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Scott J. Lilley, Kodi Rider, Jim Thorne, Marc Kassis, Steve Gibson, Andrew Howard, Kyle Lanclos, Josh Walawender, "A fiber injection unit for the Keck Planet Finder: opto-mechanical design," Proc. SPIE 12184, Ground-based and Airborne Instrumentation for Astronomy IX, 121844K (29 August 2022); doi: 10.1117/12.2628818

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

A fiber injection unit for Keck Planet Finder: opto-mechanical design

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ABSTRACT

As part of the Keck Planet Finder (KPF) project, a Fiber Injection Unit (FIU) was implemented and will be deployed on the Keck I telescope, with the aim of providing dispersion compensated and tip/tilt corrected light to the KPF instrument and accompanying H&K spectrometer. The goal of KPF is to characterize exoplanets via the radial velocity technique, with a single measurement precision of 30cm/s or better. To accomplish this, the FIU must provide a stable F-number and chief ray angle to the Science and Calcium H&K fibers. Our design approach was use a planar optical layout with atmospheric dispersion compensation for both the Science and Calcium H&K arms. A SWIR guider camera and piezo tip/tilt mirror are used to keep the target centered on the fibers.

Keywords: KPF, fiber injection unit, radial velocity

1. INTRODUCTION

A fiber injection unit (FIU) for the Keck Planet Finder (KPF) instrument was designed and built for deployment on the Keck I Adaptive Optics (AO) bench. KPF is a fiber-fed, high-resolution, high-stability spectrometer designed to characterize exoplanets via the radial velocity technique. KPF has a goal to achieve a single measurement precision of 30cm/s. The KPF instrument is designed to cover a wavelength range of 445nm to 870nm; however, the FIU will cover a wavelength range of 385nm to 1200nm in order to provide light to a Calcium H&K spectrograph, the KPF instrument and a tip/tilt guiding camera.¹⁻³

The FIU takes light from the Keck I telescope and splits it into three different paths: Calcium H&K spectrometer (385nm to 403nm), Science (440nm to 870 nm), and tip/tilt guiding (900nm to 1200nm). The two fiber paths (Calcium H&K and Science) also contain Sky fibers which are separated from the Calcium H&K and Science fibers by 10 arcseconds. An internal calibration source uses fiber-fed calibration light from the KPF instrument and feeds it to the Science and Sky fibers.

In this paper we will discuss the opto-mechanical design of the FIU for KPF. Related papers at this conference will discuss the development and status of the KPF instrument.⁴⁻⁵

1.1 Implementation on the AO bench

Several locations on the Keck I & II telescope were considered for the FIU, including a bent Cassegrain instrument port, a subsystem on an instrument at Nasmyth ports, and the AO bench. Ultimately it was decided to use the space on the Keck I AO bench to save the other locations for larger instruments as well as provide more flexibility to support cadence observations that KPF science requires. Figure 1 shows (a) the location of the FIU on the Keck I AO bench and (b) the light path from the telescope to the FIU.

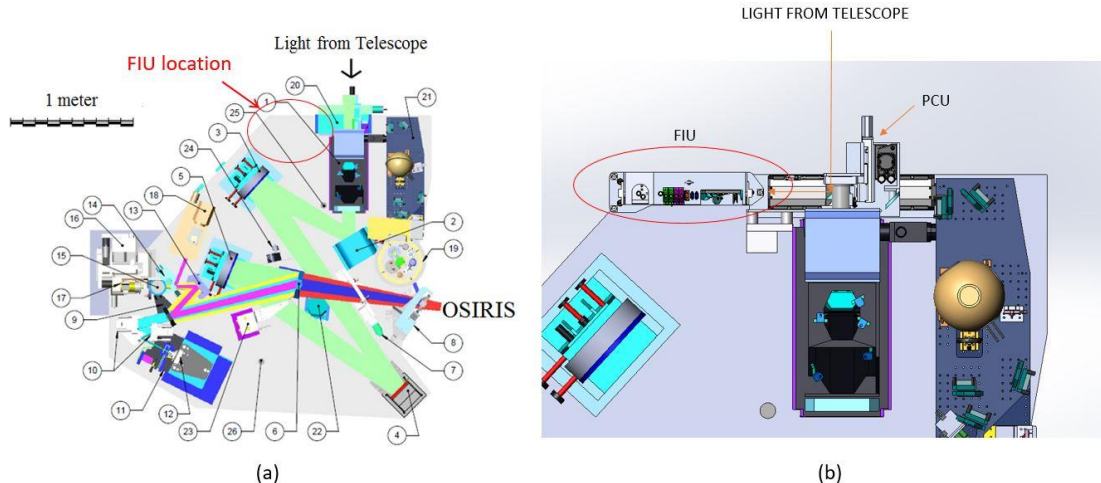


Figure 1. (a) Layout of the Keck I AO bench with location of the FIU identified and (b) enlarged view of FIU location and light path from the telescope

Light from the Keck I telescope is picked off by a fold mirror on a tip/tilt piezo stage, which is mounted to the newly commissioned Precision Calibration Unit (PCU) shown in Figure 1(b).⁴ The PCU contains a 3-axis XYZ assembly used for a variety of purposes, one of which is to place the FIU pickoff mirror in-beam when the KPF instrument is selected. The pickoff mirror is located 150 mm before the telescope focus, while the FIU is located 150 mm after telescope focus. Figure 2 shows a top-down view (as looking down towards the AO bench) of the optical layout with light from the telescope coming in from the top of the figure and only the Calcium H&K and Science paths shown in the FIU.

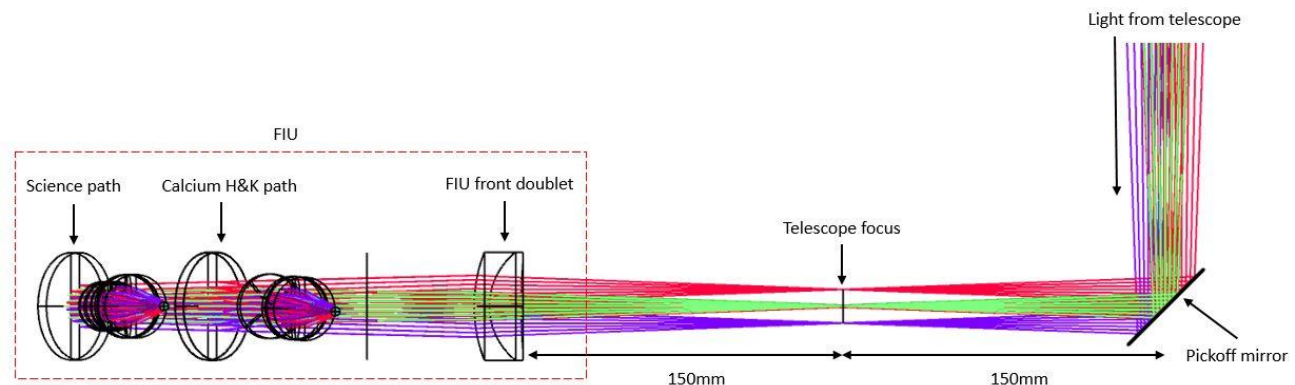


Figure 2. Top-down view optical layout showing light path from telescope (Calcium H&K and Science path shown)

1.2 Opto-mechanical design requirements and constraints

Several performance and volume constraints drove the opto-mechanical design of the FIU. The primary optical requirements that drove the design are listed in Table 1.

Table 1. Primary FIU opto-mechanical requirements

FIU #	Requirement
1	The FIU shall illuminate the Science and Science Sky fibers with wavelengths from 445nm to 870nm
2	The FIU shall illuminate the H&K and H&K Sky fibers with wavelengths from 385nm to 403nm
3	The FIU shall be capable of maintaining the centroid of the star image within ± 0.05 arc seconds RMS of the science fiber center for a duration of one hour.
4	The FIU atmospheric dispersion corrector shall maintain the centroids of the polychromatic stellar images within ± 0.05 arcseconds of the center of the science fiber, over zenith angles of 0 to 60 degrees.
5	The calcium H&K Fiber shall be co-located on the Science fiber to within 0.5 arcseconds with atmospheric dispersion $\leq 0.5''$, over zenith angles of 0 to 60 deg.
6	The FIU shall illuminate all fibers (Science, sky, Calcium H&K and Calcium H&K sky) with light from the telescope at a focal ratio of $f/3.7 \pm 0.1$.
7	The chief ray of incident light delivered by the FIU shall be parallel to the nominal optical axis of the science fiber to within ± 0.6 degrees.
8	The FIU throughput shall be $\geq 80\%$ over the science fiber bandpass.
9	The geometric blur diameter of all aberrations together (chromatic, spherical, coma, WFE, etc.) must be less than 0.35 arcseconds on sky.
10	The FIU shall illuminate the Science and Sky fibers with light from calibration fibers. The FIU Calibration fiber images shall be projected over the Science and Sky fiber faces with uniform and stable flux at $f/3.7$ and a chief-ray angle that is stable within ± 0.5 degrees.

The space allocated for the FIU on the Keck I AO bench has a footprint of about 200 mm with by 600 mm long with the height limited by the roof of the AO bench with is approximately 1m from the surface of the AO bench. This limited space drove the layout of the optical design to the vertical, “in-plane” orientation described in the following section.

1.3 Opto-mechanical layout

The FIU contains four separate optical paths: Calcium H&K, Science, tip/tilt guiding and calibration. Two fiber viewing cameras are used to image the Calcium H&K and Science fibers. Figure 3 shows the optical paths contained within the FIU. The light from the telescope is quasi-collimated by a doublet at the front of the FIU which is common to all paths except the calibration path. Next, two dichroics, with high performance coatings, are used to send the light to the Calcium H&K path then the Science path. A fold mirror sends the remaining light ($>900\text{nm}$) to the tip/tilt guider camera. The calibration path is self-contained within the FIU and uses several lenses to reformat the $F/3.7$ output beam from a calibration fiber source and a retractable fold mirror to send calibration light to the Science and Sky fibers while keeping the light path as close as possible to what would be seen on-sky.

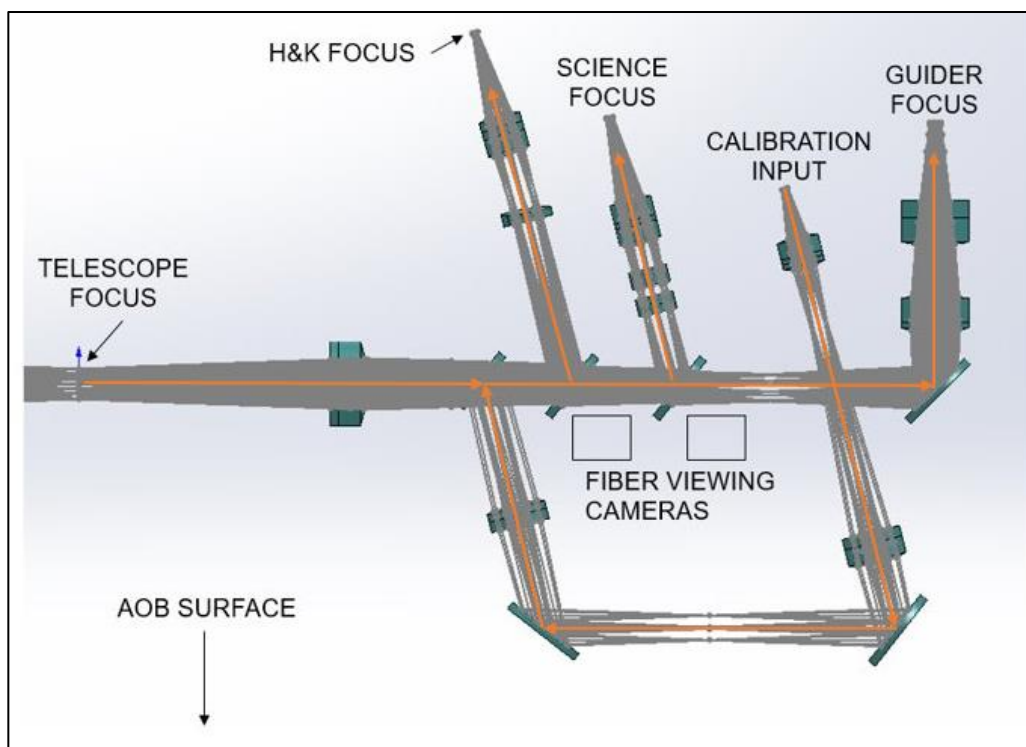


Figure 3. FIU optical layout

Table 2 describes the various fibers located within the FIU and their purpose.

Table 2. Fibers contained within the FIU

FIU Arm	Fibers	Purpose
H&K	H&K Science, H&K Sky	FIU output to Calcium H&K spectrometer
Science	Science, Sky	FIU output to main spectrometer
	Exposure Meter Sky	FIU output to Exposure Meter
Calibration	Science Cal, Sky Cal	Input to FIU from Calibration Unit

Figure 4 shows a CAD model of the FIU with various components labeled (a) and with the cover hidden (b) to show the internal components of the FIU and Figure 5 shows the overall dimensions of the FIU.

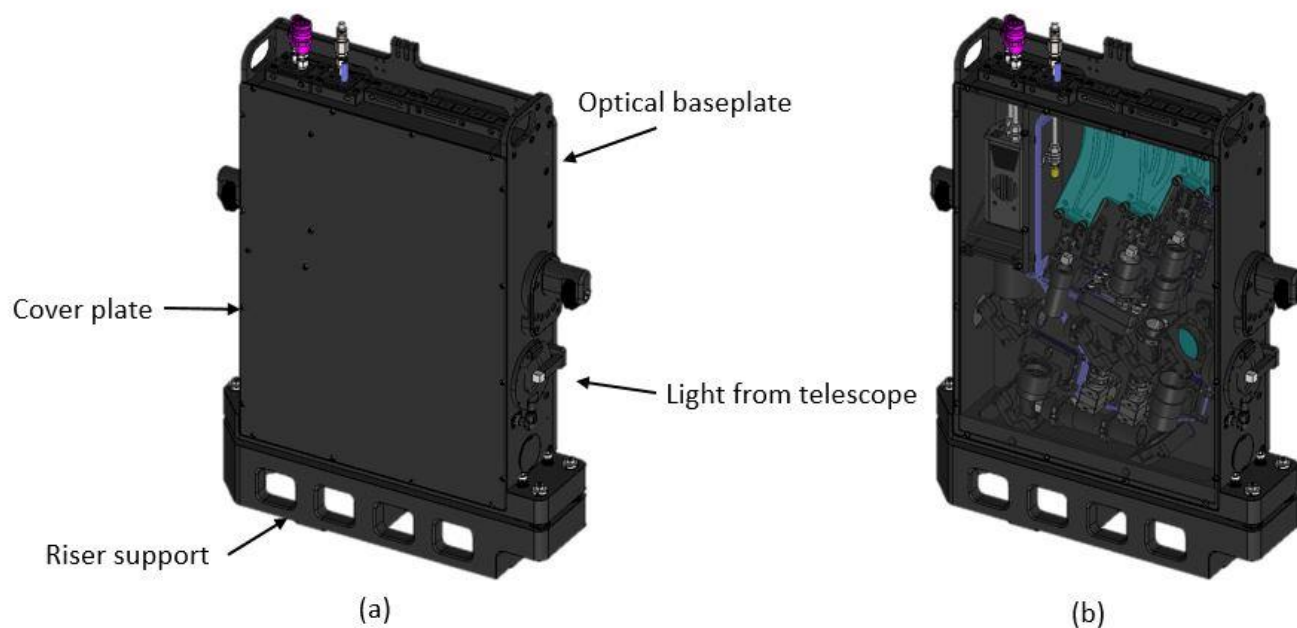


Figure 4. CAD model of the FIU showing the outer components (a) and showing the inner components with the cover hidden (b)

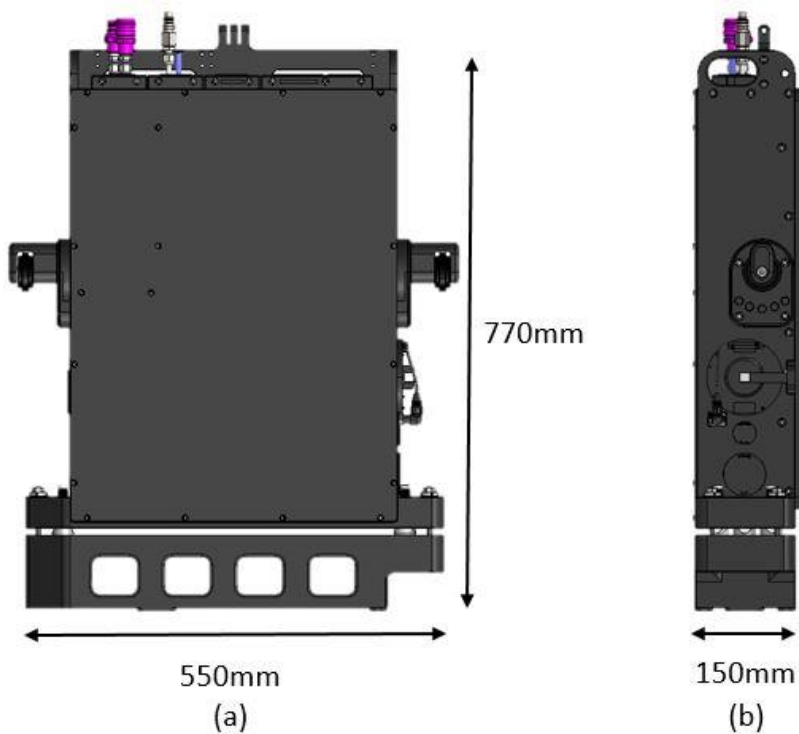


Figure 5. Side view (a) and front view (b) of the CAD model of the FIU with dimensions for scale

2. FIU OPTICAL DESIGN

The FIU takes the F/13.66 beam from the Keck I telescope and reformats it to F/3.7 for the Calcium H&K and Science fibers. The fibers have an octagonal core diameter of 225 μm and subtend a field of view of 1.14 arcseconds. A doublet lens, which is common to all paths except calibration, is used to reformat incoming light from the telescope into a quasi-collimated (slightly converging) state. From there, the light is split into the various optical paths using two dichroic beam splitters. The calibration optical path is fully contained within the FIU.

2.1 Calcium H&K optical path design

The first path in the FIU is the Calcium H&K arm. Light from the telescope is picked off by the H&K dichroic, which reflects 385nm to 403nm and passes longer wavelengths. The Calcium H&K path contains a fused silica wedge and a focusing triplet. Figure 6 shows the Calcium H&K path from the telescope focus to the fiber focus.

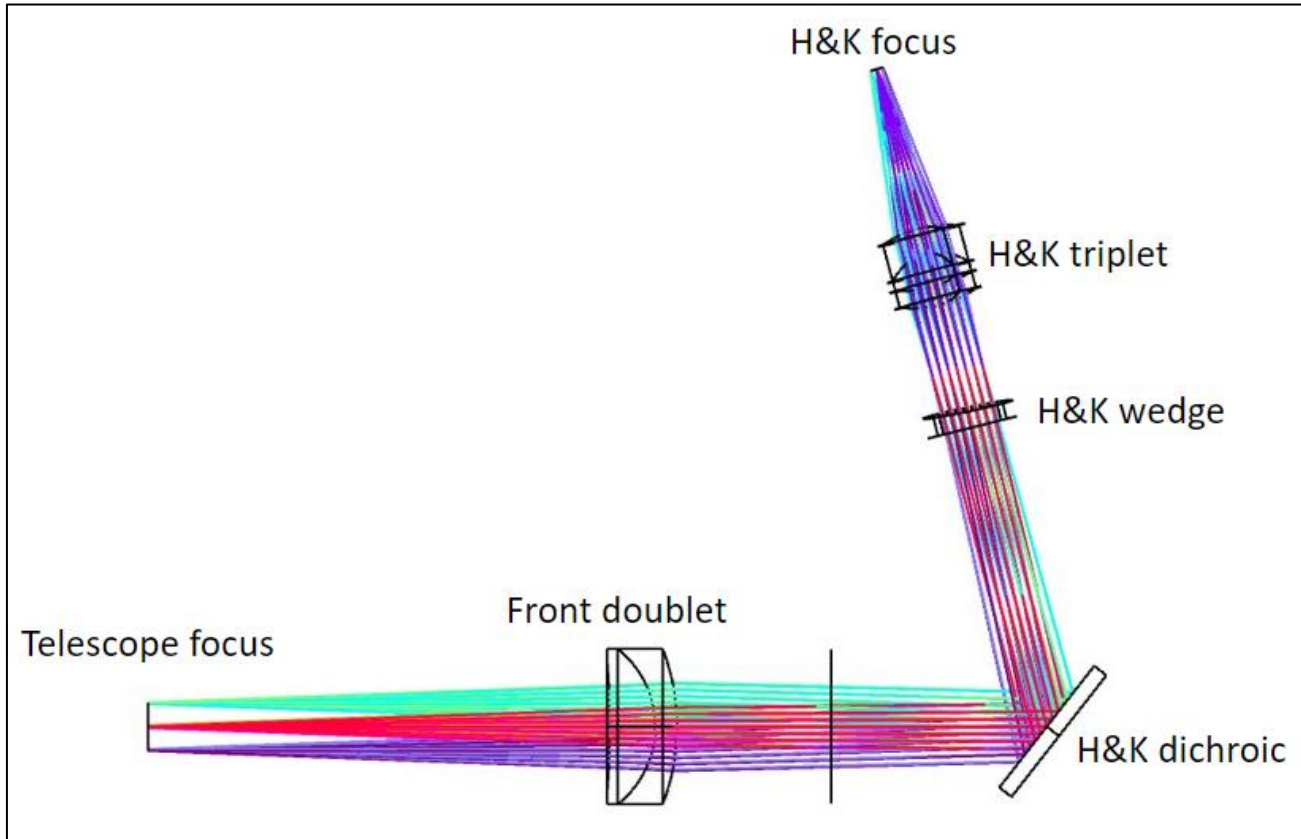


Figure 6. Calcium H&K optical path

The requirements for F/#, spot size and chief ray angle are the same for the Calcium H&K path as they are for the Science path. However, the atmospheric dispersion requirement for the Calcium H&K path is 10X that of the Science path. This allowed for the ADC prisms to be in the Science path only, increasing the throughput for the Calcium H&K fibers (see section 2.2). The fused silica wedge acts as a fixed dispersion compensator for the Calcium H&K path, optimized to minimize the dispersion at 40 degrees zenith angle. A drawback of not having an ADC in the Calcium H&K path is that the focused spot on the fiber moves as the telescope changes elevation. The solution to that is to have the Calcium H&K fibers on two-axis “ADC” stage, which moves the fibers to track the telescope motion and keep the spots centered on the fibers. An optical analysis of the Calcium H&K path shows that it meets or exceeds all the requirements, the primary ones being F/#, spot size, dispersion and chief ray angle.

2.2 Science path optical design

The next path in the FIU is the Science path, which is the primary optical path for the KPF instrument. Wavelengths greater than 405 nm are passed through the Calcium H&K dichroic to the Science dichroic. The science dichroic reflects light from 445 nm to 870 nm towards the Science path which consists of two counter rotating prisms and a triplet that focuses the light on the Science and Sky fibers. Figure 7 shows the layout of the Science path.

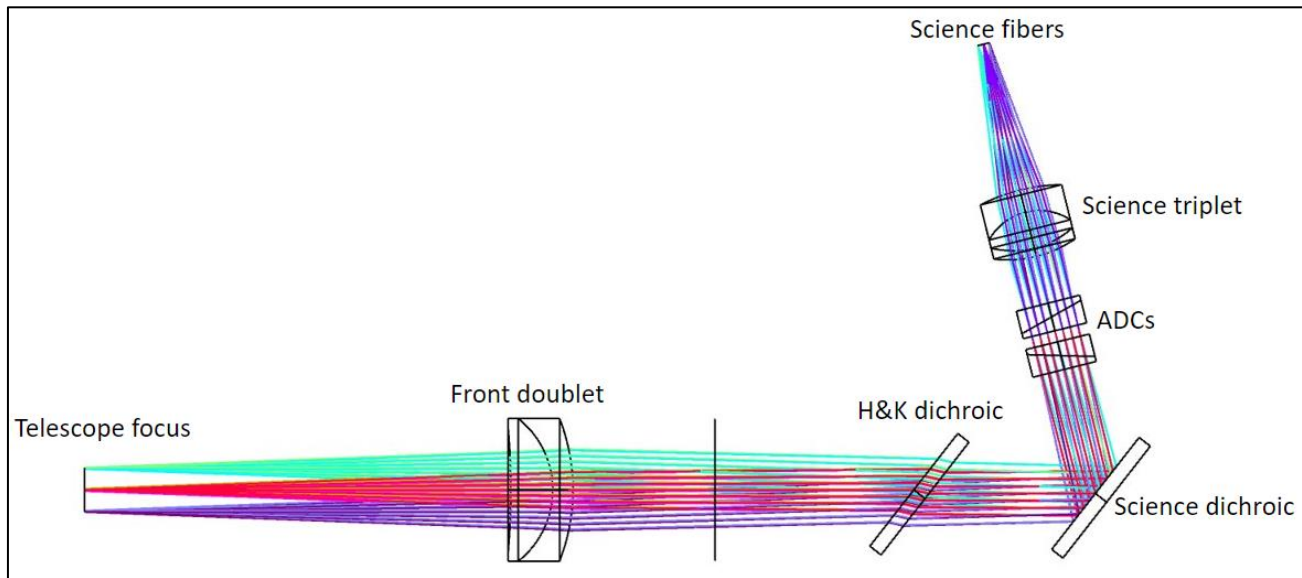


Figure 7. Science path optical layout

Two counter rotation prisms, each made of S-PHM53 and N-KZFS4 glasses, comprise the ADC. The ADC design is a modified version of the one designed for the Magellan AO system and VisAO camera.⁷ In this case, a doublet ADC is used instead of a triplet to increase the throughput of the Science path as much as possible. A slight tilt on the back surface of each prism ensures the ADC does not deviate the chief ray angle while correcting for atmospheric dispersion. This was necessary to meet the requirements listed in Table 1. A triplet, similar to the Calcium H&K triplet, focuses the dispersion corrected light onto the Science and Sky fibers.

2.3 Tip/tilt guider path optical design

Light from 900 nm to 1200 nm is passed by the Science dichroic to the guider camera path. A simple design of two doublets is used to focus the light on the guider camera at F/5. The full field of view (FOV) for the guider is 28 arcseconds and is limited by the clear aperture of the dichroics. An F/5 beam was chosen to use the full detector size of the SWIR camera for the 28 arcsecond FOV. The SWIR camera is used in closed-loop mode with the piezo tip/tilt pickoff mirror to keep the light centered on the fibers. Figure 8 shows the optical path for the guider camera.

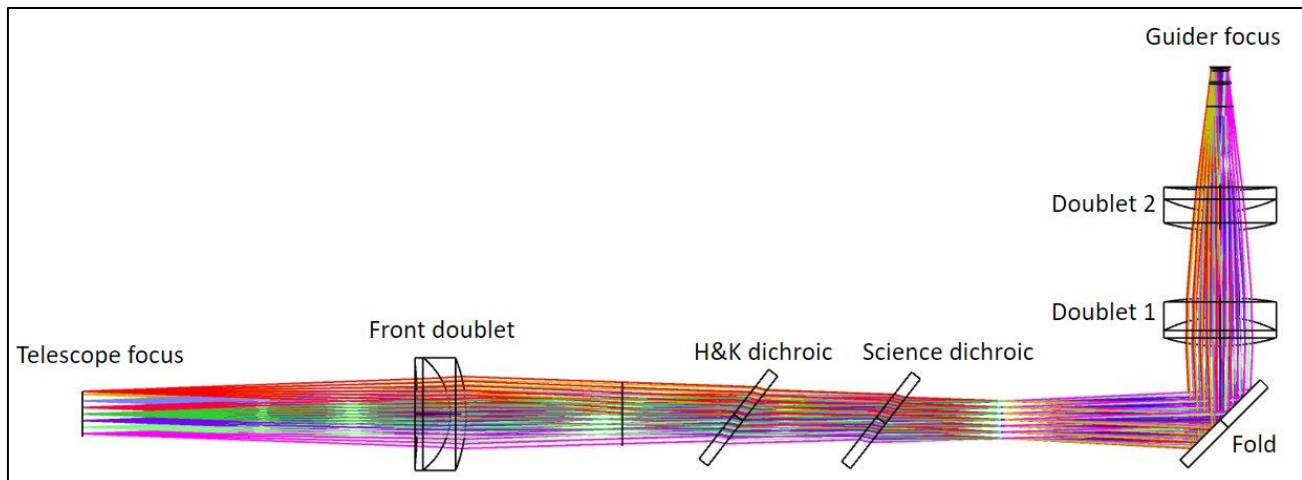


Figure 8. Guider path optical layout

2.4 Calibration path optical design

Calibration light from the KPF instrument is sent to the FIU through fibers identical to the Science and Sky fibers. Figure 9 shows the layout for the calibration path. The calibration optics have been designed to illuminate the Science and Sky fibers with a F/3.7 beam and a spot size 2X that of the science target to meet requirements listed in Table 1.

The calibration optics are designed to take a F/3.7 input beam from the calibration fibers and form an intermediate image plane that is nearly identical to the one formed by the Keck telescope. A doublet lens after the intermediate image plane (calibration doublet 2 in Figure 9) is used to mimic the FIU front doublet and match the light path as close as possible to what is seen on-sky. The last optic in the calibration path is a fold mirror on a linear stage which sends the calibration light to the FIU. The fold mirror is moved out of beam during on-sky observations (see Section 3.1 for a description of the calibration fold mirror mechanism).

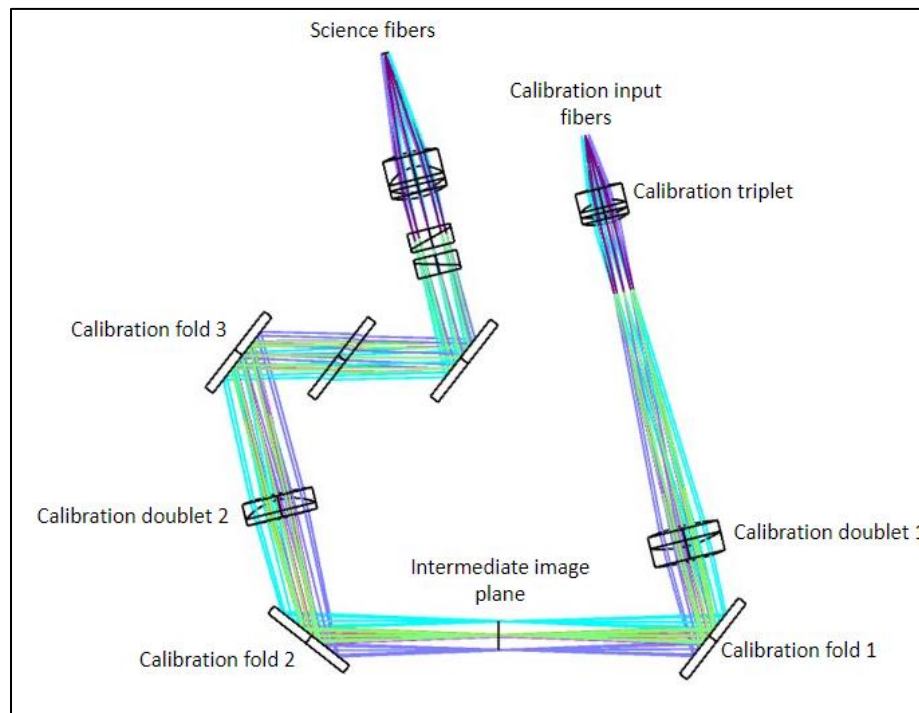


Figure 9. Calibration optical path layout

2.5 Fiber viewing cameras

Two fiber viewing cameras are used to image the H&K and Science fiber faces. It was determined during the DDR phase that there was a need to verify the position of the fibers within the FIU and to verify that the on-sky target falls on the fiber face. This was driven by the very stringent requirements for Science fiber acquisition and guiding stability as described in Table 1. The requirements for the Calcium H&K fiber are not as strict as the Science fiber, but the Calcium H&K and Calcium H&K Sky fibers are located on a 2-axis stage that corrects the atmospheric dispersion. The H&K fiber viewing camera is necessary to verify the initial FIU-to-telescope alignment and to track the performance of the Calcium H&K ADC stage. Figure 10 shows the optical path for the fiber viewing cameras. Each camera has a narrowband filter (400 nm for Calcium H&K, 550nm for Science) in order to eliminate spot elongation from atmospheric dispersion.

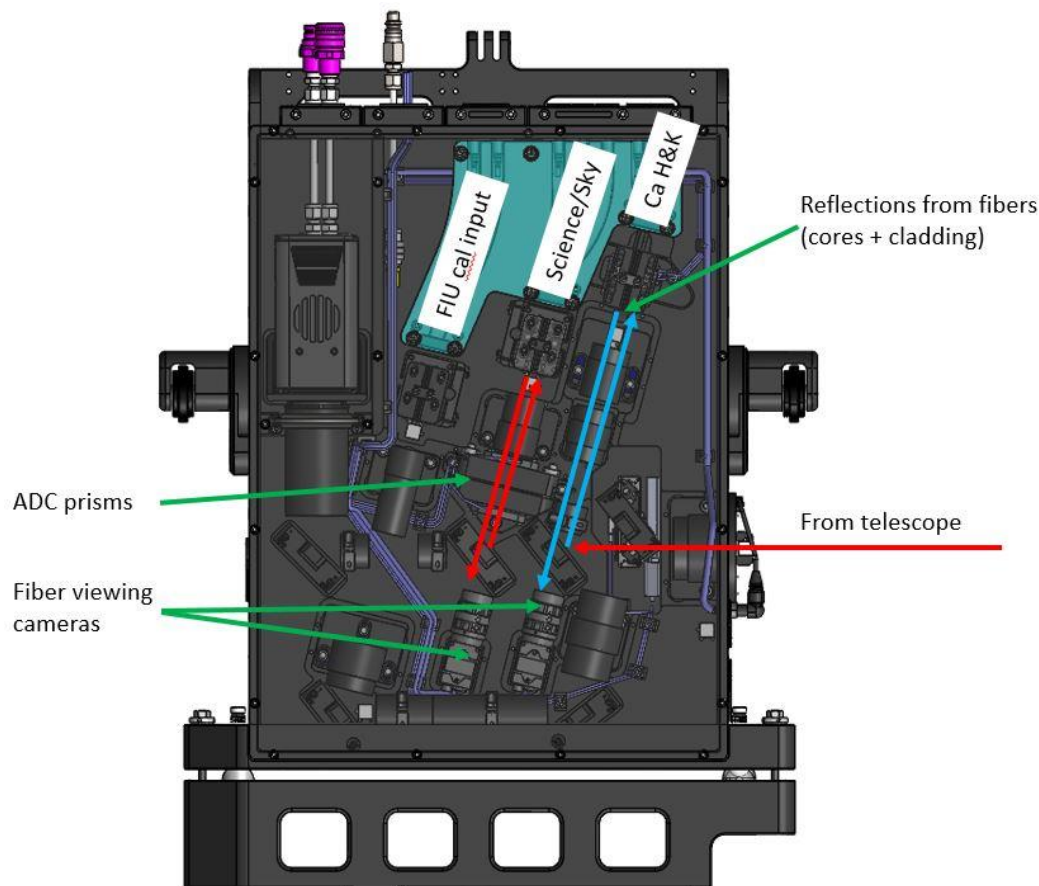


Figure 10. Optical path for fiber viewing cameras

The fiber viewing cameras use the back reflection from the fiber faces to determine centroid location. However, the flux from the reflection is very low so real-time monitoring of a typical science target during an exposure is likely not possible. The fiber viewing cameras are therefore used for alignment verification with bright targets and internal FIU alignment verification with the calibration source. Table 3 describes the various uses for the fiber viewing cameras.

Table 3. Fiber viewing camera use cases

Case	Fibers	Fiber viewing camera	Purpose
Back illuminate fibers	All	Determine pixel centroid locations on cameras	Internal FIU calibration of fiber locations
Illuminate fibers with calibration source	Science, Sky	Determine centroid location of back reflection and cross reference with centroids from back illumination	Internal calibration source alignment check
Point telescope at bright target (e.g. Vega)	Science, H&K	Determine location of on-sky target relative to back illuminated centroids	On-sky verification of FIU-to-telescope alignment

3. FIU MECHANICAL DESIGN

The FIU mechanical design consists of a combination of custom and COTS components. A kinematic mounting interface is used to couple the FIU to the AO optical bench. An articulated cable tray and extraction wheels allow the FIU to be removed from the AO bench for servicing without disconnecting electrical or fiber interfaces. Figure 11 describes the mechanical layout of the FIU.

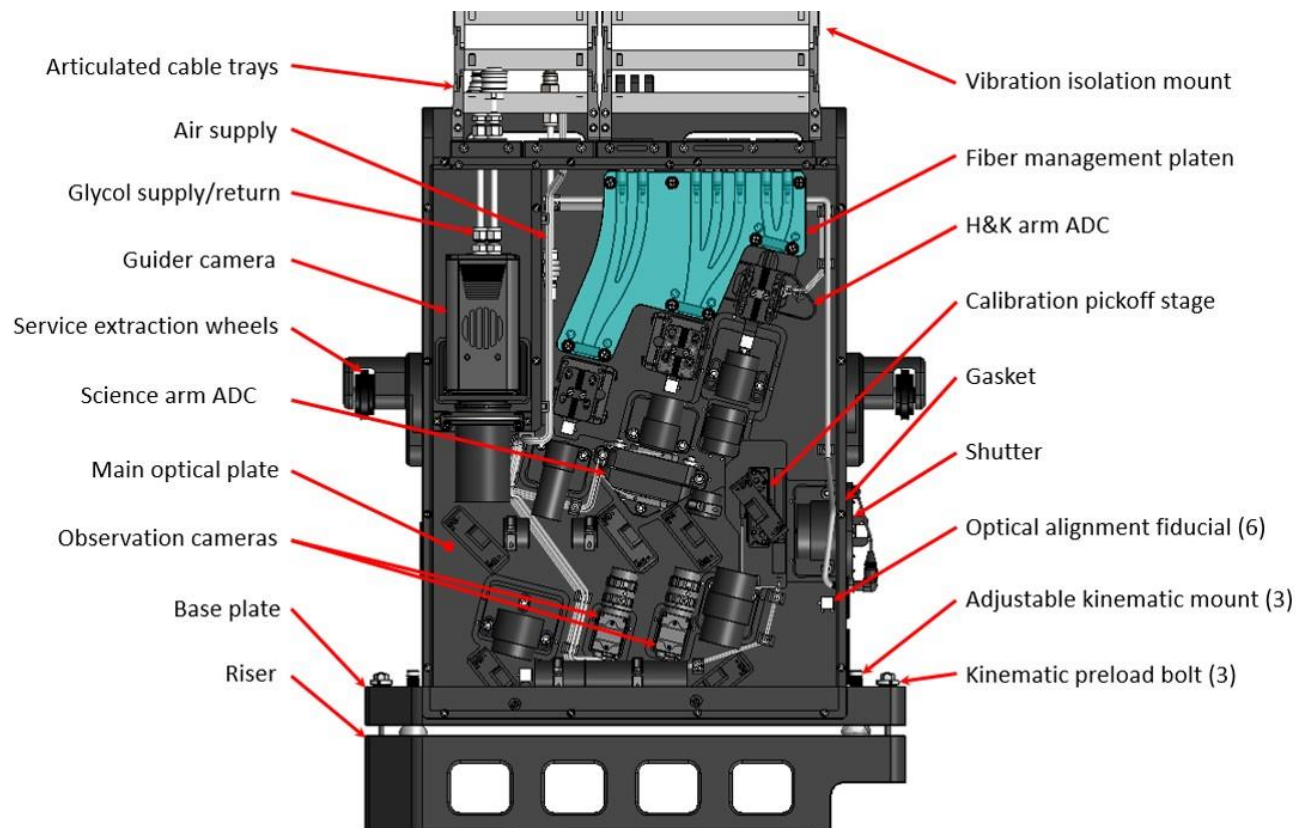


Figure 11. FIU mechanical layout

3.1 Architecture

The overall system architecture uses an adjustable kinematic lens mount design with custom cells for the lens assemblies and COTS mirror mounts. All the individual opto-mechanical assemblies attach to the main optical plate. Optical kinematic adjusters are accessible from the front and rear of the enclosure and are protected with removable covers. Figure 12 shows (a) a CAD model of a typical optical mount and (b) an exploded view of the assembly with the hardware and kinematic adjusters shown.

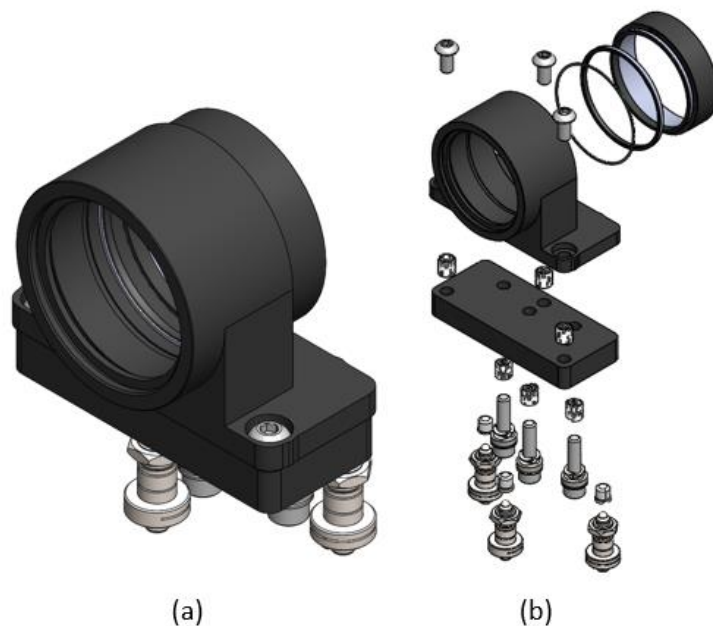


Figure 12. (a) CAD model of a typical optical mount and (b) exploded view of CAD model showing kinematic adjusters

ADC mechanisms for the Science and Calcium H&K arms use piezo stick-slip actuators. A stepper motor based linear actuator is used for the calibration pickoff mirror. All actuators are from the same vendor and use similar controllers along with digital inductive encoders to eliminate stray light within the enclosure. Figure 13 shows (a) a CAD model of the Science ADC assembly and (b) an exploded view of the model with one of the ADC rotary stages highlighted and the kinematic adjusters shown.

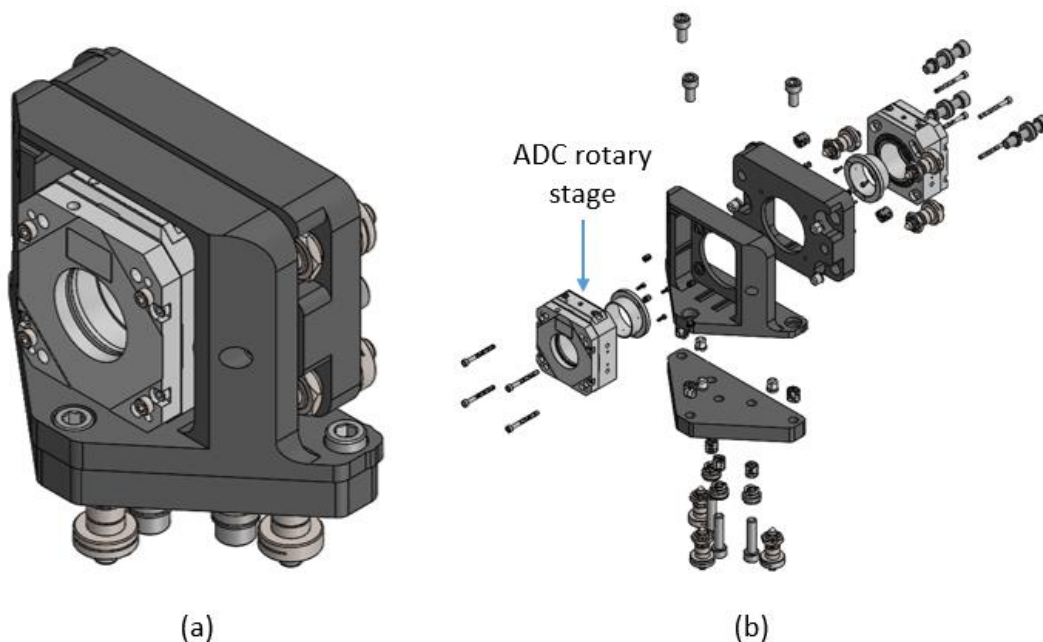


Figure 13. (a) CAD model of the Science ADC assembly and (b) exploded view of the CAD model with one of the AD rotary stages highlighted

One of the driving design requirements was managing the optical fibers during installation and servicing. A planar optical design was chosen in part to have the optical fibers exit the FIU in a way that allowed for a simple method of extraction during a servicing mission if needed. The fibers themselves are clamped into precision-machined v-grooves that precisely locate the Sky and exposure meter fibers from the Science and Calcium H&K fibers to 10 ± 0.5 arcseconds. The v-grooves also provide repeatability when changing fibers during a service mission. Figure 14 shows (a) the CAD model of the fiber assembly and (b) an exploded view of the CAD model showing how the v-groove plate attaches to the adjustable stage.

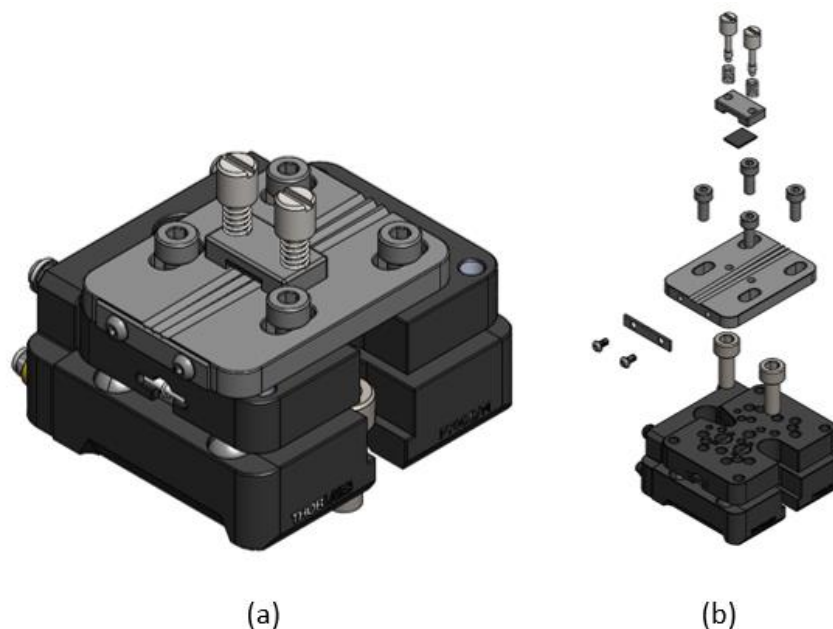


Figure 14. (a) CAD model of the fiber assembly and (b) exploded view of the assembly

Removable optical cube fiducials support the alignment of the FIU in the lab. The fiducials are placed in several key areas of the FIU and are used to define the optical axes of the various light paths. A permanent reference cube is mounted within the FIU. Figure 15 shows the locations of the alignment fiducials with the permanent fiducial pointed out.

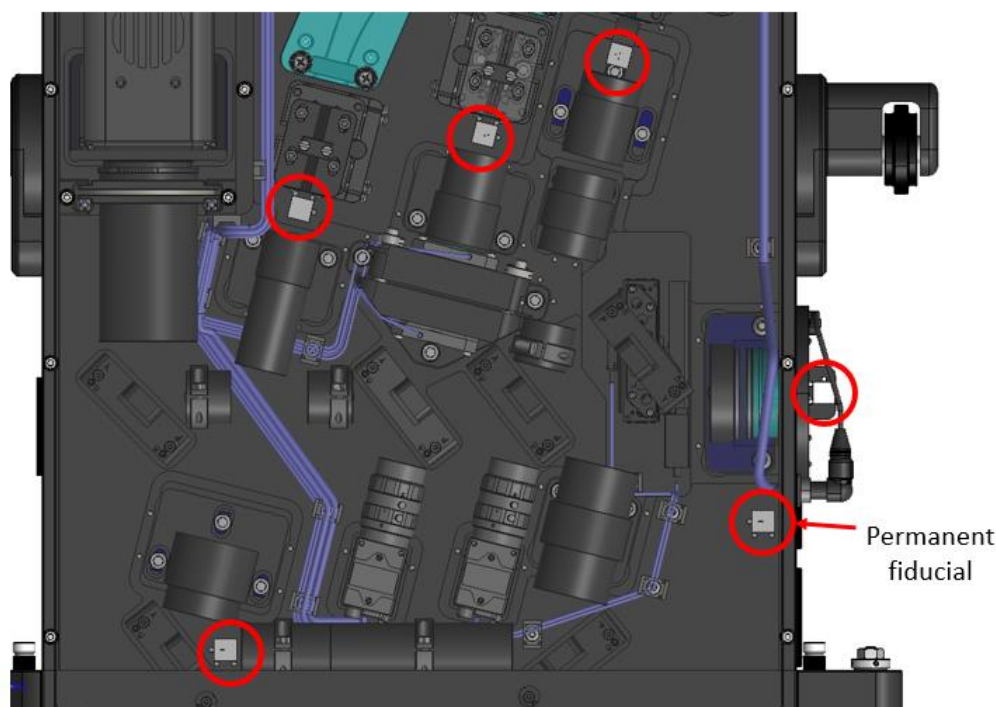


Figure 15. CAD model of the FIU with the alignment fiducials highlighted

3.2 Access

The FIU is placed in the K1 AO bench in a location that presented access challenges for both installation and for future servicing. A manual winch/pulley system along with lateral roller tracks are used to allow extraction of the FIU. A flexible “eChain” protects the minimum bend radius of the fibers (100 mm). Removal and reinstallation of the FIU is achieved with a manual hoist and pulley system, along with roller wheels and tracks on top of the optical bench. Detent pins are used to lock the unit in multiple positions for servicing. Figure 16 shows CAD images of the various stages of FIU removal from the AO bench. All the FIU components are accessible after the FIU is extracted from the AO and the front cover is removed.

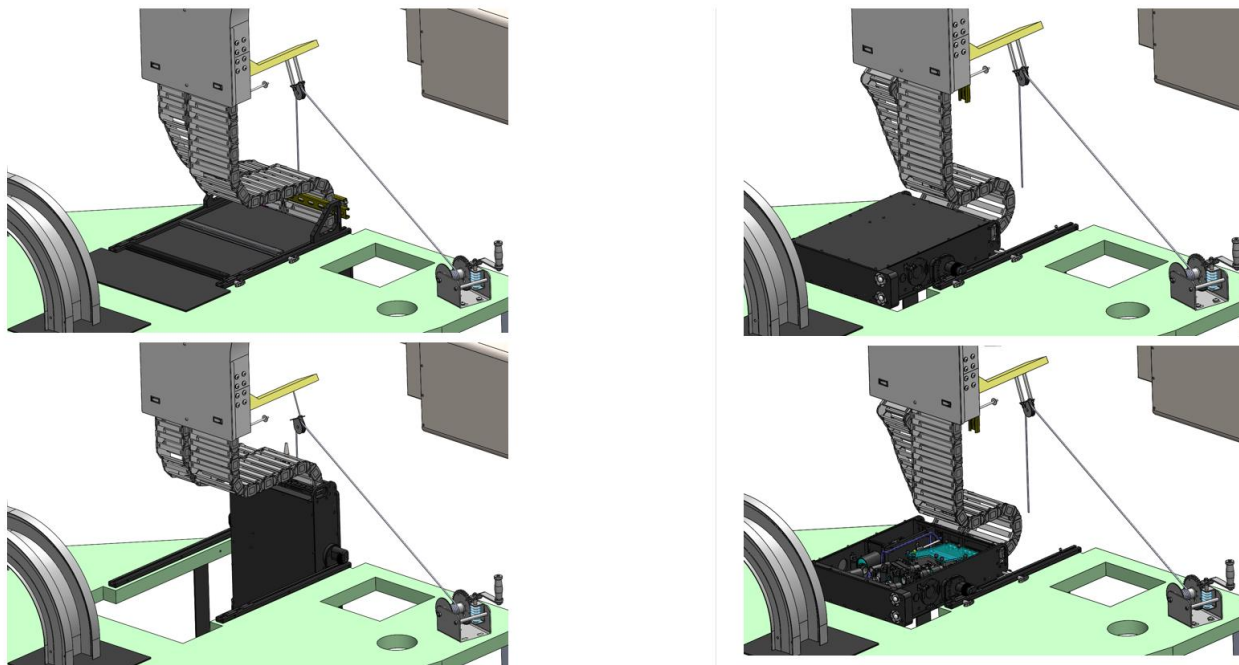


Figure 16. CAD images showing the various stages of FIU removal from the AO bench

4. FIU PERFORMANCE

The FIU was assembled and aligned at the Space Sciences Laboratory (SSL) at The University of California, Berkeley before being shipped to Hawaii for integration on the Keck I AO bench. Figure 17 shows (a) the assembled and aligned FIU in the lab at WMKO headquarters and (b) laser light injected into the Science fiber from a telescope simulator.

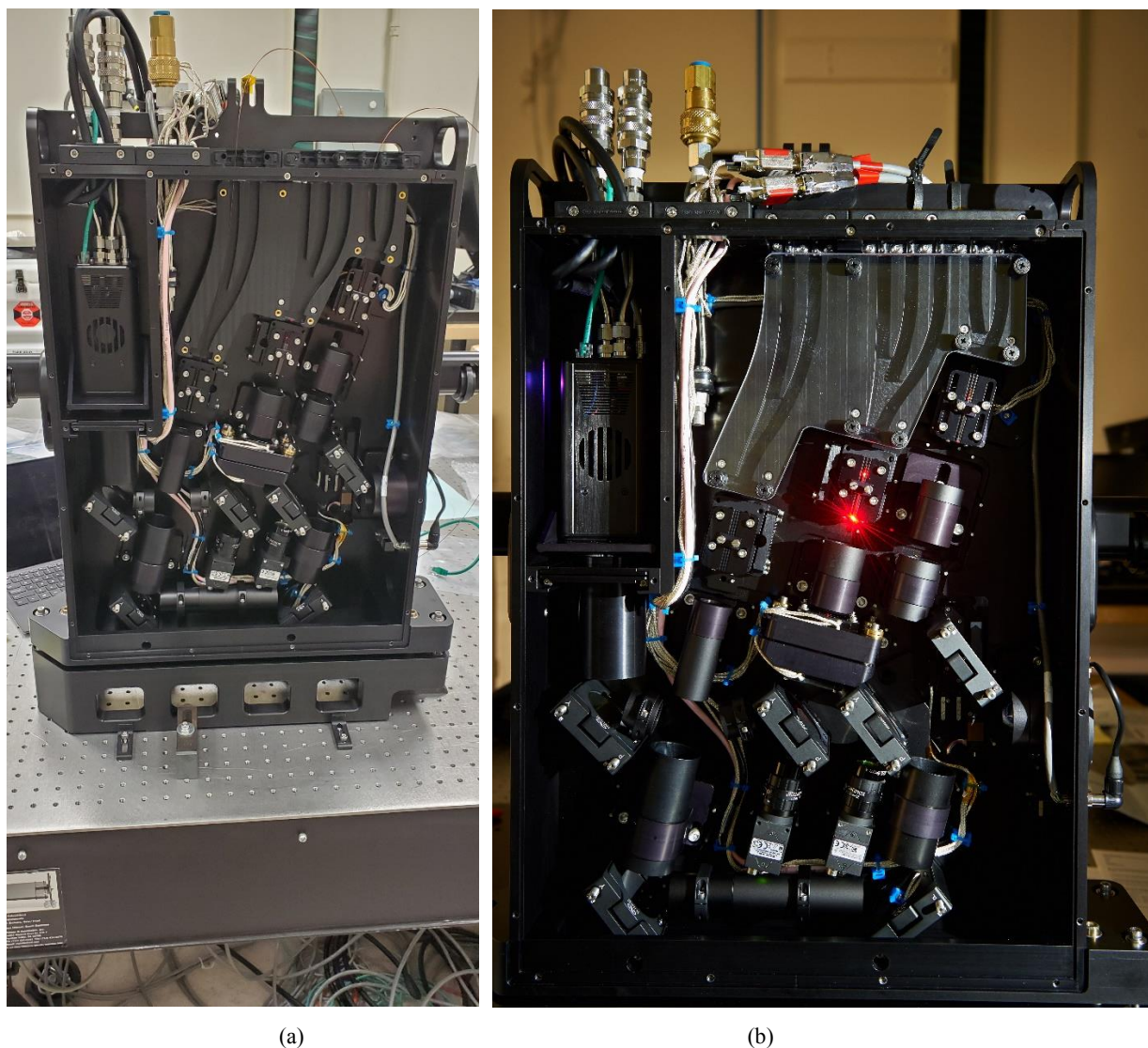


Figure 17. (a) FIU assembly in the WMKO lab and (b) FIU with laser input to science fiber

A telescope simulator and test fibers were used to verify the FIU met requirements. The lab testing of the FIU verified that the FIU met the requirements for F/#, ADC correction, spot size, fiber co-location and several others. Additional requirements verification will happen during the first on-sky commission nights. Figure 18 shows an image from the Science fiber viewing camera of a focused spot on the core of the Science test fiber.

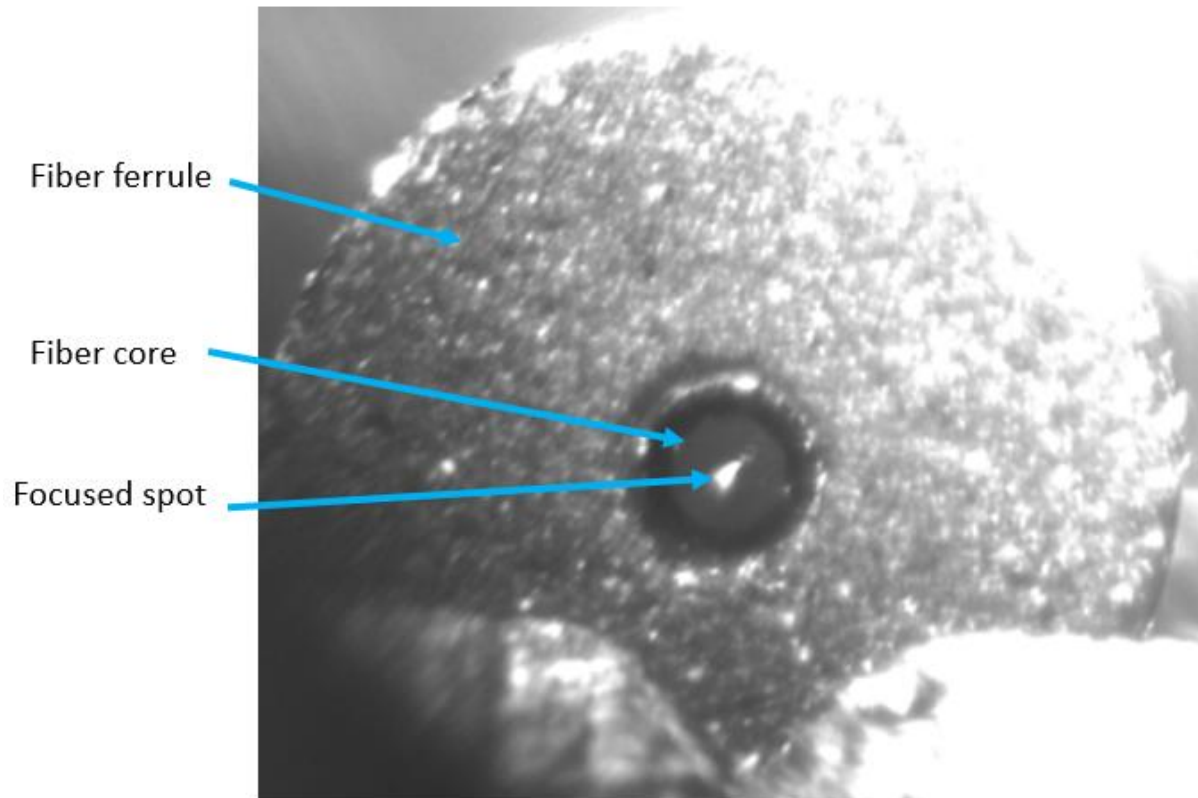


Figure 18. Image of fiber tip with light focused on the core

5. SUMMARY

A fiber injection unit (FIU) for the Keck Planet Finder (KPF) was successfully designed, assembled, and aligned in the lab. The optical design supports various optical paths while meeting all the science and mechanical requirements. The FIU mechanical layout and how it fits within the Keck I AO bench have been described in this paper. The FIU was aligned and verified to have met requirements in the lab.

The next step for the FIU, planned for Summer 2022, will be to install it on the Keck I AO bench. The fibers running from the FIU to the KPF instrument, H&K spectrograph, calibration unit and exposure meter will be installed on the telescope and into the FIU. On-sky commissioning of the FIU will begin in September 2022 in anticipation of the first on-sky night with the KPF instrument in the winter 2022.

6. ACKNOWLEDGEMENT

KPF was supported by the National Science Foundation under Grant # 2034278, by the Heising-Simons Foundation with grants 2016-042, 2018-0905, & a loan, as well as the Mt. Cuba Astronomical Foundation.

The W. M. Keck Observatory is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

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