

A ruler for the stars

Specialized optical frequency combs have profound impact on precision astronomy

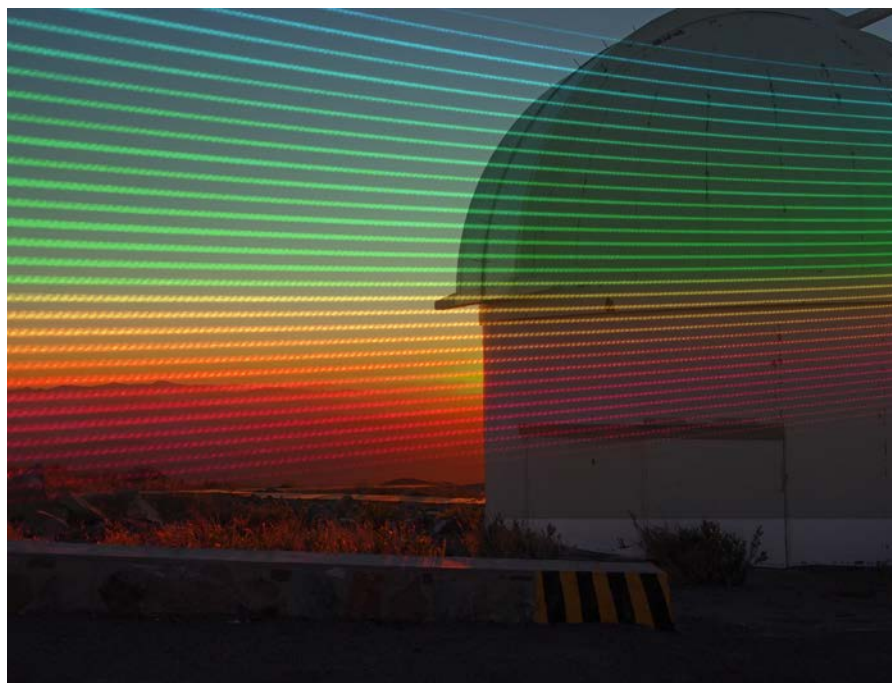
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Optical frequency combs can be used as high-precision “rulers for light” to calibrate astronomical spectrographs. This enables the measurement of tiny Doppler shifts in starlight with unprecedented accuracy, significantly enhancing the search for exoplanets and the study of stellar dynamics. In the long term, frequency combs may not only help identify Earth-like planets but also enable more precise measurements of the universe’s expansion and tests of fundamental physical laws.

Is anyone out there? That is one of the fundamental questions we ask when we look up at the starlit sky at night. On a clear, starry night, we can see several thousand stars with the naked eye. With telescopes, we can see many times that number.

By detecting and analyzing the light emitted by the stars, we can derive important information: For example, the spectral lines of starlight tell us what elements and molecules are present in a star. A star’s brightness helps us calculate its distance from us.

Analyzing starlight is always a glimpse into the past. Modern telescopes can detect individual photons, and thus analyze not only the light from stars in our own galaxy but also the light from stars in very distant galaxies. Since this light has traveled for a correspondingly long time before reaching the detector, we see the state of the respective star at the moment the light left it; the most advanced telescopes can now look back almost as far as the Big Bang.



all images: Menlo Systems

The more precisely we can resolve changes in the spectrum of starlight, the better we can decipher the messages carried by these photons. For example, analyzing starlight also helps us answer fundamental questions: How fast is the universe expanding, and how will it evolve in the future? What is the true nature of dark matter? And perhaps, one day, we may even answer one of humanity’s oldest questions: Are we alone in the universe?

How do we find planets using light?

One way to search for exoplanets, which are planets located outside our solar system, is by measuring the Doppler shift of starlight. Due to its mass, a planet orbiting a star exerts a small gravitational pull on

that star. As the star moves periodically closer and further from us, its spectral lines undergo corresponding Doppler shifts (**Fig. 1**). By detecting these minute shifts in a star’s spectrum, we can infer the existence of exoplanets.

This so-called radial-velocity method played a key role in the discovery of the first exoplanets, for which astronomers Michel Mayor and Didier Queloz were awarded the 2019 Nobel Prize in Physics [1]. In this process, the light collected by telescopes is split into its individual wavelengths or frequencies in a spectrograph, and a highly sensitive CCD camera detects the incoming photons. To determine tiny Doppler shifts in stellar spectra, precise wavelength calibration of the spectrograph is required. The more precisely a spectrograph can

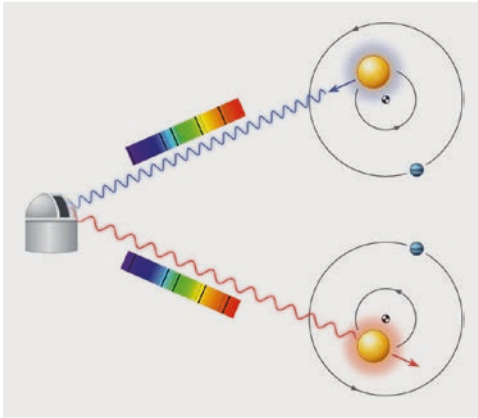


Fig. 1 Due to a planet's gravitational pull, the star is accelerated and its spectrum is Doppler-shifted

detect frequency shifts in light, the smaller the Doppler shifts it can measure. Without precise calibration however, minute drifts in the spectrograph – due to, for instance, environmental changes – are indistinguishable from a shift in stellar spectral lines.

The ideal calibration source for such a spectrograph has the following properties:

- It provides as many calibration lines as possible, spaced at equal intervals across the entire frequency range under investigation, whose frequencies are known with absolute precision.

- It has a mode spacing between adjacent calibration lines that is just large enough for the spectrograph to resolve the individual lines. Depending on the spectrograph, these spacings can range from 10 to 30 GHz.

- It produces a sufficiently uniform intensity distribution across the spectrum, ensuring that individual lines provide comparable photon statistics and can be measured precisely without weak lines becoming noise-limited or strong lines saturating the detector.

- It has stable and reproducible line shapes and intensities, so that changes in the calibration spectrum itself do not introduce apparent wavelength shifts.

Conventional calibration sources such as hollow-cathode and thorium-argon lamps provide numerous atomic emission lines and have been used successfully in astronomical studies for decades. However, their spectra do not naturally provide the combination of regular frequency spacing, uniform line distribution, precisely defined frequencies, and controlled line intensities required for the highest-precision radial-velocity measurements. Some spectral regions

contain many suitable lines, while others contain only a few, and line intensities can vary substantially. Consequently, the achievable calibration accuracy is ultimately limited by the characteristics of the individual atomic lines and by the stability of the lamp and its operating conditions.

A so-called AstroComb – an optical frequency comb designed for applications in astronomy – on the other hand, introduces a different approach to tackling these requirements.

Optical frequency combs

An optical frequency comb is a device that delivers a set of precisely controlled and evenly spaced lines in the frequency domain, which, under the right conditions, can be used as a highly accurate frequency ruler. It is most commonly generated by a mode-locked laser, which produces a regular pulse train in the time domain (**Fig. 2**), where each pulse is separated by the laser cavity's roundtrip time.

The Fourier relationship between the time and frequency domains indicates that a periodic pulse train corresponds to a discrete set of equally-spaced frequency lines, or modes. In the frequency domain, the individual comb modes, f_n , are given by the comb equation

$$f_n = n f_{\text{rep}} + f_{\text{ceo}}$$

where n is an integer mode index, f_{rep} is the pulse repetition rate, and f_{ceo} is the carrier-envelope offset frequency. The spacing between adjacent modes is given by f_{rep} , arising from the laser cavity round-trip time, and f_{ceo} is a non-zero shift of the entire comb spectrum. These two parameters – f_{rep} and f_{ceo} – are the comb's two degrees of freedom. Suitable optical and electronic control systems can then be used to stabilize both f_{rep}

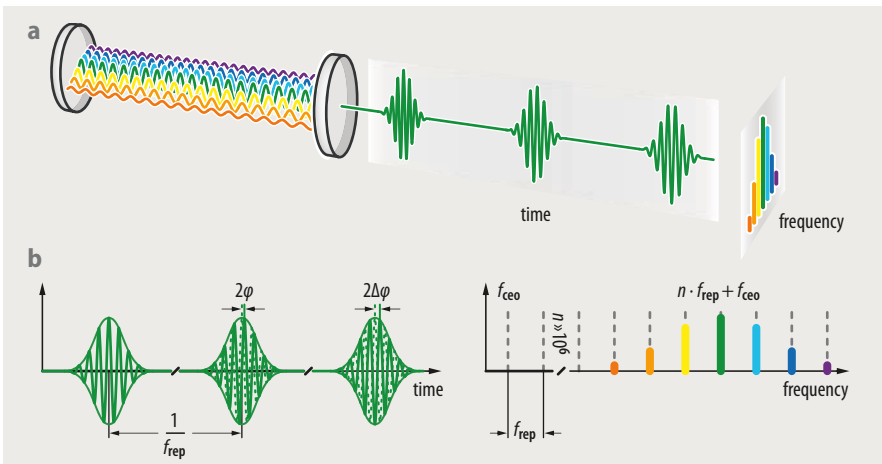


Fig. 2 An optical frequency comb produced by a mode-locked laser (a). A periodic pulse train in the time domain corresponds to equally spaced spectral lines in the frequency domain. These are separated by the pulse repetition rate, f_{rep} , and are shifted by f_{ceo} , which arises due to the carrier-envelope phase slip, $\Delta\phi$, between successive pulses (b).

and f_{ceo} . Once these two degrees of freedom are measured and stabilized, all frequencies of the OFC are known to a high precision and the comb can be used as a ruler for light [2].

This breakthrough, and the direct frequency measurements it enabled, was the topic of the Nobel Prize in Physics in 2005, for which Menlo Systems co-founder, Theodor Hänsch, was honored with a part of the prize.

How does a frequency comb calibrate a spectrograph?

A spectrograph converts the wavelength of incoming light into a position on its detector. By comparing the measured positions of the comb lines with their precisely known frequencies, one can establish the relationship between detector position and wavelength. This so-called wavelength solution can then be used to determine the wavelengths of spectral features in astronomical observations with far greater precision than can be achieved using conventional calibration lamps.

The large number of sharp, regularly spaced calibration lines spanning a broad spectral range provides dense reference points across the detector, enabling the wavelength solution to be constrained with high precision, rather

than relying on interpolation between the more sparsely spaced – and sometimes blended – lines of conventional calibration lamps.

For precision radial-velocity measurements, however, a calibration is only useful if it remains accurate over time. The spectrograph's response can drift because of changes in temperature, pressure, mechanical alignment or other environmental conditions. An OFC can therefore serve not only to establish the wavelength scale, but also to monitor and correct such drifts. The calibration must consequently be precise across the entire spectral range and sufficiently stable to maintain this precision over the long observing periods required for detecting tiny Doppler shifts.

In routine operation, comb spectra can be recorded between astronomical exposures to determine and monitor the wavelength solution. For the most demanding radial-velocity measurements, the comb can instead be recorded simultaneously with the stellar spectrum, providing a real-time reference for instrumental drifts during the exposure itself.

From laboratory frequency combs to AstroCombs

For the calibration of spectrographs, the instrument needs to

be able to resolve the modes of the OFC. The comb's mode spacing, f_{rep} , therefore needs to be larger than the spectrograph's resolution; the optimum mode spacing was found to be around three times the resolution of the spectrograph. The comb also needs to have a broadband, balanced spectrum to illuminate the spectrograph's detector evenly over a wide wavelength range. Finally, installation at remote observatories demands ultimate robustness and reliability.

Typical combs based on mode-locked lasers have mode spacings in the hundreds of MHz to a low number of GHz. This spacing cannot arbitrarily be increased, as it would require shorter laser cavity lengths. To modify it into an AstroComb, the comb light is passed through a Fabry-Pérot cavity to filter out certain modes and thereby increase the mode spacing (Fig. 3). Using this technique, comb mode spacings of up to 30 GHz can be generated, and optimally matched to the resolving power of the spectrograph.

The loss of average power caused by the filtering process is compensated for using fiber amplifiers. Additionally, the wavelength range of the original comb may not match the spectral range of the astronomical spectrograph. The comb light can then be frequency-converted using nonlinear optical fibers or

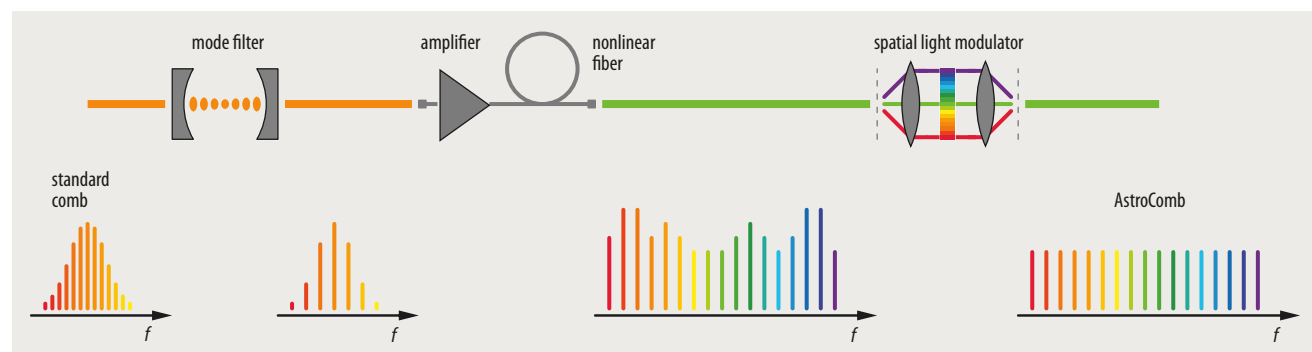


Fig. 3 The process of converting a standard optical frequency comb into an AstroComb. The comb light is first passed through a Fabry-Pérot cavity to filter the modes, then amplified and frequency-converted, before a spatial light modulator flattens the resulting spectrum.

nonlinear crystals [3]. Variations in the line intensity can lead to overexposure or poor detector utilization, reducing calibration accuracy. For even illumination of the spectrographs, the spectrum of the comb needs to be flat across the whole spectral range. This is achieved using a spatial light modulator (SLM), so the comb's spectral envelope can be shaped to equalize line intensities and optimize performance [4].

Menlo Systems' AstroCombs are based on fiber laser technology, which provides exceptional reliability, stability, ease of operation, and flexibility. This is important, as an AstroComb needs to be robust enough to be installed in remote observatories and to be remotely operated for extended periods of time, without intervention. Long-term stability is guaranteed by referencing the comb to a GPS-disciplined rubidium clock. The most modern AstroCombs are rack-mounted, turnkey, and include system operation electronics with software for full automation and remote control (Fig. 4).

AstroCombs from Menlo Systems have been installed at twelve locations worldwide. The first ever AstroComb was installed on Tenerife and is used at the Vacuum Tower Telescope (VTT) of the Kiepenheuer Institute for Solar Physics for spectroscopy of the solar surface [5]. More recently, the first fully rack-mounted AstroComb was installed with the Large Binocular Telescope (LBT) in Arizona in 2026 to study exoplanets in orbit around stars smaller than our own Sun.

Why does this matter for exoplanets, and beyond?

The primary motivation for developing AstroCombs was to improve the precision with which astronomers can measure changes in stellar spectra. But the ability to

make such measurements has implications beyond the detection of individual exoplanets. Wherever small changes in spectral frequency contain information about the physical properties or motion of an astronomical object, high-precision frequency references enable a better understanding of these signals.

For exoplanet astronomy, the ultimate goal is to detect planets that are much smaller and less massive than those that can be readily observed today. An Earth-mass planet induces only a very small reflex motion in its host star, making its Doppler signal particularly difficult to distinguish from instrumental and stellar noise. More precise and stable spectrograph calibration can therefore contribute to the search for increasingly small planets and to the long-term monitoring needed to identify their orbital pathways.

The same spectroscopic precision can also be applied to the stars

themselves. Small changes in stellar spectra can reveal stellar motion, oscillations, rotation, and activity, providing information about the structure and evolution of stars. Precise radial-velocity measurements are also valuable for studying multiple-star systems and other dynamical processes that would otherwise be difficult to resolve.

On much longer timescales, this principle can be applied to the expansion of the Universe. As the Universe expands, the redshift of sufficiently distant objects is expected to change extremely slowly over time. While this effect, known as redshift drift, is currently far too small to detect with conventional astronomical measurements, future high-precision spectrographs combined with specialized optical frequency combs could potentially make such measurements possible.

Another exciting field of application is the test of fundamental physics. Extremely accurate measurements of spectral frequencies can be used to investigate effects predicted by general relativity, such as gravitational redshift, and to study objects whose strong gravitational fields provide particularly sensitive tests of relativistic predictions. As measurement precision improves, astronomical observations are poised to be used not only to study the Universe, but also to test the underlying physical laws describing it.

AstroCombs therefore address a fundamental requirement of precision astronomy: They provide a stable, accurately known frequency ruler against which the spectrograph, and ultimately the astronomical signal, can be measured. Better calibration does not, by itself, eliminate all sources of uncertainty, but it removes one important limitation and enables increasingly demanding spectroscopic measurements.



Fig. 4 A rack-mounted AstroComb from Menlo Systems

The future of astronomical precision

For centuries, astronomers built progressively more powerful telescopes to collect more light. Today, increasingly precise instruments are allowing us to extract more information from that light, and AstroCombs are part of this development. As spectrographs become more stable and more sensitive, their calibrating systems must keep up. The next generation of instruments on the world's largest and most remote telescopes will require more accurate and reliable frequency references, especially in the hunt for Earth-like planets and measurements of extremely small changes in frequency.

The journey from the first frequency combs to today's AstroCombs is a perfect example of how

fundamental advances in physics can find new applications in unexpected fields. By providing a precise and stable reference for astronomical studies, these instruments help extend the limits of what can be measured, and, ultimately, what can be discovered.

Answering fundamental questions such as "Is anyone out there?" begins with the reliable detection and characterization of exoplanets. And how can this reliability be ensured? By turning light itself into an extraordinarily precise ruler – an AstroComb.

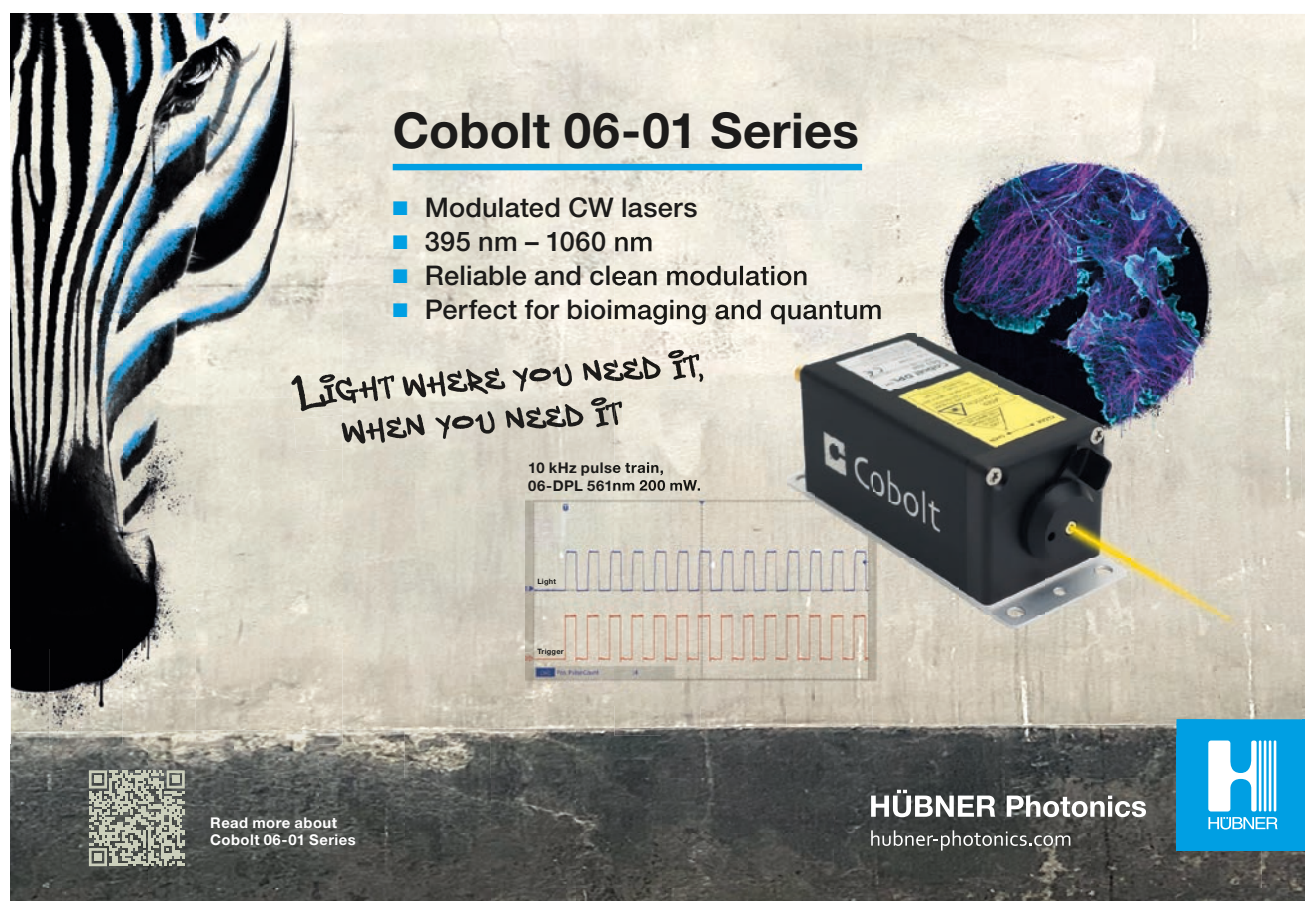
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