



Jet Propulsion Laboratory
California Institute of Technology

Roman CGI Observing Scenario 11 Time Series Simulations (Shaped Pupil Coronagraph Spectral Mode, Band 3)

John Krist

(Jet Propulsion Laboratory, California Inst. of Technology)

Revised 7 July 2023

Revised 3 March 2024 (fixed XCENTER,YCENTER header keyword values)

Acknowledgements

CGI thermal & structural finite element models (FEMs): Josh Kempenaar, Will Krieger Roman & CGI FEM integration, OS11 reaction wheel speeds, spacecraft FEM: NASA Goddard Integrated Modeling Team

CGI pointing jitter model: David Arndt, Nanaz Fathpour, Milan Mandic

OS11 definition: Brian Kern

CGI STOP model execution & analysis: John Steeves, Navtej Saini, Charley Noecker

CGI Code V model: Mike Rogers

CGI LOWFS model: Brandon Dube

CGI mask designs: A.J. Riggs, Dwight Moody

CGI diffraction model & time series generation: John Krist

CGI EMCCD model: Bijan Nemati, Sam Miller, Kevin Ludwick (all U. Alabamba, Huntsville)

Preface

- These SPC-Spec simulations are intended for evaluating post-processing algorithms
- Observing Scenario 11 (OS11) is representative of a realistic observing sequence, but does not reflect any particular requirements for total observation time, number of rolls, etc. (there is a limit of about $\pm 13^\circ$ on maximum roll relative to the nominal solar normal orientation). Note that it was not optimized for spectrographic performance – such observations may require much longer total exposures.
- OS11 is expected to be the last end-to-end time series
- The thermal+structural modeling results are significantly better than requirements
- The diffraction models intentionally include misalignments, fabrication errors, and uncertainties and do not produce the best possible dark holes, but also may be better than what we really get (they are better than requirements).

Important Note

The time series files provided in this distribution are specifically for SPC-Spec and are intended to represent the images at the plane of the spectrographic slit. The time series images are provided at $0.1 \lambda_c/D$ resolution and at 31 wavelengths spanning Band 3. It is up to the user to apply a slit pattern, disperse the signal onto the detector, and apply detector noise. The CGI spectrograph group at Goddard is planning to eventually release a program that will do this.

These simulations do not include any stellar spectrum or losses from reflections/filters/prisms/detectors. They include coronagraphic mask losses.

Some definitions

- **primary-normalized flux**: image is normalized to the flux incident on the illuminated area of the primary mirror. There are no losses from reflections, filters, QE, etc, but there are losses from masks. In the absence of masks, the total image intensity would be 1.0 over an unlimited extent.
- **normalized intensity**: the per-pixel brightness of the dark hole divided by the peak pixel of the unocculted star. This is sort of a poor man's contrast (because it does not account for field variations in the PSF, especially near the IWA).

Array dimensions are specified here in IDL ordering (fastest-varying index 1st, slowest last).

CGI SPC-Spec Band 3

- Shaped Pupil Coronagraph – Spectroscopy (SPC-Spec)
 - A pupil mask redefines the telescope obscuration pattern to create a tailored diffraction pattern at an intermediate focus
 - A bow-tie-shaped focal plane mask (FPM) with opposing 65° openings spanning $r = 2.6 - 9.4 \lambda_c/D$
 - Lyot stop (also bow-tie shaped)
- Science field is $r = 3 - 9 \lambda_c/D$
- Band 3 is 16.7% width centered at 730 nm

$$\lambda_c/D = 63.7 \text{ mas @ } \lambda_c = 730 \text{ nm}$$

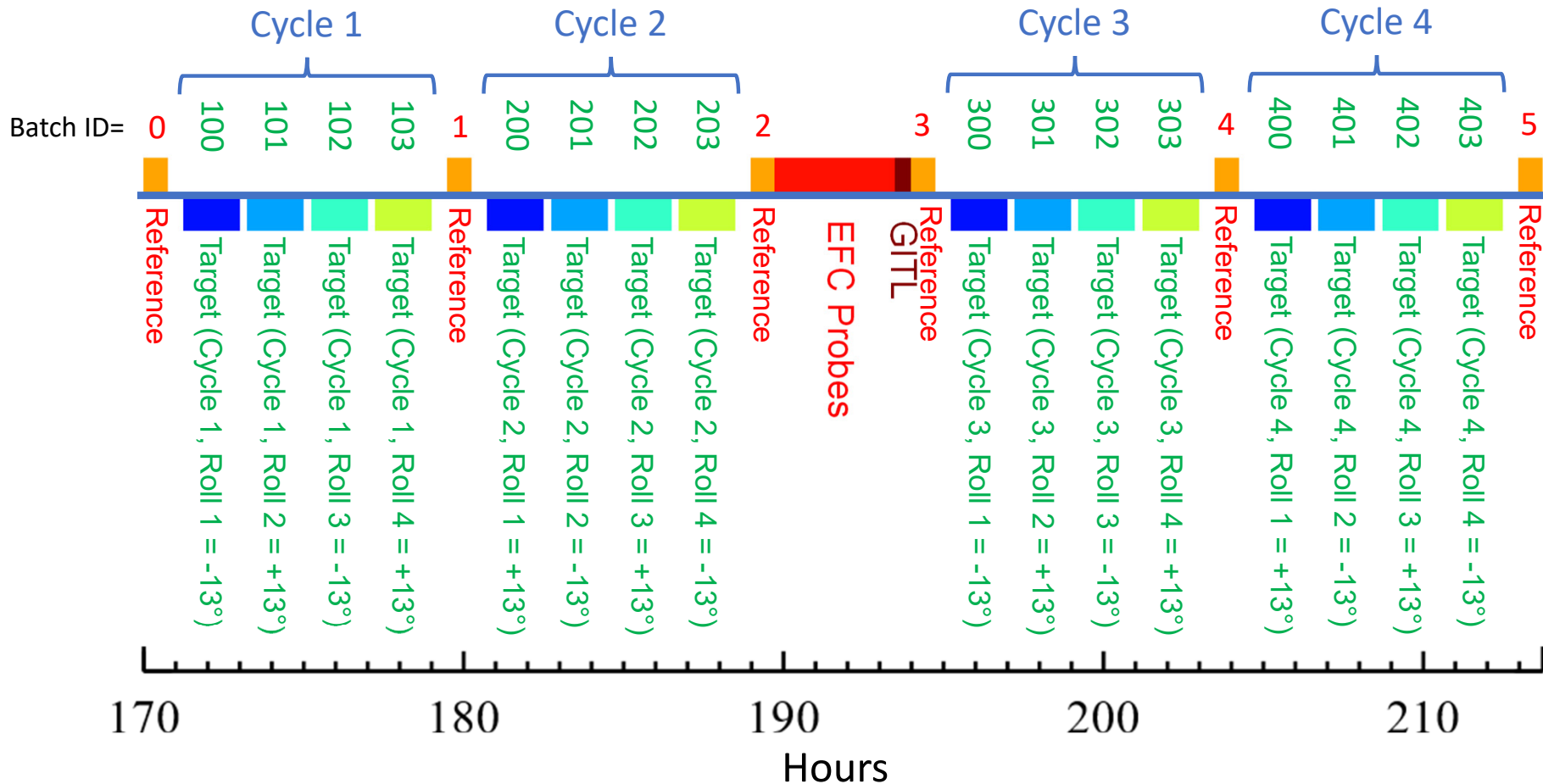
OS 11

- Begin with slew from a WFI High Latitude Survey target to the bright reference star (ζ Pup, $V=2.25$, O4I, $D_{\text{star}}=0.4$ mas), then spend days to settle and restore the dark hole
 - Assume dark hole was previously dug at some earlier time and just needs some tweaking
 - Reference star chosen to keep solar pitch change to $\sim 3.5^\circ$ to avoid large thermal changes
- Observation cycle:
 - $\sim 3/4$ hour of imaging on ζ Pup (1st observation begins at hour 170 in the timeline)
 - slew to the target star (47 UMa, $V=5.04$, G1V, $D_{\text{star}}=0.9$ mas)
 - 100 minutes of imaging 47 UMa at each of 4 rolls, alternating between -13° and $+13^\circ$ for a total of 400 min per cycle
 - slew to ζ Pup
 - $\sim 3/4$ hour of imaging on ζ Pup
- There are 4 cycles, with time between the 2nd and 3rd for one iteration of dark hole maintenance (not reproduced in these simulations)
 - 4.1 hours of total integration on ζ Pup
 - 26.4 hours of total integration on 47 UMa (both roll angles)

OS11 Nomenclature

Reference star images have batch ID's starting with 0 and incrementing by 1 with each visit

Target star images have batch ID's starting with 100 and incrementing by 1 every roll;
each cycle of target imaging starts at the next increment of 100



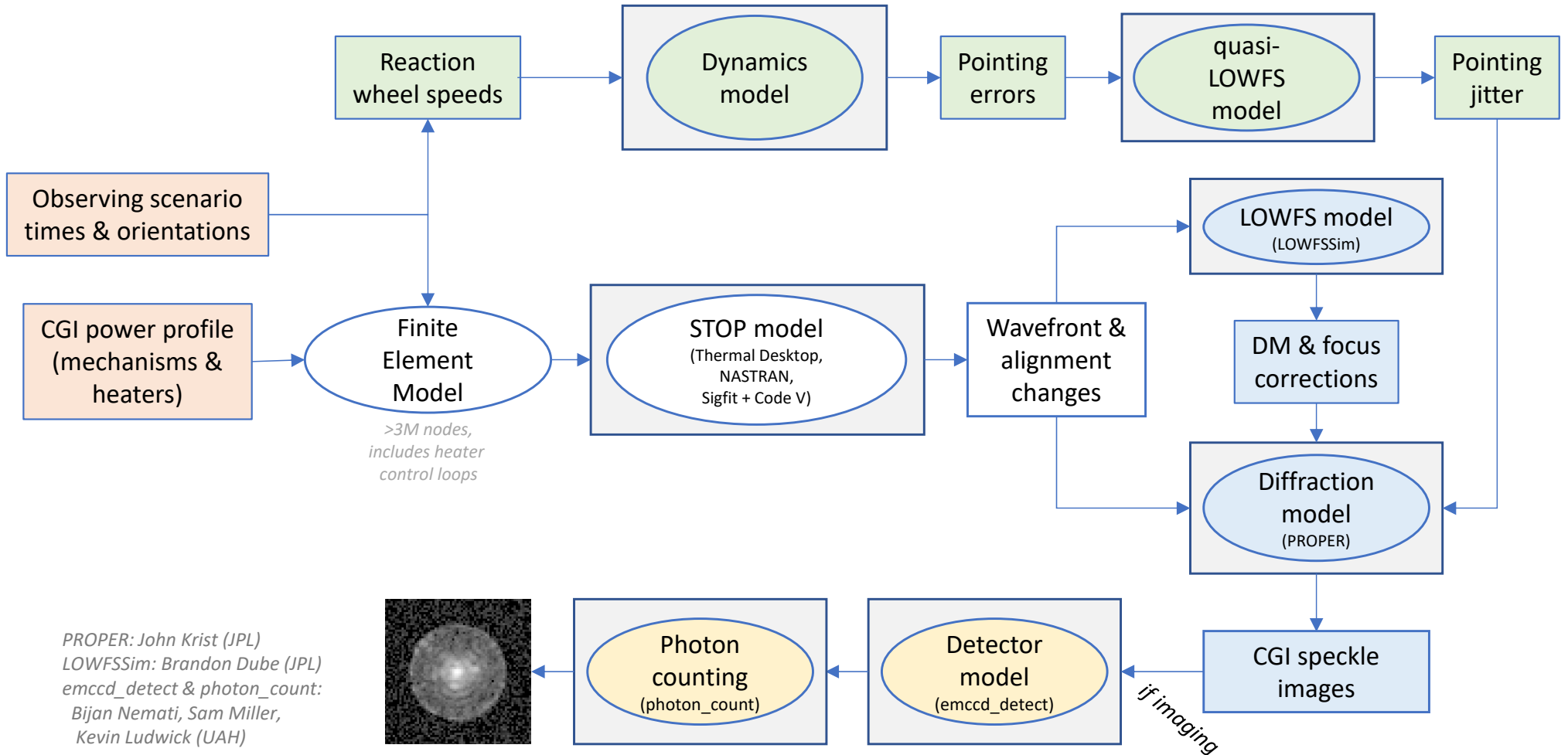
EFC Probes: apply pre-defined DM patterns & record resulting image changes; no images are provided for this span

GITL: Download probe images to ground, use them to derive wavefront error, compute new DM solutions, upload them to CGI

OS11 Modeling Timesteps

- The STOP (finite element & optical ray trace) model was run with 15 min timesteps to derive aberration & alignment changes
 - Misalignment-induced pointing offsets were compensated by repointing the observatory during ray tracing to ensure the star is always perfectly centered on the FPM (this excludes pointing jitter, which is a separate thing)
 - Results were then interpolated to 1 min timesteps
 - Includes thermal effects from solar angles, heaters, CGI mechanism movements (PAMs) & electronics
- The LOWFS model was run to measure aberration changes, which were used to derive DM and focus control compensations in the system model (see later page)
- For each timestep, PROPER produced complex-valued speckle electric fields with $0.1 \lambda_c/D$ sampling for 31 wavelengths at each of 4 polarization states (combinations of $\pm 45^\circ$ in, 0° & 90° out)
- The pointing jitter model, using reaction wheel speeds tailored for OS11, produced RMS X,Y pointing error jitters at 0.25 sec timesteps, interpolated to 1 min timesteps
- At 1st timestep, ΔE -field changes were recorded for a variety of source offsets to create a linear optical model (LOM); At each subsequent timestep, each LOM ΔE -field was added to that timestep's E-field and converted to intensity, creating an ensemble of offset-source images; a weighting function based on the Gaussian jitter & stellar size was applied to these and the resulting images summed to create that timestep's final image (all this was done separately for each wavelength and polarization component)
- The images from the four polarizations were combined

Simulation Flow (OS 11)



PROPER: John Krist (JPL)
 LOWFSSim: Brandon Dube (JPL)
 emccd_detect & photon_count:
 Bijan Nemat, Sam Miller,
 Kevin Ludwick (UAH)

Errors included in OS11 SPC-Spec time series optical model

- Static optical errors
 - Measured OTA & TCA (unmounted) optical errors, synthetic CGI optical errors matching measured (but not usable due to artifacts) error maps
 - Stand-in for phase-retrieval-derived optical error map (used for initial phase flattening and in control model); uses computed phase errors at FPM entrance pupil, multiplied by 1.1x to represent phase retrieval errors
 - Polarization aberrations (4 components: orthogonal input terms, orthogonal output terms & cross-terms)
 - Bulk shear of CGI relative to instrument carrier (@ FSM) of 0.14% of pupil diameter
- Z4-Z37 aberrations vs time due to surface deformations & misalignments
- OTA & TCA optics shifts vs time (implemented via shifts of optical error maps)
- Bulk X,Y CGI shear vs time at IC-CGI interface (in addition to initial shear)
- “Known” DM misalignments (included in system & control model)
 - 0.14 mm, -0.14 mm offsets (DM1,2)
 - 0.11°, -0.11° rotations (DM1, 2)
- “Unknown” DM misalignments (addition to known, included in system model but not control)
 - 0.11 mm, -0.11 mm (DM1, 2)
 - 0.1°, -0.1° rotations (DM1, 2)
 - 0.3% mm/actuator spatial scale change
 - DM shifts vs time due to bench deformation, IC-CGI interface tilts
- Measured flight DM characteristics, included dead actuators
 - DM bias = 40V, neighbor rule enforced
 - 15-bit DAC DM stroke quantization
- CGI DM, pupil mask, & Lyot stop offsets vs time from bench deformations & tilts at IC-CGI interface
- DM surface change due to thermal variations
- DM solution derived using EFC

Note: 1-iteration “refresh” EFC wavefront control in middle of OS11 not included here

Modeling Uncertainty Factors (MUFs) included

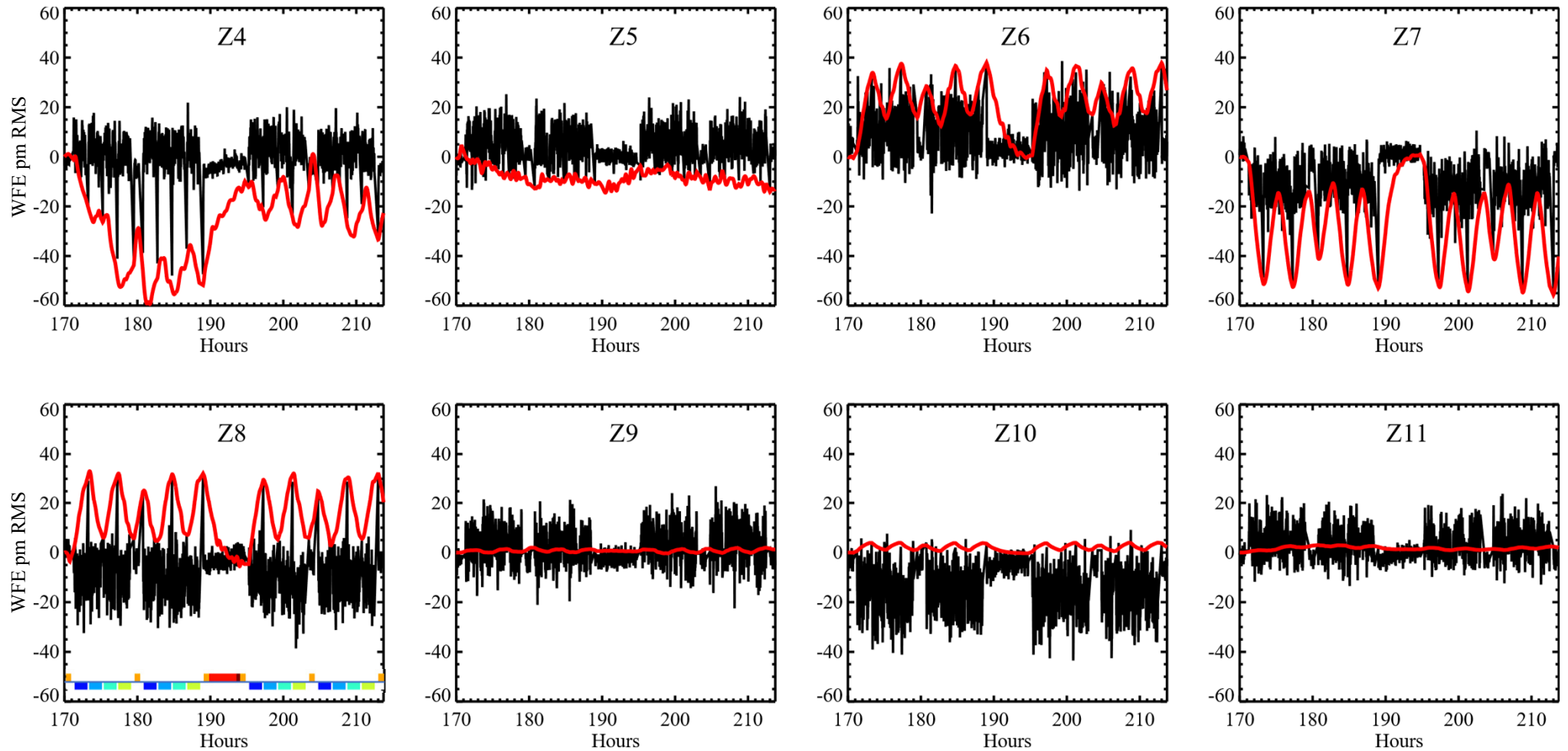
- STOP model
 - 2x structural deformation MUF
 - increases beam shear, wavefront error drift by 2x
- Dynamics model
 - Frequency-dependent jitter MUFs
 - 3x (<20 Hz), 4.27x (40-100 Hz), 8x (>100 Hz)
- Diffraction model
 - 1.5x predicted polarization-dependent aberrations
 - 2x contrast sensitivity increase to these
 - 2x contrast sensitivity to pointing jitter

LOWFS Model

- LOWFSSim model developed & executed by Brandon Dube (JPL)
 - Diffraction model with STOP-computed Zernikes as input
 - Uses same algorithms as flight for sensing and deriving corrections
 - Includes stellar fluxes & spectral types, detector effects
- LOWFS-measured Zernikes reported every 10 s with 100 s sensing bandwidth
- LOWFS is currently tuned for requirements-level aberration changes, which are much larger than those seen in OS11, so there is significant high-temporal-frequency noise that averages down over the full imaging timescales
- Defocus (Z4) controlled with Focus Correction Mechanism, Z5-Z11 with DM1
- Real LOWFS will be used to measure & control source offsets, but in these simulations those are handled separately when computing jitter

OS11 Zernike Aberrations

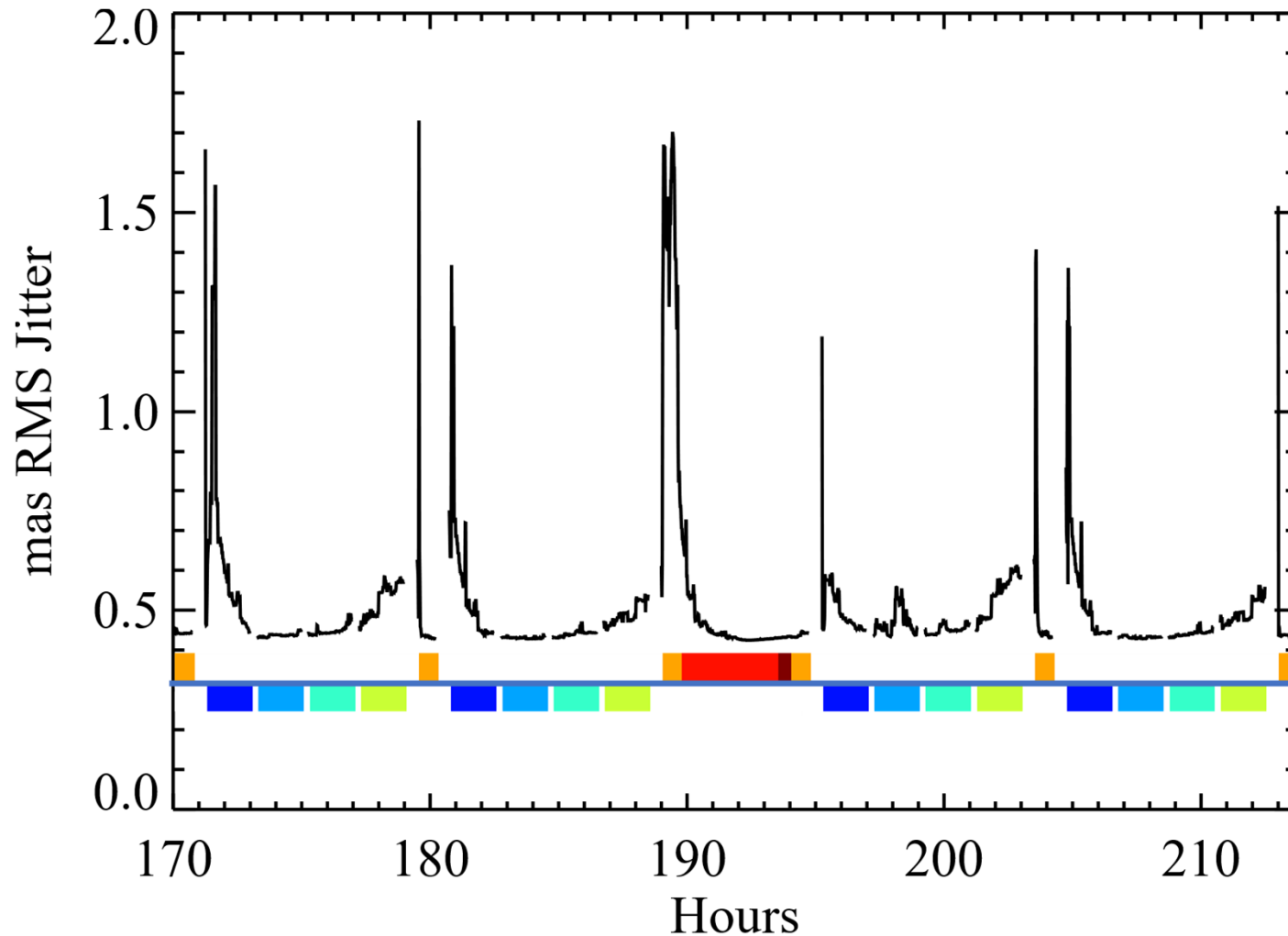
Noll ordering



red = STOP-computed zernikes, black = LOWFS-corrected zernikes (1 m timesteps)

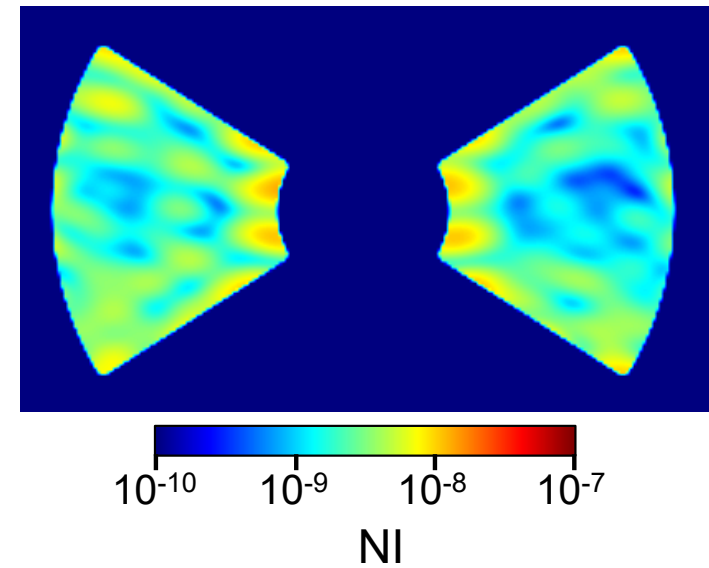
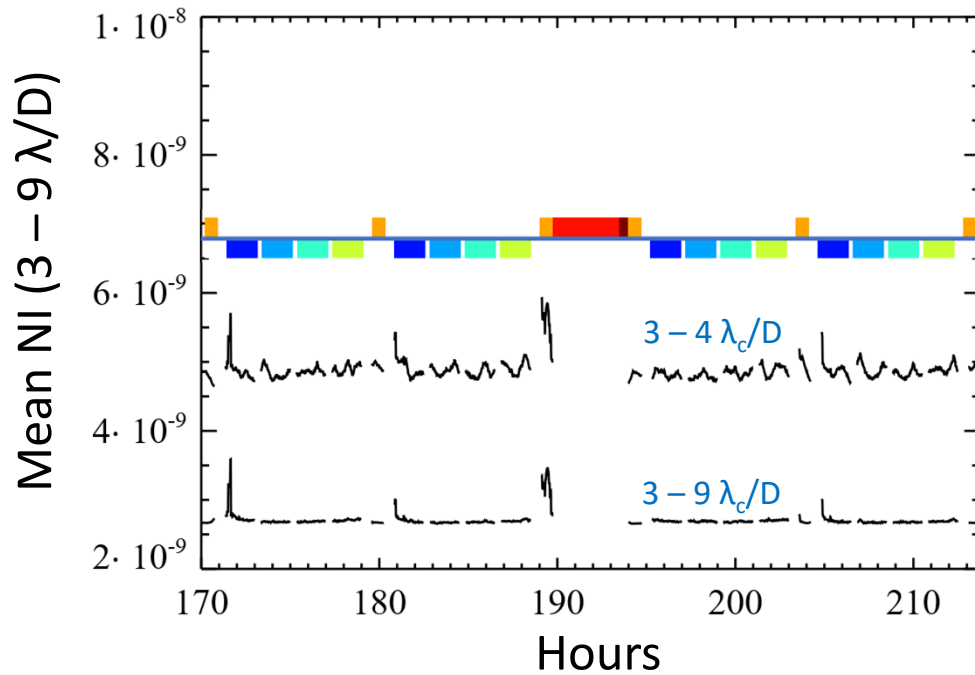
OS11 Post-correction Jitter

(RSS of X & Y RMS jitters)



The jitter floor here is set by a 0.3 mas RMS (per axis) system noise that is RSSed with the predicted post-steering-mirror jitter.

SPC-Spec OS11 Dark Hole Mean NI



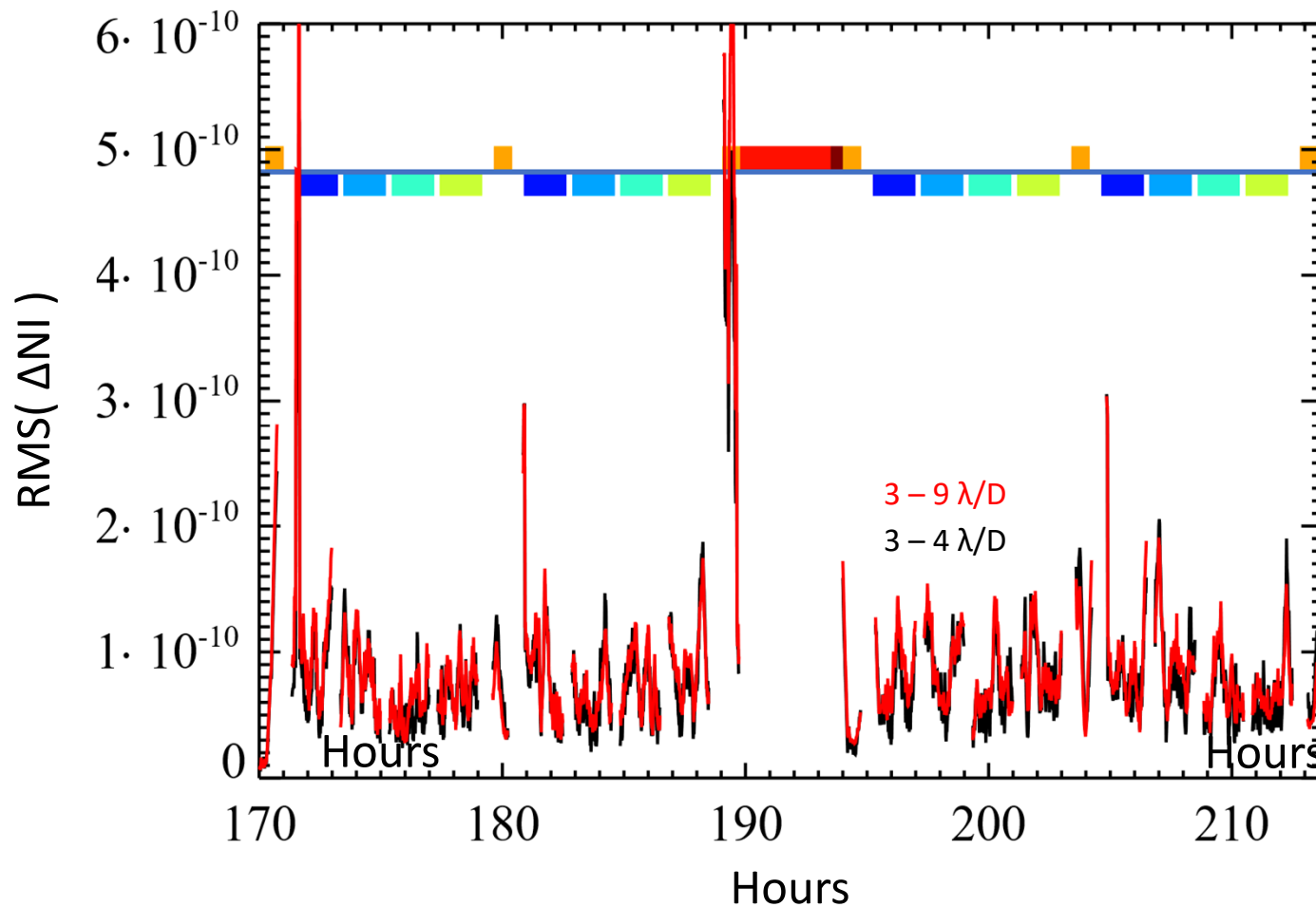
Mask applied to NI map

Mean NI over time:

$$4.9 \times 10^{-9} (3 - 4 \lambda_c/D)$$

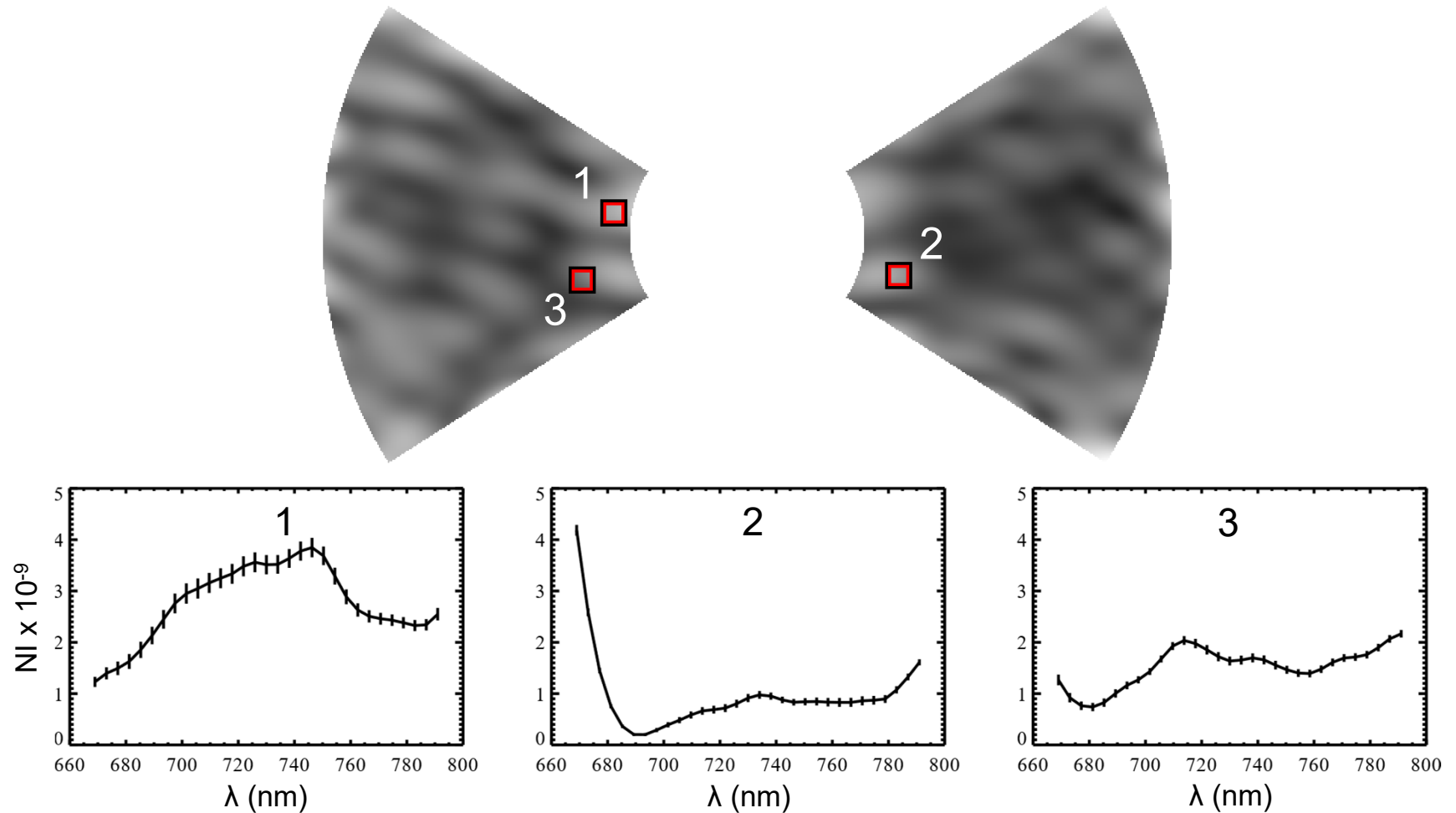
$$2.7 \times 10^{-9} (3 - 9 \lambda_c/D)$$

SPC-Spec OS11 Dark Hole Difference Relative to 1st Timestep



The high-frequency noise is due to imperfect LOWFS measurement and correction (the LOWFS was tuned for worse stability). The noise averages out over time.

SPC-Spec OS11 Dark Hole vs λ



The mean brightness variations over OS11 versus wavelength are plotted within three different regions of the SPC-Spec Band 3 field (default case, flat input spectrum). The error bars indicate the standard deviation of the variation over OS11.

SPC-Spec OS11 Time Series Files

- [spc_spec_os11_darkhole_vs_wavelength*.fits](#): OS11 time series speckle field images (no planets). The image sampling is $0.1 \lambda_c/D$. There are 31 monochromatic images per offset evenly spanning the bandpass. Each monochromatic image is primary-normalized flux (there are only mask losses). The time series is split over 5 files, each with 366 timesteps, with a total of 1830 timesteps. The dimensions of each file are [nx=275,ny=275,nlam=31,ntimesteps=366]. These contains all reference and target star images as generated by the models (1 minute cadence). The input parameters, batch IDs, and other information for each timestep are in the file [spc_spec_os11_inputs.fits](#) (described on the next page).
- [spc_spec_os11_psfs.fits](#): Simulations of point sources offset from the star by a variety of irregularly-spaced radial offsets and azimuthal offsets of -13° , 0° , and $+13^\circ$ on the left and right sides of the star. The image sampling is $0.1 \lambda_c/D$. There are 31 monochromatic images per offset evenly spanning the bandpass. Each monochromatic image is primary-normalized flux (there are only mask losses). The file dimensions are [nx=275,ny=275,nlam=31,num_radial_offsets=10,num_azimuthal_offsets=6]. The radial (λ_c/D) and azimuthal (degrees) offsets are provided in the 1-D FITS files [spc_spec_os11_psfs_radial_offsets.fits](#) [n=10] and [spc_spec_os11_psfs_azimuth_offsets.fits](#) [n=6].
- [spc_spec_os11_no_fpm_psf.fits](#): Unocculted PSF (star image with no FPM). The image sampling is $0.1 \lambda_c/D$. There are 31 monochromatic images per offset evenly spanning the bandpass. Each monochromatic image is primary-normalized flux (there are only mask losses). The file dimensions are [nx=275,ny=275,nlam=31]. The units are primary-normalized flux. This is used to convert dark hole image values in [spc_spec_os11_darkhole_vs_wavelength.fits](#) to normalized intensity (NI) by dividing the dark hole image by the maximum PSF value.
- [spc_spec_os11_fpm_mask.fits](#): Focal plane mask sampled at $0.1 \lambda_c/D$; used to determine the darkhole working region. Dimensions are [nx=275,ny=275].

spc_spec_os11_inputs.fits

This file is a FITS 2D array, [nterms=81,ntimesteps=1830] providing info for the corresponding image provided in [spc_spec_os11_darkhole_vs_wavelength*.fits](#).

nterm (starting at 0) =

- 0: Time of observation (hours, starting at 170)
- 1: Star ID (1 = target, 2 = reference)
- 2: Batch ID (see OS11 Nomenclature slide)
- 3: Roll; degrees
- 4-45: Input low order aberrations; Noll-ordered Zernikes, Z4-Z45; meters RMS
- 46-53: LOWFS-derived low order corrections (Z4-Z11); meters RMS
- 54-59: Optical surface X shift; [secondary, POMA fold, M3, M4, M5, TT fold]; meters
- 60-65: Optical surface Y shift; meters
- 66-67: CGI X & Y shear at instrument carrier interface (FSM); meters
- 68-69: DM1 X & Y shear; meters
- 70-71: DM2 X & Y shear; meters
- 72-73: DM1 & DM2 temperature; Kelvins
- 74-75: SPAM (SPC pupil mask) X & Y shear; meters (not used for HLC)
- 76-77: LSAM (Lyot stop) X & Y shear; meters
- 78-79: X & Y post-FSM pointing jitter; mas RMS per axis
- 80: Focus correction mechanism offset to compensate Z4; meters

Creating Field Point Sources with CGISim

CGISim is a Python program that generates CGI dark hole and field point source images using the PROPER propagation library and the CGI diffraction model. You can use it to produce field point source images with any offset from the star. It can be downloaded from <https://sourceforge.net/projects/cgisim>. Be sure to read the manual to understand how the images are normalized. For the “spec” mode, CGISim will generate images for 30 wavelengths.

Example code is shown below to generate an off-axis source at $(x,y)=(+300,+150)$ mas.

```
import cgisim_jpl as cgisim
import proper
import roman_phasec_proper_jpl

cgi_mode = 'spec'
cor_type = 'spc-spec_band3'
bandpass = '3'
polaxis = -10          # compute images for mean X+Y polarization (don't compute at each polarization)

# read in DM pattern provided with Phase C CGI model

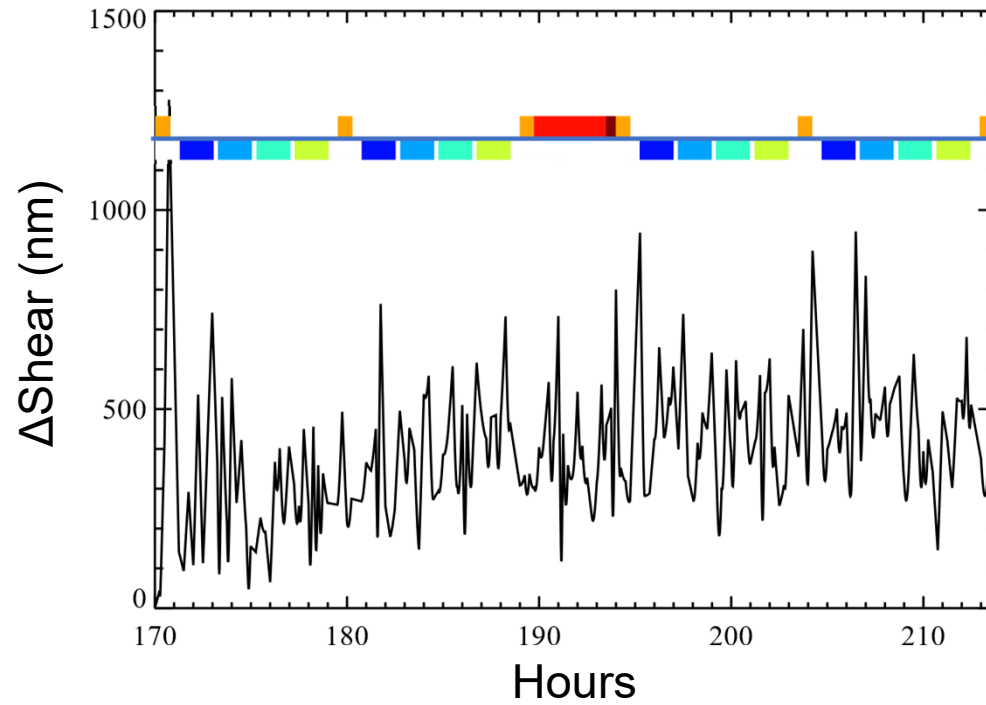
file_dir = roman_phasec_proper_jpl.lib_dir + '/examples/'

dm1 = proper.prop_fits_read( file_dir+'spc_spec_band3_mild_contrast_dm1.fits' )
dm2 = proper.prop_fits_read( file_dir+'spc_spec_band3_mild_contrast_dm2.fits' )
params = {'source_x_offset_mas':300.0, 'source_y_offset_mas':150.0,
          'use_dm1':1, 'dm1_m':dm2, 'use_dm2':1, 'dm2_m':dm2}

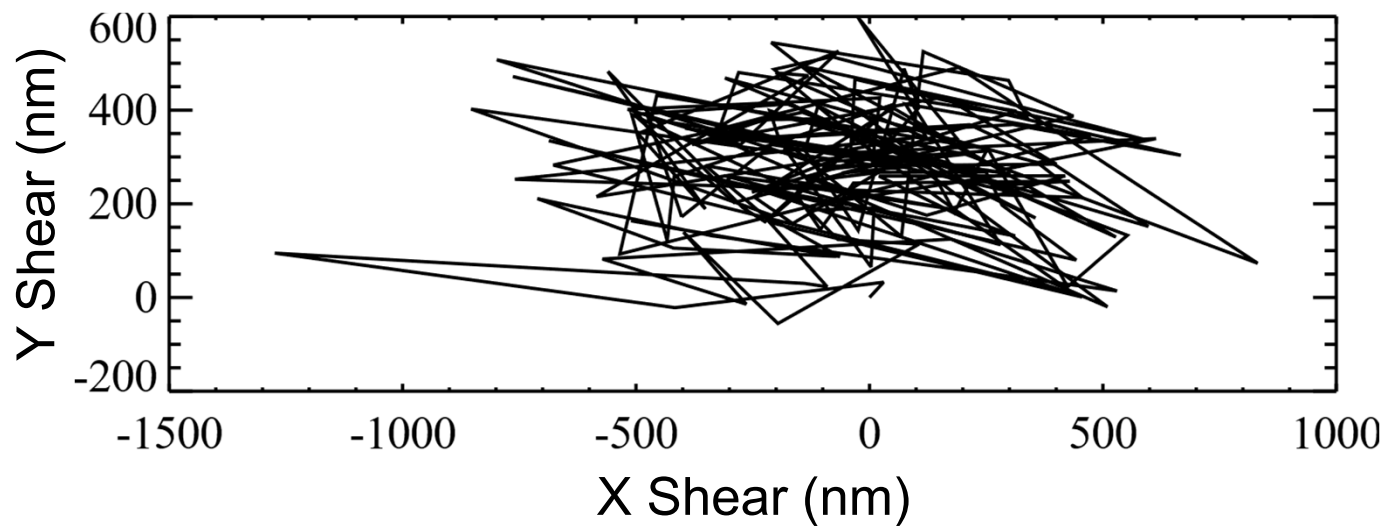
psf = cgisim.rcgisim( cgi_mode, cor_type, bandpass, polaxis, params, output_file= 'psf.fits' )
```

Additional STOP Results

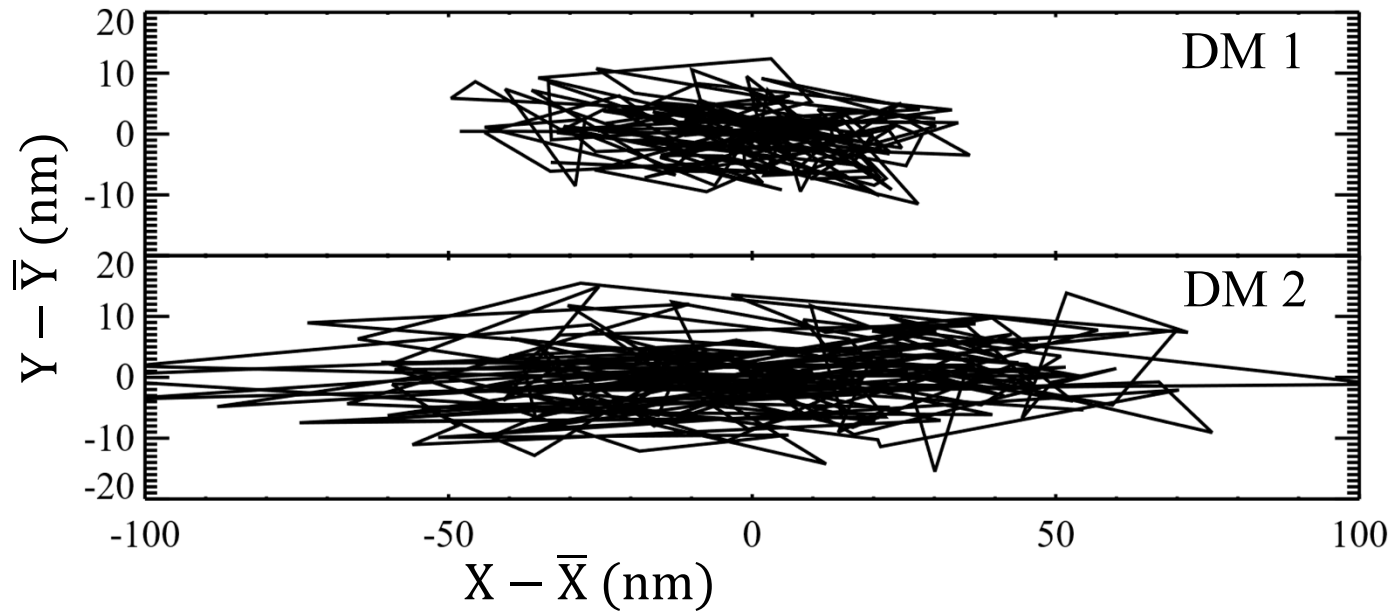
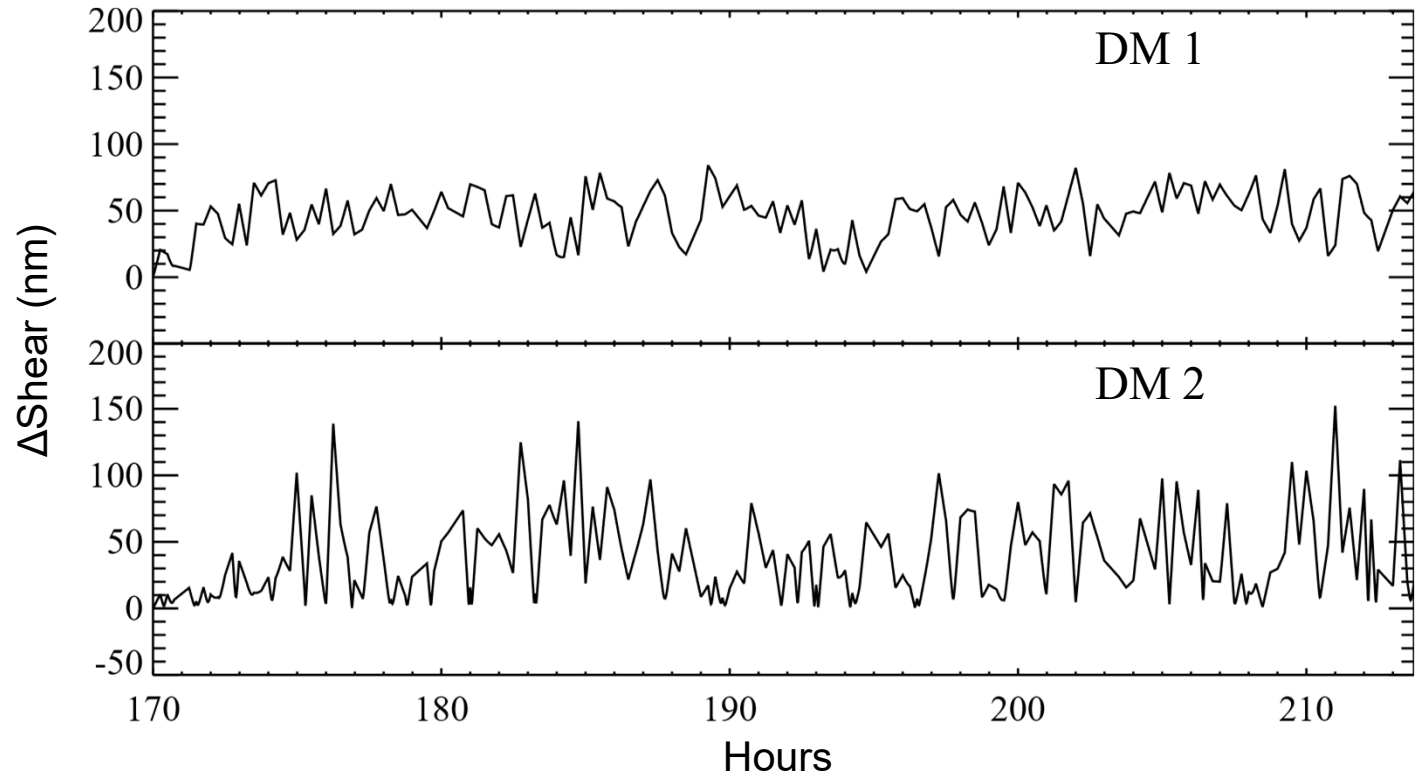
CGI bulk shear (X,Y displacement at FSM relative to instrument carrier)



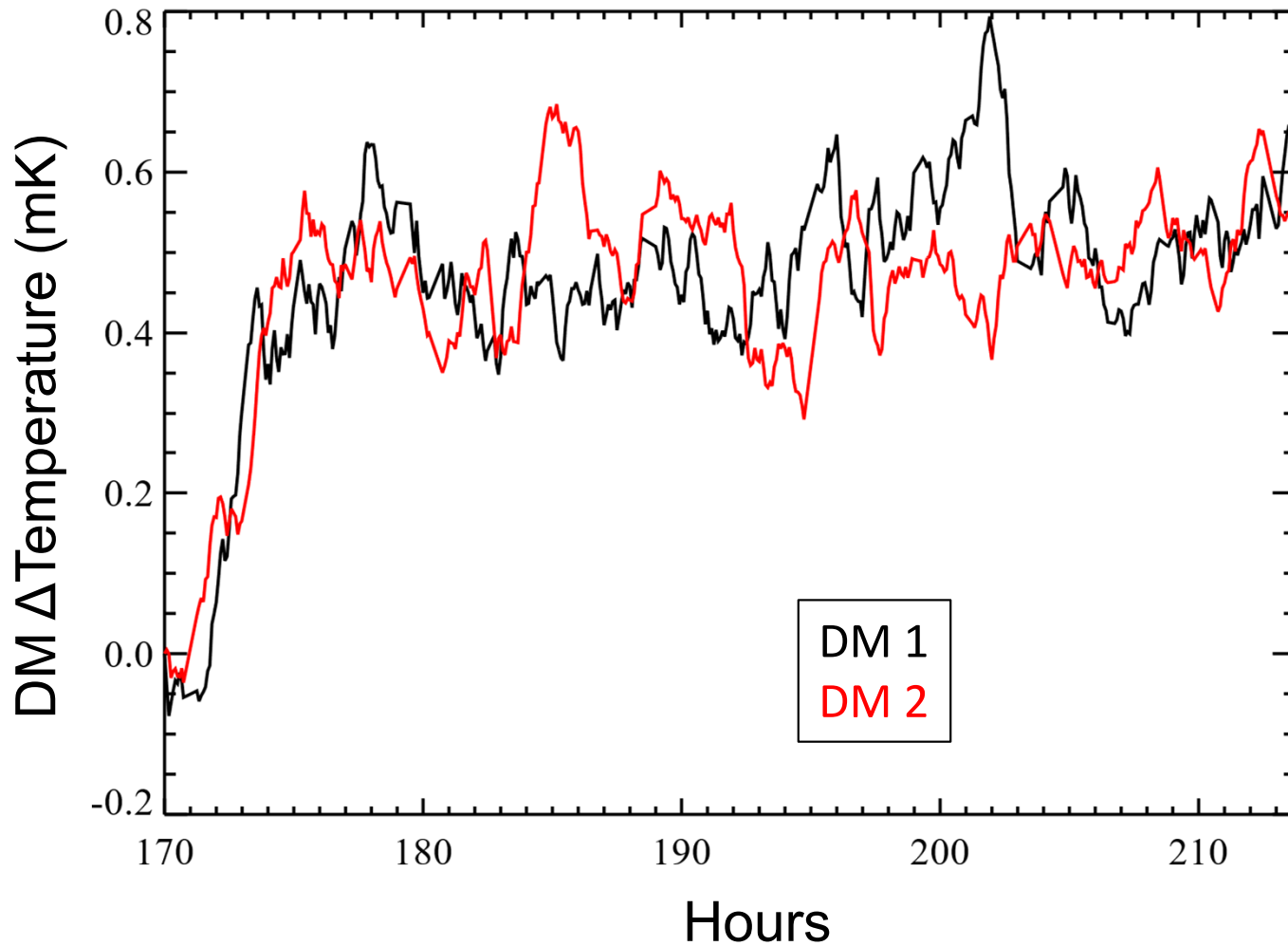
Pupil diameter
@ FSM = 40 mm



DM shear (CGI bulk shear subtracted)



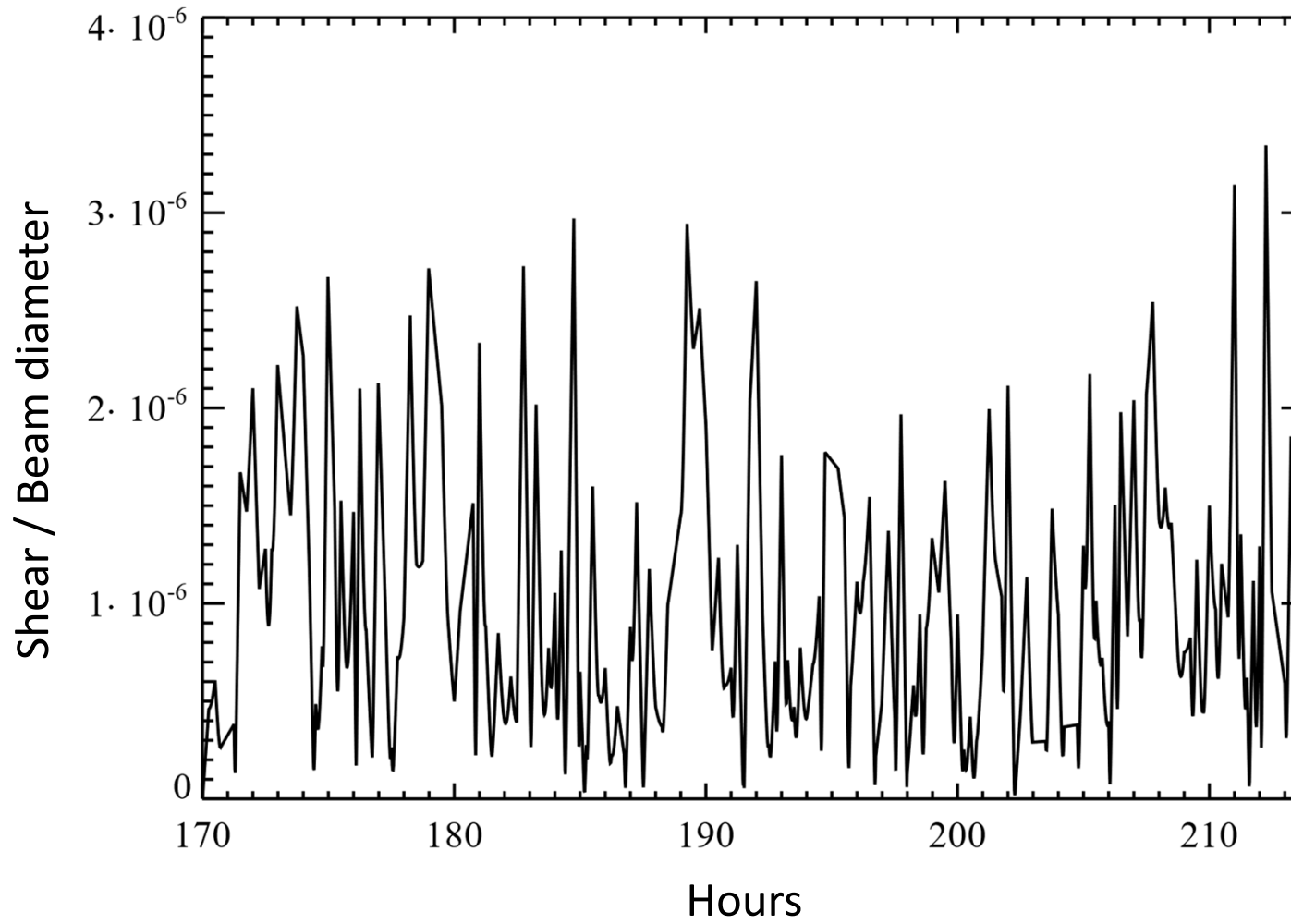
DM temperature change



DM surface change factor = $(1 + 0.026 \times \Delta\text{Temp}_K)$

Max change here is $\sim 0.0021\%$ from $t=170$ h

Lyot stop shear (CGI bulk shear subtracted)



OS11 Reaction Wheel Speeds

