PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Simulations of a near-infrared precision radial velocity spectrograph for finding planets around M dwarfs

Terrien, Ryan, Bender, Chad, Mahadevan, Suvrath, Ramsey, Lawrence, Hearty, Fred, et al.

Ryan C Terrien, Chad F. Bender, Suvrath Mahadevan, Lawrence W. Ramsey, Fred R. Hearty, William D Vacca, "Simulations of a near-infrared precision radial velocity spectrograph for finding planets around M dwarfs," Proc. SPIE 8446, Ground-based and Airborne Instrumentation for Astronomy IV, 844687 (6 February 2013); doi: 10.1117/12.926478

SPIE.

Event: SPIE Astronomical Telescopes + Instrumentation, 2012, Amsterdam, Netherlands

Simulations of a near-infrared precision radial velocity spectrograph for finding planets around M dwarfs

Ryan C. Terrien,[a,b] Chad F. Bender,[a,b] Suvrath Mahadevan,[a,b] Larry Ramsey,[a,b]
Fred Hearty,[c] William D. Vacca[d]

[a]The Pennsylvania State University, University Park, PA, USA
[b]Center for Exoplanets and Habitable Worlds, University Park, PA, USA
[c]University of Virginia, Charlottesville, VA, USA
[d]SOFIA-URSA, NASA-Ames Research Center, Moffett Field, CA, USA

ABSTRACT

We describe the development of a software simulator to support development of the Habitable Zone Planet Finder Spectrograph (HPF), currently being designed to search for planets around M dwarf stars. HPF is a near infrared R 50,000 cross-dispersed radial velocity spectrograph using a HAWAII-2 RG (H2RG) NIR array, is cooled to 200K, is fiber-fed, and operates in the Y and J bands. This instrument is funded and is in the design phase, and will be commissioned on the 10m Hobby-Eberly Telescope in 2015. Our simulations process high-resolution stellar spectra through models of the instrument, detector, and a simple extraction pipeline. Our objective is to create a a fully functional simulation of the entire HPF system, which can be used to guide spectrograph design and to aid in observation planning. We describe the fundamental design of these simulations and the tests we have performed, which verify that the simulator code is stable with inclusion of simple detector effects, and is ready for expansion to account for more complex factors such as order curvature.

Keywords: Radial Velocities, M dwarfs, NIR Arrays

1. INTRODUCTION

The Penn State Habitable Zone Planet Finder (HPF) is a R$\sim$50,000 cross-dispersed NIR spectrograph for finding planets around low-mass stars, which is currently in the design phase and will be commissioned at the 10m Hobby-Eberly Telescope in 2015.[1] Mid to late type M-dwarfs ($\sim$M4 or later) are faint at visible wavelengths, and so are challenging targets for existing precision RV surveys operating in the visible. HPF and other new instruments (e.g. CARMENES[2]) will target near-infrared (NIR) wavelengths, where these stars are brighter. However, precision RV studies in the NIR are relatively new, and must contend with hurdles such as the characteristics of NIR stellar spectra, limitations of NIR instrument design, telluric contamination, and nuances of NIR detector arrays.[3] Each of these will affect the ability of HPF to meet its design goals of 3 m/s RV precision on M dwarfs. We are developing a software simulator to evaluate and mitigate these effects prior to finalizing the instrument design.

1.1 Motivation

One top-level goal for this simulator is to evaluate optical design factors such as operating the grating in either an off-Littrow configuration or with a perpendicular (gamma) tilt, which produces slit curvature. The effect of this slit curvature is primarily realized in the extraction process, and this simulator will allow a precise evaluation of the trade off between efficiency and extraction difficulty. Choices will also arise in the selection and operation of the H2RG array. Two important parameters are the number and location of bad pixels and the quantum efficiency characteristics of the detectors. Both these factors can significantly affect the efficiency of the detector, and a trade-off between them will require evaluation in the context of final RV precision.

Further author information: (Send correspondence to R. Terrien)
R. Terrien: E-mail: rct151@psu.edu

Ground-based and Airborne Instrumentation for Astronomy IV, edited by Ian S. McLean, Suzanne K. Ramsay,
Hideki Takami, Proc. of SPIE Vol. 8446, 844687 · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.926478

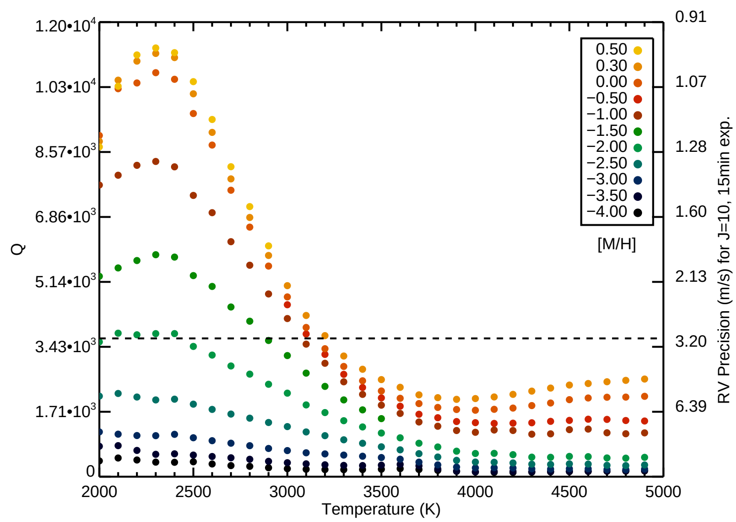

Figure 1. The Q-factor for a range of BT Settl model spectra from 2000-5000K and metallicity [M/H] from -4.0 to +0.5. The Q-factor is calculated across the combined Y and J bands. The right axis maps the Q-factor to an RV precision for a 15 minute exposure with HPF on a target with J=10. The HPF RV precision goal of 3m/s for such a target is plotted as a dashed line.

Another goal for the simulator will be to allow informed construction of the survey target list. The literature does not yet contain abundant examples of high-resolution NIR M dwarf spectra, in the context of RVs or otherwise. Using surrogates such as theoretical stellar models, and observed spectra where they exist, we can evaluate the intrinsic RV information content of M dwarfs to guide target selection and S/N requirements for our planet search survey. Moreover, different wavelength regions of stellar spectra contain different levels of RV information content. The simulator will probe the information content distribution to ensure that HPF is configured with the optimal wavelength coverage.

A commonly used parametrization of RV information content is known as the Q-factor,[4] which is essentially the weighted sum of the spectral slope. The Q-factor conveniently allows calculation of the photon-limited RV precision through

$$\delta V_{\mathrm{RMS}} = \frac{c}{Q\sqrt{N_{e^-}}}, \tag{1}$$

where δV_{RMS} is the RV precision and N_{e^-} is the total number of photoelectrons (i.e. the SNR) over the whole spectrum.

As a first step in evaluating these targets, we calculated Q-factors for a range of BT Settl model M-dwarf spectra[5] from T=2000-5000 K and with metallicity [M/H] from -4.0 to +0.5. The results are shown in Figure 1, and show that the range of targets that HPF will specifically target (M4 and later, around 3200K and cooler) have sufficient intrinsic RV information to obtain the requisite 3 m/s precision. However, this information content is reduced by telluric absorption as shown in Figure 2. HPF will be configured to leverage spectral regions with high information content and low telluric contamination, and this simulator will confirm the precise choices of which regions to target.

2. SIMULATION DESIGN

The simulator is a modular set of IDL programs–designed to simulate the entire HPF system–from starlight to extracted 1-d spectrum. The modular design allows basic tests to be performed on the overall simulator behavior, and to asses the impact on final RV precision after each incremental change or improvement. The simulator modules of can be broken down as follows:

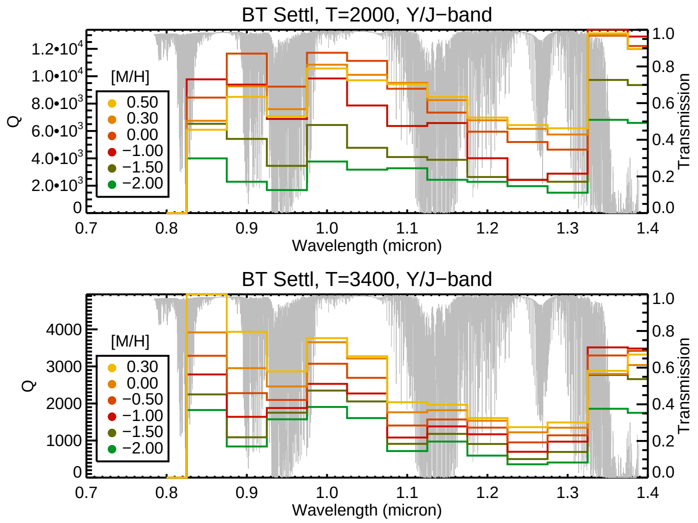

Figure 2. The Q-factors for 500-Å chunks across the Y and J bands of 3400K and 2000K BT Settl models. A telluric absorption spectrum calculated for the HET is shown in gray.

2.1 Source Model

The source input accepts 1-D, wavelength and flux calibrated, M-star spectra, either calculated model or high-resolution observed spectra. We are currently using BT Settl models for M-stars with temperatures ranging from 2000-3500 K. These models are optionally contaminated by a synthetic telluric model generated by the LBLRTM radiative transfer code[6] and customized for the McDonald Observatory.

2.2 Instrument/Optics Model

The HET is currently represented as an unobstructed 7.25 m telescope. The spectrograph is configured as a cross-dispersed echelle, with resolving power 50,000. The slit has a projected size of 0.054×0.4mm (corresponding to 3.0 pixels/resolution element on an H2RG with 18 micron pixels). Wavelength coverage illuminating the detector is from 980-1330 nm, with realistic order gaps based on a preliminary optical model. Throughput for the combined telescope and spectrograph is incorporated as a constant 0.04 (4%) in the Y & J bands.

Input from the source model is passed into the telescope and instrument model. The 1-D input spectrum is then degraded to the instrument resolution by convolution with a Gaussian kernel that has a constant width in pixels. For each order a unique kernel is defined to have a resolving power of 50,000 and sampling of 3 pixels at the center of the order. The degraded spectrum is rebinned to a new wavelength array with wavelength bins of constant size in wavelength, defined identically to the instrument kernel. The use of a pixel-based kernel and constant wavelength bins means that the effective resolving power changes in a realistic manner toward the ends of the orders.

2.3 Detector

We model the H2RG array as a self-contained IDL structure that includes a 2048 × 2048 array recording the quantized aggregate flux, as well as additional parameters that are relevant to each individual simulation, such as wavelength dependent quantum efficiency (QE); inter-pixel capacitance/cross-talk (IPC); charge persistence; bad pixel map (BPM); photon noise; dark current (DC); and read noise (RN). We interact with the model via scripts that replicate actual commands that a user might feed to a detector controller, such as: reset, non-destructive read, destructive read, etc. The detector accumulates charge through a timestep procedure, which is also controlled by the operating script. We have developed a series of generalized scripts to replicate standard observing sequences, including target and dark integrations with CDS, MCDS, and up the ramp readouts. An example CDS readout is shown in Figure 3.

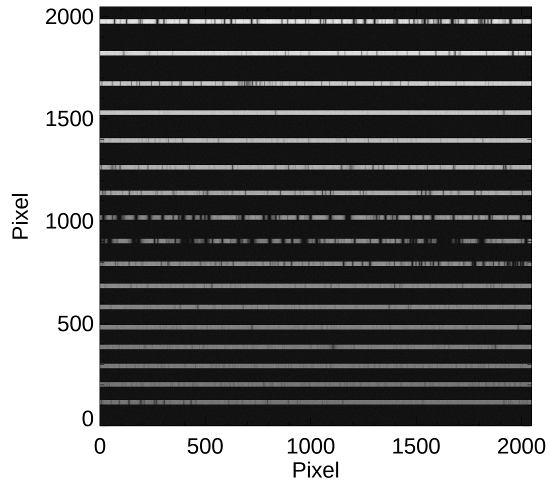

Figure 3. An example readout of the detector simulator, using a telluric-contaminated 3400K BT Settl model.

The detector characteristics QE, IPC, DC, BPM, and RN are user-adjustable input parameters, implemented as follows:

- QE uses an empirically measured functional form,[7] applied at each timestep to the incoming flux.
- IPC uses a 4 neighbor pixel bleed with coefficients drawn from a normal distribution centered on 2% with standard deviation .2% (Teledyne specification). These are applied in the readout procedure.
- Charge persistence uses an exponential decay model, implemented as a "parallel" charge array, which is combined with the actual array on readout.
- BPM uses a map with randomly selected 1% of pixels marked as bad (Teledyne goal). These yield NaN's on readout.
- DC is currently set to 0.05 e-/s (Teledyne specification), and accumulates during the timestep procedure.
- RN is currently set to 30 e- (Teledyne specification), and is added as normal noise during readout.

2.4 Extraction and CCFs

The detector model outputs 2-D images based on the source model, the telescope and instrument model, and the detector physics. These images are reconstructed into 1-D spectra using a simple sum over rows extraction with pre-defined apertures. The individual orders are continuum-normalized separately using a running maximum. An example of simulator input and the corresponding extracted spectra are shown in Figure 4. This extraction routine also implements a simple telluric correction, in which the contaminated spectrum is divided by a version of the telluric spectrum that has been processed by the simulator. Our goal is to implement a full optimal extraction-based pipeline along with order curvature, but presently a sum extraction is adequate for our current model which has straight-line orders with no uncertainty in position.

The velocity analysis is performed using a cross-correlation function (CCF) with a pre-constructed mask. The masks are constructed directly from the high-resolution BT-Settl model spectra that feed the simulator, and contain 300-400 of the strongest lines. This mask can be optionally filtered to exclude mask regions that are contaminated by telluric lines. The mask regions have widths of ±4 km/s. The mask CCF routine itself is a two-step process: the first step does a rough scan of 500 velocity shifts (of the mask points) evenly sampled between -40 and +40 km/s. The centroid of this CCF is found with an offset gaussian fit with the IDL MPFIT function. This process is then repeated for a set of 500 mask velocity shifts between ±12 km/s centered on the

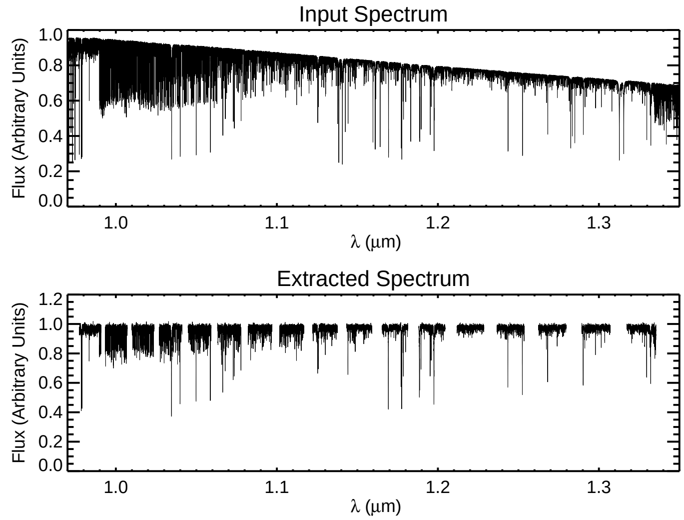

Figure 4. An example of the full input and the extracted output for a 3400K BT Settl model spectrum.

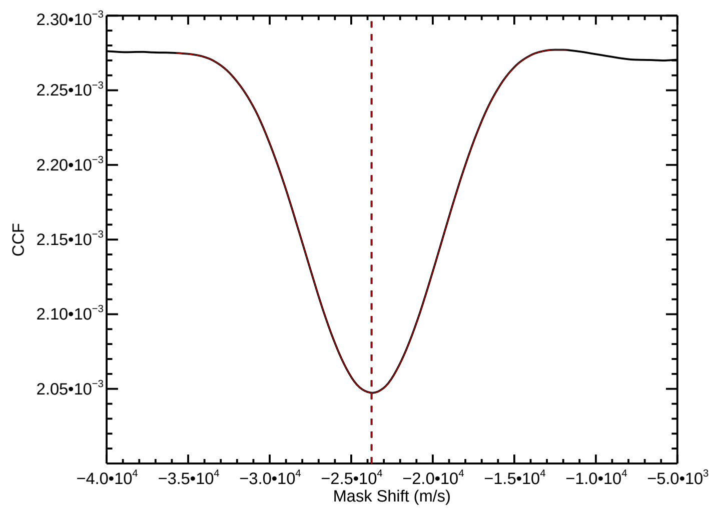

Figure 5. An example mask CCF plot for one of our simulator trials. The coarse CCF is in black and the fine CCF is in red. In this example, the centroids differ by only 50 cm/s.

centroid from the first step. The second centroid is taken as the recovered velocity. A visual example of this process is shown in Figure 5.

3. BASIC TESTS AND VERIFICATION

We have tested the intrinsic numerical precision of the simulator code using a 3400 K BT Settl model, corresponding to ∼M2, processed with the simulator. This spectrum, while useful for these tests, has less RV information content as the stars that HPF will primarily target (M4 and later). The reported precisions in this section are only for numerical tests and are not to be interpreted as what will be achievable with M4 and later targets on HPF.

First, we create a suite of 100 model spectra by applying an RV shift to the original wavelength vector. The shifts are drawn from a set of randomly generated RVs ranging from -30 to +30 km/s, roughly equivalent to the range in amplitude of the barycentric motion expected for observations of a target star carried out over a year.

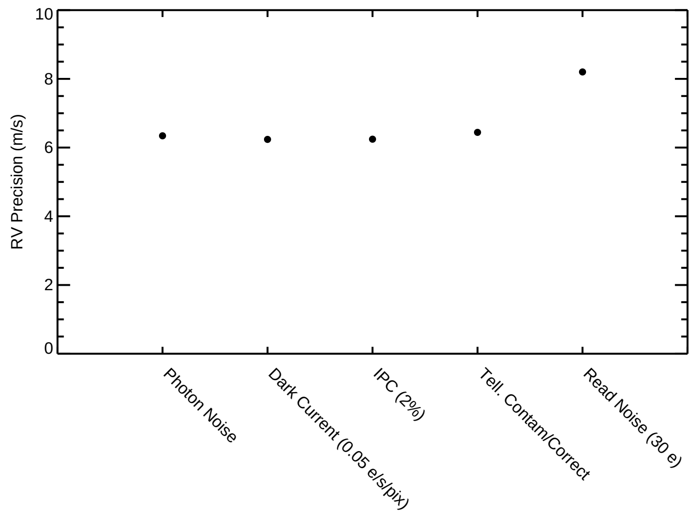

Figure 6. Tests with fundamental detector parameters. The listed parameters are tested individually. These tests used spectra with a photon-S/N of 240. All show minor effects except for read noise, which at 30 e- is a significant component of the noise at these S/N values. Since these tests use early M-type stars, they are not indicative of the achievable precision for the HPF survey itself, which will target mid-late M dwarfs.

These simulations treated the H2RG and source flux as noiseless by turning off the IPC, Persistence, BPM, DN, RN, and photon noise; in this regime we expect to recover the input RV. The standard deviation of our recovered velocities in this test are of order 1 cm/s, which is the numerical limit of our calculations.

We have also performed preliminary tests on the inclusion of the basic detector parameters described above. These tests are intended to show the validity of the implementations of various effects, and are preparation for the full-scale tests which will guide scientific and design decisions. For each test we performed 1000 trial velocity shifts (i.e. full simulator runs), and compared the measured RVs to the known input RVs. The input spectra were 3400K BT Settl models with an exposure time sufficient to produce a photon-based SN of $\sim$240 per extracted pixel. Activating these characteristics one at a time, although non-physical, tests the robustness of each implementation; Figure 6 shows the results of these tests and shows no significant numerical problems with our code. The inclusion of DC and IPC, and telluric contamination/correction (with an "ideal" telluric spectrum that corresponds perfectly to the contaminating spectrum and has no noise and no masking of heavily-absorbed regions) at the default levels negligibly affects the extracted RV precision. The RN test, however, shows an expected strong effect because the 30e-/s is a significant component of the noise.

4. CONCLUSION AND FUTURE DIRECTION

The next steps in development of the HPF simulator will include testing of QE and implementation/testing of persistence, which will be based on tests performed on the H2RG arrays used by the SDSS-III APOGEE instrument. We will also expand our model/CCF mask library to include a wider range of temperatures and metallicities, and to enable a full suite of tests with the M4 and later stars that HPF will target. We will also implement slit tilt/order curvature and an optimal extraction pipeline, as well as an alternative self-template cross-correlation RV extraction method which will be able to exploit more of the intrinsic RV information in a spectrum than the mask technique.

We have described progress on simulation development for planning the HPF survey for planets around nearby M dwarfs. These simulations are critical for optimizing the HPF design, and will also be valuable for planning and executing the M dwarf survey. As more accurate M dwarf spectra become available over the next few years, we will be able to incorporate them into our simulations to improve our survey planning.

ACKNOWLEDGMENTS

This work was partially supported by the Center for Exoplanets and Habitable Worlds, which is supported by the Pennsylvania State University, the Eberly College of Science, and the Pennsylvania Space Grant Consortium. We acknowledge support from NSF grant AST-1006676, AST-1126413, the NASA Astrobiology Institute (NAI), and PSARC.

REFERENCES

[1] Mahadevan, S., Ramsey, L., Wright, J., Endl, M., Redman, S., Bender, C., Roy, A., Zonak, S., Troupe, N., Engel, L., Sigurdsson, S., Wolszczan, A., and Zhao, B., "The habitable zone planet finder: a proposed high-resolution NIR spectrograph for the Hobby Eberly Telescope to discover low-mass exoplanets around M dwarfs," *Ground-based and Airborne Instrumentation for Astronomy III. Edited by McLean* **7735**, 227 (July 2010).

[2] Quirrenbach, A., Amado, P. J., Mandel, H., Caballero, J. A., Mundt, R., Ribas, I., Reiners, A., Abril, M., Aceituno, J., Afonso, C., Barrado y Navascues, D., Bean, J. L., Béjar, V. J. S., Becerril, S., Böhm, A., Cárdenas, M. C., Claret, A., Colomé, J., Costillo, L. P., Dreizler, S., Fernández, M., Francisco, X., Galadí, D., Garrido, R., González Hernández, J. I., Guàrdia, J., Guenther, E. W., Gutiérrez-Soto, F., Joergens, V., Hatzes, A. P., Helmling, J., Henning, T., Herrero, E., Kürster, M., Laun, W., Lenzen, R., Mall, U., Martín, E. L., Martín-Ruiz, S., Mirabet, E., Montes, D., Morales, J. C., Morales Muñoz, R., Moya, A., Naranjo, V., Rabaza, O., Ramón, A., Rebolo, R., Reffert, S., Rodler, F., Rodríguez, E., Rodríguez Trinidad, A., Rohloff, R. R., Sánchez Carrasco, M. A., Schmidt, C., Seifert, W., Setiawan, J., Solano, E., Stahl, O., Storz, C., Suárez, J. C., Thiele, U., Wagner, K., Wiedemann, G., Zapatero Osorio, M. R., Del Burgo, C., Sánchez-Blanco, E., and Xu, W., "CARMENES: Calar Alto high-resolution search for M dwarfs with exo-earths with a near-infrared Echelle spectrograph," *Ground-based and Airborne Instrumentation for Astronomy III. Edited by McLean* **7735**, 37 (July 2010).

[3] Reiners, A., Bean, J. L., Huber, K. F., Dreizler, S., Seifahrt, A., and Czesla, S., "Detecting Planets Around Very Low Mass Stars with the Radial Velocity Method," *The Astrophysical Journal* **710**, 432–443 (Feb. 2010).

[4] Bouchy, F., Pepe, F., and Queloz, D., "Fundamental photon noise limit to radial velocity measurements," *Astronomy and Astrophysics* **374**, 733–739 (Aug. 2001).

[5] Allard, F., Homeier, D., and Freytag, B., "Model Atmospheres From Very Low Mass Stars to Brown Dwarfs," *Astronomical Society of the Pacific Conference Series* **448**, 91 (Dec. 2011).

[6] Clough, S. A., Shephard, M. W., Mlawer, E. J., Delamere, J. S., Iacono, M. J., Cady-Pereira, K., Boukabara, S., and Brown, P. D., "Atmospheric radiative transfer modeling: a summary of the AER codes," *Journal of Quantitative Spectroscopy and Radiative Transfer* **91**, 233–244 (Mar. 2005).

[7] McCullough, P. R., Regan, M., Bergeron, L., and Lindsay, K., "Quantum Efficiency and Quantum Yield of an HgCdTe Infrared Sensor Array," *Publications of the Astronomical Society of the Pacific* **120**, 759–776 (July 2008).