

# Eniric: Extended NIR Information Content

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## Software

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With recent high-precision spectrographs targeting radial velocity (RV) precision at the  $10 \text{ cm s}^{-1}$  level (e.g. F. Pepe et al., 2014) in the quest to find smallest planets, it is important to understand the theoretical precision attainable in stellar spectra. *Eniric* provides a simple way to calculate the theoretical spectral quality and RV precision (i.e., information content) of synthetic and/or observed stellar spectra given vectors of wavelength and photon flux.

Written in *Python 3*, *Eniric* calculates the fundamental photon noise RV precision as formulated in Connes (1985) and F. Bouchy, Pepe, & Queloz (2001). It is an improved version of the software used in Figueira et al. (2016) for calculating the RV precision of synthetic M-dwarf spectra in the near-infrared (NIR) bands. The code was refactored, with hard-coded constraints removed, making it faster and simpler to explore a larger combination of parameters (e.g. not limited to M-dwarfs and NIR wavelengths).

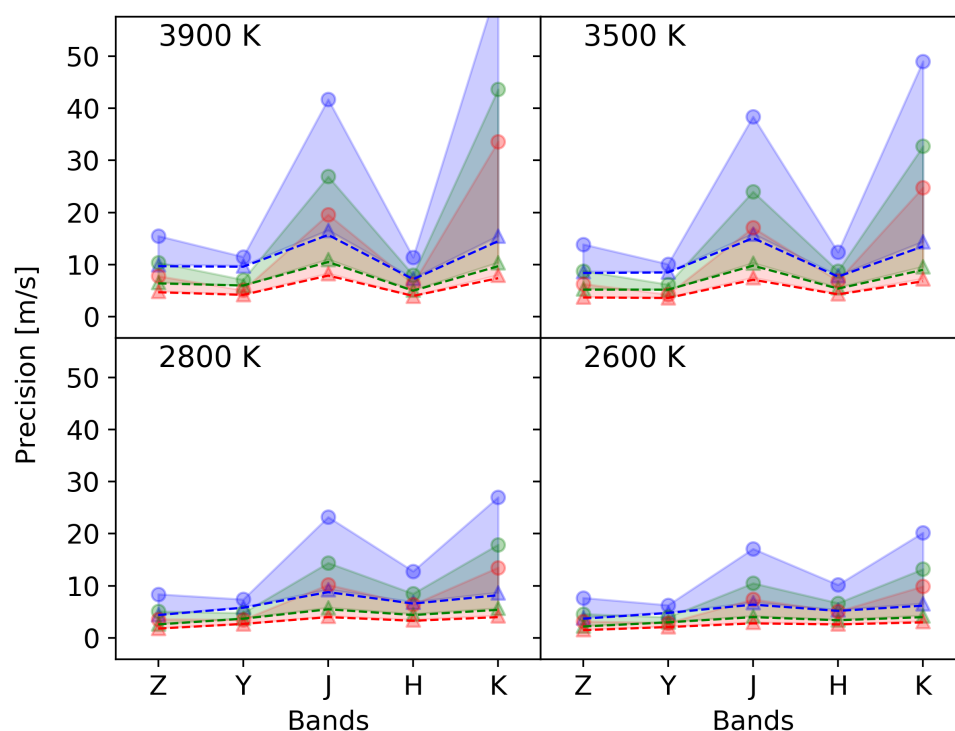
*Eniric* contains several independent functions to transform observed and synthetic spectra, such as wavelength selection, broadening, SNR normalization and to compute RV precisions.

*Eniric* performs rotational and instrumental broadening of spectra through convolution with a rotational kernel (Gray, 2005) and gaussian kernel respectively. Both kernels are wavelength dependant and do **not** require a uniformly spaced wavelength vector, unlike the convolution functions given in [PyAstronomy](#). *Eniric* utilizes the *embarrassingly parallel* nature of the convolutions (each pixel can be calculated independently of its neighbours) to compute the convolutions in parallel; the convolution results are also cached using [Joblib](#) to avoid re-computation. This improves the convolution performance but not to the level achievable by algorithms that require an equal wavelength spacing and use fixed kernels (only valid for small wavelength regions), e.g. the “fast” convolutions provided in [PyAstronomy](#).

*Eniric* enables the relative precision between synthetic spectra by allowing for normalization to a user defined signal-to-noise ratio (SNR) per pixel at a specific wavelength. Although user definable the default choice is a SNR of 100 at the center of the J-band ( $1.25 \mu\text{m}$ ) as used in Figueira et al. (2016).

The precision calculations are not limited to the large spectroscopic bands, but can also be performed on narrow wavelength slices along the entire spectrum. This allows one to explore the RV precision across the entire spectrum and perform comparison between observations and synthetic libraries (e.g. É. Artigau et al., 2018).

Extraneous information not included in the spectra (i.e., not photon noise nor line content information) can be included in the precision calculation through the use of a spectral mask. This mask can be used to indicate which spectral lines are to be included/excluded (via a binary mask) or if some spectral lines should receive more statistical weight for an external reason. For example, masks derived from an atmospheric absorption spectrum can be used to explore the treatment and correction the atmospheric absorption on the



**Figure 1:** Precision achieved with *Eniric* as a function of spectral band for stars with a rotational velocity of  $v_{\text{sin}i}=1.0 \text{ kms}^{-1}$  and temperatures 3900 K, 3500 K, 2800 K, 2600 K, corresponding to spectral types M0, M3, M6, and M9 respectively. The dashed line represents the theoretical limits imposed by the full spectrum, and the filled area represents the values within the limits set by the complete removal of atmospheric absorption regions (circles) and the perfect correction of atmospheric absorption (triangles); blue, green, and red represent the results obtained for resolutions of 60000, 80000, and 100000, respectively. The spectra were normalized to have a SNR of 100 per resolution element as measured at the center of the J-band. This is similar to Figure 1 from (Figueira et al., 2016) but with updated precision values.

RV precision (Figueira et al., 2016). A typical treatment for the Earth's atmosphere is the exclusion (via masking) of any region within  $30 \text{ km s}^{-1}$  of an atmospheric absorption line deeper than 2%, to account for Earth's barycentric motion.

The script `phoenix_precision.py` is provided to easily compute relative RV precisions for synthetic spectra from the *PHOENIX-ACES* (Husser et al., 2013) and *BT-Settl (CIFIST2011-2015)* (Baraffe, Homeier, Allard, & Chabrier, 2015) libraries. The *Grid Tools* module from *Starfish* (Czekala, Andrews, Mandel, Hogg, & Green, 2015) is used to load in the library spectra given the identifying stellar parameters i.e., temperature, logg, metallicity and alpha. The RV precision is computed under the three separate conditions of Figueira et al. (2016). These are: the full spectrum, the exclusion of regions within  $30 \text{ km s}^{-1}$  of deep telluric lines (binary mask), and the full spectrum assuming a “perfect” telluric correction in which the spectrum is recovered but with an increased variance dependant on the telluric line depth (weighted mask). The results are tabulated for all combinations of the spectral parameters, SNR, instrument resolutions, rotational velocities, pixel sampling, and wavelength choices provided to the script. An example of relative precision results is shown in Figure 1.

*Eniric* has been recently used to calculate relative RV precision of M-dwarf spectra for use in the Exposure Time Calculators of *NIRPS* (F. Bouchy et al., 2017) and *SPIRou* (É. Artigau et al., 2014), two new high-resolution NIR spectrographs. For *SPIRou* these were specifically calculated for the instruments resolution ( $R=75,000$ ) and for all stellar temperatures between 2500–4000 K. It is also currently being used to compare the theoretical precision between observed *CARMENES* spectra (A. Reiners et al., 2018) and their synthetic library counterparts.

*Eniric* is available on [GitHub](#) with documentation found in the `README.md` and at [ReadtheDocs](#) with usage examples provided as [Jupyter notebooks](#). It utilizes packages from the scientific Python stack including [NumPy](#) (T. E. Oliphant, 2015) and [SciPy](#) (Jones, Oliphant, Peterson, & others, 2001–2001--), [Matplotlib](#) (Hunter, 2007), [Pandas](#) (McKinney, 2010), and [Astropy](#) (Astropy Collaboration et al., 2013; Price-Whelan et al., 2018). It also uses [Joblib](#) (“Joblib,” n.d.), [Starfish](#) (Czekala et al., 2015), and [tqdm](#) (“Tqdm/tqdm,” n.d.).

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## References

- Artigau, É., Kouach, D., Donati, J.-F., Doyon, R., Delfosse, X., Baratchart, S., Lacombe, M., et al. (2014). SPIRou: The near-infrared spectropolarimeter/high-precision velocimeter for the Canada-France-Hawaii telescope. In *Proc.SPIE* (Vol. 9147, p. 914715). International Society for Optics and Photonics. doi:[10.1117/12.2055663](#)
- Artigau, É., Malo, L., Doyon, R., Figueira, P., Delfosse, X., & Astudillo-Defru, N. (2018). Optical and Near-infrared Radial Velocity Content of M Dwarfs: Testing Models with Barnard's Star. *The Astronomical Journal*, 155, 198. doi:[10/gddxj4](#)

- Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., Aldcroft, T., et al. (2013). Astropy: A community Python package for astronomy, *558*, A33. doi:[10.1051/0004-6361/201322068](https://doi.org/10.1051/0004-6361/201322068)
- Baraffe, I., Homeier, D., Allard, F., & Chabrier, G. (2015). New evolutionary models for pre-main sequence and main sequence low-mass stars down to the hydrogen-burning limit. *Astronomy and Astrophysics*, *577*, A42. doi:[10/gfdcsn](https://doi.org/10/gfdcsn)
- Bouchy, F., Doyon, R., Artigau, É., Melo, C., Hernandez, O., Wildi, F., Delfosse, X., et al. (2017). Near-Infrared Planet Searcher to Join HARPS on the ESO 3.6-metre Telescope. *The Messenger*, *169*, 21–27. doi:[10/gfdcsz](https://doi.org/10/gfdcsz)
- Bouchy, F., Pepe, F., & Queloz, D. (2001). Fundamental photon noise limit to radial velocity measurements. *Astronomy and Astrophysics*, *374*(2), 733–739. doi:[10/cqg52h](https://doi.org/10/cqg52h)
- Connes, P. (1985). Absolute astronomical accelerometry. *Astrophysics and Space Science*, *110*(2), 211–255. doi:[10/dk66bp](https://doi.org/10/dk66bp)
- Czekala, I., Andrews, S. M., Mandel, K. S., Hogg, D. W., & Green, G. M. (2015). Constructing A Flexible Likelihood Function For Spectroscopic Inference. *The Astrophysical Journal*, *812*(2), 128. doi:[10/gfdcsp](https://doi.org/10/gfdcsp)
- Figueira, P., Adibekyan, V. Z., Oshagh, M., Neal, J. J., Rojas-Ayala, B., Lovis, C., Melo, C., et al. (2016). Radial velocity information content of M dwarf spectra in the near-infrared. *Astronomy and Astrophysics*, *586*, A101. doi:[10/gfdcsf](https://doi.org/10/gfdcsf)
- Gray, D. F. (2005). *The Observation and Analysis of Stellar Photospheres* (3rd ed.). Cambridge University Press. doi:[10.1017/CBO9781316036570](https://doi.org/10.1017/CBO9781316036570)
- Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *Computing In Science & Engineering*, *9*(3), 90–95. doi:[10.1109/MCSE.2007.55](https://doi.org/10.1109/MCSE.2007.55)
- Husser, T.-O., von Berg, S. W., Dreizler, S., Homeier, D., Reiners, A., Barman, T., & Hauschildt, P. H. (2013). A new extensive library of PHOENIX stellar atmospheres and synthetic spectra. *Astronomy and Astrophysics*, *553*, A6. doi:[10/gfdcsf](https://doi.org/10/gfdcsf)
- Joblib: Running Python functions as pipeline jobs — joblib 0.13.2 documentation. (n.d.). Retrieved February 19, 2019, from <https://joblib.readthedocs.io/en/latest/#>
- Jones, E., Oliphant, T., Peterson, P., & others. (2001–2001--). SciPy: Open source scientific tools for Python. Retrieved from <http://www.scipy.org/>
- McKinney, W. (2010). Data Structures for Statistical Computing in Python. In (pp. 51–56). Presented at the Proceedings of the 9th Python in Science Conference. Retrieved from <http://conference.scipy.org/proceedings/scipy2010/mckinney.html>
- Oliphant, T. E. (2015). *Guide to NumPy* (2nd ed.). USA: CreateSpace Independent Publishing Platform.
- Pepe, F., Molaro, P., Cristiani, S., Rebolo, R., Santos, N. C., Dekker, H., Mégevand, D., et al. (2014). ESPRESSO: The next European exoplanet hunter. *Astronomische Nachrichten*, *335*(1), 8. doi:[12.1002/asna.201312004](https://doi.org/12.1002/asna.201312004)
- Price-Whelan, A. M., Sipőcz, B. M., Günther, H. M., Lim, P. L., Crawford, S. M., Conseil, S., Shupe, D. L., et al. (2018). The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package, *156*, 123. doi:[10.3847/1538-3881/aabc4f](https://doi.org/10.3847/1538-3881/aabc4f)
- Reiners, A., Zechmeister, M., Caballero, J. A., Ribas, I., Morales, J. C., Jeffers, S. V., Schöfer, P., et al. (2018). The CARMENES search for exoplanets around M dwarfs. High-resolution optical and near-infrared spectroscopy of 324 survey stars. *Astronomy and Astrophysics*, *612*, A49. doi:[10/gdmwfg](https://doi.org/10/gdmwfg)
- Tqdm/tqdm: Tqdm v4.31.1 stable | Zenodo. (n.d.). Retrieved February 19, 2019, from <https://zenodo.org/record/2561403#.XGtaB7iYZdg>