Rapid-prototyping a tabletop integral field spectrograph

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ABSTRACT

We successfully rapid-prototyped a mostly off-the-shelf, partially 3D-printed pathfinder version of an integral field spectrograph (IFS) in order to compress the design/build/test schedule of a final, mostly-custom IFS, by accelerating the start date of data pipeline development, thus allowing this development to progress in parallel with the design, procurement, fabrication, and alignment of the final IFS version. This parallel-path development schedule enabled us to successfully design, build, align, test, and extract a data cube from the new IFS within only 1 year, even in the face of several design setbacks. We have begun using the now-functional IFS for development of IFS sensing and control algorithms, and have also begun implementing motorized alignment upgrades that enable the systematic characterization of the tolerance (or required compensation) of its data cube extraction to misaligned images, in support of NASA's WFIRST and PISCES IFS.

Keywords: Integral field spectrograph, IFS, WFIRST, PISCES, rapid prototype, rapid prototyping, 3D printing, optomechanics

1. INTRODUCTION

The Coronagraph Instrument (CGI) of the Wide Field Infrared Survey Telescope (WFIRST) is currently baselined to include an integral field spectrograph[1,2,3]. While NASA's PISCES IFS (developed at NASA Goddard and housed in a vacuum facility at the NASA's Jet Propulsion Lab) can be used as a prototype testbed for the WFIRST IFS, it is highly taxed for time, and could be well-supplemented by a more flexible, inexpensive, non-vacuum, tabletop IFS testbed that allows for rapid upgrades and quick experiments. As such, NASA Goddard commissioned Princeton University's High Contrast Imaging Lab (HCIL) to rapidly design, build, and test such a tabletop IFS testbed (and its data pipeline) within only 1 year.

1.1 Princeton High Contrast Imaging Lab

The HCIL's main lab enables the development of algorithms and schemes for monochromatic and broadband wavefront control for exoplanet direct imaging. It includes dual deformable mirrors for double-sided dark hole generation. Its current layout is shown in Figure 1, in which the eventual IFS is shown as #14, behind a pickoff mirror that can route the beam to either the science camera (#12) or the IFS (and the pickoff can also be replaced by a beamsplitter for simultaneous use of both cameras).

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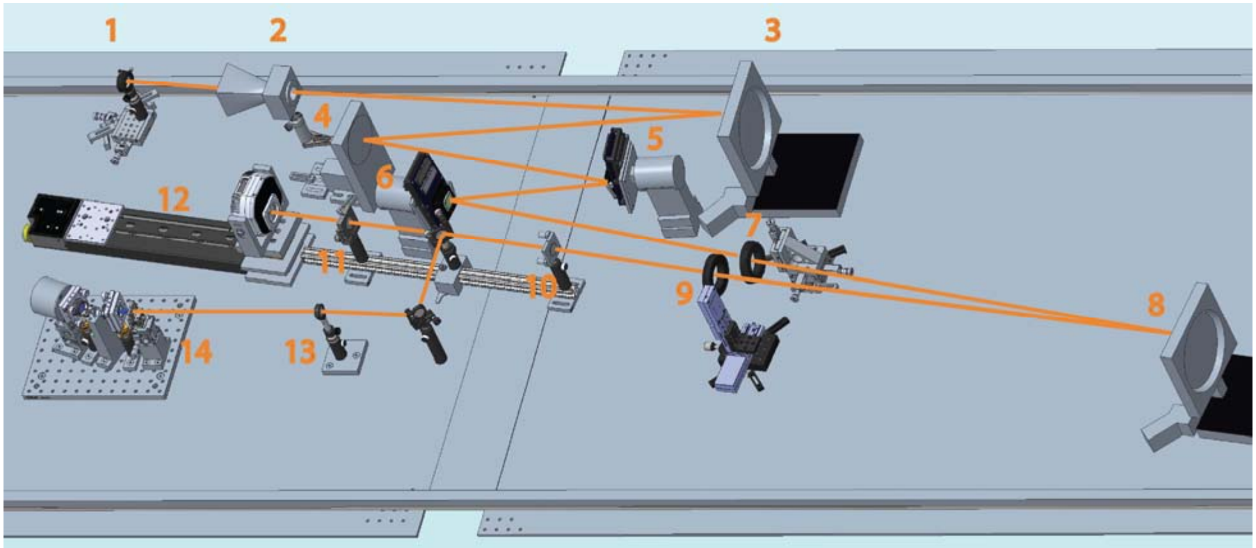

Figure 1. HCIL layout, with the following components: (1) fiber source, monochromatic or broadband (2) baffle (3) OAP #1 (4) flat mirror (5) Boston Micromachines Kilo-DM deformable mirror #1 (6) deformable mirror #2 (7) shaped pupil (8) OAP #2 (9) focal plane mask (10-11) reimaging lenses, with pickoff mirror in between (12) QSI RS 6.1S science camera (13) IFS foreoptic lens (14) IFS

2. IFS DESIGN

2.1 Programmatic challenges

The project team boasted considerable IFS design experience carrying over from our then-recent (and much more complex) CHARIS project[4], as well as synergistic opportunities to collaborate with the ongoing WFIRST IFS design effort[5]. As such, our tabletop IFS testbed (dubbed the High Contrast Integral Field Spectrograph, or HCIFS) did not present a daunting design challenge. Instead, the HCIFS presented a fairly daunting programmatic challenge: whereas our CHARIS project took us about 4 years, the HCIFS was required to be designed, built, and validated by test within only 1 year.

As an in-house, ambient-pressure, manually-aligned, subscale prototype, the HCIF's accelerated schedule was entirely justified versus that of the cryogenic, completely robotic, PI-class CHARIS instrument installed and formally commissioned at the Subaru Telescope in Hawaii. However, the one challenge of IFS development schedule that is especially hard to compress is the development of the complex data pipeline (spectral data cube extraction software) since it typically constitutes a large fraction of the project schedule, and can only be begun in earnest after either (1) developing an entire virtual software simulation of the optical train and resultant raw image, as we did for CHARIS[6], or (2) achieving a real as-built image relatively early in the project schedule.

The HCIFS project did not have the budget or manpower required to quickly develop a software simulator similar to that of CHARIS. We could, however, take advantage of the fact that our image was expected (and designed) to be roughly compatible with the CRISPY data pipeline originally developed for CHARIS[7] and eventually repurposed for the WFIRST IFS[8]. However, even just the required tailoring and tuning of the CRISPY software (along with the accompanying iterative fine-alignment of the as-built IFS) was still expected to consume a large fraction of the 1-year project schedule. So, it was imperative that we achieve a real, as-built image as soon as possible.

While, from the outset, we of course committed to embrace standard schedule opportunities like favoring heritage and commercial off-the-shelf (COTS) components, the simple optical train layout we initially settled on (described in the next section) quickly illuminated an even more impactful opportunity: while the final IFS would boast a custom 2-wedge prism and elaborate custom fine-alignment features, a minor tweak to the initial layout positioning could allow a COTS (Edmund) prism to provide readily-extractable dispersed spectra with only a slight degradation of the flatness of the spectral resolution profile, all with no other changes to the remaining optics. Additionally, while we expected the elaborate custom alignment features to be crucial to the fine-alignment of the final IFS, we expected even a coarselyaligned IFS to provide an extractable grid of spectra. So, fixed optic mounts (even slightly warped 3D-printed ones) were expected to suffice for initial generation of a usable image. And thus, we realized that an initial (nearly all-COTS) “pathfinder” IFS could enable kicking off the CRISPY data pipeline tailoring and tuning effort while we waited for the final custom prism and elaborate optomechanics to be designed and fabricated.

2.2 Optical layout

The final HCIFS optical layout is shown in Figure 2 (and described in more detail by Delacroix et al.[9]):

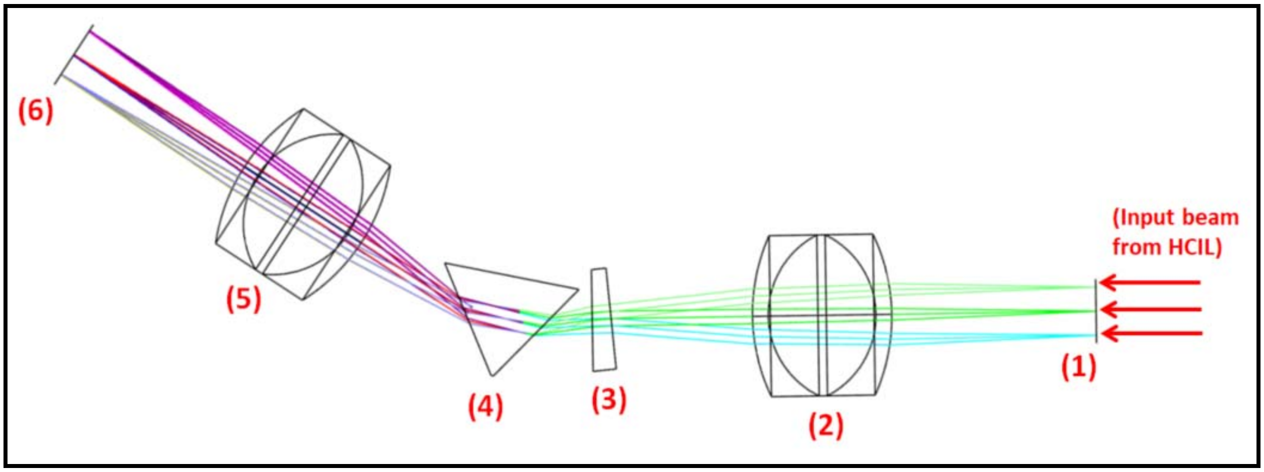

Figure 2. Final HCIFS optical layout, with the following optics: (1) 86um-pitch lenslet[9] from Advanced Microoptic Systems (2) Thorlabs TRH254-040-A-ML Hastings triplet #1 (3) Zinc Sulfide Cleartran prism wedge from BMV (4) UVFS prism wedge from BMV (5) Hastings triplet #2 (6) Starlight Xpress SXVR-H9 CCD

As mentioned, we committed to embrace standard schedule and budget opportunities like favoring heritage and COTS components. Rather than design elaborate, expensive custom lens or mirror groups, we validated by analysis that simple COTS Hastings triplets could serve as both the collimating and camera optic with sufficient achromaticity. We designed the lenslet and prism wedges to be similar those from CHARIS, and procured them from the same trusted CHARIS vendors. To save cost, we repurposed a suitable existing Starlight Xpress CCD for use as the detector.

Again, as mentioned, our optical designer realized that a COTS prism (Edmund 43-648, cleverly repurposed from its typical role as a Littrow retro-reflecting Brewster prism) could stand in (as shown in Figure 3) for the final custom 2-wedge prism with only a slight deviation of the exit beam and a slight degradation of the flatness of the spectral resolution profile, degradation deemed readily-acceptable purely for the purposes of generating an extractable grid of spectra to kick off data pipeline development work.

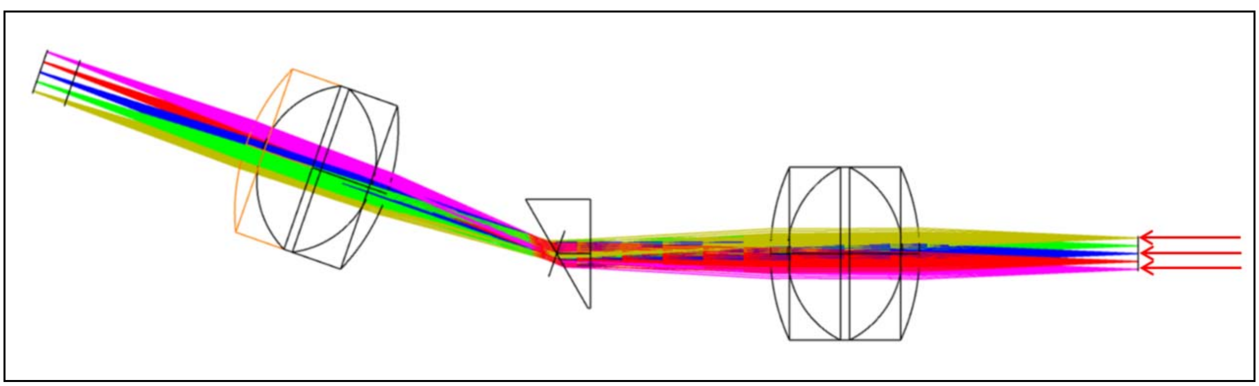

Figure 3. Prelim (nearly all-COTS) pathfinder HCIFS layout, with Edmund 43-648 prism standing in for final custom 2-wedge prism

2.3 Pathfinder IFS optomechanical design

The optomechanical design of the preliminary pathfinder IFS is shown in Figure 4, with optomechanical components of interest labeled (refer above for a detailed parts list of the optics themselves):

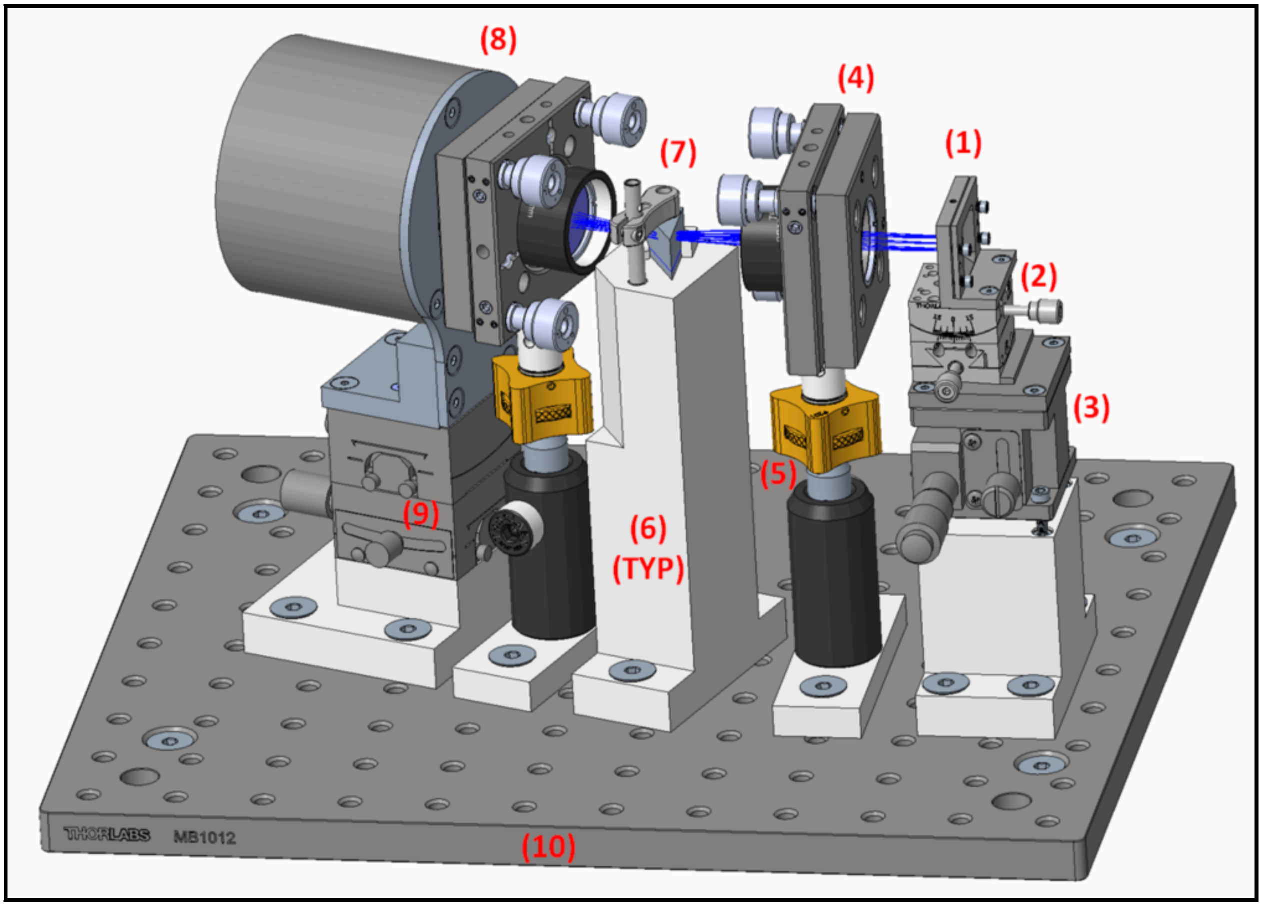

Figure 4. Prelim (nearly all-COTS) pathfinder HCIFS optomechanical design (detailed parts list below).

Details and interesting lessons-learned regarding each optomechanic are as follows (list numbers correspond to label numbers in Figure 4 above):

1. The lenslet mount is a simple, non-marring Delrin clamping frame, except the washers underneath the clamping screw heads are wave washers (McMaster 99842A103) rather than flat washers, thus enabling a gentle clamping preload and thus avoiding deformation of the lenslet. Inside the clamping frame, the lenslet is precisely indexed against hard stops, preloaded against these stops by gentle nylon-tipped set screws (McMaster 90291A074) pressed onto the opposing lenslet edge (also to avoid deformation).
2. A compact dual-axis goniometer (Thorlabs GN2) provides for fine tip and clocking alignment capability. I removed the provided base of the goniometer itself to make it more compact.
3. The Optics Focus MAZ-40-10 was the most compact height stage I could find off-the-shelf in this stiff, stable form factor. Quality was a concern for this very inexpensive alternative, but it ended up quite stiff and stable and worked fine.

4. In order to provide tip/tilt/focus fine alignment capability of the Hastings triplets while still fitting within the close clearances here, a trick was required: the Thorlabs KC1-T cage-compatible kinematic mount was employed, and the Hastings triplet was fed back through the mount (in the typically "wrong" direction).

5. A trade study was conducted to determine the most compact, stable and precise post height adjusters. The Newport (New Focus) 9201 Post Lab Jack was selected in favor of its fine resolution, easy finger access, and relative stability when unlocked for height adjustment (although all traded post height adjusters were to some degree wobbly during unlocked height adjustment). Not selected were the Thorlabs PH3T Translating Post Holder (due to its coarser resolution and wobbliness when unlocked) and the Thorlabs TRT2 (even coarser resolution, and hard to finger-access without bumping into adjacent optics).

6. At this stage, all required custom bases were 3D-printed in ABS plastic on a Stratasys uPrint fused deposition modeling (FDM) printer. This printer offers roughly +/-0.05mm as-printed local accuracy. Unfortunately, ABS plastic—while boasting great ductility—thermally warps more than other FDM materials (especially large parts), which can manifest as even worse overall surface profile accuracy. But such warping was expected (and proved) to still provide acceptable alignment for the pathfinder IFS to yield an extractable grid of spectra. Also, unfortunately, our uPrint (rather than the uPrint+) can only print in (quite reflective) white ABS, but stray light was also not a primary concern for the pathfinder. In the interest of design schedule acceleration, the design of each of these 3D-printed bases at this stage was much simpler than their final machined counterpart, offering no easy fine lateral adjustment except with ancillary clamps and kinematic positioners (such as Thorlabs KL02).

7. The prism was preloaded and indexed down onto the "roof" of its 3D-printed based by a standard, gentle nylon-tipped Thorlabs PM3 adjustable clamping arm. Its lateral position and angle relative to the beam were similarly fixed by indexing against hard stops on the 3D-printed base by nylon-tipped screws pressed onto the opposing prism wedge face. All required tapped holes in the 3D-printed base were provided by heat-set inserts (such as McMaster 93365A110). Screw-to-expand inserts (such as McMaster 92395A111) can be even more convenient for such purposes, but can tighten dangerously in brittle plastic when fully penetrated by a set screw (rather than only partially penetrated by a basic screw).

8. The detector's mounting plate had very close clearance to the final Hastings triplet, thus constraining the focus alignment range of the triplet. So there was a trade between the plate's thickness and this alignment range. The detector is quite light, and thus requires only minimal structural support, but it is slightly vibrated by a fan, thus necessitating a fairly stiff mount. So, several of these mounting plates were manufactured in a range of thicknesses to allow for trial-and-error. In practice, during final alignment, all focus alignment was found to be performable at the lenslet (rather than at the detector or the final Hastings triplet), so the thickest mounting plate was employed and no jitter was ever apparent on the image. Alternately, even stiffer detector mounting could be achieved by a typical V-groove "saddle" mount, but this was expected to be overly bulky, top-heavy and wobbly, and was not considered necessary.

9. Larger goniometers (Edmund 66-527) were employed here to provide a sturdier base underneath the larger detector, and provide its tip/clocking fine alignment capability.

10. A COTS breadboard (Thorlabs MB1012) served as the baseplate for the pathfinder IFS, and its tapped hole grid allowed for more traditional repositioning and clamping of mount bases where necessary (which did prove to be necessary for the prism mount, to steer an unexpected ghost out of the image). Four precisely-positioned countersunk screw clearance holes were machined into the COTS breadboard to allow for precisely-located mounting of the IFS onto the HCIL main lab's large optical table (with the nominal IFS position determined by a ZEMAX raytrace of the downstream portion of the main lab's beam path).

The as-built pathfinder IFS is shown in Figure 5.

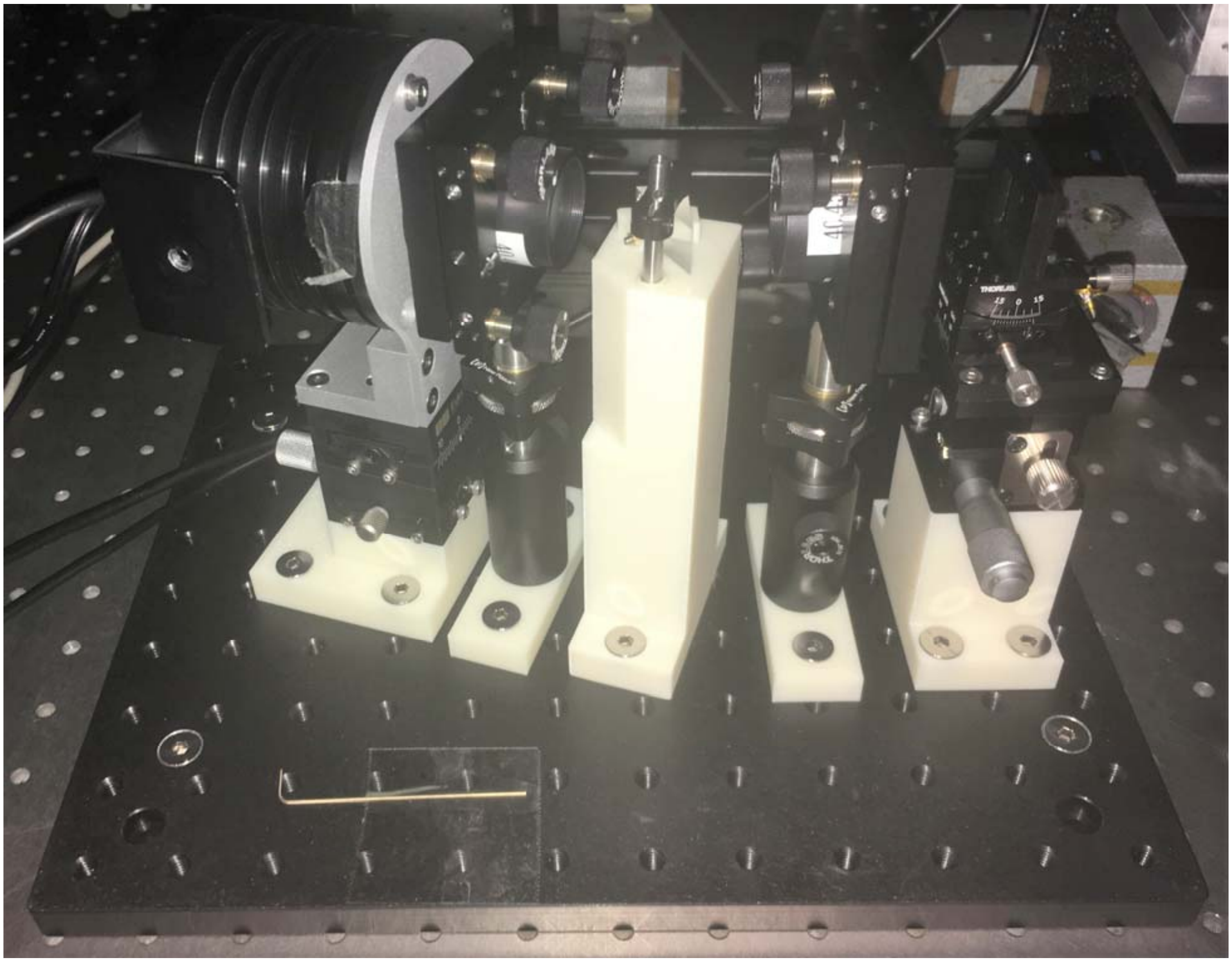

Figure 5. As-built pathfinder IFS, with temporary 3D-printed mount bases.

2.4 Final HCIFS optomechanical design

The optomechanical design of the final HCIFS is shown in Figure 6, with upgrades (relative to the pathfinder) labeled and described below:

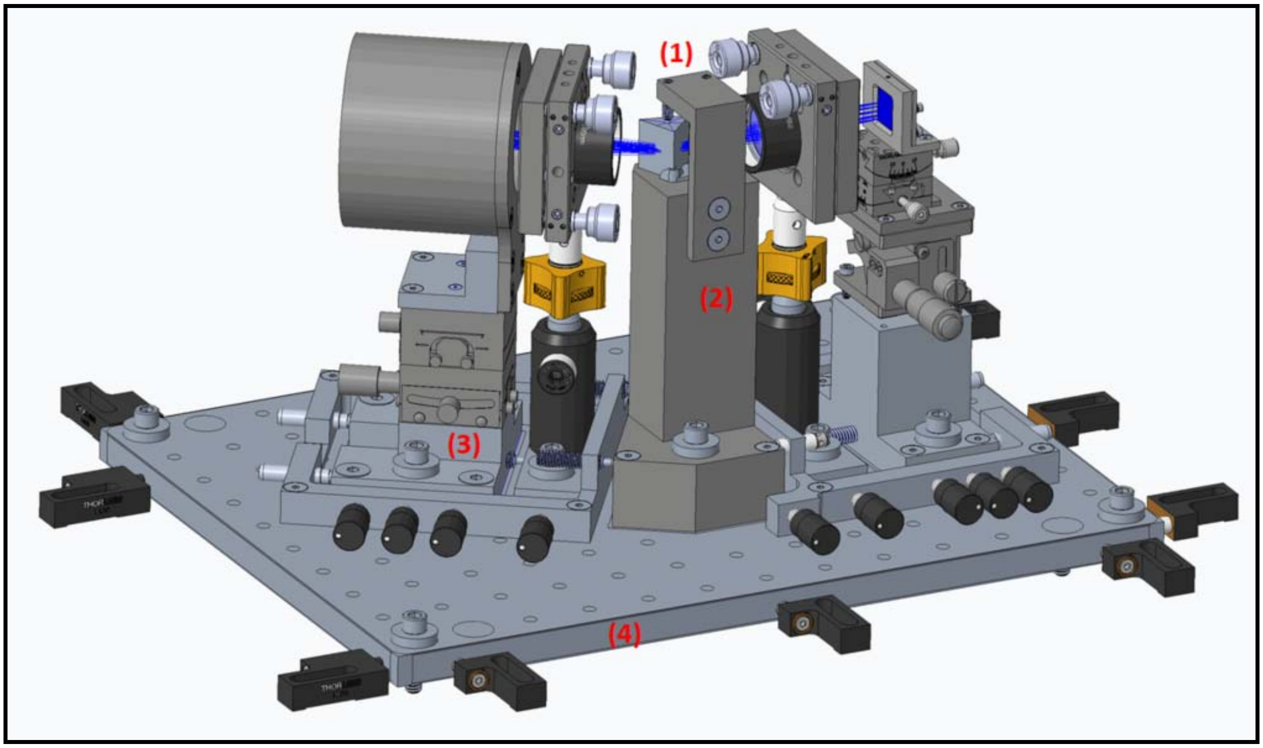

Figure 6. Final HCIFS optomechanical design, with upgrades (relative to the pathfinder) labeled and described below.

Details of the upgrades (relative to the pathfinder) are as follows (list numbers correspond to label numbers in Figure 6 above):

1. The custom prism clamping "hood" functions similarly to the Thorlabs PM3 adjustable clamping arm in the pathfinder, except now providing two precisely-centered, gentle nylon-tipped set screws to preload the 2-wedge prism down onto the roof of the base. The hood also doubles as a partial baffle around the prism.
2. All custom mount bases are now aluminum. All aluminum parts proximate to the beam (the prism mount base, its clamping hood, and the detector mounting plate) are now matte-blackened by a sequence of first bead-blasting and then black anodizing (a surface finishing sequence known to provide less reflectance than black anodizing alone).
3. The major upgrade to the final HCIFS optomechanics was laterally fine-adjustable bases. The bases are still hard-mountable to the baseplate in their precise nominal positions. But these hard-mounting screws can be removed to "unmoor" the base, which can then be fine-pushed around using the surrounding "pusher frame". The bases can be fine-pushed either by basic fine-adjustment screws (Thorlabs FAS100) or—where necessary for ultra-fine focus adjustment, such as at the lenslet or detector—by ultra-fine differential adjuster screws (Thorlabs DAS110). The pusher screws push against preload provided by spring plungers (McMaster 8476A44) on the opposing face of the base. A lesson learned here: the natural position of the lenslet and detector's focus spring plunger (as well as a desire to enable ultra-fine tilt adjustment capability) drove a single focusing DAS110 to be split into dual separate DAS110s at each location. In practice, during final alignment, these dual DAS110s were never used for tilt adjustment, and the primary fine-alignment utilized was focusing of the lenslet, which was rendered cumbersome by the need to simultaneously turn <u>both</u> of these dual DAS110s in

precise synchrony (rather than a single focusing DAS110, which would have been much easier). This cumbersomeness—in combination with an apparent need to more systematically, algorithmically traverse through the focus range to find optimal focus—eventually led to total replacement of the lenslet mount base with a motorized translation stage (Thorlabs MT1-Z8), as shown further below in Figure 9.

4. The Thorlabs breadboard was replaced by a custom machined baseplate. The final baseplate still has an (expensive) grid of tapped holes for more traditional repositioning and clamping of mount bases (never used). It was also upgraded with narrow groove patterns outlining the nominal base positions, to serve as a visual reference when they are repositioned to off-nominal positions. While the baseplate still includes countersunk screw clearance holes to precisely mount it in its nominal position on the HCIL main lab optical table, the baseplate is also now surrounded by kinematic positioners (such as Thorlabs KL02, etc.) to enable lateral fine-adjustment of the entire IFS itself. Like the mount bases above, once the baseplate is unmoored from its nominal position (by removing the hard-mounting screws) and repositioned, it then clamped down securely by separate screws that pass through sturdy ultra-thick spanning washers over top of large clearance holes (that are oversized to allow for this repositioning).

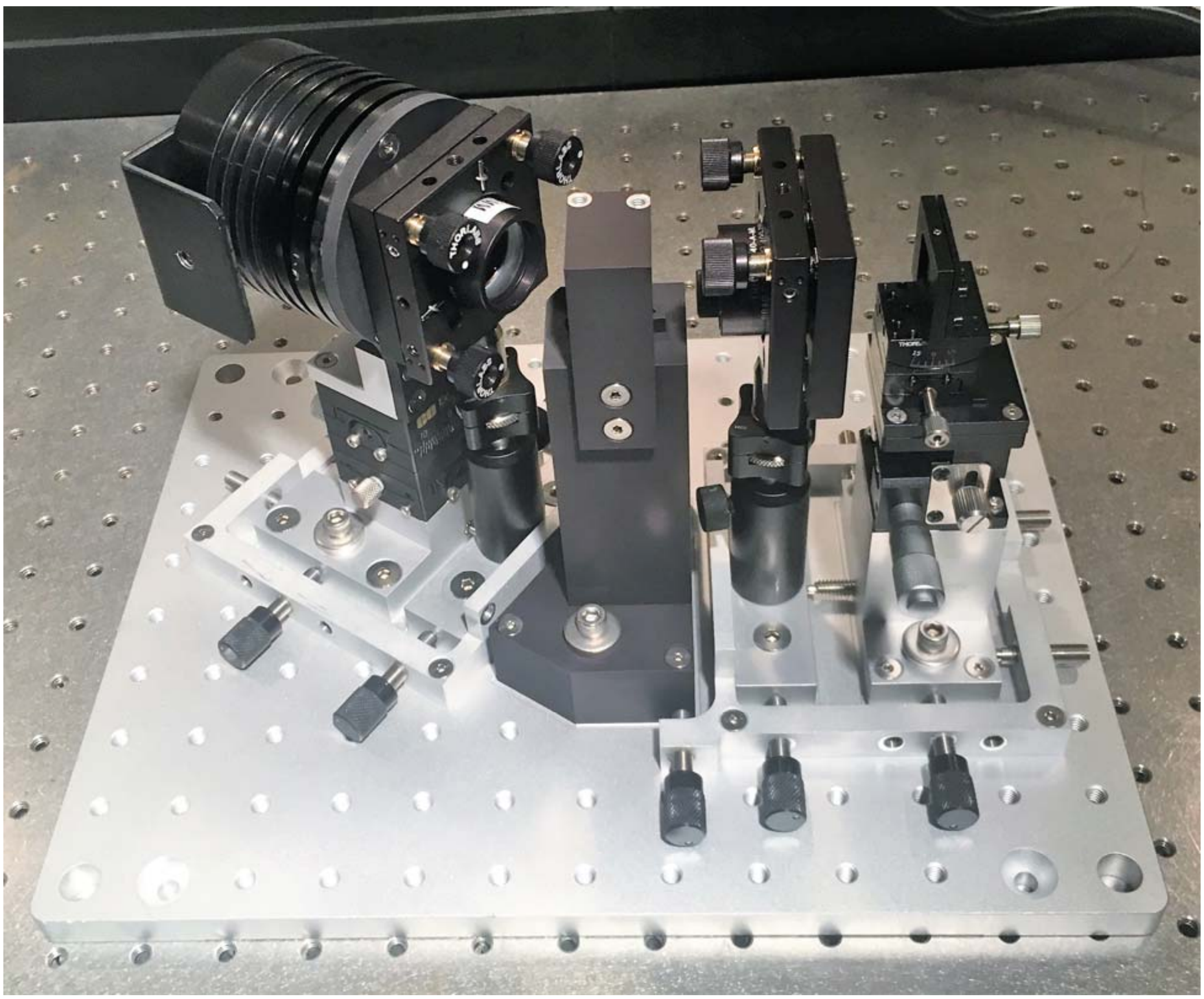

Figure 7. As-built final HCIFS.

3. RESULTS

3.1 Data cube extraction

The rapid-prototyped pathfinder approach proved successful, not only because it accelerated the start date of data pipeline work, but also because a raytracing error was found in the final HCIFS design that rendered our custom 2-wedge prism unusable as we approached the 1-year grant deadline, so it was actually the pathfinder that had to be used to generate the contract-deliverable data cube (at least until the final HCIFS could be repaired during the current year 2 renewal of the grant now). Figure 8 below shows sample frames of a data cube extracted from a pathfinder IFS image:

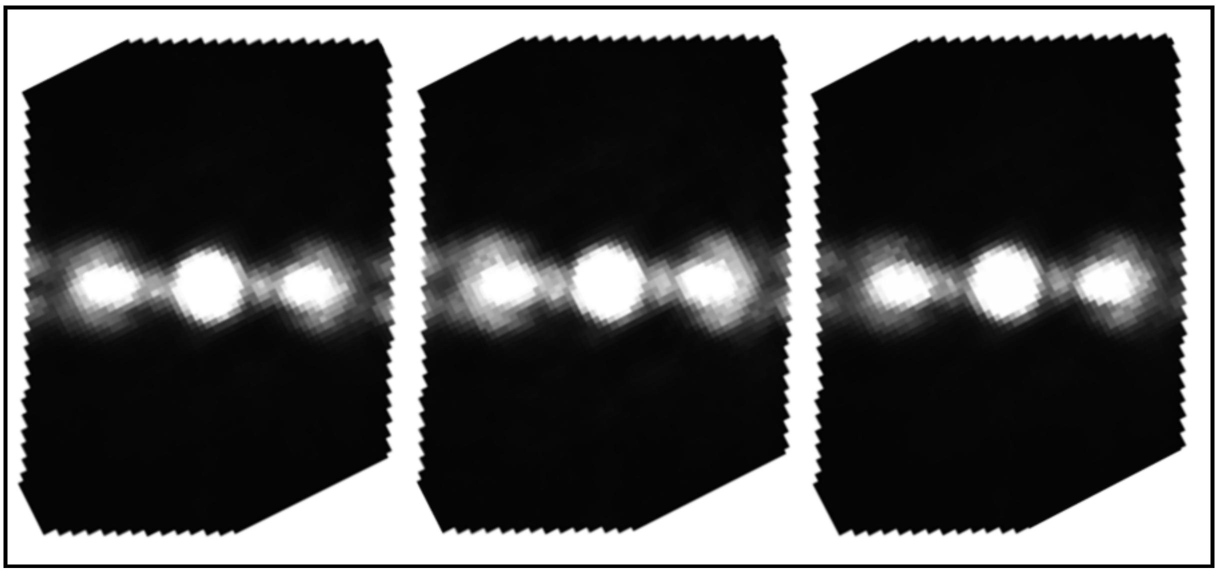

Figure 8. Sample frames of a data cube extracted from a pathfinder IFS image, traversing through its working band (610-690nm)

3.2 Future work

We were awarded a year 2 renewal of the grant, to focus on using our now-functional IFS to do agile development of IFS sensing and control algorithms in support of NASA's WFIRST and PISCES IFS. While the start date of the "year 2" work was delayed by the need to re-procure the corrected custom 2-wedge prism (due to the discovered raytrace error mentioned above), and to propagate these prism changes into slight tweaks of the optomechanics, we had actually preserved sufficient contingency budget from the year 1 grant to fund this recovery work and bridge this schedule gap.

Since the baseline WFIRST IFS does not have extensive on-orbit motorized alignment capability, it has become apparent that one of the most crucial aspects of IFS sensing algorithms to investigate is characterization of misaligned images (and the tolerance or required compensation of the data cube extraction to such misalignments). Towards this end (and also in response to the above-mentioned cumbersomeness of manually fine-focusing the HCIFS), the first step of our year 2 work has been replacement of the lenslet mount's manually fine-adjustable base with a new motorized linear stage, as shown in Figure 9 below. Using this motorized stage, we'll perform systematic, incremental slews through the defocus range of the IFS and characterize the resultant impact on the data cube extraction. Afterwards, we also hope to similarly characterize the impact of tilt misalignment by using a new motorized tilt stage.

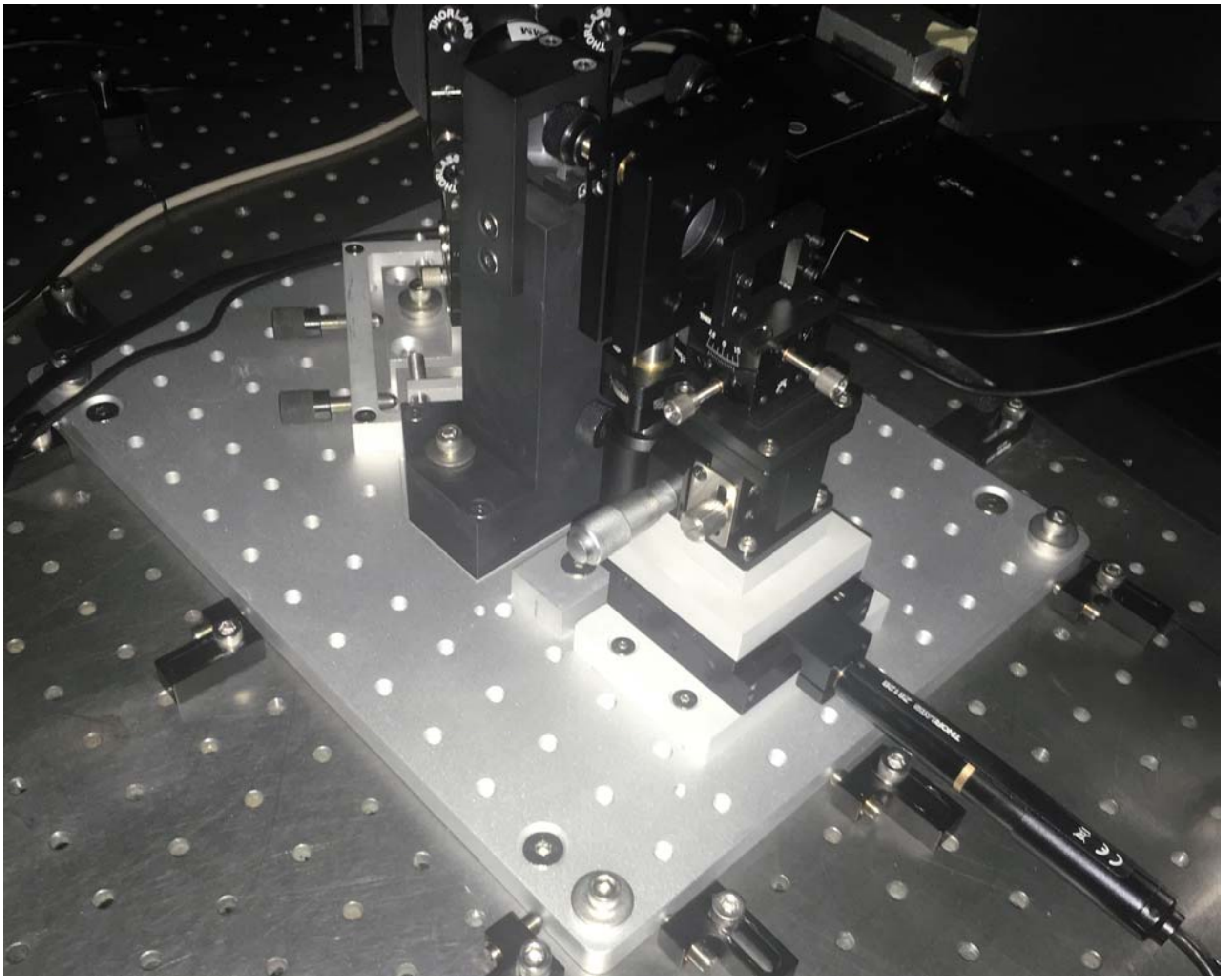

Figure 9. Latest configuration of the HCIFS, implementing a motorized focus stage (Thorlabs MT1-Z8) as the base of the lenslet mount.

4. CONCLUSION

We successfully rapid-prototyped a mostly-COTS, partially 3D-printed pathfinder version of an IFS in order to compress the design/build/test schedule of a final, mostly-custom IFS, by accelerating the start date of data pipeline development, thus allowing this development to progress in parallel with the design, procurement, fabrication and alignment of the final IFS version. This parallel-path development schedule enabled us to design, build, align, test, and successfully extract a data cube from the new IFS within only 1 year, even in the face of several design setbacks. We have begun using the now-functional IFS for development of IFS sensing and control algorithms, and have also begun implementing motorized alignment upgrades that enable the systematic characterization of the tolerance (or required compensation) of its data cube extraction to misaligned images, in support of NASA's WFIRST and PISCES IFS.

ACKNOWLEDGEMENTS

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