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# The NEID precision radial velocity spectrometer: Optical design of the port adapter and ADC

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### ABSTRACT

NEID is a new extreme precision Doppler spectrometer for the WIYN telescope. It is fiber fed and employs a classical white pupil Echelle configuration. NEID has a fiber aperture of only 0.92” on sky in high-resolution mode, and its tight radial velocity error budget resulted in very stringent stability requirements for the input illumination of the spectrograph optics. Consequently, the demands on the fiber injection are challenging. In this paper, we describe the layout and optical design of the injection module, including a broadband, high image quality relay and a high-performance atmospheric dispersion corrector (ADC) across the bandwidth of 380 – 930 nm.

**Keywords:** Echelle, Doppler technique, Radial Velocities, Atmospheric Dispersion Corrector, Fiber injection, Spectrograph, Guiding, Acquisition

## 1. INTRODUCTION

Efficient and reliable injection is a key issue for any fiber-fed spectrograph. For extreme precision Doppler spectrographs, the problem is compounded by the desire not only for high coupling efficiency, but also for the most stable injection parameters possible, as changes in input illumination are propagated to the fiber exit (and hence to the spectrograph input) long before they manifest as a drop-in injection efficiency. The exoplanet radial velocity community has responded to this particular challenge with the design of fiber links with higher scrambling (to make the instrument less sensitive to changes in guiding, etc.) as well as high performance guiding systems to stabilize the injection conditions.

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NEID is the new extreme precision Doppler spectrograph for the WIYN telescope, developed as part of the NN-EXPLORE partnership between NASA and NSF and built at The Pennsylvania State University[1]. The instrument aims to achieve a ground-breaking Doppler precision of less than 30 cm/s to enable the detection and verification of rocky planets in the habitable zones around their host stars. A significant component of the instrument design is the so-called port adapter, which comprises the optical and mechanical subsystems that couple the instrument fiber to the telescope. National Optical Astronomy Observatory (NOAO) is developing the port adapter in close collaboration with the University of Wisconsin-Madison and the NEID team.

The basic functions of the port adapter optics are to

- Adapt the native focal ratio of f/6.3 of the telescope to the desired f/4 to feed our fiber
- Provide correction of atmospheric dispersion over the full spectral range (380-930nm)
- Project calibration light onto the science fibers with the same beam characteristics as the telescope
- Provide ports for guiding and target acquisition
- Allow for fast guiding correction with a tip-tilt stage

The port adapter will be mounted on a bent Cassegrain focus, using an optical bench mounted tangentially onto the telescope, folding the beam with a mirror onto the bench holding the port adapter optics and other subsystems[2].

In developing the comprehensive error budget for NEID[3], close attention was paid to the impact of the light injection parameters not only on efficiency, but also on the minimum radial velocity error that the facility can achieve. Despite significant efforts to provide state of the art scrambling[4] and to make the spectrograph optical design as insensitive to input illumination as possible[5], the science goals of the instrument demand that the stability and quality of the fiber injection meet extremely tight requirements. The three key features of the design are very good image quality (to allow optimal coupling into our 0.92” fiber), the best possible centroiding and guiding performance[6] (to achieve the best efficiency as well as the smallest guiding-induced radial velocity variation between exposures), and very good correction of atmospheric dispersion (to avoid wavelength-dependent radial velocity offsets between exposures).

In the following, we first outline the requirements that the port adapter must meet and discuss our approach to the design; we then describe the individual components of the system in greater detail, and conclude with an update on the current status of the system.

## 2. REQUIREMENTS

The top-level requirements were derived from the full radial velocity error budget, with conservative assumptions for the scrambling properties of the fiber link, as well as considerations about coupling efficiency at Kitt Peak, a site known for its very good seeing. The driving requirements are as follows:

- <0.4” FWHM point spread function (PSF)
- Total field of view: 1.5’
- Transmission: >80% at all wavelengths
- Telecentric in central field
- <100 mas residual atmospheric dispersion over 0-58 degrees zenith distance, and <200 mas down to 70 degrees
- Enable fast tip-tilt correction
- <3’ chief ray tilt with respect to the fiber axis over the full operating range of ADC and tip-tilt mirror

As it directly affects RV performance, there was a strong desire to achieve the best possible ADC performance, and a stable pupil position (i.e., constant chief ray angle with respect to the fiber).

Considering the broad wavelength range, this resulted in a challenging optical design. We conducted a trade-off study of different ways to implement the optical system. The baseline for all the design options we considered was using Amici prisms for the ADC and a beamsplitter to pick off a portion of the starlight for guiding. We examined ways to insert the ADC directly in the converging beam of the telescope before the focus in order to reduce the number of optical elements (and hence improve transmission), versus implementing it in a collimated beam; the use of reflective as well as refractive collimators; and mirror- versus parallel plate-based tip-tilt systems[7,8]. Placing the ADC in the converging beam has the advantage of fewer optical elements and much less optical power required to convert the native f/6.3 focus of the telescope to the required f/4 with which we feed the fiber. A preliminary design showed that this is technically feasible, requiring a single focal reducer, and ADC prisms with curved outer surfaces. However, fast tip-tilt control is crucial for stable injection; given the known issues of windshake at the WIYN telescope, and the fact that the required tip-tilt mechanism for either the glass plate or a mirror upstream would be necessarily large and heavy and require significant development effort, this option was deemed unnecessarily risky.

Weighing transmission, optical quality, ADC performance, feasibility of fast tip-tilt correction, and system complexity, we finally adopted the fairly conservative approach of using a refractive collimator and camera, a fast tip-tilt mirror mounted near a pupil, and Amici prism doublets mounted in collimated space for the ADC. We considered, but decided against, powered surfaces on the prisms or the fold mirror, or different angles for the two prism pairs. We use a beamsplitter cube to pick off the guiding light and use both sides of the cube to guide and to verify the correct centration of the star on the fiber in-situ. Acquisition is further aided by using so-called coherent fiber bundles mounted around the science fiber and used as metrology fiducials.

## 3. OPTICAL DESIGN

The front end of the port adapter is fed by a single flat fold mirror which picks off the light at the bent Cassegrain port and directs it to the injection optics (see Figure 1). As discussed above, we chose to place a refractive collimator after the telescope focus, which generates a real pupil in which the tip-tilt mirror is placed at 45 degrees; the beam diameter is 28.8 mm. The collimator group is followed by a pair of ADC prisms in rotation mounts, a fast tip-tilt mirror, and a beamsplitter for guiding and precisely centering the star on the fiber. The light transmitted by the beamsplitter is focused by a camera lens onto the fiber head (Figure 2). The unvignetted field of view of all the optics is 1.5 arcminutes in the focal plane. At the two reflected ports of the guiding beamsplitter, we use camera lenses identical to the science fiber camera to focus the light onto a guide camera and fiber viewing camera. A fourth of these camera lens assemblies is installed together with a flip mirror, which sits between the ADC and the tip-tilt mirror, to inject calibration light sources into the fibers. In the whole design, we strive to minimize the number of optical surfaces to keep losses at a minimum and use highly transparent glasses from a custom catalog that includes i-Line as well as regular glasses selected for their excellent transmission down to 380 nm. All surfaces throughout the design are spherical.

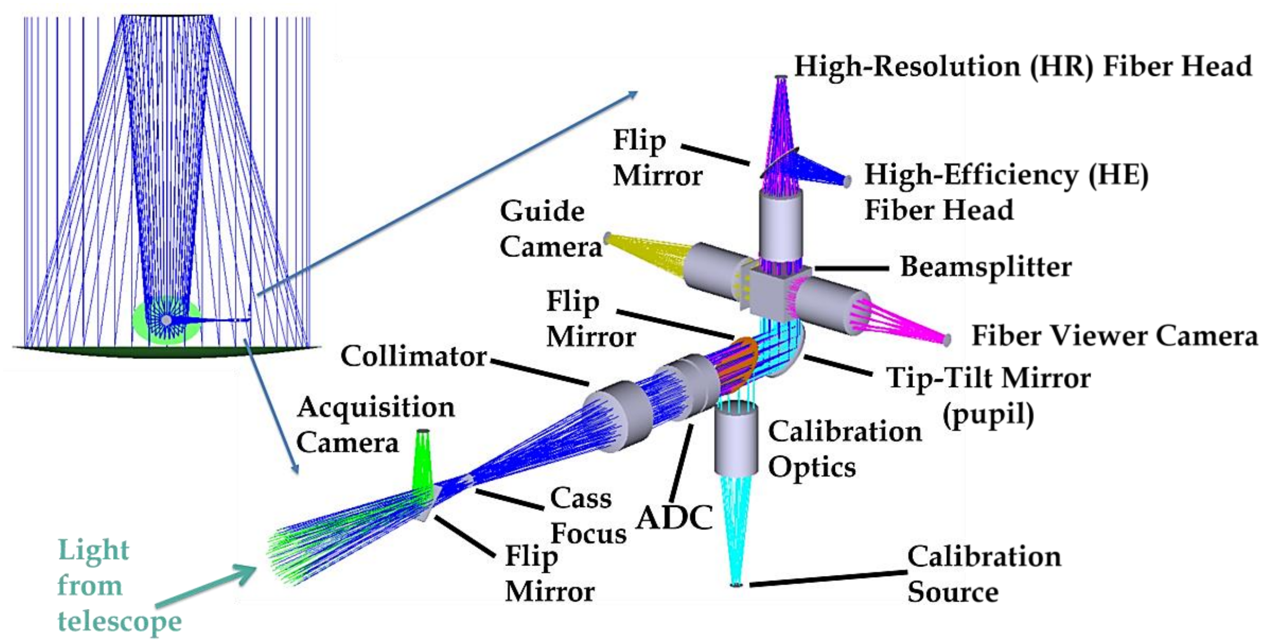


**Figure 1: Overview of the NEID port adapter optics and the location in the bent Cassegrain focus of WIYN. The port optics include a large fold mirror (not shown here) before the telescope focus to direct the light onto the port optics bench, mounted flat onto the side of the primary mirror cell.**

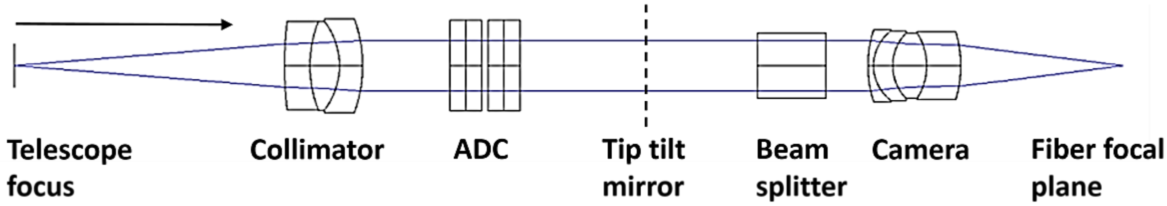


**Figure 2: Linear view of the optical system, from the f/6.3 telescope focus to the fiber focal plane. All the auxiliary ports shown in Figure 1 that follow the collimator use a quadruplet lens identical to the camera shown here on the right.**

### 3.1 Collimator

The collimator is a single triplet, using $CaF_2$ as the center element, sandwiched between two negative elements of harder glasses (BK7HT and PBL6Y). The aperture diameter is 44 mm. The collimator was optimized separately from the following optics to provide strict collimation and achromatic performance across the whole band. We have included the as-built specification of the WIYN telescope itself in the design, so the collimator delivers optimal performance together with the telescope, correcting residual spherical aberration. This has minor implications for testing, as the collimator design by itself does not deliver a perfectly flat wavefront. However, the deviation is within the dynamic range of a typical interferometer. To illustrate the design performance of the collimator, Figure 3 shows the theoretical on-axis wavefront that the collimator behind the WIYN telescope delivers.

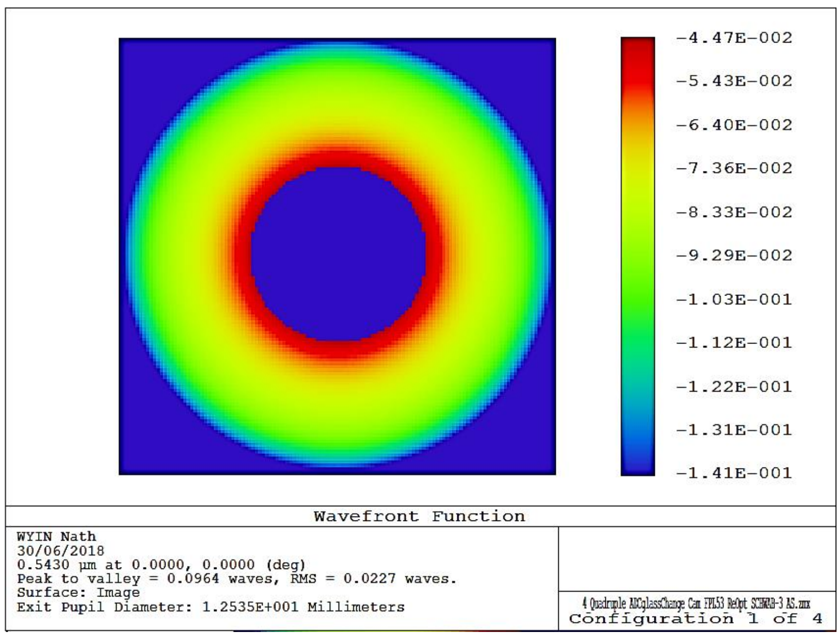


**Figure 3: Wavefront map of the collimator plus telescope, on the optical axis and for a wavelength of 543 nm.**

### 3.2 Camera

The camera design proved to be challenging, particularly in light of our desire to reduce the number of glass-air surfaces to a minimum, and the necessity of using glasses with high UV transmission. After evaluating several design options, we chose a single cemented quadruplet as the camera. The design has a diameter of 32 mm, with a focal length of 104mm working at f/4. Over the central field of 5 arcseconds, the image quality approaches the diffraction limit across the full spectral bandwidth. The lens uses a S-FPL53 element in the center, capped with two menisci (N-BAK2 and F2HT) towards the telescope and one (LF5HTi) at the exit. To avoid the complicated quadruplet design, we considered the option of using a triplet and cementing a plano-convex lens onto the exit surface of the beamsplitter cube. Somewhat surprisingly, this solution did not produce the same image quality, and would have added complexity in terms of alignment, as well as with the other exits of the beamsplitter and flip mirror. The design spot size on axis of the quadruplet solution is 0.053 arcseconds FWHM in polychromatic light; it is near diffraction limited over the central 40 arcseconds field of view in diameter (see Figure 4). To reach this level of performance, the lenses have to be fabricated and assembled to precision tolerances, in particular with respect to the wedges and centration.

It is interesting to note that the design could be made diffraction limited across the full wavelength range by reoptimizing the collimator together with the camera and allowing a very slight rebalancing of the chromatic aberrations between the two groups. This leads to a minimal deviation from strict collimation of less than f/300 across the wavelength range.

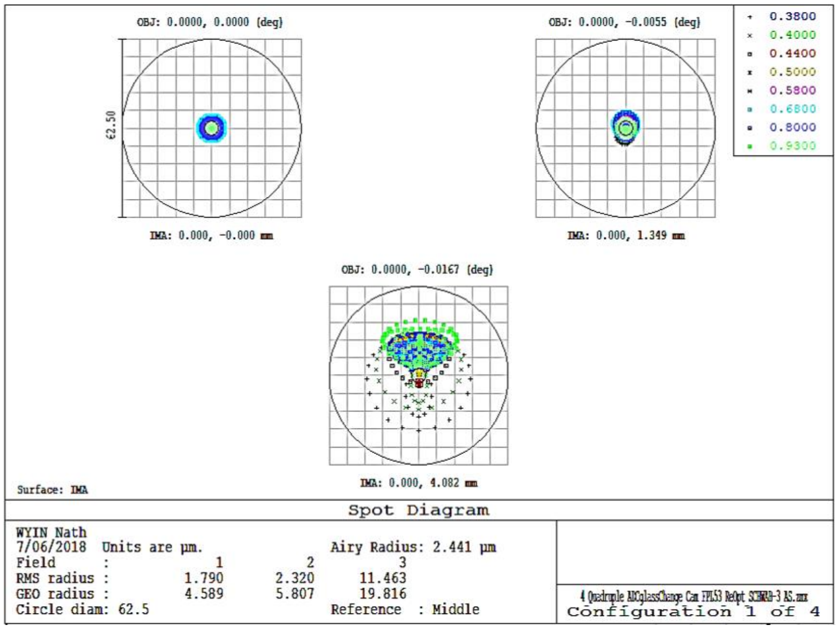


**Figure 4: Polychromatic spot diagram in the f/4 fiber focal plane, in the field center, at 20 arcseconds and a 1 arcminute radius. The large circle in each box shows the diameter of our science fiber for the high-resolution mode, with a diameter of 62.5 micron (0.92 arcseconds). The spot size on axis is 53 mas FWHM.**

### 3.3 Beamsplitter

The beamsplitter we use for guiding and acquisition is made from fused silica prisms with a 32 mm square aperture. The desired reflectivity is ~1% average across the full spectral band. A coating delivering approximately 1% everywhere between 380 and 930 nm was problematic to procure, with several vendors declining to bid; however, as we require only an average value, and can accept a coating that varies between 0% and 2%, a simple single-layer coating with a material of appropriate refractive index is a convenient and inexpensive solution. By carefully choosing the thickness of the dielectric layer (and hence the reflectivity minimum), we add another throughput boost at the blue end of the spectral range (Figure 5).

We tried to achieve the same result by using a lens cement that is not matched to the refractive index of the prism glass, effectively generating a sort of pellicle beamsplitter inside the cube. However, it proved challenging to achieve even layer thickness of the lens cement, resulting in double images, and a dielectric single-layer coating produces much more repeatable results.

The exact coating we used is a 180nm thick layer of $Al_2O_3$, which has the interference minimum at 435nm, and a maximum reflectivity of 1.25% at 830nm. As a side note, a spectrally flat coating can also be produced with a single layer, by choosing an even smaller layer thickness.

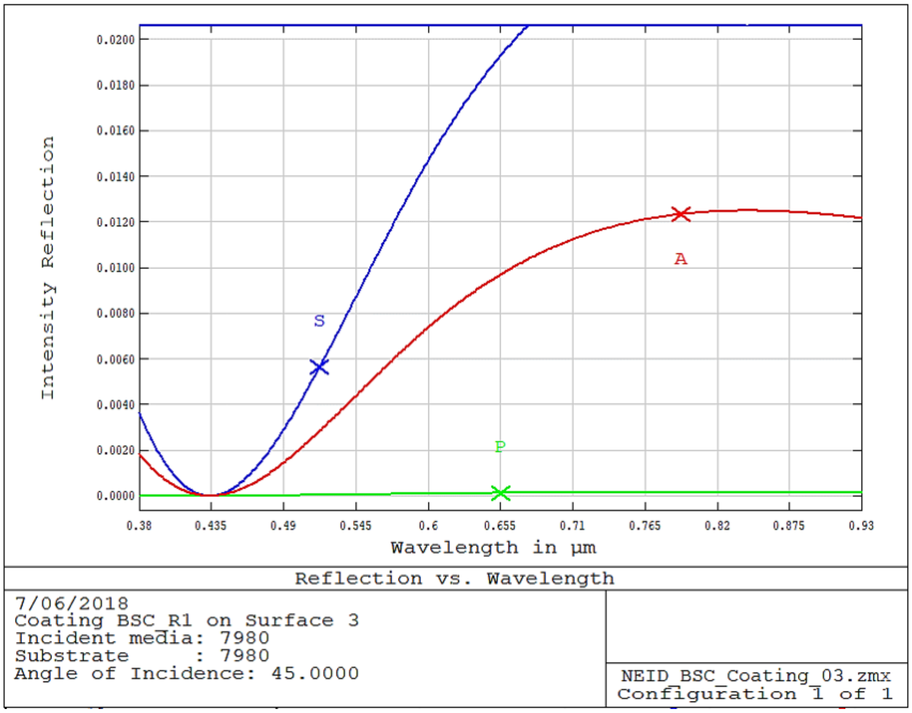


**Figure 5: Schematic reflection curve of a 180nm thick layer of $Al_2O_3$ on the inside surface of a fused silica beamsplitter cube. Curve A shows the reflectivity for unpolarized light, with a minimum at 435nm.**

### 3.4 Atmospheric Dispersion Corrector

Atmospheric dispersion can severely affect coupling efficiency into NEID's small fiber aperture of 0.92 arcseconds; this problem is compounded further by our wide wavelength range reaching down to 380nm. To address the impact on coupling efficiency, moderately good ADC performance of a few hundred milliarcseconds would be sufficient. However, another, more subtle effect of atmospheric dispersion is that the variation of the position of the photocenter of the stellar image on the fiber with wavelength and zenith angle leads prints through to the spectrograph as a wavelength-dependent spurious RV signal, because the image scrambling of the fiber is not perfect. With conservative assumptions on the scrambling properties of our fiber feed, we require the ADC to reduce the dispersion to less than 100mas peak-to-valley to hold the value assigned in our error budget. While coupling efficiency does not benefit from improving the correction beyond these levels, we ideally want even better correction to minimize the wavelength dependent RV offset to negligible levels. A third effect that is important in that context is the pupil shift that can be introduced by rotating ADC prisms, which leads to a varying angle between the chief ray and the fiber's optical axis. This also leads to a spurious RV shift, due to the variations in the illumination of the spectrograph pupil it induces. Although the design of the spectrograph's main optics was developed with sensitivity to pupil illumination variation in mind, we arrived at a requirement of less than 3 arcminutes variation, derived from simulations of the RV shift as a function of incident chief ray angle tilt.

With all the above factors considered, we chose a pair of Amici prisms in collimated space as ADC solution. The prisms are located close to a pupil and have a diameter of 40mm. We use two identical doublet prisms in AB-AB configuration. The exit surface of each doublet is angled to correct for a refractive index mismatch between the glasses we chose. An initial search produced several glass pairings with the ability to provide excellent correction of the atmospheric dispersion. The pairings we focused on all have three zero crossings for the dispersion curve, and show a residual dispersion of less than 50mas peak-to-valley at 60 degrees zenith distance. Possible combinations we investigated included (S-FPL51Y / K10), (S-FPL51Y / S-NSL3), (N-PK52A / N-BAK4) and (N-PK51 / N-BAK1). Trading between throughput, residual dispersion and the required exit surface tilt to correct for refractive index mismatch within the pair, we selected the latter. Unfortunately, during manufacturing it became apparent that even small quantities of N-PK51 were unavailable on short timescales, and we finally used the combination S-FPL53 / N-BAK1 instead, which were available immediately, to avoid further delays. This pairing has the lowest residual dispersion of all the listed options (Figure 6), however, it leaves a surface of S-FPL53 exposed to air, and requires a much larger tilt at the exit surface to keep the chief ray collinear to the optical axis. We do not expect any problems with surface degradation, considering the S-FPL53 element is sealed by hard dielectric coatings. A larger angle at the exit surface leads to a larger spread of the chief ray angle with wavelength, around a central value for which the angle is corrected. We carefully selected that wavelength such that the maximal deviation is minimized and the chief ray's variation is less than the desired 3 arcminutes for all wavelengths. The final specifications for the prisms were: the internal angle of the prism is 11.53 degrees, the external angle from N-BAK1 to air is 2.89 degrees, and the collimated beam diameter is 28.8mm, which is a compression factor of 243 with respect to the entrance aperture of the telescope.

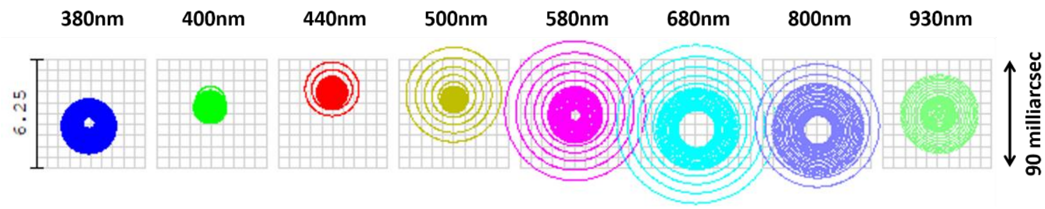


**Figure 6: Matrix view showing the spot size and relative position across the full spectral range and for a zenith angle of 60 degrees. The box size is 6.25 microns, or 90 milliarcseconds. The peak to valley residual dispersion is <30 milliarseconds.**

## 4. COATINGS

All lens surfaces as well as the ADC prisms were given hard, broadband anti-reflective coatings by Spectrum Thin Films via ion-assisted deposition to obtain good throughput over this wide spectral range. This coating was designed to meet our specification for all glasses used in one coating run. A witness sample reflectance curve is shown below (Figure 7). The port adapter mirrors were fabricated by Altechna and use their Ultra-Broadband Dielectric Mirror coating on custom sized substrates. The mirrors have excellent reflectance (Figure 8) and flatness, λ/8 at 633nm. While the port adapter includes a dry air purge, this mirror coating is robust enough to survive 100% humidity without damage. The total throughput of the whole port adapter, from the first fold mirror to the science fiber, is >81% at any wavelength.

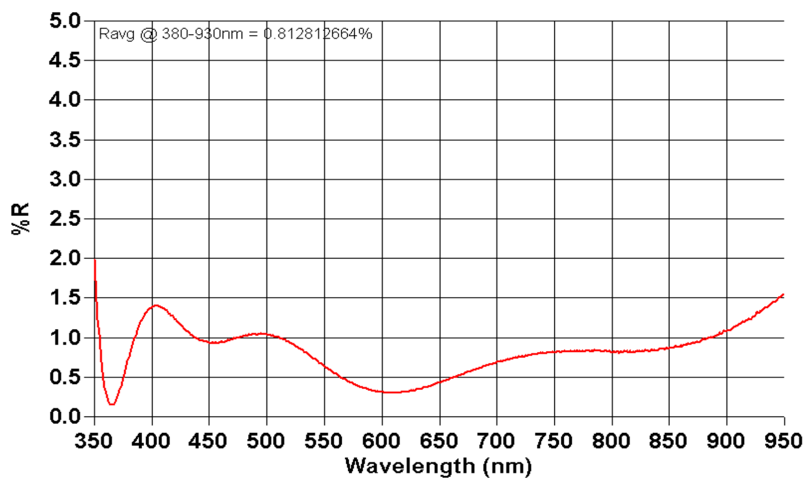


**Figure 7: Measured reflectance of AR coating on a BK7 witness sample. Due to the material difference, the witness sample behaves slightly worse than the lenses. Data by Spectrum Thin Films.**

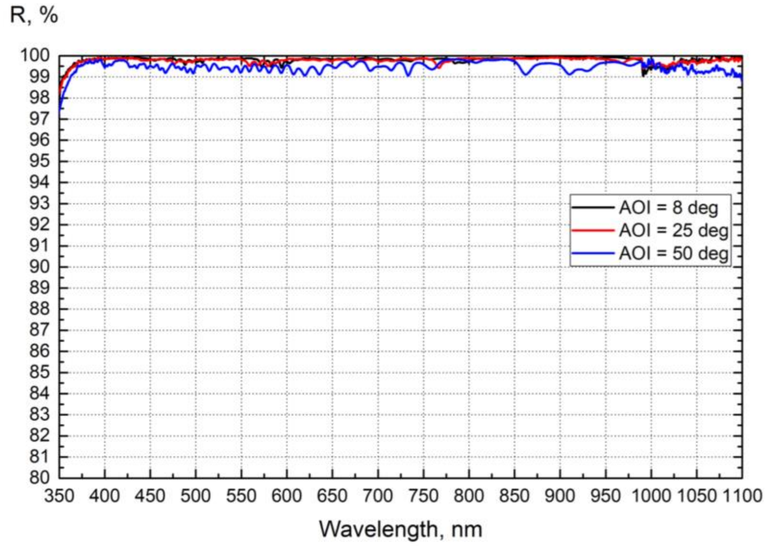


**Figure 8: Measured reflectance of the tip-tilt mirror, representative of all the port adapter mirrors. Data by Altechna.**

## 5. SUMMARY

We have developed a high performance optical design for coupling the science fibers of the NEID spectrograph to the WIYN telescope. The design includes a collimator and camera delivering an image quality that approaches the diffraction limit across the full spectral range of NEID from 380 to 930 nm. Within the collimated space, we use an ADC with a residual spectrum of less than 30 milliarcseconds at 60 degrees zenith angle, followed by a fast tip-tilt mirror for guiding corrections. A custom, low reflectivity beam splitter cube provides ports for guiding and precise acquisition of the target star. To improve throughput, we use a minimal number of glass-air surfaces, and employ a cemented triplet as collimator, and a quadruplet as camera. We have done a comprehensive tolerance analysis of the optics, which revealed tight specifications, in particular for the quadruplet. Tucson Optical Research Corporation has been selected as the vendor for the lenses and ADC prisms, and will aid NOAO staff in lens assembly. We are currently testing lens cements to ensure the cemented groups with their significant CTE mismatches, in particular between the $CaF_2$ and the mating glasses in the collimator, can withstand the temperature variations at the telescope. We had surprising problems obtaining small quantities of several glasses in the design; while we found direct replacements for all but one of them from different manufacturers, we had to redesign the ADC to replace a glass for which no replacement could be found. All the optics are currently being manufactured, and we expect to complete assembly and testing of the optics in the last quarter of 2018.

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## REFERENCES


[1] Bender, C. F., Akeson, R., Allen, L., Anderson, T. B., Bastien, F. A. et al., "The NEID precision radial velocity spectrometer: project overview and status update," Proc SPIE, Paper 10702-39, this conference (2018)

[2] Logsdon, S. E., McElwain, M. W., Gong, Q., Liang, M., Santoro, F., Schwab, C., Bender, C. F., Blake, C., Halverson, S., Hearty, F., Hunting, E., Jaehnig, K. P., Mahadevan, S., Monson, A. J., Percival, J. W., Rajagopal, J., Ramsey, L. W., Roy, A., Smith, M. P., Terrien, R. C., Timmerman, E., Willems, P., Wolf, M. J., and Wright, J. T., "The NEID precision radial velocity spectrometer: port adapter overview, requirements, and test plan," Proc. SPIE, Paper 10702-226, this conference (2018)

[3] Halverson, S., Terrien, R., Mahadevan, S., Roy, A., Bender, C. et al., "A comprehensive radial velocity error budget for next generation Doppler spectrometers", Proc. SPIE 9908, id. 99086P 20 pp. (2016)

[4] Halverson, S., Roy, A., Mahadevan, S., Ramsey, L., Levi, E., Schwab, C., Hearty, F., MacDonald, N., "An Efficient, Compact, and Versatile Fiber Double Scrambler for High Precision Radial Velocity Instruments", The Astrophysical Journal 806(1), 61 (2015)

[5] Schwab, C., Rakich, A., Gong, Q., Mahadevan, S., Halverson, S. P. et al., "Design of NEID, an extreme precision Doppler spectrograph for WIYN", Proc. SPIE 9908, id. 99087H 6 pp (2016)

[6] Percival, J. W., Gong, Q., Harbeck, D., Hunting, E., Jaehnig, K. P. et al., "The NEID precision radial velocity spectrometer: fast, first-order wavefront correction," Proc. SPIE, Paper 10702-241, this conference (2018)

[7] Tokovinin, A., Fischer, D. A., Bonati, M., Giguere, M. J., Moore, P., Schwab, C., Spronck, J. F. P., Szymkowiak, A., "CHIRON—a fiber fed spectrometer for precise radial velocities", Publ.Astron.Soc.Pac. 125(933), 1336-1347 (2013)

[8] Ihle, G., Avila, G., Kastinen, I., Lo Curto, G., Segovia, A., Sinclaire, P., Tomelleri, R., "HARPS secondary guiding", Proc. SPIE 7739 (2010)