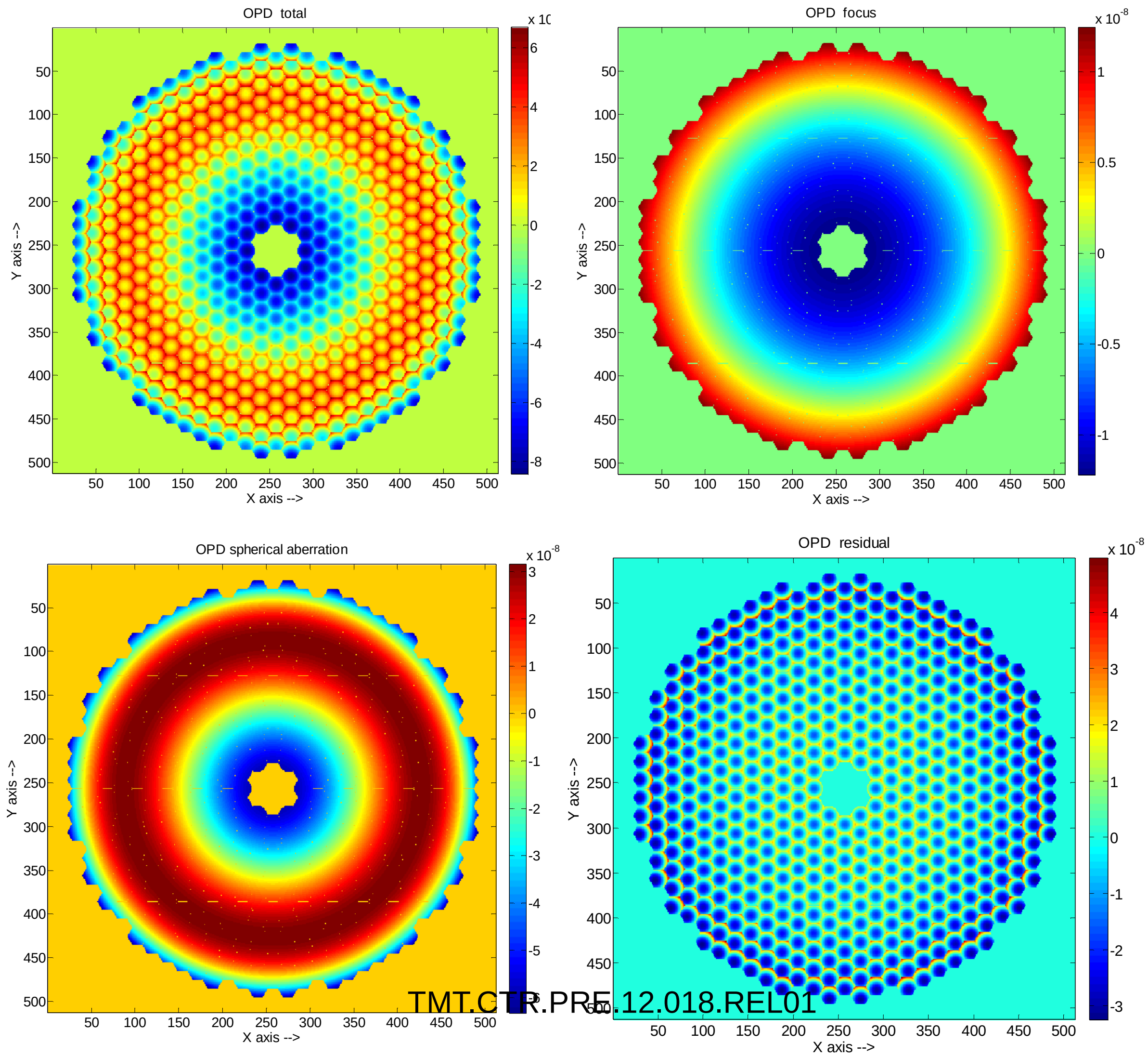
Correlated Height Drift

- Any collective drift, caused either by temperature or time, of all edge sensor height readings together maps directly to focus mode, with a high multiplier.
- +1.0 nm collective drift of all edge sensors together gives an rms OPD of ~850 nm.
- The zernike focus portion of this is removed by pistoning M2 to refocus the telescope, under control of an On-Instrument Wavefront Sensor (OIWFS).
- The residual after this refocusing is called “scalloping”.
- 9 nm of drift in the mean sensor height reading would cause 8 um rms of zernike focus without refocusing M2.

OPD for 1 micron of M1 Focus Mode (~0.8 nm correlated sensor drift) corrected with M2 Piston

Total OPD 140nm pv

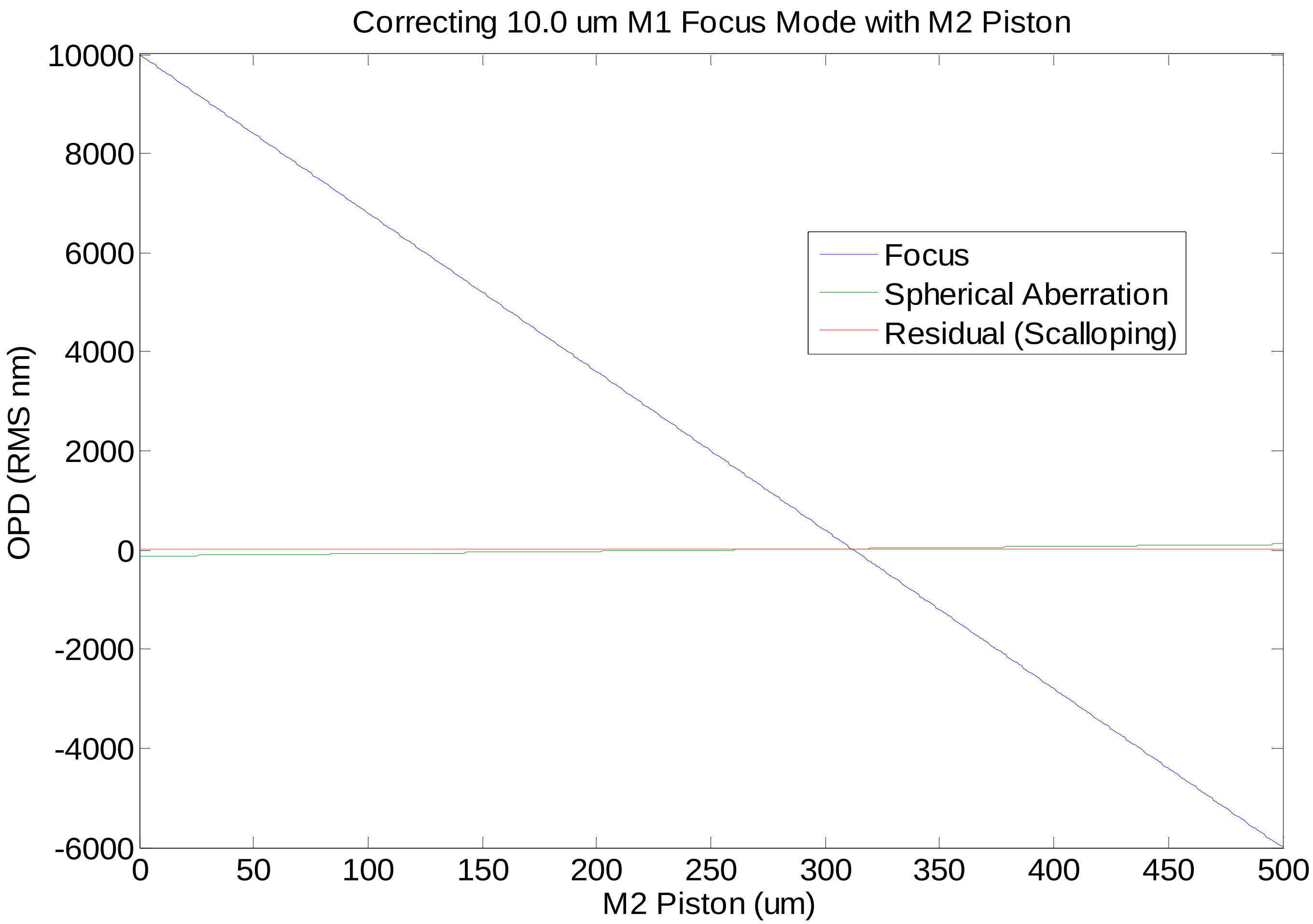
Focus OPD 24nm pv



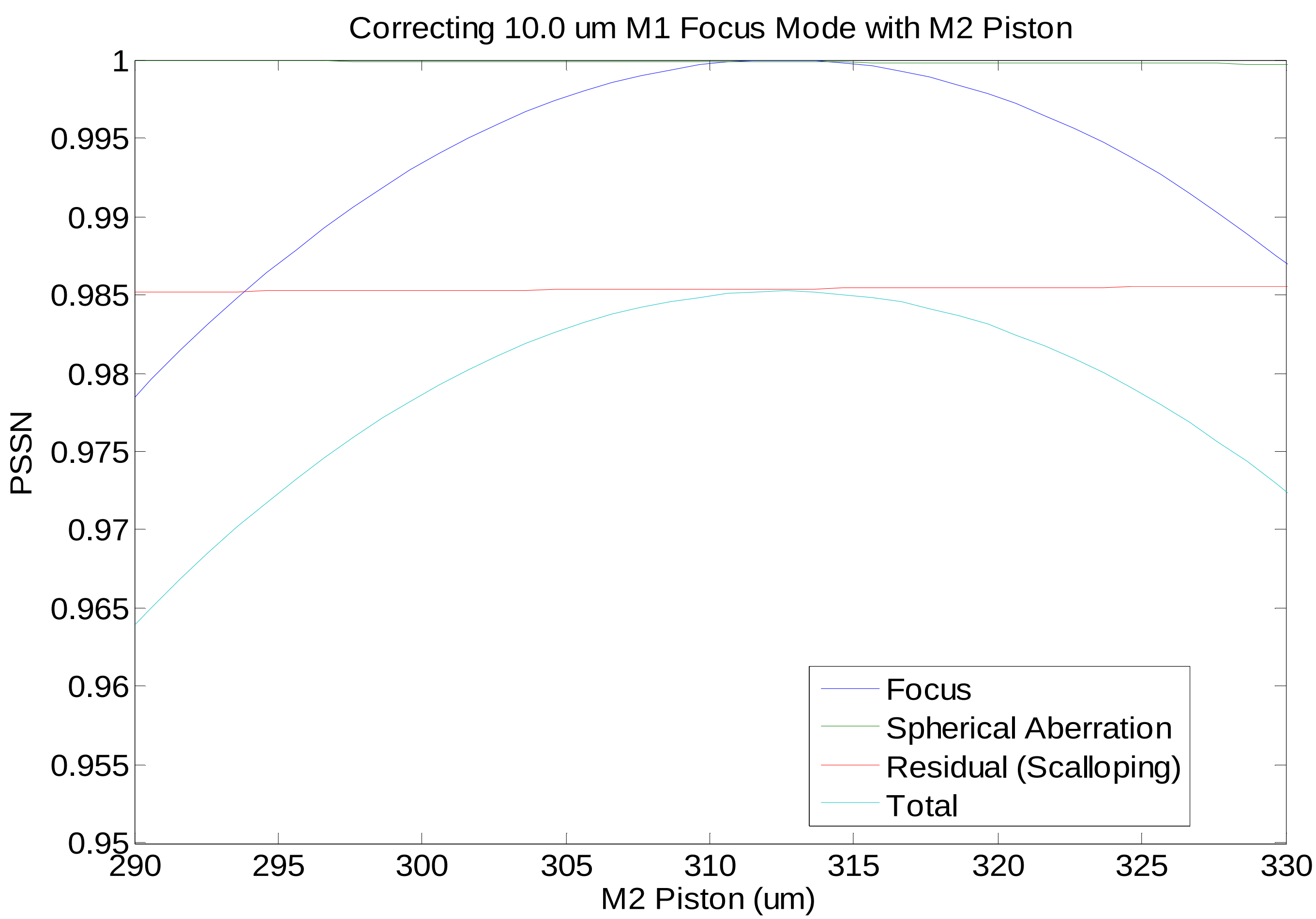
Spherical Aberration OPD 90nm pv

Residual OPD, mostly focus-mode Scalloping 75nm pv

Correcting Focus Mode by Pistoning M2



Correcting Focus Mode by Pistoning M2 (Detail)



OPD and PSSN from ~2.0 nm Correlated Sensor Drift

Parameter	No Refocus	M2 Refocus
M2 piston, microns	0.0	-57.3
Focus OPD, rms nm	1834	0.3
Focus PSSN	0.86	1.0000
SA OPD, rms nm	-17.9	9.7
SA PSSN	0.99999	1.0000
Scalloping OPD, rms nm	4.7	4.6
Scalloping PSSN	0.9994	0.9994
Total OPD, rms nm	1837	10.7
Total PSSN	0.86	0.9994

Calibration and Correlated Sensor Drift

Gap Drift

Gap Signal Offset is a Minor Effect

- The effect of adding a offset to the gap signal was simulated.
  - The intent is to model correlated drift in the gap signal.
- The calibration procedure was run with no modifications, with APS runs at

  Z= 15°, 30°, 45°, 30°, 30°

  T= 3, 3, 3, 2, 4 ℃
- The impact on PSSN was :

Gap Signal Offset	PSSN Impact
0.5 μm	1.0000
5 μm	0.9988
50 μm	0.8959

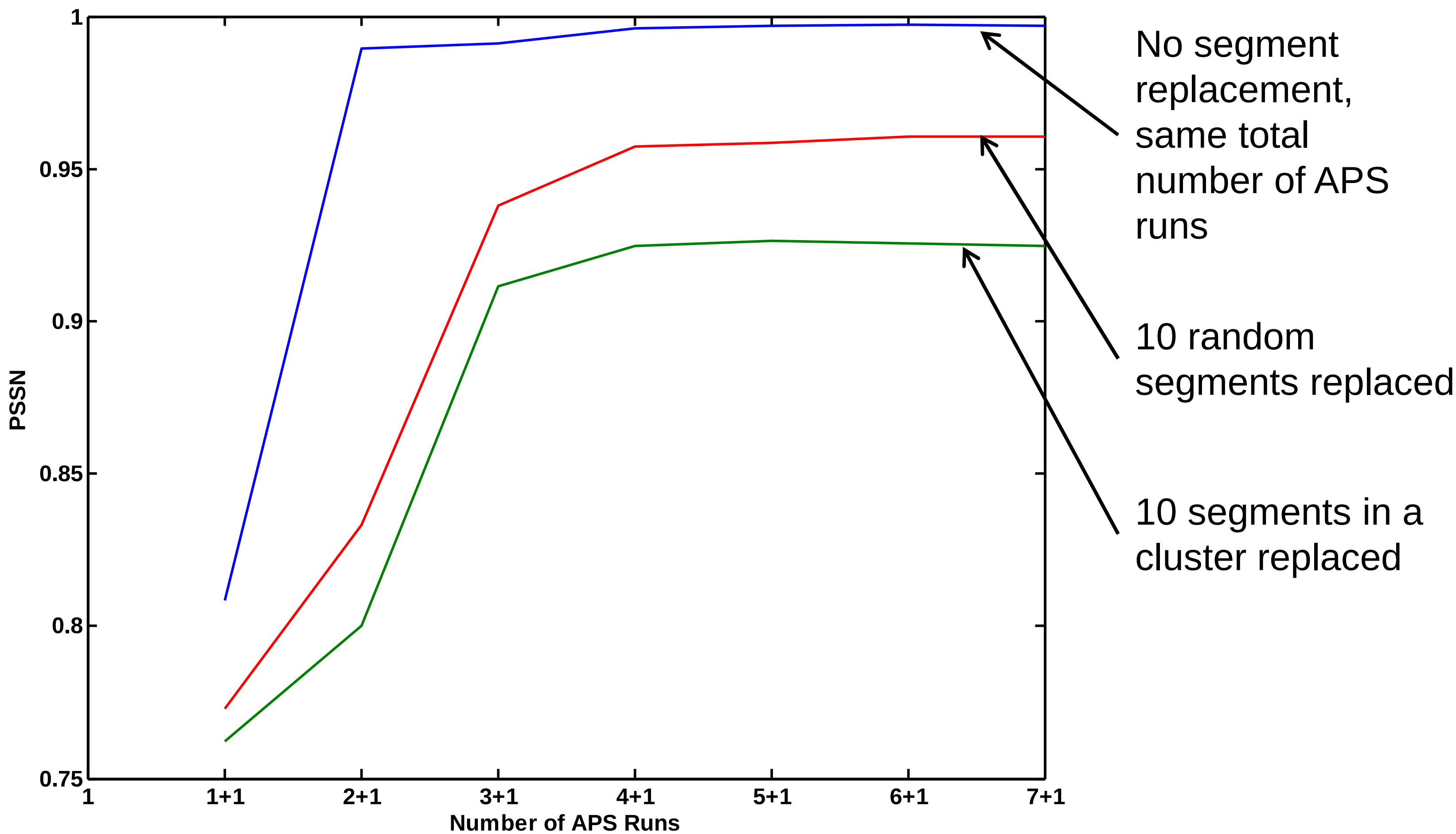
- The gap signal offset is expected to be small compared to 5 um.
- The conclusion is that gap signal offset has a negligible effect on PSSN

Modeling Segment Replacement

Modeling Segment Replacement

- The modeling of segment replacement is at an early stage.
- The cases modeled to date are
  - Calibrate with a set of N APS runs, then replace ten segments scattered at random over M1, then calibrate with one additional APS run. For N > 4, this gives a PSSN of 0.96.
  - Calibrate with a set of N APS runs, then replace ten segments in a cluster, then calibrate with one additional APS run. For N > 4 this gives a PSSN of 0.92.
- A provisional conclusion is that three APS runs at different zenith angles will be desirable after segment exchange.
- Correct modeling of segment exchange requires that each segment be given its own independent APS history. This extension of the calibration procedure is future work.

PSSN with One More APS Run After 10 Segment Replacement



Future Work

Future Work

- Model segment replacement scenarios by allowing different numbers of APS runs for different segments.
- Devise and test a scheme for sensibly deweighting old APS runs.
- Update the calibration procedure to allow non-zero global piston, tip, tilt inputs.
- Add temperature gradients in M1 to the simulation.
- Use of optical feedback to update sensor calibration coefficients (rather than just as an outer loop input)
- Use of common-mode mirror piston as a surrogate for temperature in conjunction with an APS run.
- Format the calibration and simulation routines into a form suitable for handoff to GLC and TCS, including separation into run-time portion and a hardware simulation portion.

Conclusions

Conclusions I

- The approach of using gap sensing plus multiple APS runs to calibrate the face-on sensor to correct for in-plane motion and other effects has been validated.
  - The calibration approach is powerful, modeling many effects that correlate with gap.
  - As other error sources have been identified, such as sensor sag with gravity, and sensor drift with temperature, the procedure has proven robust against these too, without modification.
- The current calibration performance model includes:
  - APS noise
  - In-plane effects from FEM & temp model
  - Best estimate of installation errors
  - Estimate of sensor (random) electronic noise
  - Sensor flexure
  - 12 nm/C sensor temperature coefficient
  - Optical feedback from Zernikes 4 through 11
  - Includes scalloping effect of focus mode, and assumes M2 refocus

Conclusions II

- Calibration PSSN incorporates four effects, with these current allocations in the TMT error budget
  - APS noise 0.9955
  - "Sensor Calibration" 0.998
  - Thermal clocking: 0.99984 (dT = 4K)
  - Decenter: 0.99956 (30→60 deg ZA)
  - The product of these is PSSN = 0.9929
- Overall performance is consistent with allocations
  - The calibration PSSN for 8 APS runs is 0.996 for zero electronic CTE
  - With current electronic drift, it's 0.993
  - With anticipated (2x) improvements to electronics: 0.995
- With respect to segment exchange, a provisional conclusion is that three APS runs at different zenith angles will be desirable.

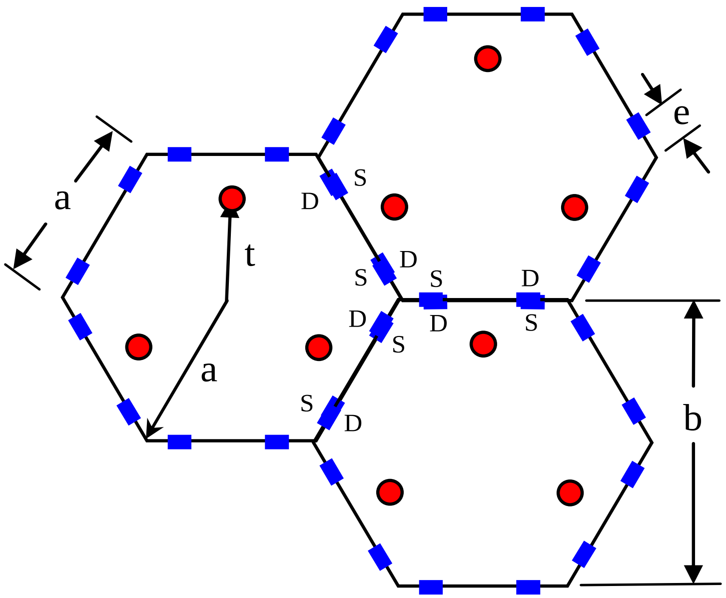
Acknowledgments

The TMT Project gratefully acknowledges the support of the TMT partner institutions. They are the Association of Canadian Universities for Research in Astronomy (ACURA), the California Institute of Technology and the University of California. This work was supported as well by the Gordon and Betty Moore Foundation, the Canada Foundation for Innovation, the Ontario Ministry of Research and Innovation, the National Research Council of Canada, the Natural Sciences and Engineering Research Council of Canada, the British Columbia Knowledge Development Fund, the Association of Universities for Research in Astronomy (AURA) and the U.S. National Science Foundation.

Backup Material

Segment Dimensions, Sensor and Actuator Locations

3 actuators / segment & 12 half sensors / segment



a = 0.716 m
b = √3 a = 1.240 m
e = 0.100 m
t = 0.531 m
492 segments
1476 actuators
2772 edge sensors
D = Sensor drive half
S = Sensor sense half

- Each sensor consists of
  – a **drive** half attached to the back of one segment
  – a **sense** half attached to the back of the adjacent segment
- Each segment has one drive half and one sense half per edge

The G and H Matrices

- The G and H matrices are used to compute shear data from gap data and to filter out the unphysical part of gap readings [Ref xx].
- The importance of computing shears from gaps is that it means the sensors do not have to measure shear, a significant simplification.
- The “pseudo-inverse” of G, notated as $G^{\dagger}$, allows the computation of changes in segment positions from changes in gaps. In Matlab notation $G^{\dagger}$ = pinv(G).
- If g = vector of changes in gaps readings, and

  Δx = vector of changes in segment inplane positions

$$\Delta x = G^{\dagger} g$$

The G and H Matrices II

- The computed segment displacements can be projected back into gap readings to create filtered gap readings, with the non-physical part removed.
- Calling g_filtered = vector of filtered changes in gaps, then

$$g\_filtered = GG^{\dagger}g$$

- Shear changes can be computed from gap changes in the same way. The same filtering benefit applies.
- Calling s = vector of changes in shears, then

$$s = HG^{\dagger}g$$

TMT and ESO Focus Mode Approaches (Doug McM)

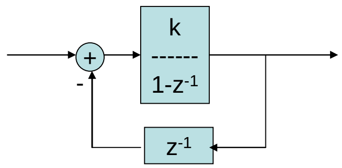
- ESO measures piston, shear, and gap (PSG) with each sensor
  - ESO does not use dihedral sensitivity
  - Shear and gap are used to
    - Provide a (quasi-static) initial estimate for focus-mode amplitude
    - Provide full knowledge of in-plane gap and shear for calibration
- TMT requires only (i) piston + (L_{eff}) x (dihedral) and (ii) gap
  - Dihedral provides better (less noisy) estimate of focus-mode than PSG
    - We can also estimate focus-mode scalloping with AO, so AO can be used to correct any correlated sensor drift between APS runs.
  - Shear can be estimated from gap
    - Noise multiplier = 2.23
    - One unobservable mode (torsion)
      - Amplitude of this mode is believed to be negligible
      - Could be observable with one or a few shear sensors

ESO and TMT Rotary Actuators

- ESO's control scheme depends on accurate measurement and control of shear. Their baseline design has a full set of shear sensors.
- To control shear as well as measuring it, ESO is baselining a rotary actuator per segment, while TMT has passive restraint only.
- TMT has studied the performance a rotary actuator as a calibration aid, to avoid the need to wait for temperature to change for full calibration.
- The report, "The Effect of Rotary Actuators on Edge Sensor Calibration for M1CS", TMT.CTR.TEC.09.011.REL01, concluded that a rotary actuator can produce enough variation in the sensor gap and shear to allow for calibration of the sensor installation errors at a single zenith angle and temperature.
- No further action has been taken on a TMT rotary actuator at this date.

Noise Bandwidth Calculation

Loop model:



Closed-loop:

$$H(z) = \frac{k}{1 + (k-1) z^{-1}}$$

Substitute z=e^{-jω}:

$$H(\omega) = \frac{k}{1 + (k-1)\exp(-j\omega)}$$

Compute power:

$$H^2(\omega) = \frac{k^2}{1 + (k-1)^2 + 2(k-1)\cos\omega}$$

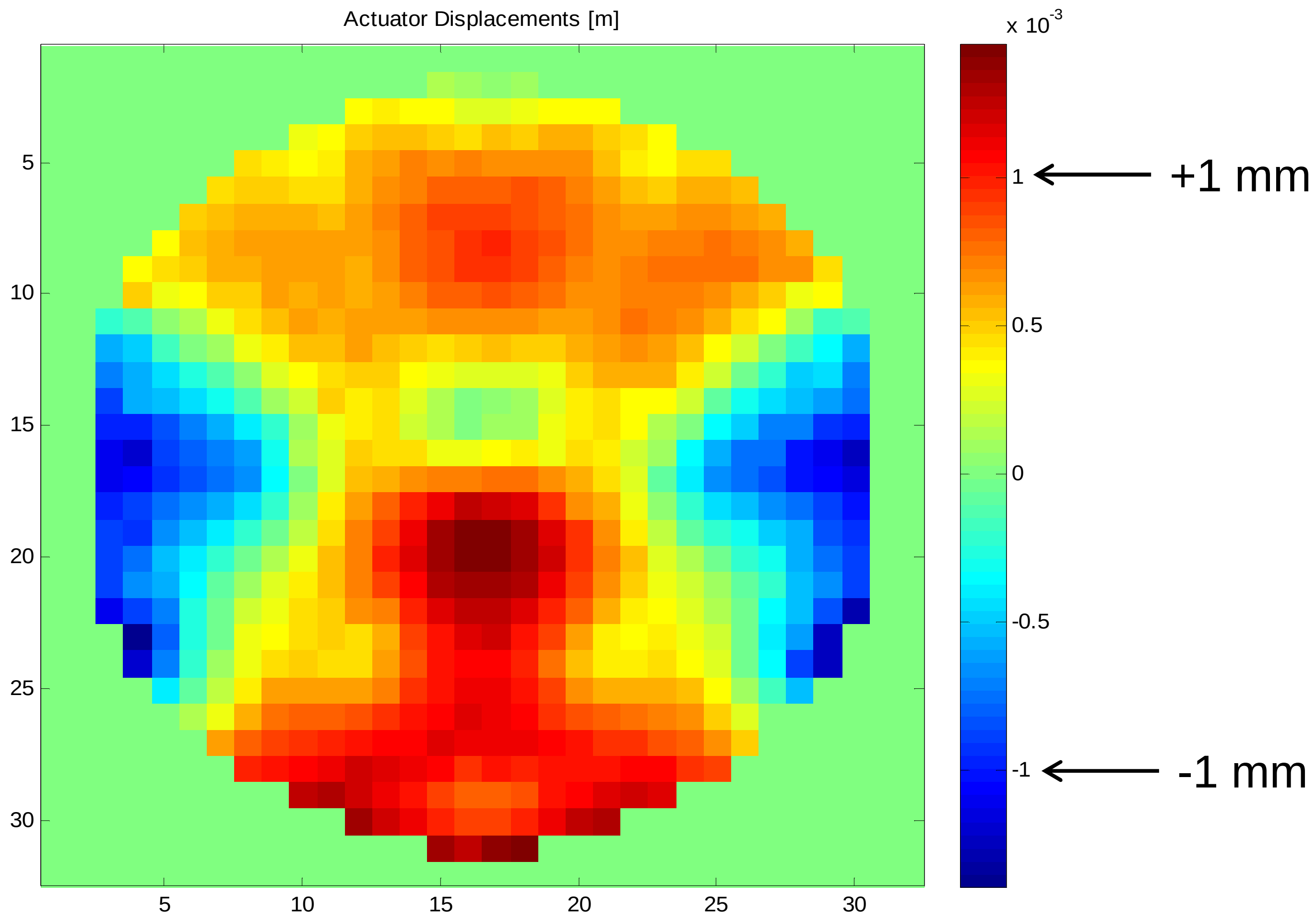
Integrate:

$$\sigma^2 = \frac{1}{2\pi} 2 \int_0^{\pi} \frac{k^2}{\left(1 + (k-1)^2\right) + \left(2(k-1)\right)\cos\omega} \mathrm{d}\omega$$

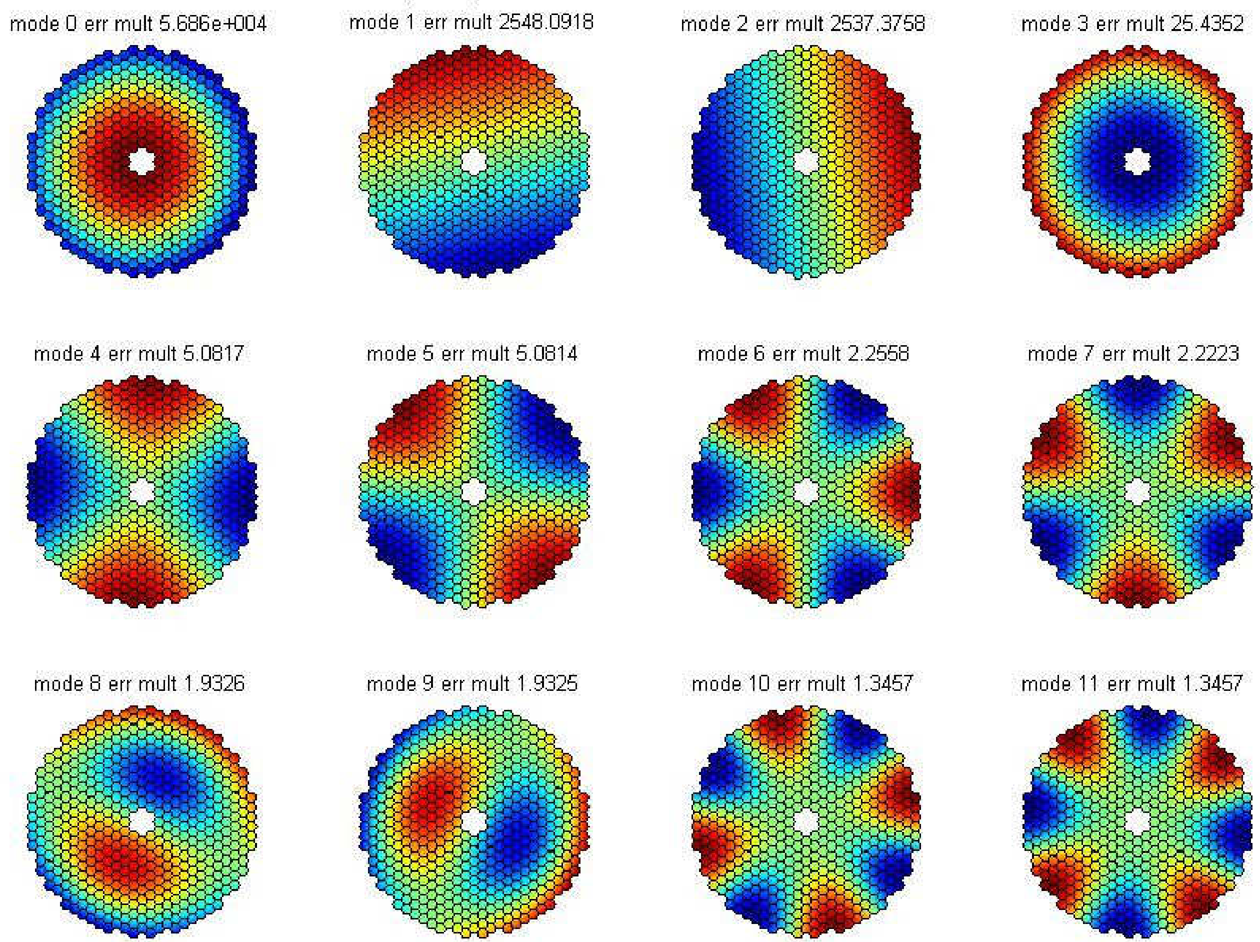
$$= \frac{k^2}{\sqrt{\left(1 + (k-1)^2\right)^2 - \left(2(k-1)\right)^2}}$$

$$= \frac{k}{2-k}$$

Actuator Amplitudes at 60 Degrees Zenith



Focus Mode Overview
The First 12 Control Modes



Simulating Installation and Calibration

- Construct an ideal M1, with perfect segments perfectly positioned.
- Apply TMT standard segment and sensor installation errors, with the telescope at a temperature "temperature_installation" (+0 C) and a zenith angle "zenith_installation" (0 deg).
- Perform simulated APS runs at a set of zenith angle and temperature pairs. Each APS run adjusts "desired_sensor_readings", "desired_pttf_readings" and "warp_settings" for best mirror figure and alignment.
- Save these data, along with “heights”, “gaps” and “shears”, for all of the APS runs, as the calibration data set. The shears recorded here are only used if the “gap_to_shear” function is not used and it is desired to model a system with shear sensors.
- Fit the height data for all APS runs to an analytic function of gap data. This gives a set of fit coefficients for each sensor. These are the calibration results.

Simulating Observation

- Move the telescope to "zenith_observing" and "temperature_observing“, that is, compute and apply FEA and temperature segment motions. Evaluate the gap readings for this mirror state.
- From the gap readings and the saved fit coefficients, compute a calibration correction.
- Apply the calibration correction, that is, change the “desired_sensor_readings”.
- Run the M1CS closed-loop simulation until steady-state is reached (150 time steps of 50 msec).
- Evaluate calibration error in sensor nm, and in image metrics OPD and PSSN.

Fitting Functions

- A fitting function computes a correction to sensor readings from fit coefficients times observables such as a gap, shear, 1/gap, gap_mean, zenith_angle.
  - Gap_mean is the average gap over all sensors. It is a measure of M1 average temperature.
- The baseline fitting function, used when fitting four or more APS runs, is fit type 13, which has a constant, a gap term and a shear term:

$$Reading\ correction = C_0 + C_1 * gap + C_2 * shear$$

- The next slide is a table of fitting functions that have been tried.
- Fit type 7 differs from fit type 13 only in that gaps and shears are computed as deltas from the gaps and shears present in a chosen APS run. It is algebraically equivalent and gives identical results to fit type 13. It was created to investigate a simple model of segment replacement.

Fitting Function Types

Fit Type	Constant (Global fit)	Gap	Shear	1/gap	Gap mean	Delta gap, delta shear	Multiple baseline
1	x	x	x	x			
2	x						
7	x					x	
8	x	x	x	x	x		
10	x		x	x	x		
11	x	x		x	x		
12		x	x				x
13	x	x	x				
14	x	x	x		x		

Fitting Functions II

- Fitting 3 APS runs with the fit type 13 gave a very large scatter with different random seeds. Fit type 14, with gap_mean added, gave much less scatter and was used in creating the plot of PSSN vs number of APS runs for the 3 APS run point.
- Fit type 12, "multiple baseline" gave marginally better results than fit_type 13 for 2 and 4 APS runs, and is used on the same plot for those points. Multiple baseline is discussed in the next slide.
- Fit type 2 has just a constant, and is used for the 1 APS run case.
- Fit types 10 and 11 gave poor results in all cases.

Multiple Baseline

- In the "multiple baseline" procedure, each sensor can use a different APS run to treat as the baseline from which to compute delta gap and delta shear.
- Fit coefficients are obtained separately for each sensor and for each candidate baseline APS run. The desired sensor readings, in-plane positions and fit coefficients from all these cases are saved in a large database.
- During observing, for each sensor:
  - Calculate the current delta gap and shear relative to each APS run, and compute a reading correction using that APS run's correction coefficients.
  - Designate the APS run with the lowest magnitude correction as the baseline APS run for this sensor.
  - Apply that run's correction to that run's desired sensor reading to get the final desired sensor reading.
- This procedure deals with ill-conditioned matrices by inverting several possible matrices and choosing the lowest magnitude correction.

References I

1. D. G. MacMartin, G. A. Chanan, “Control of the California Extremely Large Telescope primary mirror,” *Proc. SPIE* 4840, 69-80 (2003).
2. Chanan, G., MacMartin, D.G., Nelson, J., and Mast, T., "Control and Alignment of Segmented-Mirror Telescopes: Matrices, Modes and Error Propagation", Applied Optics, Vol 43, No. 6, 1223-1232 (2004).
3. MacMartin, D.G., and Chanan, G. "Measurement Accuracy in Control of Segmented-Mirror Telescopes", Applied Optics, Vol. 43, No. 3, 608-615 (2004).
4. K. Szeto et al. “TMT telescope structure system: design and development progress,” *Proc. SPIE* 7012-88 (2008).
5. Mast, T., Chanan, G., Nelson, J., Minor, R., Jared, R., “Edge sensor design for the TMT,” *Proc. SPIE* 6267, 62672S (2006).
6. Terry Mast, “Report No. 77 - TMT Edge Sensor Concepts”, TMT.CTR.TEC.07.009.REL01 (2007).
7. J. Nelson, “Edge Sensors: Abstract view,” TMT.PSC.PRE.07.004.DRF01 (2007).
8. T. Mast, J. Nelson, “TMT Image Size and Wavefront Error Budgets”, TMT Report Number 10, Vol 2, TMT.OPT.TEC.07.022.REL01 (2007).
9. G. Chanan, M. Troy, I. Crossfield, J. Nelson, and T. Mast, “The Alignment and Phasing System for the Thirty Meter Telescope,” *Proc. SPIE* 6267, pp. 62672V (2006).
10. M. Troy et al., “A conceptual design for the Thirty Meter Telescope Alignment and Phasing System,” *Proc. SPIE* 7012-125 (2008).

References II

10. Shelton, C., Troy, M., Chanan, G., MacDonald, D., “M1CS Focus Mode Analysis”, TMT.CTR.TEC.07.019.REL01 (2007).
11. Shelton, C., Roberts, L.C., “M1CS Edge Sensor Calibration Analysis II”, TMT.CTR.TEC.09.064.REL01 (2009).
12. Shelton, C., Roberts, L., Troy, M., “M1CS Inductive Edge Sensor Calibration Analysis,” TMT.CTR.08.042.REL01 (2008).
13. Jared, R., Minor, R., Doering, D., Van der Lippe, “Relative Humidity and the TMT Sensor,” TMT.CTR.PRE.07.010.REL01 (2007).
14. Roberts, S., Sun, S., Kerley, D., "Optical performance analysis and optimization of large telescope structural designs", *Proc. SPIE* 5867, 200-211 (2005).
15. Gary Chanan, “Segment In-Plane Position Sensing”, TMT.CTR.PRE.07.019.REL01 (2007).
16. Vogiatzis, K., “Probabilistic Performance Analysis ‘Standard Year’”, TMT.SEN.PRE.07.030.DRF01 (2007).
17. Roberts, L.C., Shelton, C., “The Effect of Rotary Actuators on Edge Sensor Calibration for M1CS”, TMT.CTR.TEC.09.011.REL01 (2009)
18. Shelton, C., Roberts, L.C., McMichael, I., “Focus Mode Control Analysis and Options”, TMT.CTR.PRE.09.094.REL02 (2009)

P11a_Reliability, Failure Modes, Maintenance, and Diagnostics

Chris Lindensmith

M1CS Sensor System Preliminary Design Review

Pasadena

March 29 - 30, 2012

Objective

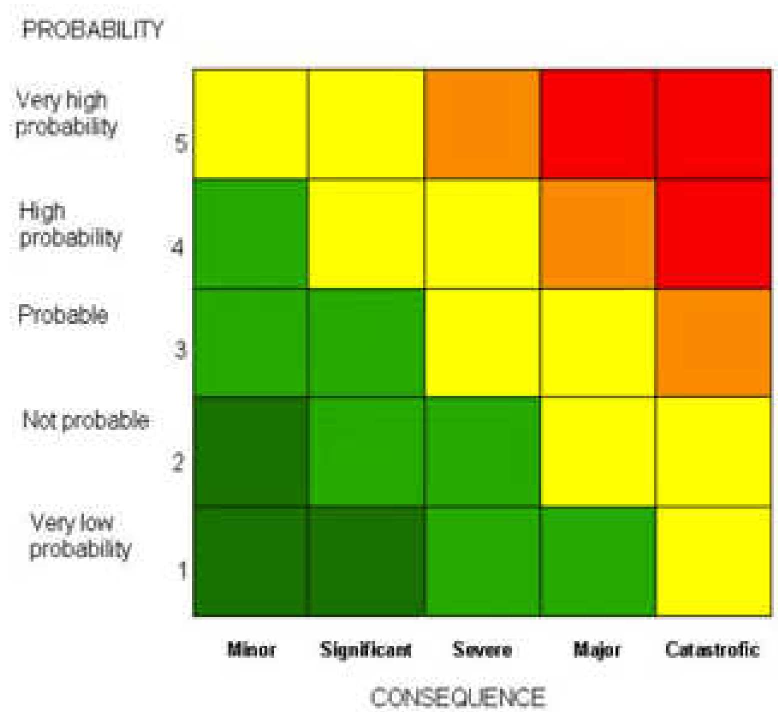
- Show that sensor system is robust against failure
  - System is redundant relative to the control requirements
  - Random failures at individual sensor level can be ignored until segment exchange time
  - Group failures at node box level can be corrected by parts swap
  - Purge system can be monitored for branch failures
  - Purge system has redundant backup (compressor and dryer)
- Algorithms have been proposed for identification of bad sensors at the M1CS level
  - Gary Chanan, after this talk

Outline

- Reliability Approach
- Sensor Reliability and Maintenance
  - Reliability
  - Failure Modes
  - Maintenance
- Electronics Reliability and Maintenance
  - Reliability & Maintenance
  - Failure Modes
- Boot and Purge Reliability and Maintenance
  - Reliability & Maintenance
  - Failure Modes
- Summary
- Diagnostics (Chanan)

Reliability Analysis Approach

- Use standard 5x5 risk table
- Identify possible risks and categorize impact and likelihood
- The risks identified here are post-delivery operational risks
  - Development risks to be addressed during the Final Design Phase are addressed later



Sensor Reliability

- Sensors are approximately 2 :1 redundant with respect to the control requirements
  - System can tolerate a large number of random failures with minimal impact
  - Detailed impact on controls remains to be modeled at system level
- Blocks and coatings are high reliability
  - Same basic technology (gold over chrome on Zerodur, with indium solder connection) that has been working on Keck for almost 20 years in the same environment
  - Sensors are set back from edge to prevent intrusion into gap during segment exchange
- Adhesive to segments may be the biggest risk (based on Keck experience).
  - Adhesive for the sensor puck will be selected by the Optics Group and will likely be the same as that selected for the pucks for the whiffle tree axial support rods.

Sensor Reliability Analysis

Risk	Impact	Likeli hood	LxI	Mitigation	Notes
Sensor failure due to contamination of surface	3	2		Full sensor system is nearly 2 to 1 redundant relative to actuators; Sensors are cleaned every 2 years when segments are exchanged	
Indium solder failure at face of sensors	3	1		Full sensor system is nearly 2 to 1 redundant relative to actuators; Solder can be reflowed and sensors remounted at segment exchange. Keck sensors use same gold/solder interface with high reliability.	in FDP, investigate alternative to indium solder
Sensor motion during earthquakes	1	1		Lab tests at 3 g peak vibration show less than 3 microns of motion. For design-maximum earthquake recalibration would be needed. Sensors in lab have run at 0.5 g peak for extended periods without significant motion, so for earthquakes at that level, no service is needed.	
Puck separation due to epoxy failure	4	1		Pucks can be reglued- the sensors do not rely on the epoxy for achieving precise location or stability.	
Puck separation due to glass cracking	5	1		Sensor system can tolerate complete refinish/re-etch/reglue of puck location. Sensor pucks use the same adhesive as the whiffle tree axial support rods.	
Sensor being bumped during segment handling	2	3		Loss of a small number of sensors has little impact. Sensors can be easily reinstalled /realigned at next segment exchange	

Sensor Maintenance

- Sensors are low maintenance
- No regular maintenance is required while sensors are mounted on the telescope
- During recoating operations:
  - Sensors need to be protected from impact
  - Sensors also need to be protected from stripping chemicals to avoid stripping gold from sensors
  - Sensors should be rinsed clean in place with DI water, alcohol, and dusted with dry air before segments are reinstalled on telescope

Electronics Reliability and Maintenance

- Reliability
  - Electronics use high quality, COTS parts
  - Statistical reliability analysis will be done as part of SCC design and development
- Maintenance
  - The sensor electronics require no regular maintenance
  - The segment mounted electronics are designed so that they are line replaceable:
    - Connectorized with easy to use connectors
      - Visibly distinct connectors for different applications
      - Will be keyed to prevent improper mating
    - Boards mounted to dust boots are removable

Electronics Reliability Analysis

Risk	Impact	Likelihood	LxI	Mitigation	Notes
ESD causing failures at electronics inputs (e.g. due to CO2 snow cleaning)	5	1		Electronics are designed to accept high overvoltage at input; segment coatings grounded(?); Segment mounted electronics are accessible and line replaceable	need to verify that segment coatings are tied to ground
Electronic component degradation causing reduced stability or increased temperature coefficient	4	2		Use of high quality components; use of common COTS parts so that replacement is possible. System will have diagnostics to aid in identifying bad sensors.	
Connector failure from sensor to electronics	4	1		Use gold plated connectors on both sides of connection. System will have diagnostics to aid in identifying bad sensors.	

Boot and Purge Reliability and Maintenance

- Reliability
  - Purge system flow rate is much higher than required
  - RH monitors will be distributed through system at regulators
  - Regulators can provide remote pressure monitoring
  - Gas system is fully redundant (but not automated switchover)
  - Boot lifetime cycling test to be done in FDP
- Maintenance
  - The purge system components (compressors, air dryers) in the mechanical room will require regular maintenance
    - Both are standard COTS systems with manufacturer recommended maintenance cycles
    - Occasional replacement of consumables
      - Oil filter on compressor
      - Desiccant in gas dryer

Dust Boot and Purge Reliability Analysis

Risk	Impact	Likelihood	LxI	Mitigation	Notes
Dust boot spring failure leaves gaps	2	1		Purge supply is oversized and can accommodate large leaks with no loss in sensor performance	
Dust boot damage during exchange	1	1		Dust boots are designed to slide back during exchange. Loss of small number of dust boots is equivalent to loss of a small number of sensors.	Dust boot mate during segment exchange will be tested more extensively prior to construction.
Contamination caused by dust boot outgassing	1	1		Delrin is a very low outgassing material (.39% TML, .02% CVCM, 0.1% WVR)	
Contamination of sensor caused by dust boot wear	1	1		Delrin AF is very low friction; forces on boot are small enough that wear is insignificant over TMT lifetime	
Failure of dry gas source	4	1		Fully redundant compressor and dessicator design	
Leak in random line segment	3	3		put remote pressure/flow and RH monitors (low cost) at telescope mounted regulators for rapid identification and repair;	
Oil leak from hydraulic lines into gas lines in wrap	5	1		Oil trap in dry gas line after the wrap	need to add this to design

Summary

- The sensor system requires very little regular service or maintenance
- Potential reliability issues have been identified and categorized for probability and impact
  - Risks are generally low, and the system is expected to be very reliable
- Mitigations have been identified
  - Many of the mitigations are already part of the implementation plan
  - The few additional mitigations will be addressed in the FDP
- Approaches to identifying bad sensors are discussed in the next presentation.

P14: Compliance, Open Issues, Risks, and Conclusions

Mark Colavita

M1CS Sensor System Preliminary Design Review
Pasadena
March 29 - 30, 2012

Agenda

- Summary by element
- Compliance with requirements
- Risks
- Wrap up

Summary: Requirements, 1

- The sensor requirements are very demanding
  - Tight error budgets
  - Face-on geometry drives various sensitivities
    - High accuracy required in measurement of $\partial C/C$
  - Tight geometric requirements on installation
- Key driving requirements
  - Non interlocking
  - Accommodate humidity and dust
  - Thermal and temporal stability
  - EMI (operation at low signal levels)
  - Low power dissipation
  - Edge lithography requirements

Summary: Requirements, 2

- Overall
  - Requirements well understood
  - Key driving requirements identified
  - Clear flowdown from OAD/ORD via M1CS DRD
- Some remaining issues to be addressed going forward
  - Validation has identified some requirements needing clarification, improvement, or reassignment, e.g.,
    - Compatibility with coating chemicals -> should become a requirement on coating and handling systems
    - Defining TBD reduced-performance budget in context of bad sensor detection
    - The BPS shall not produce particulate or chemical contamination -> needs limit: everything outgasses at some level
  - Error budgets
    - Need to work with TMT SE to deal with coupling in M1CS simulation results among APS noise, M1 in-plane errors, and edge sensor calibration
    - A more transparent allocation of sensor random noise, and correlated & uncorrelated drifts

Summary: Blocks and Coatings

- Sensor physics and subtleties addressed
- Block design responsive to requirements
  - Updates since P1 sensor
    - Carefully toleranced near-production drawings, tied to error budget
    - Updated foot geometry
      - Initial prototype blocks meet required tolerances with only minor exceptions
    - Coating edge requirements understood and clearly specified
      - Coating process identified that can achieve these requirement
      - Initial prototype coatings meet key required tolerances; exception global position
- Remaining issues
  - Revisit after next phase of prototype development
    - Confirm all coating and block tolerances
    - Review tolerances on drawings: may want to revise (loosen) some

Summary: Interconnects

- Compliant interconnect approach identified
  - Block-end approach using indium solder, like Keck
  - Identified flexible, low-capacitance cable
  - Identified prototype electronics-end connector
- Remaining issues
  - A more compact electronics connector is desired to allow better mounting of electronics
  - Would like to explore an attachment approach that does not require indium soldering

Summary: Boot

- Boot design compliant with requirements on dust, humidity, force
- Stereolith prototype built
- Tested humidity control
- Tested intersegment forces
- Tested mate/demate
- Identified quantity production approach
- Identified risks associated with design constraints
- Remaining issues
  - More testing desired for lifetime and segment interface in more accurate testbed
  - Finalize mass (part of FDP plan, which includes design of injection molds)
  - Detailed electronics interface
  - Detailed ground strap for ease of attachment
  - Finalize bonding plan / segment interface, including adhesive compatibility with injection-mold plastic

Summary: Purge system

- Key requirements and interfaces identified
- Compliant concept developed
- Major components identified (pumps and dryers)
- Key risks identified
- Remaining issues
  - Additional design work, but no major issues identified

Summary: Mounting

- Interface with segment well understood and documented in MICD (owned by optics group)
- Mounting error propagation understood and values incorporated in calibration model
- Mounting approach verified
- Optical effects of block and boot print-through to optical surface modeled
- Production mounting and testing approach identified
- Risks identified
- Remaining issues
  - No major issues
  - Minor: Belleville stacks are awkward: move to a custom spring?

Summary: Electronics & testing, 1

- The electronics, formally part of SCC, are key to meeting the sensor requirements
- Key performance requirements understood (stability/drift/power)
- Key operational requirements understood (SCC interface/reliability)
- Prototype electronics built, tested
- Completed one-iteration of improvements using the same PCB
- Test results: close to achieving key specs
  - 4.4 nm rms quadrature average drift over 24 days (vs. 3.5 nm rms / 30 days)
  - 12 nm/K thermal drift before calibration, included in calibration modeling
    - DRD drift spec is only after calibration, but would like to improve the pre-calibration effect by 2x so that PSSN impact after calibration is negligible

Summary: Electronics & testing, 2

- SPICE model built which identifies specific changes to improve performance
- Remaining issues
  - Should do another design iteration to improve measured performance; model informs what to change (i.e., bounded problem)
  - Cross talk between sensors dealt with in lab, but needs an improved solution
    - Add galvanic isolation in board build: can this eliminate need for local ground connection?
    - Address any gap/height coupling
  - More complete testing of all modes
    - Long-term stability tests have taken precedence to-date
- SCC enters PDR during construction phase
  - How much electronics we address in near-term is a risk reduction decision

Summary: Calibration - 1

- In-plane calibration approach required to achieve good performance without unrealistic mounting tolerances
- System-level requirements and operational scenarios understood, as well as traceable input parameters from telescope FEM, and segment & sensor installation tolerances
- High-fidelity simulation tool developed
- Approach works well to calibrate errors from in-plane effects
  - Approach also works well to calibrate additional errors not originally included, such as sensor flexure and electronics tempco
- The performance yields good PSSN, close to original top-down requirement
  - Note that the performance is partially limited by parameters outside of M1CS control, including APS noise and number of runs

Summary: Calibration - 2

- Areas where additional modeling could be done (not all at same priority)
  – More segment replacement scenarios, in particular, incorporating different numbers of APS runs for different segments
  – Dependence on flexure from telescope structure (don't have final structure)
  – Use of optical feedback to update sensor calibration coefficients (rather than just as an outer loop input)
  – Modeling effects of thermal gradients
  – Deweighting of older APS runs in updating sensor coefficients
  – Interaction of PTT target with calibration
  – Use of common-mode mirror piston as a surrogate for temperature in conjunction with an APS run

Summary: Other areas

- Reliability/Maintainability
  - Requirements identified
  - Maintenance approach described
  - Risks identified, ranked
  - More work needed on reduced-performance budget, accommodation of bad sensors, and associated diagnostics
    - Mostly M1CS system level items
- Safety
  - Minimal at sensor level
  - Most safety issues are at M1CS system level
- FDP tasks
  - Outlined
  - Some current open issues are FDP tasks

Compliance with requirements

Compliance spreadsheet, 1 (embedded)

0110	The sensors shall meet all performance requirements while operating within the range of temperatures of -5? C to +9? C at the sensor head.	D,A	Component selection (D): Spice model of electronics (A)
0115	The sensors shall remain functional at a level to allow servicing to be conducted, when operated over the range of temperatures of -13? C to +25? C at the sensor head	D	
0120	The sensors shall meet all performance requirements while operating within the range of ambient relative humidity of 0% to 100%, non-condensing.	D	Boot incorporated
0140	The sensors shall meet all performance requirements while operating within the range of atmospheric pressures from 0.6 atm to 1 atm.	D	
0150	The sensors shall meet all performance requirements while being oriented at zenith angles from 0? to 80? for any sensor rotation.	A,T	Deformation modeled in SolidWorks (A); repeatability tested (T); incorporated in sensor calibration model (A)
0155	The sensors shall remain functional at a level to allow servicing to be conducted while being oriented at zenith angles from 0? to 105? for any sensor rotation.	D	
0160	The edge sensors shall meet all performance requirements in the presence of TBD dust environment without requiring cleaning except during the segment removal/installation process every two years.	D	Boot incorporated; NB: TBD dust env.
0162	Any dust mitigation system shall not impart forces across the inter-segment gap that affect the reading of the edge sensor over its performance range.	D	Redundant, given next three; should probably be deleted
0163	Any dust mitigation system shall not impart forces along the z axis greater than 0.050 N (TBC) over the performance range of the sensor.	T	Tested compliant
0164	Any dust mitigation system shall not impart forces along the y axis greater than 0.100 N (TBC) over the performance range of the sensor.	T	Tested compliant
0165	Any dust mitigation system shall not impart forces along the x axis greater than 0.150 N (TBC) over the performance range of the sensor.	T	Tested compliant
0180	The sensors shall meet all performance and functional requirements in the presence of TBD EMI/RFI environment.	N/A	Unspecified environment, but sync demodulation approach is robust to broad-band noise
0220	The M1CS shall be designed to withstand repeated exposure to the environmental conditions in Table 1 (Operational Basis Survival Conditions) without damage.	D	Condensing humidity will require recalibration

Compliance spreadsheet, 2

0230	The M1CS shall be designed such that if the conditions in Table 1 or REQ-3-M1CS.SEN-0240 occur in any operating mode, the system shall be able to resume normal observations and regular maintenance operations with inspection lasting no longer than 6 hours.	D	Recalibration required if segment contract
0240	The edge sensors shall be designed such that while in any installed state (operating or non-operating) and any orientation they shall survive earthquakes up to the levels of the 10-year-return period earthquake with no damage.	T	Tested with 3 g shake
0242	After exposure to an earthquake up to the levels of the 200-year return period earthquake, once the observatory staff has resumed regular duty, the sensor system shall be able to resume normal operations within two weeks using spares that are on-site, the	T	Tested with 3 g shake
0244	The sensor and its components shall be designed to withstand the loads resulting from an earthquake up to the levels of the 1000-year return period earthquake without violating interface requirements.	D	
0280	The sensors shall be designed such that loss of power will not cause them to violate their interface requirements.	D	
0282	The edge sensors shall be capable of repeatedly being subjected to high vacuum without damage, wear, or loss of performance.	D	Boot material selection
0283	The edge sensor components that remain on the segment during recoating shall have TML<1% (TBR) and CVCM <0.1% (TBR) when tested according to ASTM-E595 (TBC) for outgassing in their fully assembled configuration.	D	Boot material selection
0290	The sensors shall not produce any particulate contamination to either themselves or their environment.	D	Strictly, there is a wear surface at the boot: need to reconcile 0290,0640,0650
0294	The sensors shall not include sources of radiation over the wavelength range 0.31 to 28 microns.	D	
0295	The sensors shall meet all performance, functional, and operational requirements in lighting conditions ranging from complete darkness to full daylight.	D	

Compliance spreadsheet, 3

0296	The sensors shall be able to withstand repeated infrequent (1/year) temperature soaks at +50 C without damage or degradation.	D	Boot material selection
0298	The sensors shall be compatible with the chemicals used in the cleaning, stripping, and recoating processes. Chemicals that may be used in this process are shown in Table 2.	D	This is not a good requirement, despite its definition of compatible to include a means of protecting the sensor. While the bricks and coatings are very robust, the boots, electronics, and everything else on the back of the segment (M1 and M1CS) are not.
0310	Each of the sensors shall conform to the electrical interface requirements defined in ICD M1CS-SEN to M1 (AD2).	N/A	This is an internal M1CS interface
0360	Each of the sensors shall conform to the mechanical interface requirements defined in MICD M1CS-SEN to M1 (AD3).	D	
0440	The average power dissipated to air by each sensor transmit and receive pair and local electronics shall be less than 200 mW.	D	Component selection (D)
0480	The sensors shall be designed without interlocking mechanisms that span the gap between segments.	D	No mechanical interlocking, but there is a ground cable 0610
0500	The boot and purge system (BPS) shall maintain the local environment in the sensor gap, including the drive and sense surfaces, at less than 40% relative humidity, for the external humidity range of REQ-3-M1CS.SEN-0115.	D/T	Tested compliant
0504	The boot and purge system (BPS) shall maintain the local environment in the sensor gap, including the drive and sense surfaces, at less than TBD dust level, for the external dust environment of REQ-3-M1CS.SEN-0160.	D	Not tested with current prototype, but similar design at TPG was effective at limiting dust ingress
0510	The BPS shall not have a negative impact on mirror seeing.	D	Not testable. Is 0520 adequate?
0520	The BPS shall provide gas to the dust boots at a temperature that is in equilibrium with the segment where the gas is being provided.	D	Will be part of purge design
0530	The BPS shall be designed to minimize the time required to mate/demate BPS components during segment removal and installation.	D/T	Tested mate/demate compliant over range of test stage
0540	The BPS mechanical design shall be compliant with the M1CS sensor to segment MICD (AD3).	D	

Compliance spreadsheet, 4

0550	The BPS shall maintain the local RH environment specified in REQ-3-M1CS.SEN-500 and dust environment in REQ-3-M1CS.SEN-0504 when subjected to intersegment relative motions of ? 0.25 mm in the z (piston) direction.	D/T	Tested compliant
0560	The BPS shall maintain the local RH environment specified in REQ-3-M1CS.SEN-500 and dust environment in REQ-3-M1CS.SEN-0504 when subjected to intersegment relative motions of ? 1.0 mm in the x (shear) direction.	D/T	Tested compliant
0570	The BPS shall maintain the local RH environment specified in REQ-3-M1CS.SEN-500 and dust environment in REQ-3-M1CS.SEN-0504 when subjected to intersegment relative motions of ? 1.0 mm in the y (gap) direction.	D/T	Tested compliant
0580	The BPS shall tolerate intersegment relative motions of ? 10.0 mm in the z (piston) direction without damage and return to a state that meets the performance requirements when the segment relative motions return to the performance range.	D	
0590	The BPS shall tolerate intersegment relative motions of ? 2.0 mm in the x (shear) direction without damage and return to a state that meets the performance requirements when the segment relative motions return to the performance range.	D	
0600	The BPS shall tolerate intersegment relative motions of ? 2.0 mm in the y (gap) direction without damage and return to a state that meets the performance requirements when the segment relative motions return to the performance range.	D	
0610	A local ground connection between members of each drive/sense pair shall be provided across the gap.	D	
0620	The BPS shall survive 200,000 (TBC) cycles of the full performance range of motion without loss of performance.	D/A	Wear calculation (A)

Compliance spreadsheet, 5

0630	The BPS shall survive 200,000 (TBC) cycles of the full operational range of motion without loss of performance.	D/A	Wear calculation (A)
0640	The BPS shall not produce particulate or chemical contamination.	D	Strictly, there is a wear surface at the boot: need to reconcile 0290,0640,0650
0650	The BPS shall have less than 1% TML (TBC) and less than 0.1% CVCM (TBC) measured according to the ASTM-E595 standard test for outgassing (TBC).	D	Delrin achieves this
0660	Components of the BPS attached to the segment glass shall have a mass of less than 100g per sensor half (TBC).	D/I	CBE is 70g based on weighing and scaling prototype. This should move to ICD.
0665	Components of the BPS attached to the segment at each sensor edge shall have masses that are consistent from unit to unit within 5 g (TBC) per sensor half.	D	This should move to ICD
1020	The sensor shall provide measurements of dz (height), ?x (dihedral angle), and dy (gap). The measurement of dz and ?x shall be combined linearly in a single output.	D	
1040	The M1CS shall use sensor gap readings to correct the sensor height readings in the presence of in-plane motion.	D/A	Extensive sensor calibration modeling
1060	The sensor system shall not require any specific externally initiated initialization procedure upon power up. The sensors shall stabilize to the correct value within 60 (TBC) minutes of a cold start up.	N/A	This is an SCC requirement
1080	The sensor electronics and sensor heads shall be interchangeable such that any electronics unit (or sensor head) can be substituted for any other electronics unit (or sensor head) without local calibration or adjustment to match the components to which it	D	APS run required
1100	The performance range for dy (gap) shall be no less than 4.8 ¦ 1.0 mm.	D/T	These were functionally tested with an earlier version of the sensor. We rely on the sensor physics model to allow us to extrapolate detailed performance testing at one point in the operational range to the full range

Compliance spreadsheet, 6

1120	The performance range for dx (shear) shall be no less than 0.0 ¦ 1.0 mm.	D/T	"
1140	The performance range for dz (height) shall be no less than ¦ 100 micron prior to the application of any electronic offset.	D/T	"
1142	The sensor shall meet all requirements over a relative height range of ¦ 0.25 microns anywhere within the performance range.	D/T	"
1160	The performance range for ?x (dihedral angle) shall be no less than 0 ¦ 1.5 mrad.	D/T	"
1180	The performance range for ?y (rotation about y) shall be no less than 0 ¦ 1.0 mrad.	D/T	"
1200	The performance range for ?z (rotation about z) shall be no less than 0 ¦ 3.5 mrad.	D/T	"
1220	The performance of the sensor shall degrade gradually from the performance range to the operational range for each axis.	D	
1222	The sign of the sensor signal shall be correct over the full operational range on all axes.	D	
1224	The operational range for dx (shear) shall be no less than 0 ¦ 2.0 mm.	D	
1226	The operational range for dy (gap) shall be no less than 4.8 ¦ 2.0 mm.	D	
1228	The operational range for dz (height) shall be no less than 0 ¦ 5 mm.	D	
1230	The operational range for ?x (dihedral angle) shall be no less than 0 ¦ 3 mrad.	D	
1232	The operational range for ?y (rotation about y) shall be no less than 0 ¦ 2 mrad.	D	
1234	The operational range for ?z (rotation about z) shall be no less than 0 ¦ 7 mrad.	D	
1145	The sensor shall provide an offset capability to the height output with a resolution of 0.5 micron or less over the performance range for height.	D/T	<0.5 um
1240	The measurement noise in dz (height) shall be less than 5 nm rms in a 2 Hz bandwidth (2.8 nm/vHz).	D/T	<2.2 nm/rHz
1280	The primary measurement noise in dy (gap) shall be less than 0.5 micron rms in a 1 Hz bandwidth. [REQ-2-M1CS-3000	D/T	<0.13 um/rHz

Compliance spreadsheet, 7

1300	A change in dx (shear) of ¦ 0.3 mm shall cause less than 5 nm change in the reading of dz (height) with respect to the sensor model.	D/A	Sensor physics model plus Maxwell model of coating edge effects (A)
1320	A change in dy (gap) of ¦ 0.3 mm shall cause less than 5 nm change in the reading of dz (height) with respect to the sensor model.	D/T	sensor physics model; we have seen some electrical cross coupling we don't understand, but which doesn't seem to be compromising performance
1330	The sensor Leff shall be at least 45 mm, that is, a change in ?x (dihedral angle) of 1.0 mrad shall cause at least a 45 micron change in the reading of dz when measured at a gap of 4.8 mm.	D	sensor physics model
1335	A change in ?z (rotation about z) of ¦ 0.1 mrad shall cause less than 2 nm change in the reading of dz (height) with respect to the sensor model.	D	sensor physics model
1340	A change in dx (shear) of ¦ 0.3 mm shall cause less than 1.0 micron change in the reading of dy (gap) with respect to the sensor model.	D	sensor physics model
1350	A change in ?x (dihedral angle) of ¦ 0.1 mrad shall cause less than 0.5 micron change in the reading of dy (gap) with respect to the sensor model.	D	sensor physics model
1355	A change in ?y (rotation about y) of ¦ 0.1 mrad shall cause less than 0.5 micron change in the reading of dy (gap) with respect to the sensor model.	D	sensor physics model
1360	A change in ?y (rotation about y) of ¦ 0.1 mrad shall cause less than 2 nm change in the reading of dz (height) with respect to the sensor model.	D	sensor physics model
1380	A change in ?z (rotation about z) of ¦ 0.1 mrad shall cause less than 0.5 micron change in the reading of dy (gap) with respect to the sensor model.	D	sensor physics model
1400	The integral linearity in the measurement of dz (height) shall be 0.1% or better over any interval within the performance range.	D	elex design - not hard
1440	The integral linearity in the measurement of the gap electrical signal shall be 0.1% or better over any interval within the performance range.	D	elex design - not hard
1460	The residual from sensor flexure shall be less than 2 nm rms averaged over the ensemble of sensors after calibration.	D/A	Flexure modeled in SolidWorks; incorporated in the sensor calibration model

Compliance spreadsheet, 8

1500	The temperature sensitivity of the offset of the height (dz) measurement for each sensor shall be 0 ¦ 1 nm/C after calibration.	D/T	We measure 12 nm/C before calibration, and incorporate that in the calibration model. Ideally, we'd like this number to be < 6 nm/C before calibration
1502	The average temperature sensitivity of the offset of the height (dz) measurement for the ensemble of sensors shall be 0 ¦ 1 nm/C after calibration.	D/T	An ensemble requirement, but met if 1500 is met
1515	The temperature sensitivity of the gap (dy) measurement for each sensor shall be 0 ¦ 0.25 micron/C after calibration.	D/T	0.18 um/C before calibration
1518	The temperature sensitivity of the gain of the height (dz) measurement for each sensor shall be 0 ¦ 0.01%/C after calibration.	D	component selection
1520	The long term drift of the offset of the height (dz) measurement for the ensemble of sensors shall be less than 5 nm rms in 30 days after calibration, and after an initial 24 h settling time in the event of a sensor replacement.	D/T	4.4 nm rms over 24 days for one sample. (NB: we interpret spec as 3.5 nm [1/2 of final variance] as the average value over the interval).
1522	The average long term drift of the offset of the height (dz) measurement for the ensemble of sensors shall be 0 ¦ 4 nm in 30 days after calibration.	D/T	4.4 nm rms over 24 days for one sample
1560	The long term drift of the gap (dy) measurement for each sensor shall be 0 ¦ 0.5 micron in 30 days after calibration.	D/T	0.2 um over 24 days
1570	The long term drift of the gain of the height (dz) measurement for each sensor shall be 0 ¦ 0.05% in 30 days after calibration.	D	Component selection
1580	The average humidity error of the height (dz) measurement for the ensemble of sensors shall be 0 ¦ 2 nm after calibration for all relative humidities in the performance range.	D	We rely on boot for this
1582	The humidity error of the height (dz) measurement for the ensemble of sensors shall be less than 2 nm rms after calibration for all relative humidities in the performance range.	D	We rely on boot for this

Compliance spreadsheet, 9

1600	The operational sampling rate shall be no less than 40 Hz.	D/T	400 Hz tested
1620	The diagnostic sampling rate shall be no less than 400 Hz.	D/T	400 Hz tested
6100	The edge sensor system shall be designed for a 50 year operational lifetime.	D	
6200	The sensor system shall comply with the TBD sensor allocation of the downtime budget.	N/A	Elex designed for robustness to ESD, but full reliability flown down not completed
6220	The sensor system shall comply with the TBD sensor reduced-performance budget.	N/A	More work needed to define requirement.
6240	Line-replaceable units of the sensor system shall be replaceable in less than 10 minutes (TBC) by a trained technician.	N/A	Maintenance plan not for PDR; needs better definition. Expect electronics to be only LRU.
7410	The sensors shall not emit electromagnetic radiation that would interfere with or degrade the performance of systems or subsystems at the observatory.	N/A	No traceable requirement at this time, but electronics emission is small and narrow band.
7540	The sensor shall not contain any corrosive or hazardous materials that could pose a threat to personnel.	D	
7560	The sensor shall not contain any highly flammable materials or generate an open spark.	D	
8000	As a goal the sensors will require no regular scheduled maintenance. It shall not be necessary to remove, release, or otherwise "manage" the sensors in order to remove a primary mirror segment from the telescope. It is acceptable to disconnect electrical	D	Is compliant as written: NB need to remove ground wire on seg exchange.
8105	All the tasks necessary to fully service a sensor during its scheduled servicing shall take no longer than 20 minutes per sensor (TBC).	N/A	Maintenance plan not for PDR, but see no difficulties in meeting this during segment replacement

Risks

These are high-level development risks and operational concerns

They augments the reliability risk matrix previously presented, which addresses post-delivery risks

Achieving required stability & accuracy

-The different face-on geometry and tight requirements for the TMT sensor leads to capacitance-measurement requirements that are ~10x harder than Keck, i.e., we can't be complacent just because Keck achieves good performance

- Risk reduction in P2 phase, and in TMT and M1CS architecture decisions
  - Generated traceable requirements
  - Investigated limitations of sensor equation: led to requirements on coating edges
  - Added dust boot to eliminate humidity concerns
  - Increased Leff 2x over P1 version to address correlated error propagation
  - Incorporated optical feedback from AGWFS and AO for low-order modes
  - Incorporated focus-mode (scalloping) sensing by AO
  - Incorporated sensor-by-sensor calibration using gap measurements
  - Verified use of sensor calibration for other systematic terms
  - Designed for high stability: blocks & electronics
  - Prototyped key components
  - Performed laboratory testing against requirements

TMT vs. Keck sensors

The in-plane geometry of the TMT sensor makes them more challenging

		Keck	TMT	
		interlocking	face-on	
		168 sensors	2772 sensors	
Sensitivity				
plate width		30	30	mm
plate height		30	20	mm
gap btwn plates		4	4.8	mm
capacitance between plates (C)		2.0	1.1	pF
sensitive axis for mirror piston z		gap	height	
$\partial C / \partial z$ (one electrode)		C / gap = 0.5	C / height = 0.06	pF/mm
Leff				
value		55	52	mm
properties		physical	$\propto$ 1/gap	
Sensitivity to in-plane motion (no mounting errors)				
segment X		none	none	
segment Y		none	$\propto$ 1/gap	
Second output		none	"gap output" $\propto$ 1/gap	
		no self cal for in-plane effects	allows for self cal of in-plane effects	

1 Accommodation of bad sensors

-Strictly scaling from Keck, TMT would have 100's of bad sensors at any one time (although we hope that the design approach taken here will lead to few bad sensors)

-Similarly scaling from Keck, which has a similar level of redundancy, good performance can be achieved if bad sensors are identified and removed from the controller

-However, with more sensors, this needs to be done more frequently

- Potential impact
  - Operational overhead, mostly
- Risk
  - Medium
- Plan
  - Bad-sensor operational plan needs development and modeling

2 Block/coating production

-The blocks and coating are specified to high accuracy

-In particular, there are tight requirements on the lithography of the coatings

- Potential impact
  - Degraded sensor performance
- Risk
  - Low
- Plan
  - Monitor / inspect prototype blocks/coatings
  - Develop robust QA plan for production

3 Electronic cross talk

-We currently require a ground lead across the gap to meet requirements (Keck also has local ground connection)

-Crosstalk was observed in the lab for adjacent independent setups

- Potential impact
  - Degraded sensor performance
- Risk
  - Medium
- Plan
  - Galvanic isolation should be included in next iteration of the design
  - Also need to address this for sensors which span node boxes

4 Electronic stability

-The electronics are close to, but not at, the drift/tempco requirements

- Potential impact
  - Degraded sensor performance
- Risk
  - Low
  - Informed by SPICE model, the design can be improved within the same power/cost envelope
- Plan

  Iterate design

5 Stability of block interconnect

-The indium/gold solder connection is not mechanically strong, and indium & gold can react under some circumstances (but usually only at elevated temperatures)

- Potential impact
  - Operational overhead, mostly, given sensor redundancy
- Risk
  - Low (Keck runs this way)
- Plan
  - Post PDR, examine alternatives to indium

6 Sensor installation tolerance

-Good sensor calibration requires sub-milliradian control of the relative sensor-to-sensor angles

-This is not controlled directly; rather, the individual blocks are positioned to high accuracy depending on the accuracy of pockets, segments, etc.

- Potential impact
  - Degraded in-plane correction
- Risk
  - Medium (or similar to other issues associated with segmentation)
- Plan
  - No action at this time

7 Calibration scenario overhead

-Multiple APS runs at different Z and T are required to achieve good performance, including after segment replacement

-Additional free variables may be required to model unforeseen errors

- Potential impact
  - Operational overhead, mostly, as the approach straightforwardly generalizes
- Risk
  - Low
- Plan
  - Additional cases should be run
  - Incorporation of multiple APS runs into TMT scenarios

8 Long term boot reliability

-Boots are essential to deal with humidity and dust

-Low allowed forces and print-through, as well as requirement for no boot management during segment install, make it a hard design

- Potential impact
  - Operational overhead, mostly
- Risk
  - Low
- Plan
  - FDP task

Summary, I

- Keck heritage, but significant differences to accommodate TMT requirements and incorporate new technology
  - Lots of sensors
  - Face-on non-interlocking design
  - Dust boots and dry-gas purge system for good performance under all conditions
  - Collocated electronics with digital i/o
  - More complicated sensor equation
  - Gap output used to linearize sensor response and as input to in-plane calibration approach
  - Operational considerations, esp. frequency of segment replacement, drives requirements

Summary, II

- Sensor requirements are well understood, traceable through the M1CS DRD to the TMT parent documents
- Key interface of mounting sensor to segment well developed
- Compliant block/coating/boot and electronics design developed and prototyped
  - Key requirements demonstrated at or close to required level
  - Additional post-PDR and FDP tasks identified to close gaps, informed by modeling
- Sensor calibration approach extensively simulated using traceable input parameters
  - Performance and sensitivity understood
  - Performance close to placeholder value in OAD, although some reallocation probably needed among APS and M1CS terms
- Operational aspects identified; key ones addressed
- Remaining risks identified; mitigation approaches discussed