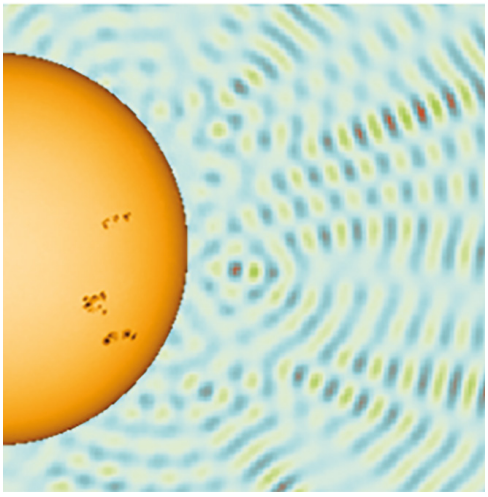
CHARLES TOWNES AND INFRARED HETERODYNE INTERFEROMETRY

Nicolas FORGET*
Institut de Physique de Nice (INPHYNI), Université Côte d'Azur, CNRS, 06200 Nice, France
*nicolas.forget@univ-cotedazur.fr



Nobel laureate Charles Hard Townes is well known for his work in quantum electronics, which led to the invention of the maser and lasers. He was also a notable figure in astrophysics and astronomy, particularly recognized as the architect of the first high-resolution optical stellar interferometer.

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Is there a scientific life after winning the Nobel Prize in Physics? For American physicist Charles Hard Townes (1915-2015), the answer is a resounding yes. Townes, who was awarded the prestigious prize in 1964 for his pioneering work in quantum electronics that led to the development of maser and laser technologies, later made significant contributions in a completely different field: astrophysics and infrared astronomy. In 1969, Townes and his collaborators detected ammonia (NH3) and water (H_2O) molecules in interstellar space. Then, in the 1990s, they discovered fast-orbiting gas clouds around a massive object, now identified as Sagittarius A*, the supermassive black hole at the center of our Milky Way. In 2009, Townes' team published the results of 15 years of observations of the red supergiant star Betelgeuse, revealing that its diameter had unexpectedly shrunk [1]. The star's sudden fluctuations in brightness—visible to the naked eye during the winter of 2019-2020—generated headlines and sparked false concerns about an imminent supernova [2]. This long-term study was made possible through the use of a heterodyne detection interferometer with extremely high angular resolution, a technical marvel combining starlight and laser light, and a true scientific and engineering feat.

Measuring the diameter of distant stars

The apparent angular diameter of stars—the tiny fraction of the celestial vault they occupy—is incredibly small. For instance, the angular diameter of Betelgeuse, one of the closest largest star, is estimated at around 45 milliarcseconds (mas), which is comparable to the angle at which a €1 coin would appear if placed about 100 km away—a challenging feat even for today's telescopes. As both amateur and professional astronomers know, most modern optical instruments cannot resolve the surface of stars. This is • • •

due to two main factors: atmospheric turbulence and optical diffraction. While the effects of atmospheric turbulence can sometimes be corrected (using adaptive optics), reduced (through observation at longer wavelengths), or avoided altogether (with space-based telescopes), optical diffraction remains a fundamental limitation. Diffraction restricts the theoretical angular resolution to approximately 1.22 λ/D, where λ is the observation wavelength and D is the diameter of the telescope's aperture. In practical terms, a telescope with a diameter of several tens of meters is required to measure Betelgeuse's angular diameter, while a telescope on the scale of hundreds of meters would be needed to resolve details on its surface.

Aperture synthesis

An alternative to direct imaging, first proposed by Fizeau in 1864 and demonstrated by Michelson and Pease in 1920, is indirect imaging through aperture synthesis, more commonly known as interferometry in the optical domain. To fully appreciate the revolutionary originality of this counterintuitive approach, it's essential to revisit the fundamentals: a star is an extended source composed of many independent points, each emitting its own wave. However, because the star appears under an extremely small angular diameter, these waves interfere constructively (by symmetry), forming a common wavefront – a quasi-plane wavefront - near the observer's line of sight. Despite this, the star's large and incoherent surface is revealed through random spatial variations in this quasi-wavefront. The characteristic scale of these variations depends on the star's angular size (Figure 2). The smaller the apparent diameter of the star, the larger this characteristic distance becomes, as we approach the case of a perfect point source, which behaves like a true plane wave. The van Cittert–Zernike theorem formalizes this principle, stating that, under certain conditions commonly met in astronomy, the inverse Fourier transform of the spatial coherence function corresponds to the intensity distribution of the source—in practical terms, the image of the source.

How can the spatial coherence function be measured? Conceptually, the solution is straightforward: it requires a differential approach. Using two telescopes, for instance, one remains fixed as a reference while the other 'samples' the wavefront at varying distances from the first. Ideally, this sampling should occur in a plane orthogonal to the observation plane. However, due to the inclination of the observed star relative to the local vertical and the Earth's rotation, this is generally not feasible. Geometric corrections, however, allow for these effects to be accounted for—or even exploited.

What is the physical observable in this case? Generally, it is the degree of correlation between the temporal fluctuations in the amplitude (or intensity) of the electric fields detected by the telescopes. At first glance, this seems rather simple to retrieve: simply measure these fluctuations and then calculate the correlation mathematically, repeating the process for different relative positions of the telescopes. However, in practice, measuring these fluctuations is challenging because they occur over time scales that are too short to be captured by electronic systems. There are a few exceptions to this limitation, such as relatively low-frequency radio waves (up to a few tens of GHz), which can be sampled, processed, transmitted, and correlated in real time using fast electronic systems. This advantage is extensively utilized in radio astronomy, where aperture synthesis is the standard imaging technique.

Figure 1. Charles Townes at ISI in 2008, cleaning one of the siderostats with a jet of compressed carbon dioxide. [Cristina Ryan]

From radio astronomy to heterodyne interferometry

Charles Townes was no stranger to radio astronomy. As early as 1956, he had used his first tunable maser as an amplifier for radio astronomy. In fact, most of the technological building blocks of radio astronomy have optical counterparts—or almost all of them—and it was this challenge that Townes would overcome. A key method in radio astronomy is heterodyne detection, which reduces the frequency of the electromagnetic carrier wave while preserving the information carried by the field envelope. This frequency reduction is crucial for enabling electronic

systems to amplify, detect, and correlate the signals. Technically, heterodyne detection relies on mixing the incoming signal with a reference wave known as the "local oscillator." The very principle of aperture synthesis assumes that all heterodyne detections across the radio telescope array use the same ultra-stable local oscillator. In practice, this requires a clock based on a frequency reference—often a hydrogen maser. This was another intersection with Townes' earlier work, particularly since the optical equivalent of a radiofrequency local oscillator is a laser, of which Townes was also the co-inventor!

Shortly after receiving the Nobel Prize, Townes decided to step down from his administrative role and return to fundamental research. He joined the Department of Physics at the University of California, Berkeley, and, with his students, began adapting radio interferometry techniques to optical wavelengths. Instead of using electronic oscillators, they employed CO_2 lasers with a wavelength of 10.6 µm. This choice was driven by both technical and scientific reasons: these lasers were readily available, the effects of atmospheric turbulence were reduced, and there was good atmospheric transparency between 9 and 11 µm. Additionally, this wavelength allowed better observation through interstellar dust clouds.

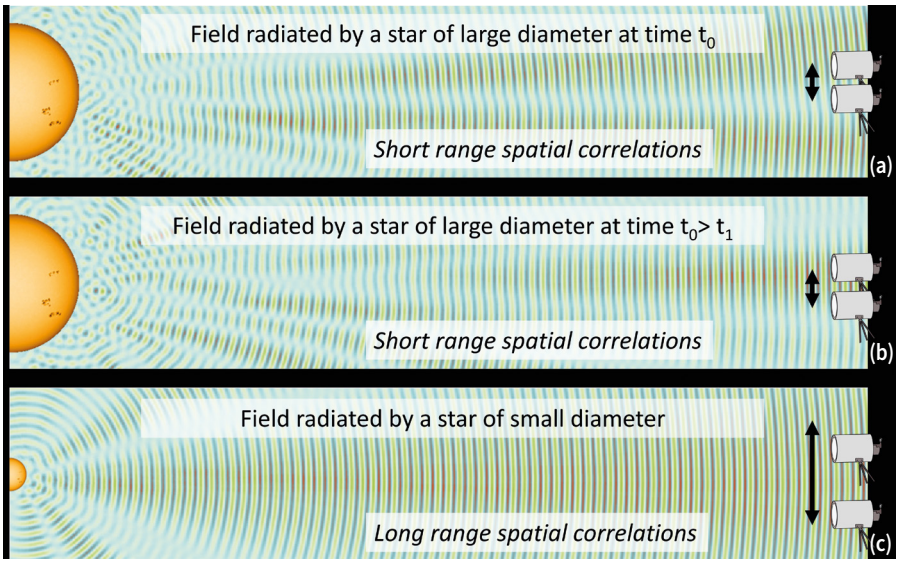

Figure 2. Numerical simulations illustrating the van Cittert-Zernike theorem and the principle of aperture synthesis. An extended incoherent source generates, at great propagation distances, wavefronts that exhibit random variations over time (Figure (a) and Figure (b)). However, the scale of the typical spatial variations, the coherence length, depends on the shape and angular dimension of the source (Figure (c)).

The Infrared Spatial Interferometer (ISI)

Following preliminary tests at the Kitt Peak National Observatory and a decade of technological development, the Infrared Spatial ● ● ●

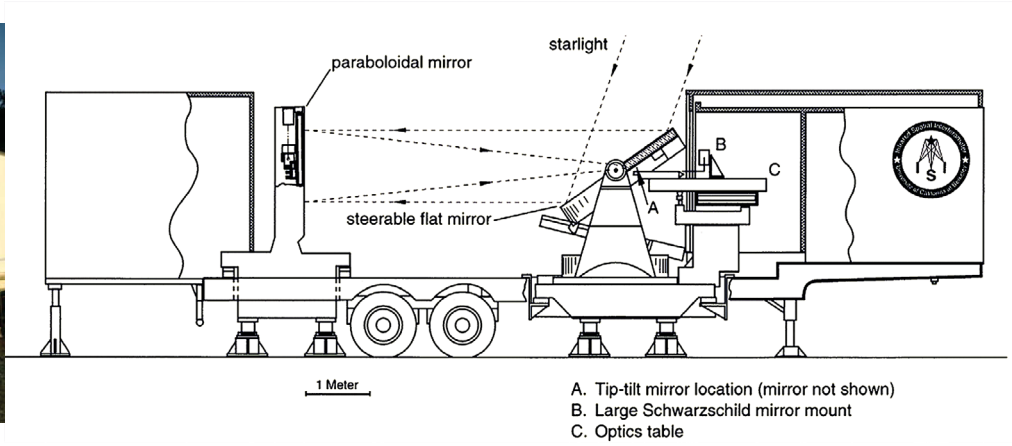

Figure 3. View and cross-section diagram of the mobile telescopes.

Interferometer (ISI) was completed in 1988 at Mount Wilson, California. The ISI is a marvel of ingenuity, combining mechanical, optical, and electronic engineering [3]. Despite its technological sophistication and complexity, users describe it as both robust and highly functional. The instrument consists of two, later expanded to three, 1.65-meter (65-inch) telescopes, which can be moved over distances of up to 85 meters. The telescopes utilize a Pfund-type optical configuration, an uncommon design that pairs a 2-meter adjustable flat mirror, known as a siderostat, with a 1.65-meter fixed parabolic mirror, operating at f/3.14. The siderostat is centrally perforated so that the parabolic mirror's focal point forms behind it, where an optical table is located (Figure 3). This compact architecture allows the telescope to be mounted on a standard semi-trailer, enabling it to be transported to different locations. At each site, the telescopes are secured on concrete pads through the trailer. The siderostat's orientation is computer-controlled, adjusting every second via an infrared camera to track the stellar target under observation. A second motorized mirror (tip-tilt) compensates for rapid directional fluctuations caused by atmospheric turbulence, making corrections several dozen times per second. To achieve this, a dichroic mirror separates the near-infrared light (used for tracking) from the mid-infrared light (used for measurements). Inside each telescope is a CO_2 laser, monochromatic and ultra-stable, tunable between 9 and 12 µm across various laser transitions. One of the cavity's end mirrors is mounted on a piezoelectric element, allowing precise tuning of the emission wavelength. A partially reflective mirror combines starlight and laser light, with their resulting interference beats detected by a fast (2.6 GHz) HgCdTe photodetector, cooled by liquid nitrogen.

The critical aspect of the ISI architecture is the wavelength and phase locking of the various CO_2 lasers. The technique chosen by Townes and his team is highly complex but remarkably effective. To give a sense of the system's sophistication, here is a brief and partial summary. The CO_2 lasers are intentionally set to operate at slightly different optical frequencies, with a 1 MHz difference between them. A portion of the 'slave' laser's beam is transmitted through free space to the 'master' CO_2 laser, where the 1 MHz beat frequency between the two is compared to a reference clock (a stabilized crystal oscillator). This comparison stabilizes the frequency and phase difference between the lasers by applying feedback to the piezoelectric mirror of the 'slave' laser. Simultaneously, the free-space optical paths are interferometrically stabilized to eliminate environmental factors from affecting the differential phase measurement. Now, imagine all of this operating between semi-trailers spaced tens of meters apart at an altitude of 1,742 meters—it's a remarkable technical challenge.

The RF signals generated by the HgCdTe detectors are dynamically resynchronized using coaxial cables of varying lengths, adjusted via an electromechanical switch, and then combined in the equivalent of a 50/50 splitter. The frequency difference between the RF signals produces a 1 MHz beat signal, whose amplitude is proportional to the product of the RF signals, and thus to the degree of correlation. This correlation signal is then demodulated, calibrated, and digitized. The sophistication of the detection system goes even further. As the Earth's rotation causes a varying rate difference between the telescopes, this is calculated and compensated for by slightly adjusting the frequency of the 'slave' laser, ensuring that the correlation signal maintains a constant amplitude modulation (100 Hz), regardless of the target's position in the sky. All of this equipment is controlled by a network of computers, including several real-time systems and Intel

486 processors – because, yes, indeed, this impressive piece of engineering dates back to the 1980s and 1990s!

The legacy of ISI – Berkeley's ISI remained the only high-angular-resolution interferometer operating in the mid-infrared for nearly two decades. Its innovative technology enabled the study of celestial objects with an angular resolution that, for a long time, was unmatched in this wavelength range (3 mas at 11 µm). However, over time, heterodyne interferometry has been largely replaced by direct optical recombination interferometry due to the latter's much higher sensitivity. The primary limitation of heterodyne detection is its extremely narrow spectral bandwidth (~2 nm), which significantly restricts the usable light flux and, consequently, the faintest objects that can be observed. Despite this, the ISI highlighted several technical and practical advantages of heterodyne detection: the lack of need for optical path stabilization on the stellar light path, the ability to accumulate data across multiple observation sessions, and the reliability of its data calibration. Perhaps most importantly, the ISI demonstrated that the modularity of the heterodyne approach is compatible with large-scale expansion. This concept is now a key focus of research in optical interferometry, where the goal is to massively parallelize detection channels to increase spectral coverage and, ultimately, the sensitivity of heterodyne detection. Emerging technologies like integrated optics and frequency combs hold the potential to overcome this limitation and could lead to a revival of heterodyne interferometry.

HETERODYNE INFRARED INTERFEROMETRY ON THE FRENCH RIVIERA

In 1974, Jean Gay (1937-2024) joined the nascent Centre for Research in Geodynamics and Astrometry (CERGA, now the Côte d'Azur Observatory) with a proposal for a heterodyne infrared interferometer, abbreviated as SOIRDETE, which stands for Synthèse d'Ouverture en Infra Rouge par Détection Hétérodyne (Infrared Aperture Synthesis by Heterodyne Detection). After extensive development efforts, which included constructing a building, developing two twin telescopes (2x 1 m), and forming a team, the project was ultimately not pursued. Jean Gay then became part of the ISI team, where he spent a year. In the early 2000s, SOIRDETE was revitalized and renamed C2PU (Centre Pédagogique Planète Univers, Planet-Universe Educational Center). It has since evolved into an active training and research center that has played a crucial role in the revival of intensity interferometry [4].

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