# WFIRST CGI Milestone 9 Dynamic Contrast Demonstration Status Update

**January 27, 2017**

**WFIRST Coronagraph Testbed and Modeling Teams**

# Outline

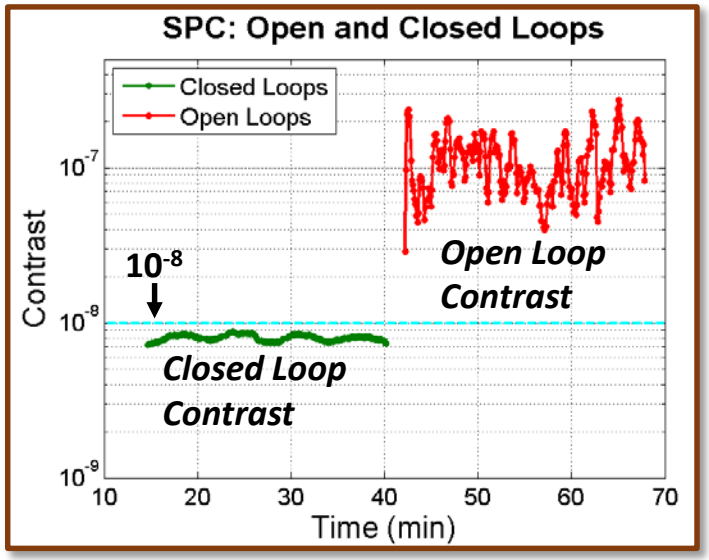
- Summary of the last Milestone 9 review
- Summary of progress since the last MS9 review
- Dynamic test results: HLC and SPC modes
- Static contrast improvements: HLC and SPC modes
- Dynamic results discussion
- Conclusion and future work
- Backup slides

# MS9 Review and TAC Comments

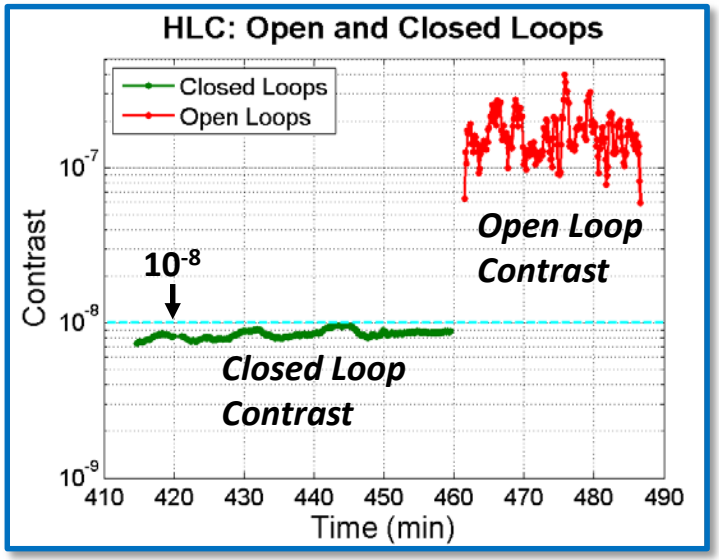
- **At the Milestone 9 review on 11/8/2016, the following results were presented:**
  - Static OMC contrast reaching $9 \times 10^{-9}$ with a recently reconfigured testbed pseudo-star and OTA front end, that reduced unmodulated light
  - Dynamic test results showing LOWFS/C performance in controlling pointing and focus errors (HLC) during testing done with the earlier front end, at a worse static contrast level
  - These tests were done separately; dynamic testing with LOWFS/C had not been carried out yet with raw contrast better than $10^{-8}$
- **TAC MS9 report comments:**
  - "it must be noted these quoted contrasts for Milestone #9 were obtained through static testing in the HCIT. Modeling of the expected degradation in a dynamic environment was also performed, but the contrast measurements were not performed simultaneously with the dynamic jitter."
  - "The TAC encourages the team to continue their efforts with both the SPC and the HLC in the dynamic testing environment to enable Milestone #9 to be truly achieved for either, or both, methods."
- **Scope of this review:**
  - New results showing "both the SPC and the HLC [performance] in a dynamic testing environment"
  - New results showing improved static SPC and HLC contrast performance

# Summary of Testbed Results

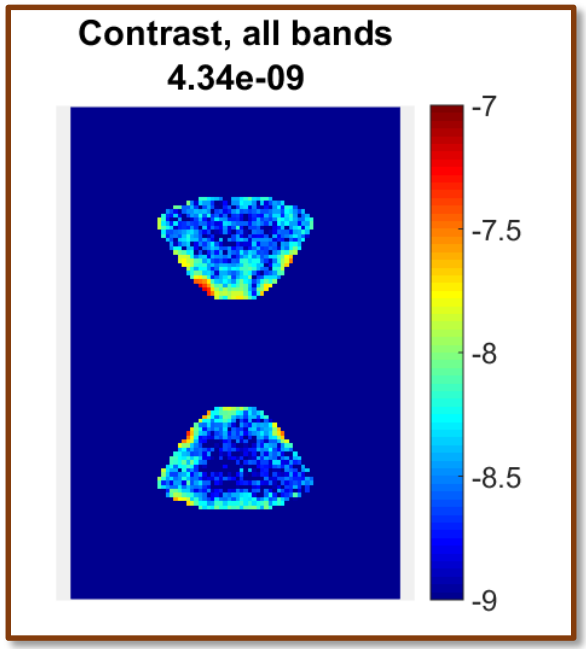
## SPC Dynamic Test (10% at 550nm)




## HLC Dynamic Test (10% at 550nm)




## Best SPC Static Contrast (10% at 550nm)

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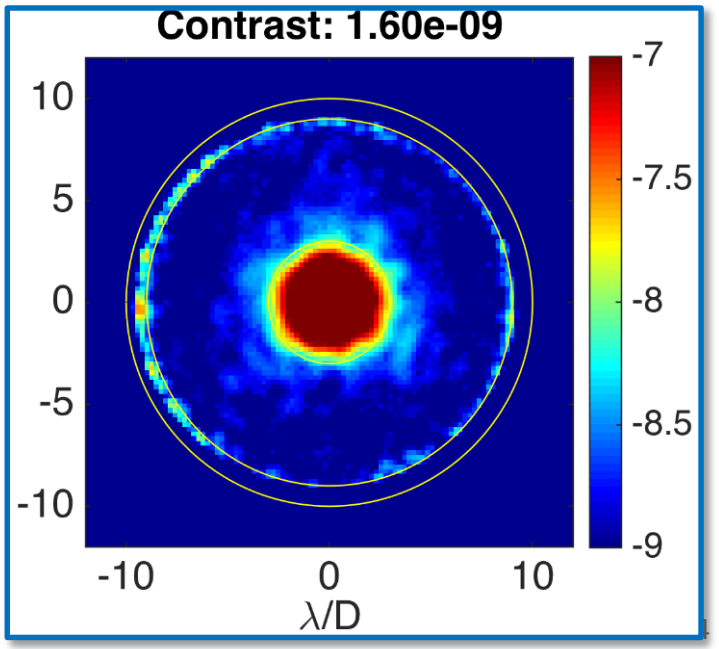
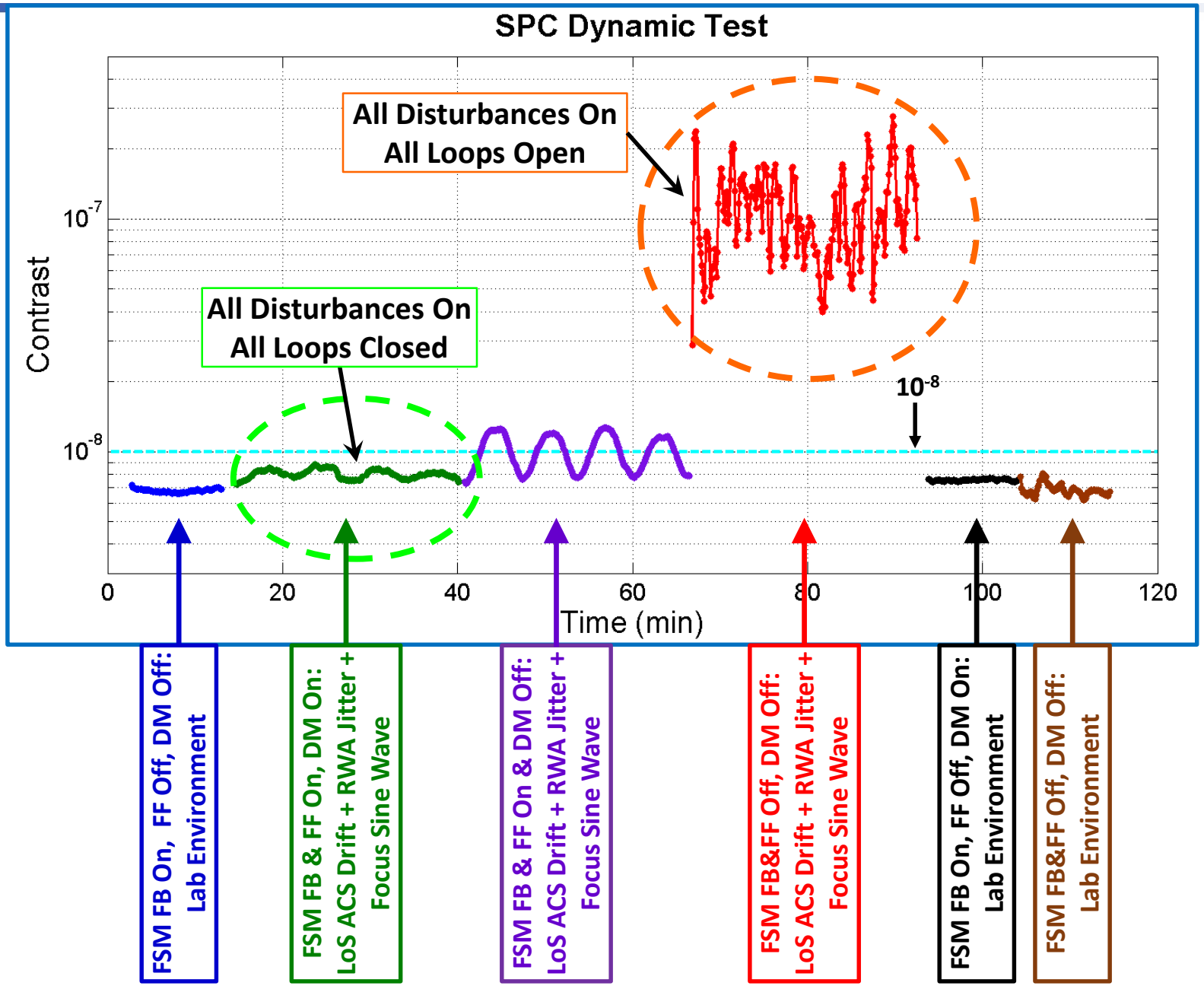


# Summary of Progress Since Review

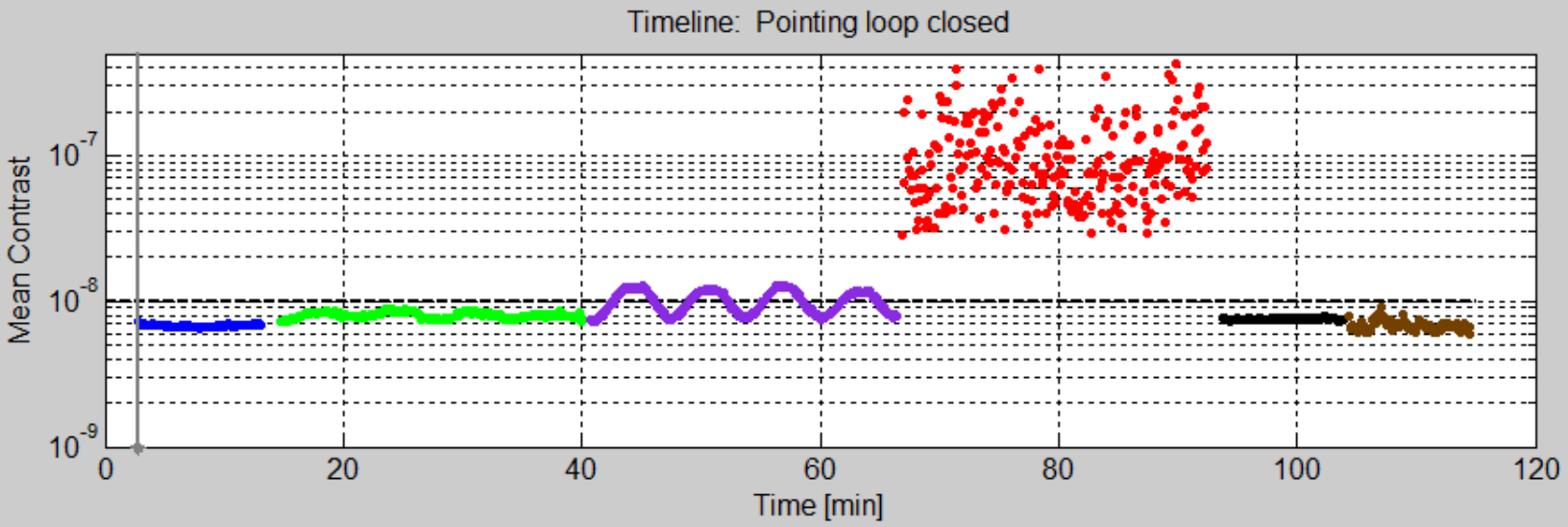
- **Static tests**
  - Further updates to the testbed pseudo-star (replaced COTS pinhole with a clean, JPL-made pinhole) greatly reduced unmodulated starlight residual.
  - Improved wavefront control algorithm approach (regularization schedule) reduced modulated starlight residual
  - In combination, these resulted in a significant improvement of static OMC contrast levels:
    - **$1.6 \times 10^{-9}$ for HLC static: full 360% 3-9 λ/D annulus, 10% broadband centered at 550nm**
    - **$4.3 \times 10^{-9}$ for SPC static: 2x65% 2.8-8.8 λ/D bowtie, 10% broadband centered at 550nm**

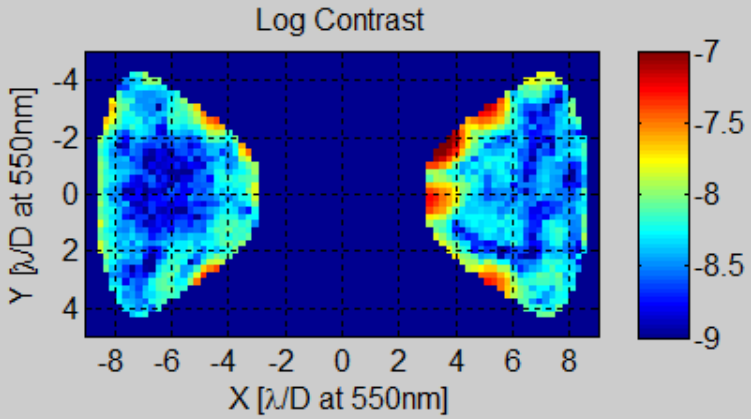
- **Dynamic tests**
  - Dynamic testing with the new front end and lower static contrast is in progress, injecting and correcting dominant on-orbit disturbances: Pointing drift/jitter and focus drift
  - **Recent results show dynamic OMC (both HLC and SPC mode) contrast better than $1 \times 10^{-8}$ in presence of WFIRST flight-like dynamic disturbances and LOWFS/C correction**
  - Improved LOWFS/C robustness and performance
    - LOWFS reconstructor built from the testbed sensor response of FSM and DM
    - Better DM actuator gain calibration to reduce the DM low order WFE correction residual error
    - Sensing “pupil shear modes” reduces LOWFS sensor error from testbed non-common path drift (SPC mode)
    - Multiple ringers in feedforward control to increased the notch filter bandwidth (~0.25 Hz)
    - Feedforward to suppress the “uncooperative” frequency at ~120 Hz

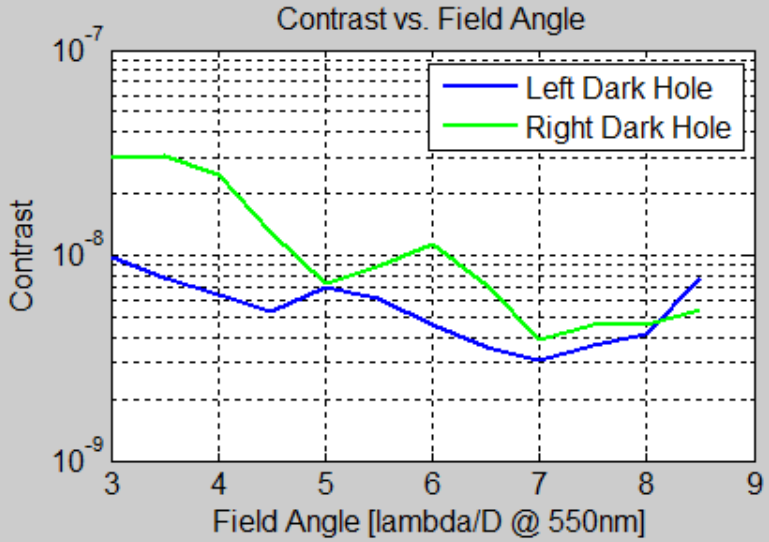
# SPC+LOWFS/C Dynamic Test Result



# SPC + LOWFS/C Dynamic Test: Movie



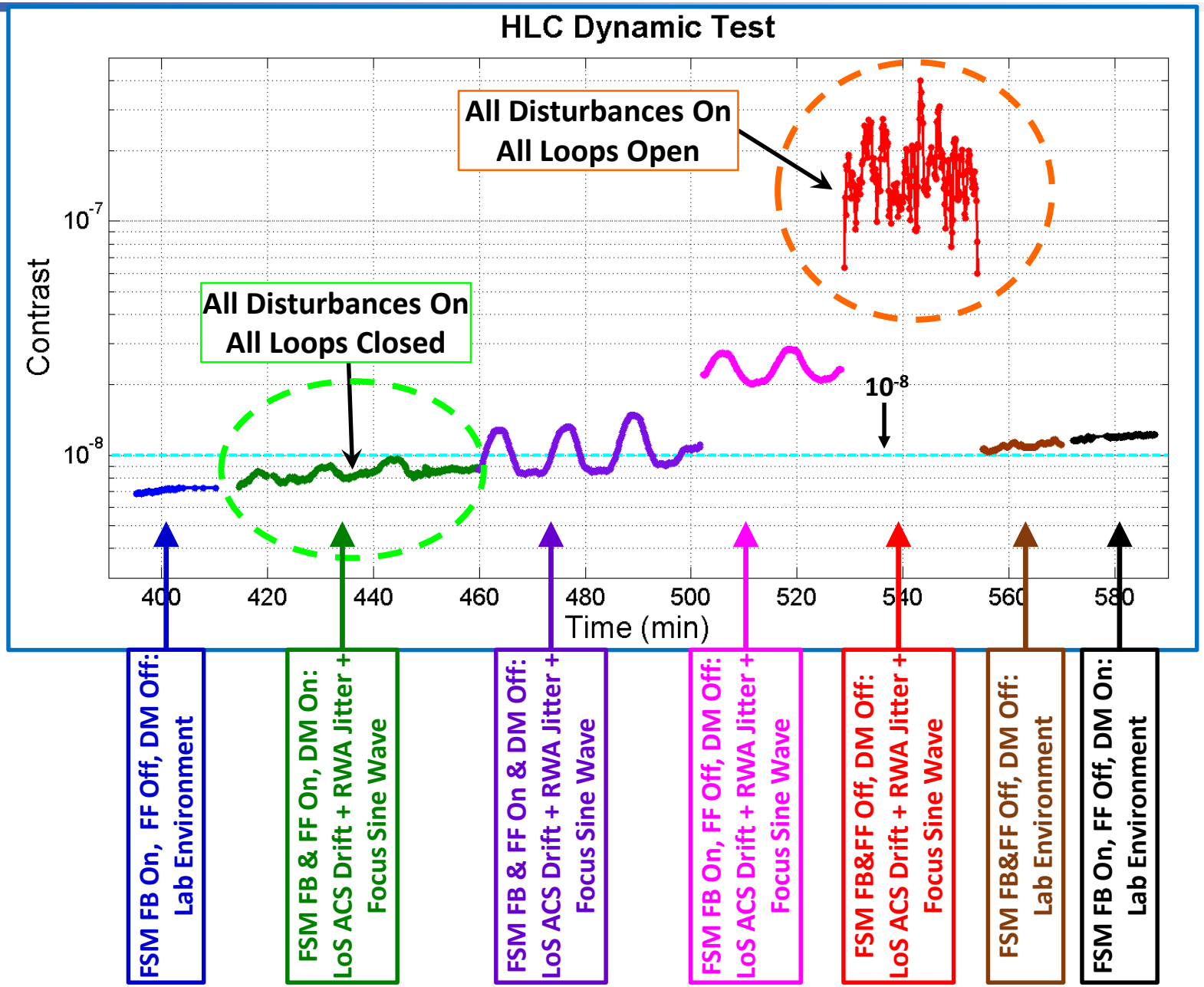



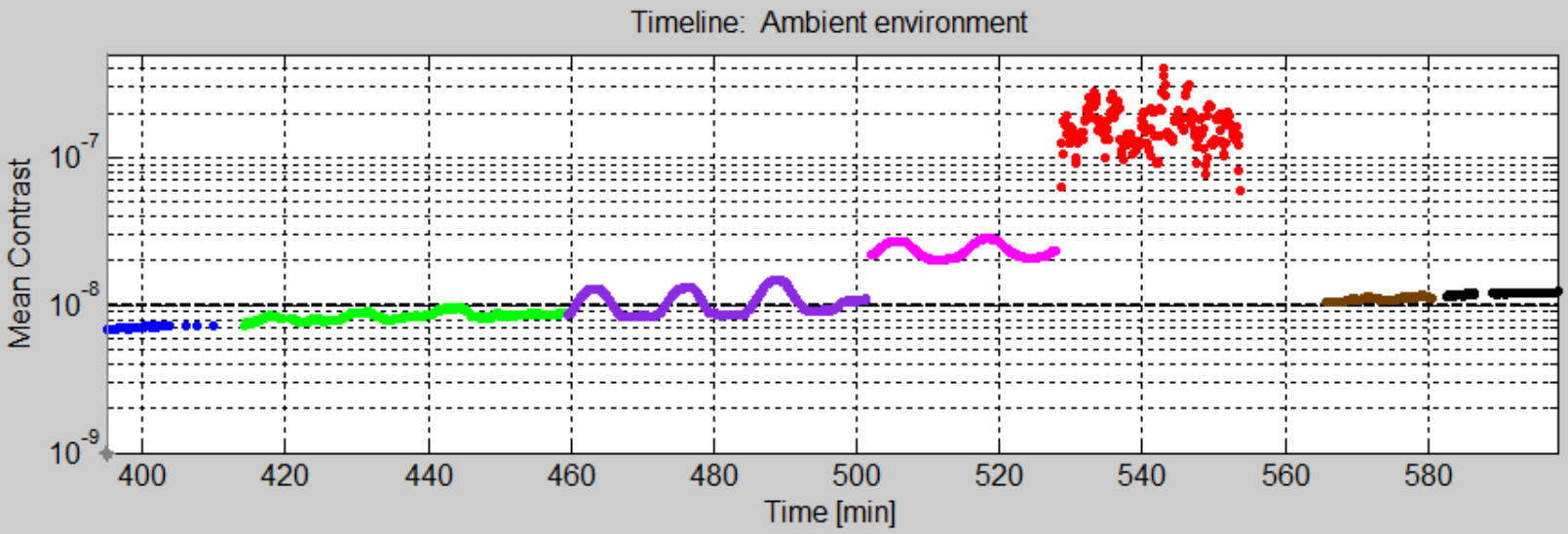
# SPC+LOWFS/C Dynamic Test Result

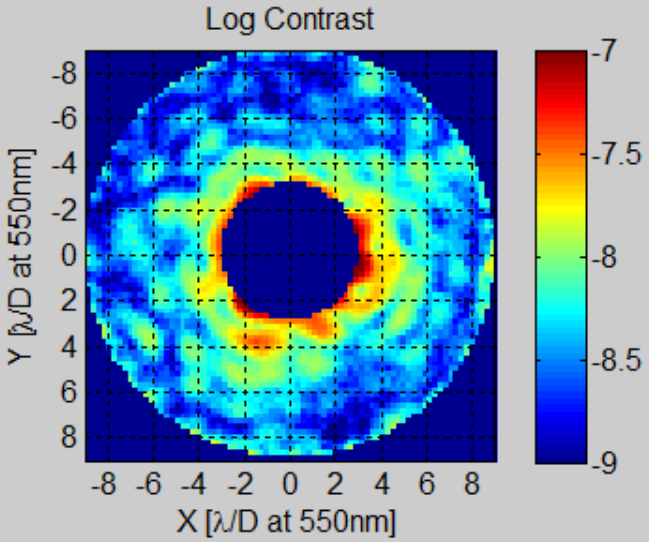
- **SPC dynamic test demonstrating coronagraph contrast <1x10$^{-8}$ with simulated on-orbit pointing and focus disturbances and LOWFS/C sensing & correction.**
- Coronagraph Mode: Shaped Pupil Coronagraph
  - Contrast recorded with a 10% bandwidth filter centered at 550 nm.
- Line-of-sight Error Injected: 14 mas rms drift + CBE line of sight jitter at 600 rpm wheel speed (72 harmonic tones)
  - LoS error injected by OTA Simulator's Jitter Mirror (JM)
  - LoS error corrected by OMC's Fast Steering Mirror (FSM) with both feedback and feedforward loops
- Low Order WFE Injected: 2 nm p-v focus disturbance (4x worse than expected WFIRST thermal drift)
  - Focus injected by modified OTA Simulator's source stage
    - Sinusoidal focus disturbance with period of 750 sec. In each section of test OTA put out ~2 disturbances cycles.
  - Focus corrected by one of OMC's deformable mirrors (DM).

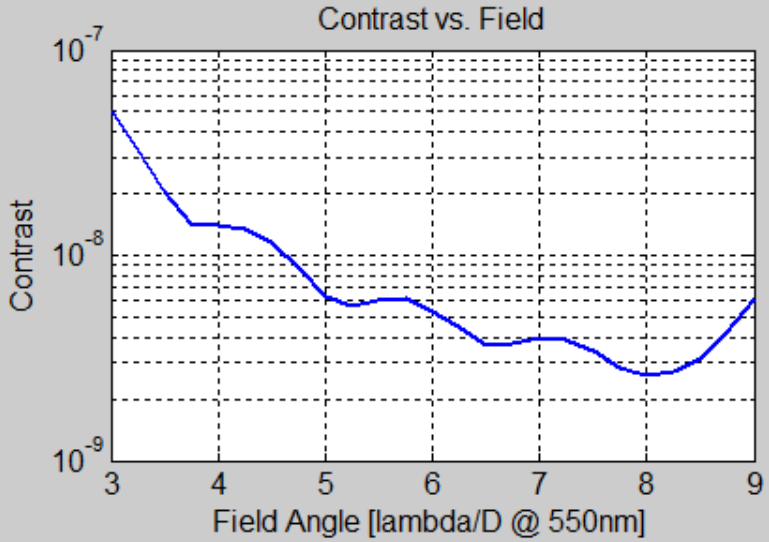
# HLC+LOWFS/C Dynamic Test Result



# HLC + LOWFS/C Dynamic Test: Movie



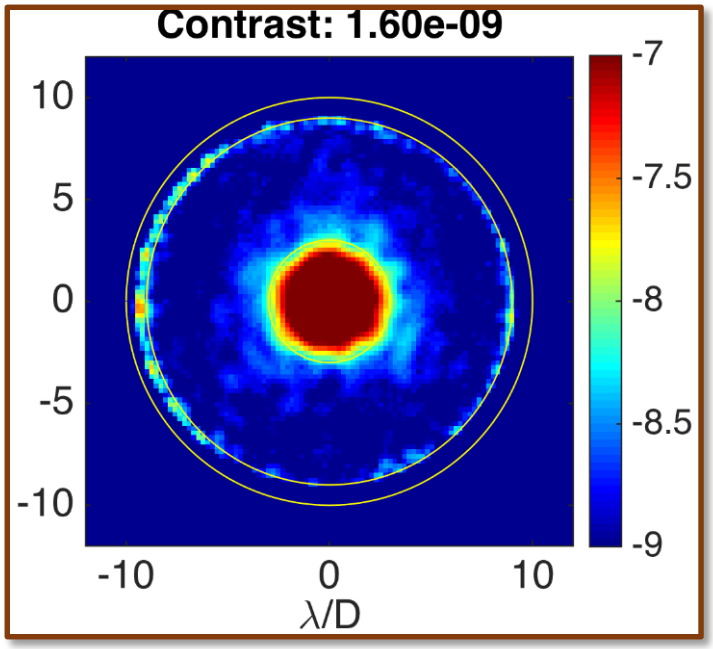



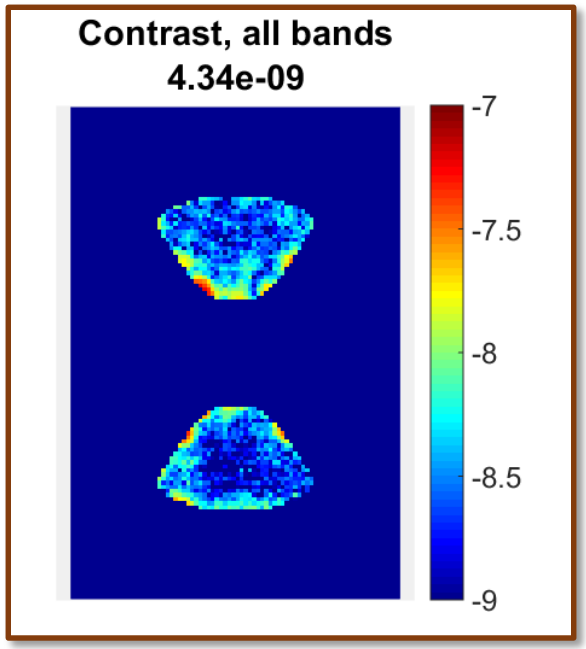



# HLC+LOWFS/C Dynamic Test Result

- **HLC dynamic test demonstrating coronagraph contrast <1x10$^{-8}$ with simulated on-orbit pointing and focus disturbances and LOWFS/C sensing & correction.**
- Coronagraph Mode: Hybrid Lyot Coronagraph
  - Contrast recorded with a 10% bandwidth filter centered at 550 nm.
  - At the start of test HLC has ~0.2nm focus bias, which made the contrast perturbation non-symmetric
- Line-of-sight Error Injected: 14 mas rms drift + CBE line of sight jitter at 600 rpm wheel speed (72 harmonic tones)
  - LoS error injected by OTA Simulator's Jitter Mirror (JM)
  - LoS error corrected by OMC's Fast Steering Mirror (FSM) with both feedback and feedforward loops
- Low Order WFE Injected: 1 nm p-v focus disturbance (2x worse than expected WFIRST thermal drift)
  - Focus injected by modified OTA Simulator's source stage
    - Sinusoidal focus disturbance with period of 750 sec. In each section of test OTA put out ~3 disturbances cycles.
  - Focus corrected by one of OMC's deformable mirrors (DM).

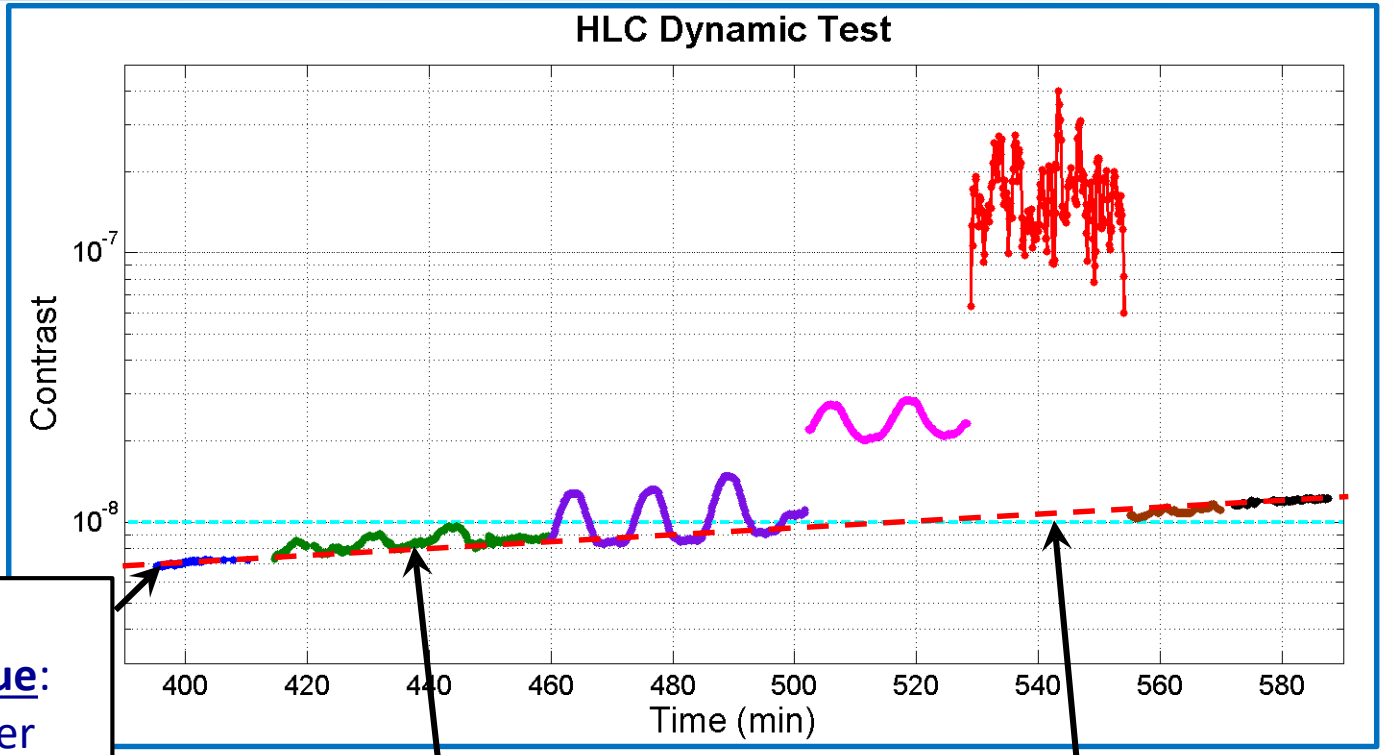
# Static Contrast: HLC and SPC




- **OMC testbed static contrast has significantly improved for both HLC and SPC modes**
- **Latest contrast results (10% bandwidth at 550 nm): SPC = $4.3 \times 10^{-9}$ and HLC = $1.6 \times 10^{-9}$**
  - Better wavefront control algorithm by alternating the EFC control aggressiveness (regularization).
  - Replaced the commercial metallic, laser-burnt pinhole with a pinhole made at JPL using e-beam lithography, etched in a thin silicon wafer.
  - Reduced testbed LoS jitter by turning off the strain gauges on jitter mirror and fast steering mirror (HLC)

# Dynamic Test Results Discussion




**Starting contrast worse than the best static value**:

- Scoring with 10% filter while EFC was done with 5 uniformly weighted 2% bands -> 10% worse
- Jitter Mirror and FSM strain gauges on -> adds ~3.4e-9 contrast

Both are TB specific, not flight relevant

**Focus post-correction residual contrast:**

- DM gain calibration errors (recently improved, will be improved further)
- Residual focus (minor)

**Testbed drift**:

- Drift is sporadic and needs further exploration.
- Relevant to future low flux/long duration tests.

# Summary and Future Work

## Milestone 9 Results:

- Demonstrated WFIRST Occulting Mask Coronagraph $<10^{-8}$ raw contrast with 10% broadband light centered at 550 nm in a simulated dynamic environment.
  - Both SPC and HLC modes meet this threshold
- After testbed algorithm and hardware improvements guided by modeling, the testbed has reached the best levels of static contrast ever demonstrated with an obscured aperture.

## Future testbed work will focus on increasing fidelity end-to-end demonstrations on path toward TRL6:

- Broadband wavefront control using IFS data cubes
- Starlight suppression with low photon flux
- Dark hole convergence rate consistent with model predictions
- Speckle stability with LOWFS/C for post-processing
- Continue CGI+LOWFS/C testing with disturbances from the updated WFIRST jitter and thermal observatory models