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The NEID Port Adapter: On-Sky Performance

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ABSTRACT

Here we detail the on-sky performance of the NEID Port Adapter one year into full science operation at the WIYN 3.5m Telescope at Kitt Peak National Observatory. NEID is an optical (380-930 nm), fiber-fed, precision Doppler radial velocity system developed as part of the NASA-NSF Exoplanet Observational Research (NN-EXPLORE) partnership. The NEID Port Adapter mounts directly to a bent-Cassegrain port on the WIYN Telescope and is

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responsible for precisely and stably placing target light on the science fibers. Precision acquisition and guiding is a critical component of such extreme precision spectrographs. In this work, we describe key on-sky performance results compared to initial design requirements and error budgets. While the current Port Adapter performance is more than sufficient for the NEID system to achieve and indeed exceed its formal instrumental radial velocity precision requirements, we continue to characterize and further optimize its performance and efficiency. This enables us to obtain better NEID datasets and in some cases, improve the performance of key terms in the error budget needed for future extreme precision spectrographs with the goal of observing ExoEarths, requiring ~ 10 cm/s radial velocity measurements.

Keywords: radial velocity instrumentation; NEID; exoplanets; systems engineering

1. INTRODUCTION

The detection and characterization of exoplanets continues to be a key science priority for the astronomical community as outlined in the recent 2020 Decadal Survey on Astronomy and Astrophysics.[1] Since the discovery of the first exoplanet, 51 Pegasi b,[2] radial velocity (RV) measurements have been an important part of this detection and characterization effort, setting constraints on planetary orbits and masses. However, both instrumental and astrophysical noise (e.g. stellar jitter) have historically hampered our ability to make precise RV measurements. NEID[*] (PI Suvrath Mahadevan) is part of a new generation of extreme precision radial velocity (EPRV) spectrographs that, through concerted effort to reduce instrumental noise, reliably achieve on-sky RV measurements in the sub-m/s regime[3] and are paving the way towards the detection of ExoEarths.

Installed at the WIYN 3.5 m Telescope[†], the NEID spectrograph is a high-resolution (R$\sim$ 110,000 or R$\sim$ 70,000 in NEID's "high resolution" and "high efficiency" modes respectively), optical (380-930 nm), fiber-fed spectrograph.[4] In order to reduce instrumental noise, the spectrograph itself is isolated from the telescope in a specially-designed, thermally-isolated clean room on the ground floor of the observatory. To couple the light from the telescope to the spectrograph the NEID system also includes a"Port Adapter," which mounts directly to the WIYN telescope at a bent Cassegrain port. The Port Adapter couples stellar light to either the high resolution (HR) or high efficiency (HE) mode fiber that run through the telescope down to the spectrograph and can also couple calibration light or sunlight from NEID's solar telescope[5] to these same fibers by inserting an additional fold mirror into the beam. The reader is referred to Schwab et al. (2018)[6] for a description of the Port Adapter's optical design and to Logsdon et al. (2018)[7] for an overview of the opto-mechanical design and a discussion of the development of the Port Adapter's error budgets and test plans prior to commissioning.

The Port Adapter was delivered to WIYN in October 2019 and began commissioning in November 2019. Commissioning of the entire NEID system began in December 2019, but was paused in March 2020 due to a seven month, COVID-19 motivated observatory shutdown. NEID commissioning resumed in late-Fall 2020 and was completed in Spring 2021. While commissioning, the NEID queue team also executed several Shared Risk science programs. NEID passed its operational readiness review in Summer 2021 and the first full semester of normal, queue science operations began in August 2021. This proceedings provides a brief overview of the Port Adapter performance one year into normal NEID science operations and looks forward to areas of planned and potential future improvement as we continue to work towards optimizing the performance and efficiency of the Port Adapter to ensure NEID delivers optimal datasets.

2. PORT ADAPTER ON-SKY PERFORMANCE FOR KEY REQUIREMENTS

To achieve sub-m/s RVs on-sky and < 30 cm/s single-measurement instrumental precision, every subsystem of NEID is designed to minimize instrumental noise following a detailed RV error budget.[8] As described in more detail in Section 3 of Logsdon et al. (2018),[7] the Port Adapter requirements were derived from the NEID RV

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[*] NEID is both an acronym and a word. NEID stands for the **N**N-Explore **E**xoplanet **I**nvestigations with **D**oppler Spectroscopy and also derives from the O'odham word 'neid' meaning "to see/visualize." Kitt Peak National Observatory is located on the Tohono O'odham Reservation.

[†] The WIYN Observatory is a joint facility of the NSF's National Optical-Infrared Astronomy Research Laboratory, Indiana University, the University of Wisconsin-Madison, Pennsylvania State University, the University of Missouri, the University of California-Irvine, and Purdue University.

error budget and are primarily driven by the need for stable light injection into the science fibers. Stable light injection requires both static and dynamic precision to minimize both far- and near-field scrambling errors in the fibers.[8] Thus, to stably inject light into our fibers, we require both a static positional accuracy – placing the star or calibration light within 3 microns of the geometric center of each fiber with every acquisition – and stability – holding the star at the center of the fiber while minimizing changes in incoming beam characteristics. In practice, our need for stability sets requirements on 1) guiding precision, 2) atmospheric dispersion correction, and 3) telescope focus monitoring.

2.1 Guiding Summary

For a detailed analysis of our guiding performance, see Li et al. (this conference).[9] Here, for completeness, we briefly summarize guiding performance compared to our guiding requirement. This guiding requirement is split into two stellar brightness ranges. For bright stars ($V < 12$ mag), the stellar PSF, as measured by the root mean square (RMS) centroid motion over 1-minute intervals while guiding, must be maintained to within the central $0.05''$ (3.4 microns for a f/4 beam) of the science fiber under median seeing ($0.8''$) and wind conditions (< 15 mph). For faint targets (12 mag $< V < 16$ mag), this requirement relaxes to $0.2.''$ As detailed in Li et al. (this conference),[9] the tracking precision of the WIYN telescope alone is not sufficient to achieve this level of guiding precision. Thus, the Port Adapter is capable of “fast guiding” using an closed loop system featuring a versatile, EMCCD guide camera and a tip/tilt mirror located at the image pupil (see also Percival et al. (2018)[10] for more details on the design and lab characterization of the tip/tilt loop). In order to demonstrate long-term RV performance, NEID’s commissioning extended over several months. At the end of that commissioning period, NEID’s median guiding performance for bright targets was $0.059 \pm 0.017.''$ After a year of science operation, the current value is similar: $0.053\pm 0.015''$ (see Appendix A in Li et al. this conference). For faint targets, we were meeting our requirement at the end of our commissioning period. After a year of science operation, our faint star guiding requirement has been exceeded in some cases (see Figure 6 in Li et al.). This is likely driven by relatively slow guiding loops on very faint stars in poor seeing conditions. Though our guiding performance is a little short of the requirement for both bright and faint targets, as noted above, NEID is still meeting its RV performance requirements, and plans are in place to continue to improve guiding performance (see Section 3).

2.2 Atmospheric Dispersion Correction

In order to correct for the chromatic light loss due to atmospheric dispersion, the Port Adapter employs a pair of Amici prism doublets as an atmospheric dispersion corrector (ADC) assembly.[6] As with our guiding requirement, our atmospheric dispersion correction requirement is split into two different ranges, in this case determined by zenith distance. Our ADC performance requirement is specified as a maximum peak to valley displacement error across the NEID bandpass (380-930 nm) of $0.1''$ down to a zenith distance of $58°$ and $0.2''$ down to $71°$. Atmospheric dispersion is not only dependent on zenith distance (elevation), but also on time variable atmospheric conditions such as temperature, pressure, and humidity. Often an atmospheric model is employed to inform telescope site-specific ADC corrections and the efficacy of these atmospheric dispersion corrections has been shown to be model dependent, particularly at large zenith distances (see, for example, Pano 2014[11]). To validate and optimize our on-sky ADC performance, we directly measure residual dispersion after an initial ADC correction using a crossed Ronchi grating (i.e. dispersion in both x and y), installed on a moveable stage in collimated space in front of the guide camera, and adjust the relative prism doublet rotation angles until the dispersion is minimized following a similar methodology to Pathak et al. (2016, 2018)[12,13] (see Figure 1). From our Ronchi-grating informed optimal ADC positions, we have developed a set of seasonal empirical ADC look-up tables that automatically update the ADC position as a function of airmass (elevation) throughout each observation (see Figure 2). By updating our look-up table for seasonal variations, we can achieve a 1σ error of $0.1''$ ($0.2''$ if averaged over the year instead of seasonally), meeting our requirement at all relevant zenith distances. These look-up tables are periodically spot checked with new Ronchi grating images to verify performance.

2.3 Focus

Defocus has a direct impact on fiber coupling efficiency and, if the defocus is significant, on guiding performance as well, so real-time monitoring of the telescope focus is required for optimal performance. To that end, our

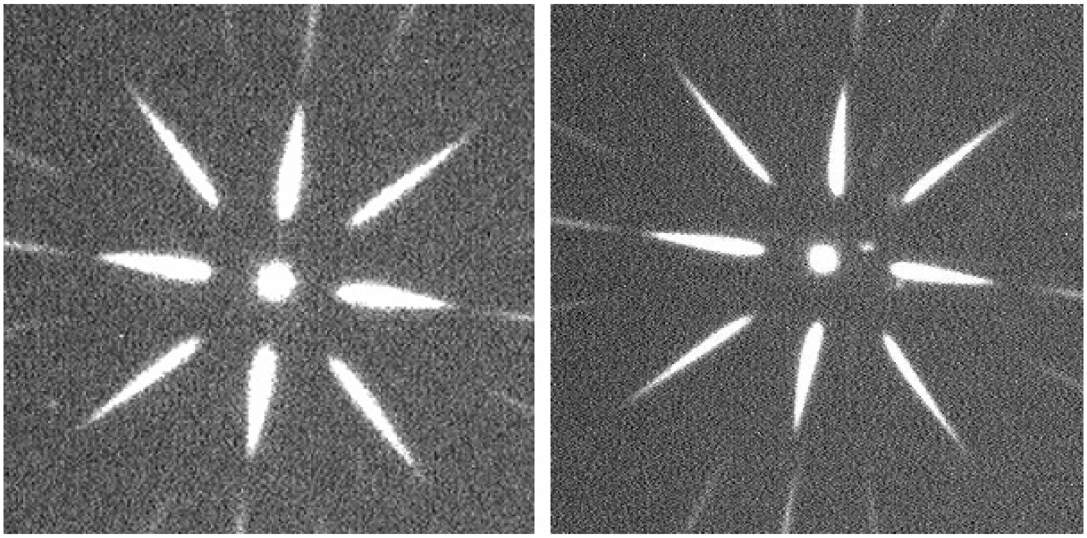

Figure 1. On-sky Ronchi grating images used to measure residual atmospheric dispersion after an ADC correction. Left: A good ADC correction with the 1st order diffraction in line with the 0th order spot. No further ADC rotation adjustment required. Right: An exaggerated, poorer correction with curvature to the right in the 1st order diffraction pattern visible, particularly in the y-axis.

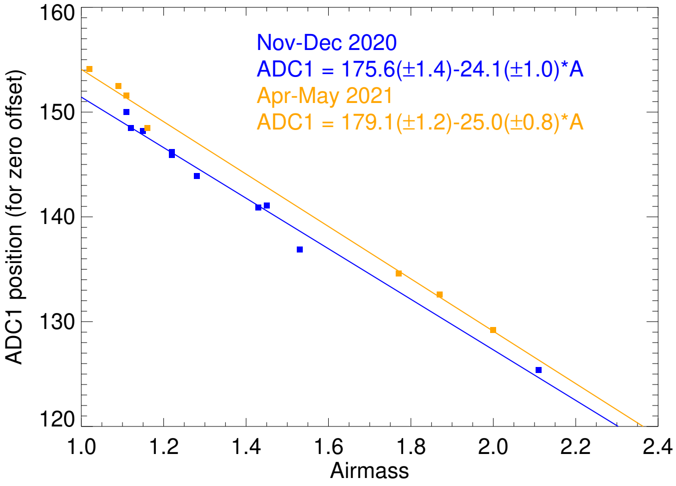

Figure 2. ADC1 position vs. Airmass as measured using NEID Guide Camera images of a Ronchi grating during two different seasons – Nov-Dec 2020 (blue) and Apr-May 2021 (golden yellow). Independently fitting each season reduces the scatter by a factor of two compared to simultaneously fitting all data.

focus requirement states that the telescope must achieve and maintain focus of the beam at the science fiber to ±30 microns under median seeing and wind conditions with V ≤16 mag stars. The WIYN Telescope has an established look-up table that automatically adjusts focus as a function of ambient temperature as well as a primary mirror thermal control loop that strives to match the mirror temperature to the ambient dome temperature. However, the primary mirror thermal system cannot always instantaneously and safely accomodate rapid or large temperature changes, such as the large drop in ambient temperature at sunset. Thus, during normal WIYN operations, it is typical practice for observers to perform manual focus sweeps and adjustments using instrument-specific cameras.

Manual focus adjustments are possible using the NEID guide camera and have the advantage that they can be done by the NEID queue observer with no additional optics or software. However, manual adjustments are time consuming and rely on regular human monitoring. Thus, in order to both provide an independent probe of how well manual guide camera focus corrections perform compared to our focus requirement and to enable the eventual implementation of a completely automated focus routine, the NEID Port Adapter includes a toroidal lens that is installed on the same moveable stage in front of the guide camera that our Ronchi grating is installed on. This toroidal lens arrived in Spring 2021, replacing a roof prism that was originally intended to provide our independent focus measurements, but was found to impede image stability. Using the toroidal lens, we can uniquely probe both intra- and outra- focus changes by measuring the ellipticity of a star as imaged on the guide camera. If the telescope is at optimal focus, a star spot will be circular, and if the telescope drifts out of focus, that same star spot becomes more elliptical in either the x or y axis (as seen from the guide camera; see Figure 3). By performing a manual focus sweep to achieve best focus, inserting the toroidal lens, and then systematically and purposefully adjusting the secondary mirror to either side of focus, we probed the sensitivity of the toroidal lens and showed that it is sensitive to 30 microns of focus change in nominal conditions (see Figure 4) and, indeed, out to 1.5″ seeing. Moreover, by monitoring the Queue Observers' manual focus adjustments with the toroidal lens and no automatic adjustment, we found that their by-eye adjustments were also sensitive to focus changes at better than 30 microns in nominal conditions, thus meeting our focus requirement in manual mode.

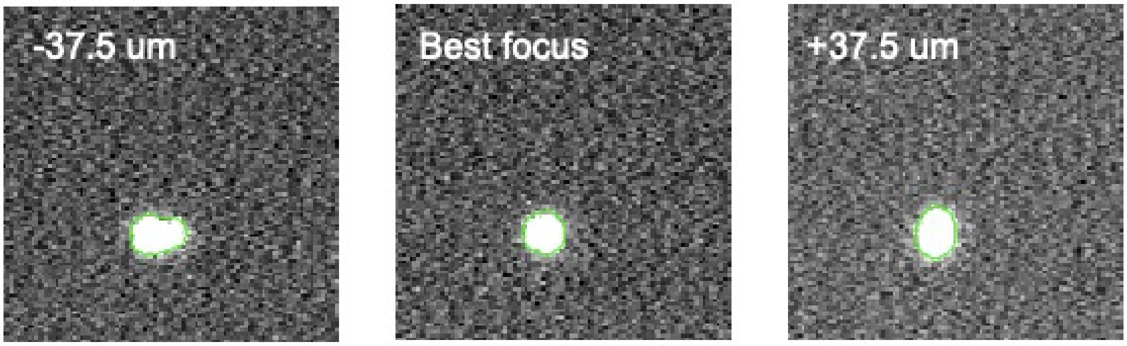

Figure 3. Left to Right: NEID guide camera images of a star at −37.5, 0, and +37.5 microns of defocus respectively. Notice that the in-focus spot is circular, whereas the out-of-focus spots are elliptical in either the x or y axis depending on whether they are intra- or outra- focus. By measuring the ellipticity while guiding and applying small corrections in a closed loop process with the telescope secondary mirror, we can automate focus monitoring of the telescope during routine NEID operations.

3. FUTURE IMPROVEMENTS

NEID has recently completed its first year of nominal science operations. During that time, the NEID Port Adapter has provided a precise and stable fiber feed that, combined with the precision of the other NEID subsystems, has allowed NEID to regularly achieve sub m/s RV precision on-sky. However, we are continually looking for ways to continue improving the performance of the Port Adapter as we strive for the best NEID data possible and look forward to the future goal of detecting ExoEarths around Sun-like stars. To that end, we have several planned and potential future upgrades. Here we focus on the upgrades that are relevant to our guiding, ADC, and focus. First off, the reader is encouraged to reference McBride et al. (this conference)[14] and Li et al. (this conference),[9] for detailed discussion of our efforts to measure, isolate, and minimize external sources of telescope vibration to improve the performance of our guiding loop. We are also actively working to update our guiding software to improve acquisition times and centroiding performance in crowded fields. We will continue to use NEID's Ronchi Grating to build high-fidelity seasonal (temperature and elevation driven) look-up tables and potentially probe more systematically for secondary effects (e.g. pressure, humidity, etc). As briefly noted above, our toroidal lens provides a powerful external probe of our focus precision, but we do not yet have a fully automated focus loop in place, though the hardware and most of the software is in place and simply needs a small

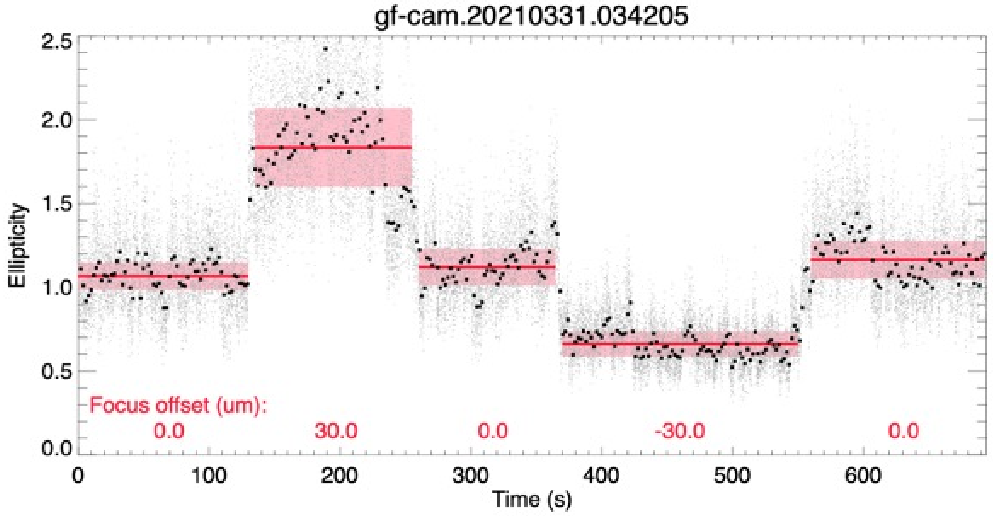

Figure 4. A plot showing spot ellipticity, as measured from guide camera images with the toroidal lens in the beam, over time during a fast guiding loop as the secondary mirror is moved into and out of focus by 30 microns in 0.7-0.8″ seeing. The grey points are ellipticity measurements made at the native fast guiding frame rate, the black points are 2s rolling averages, and the red lines and color bars indicate the average ellipticity and 1 sigma error bars at each focus offset. The toroidal lens is sensitive to 30 micron focus offsets and sufficient for independently measuring any focus drifts that exceed our requirement.

amount of additional on-sky testing and verification. We look forward to implementing these improvements and to the upcoming semesters of NEID science.

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