limited by the absolute accuracy of the Rb frequency reference used for these measurements. This result is in good agreement with the ThAr calibration. The absolute frequencies of all other calibration lines from the blue astro-comb were then determined simply by counting comb teeth. Absolute frequency errors associated with finite side mode suppression described above as well as source-comb line-to-line intensity variation and etaloning in the FPC substrates [22] were also < 0.001 GHz for all spectral features used, thus providing an absolute calibration of the TRES spectrograph across the full calibration spectrum. Stabilizing the Rb frequency reference to the Global Positioning System (GPS) and straightforward improvements in FPC implementation will improve astro-comb accuracy by more than an order of magnitude.

Comparisons of astro-comb calibrations to those from Th:Ar lamps and characterizations of astro-comb systematic errors demonstrate an accuracy and reproducibility of calibrations with the astro-comb below the 1 m/s level. To determine the radial velocity of an astronomical target star, the high accuracy astro-comb calibrations must be applied to the stellar spectrum. This requires, in addition to a very stable, high-performance astrophysical spectrograph, that calibration light and stellar light exit the optical fiber coupling the telescope to the spectrograph with the same transverse mode profile. Key to this behavior is mode scrambling in the optical fibers. State of the art fiber-fed astrophysical spectrographs often rely on double image scramblers [24] to ensure that transverse modes of the optical fibers are consistently filled. With such techniques, long-term performance is presently at the 1 m/s level [1] due to a combination of Th:Ar calibrator performance, telescope guiding, and mode scrambling. To further improve fiber mode scrambling, multi-mode optical fibers with square and octagonal cross-sections are being studied. The authors plan to investigate the long-term stability of calibrations by comparing stable radial velocity stars to an astro-comb at such a spectrograph.

4. Conclusions

We used two astro-combs, each consisting of a laser frequency comb integrated with a Fabry-Pérot filtering cavity, to calibrate the absolute frequency (or wavelength) of a high-resolution astrophysical spectrograph over a 100 nm band in the deep red and over 20 nm in the blue. We reliably operated the astro-combs over several weeks in 2009 and 2010 at the Fred Lawrence Whipple Observatory (FLWO) on Mt. Hopkins in Arizona, and repeatedly calibrated the TRES spectrograph. Expressed in terms of measurement sensitivity to changes in the precision radial velocity (PRV) of stellar sources, relevant to searches for small exoplanets, the astro-combs provided spectrograph calibration sensitivity < 1 m/s, limited primarily by the environmental sensitivity of the TRES spectrograph, and obtaining absolute agreement with thorium argon lamp calibration.

In ongoing work, we are preparing both to calibrate broader, visible wavelength bands and to apply the obtained sub-m/s calibration sensitivity to stellar PRV observations. To this end we have assembled and are presently characterizing a “green astro-comb” comprising a 1 GHz repetition rate Ti:Sapphire laser, a coherent wavelength shifting element based on a short, tapered photonic-crystal fiber (PCF) [25], and a broadband Fabry-Pérot filter cavity based on zero dispersion group delay mirror sets [26, 27]. Improved spectrograph wavelength calibration is not limited to exoplanet research — a broad cross section of astrophysical problems may be addressed, perhaps including the nature and dynamics of dark energy [28, 29], and the constancy of fundamental constants over cosmological time scales.

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