Astronomical frequency comb for calibration of low and medium resolution spectrographs
innoFSPEC at AIP has several years expertise in astronomical instrumentation.

innoFSPEC successfully developed a new technique to generate an optical source (called astro-comb) suitable for calibration of low and medium resolution spectrographs.

The instrument is compact and easy to operate and has been tested on-sky using the Potsdam Multi-aperture Spectrometer (PMAS) at the 3.5 m telescope at the Calar Alto Observatory (Spain).

The instrument offers a continuous tune of the position of the calibration lines – this brings the possibility of a complete characterization of the line spread function of the spectrograph at any resolution.

We seek for partners at GEMINI that can use this instrument and could request for additional features of our tunable calibration source.
The next slides describe the standing problems in wavelength calibration and results of the on-sky test with the frequency comb source developed at innoFSPEC Potsdam.
Wavelength calibration

Use of astronomical instrumentation relies heavily on accurate **calibration** procedures.

- Spectrographs are calibrated in: wavelength and flat field.
- Throughput: Response of whole telescope optics and spectrograph.

- Accurate **wavelength calibration** is required for:
  - Search for extra-solar planets via the radial velocity method.
  - Search for time variation of the fine structure constant ($\alpha$).
  - Measurement of the acceleration of the universe expansion.
  - Stellar population.

- Wavelength calibration sources:
  - Lamps of He, U-Ne, Th/Ar, Hg.
  - Iodine cells.
Calibration sources

- Lamps characteristics limit the accuracy of wavelength calibration:
  - Lines are not equally spaced nor equally intense.
  - Lines are blended.
  - Narrow spectral coverage.
  - Lines’ frequencies are known with $\Delta \lambda / \lambda = 10^{-7}$ accuracy.

- ‘Ideal’ wavelength calibration source:
  - Equally spaced and equally intense lines.
  - Lines spaced 3-4 times the resolution of the spectrograph.
  - Spectral coverage over the whole spectrograph operation range.
  - Lines’ frequencies known with $\Delta \lambda / \lambda = 10^{-8}$ accuracy or better.
Astro-comb

Astro-combs (astro-combs) have the characteristics of an ideal calibrator: but too tightly spaced lines.

Comb mode spacing is increased by filtering with Fabry-Perot cavities.

Astro-combs are commercially available at 500-700 K Euro
Any alternative to actual astro-combs?

- Actual astro-combs are complex and expensive.

- We developed a tunable and compact astro-comb for medium and low resolution spectrographs.

- The astro-comb stability is tracked with a wavemeter having 0.3 pm resolution.

- The comb lines are stable within 0.025 pm during the astro-comb exposure time.
Initial lasers

- Broadband spectrum (400 nm bandwidth) centered at 1580 nm.
- Optical-signal-to-noise ratio > 30 dB.
- 170 equally spaced lines are generated out of 2 lasers.
- After frequency doubling, spectrum is centered at 800 nm.
On-sky test with PMAS at Calar Alto

- PMAS: Integral Field Instrument at the Calar Alto Observatory 3.5 m telescope:
  - Wavelength coverage from 390 to 930 nm
  - 4096×4096 CCD detector with 15 mm pixel size.
  - Resolution of ~7000 (@800 nm).

- Neon: 20 randomly distributed lines with very unequal intensities.

- Astro-comb: 300 lines evenly spaced in frequency.
A P3d data reduction software allows analyzing the measured spectra.

Each comb line is sampled by ~5 pixels: fitting uses a Gaussian function.

Determination of the centroid and the width of each comb line.

Calculation is performed for each of the 400 fibers.

Line profile (width) measures the resolution of the spectrograph.
The astro-comb can be set for several comb spacing.

- Appropriate for low-, medium- and high-resolution spectrographs.
- Frequency equidistancy is verified with 1 pm accuracy.
- Useful for assessing line spread function characteristics.
Exposures of OH emission lines were calibrated either with Neon (black) or astro-comb (green and red) light.

The wavelengths of the OH doublets are indicated with vertical lines.

Due to the lack of Neon lines at some spectral intervals the calibration is inaccurate up to 20 pm.

Astro-comb offers more accurate wavelength calibration.
Ca-triplet exposures in stars

- Exposures on several stars to analyze Ca triplet absorption lines.
- Wavelength calibration is performed with Neon and astro-comb.
- Examples with HD3765 and HD219538 show the ability of astro-combs to perform wavelength calibration perhaps with superior accuracy than Neon lamps.
Conclusions

- Simple scheme for tunable astro-comb generation was demonstrated.
- Astro-comb provides much more calibration (stable) lines than lamps.
- On-sky test shows astro-comb suitability through examples with OH emission lines detection and stellar exposures.
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