

# Designing the First Deployable Infrared Astrocomb and Enabling the Search for Nearby Habitable Worlds

Project Dates: Dec 2015 – March 2018

The search for and subsequent study of exoplanets around stars beyond our Sun is driven by profound scientific questions: Are Earth and our solar system unique? What is the mass-radius relationship of exoplanets? Is there life elsewhere and what are the conditions under which it evolves? These are questions that the newly deployed Habitable-zone Planet Finding (HPF) Spectrograph and its astrocomb calibrator hope to help answer. Installed at the 10m Hobby-Eberly telescope earlier this year, the duo has begun searching stars close to earth, trying to detect periodic radial velocity (RV) Doppler shifts in the star-light that can provide evidence of unseen orbiting planets and information on their mass. This system is unique in that it is searching the near infrared region of the spectrum, allowing it to study M-Dwarfs, a class of stars which make up 70% of those closest to earth. Although the RV technique has been used extensively by other spectrographs (typically in the visible region of the spectrum), and has lead to the detection of hundreds of planets, the schemes have lacked the sensitivity required to identify earth analogs. HPF is the first spectrograph capable of reaching the required precision, thanks to a real-time laser-calibration source, known as an ‘astrocomb’, that I developed with colleagues at NIST over the last two years.

I led the research, design, and engineering of the laser-calibration system (astrocomb), a role which required me to perform hands-on basic scientific research, budgeting, optical-, electrical-, and mechanical-design, and the system engineering required for integration with HPF and its eventual deployment at the McDonald Observatory. The project deliverable was clear, the spectrograph required a multi-color laser source, known as an optical frequency comb, which is made up of an equidistant grid of laser lines spanning the full optical bandwidth of the spectrographs operating range (800-1300 nm). The grid of laser lines would provide a precise realtime frequency ruler that the starlight could be referenced against to calibrate out the instrumental drifts in the telescope and allow measurement of RV signatures below the noise floor of the instrument. What was not clear to the scientific community at the time, was the approach to generate such a frequency spectrum. Although frequency combs have been recognized as critical for precision RV astronomical spectrographs, the desired parameters for most proposed ‘astrocombs’ are not well matched to the capabilities of traditional comb technology, making the development beyond the laboratory proof-of-concept stage a challenging realization. The most demanding constraints, are the combination of broad spectral coverage, 10+ GHz spacing between laser lines, and operational robustness in a telescope environment. In HPF’s case, this meant generating 5000+ stabilized lines exactly spaced by 30 GHz with each one having equal power. The solution required a novel approach to the problem.

By adapting a less-traditional electro-optic method to comb generation, a technique I studied at Purdue, and leveraging that alongside custom fabricated non-linear waveguides fabricated at NIST, we were able to produce a robust spectrum simultaneously meeting the line-spacing and spectral coverage requirements. In fact, our design has the broadest bandwidth and largest frequency spacing out of any demonstrated astrocomb. Then leveraging again lessons learned during my time at Purdue, I designed a custom optical pulse shaper, which provided programmable and dynamic equalization of the power across all the comb lines. To insure the comb lines did not drift, we locked them to a GPS-disciplined atomic frequency reference which provided traceable short and longterm frequency stability. Finally, we fully-engineered the system for remote deployment which involved custom fabrication of devices, and software development to run and monitor the system remotely.

The astrocomb was deployed and installed in February of this year, and has already been used to calibrate the HPF spectrograph to a precision of 10 cm/s, a record in this wavelength regime. The results from this design move beyond an isolated technology demonstration and open up a new wavelength regime for astronomers for the first time. The coupled HPF and frequency comb on one of the largest optical telescopes in the world is the working model for future precision near-infrared RV spectroscopy and charts a path to discovery and characterization of Earth-mass planets in the Habitable Zones of the nearest stars. More broadly, the techniques we developed to generate a broadband high-repetition rate optical frequency comb are applicable to other areas in science and engineering from precision timing to enabling the next generation high-speed optical communications systems.

This was a project I feel truly lucky to have been a part of. I was able to employ techniques from Purdue that were originally aimed for applications in optical communications, and RF-photonics, and pair those with new technology developed at NIST to provide a unique and novel design solution to a challenging problem. This project left me with a optimistic outlook for the future of integrated photonics, opened my eyes to the wonder of precision astronomy and the search for other life, and ingrained in me the true power of cross-disciplinary research.

Presentations on design work:

Andrew J. Metcalf, et al, “30 GHz Frequency Comb Spanning 160 THz in the Near-Infrared”, CLEO, 2017, FTu3D.7

Andrew J. Metcalf, et al, “Infrared Astronomical Spectroscopy for Radial Velocity Measurements with 10 cm/s Precision”, CLEO 2018, jTh5A **postdeadline**

Andrew J. Metcalf, “Tailoring Frequency Combs for Astronomical Spectrograph Calibration”, CEHW Seminar Series, Penn State Univ., March 27<sup>th</sup> 2017

Two journal manuscripts, intended for peer-review, are currently in preparation.