

Bachelor Project in Physics

Jakob Harteg, wmc573

June 2022, University of Copenhagen

1 Introduction

The radial velocity method was used to discover the first exoplanets and continues to be one of the main methods for the discovery and characterization exoplanets [3]. With new extreme-precision spectrographs such as EXPRES, we are slowly approaching the precision necessary for the discovery of Earth-sized planets around Sun-like stars. To achieve such precision however, it is necessary to understand and mitigate many effects. This includes the movement of the Earth relative to the center of mass of the solar system (bary-centric corrections), light scattering in the Earth's atmosphere (tellurics), light scattering inside the spectrograph (blaze). Furthermore a general wavelength calibration of the spectrograph data is needed, the quality of which of course directly influences the precision of the final radial velocities that can be obtained. To perform this calibration on the EXPRES spectrograph a laser frequency comb (LFC) is used. The full procedure from raw data to results, also spoken of as the pipeline, is extensive and described in more detail in [6]. This project mainly revolves around performing the calibration and subsequent computation of the radial velocities, and will ignore remaining parts of the pipeline by using already corrected data. The aim of this project is method exploration and development, and not exoplanet detection.

2 Theory

2.1 Radial velocity method for exoplanet detection

The radial velocity method is one of the few current methods of detecting exoplanets. Two celestial bodies in orbit around each other, such as a star and a planet, orbit their common center of mass (barycenter). This means that the star, although typically much more massive than the planet, is also in movement relative to an outside observer. The larger the planet is, compared to the star, the larger this movement will be. For now, it is not possible to directly observe exoplanets. One way of indirect detection however is thus measuring the movement of the star. We can measure the relative movement of a star through the doppler effect; the electromagnetic spectrum of the star observed on Earth will be blue shifted when the star is moving toward us and red shifted when moving away. The potential indirect signal of a planet will thus consist of a periodic doppler shift in the spectrum of the host star. For this method in general, several years of data collection is necessary. One should at least have one full orbit of observational data, and, to decrease statistical uncertainties, several orbits is preferential.

A large planet like Jupiter induces a radial velocity (RV) in the Sun of about 12.7 m/s when observed in its plane of orbit. While a small one like Earth only induces an RV of about 9 cm/s. (p. 29, [3]). In the hunt for detecting Earth-sized planets around Sun-like stars, a new generation of spectrographs are appearing called extreme-precision radial velocity (EPRV) spectrographs. The EXtreme PREcision Spectrograph (EXPRES) is one such spectrograph, data from which this project is based on.

todo: Possibly describe the RV calculation in more [detail](#) and compute Earth K.

2.2 Description of the instrument

The EXtreme PREcision Spectrograph or EXPRES is situated at the Lowell Observatory's 4.3m Lowell Discovery Telescope (LDT) near Flagstaff, Arizona, U.S.A. The LDT allows for up to 280 partial nights of observation per year.

Like in many spectrographs, at the heart of EXPRES is a Charge Coupled Device (CCD). A CCD is a silicon-based multi-channel photon detector consisting of a large number of small light-sensitive areas called pixels. The CCD is EXPRES an STA1600LN CCD backside illuminated image sensor with a $10,560 \times 10,560$ array containing $9\mu\text{m} \times 9\mu\text{m}$ pixels. When a photon hits a pixel it is converted into a charge, and each pixel can thus supply independent measurements. Since a one dimensional sensor would be impractical, EXPRES is constructed in such a way, that it wrap the spectrum inside the CDD, meaning that the spectrum starts in the top row of the sensor, and continues in the second row. Short wavelengths are thus to be found in the top of the CCD and long wavelengths at the bottom. [4]. **todo:** maybe add illustration

EXPRES is housed in a vacuum enclosure to minimize changes in temperature and pressure, which can otherwise cause the spectra to change position on the CCD and thus lead to errors in the RV measurements.

Wavelength calibrations are performed with the use of a Laser Frequency Comb (LFC), produced by Menlo Systems, which is a laser source whose spectrum consists of a series of discrete, equally spaced frequency lines. The LFC however also needs calibration for which a Thorium Argon (ThAr) lamp with known frequencies is used.

Barycentric corrections are derived from the EXPRES exposure-meter, which is essentially a smaller, less precise spectrograph. Described in detail in [1]. EXPRES as a whole is described in technical detail in [2].

2.3 Description of the data

EXPRES data are meant to serve as an example of the data being produced by next-generation spectrographs.

The data used in this project was supplied by Lily Zhao and is by no means raw data, but data that has already gone through a lot of processing.

For development of RV extraction method, observations from four stars were used:

- HD 101501 (45 observations, 22 nights, Feb. 10, 2019 - Nov. 26, 2020)
- HD 26965 (114 observations, 37 nights, Aug. 20, 2019 - Nov. 27, 2020)
- HD 10700 (174 observations, 34 nights, Aug. 15, 2019 - Nov. 27, 2020)
- HD 34411 (188 observations, 58 nights, Oct. 08, 2019 - Nov. 27, 2020)

todo: For development of a LFC calibration method data from was used

2.3.1 Data structure

The data used in this project consists of already packaged FITS (Flexible Image Transport System) files, which is a portable file standard widely used in the astronomy community to store images and tables. There is a FITS file for each observation, containing a variety of measurements for each pixel on the CCD. The rows of the CCD data are referred to as orders. There are 86 orders each of which has values from 7920 pixels. Drawing a coordinate system on the CCD, we are thus moving through pixels as we go along the x-axis and through orders as we go along the y-axis.

This would give the CCD the very elongated dimensions of 86×7920 , but as mentioned earlier, the CCD is actually square. The orders however hit the CCD at an angle and for this reason *order tracing* is necessary. Order tracing reduces each order from 2d array to a 1d array, which means the final image comes out much shorter in the vertical/order dimension. Described in detail in section 3.2.1 of [6].

Furthermore, the CCD is not equally sensitive everywhere, and there are areas along the edges that are deemed unuseful. The data comes with a mask which shows which pixels are should be used.

To perform the calibration the following variables are used: `spectrum`, `uncertainty`, `wavelength` and `continuum`. To perform the RV extraction on the pre-calibrated data the following variables are used: `bary_excalbur`, `excalibur_mask`, `spectrum`, `uncertainty` and `continuum`.

2.3.2 Noise and errors

2.3.3 Correction: Scatter / blaze

2.3.4 Correction: Tellurics

2.3.5 Correction: Bary centric corrections

3 Data Analysis

3.1 Calibration

Finding peaks and comparing to equation frequencies

3.1.1 Comparison of poly fit with interpolation

(Also specify run times)

3.2 RV extraction

- Hist fit / cross-correlation
 - Order approach
 - Feature approach
 - (Run times)
- Extracting relative radial velocities from over constraint system (Matrix reduction to circumvent correlations)
- Future ideas
 - Auto encoder

4 Results

5 Discussion

6 Conclusion

References

- [1] Ryan T Blackman, JM Joel Ong, and Debra A Fischer. The measured impact of chromatic atmospheric effects on barycentric corrections: Results from the extreme precision spectrograph. *The Astronomical Journal*, 158(1):40, 2019.
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- [3] Christophe Lovis, Debra Fischer, et al. Radial velocity techniques for exoplanets. *Exoplanets*, pages 27–53, 2010.
- [4] n. a. What is a ccd detector?, n.d.
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- [6] Ryan R Petersburg, JM Joel Ong, Lily L Zhao, Ryan T Blackman, John M Brewer, Lars A Buchhave, Samuel HC Cabot, Allen B Davis, Colby A Jurgenson, Christopher Leet, et al. An extreme-precision radial-velocity pipeline: First radial velocities from expres. *The Astronomical Journal*, 159(5):187, 2020.