

Development of the WFIRST CGI Integral Field Spectrograph

Tyler D. Groff^a, Neil Zimmerman^a, Maxime J. Rizzo^a, Samuel Gaylin^b, Nicholas Nicolaeff^c, John Titus^c, Rose Mountcastle^d, Qian Gong^a, David Harvey^b

^aGoddard Space Flight Center, Greenbelt, MD USA

^bGenesis Engineering Solutions, Lanham, MD USA

^cATA Aerospace, Greenbelt, MD USA

^dLentech Engineering, Lanham, MD USA

ABSTRACT

The principal science goal of directly imaging exoplanets is spectroscopy. Future mission concepts such as LUVOIR and HabEx have baselined their science instruments to use an integral field spectrograph (IFS) to maximize observing efficiency. Coronagraphic imaging with an IFS has strong heritage at ground observatories, having produced planet and brown dwarf near-infrared spectra at contrast floors as low as high 1×10^{-6} levels. As a technology demonstration for future missions the WFIRST coronagraph instrument (CGI) will demonstrate the ability to measure spectra in visible light with at contrast levels sufficient for detecting Earth-like planets. The spectrograph was originally meant to match that of future missions; an independent IFS channel for wavefront control and imaging spectroscopy. Due to a series of de-scopes as the project progressed, the baseline spectroscopic capability of CGI is no longer an IFS but a zero deviation optical prism and slit used in conjunction with the direct imaging camera. Regardless, CGI advanced a lenslet IFS through the preliminary design phase of a flight project. Here we present that development as the challenges and requirements of an IFS for coronagraphy are quite unique and relevant to future missions. With that development in place, we also present the initial design of the zero optical deviation prism, highlighting the relative challenges and performance of each concept.

Keywords: High Contrast Imaging, Coronagraphy, Integral Field Spectrograph, Imaging Spectroscopy, Exoplanets

1. INTRODUCTION

The Wide Field Infrared Survey Telescope (WFIRST) coronagraph instrument (CGI) will be the first high contrast imager in space and is a key demonstration for future missions such as the Habitable Exoplanet Surveyor (HabEx) and the Large UV/Optical/IR (LUVOIR) Surveyor.^{1,2} As a technology demonstrator for future missions, a lenslet-based integral field spectrograph (IFS) was being developed as one of the two back-end cameras to the coronagraph. A lenslet-based IFS has the ability to accommodate a large number of spatial samples in a relatively compact design and provides time resolved data that simultaneously spans spatial and spectral dimensions. Some of the principal advantages of this capability are the ability to dig a dark hole with the deformable mirrors, spatial isolation of speckle from the planet spectrum, the ability to measure speckle and astrophysical background over the field, and the ability to extract spectra of multiple objects anywhere within the coronagraphic field of view (FOV).

Due to a set of CGI-level de-scopes, the IFS had to be removed to save on the cost and complexity of an additional channel and detector. The alternative is a zero optical deviation prism and deployable slit within the direct imaging (DI) channel. By using the slit and prism with the direct imaging camera (DICam) CGI maintains a spectroscopic capability at unprecedented contrast levels, albeit with less net functionality than the IFS. The fundamental parameters of either spectroscopic concept are identically driven by the ability to detect methane absorption features present between 600 and 790nm at a minimum spectral resolution of R50. The highest spectral resolution is constrained for the sake of achieving a signal-to-noise ratio (SNR) greater than 10

Send correspondence to Tyler D. Groff tyler.d.groff@nasa.gov

within a constrained observation period. For this reason, there are two prism groups, respectively optimized for the two CGI spectroscopy bands using the shaped pupil coronagraph. Additionally, to support the mandate of starshade readiness we leave sufficient slots in the mechanism to match the spectral range of the IFS, out to 975nm.

The development of the zero deviation prism concept has afforded the opportunity to think deeply about the relative performance and operations concepts of the IFS and zero deviation prism, which has been very instructive in understanding the spectroscopic design space for future missions. With most of the development to-date surrounding the IFS, we first present the requirements and design challenges unique to building a flight-capable IFS. We then present the opto-mechanical design concept and performance predictions supporting the long duration, high contrast images the IFS must acquire. Finally, we present the new DI slit and prism concept and compare operational cases with the IFS.

2. IFS REQUIREMENTS AND DESIGN CHALLENGES

An IFS, shown schematically in Fig. 1, places a lenslet array at an image plane within the instrument to sample the field and compress the incident light into a grid of spots directly behind the lenslet array. These spots act as the input to a traditional spectrograph that collimates, disperses, and images onto a detector. The spectra are then extracted from a 2-dimensional detector and reconstructed into a 3-dimensional data cube (x, y, λ) . The

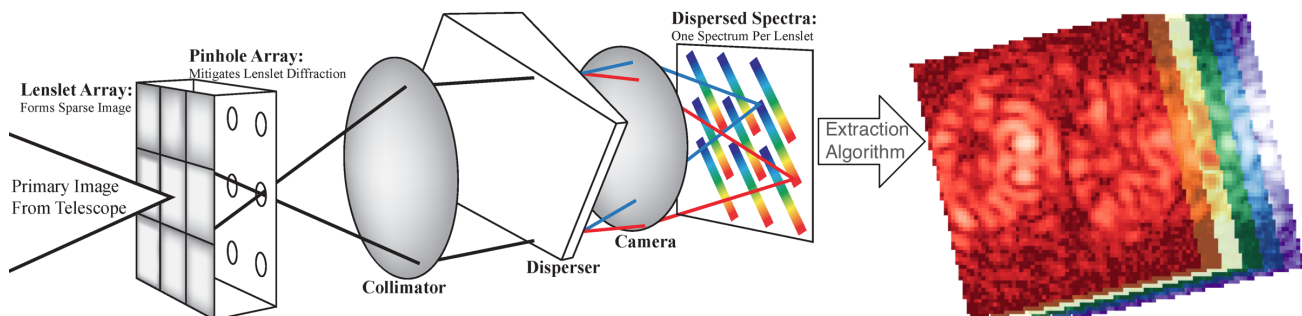


Figure 1. The lenslet array of an IFS Nyquist samples the broadband (15%) image. The spectrograph optics interlace the spectra on the final focal plane, and a data extraction algorithm is used to reconstruct the data cube.

field of view (FOV) of the CGI IFS is ~ 2.1 arcseconds, comparable to the field of view in current ground-based extreme adaptive optics (ExAO) systems such as SCExAO-CHARIS at Subaru,^{3,4} GPI at Gemini,⁵ and SPHERE at the VLT.⁶ To provide a clear example of what the CGI IFS will be able to capture within its field of view, Fig. 2 shows the CGI IFS field of view and coronagraph point spread function (PSF) overlaid onto images of M5 and HR8799 taken with SCExAO-CHARIS. The general performance of the CGI IFS is in family with the state of the art exoplanet IFS specifications being used on ExAO systems today. The baseline operations plan for CGI, described fully in Krist et al.,⁷ is to dig the dark hole and achieve high contrast on a bright ($V_{\text{mag}} \sim 2$) star, then slew to the target ($V_{\text{mag}} \sim 5$) star and execute a series of rolls and chops between the reference and target. The target star is observed in two different roll angles on a 2 hour cadence, while revisiting the reference star every ten hours. Performance predictions and raw contrast sensitivity analysis of these observations are described in Zhou et al.⁸ One example simulation of CGI IFS exposures given input simulations of the speckle field is shown in Fig. 3. For all observations, the exposure is developed through a series of ~ 100 second exposures which are co-added to reach the final integration time. The exposure time is set specifically to have an average of ~ 0.1 photons per frame arrive at the detector to support the photon counting mode that the detector is operated in. Thus, the set of frames look like the image shown in Fig. 3(a) and as they are co-added the dispersed coronagraphic image can finally be scene with increasing signal-to-noise ratios (SNR) as is seen when comparing Fig. 3(b) to Fig. 3(c). In this context, for the co-adding method to provide the image shown in Fig. 3(c) the IFS optics must remain stable to all disturbances since one cannot simply shift and co-add individual frames in response to drift of the micro-spectra on the detector. The need to be highly stable over the period of hours as we chop between reference and target star is what drives the optical and mechanical design of the CGI IFS. Much of the work to date has been to define global stability requirements for the instrument in

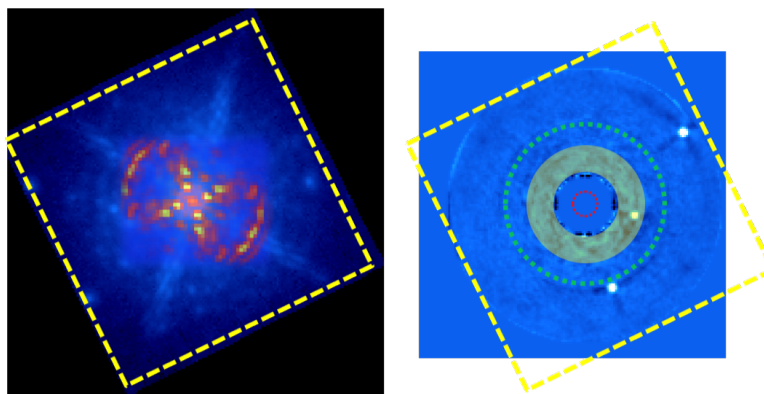
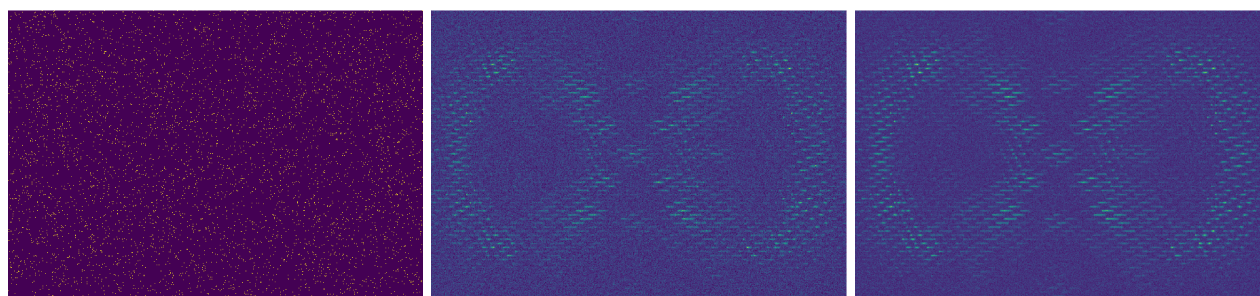


Figure 2. The Shaped Pupil coronagraph (left) and requirements (right) overlaid onto images of M5 and HR8799 taken with SExAO-CHARIS. The field of view of the CGI IFS is comparable to current state of the art ExAO IFS designs such as GPI and SExAO-CHARIS. (yellow-dashed) CGI IFS FOV. (green dashed) Coronagraph OWA. (red dashed) Coronagraph IWA. (yellow band) range of requirements definition.



(a) 100 sec

(b) 1 hour

(c) 27 hours

Figure 3. Characteristic dispersed images as a function of total exposure time. The extremely low signal drives a host of strict stability requirements on the IFS.

response to the jitter environment of CGI due to the reaction wheels, and thermal variation as the spacecraft re-points to the two stars.

A tolerance analysis of the IFS optics has revealed that boresight drives alignment and stability requirements long before wavefront error allocations are exceeded. We therefore use image plane motion at the lenslet and detector planes as the parent requirements for all optical tolerancing. Evaluating the boresight motion at these planes as a function of all six degrees of freedom for each optical element, we decompose misalignment requirements by element across three major categories; ground-to-orbit static misalignment and mechanism repeatability represent the static misalignment, while thermal, and jitter allocations are set to capture the observatory dynamics. Making the conservative assumption that their motions are uncorrelated we allocate a tolerance to each element and combine their contributions to bore sight motion via a root sum square (RSS). This allows us to assign larger tolerances to more sensitive degrees of freedom while keeping the RSS boresight stackup below the required net deviation at the lenslet and detector planes. This guides the optical and mechanical design presented in Sec. 3, and provides clear performance metrics for the thermal and structural analysis in Sec. 4. Eventually the thermal and structural models will be fed back into the optical model for a full stop analysis, but this approach makes it much more efficient to evaluate the current best estimates (CBEs) against a realistic set of optical requirements.

3. IFS OPTICAL AND MECHANICAL DESIGN

The IFS captures an instantaneous bandpass up to 20% centered anywhere in the range 600 to 975nm. The coronagraph masks only support two 15% bandpasses from 610 – 710nm (660 band) and 675 – 785nm (730 band), but a continued requirement to support a potential starshade mission adds two more 20% bandpass from 656 – 800nm and 799 – 975nm that the spectroscopy modes of CGI must support.

The IFS receives a 5mm collimated beam, and forms an $F/527$ image onto a square-packed lenslet array with a $174\text{ }\mu\text{m}$ pitch. The lenslet array and spectrograph relay optics are $F/8$, forming the dispersed image onto a 1024×1024 EMCCD 201 sensor from Teledyne-E2V. Performance predictions and performance estimates of the EMCCD and requirements can be found in Morrissey et al.⁹ and Effinger et al.¹⁰ The imaging group shown in

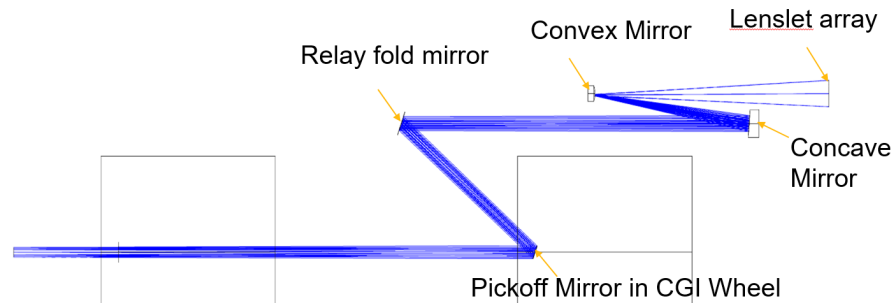


Figure 4. The IFS receives a 5mm collimated beam, and images onto the lenslet array by an off-axis Cassegrain. The ray bundle shown is the chief ray of each field point in the image.

Fig. 4 is a reflective off-axis cassegrain design. The first optic is a fold mirror, which only exists for packaging purposes within CGI. The field points shown in Fig. 4 highlight the highly non-telecentric image space at the lenslet array. The spectrograph collimator, prism, and imaging groups shown in Fig. 5 are all refractive elements.

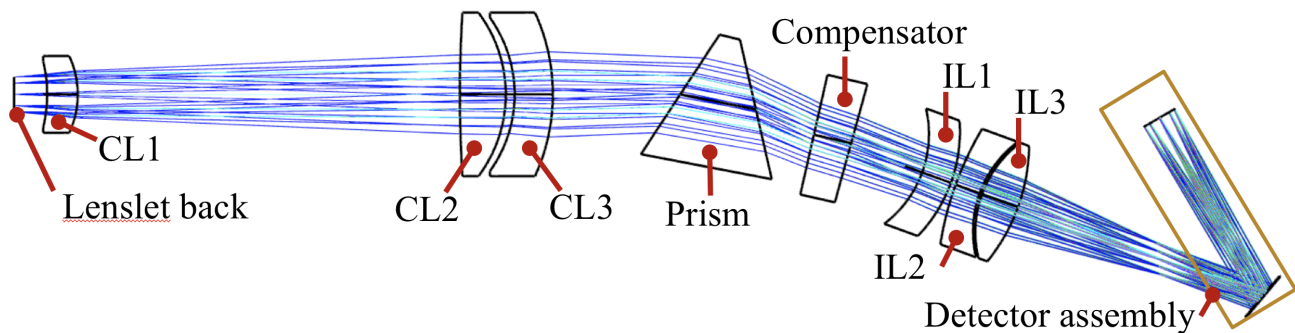


Figure 5. The spectrograph optics after the lenslet array, utilizing a single field corrector and achromat doublet in both the collimator and imaging subassemblies, and a two-element disperser for near-constant spectral resolution.

The collimator and camera optics are all spherical surfaces, and they compensate one another to provide very good image quality at the final focal plane over the entire field of view. Since the required total bandpass is much less than a full harmonic and there are large field angles within the spectrograph, the baseline design of the system is refractive. This maintains good image quality at the maximal field points without complicating the packaging with a multi-element reflective system. Something interesting to note is that the FOV of the IFS is nearly a factor of two larger than what the shaped pupil coronagraph provides. The detector size required for an IFS is a function of the interlace chosen for the spectra, the instantaneous bandpass that must be imaged, the spectral resolution, and FOV. For the CGI IFS, we are constrained to a 1024×1024 EMCCD201. Regardless, Fig. 6 shows the detector size required as a function of spectral resolution and FOV for the required bandpass and interlace ratios of the CGI IFS. At R50 and a coronagraphic FOV of ~ 1.1 arcseconds, there is a very healthy margin for the IFS to accommodate the FOV requirements. This helps to alleviate ground-to-orbit alignment variance, which is very important since tip-tilt offsets of the pupil are highly magnified by the $F/527$ image formed on the lenslet array.

The IFS optomechanics are purpose built first and foremost to meet our tight alignment and stability requirements. The alignment requirements are strict, but are within standard capabilities. However, much like the rest of CGI, stability is paramount. This is particularly true for the IFS, where exposures can take

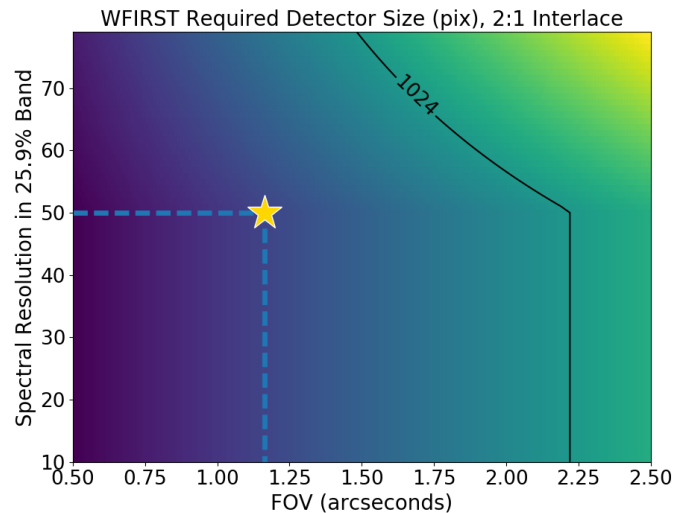


Figure 6. The IFS field of view is approximately a factor of two larger than the coronagraph field of view, providing significant margin against ground-to-orbit misalignment.

hundreds of hours. A model of the IFS optomechanics is shown in Fig. 7. Much of the precision motion control

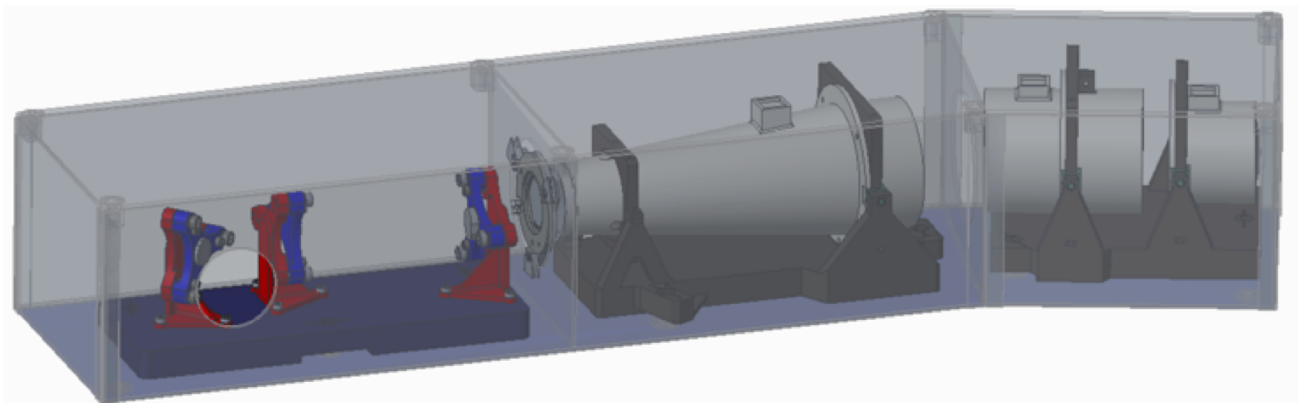


Figure 7. The end-to-end optomechanical layout of the CGI IFS. The optics are put together as major sub-assemblies for the imaging mirror group, the lenslet array, the collimating lens group, prism group, and imaging lens group. All major sub-systems are integrated into a single carbon-fiber sub-bench, shown partially transparent for clarity.

is accommodated with a set of flexures. All of the mounts are Titanium alloy, and will have a flexure-based mounting scheme onto the carbon fiber sub-bench. The sub-bench is a matching carbon-fiber layup to the CGI bench so that the IFS can be installed with a rigid kinematic structure, guaranteeing that the critical alignment tolerances at input and output are maintained. In all cases, the IFS relies on bench-level alignment in the plane of the optical bench. Tip control is carried internally to the mounts to simplify the alignment. Any height corrections must be done via shims. The lenslet array is mounted in a kinematic housing that allows it to be clocked after the system has been aligned. The prism mount also has clocking capability. We assume that the detector clocking will be controlled by machine tolerance only, so these two degrees of freedom are necessary to correctly orient the micro-spectra on the detector and fine tune the interlacing of the spectra. With the addition of the carbon fiber sub-bench, the lenslet array mount is now integrated into the sub-bench support structure. This simplified the mechanical design and saved both mass and volume within the IFS.

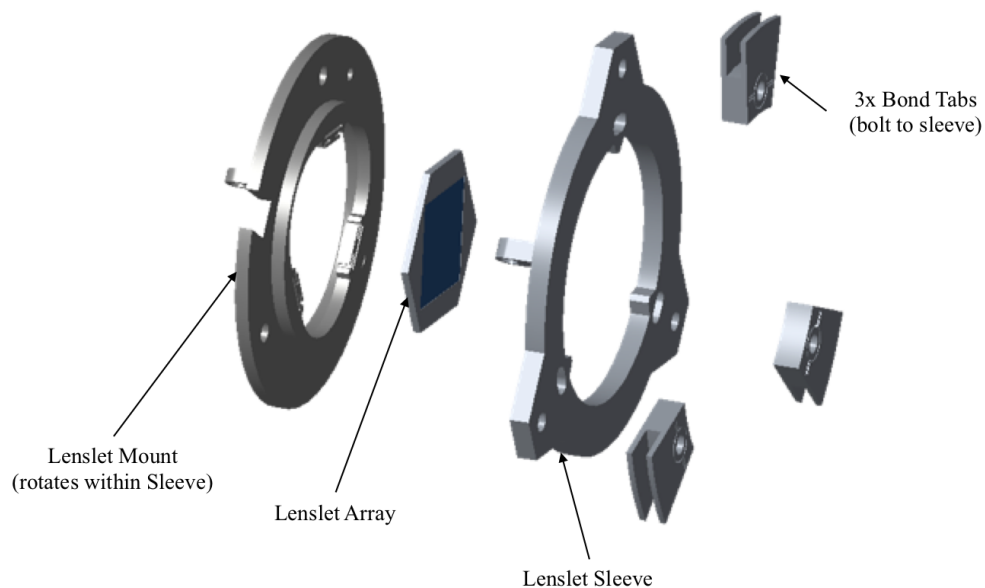


Figure 8. Exploded view of the lenslet array mount, which is held kinematically in the axial direction with a wave washer to define the preload and a radial flexure to control lateral stability of the mount.

4. PERFORMANCE PREDICTIONS

Being near the edge of the bench with a detector and radiator panel nearby, there is a non-negligible spatial gradient that impacts key modes (such as lenslet clocking stability). The IFS thermal model is meshed with the rest of the CGI thermal model to understand response to both dynamic variation and physical gradients across the system. Being highly stabilized and relatively tolerant to wavefront error variation, the principal goal of the modeling is to estimate boresight motion at the lenslet and detector planes. The IFS models are integrated into

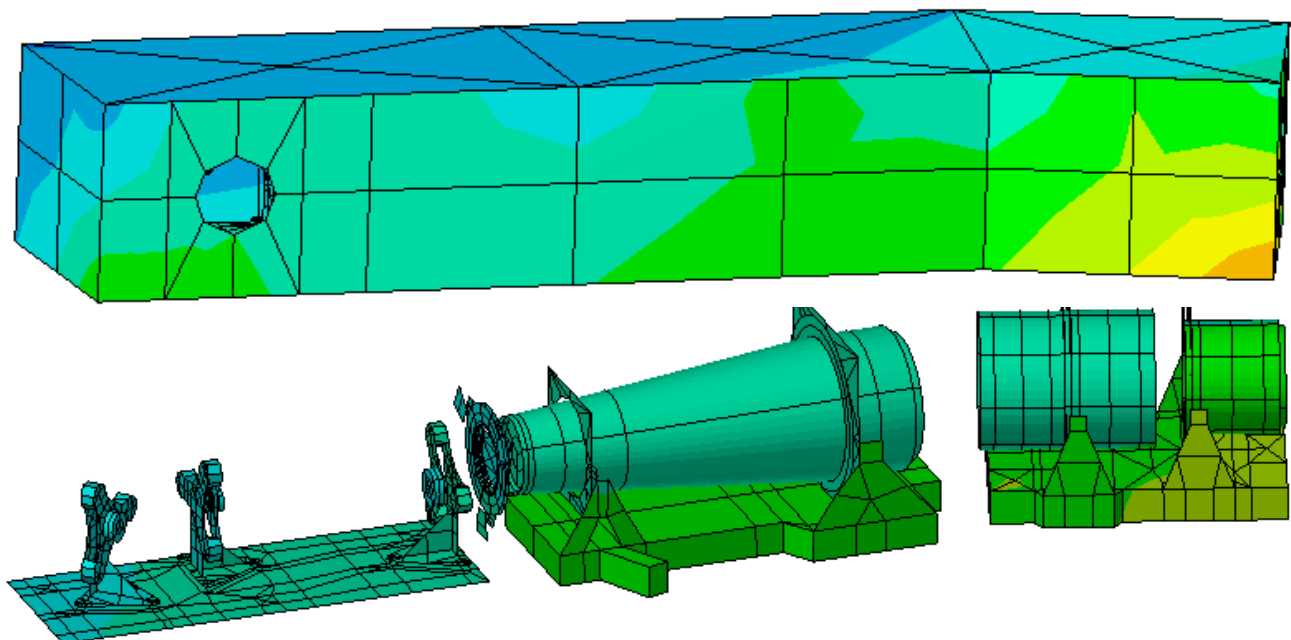


Figure 9. An example thermal mesh of the IFS optomechanical sub-assemblies and sub-bench are used to produce performance predictions with FEMAP. Gradients are driven by the proximity of the IFS to the CGI radiator, but are small due to careful thermal blanketing.

the CGI thermal model to better understand our true environment, but we also model the IFS in representative cases using boundary conditions associated with various operating modes provided by CGI. A representative thermal mesh of the IFS assemblies is shown in Fig. 9. The temperatures and gradients are, by design, small to maintain stability for all of CGI. To demonstrate compliance with the RSS boresight tolerances, the output from the thermal model is mapped onto the structural mesh of the IFS to capture thermally induced stresses (important for survival requirements) and strains. Examples of the structural mesh are shown in Fig. 10. It is

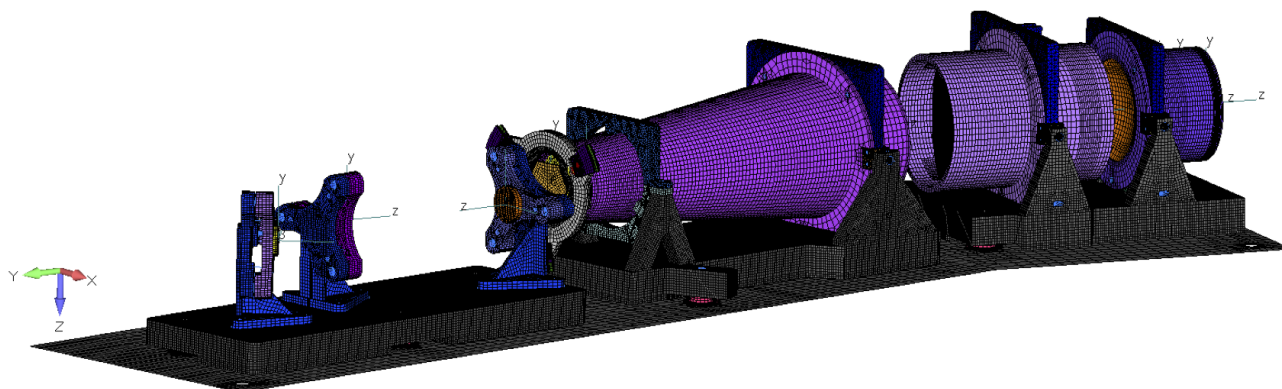


Figure 10. An example thermal mesh of the IFS optomechanical sub-assemblies and sub-bench are used to produce performance predictions with FEMAP. Gradients are driven by the proximity of the IFS to the CGI radiator, but are small due to careful thermal blanketing.

worth noting that in the case of thermally induced boresight motion the RSS stackup of the optical tolerances is conservative. For example, if the bulk temperature rises by 1K all of the optical mounts and detector housing will expand and contract together and the net alignment as seen by the detector or lenslet array remain largely unchanged. Given that CGI has closed loop thermal control to dynamically stabilize the instrument, variation in physical gradients will be the most significant deviation from common motion changes.

For final performance estimates, the IFS structural model was run against three critical thermal cases. The nominal on-orbit case is used to provide a CBE for the ground-to-orbit misalignment due to the change in environment from the lab to on-orbit. Robustness to thermal drift is provided by running the hot and cold operational cases and tracking the change between those extreme states. In all cases the CBEs meet the requirement with margin.

5. ZERO OPTICAL DEVIATION PRISM

The simplified spectroscopic capability now included in CGI is a zero optical deviation prism. Since the beam must be constrained to have zero deviation at a particular wavelength, the dispersion profile becomes nonlinear which requires that we distinct prism groups, one for the 660 band and another for the 730 band. Additionally, one slot exists in CGI third prism is carried to accommodate the redder starshade band but this is not included in the scope of this design effort. The CGI 730nm band filter is useable for the band 2 starshade filter, so only one additional slot was required to support both starshade bands. To prevent the entire image from being dispersed, a slit is placed over the location of the companion we intend to take a spectrum of. In effect, the spectroscopy mode is now a deployable slit, relying on the X-Y capability of the CGI mechanisms to precisely locate the slit on the planet location. In both the IFS and zero deviation prism cases the spectrum would not have been taken without having detected it in the undispersed modes first, so the operations concept collapses to a question of pointing repeatability. Initial indications are that this will not present us with a challenge, and spectral calibration will simply be a function of field position. A schematic of the two zero deviation prisms is shown in Fig. 11. The imaging lens is not shown in this design, but is a doublet design that is common to all of the CGI imaging modes. The focal length of the optic is 260mm and the nominal spectral resolution is still a minimum of R50. Due to the nonlinearity of the prism, we specify that resolution at a specific wavelength. In the final design this will likely be at the red edge of the methane absorption features we expect to observe in each band. The current design, used for the initial feasibility study, is shown in Fig. 12. One interesting design point

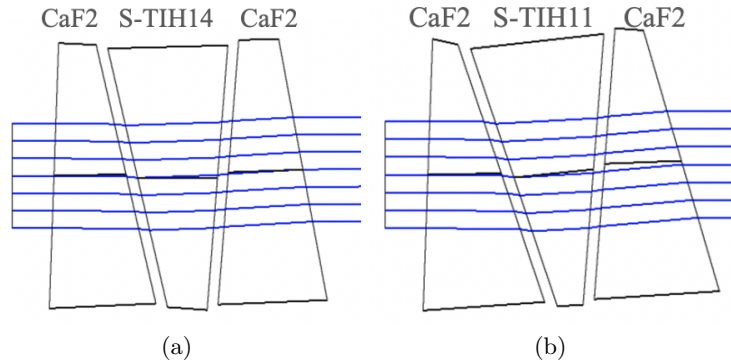


Figure 11. The prism groups for the zero optical deviation modes are 3-element designs to minimize angles of incidence for better antireflection coating capability.

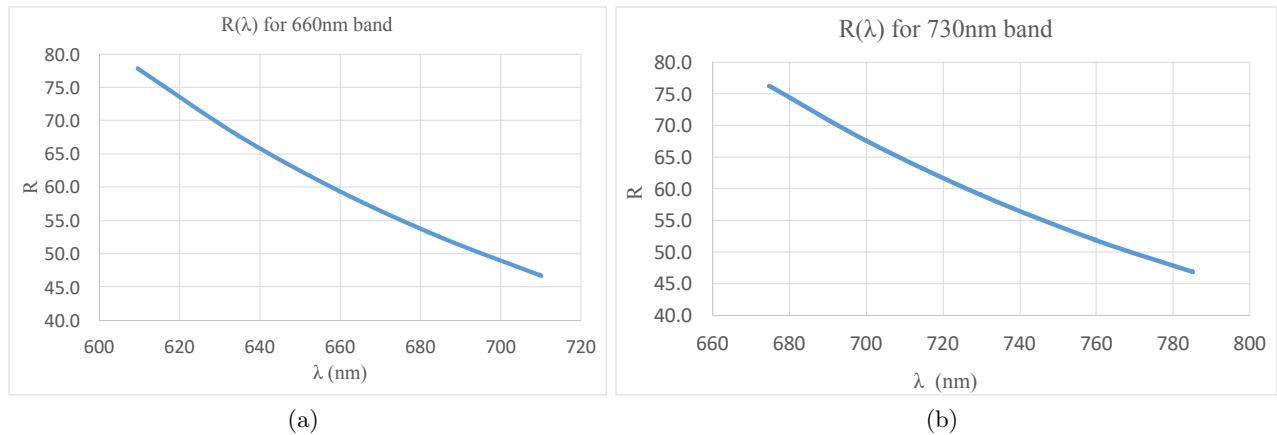


Figure 12. The dispersion profile of the zero optical deviation prisms is less linear than the IFS due to the added constraint that the optical axis remain fixed for a specified wavelength.

is how the spectral resolution is defined. The spectral resolution is commonly defined as the motion of the PSF equivalent to the full-width-half-maximum (FWHM) of the PSF. For the shaped pupil, this is approximately 5 pixels on the detector as opposed to the two one would expect for a Nyquist-sampled image. This larger size is a symptom of both the larger core of the shaped pupil and the shorter wavelength at which the direct imaging camera must sample the PSF at to accommodate the shorter hybrid lyot bandpasses.

6. SUMMARY

The CGI IFS is designed to provide R50 spectra in 20% bands between 600 and 1000nm. The key challenges in this particular IFS are all related to launch survival and the very long exposure times in an L2 space environment. Throughput and stability are paramount in a scenario where we must be able to co-add tens of hours of exposure to produce over 2,000 microspectra that achieve $\text{SNR}=10$ at 5×10^{-8} contrast on a $V_{\text{mag}} = 5$ star. Additionally, we must close the wavefront control loop with the IFS, which imposes stability and accuracy requirements that must be calibrated and maintained during on-orbit operations to achieve such high contrast in the first place. The on-orbit operations concept, supporting optical tolerances, and performance predictions are used to demonstrate that the IFS can in fact meet these stringent requirements and achieve the highest contrast spectral measurements of exoplanets ever taken. The development here demonstrates a requirements structure and point design that meets the performance challenges associated with feeding an $\sim F/500$ image into an $\sim F/8$ lenslet array and spectrograph, demanding that it be robust to both launch and environmental variations during flight operations. While every instrument is different, we provide an architecture suitable to the unique traits of an imaging spectrograph, particularly one suitable for high-contrast spectroscopy of exoplanets. With the development heritage reviewed and in place, we now move to the zero optical deviation prism. The design has

equivalent or better SNR performance, albeit with the limitation that only one planet may be characterized at a time and the ability to spectrally characterize the speckles is lost. Regardless, the design and operations concept for the zero deviation prism are feasible and will provide spectra of the highest contrast targets to-date.

Acknowledgements

This research was carried out at Goddard Space Flight Center for the WFIRST Coronagraph Instrument technology demonstrator.

The WFIRST Coronagraph Instrument is lead by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

1. B. Mennesson, J. Debes, E. Douglas, B. Nemati, C. Stark, N. Kasdin, B. Macintosh, M. Turnbull, M. Rizzo, A. Roberge, N. Zimmerman, K. Cahoy, J. Krist, V. Bailey, J. Trauger, J. Rhodes, L. Moustakas, M. Frerking, F. Zhao, I. Poberezhskiy, and R. Demers, "The wfirst coronagraph instrument: a major step in the exploration of sun-like planetary systems via direct imaging," in *Proc. SPIE, Proc. SPIE* **10698**, p. 106982I, 2018.
2. R. Demers, "Review and update of wfirst coronagraph instrument design and technology," in *Proc. SPIE, Proc. SPIE* **10698**, p. 106982J, 2018.
3. N. Jovanovic, O. Guyon, J. Lozi, T. Currie, J. Hagelberg, B. Norris, G. Singh, P. Pathak, D. Doughty, S. Goebel, J. Males, J. Kuhn, E. Serabyn, P. Tuthill, G. Schworer, F. Martinache, T. Kudo, H. Kawahara, T. Kotani, M. Ireland, T. Feger, A. Rains, J. Bento, C. Schwab, D. Coutts, N. Cvetojevic, S. Gross, A. Arriola, T. Lagadec, N. Kasdin, T. Groff, B. Mazin, Y. Minowa, N. Takato, M. Tamura, H. Takami, and M. Hayashi, "The scexao high contrast imager: transitioning from commissioning to science," in *Proc. SPIE*, **9909**, p. 99090W, 2016.
4. T. Groff, J. Chilcote, N. Kasdin, M. Galvin, C. Loomis, M. Carr, T. Brandt, G. Knapp, M. Limbach, O. Guyon, N. Jovanovic, M. McElwain, N. Takato, and M. Hayashi, "Laboratory testing and performance verification of the charis integral field spectrograph," in *Proc. SPIE*, **9908**, p. 99080O, 2016.
5. J. E. Larkin, J. K. Chilcote, T. Aliado, B. J. Bauman, G. Brims, J. M. Canfield, A. Cardwell, D. Dillon, R. Doyon, J. Dunn, *et al.*, "The integral field spectrograph for the gemini planet imager," in *Proc. SPIE*, **9147**, p. 91471K, 2014.
6. J. Beuzit, M. Feldt, K. Dohlen, D. Mouillet, P. Puget, F. Wildi, L. Abe, J. Antichi, A. Baruffolo, P. Baudoz, *et al.*, "Sphere: a planet finder instrument for the vlt," in *Proc. SPIE*, **7014**, p. 41, 2008.
7. J. Krist, R. Effinger, B. Kern, M. Mandic, J. McGuire, D. Moody, P. Morrissey, I. Poberezhskiy, A. Riggs, N. Saini, E. Sidick, H. Tang, and J. Trauger, "Wfirst coronagraph flight performance modeling," in *Proc. SPIE, Proc. SPIE* **10698**, p. 106982K, 2018.
8. H. Zhou, J. Krist, E. Cady, and I. Poberezhskiy, "High accuracy coronagraph flight wfc model for wfirst-cgi raw contrast sensitivity analysis," in *Proc. SPIE, Proc. SPIE* **10698**, p. 106982M, 2018.
9. P. Morrissey, L. Harding, M. Bottom, R. Demers, R. Effinger, D. Nieraeth, L. Hovland, Y. Muruyama, B. Nemati, N. Bush, D. Hall, R. Burgon, and A. Holland, "Photon counting emccd developments for the wfirst coronagraph," in *Proc. SPIE, Proc. SPIE* **10709**, p. 107090B, 2018.
10. R. Effinger, B. Nemati, M. Rizzo, P. Morrissey, L. Harding, M. Bottom, D. Pontrelli, R. Demers, N. Bush, D. Hall, R. Burgon, and A. Holland, "Wfirst coronagraph detector trap modeling results and requirements," in *Proc. SPIE, Proc. SPIE* **10709**, p. 1070917, 2018.