Application Note
SPECTROSCOPY

**Czech Metrology Institute (CMI), Prague**

**Menlo Systems, Martinsried**

# Comb teeth resolving Fourier transform spectroscopy

**Authors:** Petr Balling (CMI), Benjamin Sprenger (Menlo Systems)

**Contact email address:** b.sprenger@menlosystems.com

The Czech Metrology Institute (CMI) investigates femtosecond comb interferometric spectroscopy in a conventional arrangement with a moving mirror. An auxiliary cw laser is used for linearization of the sampling. Scanning and detection over an interval longer than the distance between two consecutive pulses of the frequency comb allow for spectrally resolving the individual frequency modes of the comb. Fourier spectroscopy typically uses a scanning arrangement including balanced lengths of interferometer arms, and the sample is placed at the interferometer output in front of the detector. In our case, highly unbalanced arm lengths can be used (due to the limited space in our laboratory only up to ~7 m arm length difference has been tested). For the investigation of phase properties the sample is alternatively placed inside the interferometer.

In order to resolve the comb modes we need a continuous scan longer than one $l_{pp}$ (pulse-to-pulse distance), i.e. for the Fourier transform the interferogram should contain at least two fringe packets corresponding to consecutive pulses of the frequency comb. In an ideal case (offset frequency equal to zero, vacuum scan, exactly selected length of processed region and matching sample rate) the Fast Fourier Transform (FFT) would calculate results exactly at the positions of real comb teeth. In all other cases there is a mismatch between the sets of wavelengths resulting from the FFT and the wavelengths of the real comb teeth. We have solved this problem by completing the set of samples by zeros (zero padding) – the result being that the FFT calculates more than three spectral points per lobe of one comb tooth. Points belonging to one real comb tooth are then interpolated. The output parameters of the modeling are amplitude, phase, and air wavelength of each comb tooth (deduced from the air wavelength ratio of the reference cw laser and the comb tooth). Precise knowledge of the comb mode frequency leads to a precise estimation of the spectral characteristics of inspected phenomena.

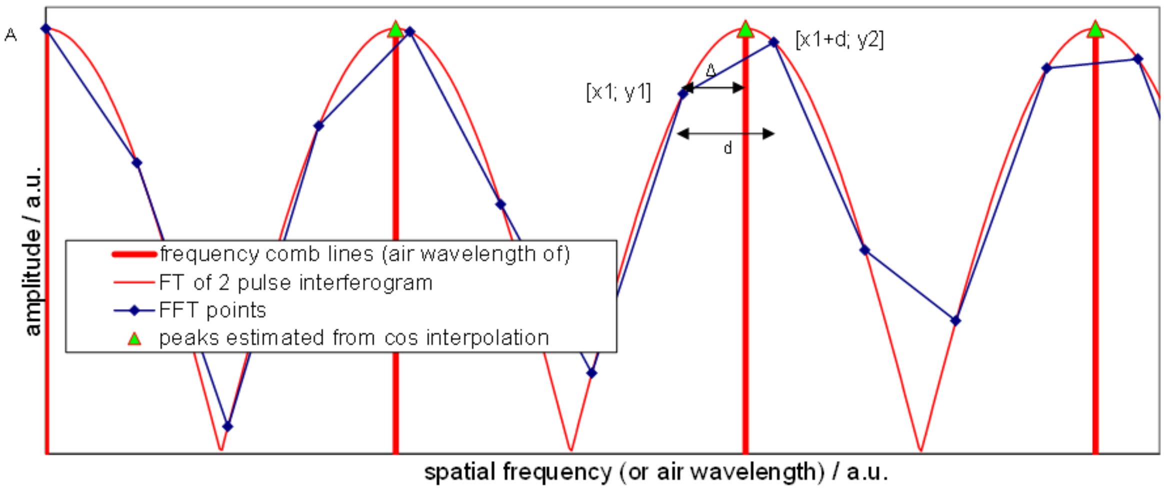


**Figure 1:** Illustration of amplitude and wavelength modelling of comb modes from FFT data calculated for an M=2 interferogram.

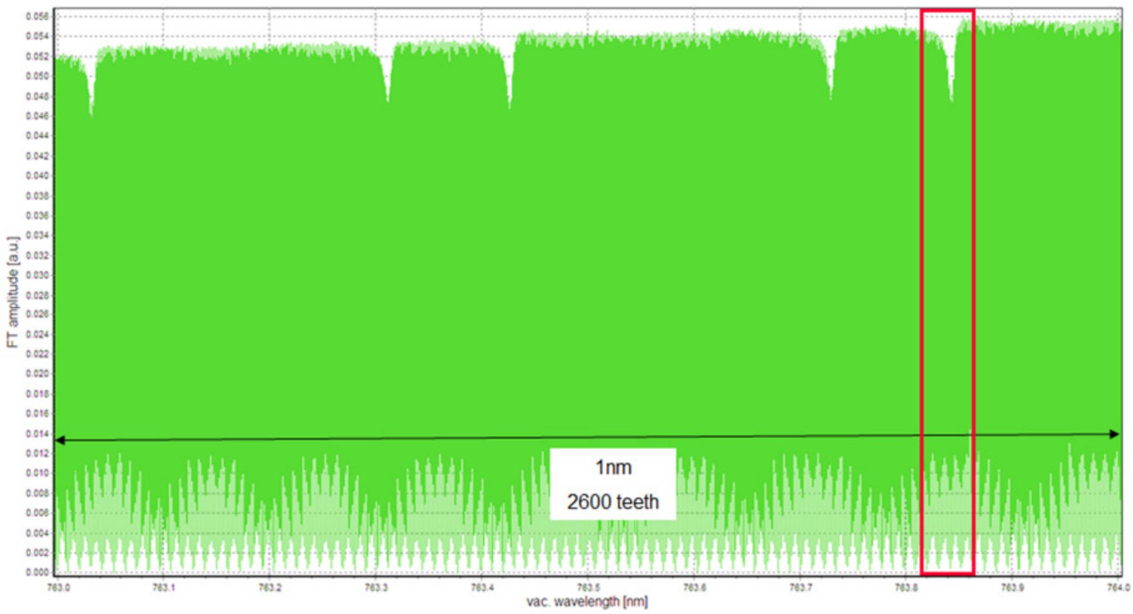


**Figure 2:** Raw FFT data: $O_2$ lines are visible

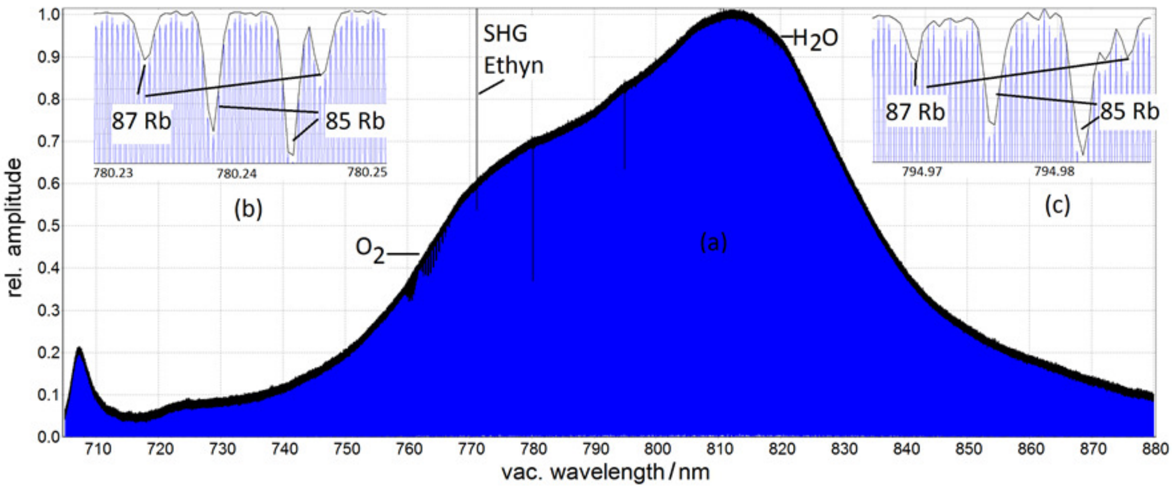


**Figure 3:** Example of fs comb spectra transmitted through 9 cm Rb vapor cell. Blue: raw data calculated by FFT. Black: modelling of comb teeth peaks. (a) Spectra measured using the FT spectrometer, 430 thousand teeth (oxygen and water vapor absorption in ambient air is also visible). Inset (b): $D_1$ lines of $^{85}Rb$ and $^{87}Rb$. (c) $D_2$ lines of $^{85}Rb$ and $^{87}Rb$. For a better image of the narrow shape additional points may be obtained using a slightly changed repetition rate $f_r$.

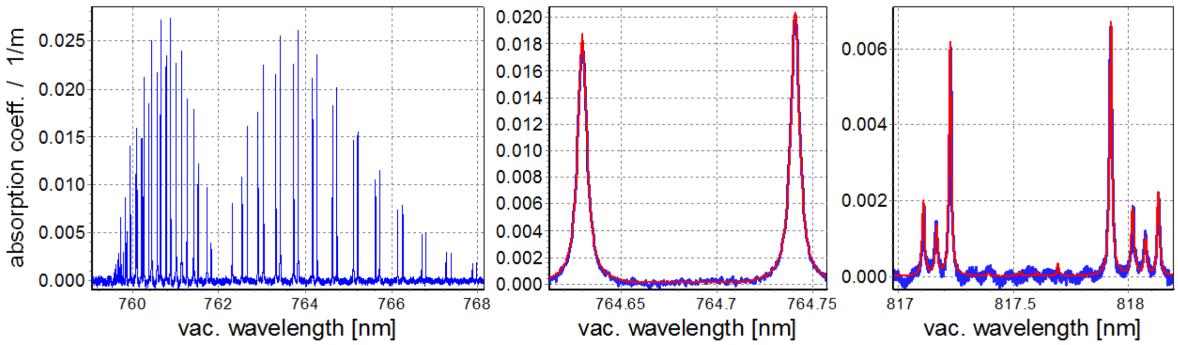


**Figure 4:** Example of an air absorption measurement for a 6.837 m interferometer arm displacement, the average result of 12 scans is shown. (a) Oxygen A-band at 762 nm. (b) Detail of the measured line profile (blue) compared with a model based on HITRAN data (red). (c) A few water vapor lines (78 % rel. humidity).

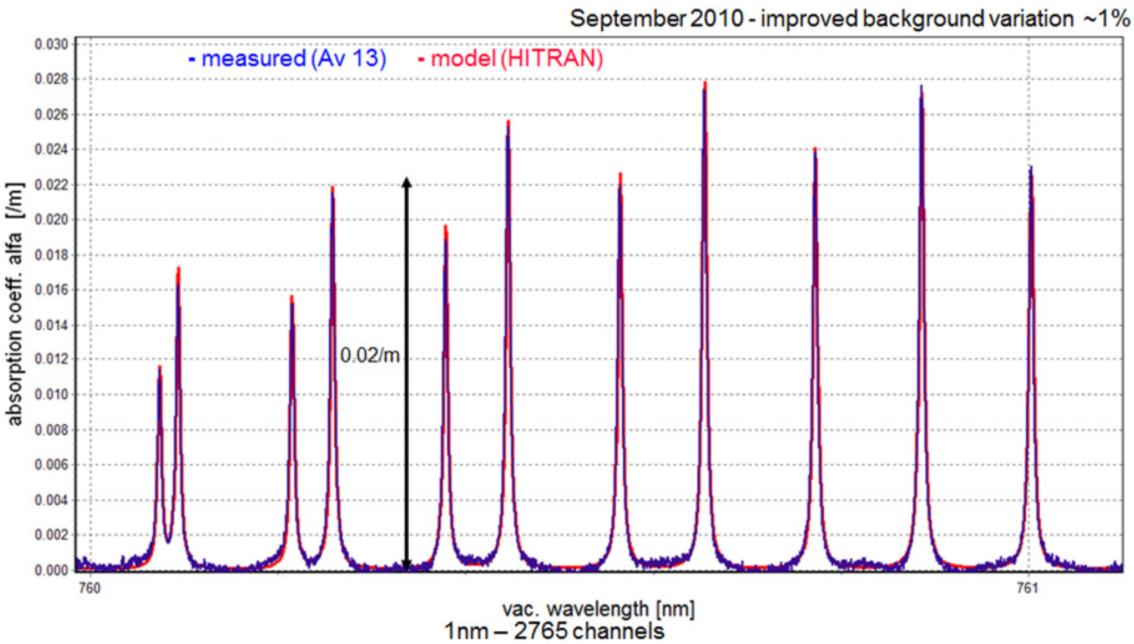


**Figure 5:** Detail of some $O_2$ lines from A-band at 762 nm, measured in 6.8 m of air.

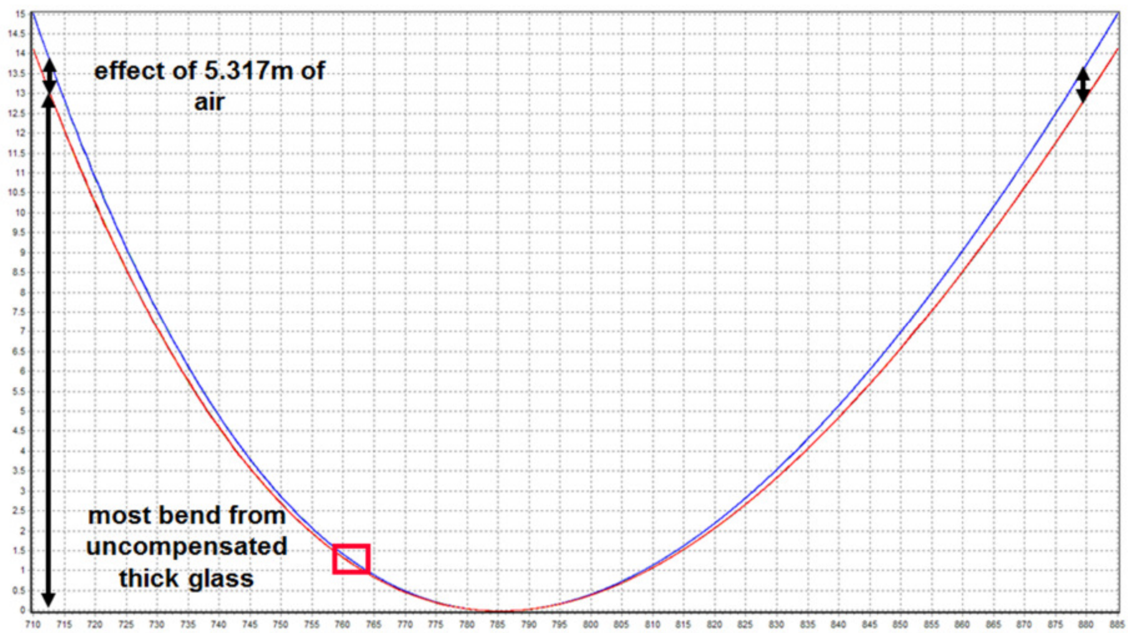


**Figure 6:** Spectral phase ~ second derivative of n(λ): comparing spectral phase curves at the same stationary points of different pulses.

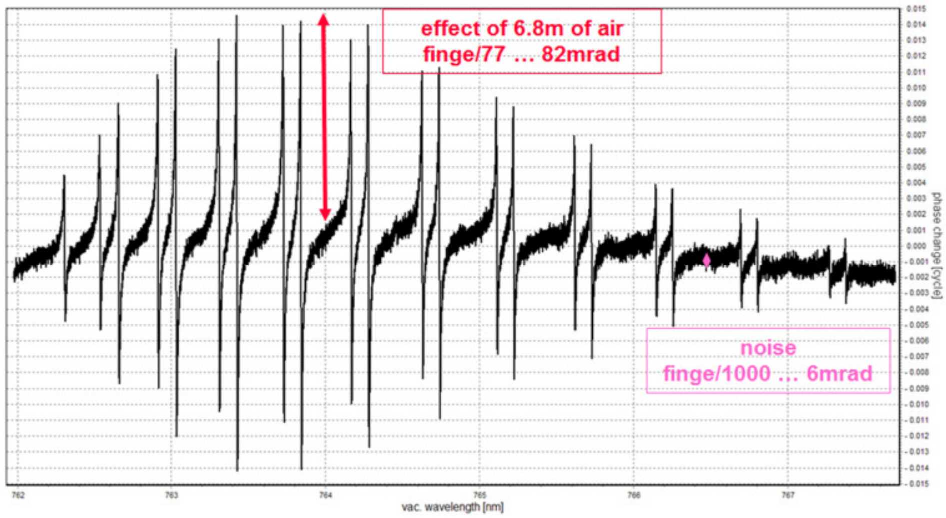


**Figure 7:** Change in spectral phase caused by 6.8 m displacement in air – average of 13 scans of $O_2$ at 765 nm.

## Publications:

P. Balling, P. Kren: Absolute frequency measurement of wavelength standards 532 nm, 543 nm, 633 nm, and 1540 nm; Eur. Phys. J. D 48, 3-10 (2008)

P. Balling, P. Kren, P. Masika, and S.A. van den Berg: Femtosecond frequency comb based distance measurement in air; Opt. Express 17, 9300-9313 (2009)

P. Balling, P. Masika, P. Kren, and M. Dolezal: Length and refractive index measurement by Fourier transform interferometry and frequency comb spectroscopy; Meas. Sci. Technol. 23, 094001 (2012)

## Weblinks:

Institute website:
www.cmi.cz

## Contact information:

Menlo Systems GmbH
Am Klopferspitz 19a
82152 Martinsried
Germany

Tel.: +49 89 189 166 0
Fax: +49 89 189 166 111

Contact person: Dr. Benjamin Sprenger
Email: b.sprenger@menlosystems.com

www.menlosystems.com