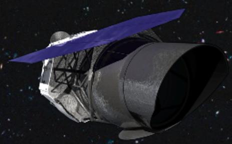


HIGH PRECISION POINTING CONTROL FOR WFIRST CGI INSTRUMENT

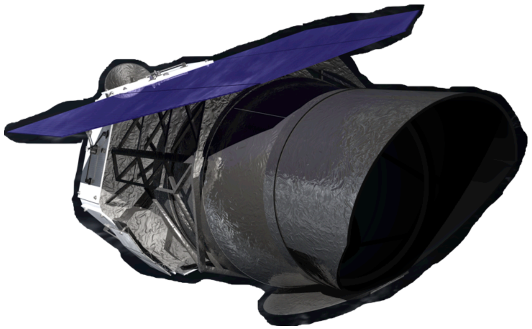
Nanaz Fathpour
Oscar Alvarez-Salazar, David Arndt, Milan Mandić, Joel Shields, Sam Sirlin, and Alfredo Valverde
Guidance & Control Section
Jet Propulsion Laboratory

2/6/2019

Jet Propulsion Laboratory
California Institute of Technology

WFIRST CGI Mission Summary

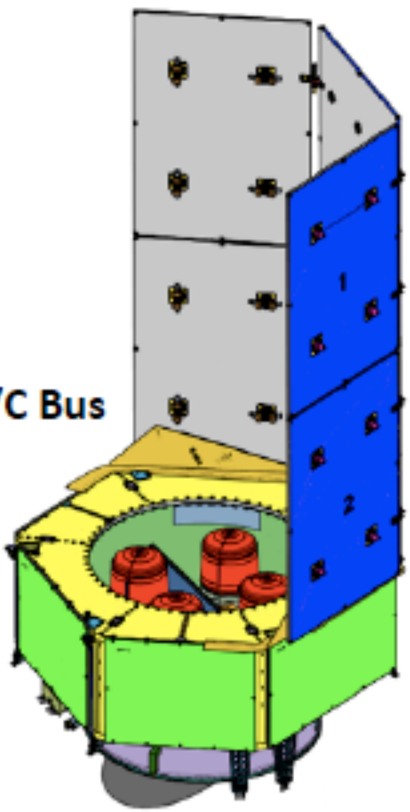
- WFIRST, the Wide Field InfraRed Survey Telescope, is a NASA observatory
- Science objectives:
  - Dark Energy: Investigate acceleration of the expansion of the Universe
  - Exoplanets: Search for extra-solar planets (Microlensing, and Coronagraph tech demo)
  - Host General Observer (GO) & Guest investigator programs for general astrophysics
- Observatory:
  - 2.4 m primary mirror telescope enables Hubble quality imaging over 100x more sky
- Mission Life: 5 years (+ ~3 months checkout)
- Mission orbit: Sun-Earth L2
- 2 instruments:
  - Wide Field Instrument (WFI @ GSFC)
  - Coronagraph Instrument (CGI @ JPL)
- Mission Classification:
  - WFIRST: Class A flagship mission
  - CGI: Class C Tech Demo



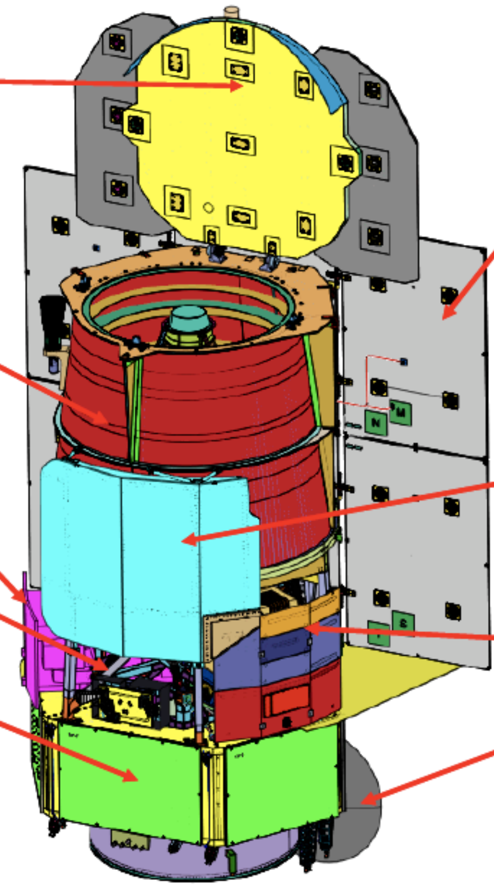
- WFIRST CGI will be used for direct imaging and spectroscopy of planets and debris disks
- WFIRST CGI is a direct predecessor to potential future flagship direct imaging missions aimed at Earth-like exoplanets (HabEx & LUVOIR)

Observatory Configuration

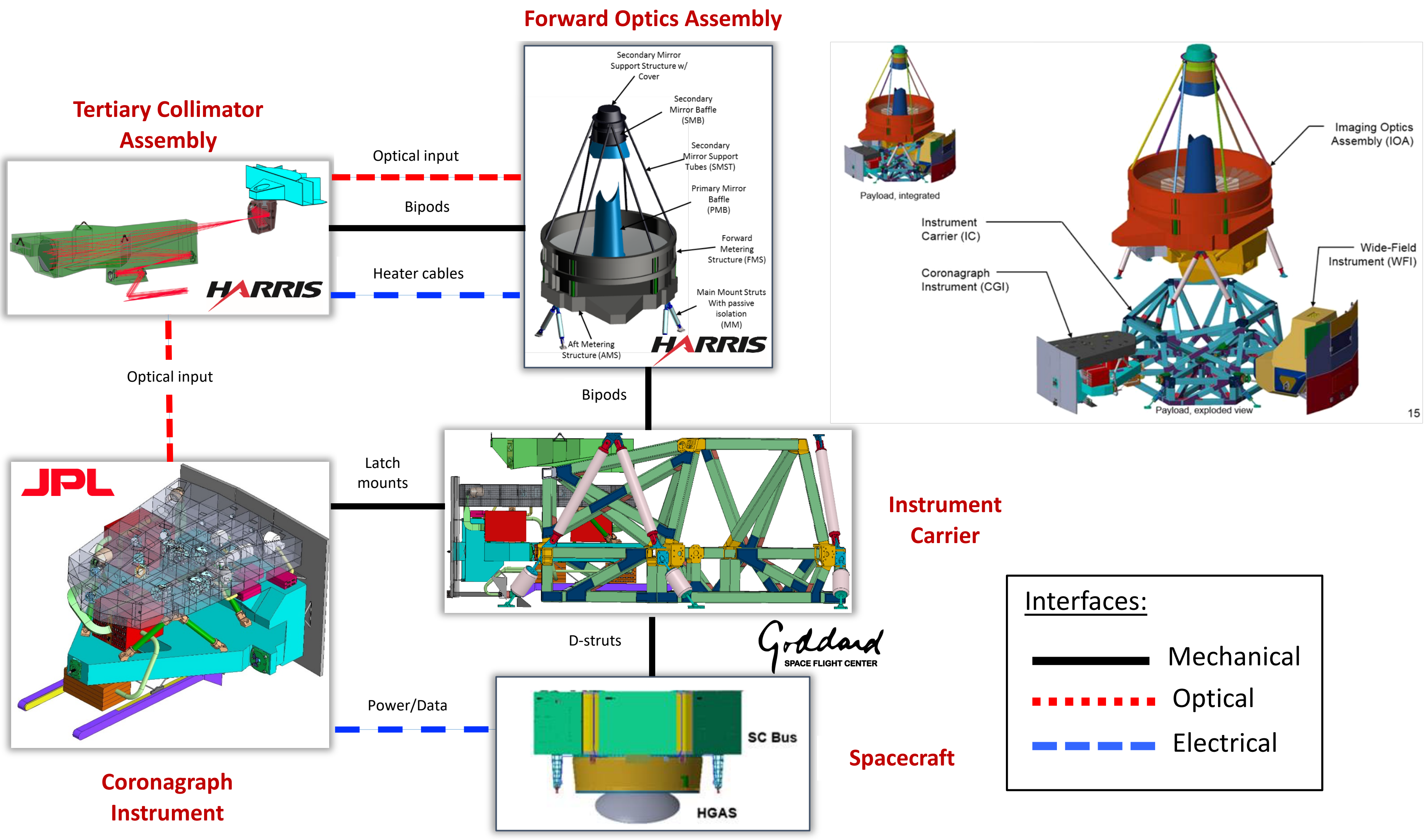
Observatory = Spacecraft + Payload



Observatory Overview

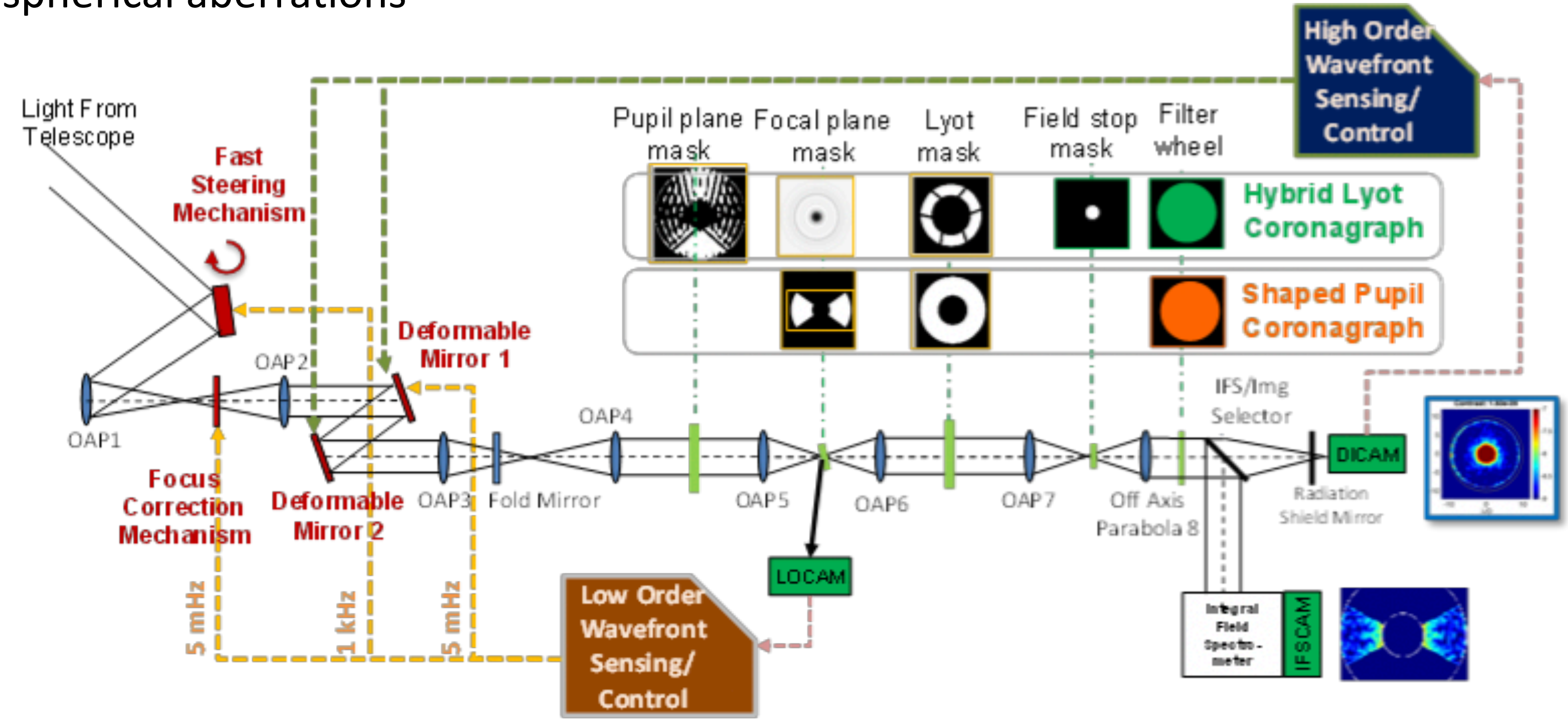


CGI Interfaces to WFIRST Observatory & Spacecrat



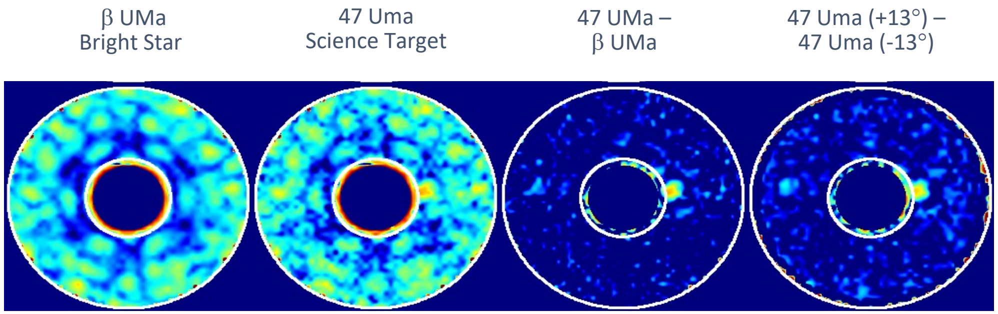
WFIRST Coronagraph Instrument CGI

- The CGI Coronagraph Occulting Mask has two operating modes.
  - Hybrid Lyot Coronagraph (HLC) and
  - Shaped Pupil Coronagraph (SPC)
- Low Order Wavefront Sensing and Control (LOWFS/C) and High Order Wavefront Sensing and Control (HOWFS/C) loops are shown
- The LOWFS/C measures and corrects tip-tilt, focus, astigmatism, coma, trefoil, and spherical aberrations



WFIRST & CGI key pointing Requirements

- **CGI Pointing Stability Requirement:** WFIRST CGI shall have root mean square residual pointing jitter less than 0.8 mas per axis on-sky equivalent for V <= 5 stars for observations between 5 and 40 hours.
  - Average LoS error maps into the average speckle level (contrast stability). Lower (worse) contrast means more residual starlight. That adds shot noise to measurement of the planet.



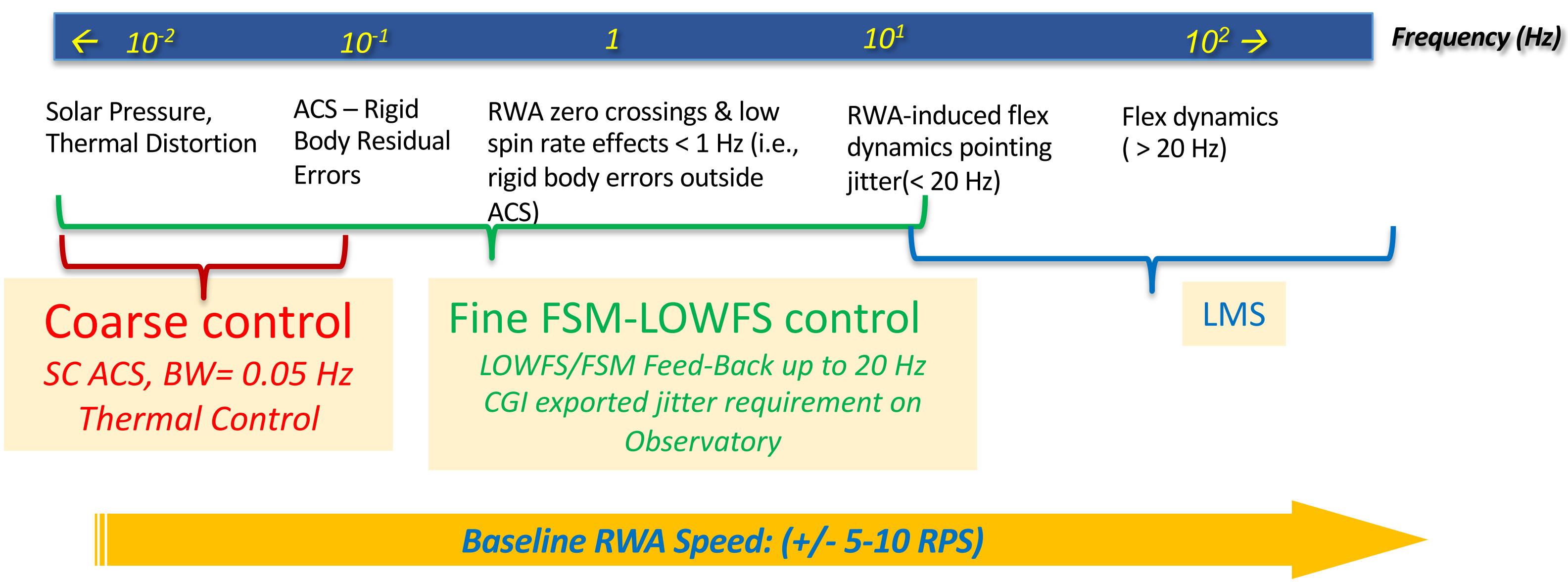
- **WFIRST ACS Pointing Requirement:** ACS residuals shall be less than 8 mas, 1-sigma.

- **WFIRST Observatory Line of Sight jitter in the WFI channel Requirement:** High frequency Jitter due to RWA broad-band and harmonic jitter shall be less than 12 mas, 1-sigma.

CGI Pointing: Control Strategy vs. Frequency

Need to meet pointing requirements with the following disturbance sources:

- **Disturbances:**
  - Static Errors: Constant pointing offset between science and LOWFS sensors
  - Quasi static Distortions: Thermal-distortion of optical train, solar pressure torque, Thermal drift between CGI and WFI boresights
  - ACS: Observatory rigid body attitude error due to ACS (residuals: (8 mas @ CGI, BW = 0.05 Hz)
  - Flexible dynamics Jitter due to RWA broad-band and harmonic jitter (12 mas @ CGI)
    - **Exported jitter requirement: 0.57 mas**
  - Flexible dynamics at the CGI bench



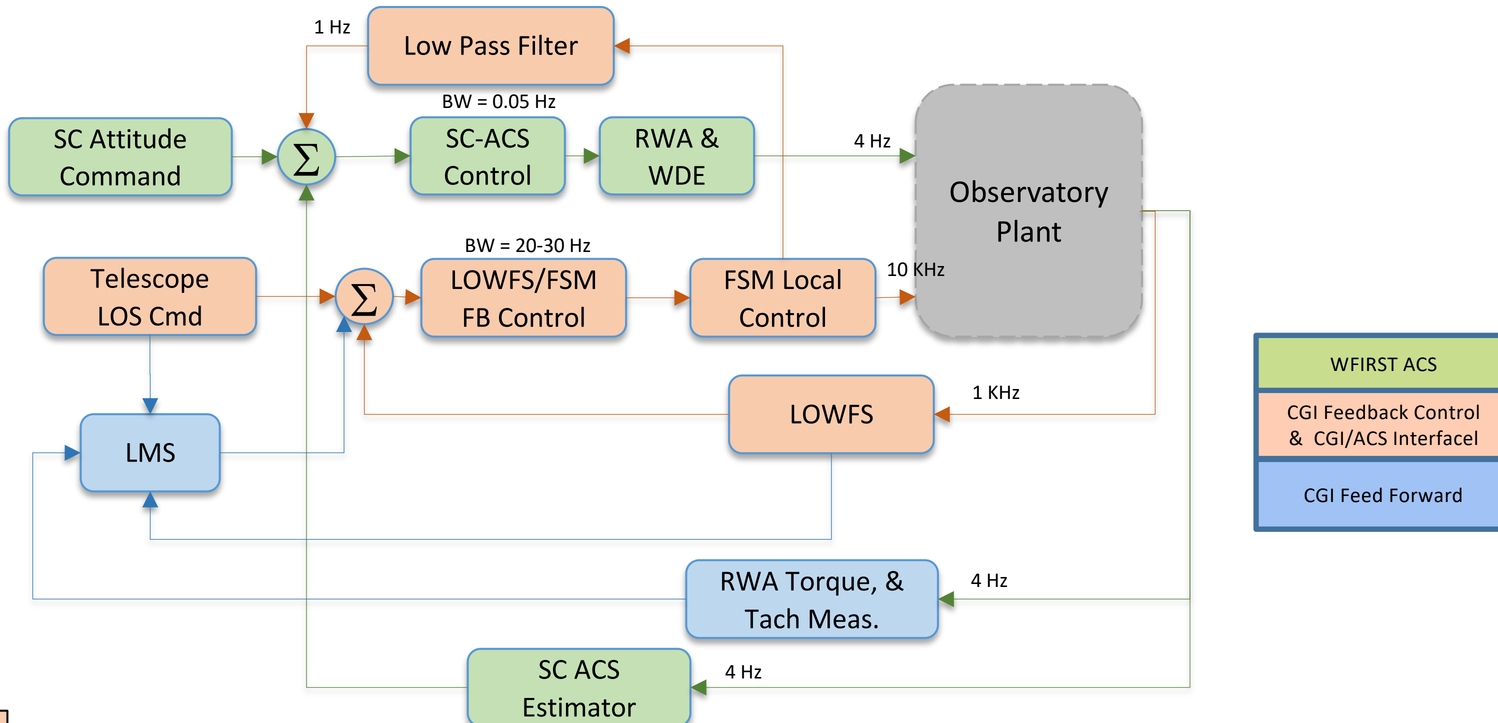
CGI Jitter Mitigations

- WFIRST Project has decided to take an integrated approach to CGI stability requirements
  - WFIRST Project is responsible for meeting the CGI stability requirements (from reaction wheels and thermal effects) *after* applying the CGI close-loop rejection function
    - Exported jitter requirements on WFIRST project side
  - Adding Payload Vibration Isolation System (PVIS) between the S/C bus and Payload with D-struts
  - Adding Reaction Wheels Isolation System (RWIS)
  - Avoiding moving HGA & other mechanisms during science observations
  - Limiting RWA speeds during CGI observations
  - CGI Nested control loops to reject high frequency jitter

CGI PACE Pointing Architecture For Science Tracking Mode

Acronyms:
ACS: Attitude Control System
FSM: Fast Steering Mirror
LOS: Line Of Sight
LOWFS: Low Order Wave Front Sensing
LMS: Least Mean Square
RWA: Reaction Wheel Assembly
WDE: Wheel Drive Electronics

CGI-S/C ICD:
Tracking all interfaces between WFIRST ACS & CGI PACE



LOWFS-FSM Feedback loop:
- -BW: 20-30 Hz,
- -Sampling rate: 1 KHz

FSM local loop:
- -BW > 150 Hz,
- -Sampling rate: 10KHz

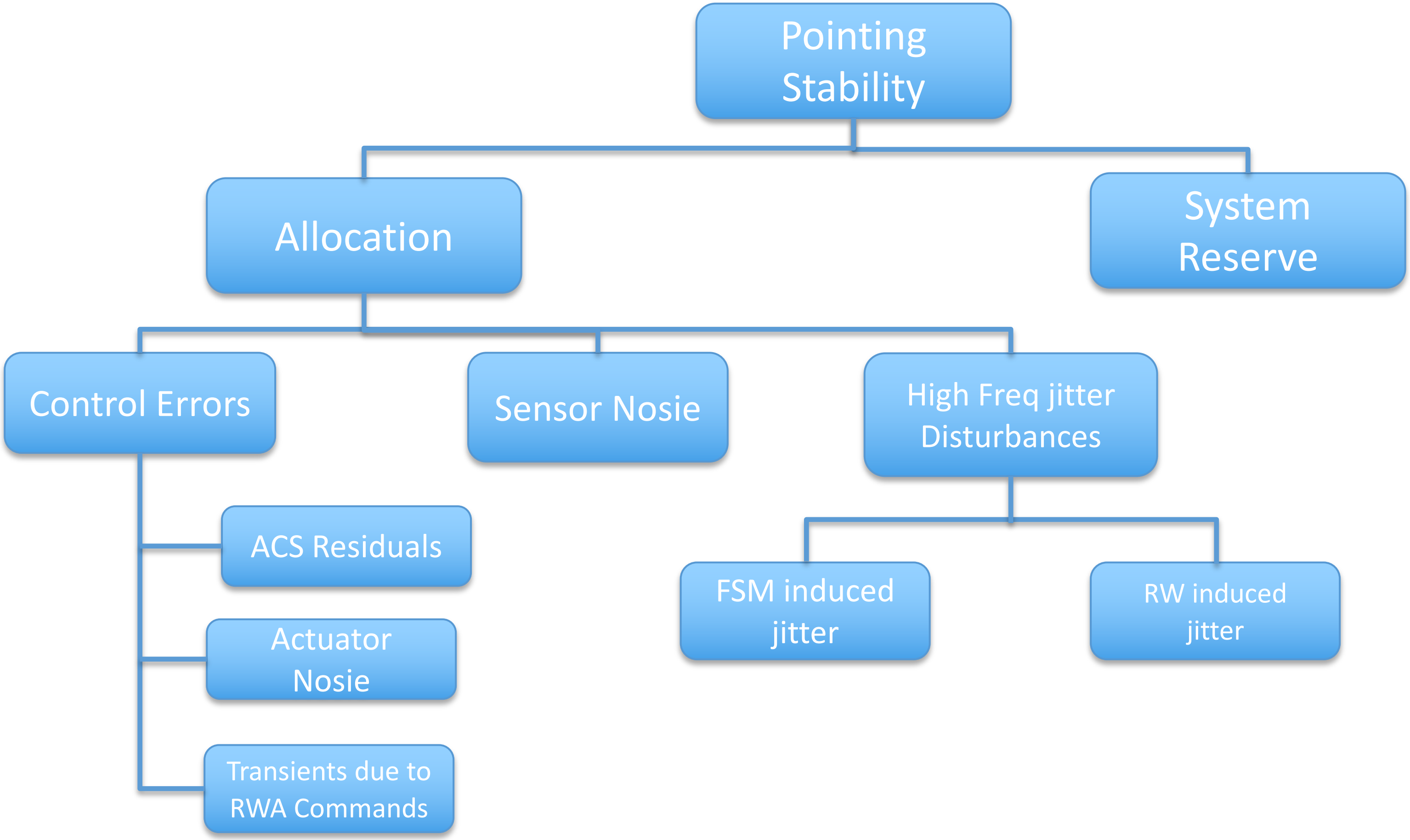
WFIRST ACS Feedback loop:
- - BW: 0.05 Hz,
- - Sampling rate: 4 Hz

Sensor1: LOWFS (sampled at 1 KHz)
Sensor2: Reaction wheels tachometer (sampled at 4 Hz)

Actuator: Fast steering mirror with local loop

Key requirement: residual pointing error:
< 0.7 mas RMS per axis for 70% of the CCD frames over 5-40 hours

Pointing Error Budget



Fast Steering Mirror (FSM)

- FSM is used to suppress LOS jitter, and compensates for pointing errors relative to the system's calibrated optical train due to the following:
  - Observatory Rigid body motion, OTA and CGI optical train changes up to LOCAM
- Once the LOS is acquired in the LOWFS camera FOV, the FSM is then used to suppress drift and jitter caused by low frequency thermal LOS drift, midrange frequency attitude control system (ACS) LOS drift, and high frequency tonal reaction wheel (RWA) LOS jitter.
- As the low frequency and midrange frequency LOS varies, the FSM will develop an offset. This offset is sensed by local sensors on the FSM and mapped to an attitude correction to send to the spacecraft ACS.
- This attitude correction desaturates the FSM stroke and is used by the ACS system to improve pointing knowledge and accuracy.
- Maintaining the FSM near its center is also important in terms of mitigating beamwalk which can adversely impact CGI science performance.
- FSM mechanism will be actuated with three PZTs in a triangular configuration and will have a local control loop with sensors (strain gauges) that measure tip, tilt and piston of the optic.
- The purpose of the local control loop is to linearize the response of the mechanism and to aide in decoupling the tip and tilt responses.

Control Analysis Simulation Testbed (CAST)

- Pointing Acquisition, and Control Element (PACE) is responsible to meet CGI pointing requirements
- PACE used CAST to predict pointing performance
- CAST produces time-domain simulation with highest model fidelity available
- CAST assess performance for various control architectures for LOS pointing
- CAST Evaluates model-based LOS pointing performance for entire observation (tens of hours)
    - Will include S/C slews and rolls, with required mode changes, and reaction wheels speeds profiles
    - Will require computing power to support this level of processing
    - Helps with operational design, by identifying “quiet” regions in wheel speed space
- Assist with V&V and testbed activities
    - Identify potential risks and their mitigations
- Error sources:
    - External torques
    - CGI bench disturbacnes
    - RW disturbances, quantization etc.
        - Ripple and Cogging, Bearing drag,
    - Sensor Noises
        - WFI, LOWFS, Tachometer noise models
- Outputs:
    - LOS error and attitude errors
    - Optical element rigid body motions

Reaction Wheels induced LoS jitter

- GSFC IM team provides integrated models of the observatory
- Figure 1 shows Los X due to RW disturbances for 6 wheels
- Figure 2 shows attenuated LoS x after the feedback control
- During CGI observations, wheel speeds would be limited to speeds between +/- 10 RPS

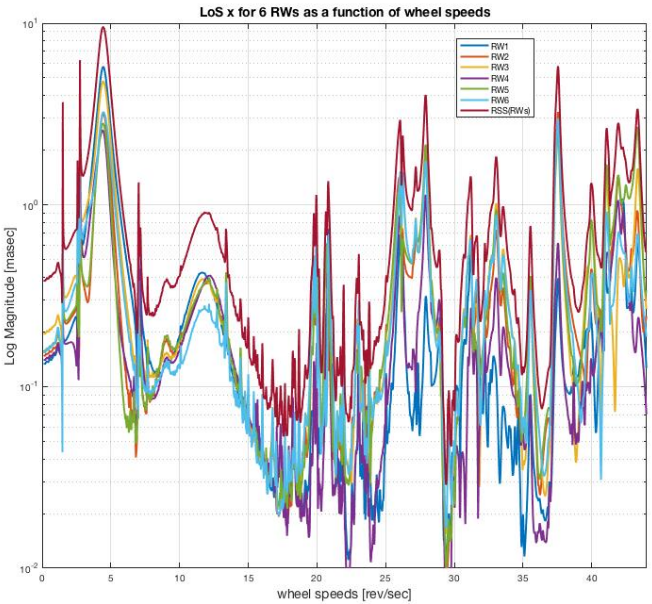


Figure 1. LoS x as a function of wheel speeds for 6 wheels Open loop

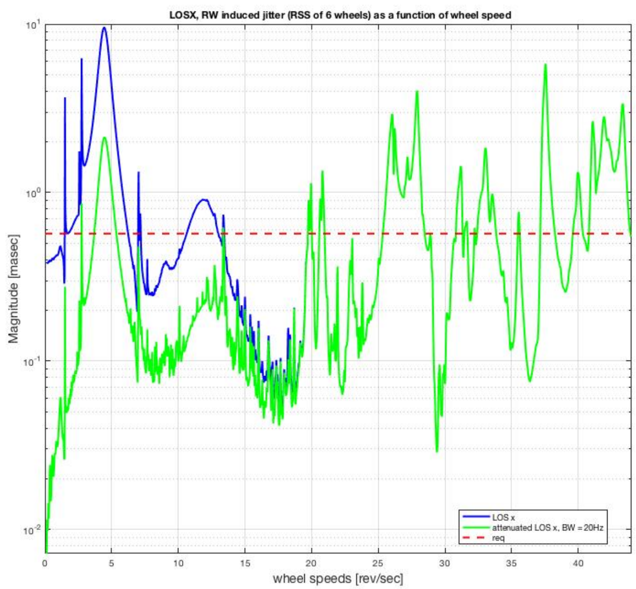


Figure 2. LoS x as a function of wheel speeds for 6 wheels (RSS of 6 wheels,-- open loop & closed loop)

An Example with Feedback, and Feedforward loops

- This simulation result uses realistic sensor noise, actuator, disturbance, and tachometer errors with a wheel speed profile between +/- 10 RPS in Figure 1.
- Figure 2 shows an example of a case with ACS, and RWA disturbances, open loop, closed loop FB, and FB/FF

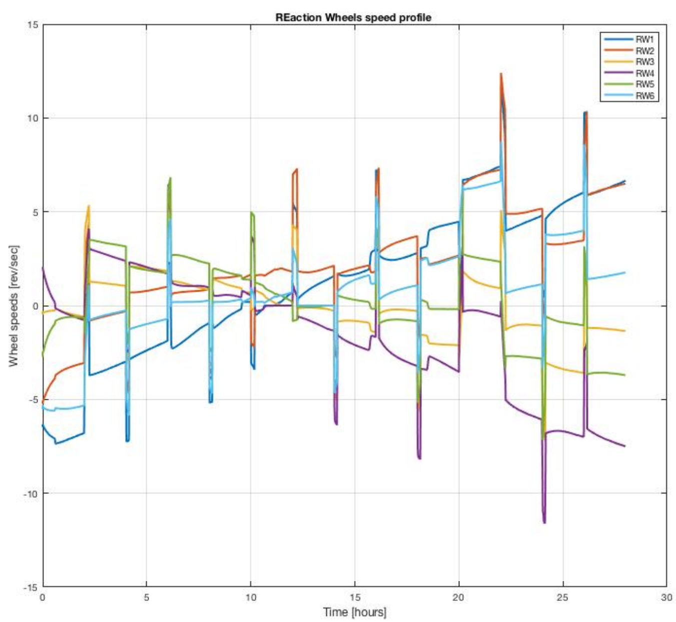


Figure 1. Initial reaction wheel speeds selected from time periods between slews.

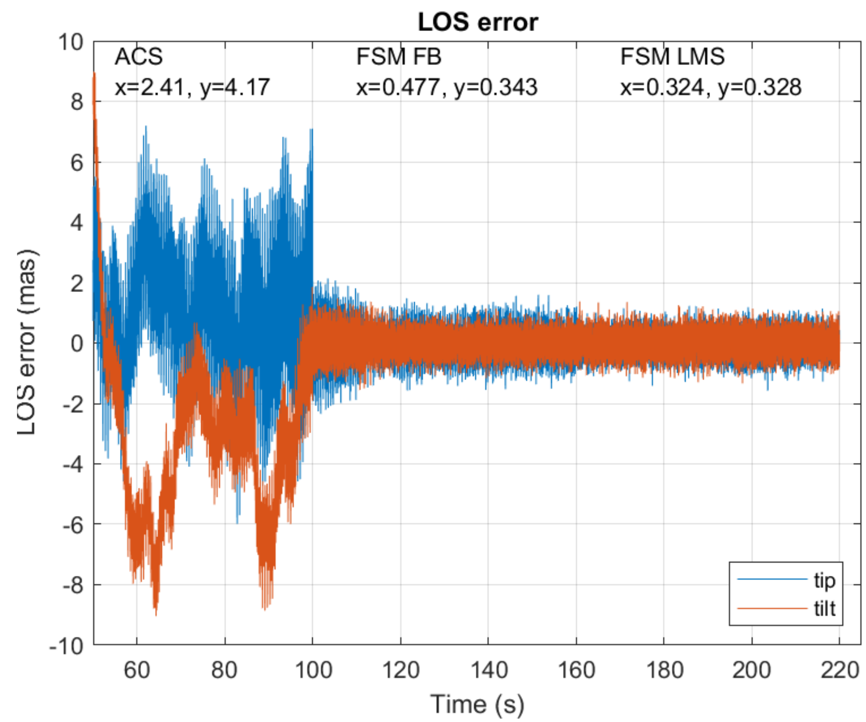
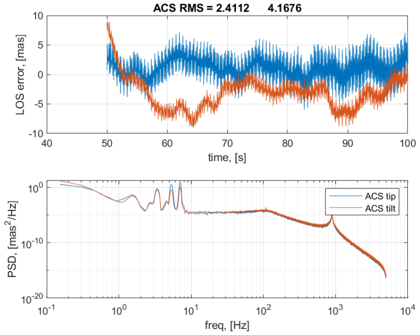


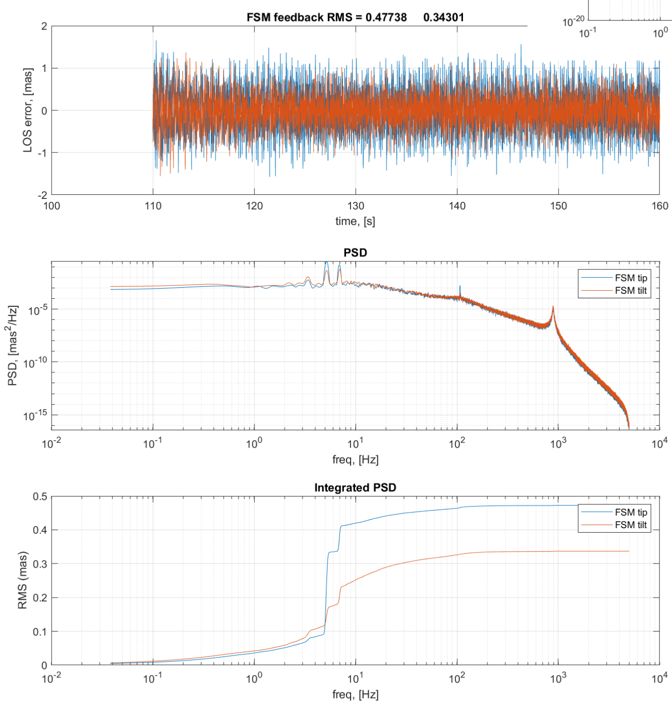
Figure 2. Example on open loop, FB, and FB/FF based on wheel speed profiles on Figure 1

Open loop, FB, and FB/FF Example due to RWA disturbances

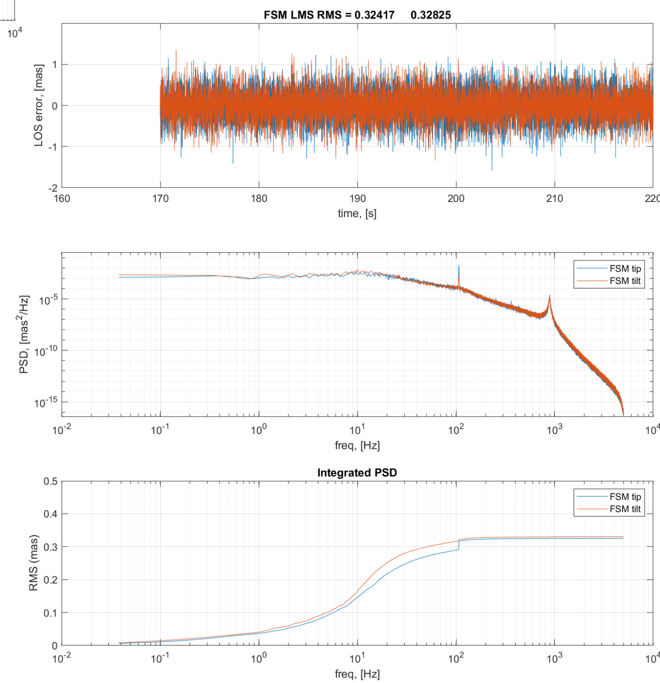
ACS loop only



ACS loop & FB



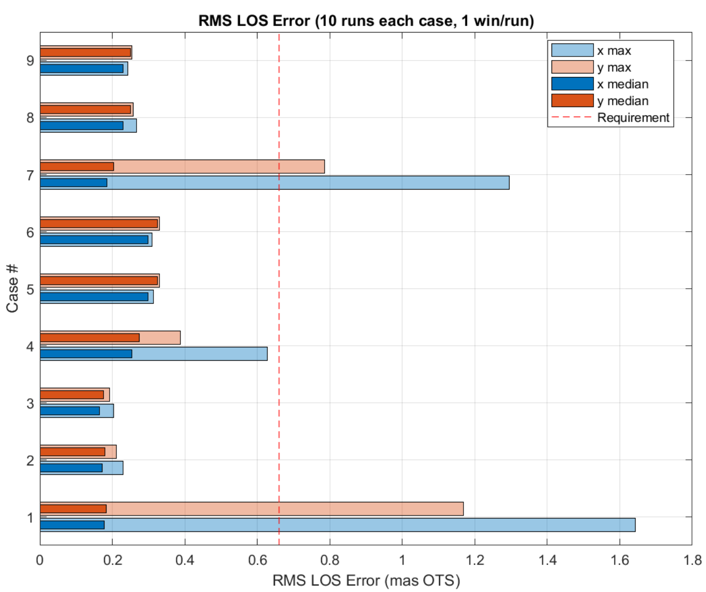
FB & FF



Some Results for 3 feedback loops designs

- 3 sets of Feedback loops with different bandwidths (2, 10, 20 Hz)
- For low bandwidth feedback loops, at 2, and 10 Hz, requirements are not met with just feedback, and requires LMS to be turned On
- Feedback loop with 20 Hz bandwidth is at 20 Hz, requirements are met with feedback only case, while LMS provides an improvement in robustness and margin

Case #	Feedback Bandwidth (Hz)	LMS	RW Speed (RPS)	Lowpass torque cmd And calibrated tach
1	2	Off	1-10	Off
2	2	On	1-10	Off
3	2	On	1-10	On
4	20	Off	1-10	Off
5	20	On	1-10	Off
6	20	On	1-10	On
7	10	Off	1-10	Off
8	10	On	1-10	Off
9	10	On	1-10	On



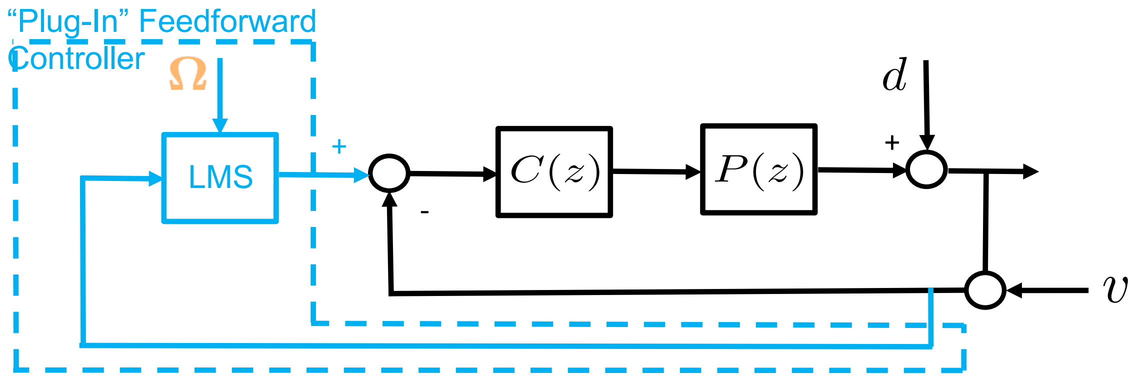
Summary

- Pointing stability due to LoS jitter is one of the key requirements on WFIRST CGI
- Few mitigation strategies have been incorporated to met tight pointing requirements
- Payload, and RW isolation systems on WFIRST observatory
- Limiting wheel speeds to +/-10 RPS during CGI observations
- The pointing system includes three nested feedback loops: ACS, FSM local control, and FSM/LOCAM feedback loop, to remove low frequency drift, and suppress high frequency jitter induced by spacecraft reaction wheel disturbances.
- The feedforward loop (LMS) rejects high frequency tones excited by reaction wheels tonal frequency.
- Pointing algorithms are planned to be implemented on an FPGA
- Recent results show that CGI meets tight pointing requirements with feedback loop (bandwidth at 20 Hz), while feedforward LMS adds robustness and margin.
- CGI PDR will be in Summer 2019

Back up slides

LMS (Least Mean Square) What Is It?

- LMS is "Plug-in" add on to the feedback loop that is used to reject sinusoidal tones. LMS uses wheel speed signals from the spacecraft to aid in rejection of the harmonic disturbances caused by imbalances in the reaction wheel assemblies (RWA). (The spacecraft ACS uses 6 wheels.)



- Having the LMS address the RWA disturbance allows one to use the feedback to independently address ACS LOS variations and in-band sensor noise jitter.