Daniel K. Inouye Solar Telescope

Commissioning & Calibration of DKIST

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NSO National Solar Observatory

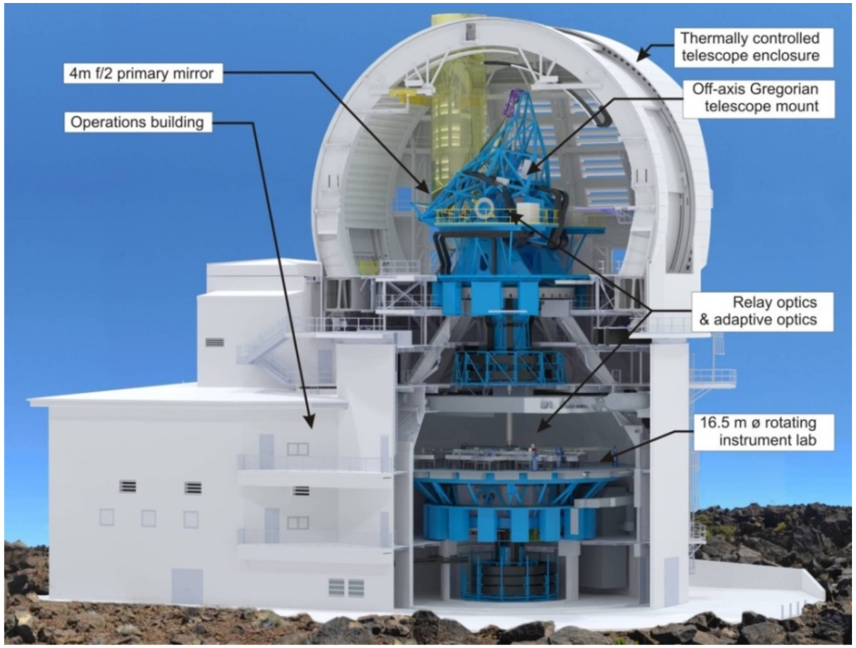
NSF

AURA

www.nso.edu

The telescope

- Four-meter aperture
- All reflecting, off axis design
- Integrated adaptive optics
- Low-scattered light
- High-precision polarimetry
- Facility-class instruments
- A site with excellent seeing and coronal skies



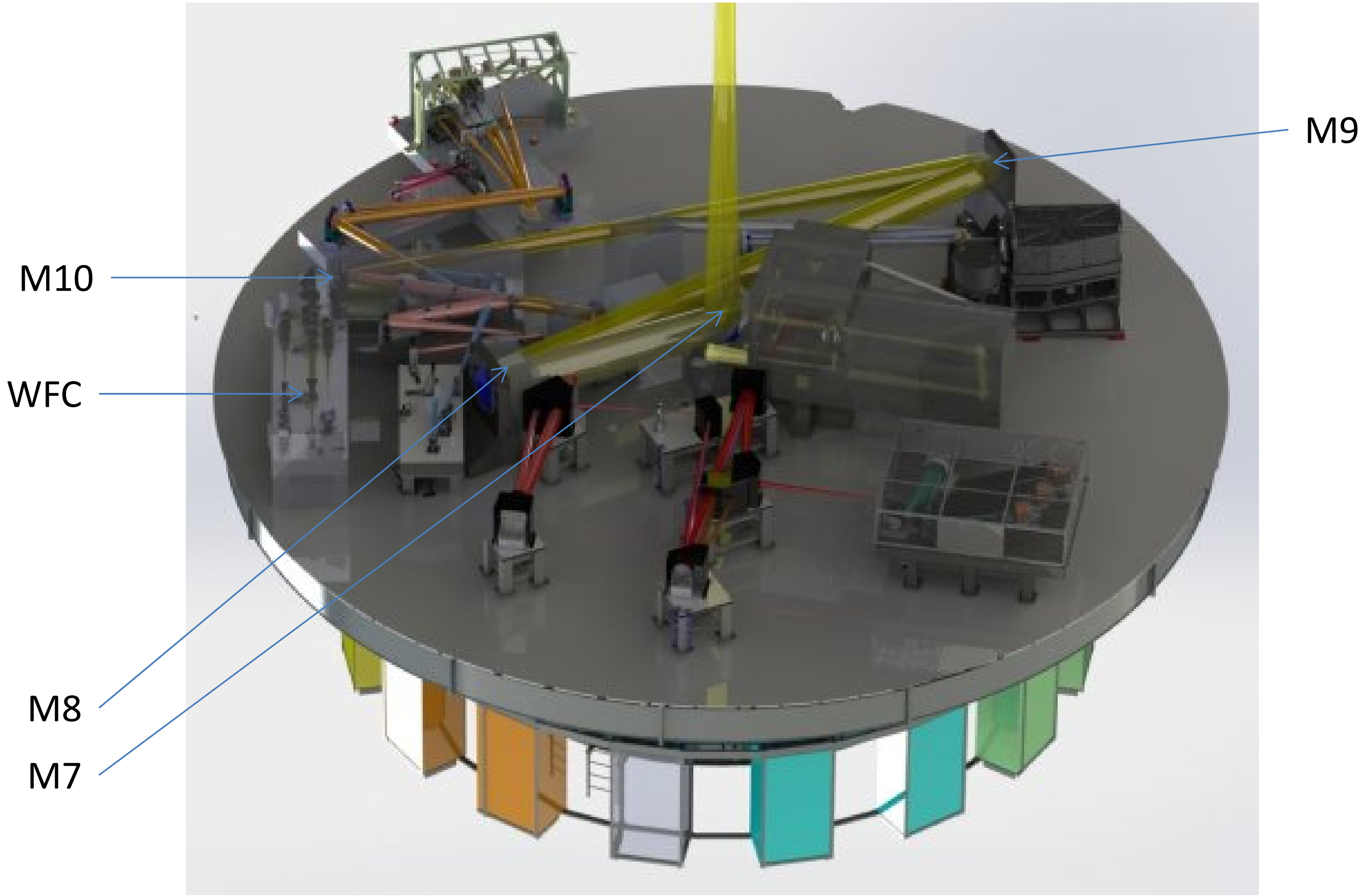
Spatial Resolution (25km@500nm)

Polarimetry (accuracy:5x10-4; sensitivity: <10-5)

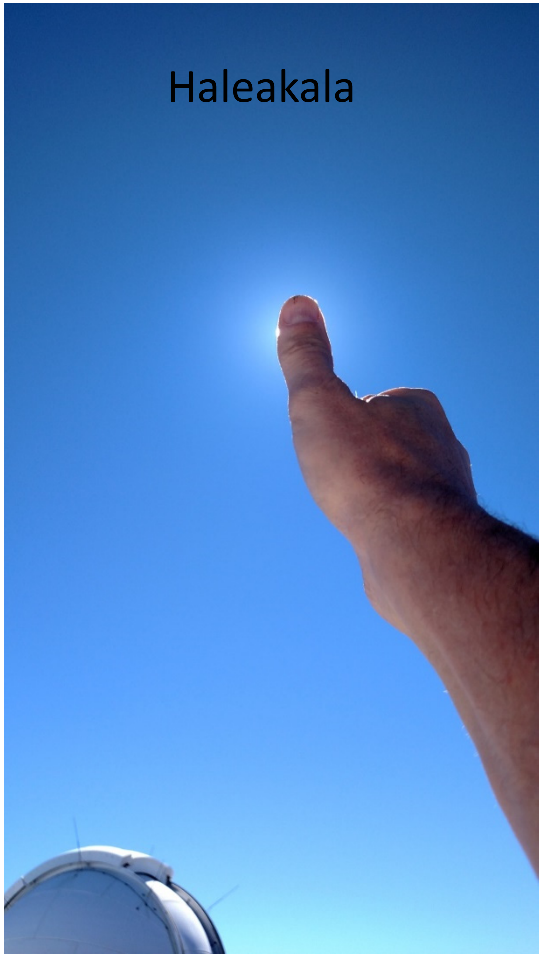
Large collecting area ; Low Scattered Light

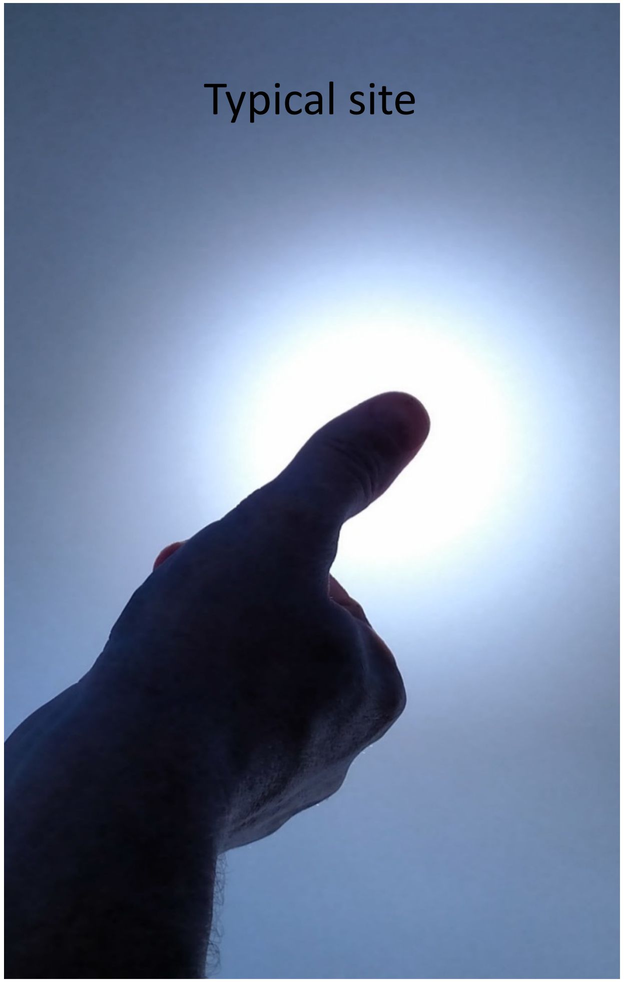
Simultaneous UV, VIS, NIR & Far Infrared

Instruments & Coude Lab

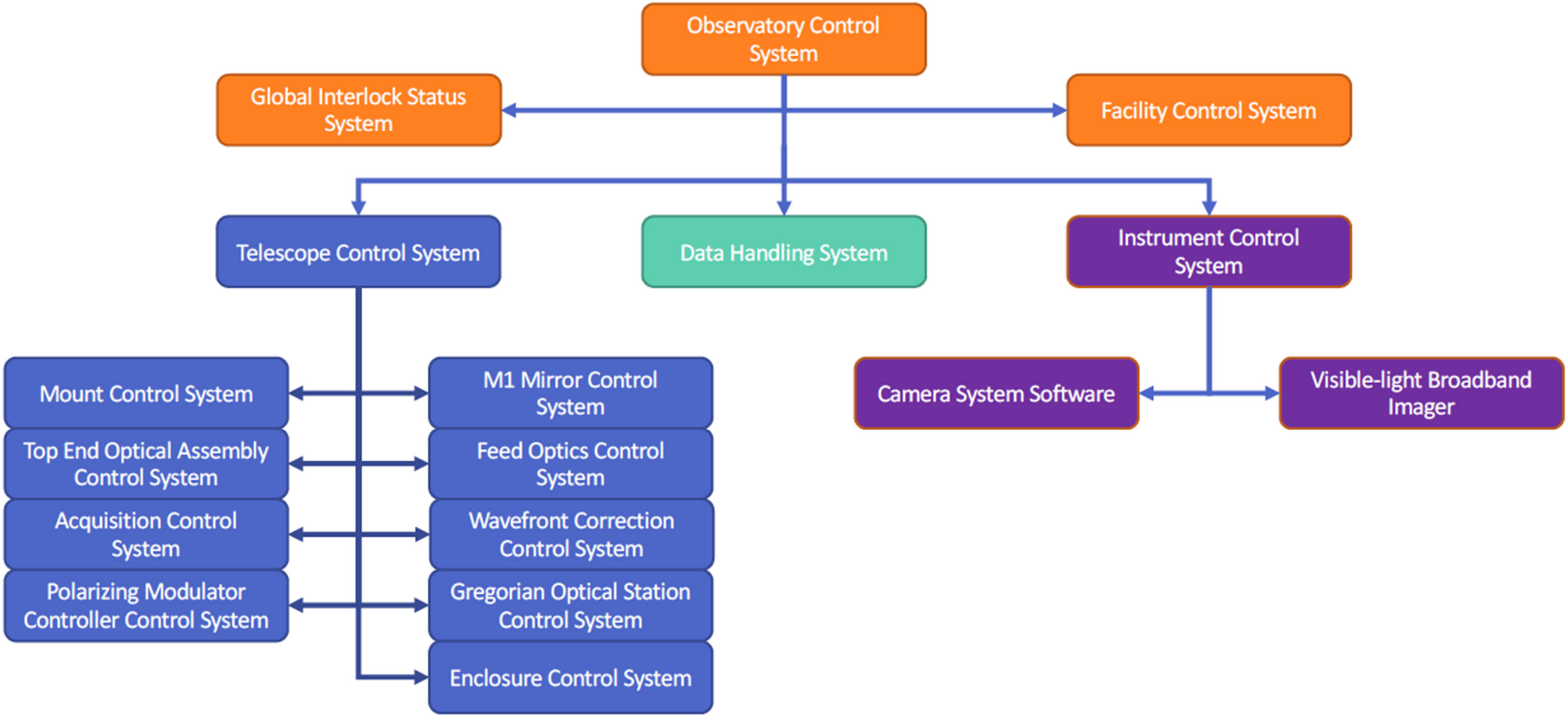


The site

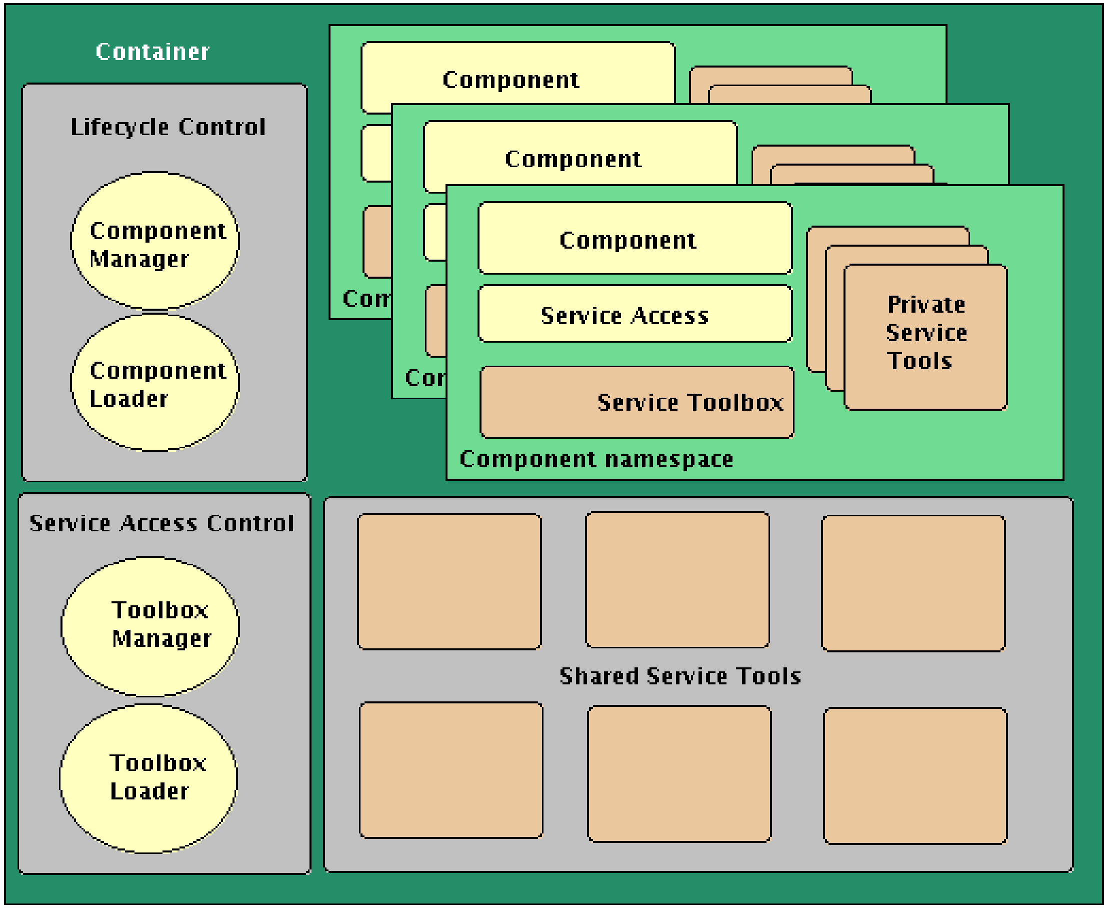




Control System



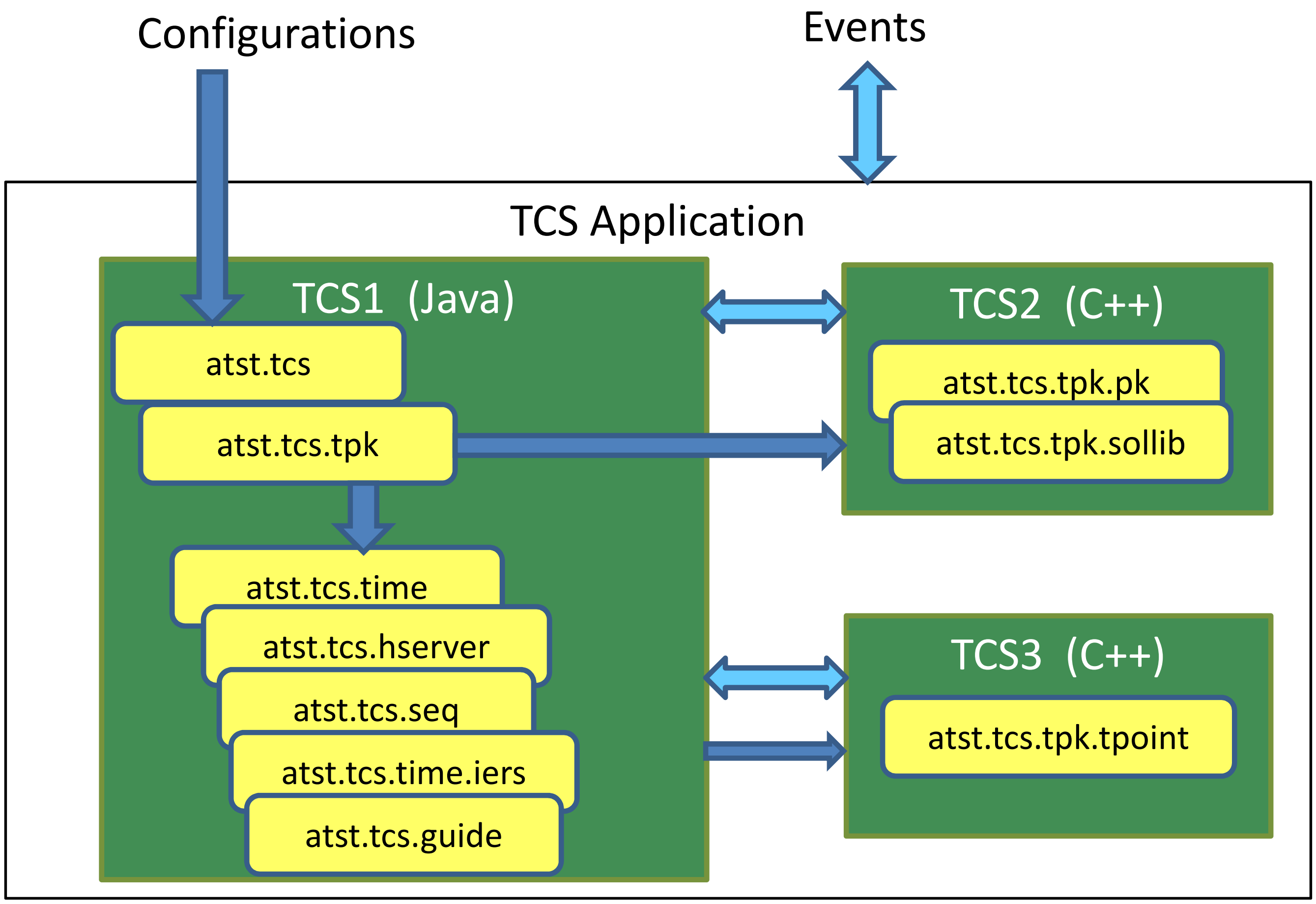
Containers & Components



Common Services

- Log Service – record messages in permanent store
- Connection service – allows components to find each other by name
- Event Service – publish-subscribe mechanism
- Health service – uniform mechanism for monitoring a components state
- Property Service – permanent store of attributes & metadata
- Archive Service – log attributes to archive database

Example (TCS)


Configurations
Events
TCS Application
TCS1 (Java)
atst.tcs
atst.tcs.tpk
atst.tcs.time
atst.tcs.hserver
atst.tcs.seq
atst.tcs.time.iers
atst.tcs.guide
TCS2 (C++)
atst.tcs.tpk.pk
atst.tcs.tpk.sollib
TCS3 (C++)
atst.tcs.tpk.tpoint

Control System Integration & QA

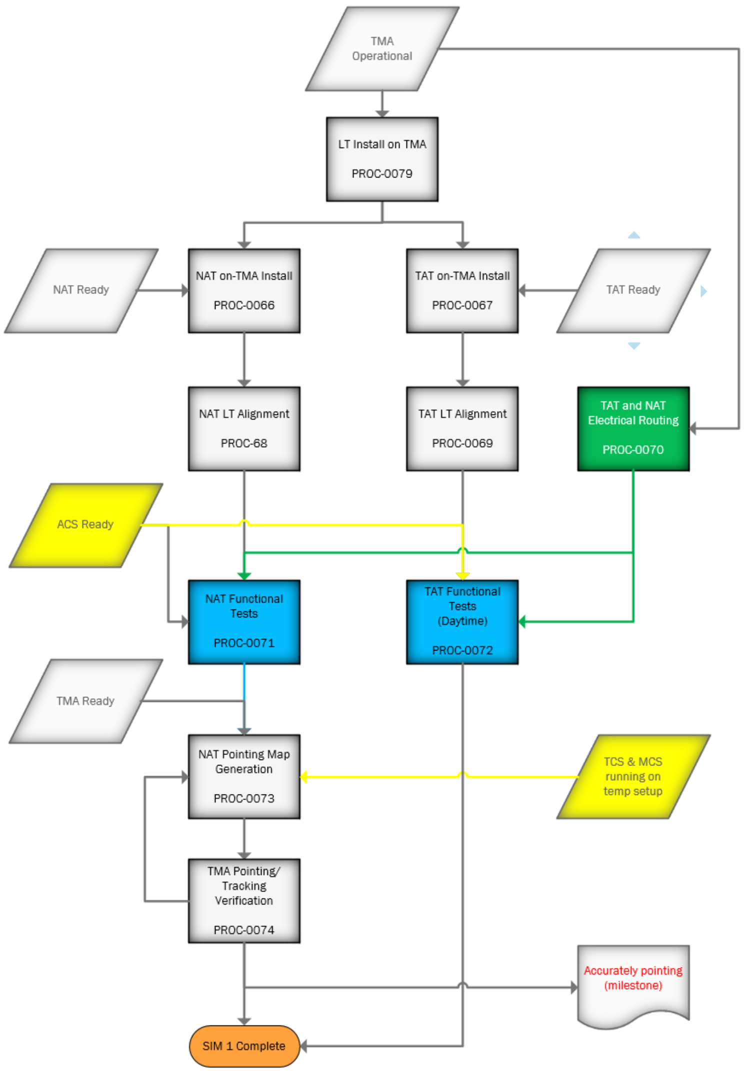
- All control systems delivered with simulators
- End to End Simulator (E2E) in Tucson & Boulder
  - Can run whole control system TCS, DHS, ICS, Camera lines etc.
- QA system spawns virtual machines and executes tests each night
  - See TUPHA008 for further details

System Integration Modules

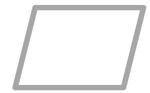
- SIM 1: Telescope Pointing Map
- SIM 2: M1 Integration
- SIM 3: M1 + M2 Integration
- SIM 4: M1 – M6 Integration
- SIM 5: Coudé Optics + FIDO Integration
- SIM 6:
  - 6a: Visible Broadband Integration (VBI) Integration
  - 6b: Wave-front Control (WFC) Integration
- SIM 7: First Light Initiative (FLI)
- SIM 8: Gregorian Optic Station (GOS) Integration
- SIM 9:
  - 9a: Cryo-NIRSP Integration
  - 9b: DL-NIRSP Integration
  - 9c: ViSP Integration
  - 9d: VTF integration
- SIM 10: Polarization Calibration
- SIM 11: Multi-Instrument Verification

Telescope Pointing

SIM 1, Telescope Pointing Map



- Rectangular blocks represent independent activities.



- Rhomboid blocks are precondition requirements.

- Document blocks represent milestones for the work.

- Ovals represent the SIM completions and linkages to other SIMs

Commissioning & Calibration

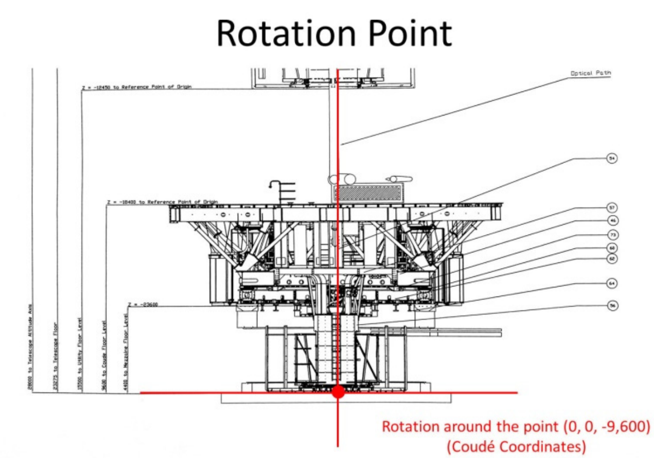
- Image jitter
- Pointing tests
- Open loop lookup tables
- World Coordinate System Calibration

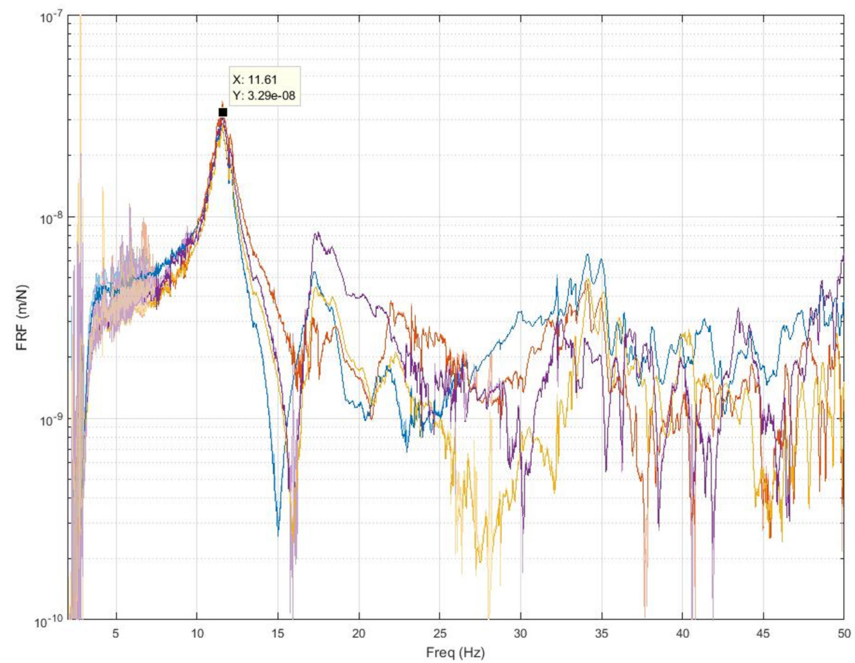
Image Jitter & Coude SAT

- Total image jitter budget from all sources is 75mas
- How to quantify this without an image ? Encoders + accelerometers + optics model
- Factory results were 17 mas from mount & 5 mas from coude
- Results on site were 0.5 mas for coude
- BUT coude was balanced and lightly loaded

Model

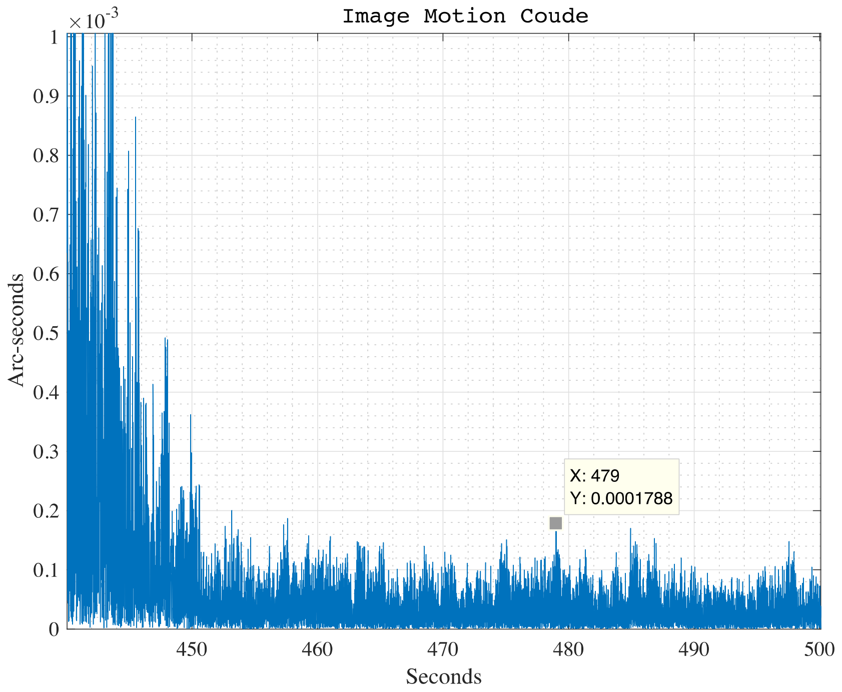
- Assume rigid body rotation
- Rotation is about point 9.6m below coude
- This is the primary structural mode





Measurements

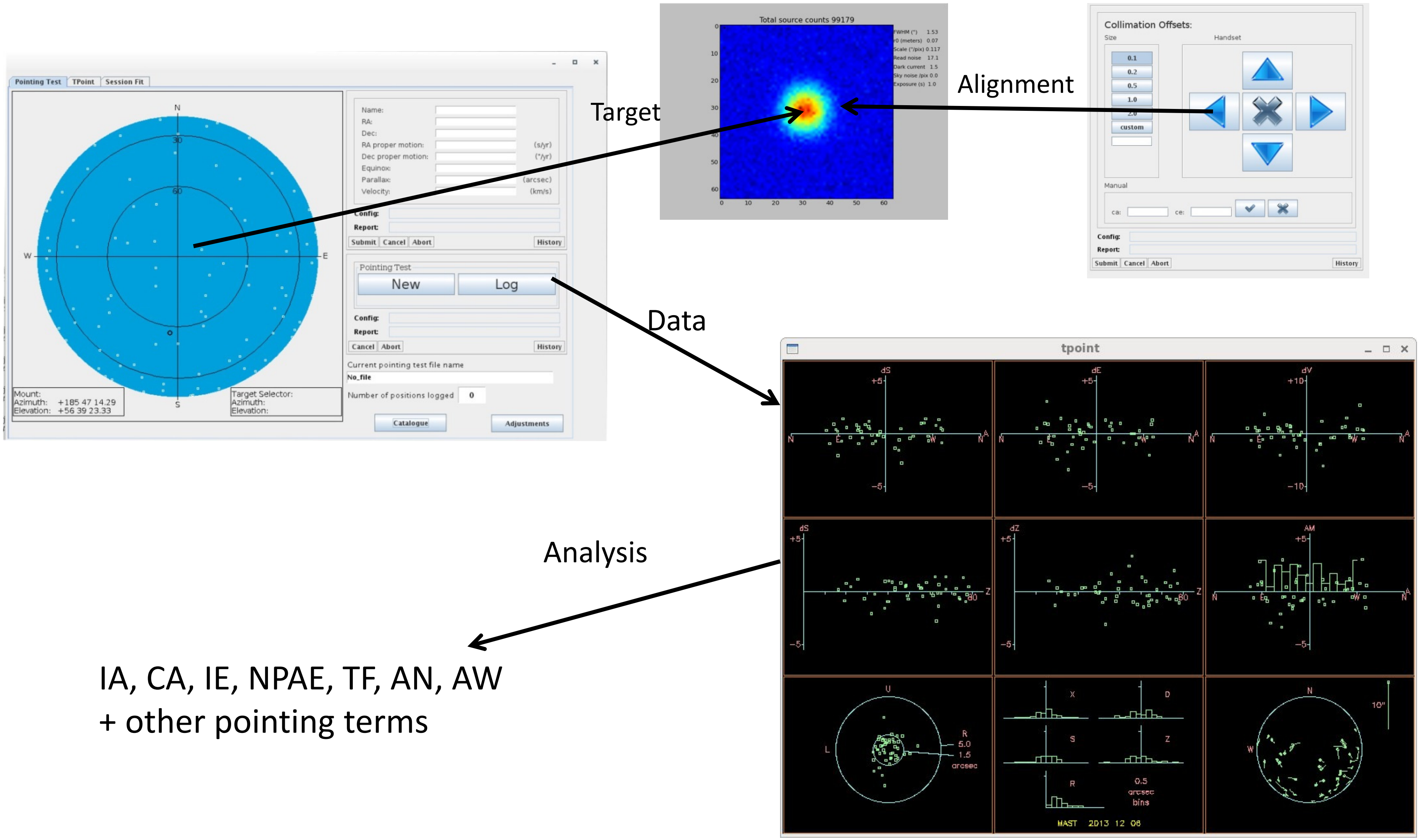
- Various typical "tracks" were executed
- Accelerometer data converted to displacements
- Optics model (M7 – M10) used to convert to image motion in focal plane



Pointing Tests

- Good absolute pointing is important for target acquisition and open loop tracking
- DKIST specification is 1.7 arcsec rms anywhere on sky
- Sun itself is not a good pointing target as the only absolute position is the limb
- Pointing tests will be performed on stars at night initially with NAT finally with Context Viewer

Pointing Tests



IA, CA, IE, NPAE, TF, AN, AW
+ other pointing terms

M1/M2 lookup tables

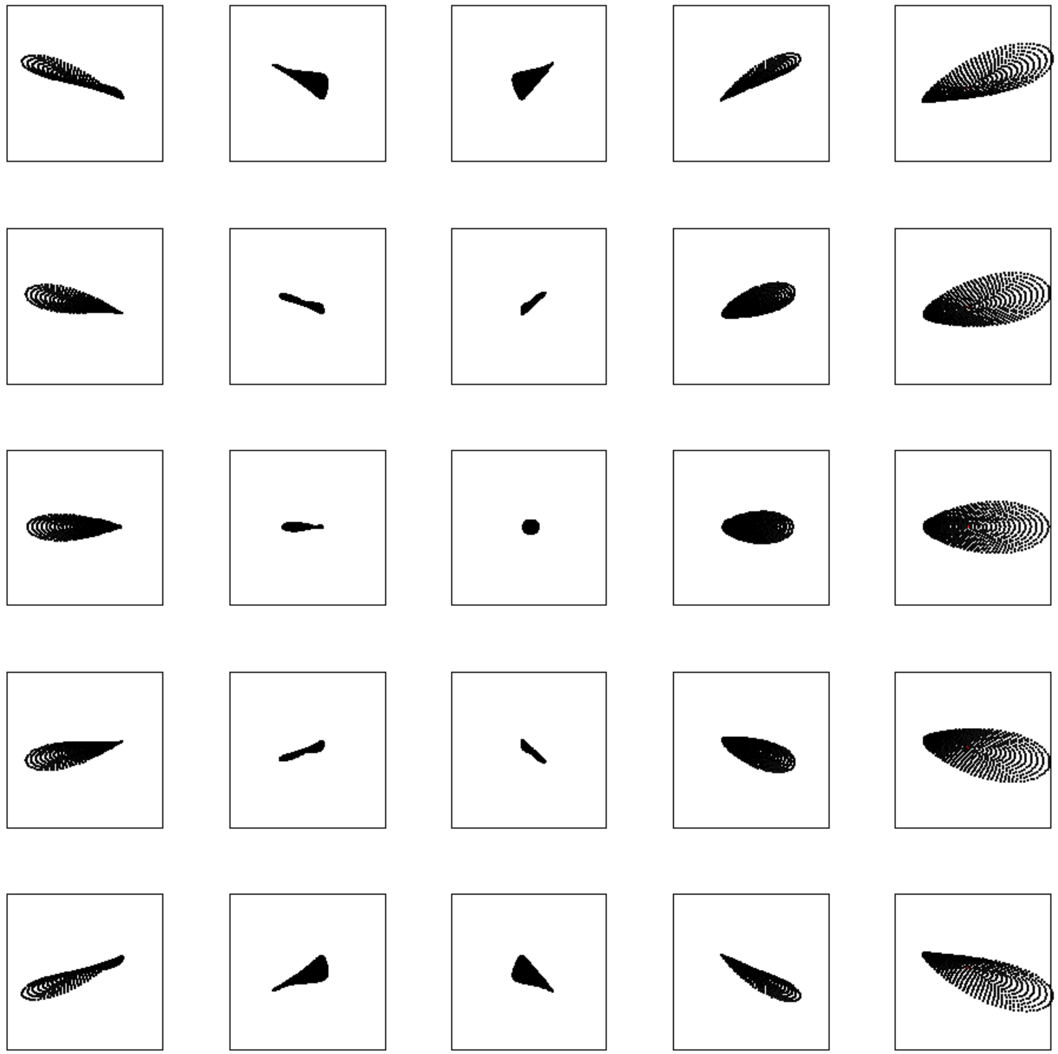
- Need good image quality when wavefront correction is not available e.g. coronal observations
- Primary mirror is thin (75 mm) so needs active support
- Top end (M2) sags as elevation changes
- Initial LUTs will be determined using a commissioning Shack-Hartmann wave front sensor

M1/M2 Lookup tables

- Optics model predicts wave front as a function of position x, y z in focal plane.
- Decompose wave front into Zernike terms
- WFS will measure focus, coma astigmatism on a grid say 3x3x3 using observations of polaris
- Minimize measurements compared to model to solve for position of primary focus

M1/M2 Lookup tables

- Optic nction
  of po
- Deco ns
- WFS sm on
  a gric olaris
- Minir nodel
  to sol



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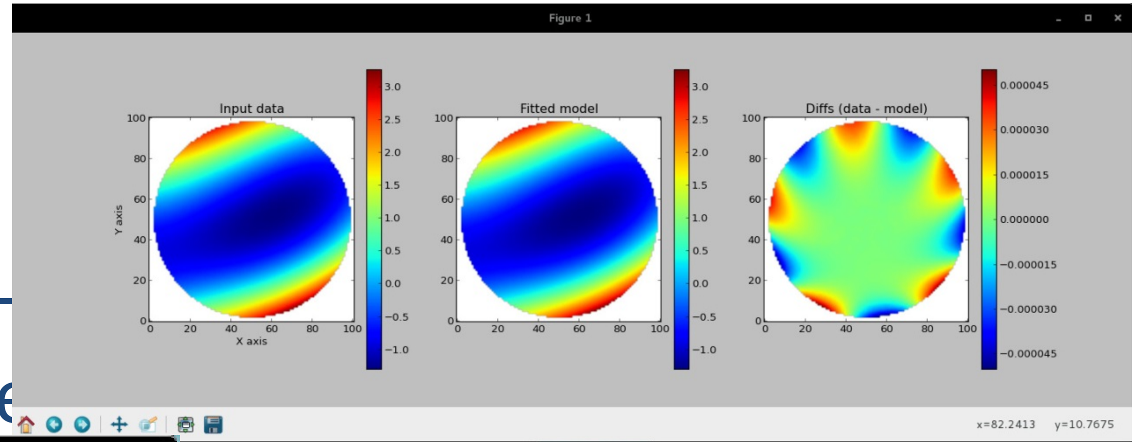
DKIST
DANIEL K. INOUYE SOLAR TELESCOPE



- Optics model pre … cal plane.
- … nt into Zernike terms
- … us, coma astigmatism on
- … observations of polaris
- … nts compared to model
- … f primary focus

Fit wavefront data

Fit Zernike coefficient values

Fringe index	Noll index	Ansi n, m	Polynomial	Select	Value (microns)
1	1	(0, 0)	1	☑	0.006010
2	2	(1, 1)	2ρ*cos(θ)	☑	0.015502
3	3	(1, -1)	2ρ*sin(θ)	☑	0.040833
4	4	(2, 0)	√3*(2ρ²-1)	☑	0.723423
5	6	(2, 2)	√6ρ²cos(2θ)	☑	-0.592674
6	5	(2, -2)	√6ρ²sin(2θ)	☑	0.593140
7	8	(3, -1)	√8(3ρ²-2)ρcos(θ)	☑	0.080991
8	7	(3, 1)	√8(3ρ²-2)ρsin(θ)	☑	0.063732
9	11	(4, 0)	√5(6ρ⁴-6ρ²+1)	☑	-0.003902
10	10	(3, 3)	√8ρ³cos(3θ)	☑	0.014925
11	9	(3, -3)	√8ρ³sin(3θ)	☑	0.014912
12	12	(4, 2)	√10(4ρ²-3)ρ²cos(2θ)	☑	0.002824
13	13	(4, -2)	√10(4ρ²-3)ρ²sin(2θ)	☑	-0.003162
14	16	(5, 1)	√12(10ρ⁴-12ρ²+3)ρcos(θ)	☑	-0.000256
15	17	(5, -1)	√12(10ρ⁴-12ρ²+3)ρsin(θ)	☑	-0.000110
16	22	(6, 0)	√7(20ρ⁶-30ρ⁴+12ρ²-1)	☑	0.000017
17	14	(4, 4)	√10ρ⁴cos(4θ)	☑	0.000387
18	15	(4, -4)	√10ρ⁴sin(4θ)	☑	-0.000388
19	18	(5, 3)	√12(5ρ²-4ρ)ρ³cos(3θ)	☑	-0.000101
20	19	(5, -3)	√12(5ρ²-4ρ)ρ³sin(3θ)	☑	-0.000094
21	24	(6, 2)	√14(15ρ⁴-20ρ²+6)ρ²cos(2θ)	☑	-0.000010
22	23	(6, -2)	√14(15ρ⁴-20ρ²+6)ρ²sin(2θ)	☑	0.000014
23	30	(7, 1)	√16(35ρ⁶-60ρ⁴+30ρ²-4)ρcos(2θ)	☑	7.524961e-07
24	29	(7, -1)	√16(35ρ⁶-60ρ⁴+30ρ²-4)ρsin(2θ)	☑	-8.573356e-08

Pupil radius (mm) 2000.000

Read data | Select all | Clear all | Fit data | Display results

- (•) Image
- ( ) Wire frame
- ( ) Surface plot

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M1/M2 Lookup tables

- Move WFS to best focus
- Close loop to M1 and off load residual wavefront errors. The sensitivity matrix yields forces to be applied to mirror

$$F_i = M_{ij} Z_j$$

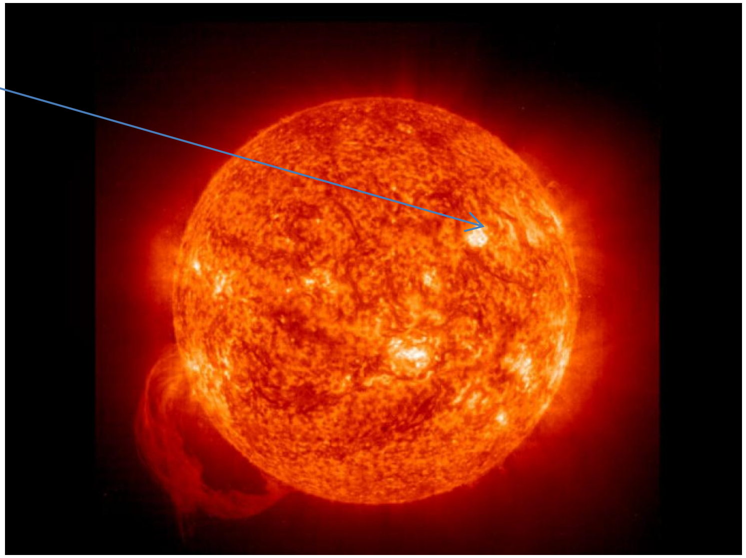
- Repeat process at different elevations and fit

$$Z = A\cos(el) + B\sin(el) + C$$

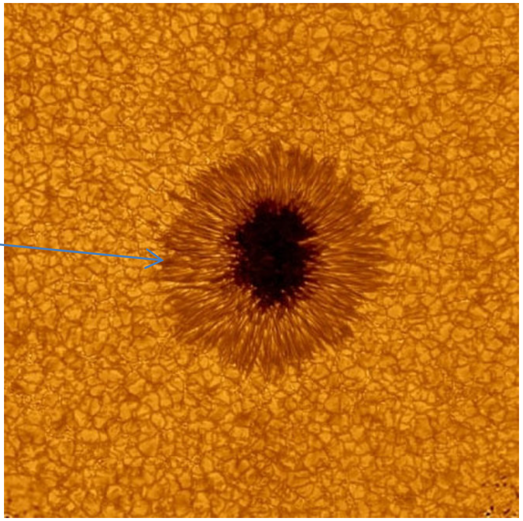
Both for M2 x,y,z and for M1 Zernikes Z_4 to Z_{24}

World Coordinate System

- Where does this feature appear on my detector?



- What are the solar coordinates of this point in my image?



World Coordinate System

- All transformations are linear

$$X = a[0] + a[1] * x + a[2] * y$$
$$Y = a[3] + a[4] * x + a[5] * y$$

- TCS x, y -> Sky (T2S)
- Context viewer pixels -> TCS x, y (C2T)
- Instrument pixels -> CV pixels (I2C)
- Only T2S has skew otherwise a[1] = a[5] and a[2] = -a[4]

$$\xi, \eta = T2S(C2T\left(I2C(p_x, p_y)\right))$$

DKIST Commissioning & Calibration

Questions ?