Requirements and Design Reference Mission for the WFIRST-AFTA Coronagraph Instrument

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ABSTRACT

The WFIRST-AFTA coronagraph instrument takes advantage of AFTAs 2.4-meter aperture to provide novel exoplanet imaging science at approximately the same instrument cost as an Explorer mission. The AFTA coronagraph also matures direct imaging technologies to high TRL for an Exo-Earth Imager in the next decade. The coronagraph Design Reference Mission (DRM) optical design is based on the highly successful High Contrast Imaging Testbed (HCIT), with modifications to accommodate the AFTA telescope design, service-ability, volume constraints, and the addition of an Integral Field Spectrograph (IFS). In order to optimally satisfy the three science objectives of planet imaging, planet spectral characterization and dust debris imaging, the coronagraph is designed to operate in two different modes: Hybrid Lyot Coronagraph or Shaped Pupil Coronagraph. Active mechanisms change pupil masks, focal plane masks, Lyot masks, and bandpass filters to shift between modes. A single optical beam train can thus operate alternatively as two different coronagraph architectures.

Structural Thermal Optical Performance (STOP) analysis predicts the instrument contrast with the Low Order Wave Front Control loop closed. The STOP analysis was also used to verify that the optical/structural/thermal design provides the extreme stability required for planet characterization in the presence of thermal disturbances expected in a typical observing scenario. This paper describes the instrument design and the flow down from science requirements to high level engineering requirements.

1. INTRODUCTION

The WFIRST-AFTA (Wide Field InfraRed Survey Telescope-Astrophysics Focused Telescope Asset) is a NASA space observatory that has been designed to probe dark energy, carry out wide field Near Infrared (NIR) surveys and to discover and characterize extrasolar planets (hereafter exoplanets) in the visible spectrum. WFIRST-AFTA will make use of an existing 2.4 m aperture telescope, and will advance what is currently possible in exoplanet spectral characterization and imaging. The telescope feeds an instrument suite consisting of a Wide Field Imager (WFI) and a Coronagraph Instrument (CGI). These two instruments are complementary. The WFI will collect NIR statistical data on planetary systems over large regions of the sky using gravitational lensing, whereas the coronagraph will carry out direct imaging and detailed visible spectroscopy of a sample of exoplanets. The coronagraph will be able to detect and characterize cold Jupiters, mini-Neptunes and possibly super-Earths (Spergel et al.[1]), for the first time directly imaging planets analogous to those in our Solar System. This spectroscopic characterization will reveal the atmospheric composition of these planets and will be used to search for spectral signatures of life. In addition, the coronagraph will be used to characterize debris disks in and around planetary orbits - an important tool that can be used to improve our understanding of planet formation.

The Jet Propulsion Laboratory has been developing coronagraph technology and a Design Reference Mission (DRM) CGI design funded by NASA under the WFIRST project study office at Goddard Space Flight Center (GSFC). If WFIRST becomes a flight project, the CGI is likely to be a guest observer instrument paired with the

WFI. The CGI will observe for a total of one year over a six year mission, but cannot drive the mission or spacecraft requirements. The JPL-led coronagraph technology development team includes Princeton University, University of Arizona, NASA Ames Research Center (NARC), Space Telescope Science Institute (STScI), CalTech IPAC, Northrup Grumman Xinetics and GSFC. The CGI technology development is described by Poberezhskiy et al[1] in another article in this proceedings. The technology development program will advance the NASA Technology Readiness Level (TRL) of the CGI to TRL-5 and is expected to be completed in FY16.

In parallel with the technology development a DRM instrument design for the coronagraph has been developed. The CGI that resulted from design cycle 5 was described in detail in the Science Definition Team (SDT) final report released in January 2015[2]. The cycle 5 optical design is described by Tang et al[3] in this proceedings. The CGI design resulting from design cycle 6 is the subject of this paper. The only significant change in requirements for design cycle 6 is a change from Geosynchronous Orbit (design cycle 5) to a direct insertion to L2 orbit.

2. CORONAGRAPH INSTRUMENT CONCEPT

The science objectives of the CGI are planet imaging, planet spectral characterization and characterization of debris disks. The DRM coronagraph design is based on the successful High Contrast Imaging Test-bed (HCIT) at JPL. In order to adequately form images and collect spectra of exoplanets, it is necessary to suppress the starlight to a contrast of order 10^{-9} for cold Jupiters, mini-Neptunes and super Earths. The coronagraph accomplishes this by using i) a series of masks to reject starlight, block diffracted light, and to reduce starlight speckles, and ii) an adaptive optics system, employing a pair of 48×48 actuator deformable mirrors (DMs) in order to eliminate residual speckles due to optical imperfections in the entire optical beamtrain. The result is a high contrast point spread function (PSF) with a dark hole between inner and outer working angles allowing observations of faint companions. The performance specifications for the DRM design cycle 6 CGI are displayed in Table 1. In a typical observation, the high contrast dark hole is produced while the instrument is observing a bright calibration star. The coronagraph DM and mask settings are then frozen while the telescope slews and points to a target or science star. The "raw contrast" produced by the CGI on orbit is further improved on the ground using data post processing algorithms. There are several such existing algorithms developed on the coronagraphs in ground-based observatories. Using these algorithms, the starlight speckle measured on a bright (calibration) star is subtracted from the image taken on a dim target (science) star to reveal exoplanets or debris disks.

Table 1 Performance specifications for the Coronagraph Instrument

Instrument Imaging Bandpass	430 – 980 nm	Measured sequentially in 10% bands
Instrument IFS Bandpass	600 – 980 nm	Measured sequentially in 18% bands
Inner Working Angle [radial]	150 mas	At 550 nm, 3λ/D driven by AFTA pupil obscurations
	270 mas	At 1 μm
Outer Working Angle [radial]	0.5 mas	At 550 nm, 10λ/D driven by 48×48 format DM; Can access larger working angles with some contrast degradation
	0.9 mas	At 1 μm (imaging camera)
Detection Limit (Contrast)	10^{-9}	Cold Jupiters; deeper contrast unlikely due to pupil shape and extreme stability requirements
Spectral Resolution	70	R = λ/δλ (IFS)
IFS Spatial Sampling	17 mas	3 lenslets per λ

A schematic functional block diagram of the CGI is shown in Figure 1. In order to maintain the contrast stability over long observation times a Low Order WaveFront Sensor (LOWFS) and Control system in the coronagraph is used to sense and correct lower order wavefront error resulting from i) thermally induced optical misalignment and optical surface distortions and ii) Line of Sight (LOS) jitter caused by vibration sources such as the spacecraft reaction wheels and the WFI cryo-cooler. A Zernike wavefront sensor uses the rejected starlight to sense aberrations from Z1,2 (x- and y-tilts) up to and including Z11 (spherical aberration)[4]. The x- and y-tilts resulting from LOS jitter are corrected using a Fast Steering Mirror (FSM) whereas the low order wavefront drifts are corrected by both a pistoning fold mirror for focus correction and the DMs for other low order aberrations such as astigmatisms and comas.

The WFIRST-AFTA coronagraph instrument can operate in two modes: i) a Hybrid Lyot Coronagraph (HLC) for exoplanet photometry and discovery and ii) a Shaped Pupil Coronagraph (SPC) for exoplanet spectroscopy and debris disk characterization. The HLC uses a focal plane phase-amplitude mask whereas the SPC uses a pupil mask with binary apodization. The flight instrument comprises a single optical beam train that will be operated in either the HLC or SPC mode depending on the particular science observation. The Coronagraph Instrument switches between the two operational configurations using active rotary mechanisms to change pupil masks, focal plane masks, Lyot masks, band pass filters and an actuated fold mirror to select either the imaging camera or the Integral Field Spectrograph (IFS). The two different coronagraphic configurations of the optical beam train are illustrated schematically in Figure 2. In both the HLC and SPC modes, the pair of DMs are used to effect closed-loop reduction of speckle. This dual mode architecture enables the optimum coronagraph configuration to be used for the different types of planet/disk characterization. The two coronagraph architectures are complementary. The HLC can achieve deeper contrast at some ranges of working angles which makes it suitable for planet imaging whereas the SPC is relatively insensitive to jitter and has lower chromaticity, making it a better match for spectroscopy.

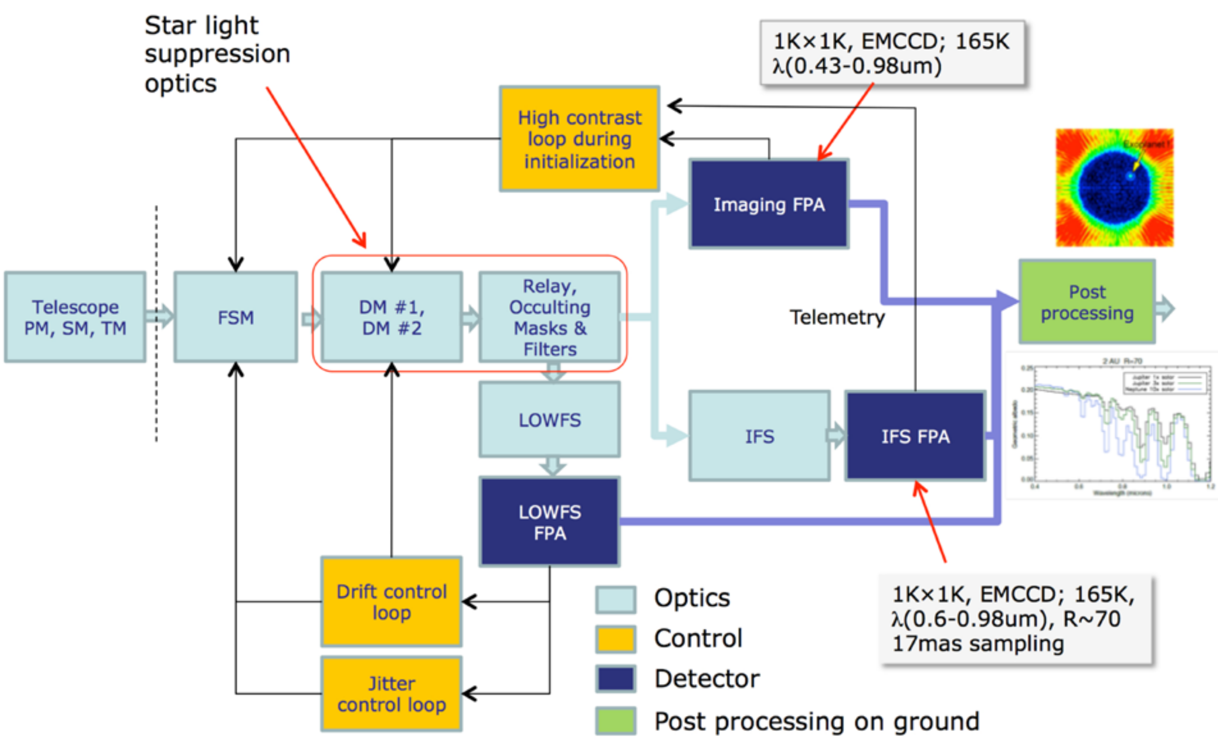

Figure 1 Functional block diagram of the Coronagraph Instrument illustrating control loops and servo functions.

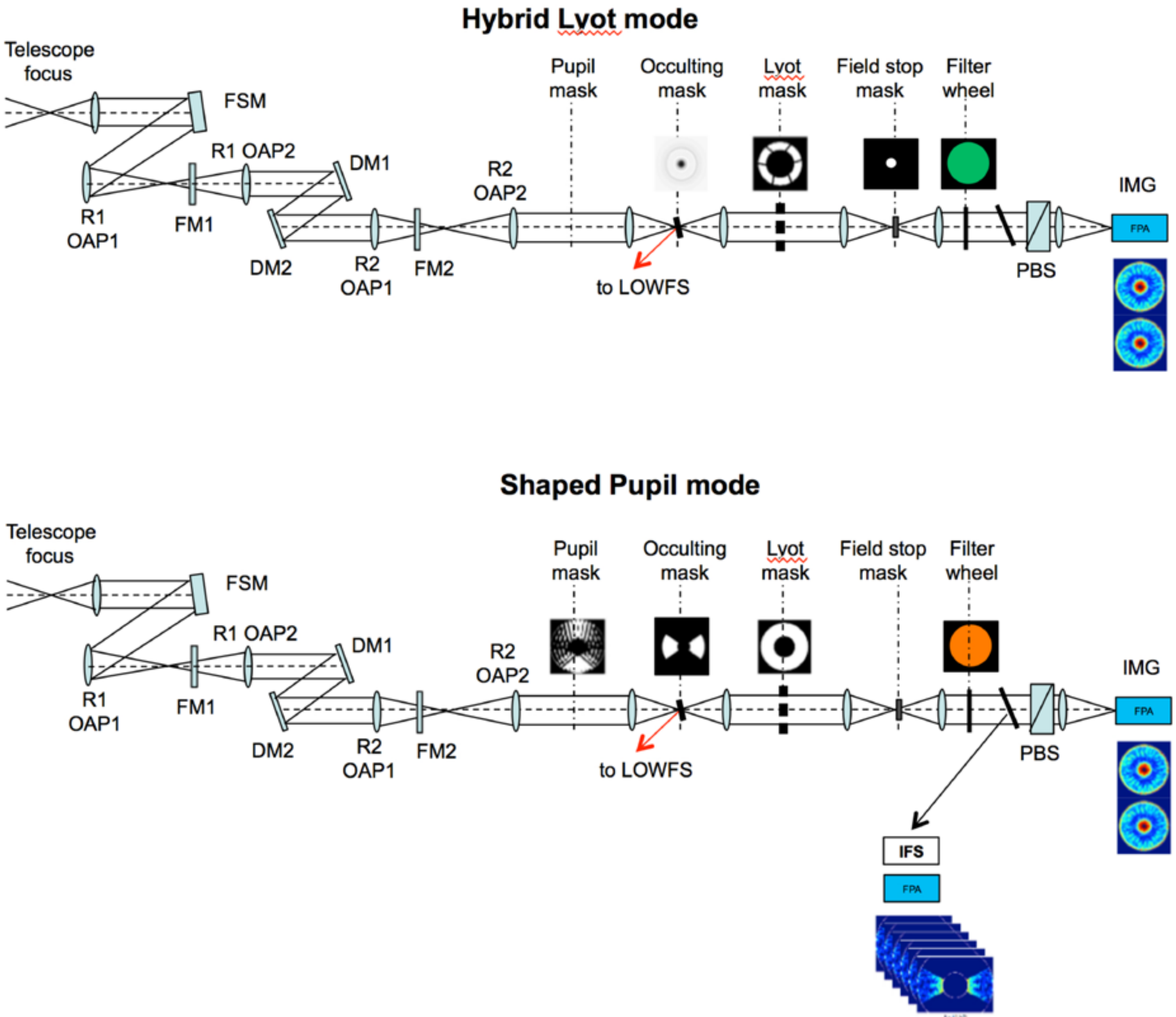

Figure 2 Schematic illustration of the two separate configurations of a single optical beamtrain. The instrument is operated in either a Hybrid Lyot or Shaped Pupil Coronagraph using mechanisms to change masks, color filters and lenses. The optical beamtrain is shown in the Hybrid Lyot configuration (above) and Shaped Pupil configuration (below).

When carrying out planet discovery, photometry and disk imaging, the HLC or SPC relays an image of the high contrast “dark hole" onto the imaging camera. A stationary polarizing beamsplitter in front of the imaging camera separates the dark hole image into two orthogonal polarizations, whose two resulting images fill a small rectangular area of the detector. The dark hole can be optimized for one polarization at a time or for an average of the two. The best contrast results from optimization of one polarization only, although both are recorded by the imaging camera. When taking planetary spectra, by contrast, the IFS relays an image consisting of a regular grid of spectrally dispersed PSFs onto the detector.

Several aspects of the IFS design (McElwain et al.[5]) reduce the already very low light level of the planet image from the coronagraph. The IFS separately collects spectra across the visible spectrum in three separately detected 18% wide sub-bands centered at 660, 770 and 890nm. At the input of the IFS is a lenslet array used for spatial sampling the dark hole, where the PSF sampling on the lenslet array is 3×3 lenslets per λ/D (PSF core). A two-element prism spectrally disperses the PSFs along a single axis, reducing spreading the light on the detector. Thus, the very low expected photon count requires sub-electron read noise, dark current and clock induced charge (CIC) to carry out planet spectroscopy.

3. CONTRAST ERROR BUDGET

A key limitation in planet detection is the uncertainty associated with the process of subtraction of starlight speckle from the science image. This is essentially a probability of false positive or false negative planet detection. There are several contributors to this uncertainty. An error budget for the instrument contrast is shown in Figure 3. The total planet/star contrast after data post processing is required to have a value of no worse than 3×10^{-9}. Assuming an instrument signal to noise ratio of 5, the total contrast uncertainty is 0.6×10^{-9} or 0.6 parts per billion (ppb). An engineering reserve of 25% is removed from this allocation, leaving 0.45 ppb for the uncertainty or contrast errors. There are three significant contributors to this uncertainty:

1. *Brightness dependent errors on the science star* – These are errors due to Poisson noise, detector read noise, dark current, CIC, etc
2. *Speckle calibration error* – This is the uncertainty associated with the calibration of the starlight speckle pattern on a calibration star and using this to subtract the speckles from the science star image. There are errors in measurement of the brightness of the (bright) calibration and (dim) science stars as well as error in scaling between the two.
3. *Speckle modeling error* – this encompasses all errors in the model used to remove speckle variation due to disturbances such as line of sight pointing jitter and instrument thermal drift. The model will be a combination of first principles physics and empirical relationships between disturbances and starlight speckle. During in-orbit checkout, the response of speckle to known stimuli will be characterized and used to predict speckle variation versus observed disturbances.

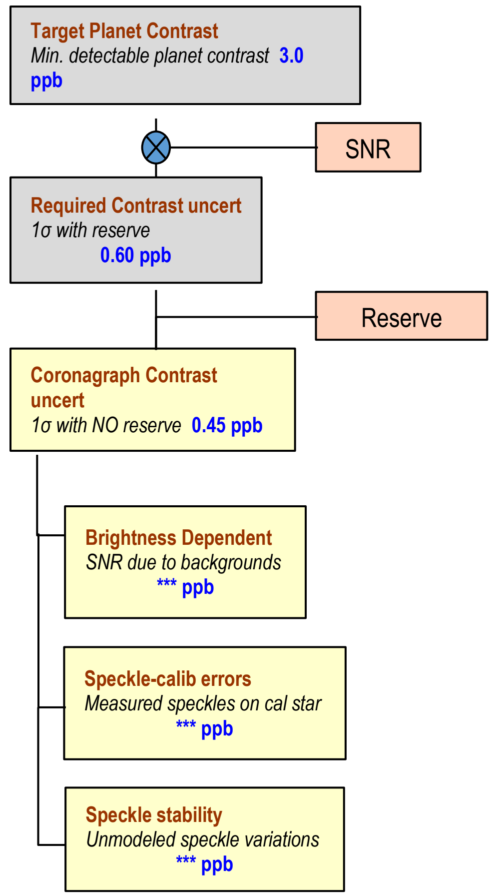

Figure 3 Overview of the CGI contrast error budget. Error boxes containing three asterisks do not yet have allocations.

4. CORONAGRAPH DESIGN CYCLE 6

a. Optics and Structure

Some of the key features of the cycle 6 CGI design are the i) consolidation of all CGI optics including the spectrograph optics onto a single horizontally oriented optical bench, ii) the updated design of HST-proven latch concept that enable robotic instrument replacement in orbit and iii) the use of radiators for passive cooling of detectors and electronics. The most significant improvement in the CGI, however, is the structural and thermal separation of the collimator optics from the coronagraph core optics. The collimator optics assembly, consisting of a tertiary mirror (M3), a collimator (M4) and a pair of fold mirrors mounted on a monolithic carbon composite bench, is thermally insulated on all sides and contains heaters and temperature sensors for closed loop temperature control at the level of hundreds of milli-kelvin. Since the AFTA telescope comprises only a Primary and Secondary mirror, the addition of a tertiary completes the telescope and forms a three mirror anastigmat (TMA). The entire collimator assembly is mechanically attached with bipods to the AFTA telescope on the very stable Aft Metering Structure (AMS). In the previous design cycle, the collimator assembly was embedded in the CGI structure which was attached to the spacecraft Instrument Carrier (IC). Since the IC is not as thermally stable as the AMS and since the optical interface between the collimator assembly and the CGI is collimated light, the mounting of the collimator assembly directly to the AMS is predicted to reduce the contrast sensitivity of the CGI to thermal drift of the IC by a factor of 1000. As shown in Figure 4, the CGI is mounted to the IC whereas the collimator is mounted to the telescope. The collimator optics reduce the large static wavefront error of the off-axis beam emerging from the AFTA telescope secondary mirror (M2) from a level of 13,570 nm rms to 4 nm rms. Moreover, the output wavefront of the collimator optics is very insensitive to line of sight (LOS) pointing error. The RMS variation of the LOS pointing jitter incident on the coronagraph is expected to be 14 milli-arcseconds. The resulting RMS variation of wavefront coming off of the collimator mirror, M4, is 400 picometers and the variation of coma only off of M4 is 16 picometers. Both the tertiary, M3, and collimator mirror, M4, have simple conic surfaces and are thus easy to fabricate.

Since the collimator assembly is integrated with the telescope, it is a permanent fixture and is not replaced in a robotic servicing mission. The collimated output of the collimator assembly is a useful optical interface for a narrow field of view replacement instrument at the end of life of the CGI. The field of view of the replacement instrument can be as much as 100 arc-seconds at 430 nm. The design specifications of the cycle 6 CGI appear in Table 2. The mass and power figures are current best estimates.

A partial assembly CAD rendering of the CGI is shown in Figure 5. In order to provide an unobstructed view of the CGI optical bench, the collimator assembly bench and support structure were made invisible, showing the collimator assembly optics floating above the CGI bench. The large triangular backbone (shown in blue in the figure) below is the CGI support structure which will be attached to the spacecraft IC using three latches located at the three vertices of the triangle (only two of three latches are visible in the figure). The latch design has the design heritage of the Hubble Space Telescope (HST)-proven 3-2-1 latches. The three latches constrain the motion of the mechanical interfaces in three, two and one degree(s) of freedom, respectively. The CGI optical bench is supported by the triangle via three bipods. Below, the instrument electronics box is supported by a small support frame (rendered in green in the figure) which is attached to the triangular frame by bipods. The entire CGI bench, structure and electronics box are surrounded and insulated by a thermal shroud (not shown in the figure). The three heat radiators are attached to the thermal shroud by bipods. Two of the radiators transport heat from the CGI cameras and associated electronics via heat straps. The third radiator transports heat from the CGI electronics box via a heat pipe.

The imaging and IFS cameras will use identical 1024×1024 format EMCCDs for imaging and spectroscopy, respectively[6]. The selected EMCCD, the e2V CCD201-20, is currently undergoing flight qualification radiation testing led by JPL.

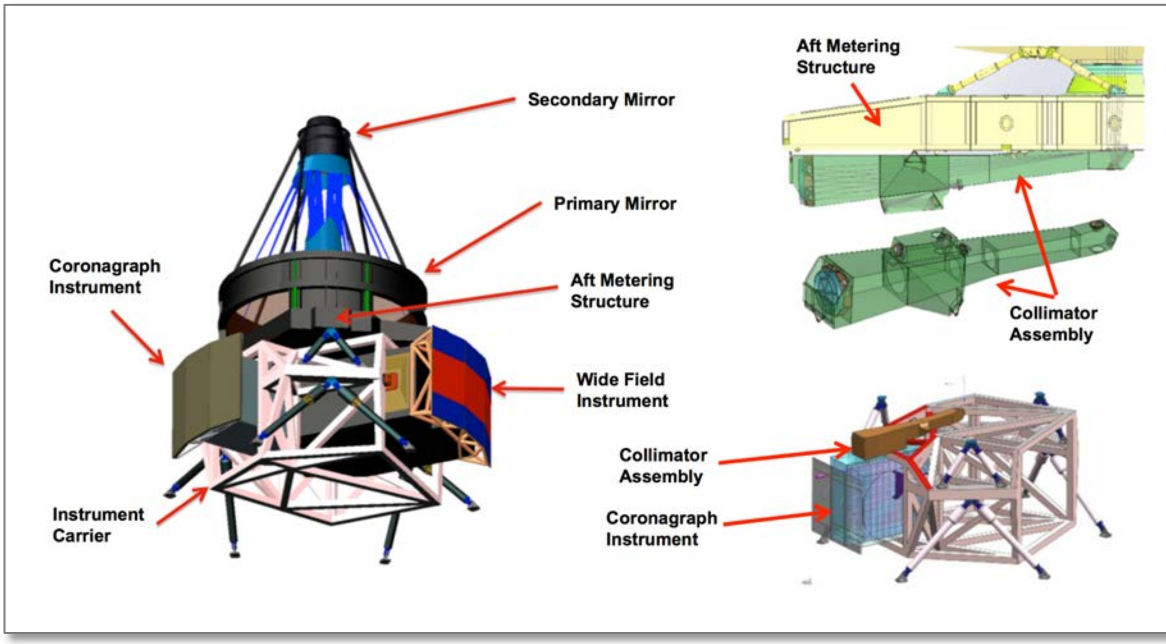

Figure 4 CAD model renderings of the payload, coronagraph instrument, collimator assembly and the telescope. The collimator assembly – directly attached to the telescope AMS and with a dedicated thermal control system – is very thermally stable. This is a key design factor resulting in the thermal stability of the coronagraph. The AMS is more thermally stable than the IC.

Table 2 Coronagraph Instrument design specifications

Design Specification		Value	
As-designed Static WFE [rms]	After M2	13,570	nm
	After M4	4.0	
Dynamic WFE (14 mas LOS Jitter variation) [rms]	After M4	400	pm
	After M4 (Coma only)	16	
Throughput (excludes detector QE and psf sampling by the IFS lenslet array)	SPC (IFS)	0.04	N/A
	HLC (Imaging)	0.05	
Imaging FOV [radius] for debris disk science	34λ/D @ 550 nm 20λ/D @ 950 nm	1.62	arc sec
Imaging FOV [radius]	Without masks	10×5	arc sec
Imaging pixel plate scale		0.01	arc sec
Mass	Current Best Estimate	132	Kg
Peak Power		216	Watts
Average Power		167	

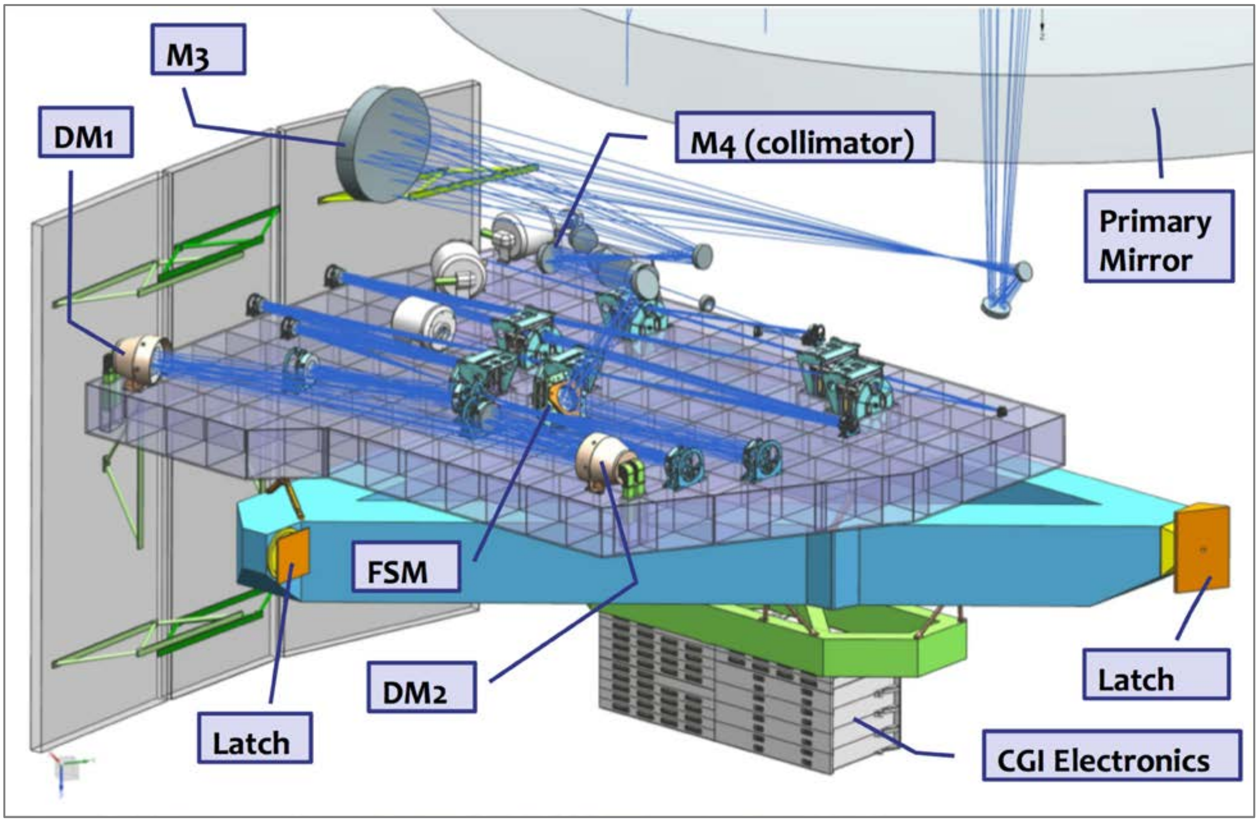

Figure 5 CAD model of CGI interior. The blue triangle is the CGI support structure attached to the spacecraft Instrument Carrier. The gray panels at the left are the heat radiators. The collimator optics are shown without mounts and support structure to provide a clear view of CGI optics.

b. Mechanisms

In addition to the two DMs there are ten optical elements in the CGI—listed in Table 3—with active mechanisms, seven of which are of identical design. The mechanisms serve i) to transform the beamtrain between the two coronagraph architectures, HLC and SPC, ii) to set the coronagraph band width, iii) to select either the imaging camera or the IFS, iv) to fold the light from a internal calibration source into the CGI beam path and v) to close a shutter in the CGI protecting the EMCCDs from possibly damaging high flux light.

Table 3 List of active CGI optical mechanisms excluding the DMs.

Mechanism	**Description**
Fast Steering Mirror	Tip and tilt 200mm from pupil plane (PM conjugate) Operates at up to 1 KHz based on feedback from low-order wave-front sensor (LOWFS) Dynamic range = 30 as / 60 mas = 500 (TBR) Resolution of 60 mas (TBR) (to correct telescope pointing to 1mas = 120mas in coronagraph = 60mas in mirror angle.)
Shaped Pupil Mask Changer	5 positions (4 SPC masks, 1HLC open slot)
Focal Plane (occulting) Mask Changer	14 positions (11 SPC masks, 2 HLC masks, 1 open slot)
Lyot Stop Changer	4 positions (1 SPC mask, 2 HLC masks, 1 open)

Field Stop Changer	3 positions (1 SPC open, 2 HLC stops)
Color Filter Changer	13 positions ([4] 5% filters, [2] 6% filters, [2] 10% filters, [3] 18% filters, 1 open, 1 dark)
Camera Selector Changer	3 positions (1 lens for IMG cam, 1 fold mirror for IFS, 1 lens for pupil image on IMG cam)
Focus Mirror Adjust	Linear positioning stage for focus correction
Shutter	To protects optics when not in operation
Flip Mirror	Reflects an internal source for calibration

c. Electronics

The instrument electronics architecture is intended to allow for parallel integration and test (I&T) of subsystems and to thereby reduce the total time and resources required for instrument I&T. A functional block diagram of the current baseline electronics architecture is shown in Figure 6. The core of the instrument electronics is a cPCI card cage containing the RAD 750 instrument computer, a housekeeping unit (HKU), a Digital Processing Unit (DPU) and the power supply. The RAD 750 computer is the overall instrument manager. The DPU is an FPGA-based board that will carry out high speed data manipulation including the wavefront correction required by the LOWFS and control system. The DPU has both a Spacewire and 1553 data interface. The Spacewire interface will be used for science data telemetry whereas the 1553 interface will be used for command and engineering data telemetry. All subsystems are powered by 28 volt interfaces and low-voltage differential signaling (LVDS) digital interfaces. The cPCI card cage and its four cards are existing flight designs with NASA TRL ranging from 6 to 9. The DPU and HKU in particular are being used for the Orbital Carbon Observatory 3 (OCO3) and ECOSTRESS missions led by JPL and both cards are compatible with the L2 environment. The spacecraft power interface provides current fault and EMI EMC protection to the spacecraft. Since the CGI is expected to fall into NASA risk class C, the design calls for single string high reliability subsystems and components.

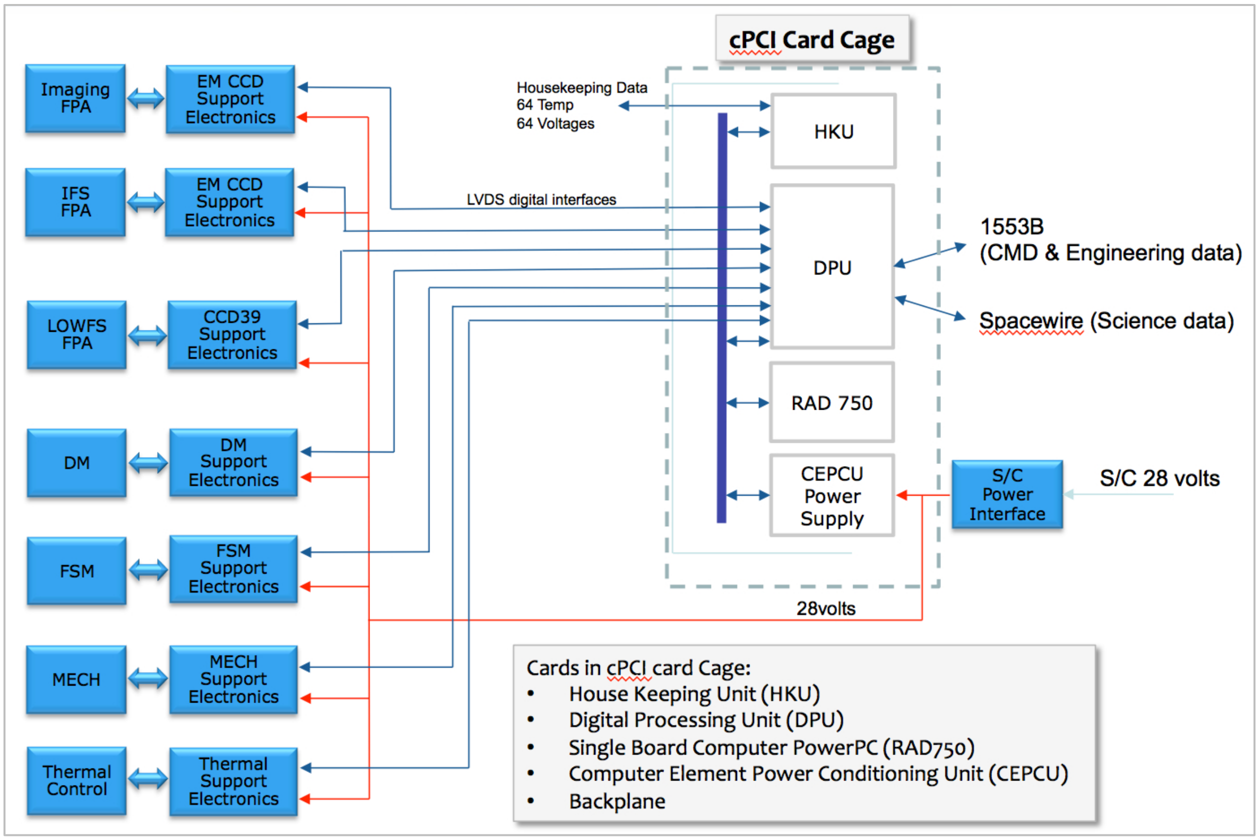

Figure 6 Functional block diagram of the CGI electronics.

5. SUMMARY

The WFIRST-AFTA study project has completed the cycle 6 design of a Coronagraph Instrument (CGI) that is expected to image and spectrally characterize exoplanets and to image extra-solar debris disks. The collimator optics assembly is the optical interface between the CGI and the telescope and is designed specifically to reduce the large off-axis wavefront error from the AFTA telescope. The collimator assembly output wavefront is very stable in the presence of LOS pointing error from the telescope. A compact, single optical bench contains all the sensors, masks, filters and active optics of the CGI including the two DMs and the FSM. The cycle 6 CGI design also includes full mechanical support structure, latches for robotic attachment and removal from the spacecraft instrument carrier, system electronics, thermal control and thermal insulation. The cycle 6 optical/mechanical/thermal design will be analyzed in the near future in a rigorous STOP (Structural Thermal Optical Performance) analysis task.

6. ACKOWLEDGEMENTS

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