

Advances in Optical / Infrared Interferometry

Frank Eisenhauer¹, John D. Monnier² and
Oliver Pfuhl³

¹Max Planck Institute for Extraterrestrial Physics, 85748 Garching, Germany;
email: eisenhau@mpe.mpg.de

²Astronomy Department, University of Michigan, Ann Arbor, Michigan 48104,
USA; email: monnier@umich.edu

³European Southern Observatory, 85748 Garching, Germany; email:
opfuhl@eso.org

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Keywords

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Abstract

After decades of experimental projects and fast-paced technical advances, optical / infrared (O/IR) interferometry has seen a revolution in the last years. The GRAVITY instrument at the VLTI with four 8 meter telescopes reaches thousand times fainter objects than possible with earlier interferometers, and the CHARA array routinely offers up to 330 meter baselines and aperture-synthesis with six 1 meter telescopes. The observed objects are fainter than 19 magnitude, the images have sub-milliarcsecond resolution, and the astrometry reaches microarcsecond precision. We give an overview of breakthrough results from the past 15 years in O/IR interferometry on the Galactic Center, exoplanets and their atmospheres, active galactic nuclei, young stellar objects, and stellar physics. Following a primer in interferometry, we summarize the technical and conceptual advances which led to the boosts in sensitivity, precision, and imaging of modern interferometers. Single-mode beam combiners now combine all available telescopes of the major interferometers for imaging, and specialized image reconstruction software advances over earlier developments for radio interferometry. With a combination of large telescopes, adaptive optics, fringe-tracking, and especially dual-beam interferometry, GRAVITY has boosted the sensitivity by many orders of magnitudes. Another order of magnitude improvement will come from upgrades with laser guide star adaptive optics. In combination with large separation fringe-tracking, O/IR interferometry will then provide complete sky coverage for observations in the Galactic plane, and substantial coverage for extragalactic targets. VLTI and CHARA will remain unique in the era of upcoming 30-40m extremely large telescopes (ELTs).

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1. INTRODUCTION

Optical and infrared (IR) interferometry is experiencing tremendous advances from leaps in sensitivity, precision, angular resolution, longer baselines, and better imaging.

In this review, we present the technical and scientific achievements in optical/IR (O/IR) interferometry from roughly the past decade. We focus on the two main science-producing O/IR interferometers in the world, the European Southern Observatory's Very Large Telescope Interferometer (ESO VLTI), in particular GRAVITY, and the Georgia State University Center for High Angular Resolution Astronomy Array (GSU CHARA). In addition, the Large Binocular Telescope Interferometer (LBTI) and the Navy Precision Optical Interferometer (NPOI) are still in operation and will be discussed briefly.

Earlier reviews by Quirrenbach (2001) and Monnier (2003) thoroughly discussed the history of O/IR interferometry. More recently, a number of textbooks (Glindemann 2011, Labeyrie et al. 2014, Buscher & Longair 2015) have been introduced that augment the classic radio interferometry textbook from Thompson et al. (2017). We refer the reader to these sources for details beyond our cursory treatment.

In this introduction we will give a short history of the field, make comparisons to the more familiar radio interferometry, and motivate the reasons for the recent performance increases.

1.1. Short history of optical / infrared interferometry

The history of O/IR interferometry can be divided into three periods: The classical period from 1868-1930, the early-modern period from 1956-2005, and the modern "present" day from ~ 2000 to now. In this review, we propose that the 4th era has begun, one marked by GRAVITY and dual-beam phase-referencing on 8-10 meter (m) class telescopes that truly revolutionizes O/IR interferometry sensitivity.

The earliest period is rooted firmly in 19th century classical physics. Fizeau (1868) laid the foundation for how interference could be used to measure the sizes of stars by dividing the pupil of a telescope into small sub-apertures. The light from each pair of sub-apertures creates a "fringe", the basic result of a Young's two-slit interference experiment. In this arrangement, each point source creates its own sinusoidal fringe pattern; thus, an extended object will create a low contrast interference as the peaks and troughs partially overlap to blur out the dark, destructive nulls present for point sources. Later, Stephan (1874) attempted on-sky experiments but was not able to resolve any stars. The effective angular resolution of an interferometer θ is defined as half the fringe spacing, $\theta = \frac{\lambda}{2B}$, expressed in radians for a wavelength λ and a baseline between sub-apertures of B .

Soon after Fizeau's and Stéphan's pioneering work, Michelson developed a more thorough mathematical treatment, including coining the term "fringe visibility" to describe the coherence – with a visibility of unity corresponding to a perfect fringe with 100% destructive interference at the fringe troughs and with a zero visibility for no interference at all. Michelson first deployed this method to measure the sizes of Jupiter's moons (Michelson 1891), eventually resolving Betelgeuse at 47 milli-arcseconds (mas) using a 20-foot interferometer on top of the Mt. Wilson 100" telescope (Michelson & Pease 1921). This "classical" period ends with the largely-unsuccessful experiments to build the first truly long-baseline (50-foot) interferometer (Pease 1930).

The early-modern period of O/IR interferometry picks up with advances in electronics, optics, and detectors. The earliest revivals of long-baseline interferometry exploited new

Astronomical interferometry:

Technique combining light from different telescopes to increase the angular resolution, taking advantage of the wave nature of light

Optical / Infrared

(O/IR): Wavelengths $\approx 0.4 - \text{few } 10 \mu\text{m}$, with direct detection of photons, and observable from ground (other than far IR $\approx \text{few ten - hundreds } \mu\text{m}$)

Wavelength bands:

V: $0.5 - 0.6 \mu\text{m}$
R: $0.6 - 0.7 \mu\text{m}$
J: $1.1 - 1.4 \mu\text{m}$
H: $1.5 - 1.8 \mu\text{m}$
K: $2.0 - 2.4 \mu\text{m}$
L: $3.0 - 4.0 \mu\text{m}$
M: $4.6 - 5.0 \mu\text{m}$
N: $7.5 - 14.5 \mu\text{m}$

Fringe: Other word for interference pattern

Angular resolution:

Smallest angular scale which can be well measured, typically full half width of a point source

Diffraction limit:

Angular resolution $\frac{\lambda}{D}$ of a perfect telescope without aberrations and no blurring atmosphere

Resolution of interferometer:

Given by the separation between telescopes, $\frac{\lambda}{2B}$

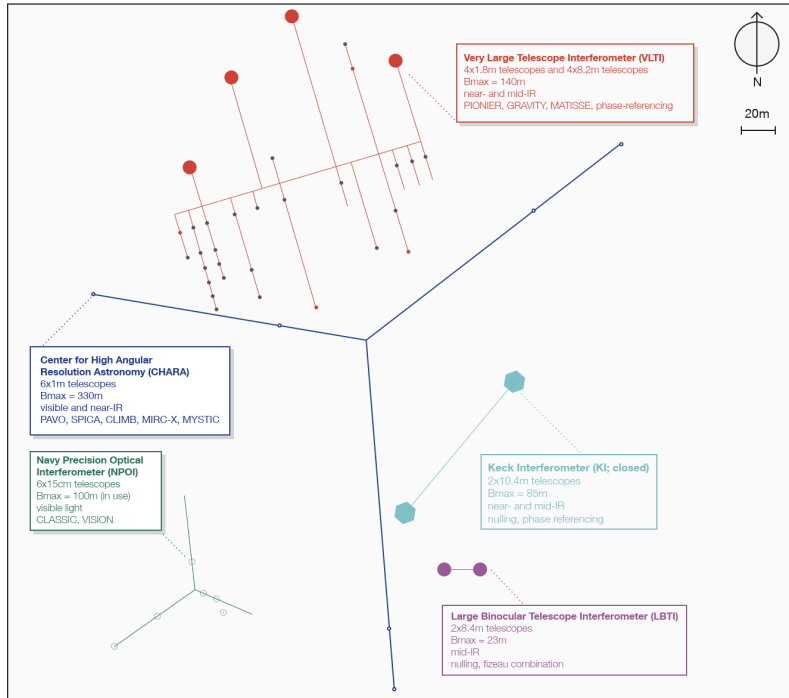


Figure 1

This sketch shows the footprints of modern O/IR interferometers, with telescopes and baselines to scale. The telescopes for LBTi (purple), CHARA (blue) and VLTi-UTs (red large circles) are fixed while the NPOI (green) and VLTi-ATs (red small circles) telescopes are mobile and can be re-positioned.

Direct detection:

Detecting the photons e.g. by creation of photo-electrons in semi-conductor, also called homodyne detection

Heterodyne

detection: Measuring the strength of the electric field by mixing with a local oscillator and measuring the power of the beating

technologies, such as intensity interferometry (Brown & Twiss 1956, Hanbury Brown et al. 1967) and heterodyne interferometry in the MIR by Nobel physicist Charles Townes (e.g., Johnson et al. 1974). Following pioneering work by Labeyrie (1975), early “direct detection” interferometers, such as the Mark III (Shao et al. 1988), I2T (Koechlin & Rabbia 1985), IRMA (Dyck et al. 1993), and others (di Benedetto & Conti 1983), emerged and established the principles of our modern facilities, where light beams are collected at widely-separated telescopes, often transported through vacuum pipes, brought into coherence using moving delay lines, and finally interfered directly on a detector.

Many of the projects in the 1980s and 1990s led directly to 2nd generation facilities: Narrabri intensity interferometer → SUSI (Davis et al. 1999), McMath heterodyne interferometer → ISI (Hale et al. 2000), I2T → GI2T (Mourard et al. 1994), Mark III → NPOI (Armstrong et al. 1998) + PTI (Colavita et al. 1999), aperture masking → COAST (Baldwin et al. 1994), IRMA → IOTA (Traub et al. 2003). While all facilities from this era, except for NPOI, have been shut down, their collective technical impact has been impressive, setting the stage for the modern age.

The 3rd, so-called “modern” era starts with the debut of the “flagship facilities” VLTi (Lena 1979, Beckers et al. 1990, Schöller 2007), NASA Keck Interferometer (Colavita et al. 2013), CHARA (ten Brummelaar et al. 2005), LBTi (Defrère et al. 2016) along with the

evolution of NPOI. All of these facilities (except for the Keck Interferometer) are still operating as of 2022. See Figure 1 for the physical layout of these arrays. The only major facility under construction today is the Magdalena Ridge Optical Interferometer (MROI; Buscher et al. 2013), which aims at combining up to ten 1.4m telescopes over 350m baselines. Within the past decade, no new interferometers have come online.

For a more historical perspective of O/IR interferometry, see the timeline explored by Lawson (2000) as well as the treatments by Léna (2020) and McAlister (2020).

1.2. Comparison with radio interferometry

Even the largest, single radio telescopes of the 20th century barely reach the angular resolution of Galileo's first optical telescope from 1609. There is no practical way to build single telescopes large enough to sufficiently reduce the diffraction of the long radio-wavelengths. Therefore, ever since the development in the 1950s, aperture synthesis interferometry (Jennison 1958, Ryle & Hewish 1960) has been the standard choice for high angular resolution telescopes in the microwave and radio bands (Thompson et al. 2017). Why has this not been the case in O/IR astronomy?

The principle of radio aperture synthesis interferometry is to measure the correlated flux from a celestial source on a number of baselines, each with two antennas, for different baseline length and orientation on sky. The source brightness distribution is then given by the Fourier transform. Each radio telescope is diffraction limited, with a flat wavefront across its aperture. With low-noise, phase-sensitive radio-amplifiers, all baselines can be measured simultaneously with little loss of signal or extra noise even for many telescopes. Since early radio interferometry operated at long wavelengths and narrow bandwidths, the coherence length is large, and the interference not much perturbed by the Earth atmosphere. As a result, the fringe can be maintained fairly easily over a long time and over a wide field of view.

The situation in the O/IR is very different. Because of the short wavelengths, the product of coherence length and -time is $\approx 10^{6\cdots 8}$ smaller than in the radio. Other than in the radio, there are no low-noise heterodyne mixers and amplifiers in the O/IR, such that for multiple aperture interferometry the beams have to be split multiple times, resulting in large light losses. On the positive side, flux densities for thermal sources - like stars - are substantially larger for O/IR wavelengths, however, this advantage is eaten up by the need for multi-mirror, free beam propagation with much lower throughput. Taken together it is clear that O/IR interferometry is orders of magnitude more challenging than radio interferometry.

This is especially the case when aiming for long exposures, which require to find at least one bright- and close-enough object to stabilize the fringes. While this is the case all over the sky for radio interferometers, we are very far from this situation in the optical because of atmospheric turbulence. But we are currently witnessing this transition for IR wavelengths with performance increase by large factors.

1.3. Performance increase by large factors

We suggest a 4th era of O/IR interferometry has begun with GRAVITY and the advent and routine use of dual-beam phase-referencing on 8-m class telescopes (Figure 2). The combination of adaptive optics (AO), dual-beam interferometry, and the ability to track the fast atmospheric fluctuations on a bright nearby star has allowed a breakthrough in

Aperture masking:

Technique to recover diffraction limit of a telescope by placing a mask over the telescope, which only allows light through a small number of holes

Speckle

interferometry:

Technique to recover diffraction limit of a telescope by recording a series of short exposures

Radio: Wavelength range from \lesssim mm - meter, observed by radio techniques, i.e. the amplification and mixing of the electric field (heterodyne)

Aperture synthesis:

Technique to produce images by interferometry with an array of telescopes

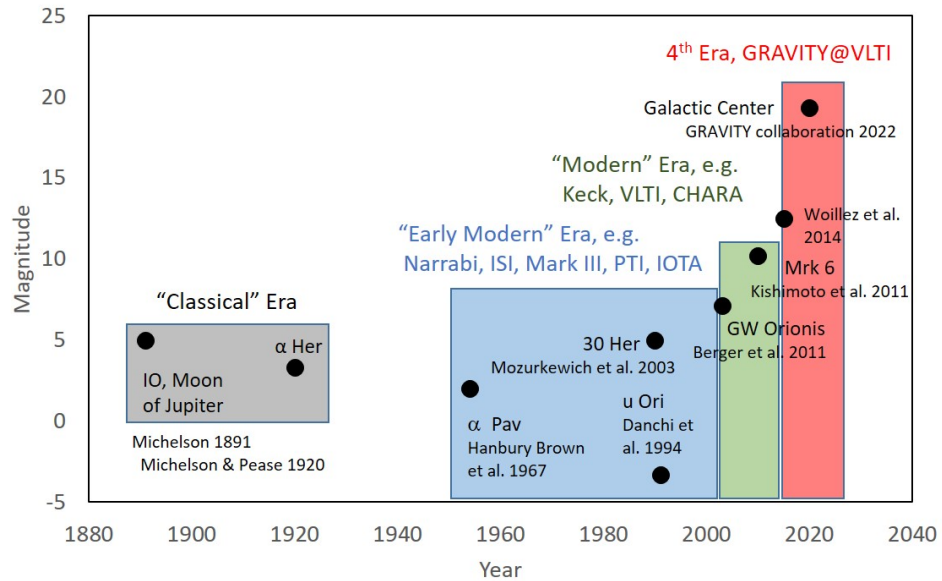


Figure 2

Sensitivity of O/IR interferometry from the “classical” era with visual “by eye” measurements, followed by the “Early Modern” and “Modern” eras, to the latest advances from the “4th” era with dual-beam phase-referencing. After a century of moderate improvement, the last decade has seen an increase by several order of magnitudes.

sensitivity, extending coherent integrations from 50 milliseconds (ms) to >50 seconds (s), a 1000-fold jump. While the first demonstration was the early ASTRA experiment on the Keck Interferometer, the VLT/GRAVITY project, initiated in 2005 by later Nobel Laureate Reinhard Genzel, has mastered the technique, and together with new detectors, integrated optics and improved laser metrology, allowed breakthroughs on the Galactic Center, exoplanets, and active galactic nuclei.

INTRODUCTION - SUMMARY POINTS

1. O/IR interferometry has matured and is offered at four major facilities.
2. VLT and LBTI possess 8-m class telescopes for high sensitivity, CHARA and NPOI provide higher angular resolution and focus on imaging.
3. A new era of dual-beam phase-referenced interferometry has begun, allowing fringe detection on objects fainter than 19 magnitude with VLT/GRAVITY.

2. ASTROPHYSICAL BREAKTHROUGHS

2.1. Imaging of stellar surfaces

The current 4- and 6-telescope arrays have made interferometric imaging routine. Simple objects like binary stars have been imaged for some time but rarely offered advantages over model fitting. More challenging and scientifically-fruitful is imaging of stellar surfaces,

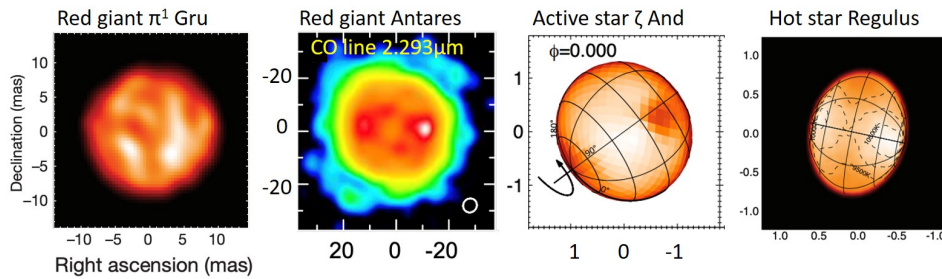


Figure 3

The last decade has seen a breakthrough in stellar imaging as 4- and 6-telescope interferometers now have sufficient uv coverage and angular resolution to resolve the surfaces of red giants and supergiants, magnetically active stars, and even the closest hot rapid-rotators. Figures reproduced with permissions (from left to right: Paladini et al. 2018, Ohnaka et al. 2017, Roettenbacher et al. 2016, Che et al. 2011).

where complex phenomena, such as convection and magnetic fields, play out and defy simply parameterization.

Evolved stars host a number of non-trivial and interesting kinds of stellar physics – pulsations, dust production, convective spots – and these change on monthly to yearly time scales. Early imaging efforts (e.g., IOTA; Haubois et al. 2009) suffered from sparse uv coverage due to the small number of telescopes and limited baselines available. More recently, efforts at the VLTI ATs and CHARA have led to remarkable images of red giants (Figure 3). They include state-of-the-art images by Paladini et al. (2018) with approximately eight pixels across the photosphere, and rigorous interpretations inferred through 3D numerical simulations (e.g., Chiavassa et al. 2009). With high spectral resolution, it is now possible to go beyond diameters and imaging of molecular shells (e.g., Perrin et al. 2004, 2020, Le Bouquin et al. 2009) and even *kinematically* resolve motions within molecular shells using, e.g. CO bandhead transitions (Ohnaka et al. 2017).

The long baselines of CHARA open up imaging for stars too far away or too small for other arrays. Sunspots caused by stifled convection from strong localized magnetic fields are seen on the Sun and inferred on other stars from photometric variations. Roettenbacher et al. (2016) and Parks et al. (2021) published images of huge magnetic spots on all sides of the ζ And and λ And systems respectively, finding asymmetric distributions of spots quite unlike Sun’s.

Lastly, sub-mas angular resolutions also allow imaging the bloated surfaces of the brightest, rapidly-rotating, hot stars (e.g., van Belle 2012), e.g., the surface of the B-star Regulus with a highly-oblate surface distorted by centrifugal forces and strong equatorial “gravity” darkening (Che et al. 2011). Results on a half-dozen hot stars have led to new insights into non-spherical energy transport and advanced first-principle modelling of rotating stars (e.g., Espinosa Lara & Rieutord 2013)

2.2. Revealing the inner astronomical units of circumstellar disks

One of the most fast-developing and exciting areas of astronomy today is planet formation. The mas angular resolution of O/IR interferometers translates into about 0.1 Astronomical Units (AU) physical scale at nearby star forming regions, revealing the signposts of planet-

Interferometric Imaging:

see Aperture Synthesis, technique to make images with interferometers

Red giant star: Large and therefore luminous star in a late phase of its evolution, where the atmosphere is inflated and tenuous

Young Stellar Object (YSO): Star in early phase of evolution, still surrounded by a circum-stellar disc

T Tauri star: Low mass YSO ($< 0.2 M_{\odot}$)

Herbig Ae/Be star: Intermediate – high mass YSO ($2 - 8 M_{\odot}$)

H α and Br γ : Hydrogen emission lines at 656 nm and 2.16 μm

CO band: Band of molecular absorption or emission lines from Carbon monoxide, typically observed at K-band

FU Orionis star: YSO displaying extreme change of brightness and temperature

AGB star: Asymptotic giant branch star - evolved, cool star, often creating circumstellar envelopes

formation, orbiting and outflowing dust, and complex physics of the star-disk connection which generated jets and outflows and transports angular momentum to the forming star (see, e.g., Dullemond & Monnier 2010, for an overview). IR interferometry combined with ALMA’s view of the outer disk (e.g., Andrews et al. 2018) and O/IR coronagraphy of scattered light (e.g, Benisty et al. 2022) is providing a rich and comprehensive picture of how planets are assembling in the earliest stages of their formation.

The advent of sensitive 4-telescope combiners at VLTI have revolutionized studies of young stellar objects (YSO) by vastly increasing the number of objects observable, expanding wavelength coverage, improving homogeneity of the samples, and probing asymmetries using closure phases. Lazareff et al. (2017) and Gravity Collaboration et al. (2019c) measured homogeneous sizes and orientations of over dozens Herbig Ae/Be stars in H- and K-bands, vastly improving the data quality over earlier pioneering studies (e.g, Monnier & Millan-Gabet 2002). The size-luminosity diagram (Figure 4) shows a robust correlation over many orders-of-magnitude in luminosity, though with large scatter, potentially due to stochasticity from the formation of young planets. Kluska et al. (2020a) used advanced image reconstruction algorithms for some of these targets (HD 45677 in Figure 4), finding only a few ring-like structures, with more often centrally-bright emission. Recent multi-epoch studies have further found a strong time variability in some objects (Kobus et al. 2020, Gravity Collaboration et al. 2021f), the cause of which is unclear. A large sample of T Tauri disks in the K-band (Gravity Collaboration et al. 2021e) also found a strong breakdown of the size-luminosity relation (in line with earlier Keck Interferometer results; Akeson et al. 2005), related to greater importance of scattering and accretion.

The Keck Interferometer and VLTI have also allowed to spatially and spectrally resolve the Hydrogen Br γ line, probing the kinematics of accretion and the “star-disk” connection on sub-AU scales. Early studies did not find a clear picture, some disks showed compact Br γ emissions smaller than the dust ring, while other showed emission on the same scales (Kraus et al. 2008, Eisner et al. 2009). While only a few results have been obtained so far (e.g., Bouvier et al. 2020), GRAVITY has the potential to carry out a large survey of Br γ line emission as well as the CO bandhead (e.g., Gravity Collaboration et al. 2020d, Wojtczak et al. 2022). CHARA/VEGA (Perraut et al. 2016) was first to resolve the H α line in the accretion disk of AB Aur, finding a larger-than-expected extent from the magnetocentrifugal wind launched between the star and dusty disk’s inner edge.

The shape of the dust sublimation front and contribution of gas/dust emissions very close to the star are too small to be definitively resolved by VLTI. CHARA, with > 300 m baselines, has fully resolved the inner disk emission for two bright Herbig Ae/Be stars and found strong emission coming from inside the putative dust evaporation front (Setterholm et al. 2018), corroborating earlier studies (e.g., Benisty et al. 2010). Recently, VLTI and CHARA data has been combined to directly image the rim shape for the Herbig Be star v1295 Aql (Ibrahim et al, in press), finding a bright thin ring but with mysterious inner emission (see rightmost panel of Fig.9).

New IR interferometry has validated some untested theory and solved long-standing mysteries. Labdon et al. (2021) found the disk temperature profile of the prototype FU Ori object to closely match $T \propto r^{-\frac{3}{4}}$, a 30-year old prediction by Hartmann & Kenyon (1985). The Br γ emission around TW Hya was interpreted as definitive proof of the magnetospheric accretion paradigm (Gravity Collaboration et al. 2020f). The complex dust geometry for the young interacting system GW Ori was finally solved by Kraus et al. (2020a). Lastly, Labdon et al. (2019) and Bohn et al. (2022) combined IR interferometry with adaptive optics to

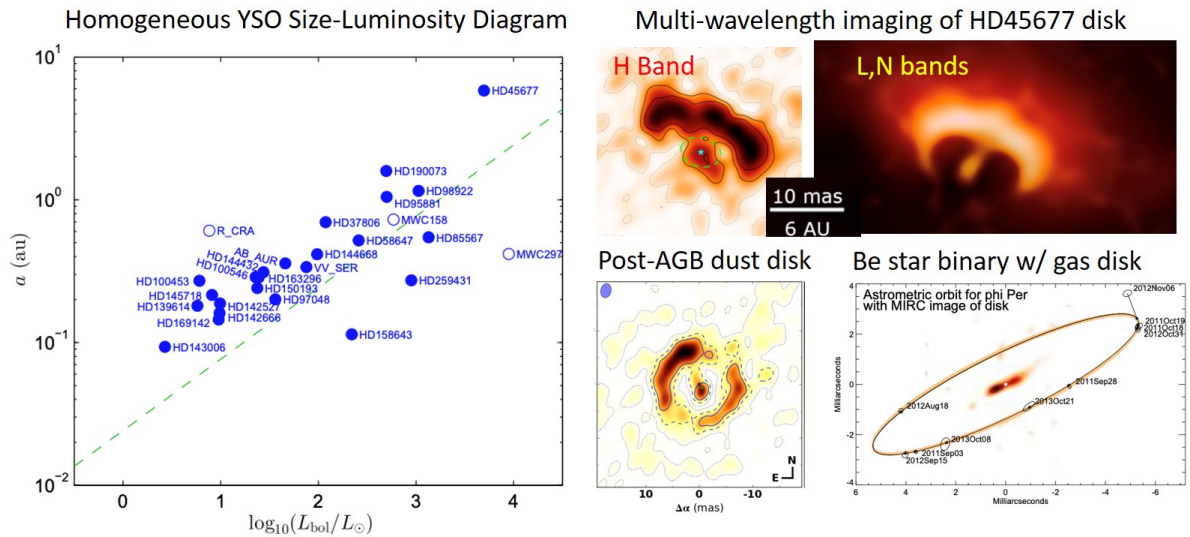


Figure 4

IR interferometers now probe statistically-significant, homogeneous samples of YSOs, for example to study their size-luminosity relation (left). Further, it is the only current technology that can image the inner AU of planet-forming disks, Be star gas disks, interacting binaries, and circumbinary disks. Figures reproduced with permission (Lazareff et al. 2017, Kluska et al. 2020a, Lopez et al. 2022, Hillen et al. 2016, Mourard et al. 2015)

prove that inner disk misalignments produce the dark shadow bands seen at 100 AU scales for many disks.

Disks and outflows have also been imaged around other kinds of stars. Mourard et al. (2015) were able to image the ϕ Per disk with CHARA in both Br α and continuum (Figure 4), showing a clear connection between the disk geometry and close-in binary companion. Circumstellar disks can also form in close interacting binaries (Figure 4, Zhao et al. 2008) and in post-AGB systems (Figure 4, Hillen et al. 2016). The recent commissioning of the MIR combiner VLTI-MATISSE (see early result by Lopez et al. 2022, in Fig.4) will revolutionize studies of dusty outflows in a wide variety of environments including AGB stars (e.g., Chiavassa et al. 2022).

2.3. Testing the black hole paradigm in the Galactic Center

Motivated by the discovery of the first quasars in the 60s, Lynden-Bell & Rees (1971) proposed that most galactic nuclei, including the Galactic Center might host a supermassive black hole (SMBH). The discovery of the compact radio source SgrA* (Balick & Brown 1974) at the core of the central nuclear star cluster provided some evidence for their proposition. However, SgrA* is faint in all bands other than the radio and sub-millimeter. With abundant gas in the inner 1 parsec (pc) to fuel a potential SMBH, the case for an extremely underluminous SMBH was considered fairly unconvincing. This only changed with the advent of NIR Speckle and AO images of the central 1 pc. Proper motions and later full orbits of stars demonstrated the existence of a compact central mass. The combination of precision astrometry better than 1 mas with spectroscopy allowed to weigh the enclosed

Black hole: Object so massive and compact that not even light can escape, consequence of the General Relativity theory by Albert Einstein

SgrA*: Name of the radio source in the Galactic Center - the black hole

2020 Nobel Prize in Physics for the Discovery of the Galactic Center Black Hole

The Nobel Prize in Physics 2020 was awarded to Reinhard Genzel and Andrea Ghez for the "discovery of a supermassive compact object at the centre of our galaxy" and to Roger Penrose "for the discovery that black hole formation is a robust prediction of the general theory of relativity". The discovery of the Galactic Center is building on the experimental breakthrough in high angular resolution astronomy over the last 30 years, starting from Speckle Interferometry to recover the diffraction limited resolution of large telescopes in the 1990s, followed by AO and imaging spectroscopy in the 2000s, and initiated by Reinhard Genzel in 2005, with GRAVITY long baseline interferometry (since 2017) providing mas resolution imaging and few ten micro-arcsecond astrometry - the topic of this article.

Event horizon: The boundary of no escape. Its size is given by the Schwarzschild radius $r_s = \frac{2GM}{c^2}$, where G is the gravitational constant, M the mass of the black hole, and c the speed of light

Innermost last stable circular orbit (ISCO): Closest orbit for particles, before general relativistic effects drag matter irrevocably into the black hole

S-stars: Population of young, high-mass stars orbiting close to the black hole

Flares: Sporadic emission at IR and X-rays, raising by factor few ten to hundreds above quiescent emission

mass, to measure its distance and to set tight constraints on the density and therefore on the nature of the enclosed mass. By the end of the 2000s, the analysis of several dozen orbits in combination with radio measurements of the size and motion of SgrA* established that the radio source must be a massive black hole with about $4 \times 10^6 M_\odot$, "beyond any reasonable doubt" (for a review, see Genzel et al. 2010).

The dynamical measurements from AO images allowed to derive the mass of the central object with a few percent accuracy. The motion of the stars follow almost perfect Keplerian orbits, even for stars like S2 that passes the central source as close as $1400 r_s \approx 120$ AU (Schwarzschild radius: $r_s = 2GM/c^2$). Following the pericenter passage of S2 in 2002 it became clear that the first-order General Relativity (GR) effects will come in reach with precision observations (Rubilar & Eckart 2001). Despite the fact that a black hole is a genuine prediction of GR, the signatures of GR on the stellar orbits with the leading post-Newtonian terms ($O(\beta^2)$, $\beta = v/c$), namely gravitational redshift and Schwarzschild precession, are small perturbations w.r.t. the Keplerian motion (for a review, see Alexander 2005). The gravitational redshift scales with $\beta^2 \approx r_s/r$, in case of S2 approx. 200 km/s compared to the maximum velocity of 7700 km/s at pericenter passage. The Schwarzschild precession rotates the elliptical orbit by $\approx 12.1'$ per 16 yr revolution. In order to measure the effects, a significant (factor 4 – 10) improvement in astrometry compared to what was possible in 2010 was needed. This posed one of the main science drivers for the development of the GRAVITY instrument (Eisenhauer et al. 2008, Paumard et al. 2008). Since the first light (Gravity Collaboration et al. 2017a), GRAVITY has been regularly monitoring observing the central S-stars and SgrA*. On May 19, 2018, S2 passed pericenter with 2.6% of the speed of light. By simultaneously monitoring the stars radial velocity and motion on the sky, Gravity Collaboration et al. (2018a) were able to detect the gravitational redshift and transverse Doppler effect at high significance (later confirmed by Do et al. 2019). The statistical robustness of the redshift detection was further improved by Gravity Collaboration et al. (2019a) to more than 20σ significance. Amorim et al. (2019) used two atomic transition lines in the spectrum of S2 to test one pillar of the Einstein equivalence principle and thus General Relativity, the local position invariance (LPI). By separately measuring the redshift of the hydrogen and helium lines in the stellar spectrum, effectively two independent clocks can be probed, while moving through the black hole's gravitational potential. The results set an upper limit on a violation of the LPI of 5×10^{-2} for a change of potential which is six magnitudes larger than accessible with terrestrial experiments.

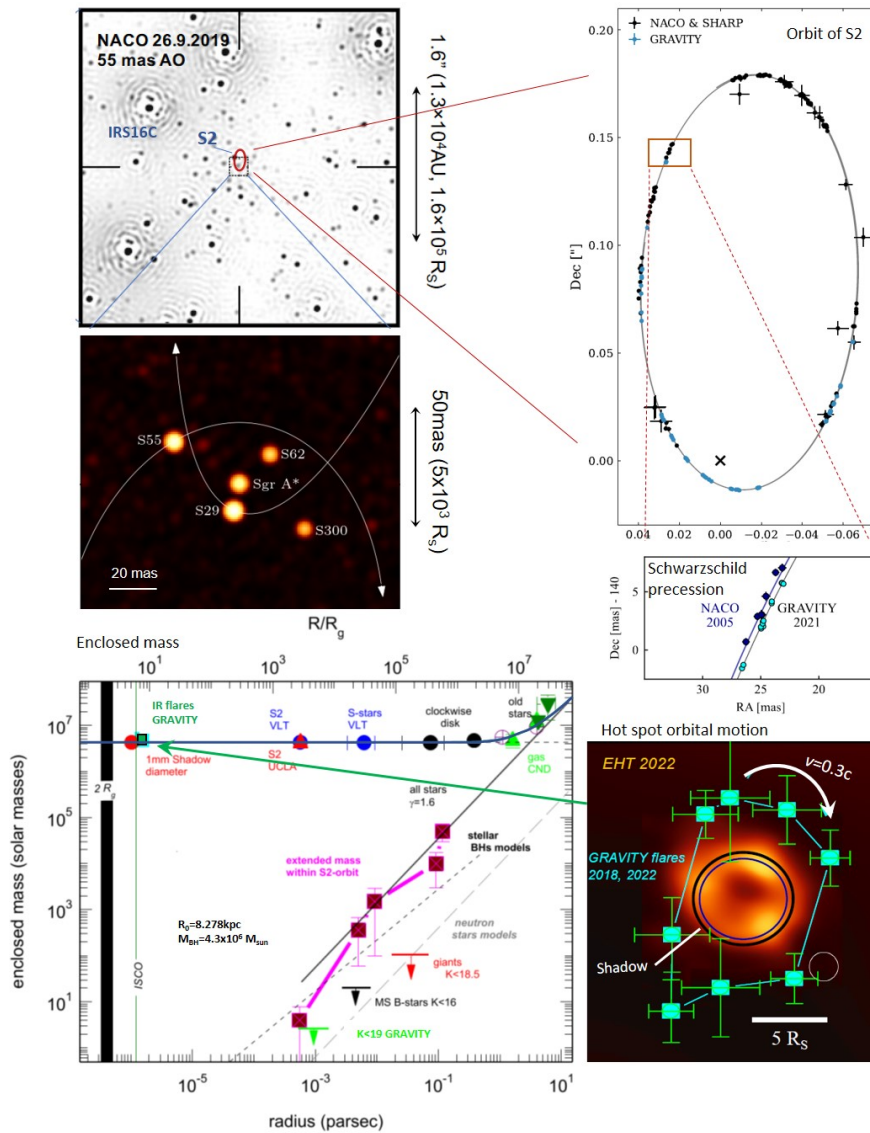


Figure 5

Upper left: AO image of the Galactic Center obtained with an 8-m telescope. Middle left: Interferometric image of the central 0.1'' (Gravity Collaboration et al. 2022a, 2021a). The crowded region cannot be resolved with single telescope observations. Upper right: S2-SgrA* orbit. (Gravity Collaboration et al. 2020b). Middle right: Zoom on the orbit of S2. The orbit does not close due to the Schwarzschild precession (Gravity Collaboration et al. 2020b, 2022b). Lower left: Enclosed mass in of the central 1 pc centred on SgrA*. Lower right: IR flare positions observed over approx. 30 min. The motion shows a ($i \sim 30^\circ$) orbit of a hot spot at $3-4 r_s$ (Gravity Collaboration et al. 2018b, in prep.). The background shows the EHT image of SgrA* (from Event Horizon Telescope Collaboration et al. 2022).

Gravitational redshift:

Spectroscopic signature that time slows down close to a black hole

Schwarzschild precession:

Precession of elliptical orbits resulting from curved space time

Einstein equivalence principle:

Outcome of any local non-gravitational experiment in free fall is independent of the velocity and its location

Only a few months after the pericenter passage of S2, GRAVITY captured several bright flares showing circular motion of the emission region (Figure 5, Gravity Collaboration et al. 2018b). The observed motion shows an orbit of a compact polarized “hot spot” of IR synchrotron emission at approximately 3 to 5 Schwarzschild radii of a black hole of 4.3 million solar masses. This corresponds to the region just outside the innermost, stable, prograde circular orbit (ISCO) of a Schwarzschild–Kerr black hole. The simultaneous motion, light curve and polarisation measurements of the flares allowed to constrain the inclination of the flaring region to a near face-on ($i \approx 30^\circ$) orbit. The results are in remarkable agreement with the inclination and size later derived for the radio image of SgrA* (Event Horizon Telescope Collaboration et al. 2022), suggesting that IR and radio emission originate both from the same region. The flare detection and the EHT image provide unique evidence that 4.3 million solar masses are contained in a region of a few r_s (Figure 5, lower left), a mass density only explained by a black hole. Gravity Collaboration et al. (2020a) substantiated that SgrA* has two states: the bulk of the IR emission is generated in a lognormal process with a median flux density of 1.1 milli-Jansky. This quiescent emission is supplemented by sporadic bright flares that create the observed power law extension of the flux distribution, and which are also observed in X-rays.

Two years after the detection of the gravitational redshift, Gravity Collaboration et al. (2020b) reported the detection of the prograde Schwarzschild precession induced by the gravitational field of the SMBH (Figure 5). The authors measured the mass of the black hole with 0.4% accuracy and ruled out the presence of a binary SMBH. Gravity Collaboration et al. (2022b) refined the measurement and set an upper limit on an extended mass, e.g. a putative cusp of stellar remnants surrounding the SBMH, of less than $3000 M_\odot$ within the apocenter of S2.

The monitoring of the S-stars not only allowed to test the black hole paradigm but also allowed tackling a classical astrophysical problem; the distance of the sun from the Galactic Center. GRAVITY determined the distance between the Sun and the SMBH to $R_0 = 8277$ pc with 0.4% accuracy (Gravity Collaboration et al. 2019a, 2020b, 2021b), confirming that the SMBH is located at the center of the Milky Way Bulge ($R_{0,bulge} = 8210 \pm 80$ pc, Bland-Hawthorn & Gerhard 2016).

GRAVITY has delivered precision tests of Einstein’s general theory of relativity and the so far strongest experimental evidence that the compact mass in the Galactic Center (SgrA*) is indeed a Schwarzschild-Kerr black hole. What can we expect in the future? The upgrade of GRAVITY with its current sensitivity limit of $K \approx 19.5$ (Gravity Collaboration et al. 2021a) to GRAVITY+ (Eisenhauer 2019, GRAVITY+ Collaboration et al. 2022) will push the sensitivity limit to $K > 22$, with the expectation to reveal more stars on even smaller orbits than S2. The astrometry from interferometry and the radial velocities from upcoming 30-40 m telescopes will then allow to probe higher-order GR effects such as frame dragging of space time due to the spin of the black hole or the imprint of the black hole’s quadrupole moment, and thereby might even provide a test of the general relativistic no-hair theorem.

Active Galactic Nucleus (AGN):

Center of a galaxy, for which the emission is dominated by the accretion on a massive black hole

2.4. Resolving the Broad Line Region and imaging the hot dust in Active Galactic Nuclei

An Active Galactic Nucleus (AGN) is a massive accreting black hole in the center of a galaxy with an Eddington ratio $L_{AGN}/L_{Edd} > 10^{-5}$, where L_{AGN} is the bolometric

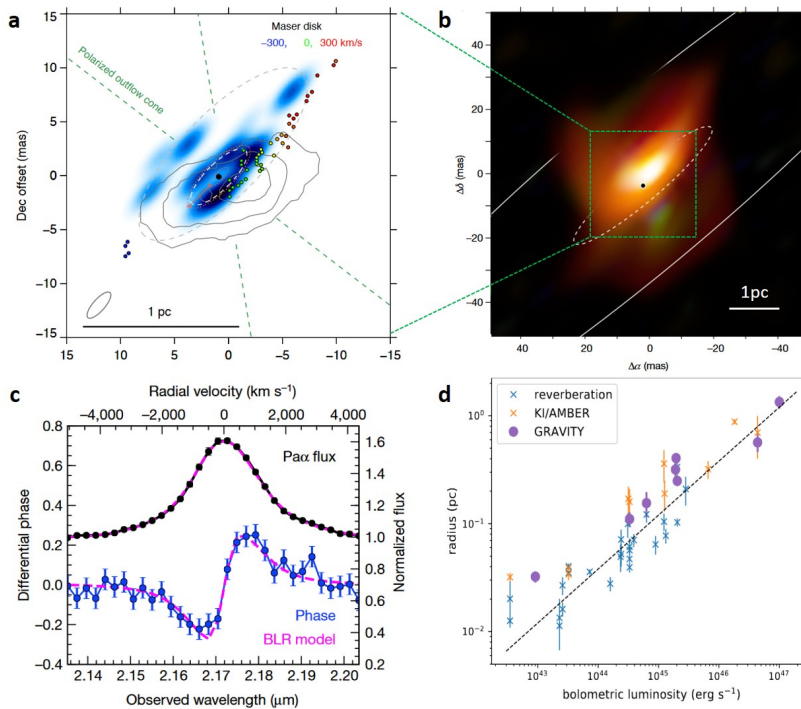


Figure 6

(a): K -band image of the inner 2 pc of NGC 1068 (Gravity Collaboration et al. 2020h). The dashed white ellipse corresponds to the dust sublimation radius. The filled black circle indicates the the AGN, and the kinematic centre of the masers (coloured circles); (b): MATISSE multi-color image of NGC 1068 (credit: ESO/Jaffe, Gámez Rosas et al. 2022); (c): Gravity Collaboration et al. (2018c) spatially resolved the broad emission line kinematics of 3C 273. Pa α line profile (black) showing non-zero phases and a change of sign across the broad emission line; (d): Radius-luminosity relation for dust size measurements (blue and orange crosses: from literature, filled circles: Gravity Collaboration et al. (2020e)). The dashed line is the $R \sim L^{1/2}$ fit to reverberation measurements (Koshida et al. 2014).

luminosity and L_{Edd} is the Eddington luminosity (e.g., Netzer 2015). AGN are thought to play an important role in galaxy evolution: energy released by AGN through radiation or powering outflows (i.e. AGN feedback) can transform star-forming galaxies into quiescent galaxies. The unified model of AGN assumes that a dust torus obscures the central engine, accretion disc, and the Broad Line Region (BLR), such that the AGN can only be observed directly from polar directions (Antonucci & Miller 1985).

IR interferometry has played a crucial role in the study of the torus region because the apparent size of 1 pc at the distance of the closest AGNs (~ 20 Mega-parsec (Mpc)) is < 10 mas, a scale which can only be resolved with long baseline interferometry. While AGN are intrinsically bright in the IR, their relatively large distances require 8-m telescopes for observations. Early papers, using single baseline interferometers and V^2 -fitting, identified the presence of multiple dust components with an elongated (1.4×0.5 pc) 600 – 800 K dust core (e.g. Jaffe et al. 2004). About two dozen AGN have been partially resolved with

Quasar (QSO):

Extremely luminous AGN, with unobscured view on the central black hole and accretion disc, brightest objects in the universe

Broad Line Region (BLR):

Ionized gas clouds moving at high speed close to the black hole, observed as broad emission lines

Dust Torus: Opaque material in the equatorial plane obscuring the direct view on the central black hole

Spectro-astrometry:

A differential measurement providing μas astrometry tracing the photo-center shift across an emission line

the Keck interferometer (e.g. Swain et al. 2003, Kishimoto et al. 2011), early VLTI (e.g. Burtscher et al. 2013), and more recently GRAVITY (Gravity Collaboration et al. 2020e, Leftley et al. 2021). This led to a dust size-luminosity relation for nearby AGN, independent of the relation inferred from dust reverberation mapping (Figure 6d).

The advent of the 2nd generation VLTI instruments and the combination of four 8-m telescopes allowed for the first time to reconstruct images with GRAVITY and MATISSE. Gravity Collaboration et al. (2020h) resolved the central 2 pc of NGC 1068 in K-band with a spatial resolution of 3 mas (Figure 6a) and found a ring-like structure on sub-pc scales. The size matches that expected for the dust sublimation region, and the apparent orientation is similar to that of the maser disc, arguing for a common origin. This scenario is at odds with a geometrically and optically thick clumpy torus and instead argues for the presence of a dusty thin disc around the AGN, which is screened by dense and turbulent gas distributed on scales of 1–10 pc, e.g. from AGN-driven outflows. This interpretation has been contested by Gamez Rosas et al. (2022), who resolved the central region with MATISSE at lower resolution but longer wavelengths from 3.7 – 12 μm (Figure 6b). The derived dust temperatures and absorption values are consistent with a thick, nearly edge-on disk as predicted by the torus model. The different interpretation is largely driven by the assumptions made to align the radio continuum and maser emission and IR image.

The BLR with an angular size < 0.1 mas is even smaller than the hot dust region, and it is impossible to image even with the VLTI. Instead, the kinematics can be studied by “spectro-astrometry”, which measures the photo-center shift of the atomic gas as a function of wavelength (or velocity) across the emission line. The photo-center shift results in a small differential phase signal $< 1^\circ$, whose detection requires high sensitivity and deep integrations. Gravity Collaboration et al. (2018c) for the first time detected the characteristic S-shaped phase signal of a rotating disk in the broad Pa α emission line of the quasar 3C 273 (Figure 6c). The signal is well described by a model (following Pancoast et al. 2014) of fast moving gas clouds in a thick disk in Keplerian rotation around a supermassive black hole of $1.5 - 4.1 \times 10^8 M_\odot$. The inclination and position angles agree with those inferred for the radio jet. The measured emission radius is $R_{\text{BLR}} = 0.12 \pm 0.03$ pc (at an angular diameter distance of 548 Mpc). To this day, three BLRs have been resolved successfully with spectro-astrometry (3C 273, NGC 3783 and IRAS 09149-6206; Gravity Collaboration et al. 2018c, 2020c, 2021d, Figure 6), which revealed their structure, kinematics and angular BLR sizes with an unrivaled spatial resolution. The joint analysis of the angular BLR size measurement from GRAVITY and the linear BLR size from reverberation mapping campaigns allowed Wang et al. (2020) to derive an angular distance of 3C273 of 552_{-79}^{+97} Mpc and an independent measurement of the Hubble constant $H_0 = 72 \text{ kms}^{-1} \text{ Mpc}^{-1}$ with 15% uncertainty. In a similar way, Gravity Collaboration et al. (2021c) found a geometric distance to NGC 3783 of 39.9_{-12}^{+15} Mpc and derived H_0 with a 30% uncertainty. GRAVITY already demonstrated first fringes of a redshift $z=2.5$ quasar (GRAVITY+ Collaboration et al. 2022). Future BLR observations of a reasonably sized sample (≈ 30 AGNs) will provide a new tool for measuring the masses of black holes at cosmological distances, and might allow to test the H_0 tension with $< 3\%$ accuracy (Wang et al. 2020). A similar tool might be provided by the interferometric dust parallax measurement as introduced by Honig et al. (2014).

2.5. Observations of exoplanets and spectroscopy of their atmosphere

While only applicable for a few dozen exoplanets so far, direct imaging offers the unique possibility to probe the thermal emission from the exoplanet's atmosphere, key for measuring the composition of their dense atmospheres. However, direct imaging is impaired by the small separation and the contrast between the exoplanets and their host stars, and only young, hot ($\lesssim 1000$ K) and far ($\gtrsim 10$ AU) planets are observable by AO and coronagraphy. IR interferometry has pushed both limits by orders of magnitude, providing the so far best-quality, high-resolution spectra from hot planets, orbit measurements with few ten micro-arcsecond (μas) astrometry, and first direct observations of planets previously known only from radial velocities.

The first detection of an exoplanet with interferometry (Gravity Collaboration et al. 2019b) was HR 8799 e, a planet only $0.39''$ from its host star. The spectra from GRAVITY are roughly ten-times higher signal-to-noise than possible with single telescope observations. This allows retrieving the properties of clouds and disequilibrium chemistry in the exoplanet atmosphere (Mollière et al. 2020) and to calibrate the mass-luminosity relations for protoplanets. Since this breakthrough, a series of observations have led to spectra for, e.g., β Pic b,c (Gravity Collaboration et al. 2020g, Nowak et al. 2020, Lagrange et al. 2020) and the PDS 70 protoplanets (Wang et al. 2021). The spectrum from β Pic b (Figure 7) allowed to peer into the formation history of this exoplanet: the low C/O ratio measured from the exoplanet spectrum, and the high mass of the exoplanet determined from astrometry, suggest a formation through core-accretion, with strong planetesimal enrichment.

The higher angular resolution and better contrast of interferometry has also led to first direct detections of exoplanets, which were previously known from radial velocity measurements, but which are too faint and too close to the host star for imaging with AO and coronagraphs. The first of these radial velocity planets detected and characterized with interferometry was β Pic c (Nowak et al. 2020, Lagrange et al. 2020), an $8\text{--}9 M_{\text{Jupiter}}$ planet, orbiting at a distance of only 2.7 AU inside the planet β Pic b discussed above. β Pic c is 11 mag fainter – a factor 25000 – than the host star, and was detected at a separation as close as 96 mas. The astrometric errors for the β Pic b,c planetary systems are as small as $20\text{--}50 \mu\text{as}$. This allowed for the first time measuring the mass of an exoplanet from its gravitational imprint on the astrometry of another planet (Lacour et al. 2021).

One limitation for the direct detection of radial velocity planets by interferometry is the small field of view, and that the radial velocity technique does not provide the inclination of the orbit, therefore the direction to look for the planet. The β Pic planetary system is exceptional in this sense, because it is seen edge-on, both the debris disk as well as the orbit of the outer planet, thereby providing a good prior estimate for the location of the radial velocity planet. The second radial velocity planet directly detected by interferometry was HD 206893 c (Hinkley et al. 2022), an $\approx 12 M_{\text{Jupiter}}$ planet at the limit of the brown dwarf regime, maybe one of the rare planets exhibiting Deuterium burning in its center. In this case the detection of the radial velocity planet was guided by GAIA astrometry, which narrowed down the patrol field to be surveyed with the interferometer. Many additional planet detections are expected from GAIA astrometry (Wallace et al. 2021), which will be reachable with interferometry, but not with traditional coronagraphic imaging. The GRAVITY+ upgrade (Eisenhauer 2019) is expected to then see emission from > 40 gas giant exoplanets in the young co-moving groups close to the Earth, and an additional 30 exoplanets in more distant star forming regions.

Exoplanets have also long been sought using astrometry between two stars (Shao &

Exoplanet: Planet outside the solar system

Directly detected planet: Emission from the exoplanet is directly seen in high contrast imaging or interferometry

Radial velocity planet: Exoplanet detected by the reflex motion and resulting radial velocity of its host star. Recognized with the 2019 Nobel Prize in Physics

Transiting exoplanet: Exoplanet which blocks some of the starlight as it passes in front of its host star

C/O ratio: Abundance ratio of Carbon over Oxygen, a tracer for planet formation history

GAIA: Space observatory measuring the positions, distances and motions of stars with unprecedented precision

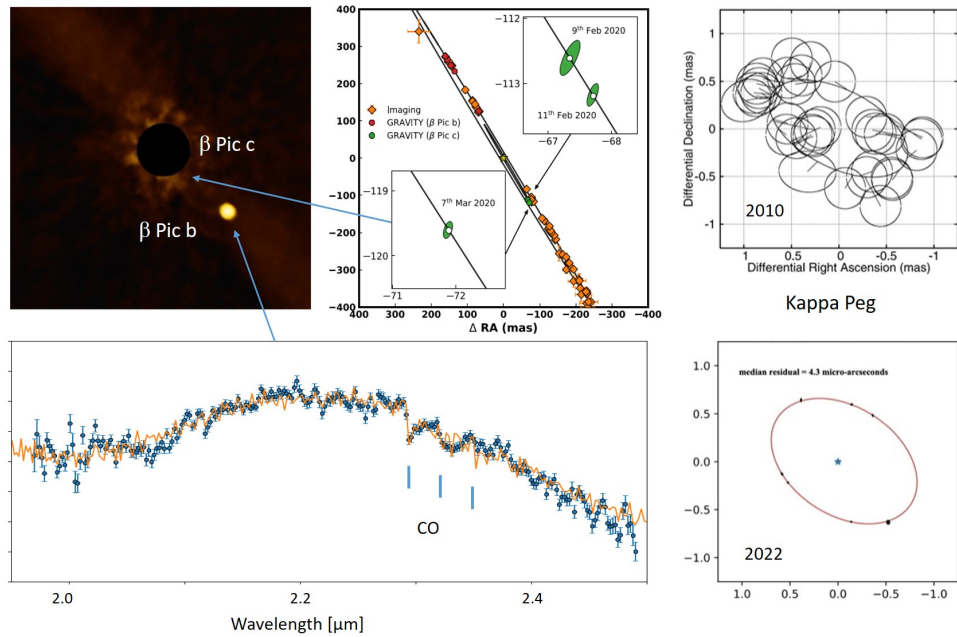


Figure 7

Interferometric observations of exoplanets: top left: AO image of the β Pic b exoplanet (credit: ESO/Lagrange/SPHERE consortium). The GRAVITY observations have resulted in the by far best spectrum of its atmosphere (bottom), and allowed to measure its C/O ratio, indicating that the planet has probably formed through core-accretion with strong planetesimal enrichment (Gravity Collaboration et al. 2020g). The superior contrast and angular resolution of GRAVITY also led to the first direct detection of an exoplanet, which was previously known only from radial velocity measurements (β Pic c; Lagrange et al. 2020, Nowak et al. 2020). The right panels illustrate the radical improvement in astrometry of binary stars over the past decade (top: astrometric wobble of κ Peg B from PTI (Muterspaugh et al. 2006) and CHARA (Gardner et al. 2021), which should allow discovery of new exoplanets in the next years.

Microlensing:

Gravitational magnification of a background star by another object passing in front, increasing its brightness. The lensed image is unresolved by single telescopes

Colavita 1992). The GRAVITY collaboration has followed up this route with differential astrometry of young, nearby visual binary system, e.g. GJ 65 AB, WDS J20452-3120 BC, and HD 142 AB, but results have not been published to date. The PHASES project on the Palomar Testbed Interferometer (PTI) measured differential phase between two close-by stars, achieving $\approx 100 \mu\text{s}$ precision (Muterspaugh et al. 2010). This concept was updated for CHARA/MIRC-X and VLTI/GRAVITY observations using precision wavelength calibration and medium spectral dispersion to overlap fringe packets, and demonstrated $\approx 10 - 20 \mu\text{s}$ differential precision sufficient to detect giant exoplanets, though none have been reported so far (Gardner et al. 2022).

2.6. Other major advances

There are many other notable firsts from O/IR interferometry in the past decade. Dong et al. (2019), Zang et al. (2020), Cassan et al. (2022) were able to resolve the multiple images and arcs formed during a microlensing event. Kraus et al. (2020b) used μs spectral-

differential astrometry to measure the rotation axis of an individual star (Kraus et al. 2020b). The high-mass x-ray binaries SS 433 and BP Cru were probed with μas spectro-differential astrometry to resolve the gas and jet in these systems (Gravity Collaboration et al. 2017b, Waisberg et al. 2017). Kloppenborg et al. (2010) imaged the transit of a mysterious edge-on dusty disk across the face of the bright star ϵ Aur. Schaefer et al. (2014) watched Nova Del 2013 expand from 0.4 mas on day 2 to > 10 mas a month later.

Interferometry is also used to measure fundamental properties of stars and our current facilities allow for extensive and rigorous surveys of stellar diameters as well as binaries. Here, we highlight the contributions by Boyajian et al. (2012) to calibrate the effective temperature scale for main sequence solar-type stars, Huber et al. (2012) to link precision diameters with asteroseismology using the sensitive visible-light CHARA/PAVO combiner (Ireland et al. 2008), Sana et al. (2014) to determine binary statistics for massive stars, Gallenne et al. (2015) to measure masses for important distance-ladders Cepheids, Montargès et al. (2021) to unveil the cause of Betelgeuse’s recent dimming, and Richardson et al. (2021) to measure the first dynamical mass of a N-rich Wolf-Rayet star using a binary separated by only $a = 0.79$ mas.

ASTROPHYSICAL BREAKTHROUGHS - SUMMARY POINTS

1. Imaging the surfaces of stars with sub-milliarcsecond resolution – including evolved stars, magnetic starspots, rapidly-rotating hot stars – is now routine.
2. Warm and hot dust can be imaged around a large number of planet-forming disks and mass-losing stars, revealing unexpected dynamics and complexity.
3. Few 10 μarcsec astrometry of stars and gas as faint as $m_K = 19$ allowed to test GR in the vicinity of the Galactic Center supermassive black hole.
4. Near- and mid-IR imaging of AGN allow testing the unified model. Spectro-astrometry of BLRs provides a new tool to measure black hole masses and distances.
5. Superior contrast and angular resolution of interferometry produce better exoplanet spectra and orbits than AO coronagraphy.

3. INTERFEROMETRY PRIMER

3.1. Two telescope interferometer, angular resolution and field of view

Young’s two-slit experiment illustrates the basic principles of interferometry (Figure 8). When parallel wavefronts from a distant point source go through an aperture with diameter D , the light diffracts over a full-angle $\theta_{\text{beam}} = \frac{\lambda}{D}$, where λ is the observing wavelength. This angle is often referred to as the primary beam and typically sets the maximum field of view for most O/IR interferometers. When light goes through another aperture separated from the first by a baseline B , the electric fields interfere and produce a sinusoidal oscillation (“fringe”) with a spacing of $\theta_{\text{fringe}} = \frac{\lambda}{B}$ (Born & Wolf 1999).

The number of fringes across the pattern is $\frac{B}{D}$, but this will be limited when using a broad spectral bandwidth. Then the number of fringes across an interferogram is set by the coherence length $\Lambda = \frac{\lambda^2}{\Delta\lambda}$ and will be equal to the spectral resolution $R = \frac{\lambda}{\Delta\lambda}$. If R is too small, fringes will not completely fill the diffraction pattern and this will further restrict the effective field of view to $\theta \sim \frac{\lambda}{B} R$. The coherent field of view matches the telescope diffraction limit for a spectral resolution $R = \frac{B}{D}$, which is typically the lowest fractional

Microquasar: Stellar mass black hole with mass accretion from a companion star, strong emission and jets, similar to supermassive black hole quasars

Primary Beam: Diffraction-limited field of view of on telescope $\Theta = \lambda/D$

Fringe Spacing: Interference pattern projected onto sky $\Theta = \lambda/B$

Spectral Resolution: $R = \frac{\lambda}{\Delta\lambda}$

Bandwidth-smearing field-of-view: $\theta = R \frac{\lambda}{B}$

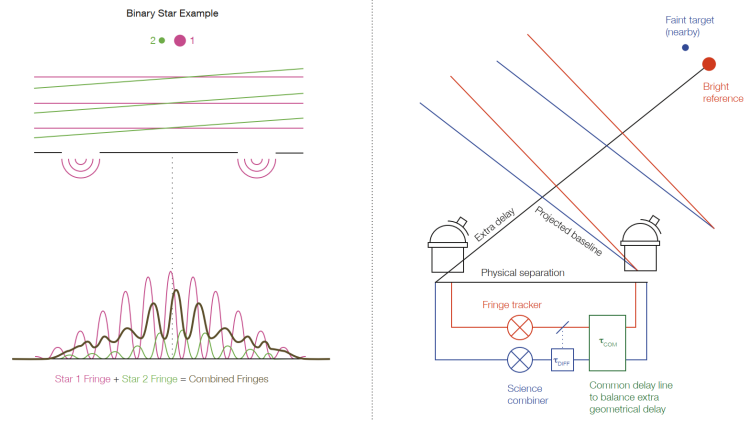


Figure 8

Young’s two-slit experiment (left panel) illustrates the basics of optical interferometry. Each part of a distant source (red+green) will create its own fringe that will incoherently add together (black). The right panel shows the basic elements of a practical ground-based dual-beam interferometer. Light from two fields are delayed together (τ_{common}) to account for common geometrical delay and then split to allow differential delay ($\tau_{\text{differential}}$). The reference starlight (red) is detected at the fringe-tracking combiner and the derived atmospheric delays are then fed-back to the common delay line, allowing longer coherent integration on the science combiner (blue). This is analogous to a wavefront sensor/deformable mirror in a natural guide star AO system.

Fringe visibility \tilde{V} :

Complex number representing amplitude and phase

(u,v) point: The projected baseline (East, North) of the interferometer as seen from the object in units radians^{-1} , associated with each visibility point

bandwidth used in practical interferometers.

3.2. Complex visibilities

When an interferometer looks at a complex object, the interference pattern changes with respect to that of a point source. Figure 8a illustrates the basic principle. Each point of light on the distant source will create its own interference fringe slightly shifted with respect to each other, since the wavefronts are slightly tilted, and with an intensity proportional to the brightness of each part of the source. Since astronomical sources are incoherent, these two sine waves add up in power resulting in a sine wave that is characterized by a fringe amplitude and phase. The normalized amplitude of the fringe is called the contrast or the “visibility” V where unity means the fringe is fully-modulated, creating dark destructive nulls and bright constructive peaks; a zero visibility shows no modulation across the interferogram. O/IR interferometrists have historically used this normalized visibility since the total flux is often poorly measured. Radio astronomers use the coherent flux instead – the total flux times the normalized visibility – with units of flux density ($\text{W}/\text{m}^2/\text{Hz}$), and this practice is becoming common for some IR applications when the normalization is problematic, for example in the thermal IR. The relative position of the fringe gives the “phase” ϕ of the interference. The combination of the two quantities visibility amplitude V and phase ϕ forms the “complex visibility” $\tilde{V} = e^{i\phi}$.

Interpreting this complex visibility is straightforward. Since each point on the sky creates a sine wave, the final observed complex visibility \tilde{V} is simply an integral of sky intensity times sine waves, otherwise known as a Fourier Transform. This relationship

is captured by the van Cittert-Zernike Theorem: $\tilde{V}(u, v) \propto \int_{\text{sky}} I(\alpha, \delta) e^{-2\pi i(u\alpha + v\delta)} d\alpha d\delta$, where $I(\alpha, \delta)$ represents the target brightness distribution on the sky as function of right ascension (α) and declination (δ) and (u, v) represents the projected baseline in (east, north) components.

3.3. Atmospheric coherence lengths and times

In order to translate the elegant principles of interferometry to a practical facility, we must also account for properties of the atmosphere. In this section we will just introduce the basic picture with further elaboration in §5, and refer the reader to a more in-depth treatment by Quirrenbach (2000).

The ideal picture of an interferometer starts to break down when we consider light propagating through the atmosphere. The perfectly flat wavefronts at the top of the atmosphere become distorted as they encounter varying densities of air. Simplistically, we can follow each ray and add up the time delay caused by the index of refraction of air. Rays close together go through essentially the same air and so have small root-mean-square (RMS) variation while rays far apart become more different. The Fried parameter r_0 , or atmospheric coherence length, is defined as the diameter of the circular aperture that has an average RMS wavefront error of 1 radian in phase. This value is wavelength dependent both because the phase depends on wavelength and the index of refraction varies some with wavelength. The theory of Kolmogorov turbulence predicts that $r_0 \propto \lambda^{\frac{6}{5}}$, and that telescopes with diameters $D > r_0$ will have long-exposure images with seeing limited angular resolution $\theta_{\text{seeing}} = \frac{\lambda}{r_0} \propto \lambda^{-\frac{1}{5}}$. Thus, seeing-limited image quality improves into the IR counter to the diffraction limited performance. Sites with excellent seeing will have $r_0 \approx 20$ cm in the visible (500 nm) and $r_0 \approx 1$ m at K band (2.2 μm). As explained later, the limitation of r_0 can be overcome by including AO.

Most observations in astronomy have long exposure times, minutes or even hours. For interferometry, this is only possible when actively stabilizing the fringes to well better than a wavelength, a technique called fringe-tracking (§5.3). Otherwise, the turbulent atmosphere causes time-varying optical path lengths above each telescope and a changing phase of the interference fringe. As the phase changes, the troughs and peaks will blur together in a long exposure ruining the measurement. Thus, interferometers must observe fringes with short exposure time to “freeze” the atmospheric motions. It is useful, though incomplete, to adopt Taylor’s frozen atmosphere hypothesis that assumes the wavefront errors are fixed as they are blown across the telescope aperture at a wind velocity v . If so, then the typical coherence time is given by $\tau_0 = \frac{r_0}{v}$. For upper atmosphere speeds of 10 m/s, we find $\tau_0 \approx 20$ ms in the visible at excellent sites, though jetstream speeds of > 50 m/s can drastically reduce the coherence time to < 3 ms. Again, note the coherence time will be much improved in the IR compared to visible due to the dependence on r_0 .

Combining r_0 and τ_0 leads to the concept of a “coherent volume” of photons that can be used for estimating sensitivities. Without AO and fringe-tracking, the largest useful aperture is r_0 and the longest coherent integration time is τ_0 , thus the photon volume is proportional to $r_0^2(c\tau_0) \propto \lambda^{3.6}$, according to Kolmogorov turbulence. This strong dependence on wavelength explains why IR interferometry has been much more developed than visible light interferometry. §5 will show how advanced methods now can largely overcome this traditional limitation to interferometry sensitivity, boosting fringe sensitivity by over $\times 1000$ in the past 10 years.

Fried parameter r_0 :

Diameter for which the root-mean-square (rms) wavefront error introduced by the atmosphere is 1 rad

Coherence time τ_0 :

Time span for which the rms phase fluctuations from the atmosphere are 1 rad

Coherence length:

Path difference $\Lambda = \frac{\lambda^2}{\Delta\lambda}$ between the telescopes, for which the fringe contrast drops to 0.5

Isoplanatic angle θ_0 :

Angular separation, for which the phase difference of two objects fluctuates by 1 rad rms

Delay line: Device to delay light from one interferometer arm compared to another, typically to account for geometrical delays

Beam combiner: Instrument to bring light from separate telescopes together in order to measure mutual coherence

ABCD: Shorthand for measuring interference at four phases $0, \pi/2, \pi, 3\pi/2$ in order to determine mean power, fringe amplitude, and phase

3.4. Practical implementation

While the monolithic binocular mount of the LBTI resembles Young’s two-slit configuration, most interferometers are an abstraction of this experiment. The apertures are replaced by telescopes which must be corrected by AO or be limited to a size $\approx r_0$. Once corrected, light from each telescope is sent to the delay lines. The wavefronts for each telescope must be dynamically delayed based on the sky position of the target since wavefronts arrive obliquely, intercepting some telescopes before others. In order to measure an interference fringe, the optical path difference between telescopes must be stabilized either within a coherence length using group-delay tracking or within 1 radian by phase tracking, the latter allowing long coherent integrations. For wide-field phase-referencing (separation $> 10''$; only at VLTI), the light from the reference and science targets must be split at the telescope and sent through the delay lines on separate beams. Along the way, we must seek to minimize any differential dispersion and birefringence, while maintaining high transmission. With typically more than 20 surfaces from the telescope up to the instrument, the beamtrain transmission alone is typically low ($< 20\%$ in IR, $< 10\%$ in visible). Once the optical path differences and differential polarization (e.g., by half- and quarter-wave plates) have been compensated, all the beams can now be interfered. Figure 8 (right panel) illustrates these basic components of today’s interferometers.

Beam combiners fall into two general categories: “all-in-one” or “pairwise”. As the name implies, an all-in-one combiner will overlap light from several telescopes together, creating many fringes simultaneously. To distinguish different baselines, the interference patterns are either coded spatially (e.g., in image-plane) or modulated temporally. In a pairwise combiner, the light is split up and combined in pairs, so each combiner only has two input beams. Also here, the interference can be scrutinized with either temporal-modulation using a beamsplitter or through a so-called “ABCD” combiner, which further splits the beams and adds an extra combiner to allow four quadrature fringe phases to be measured simultaneously. The ABCD quadrature can also be achieved by temporal modulation and reading the detector at four fixed phase shifts. CHARA/MIRC-X is an example of an all-in-one combiner, VLTI/GRAVITY is an example of a pair-wise combiner using the ABCD method, and NPOI/CLASSIC combiner combines aspects of both.

In order to improve calibration of fringe coherence, most combiners apply some kind of “spatial filtering” to remove aberrations from the incoming beams before interference. The purest way to do this is using single-mode waveguides such as small-core fibers or planar waveguides, although pinholes can also be used (e.g., VLTI/MATISSE) when no fibers are available. During this process, the single coherent flux can fluctuate wildly with atmospheric turbulence, although AO improves this. For calibration, the coupling fraction into the single-mode must be monitored in real time. The FLUOR combiner on IOTA (Coudé du Foresto et al. 1998) pioneered the use of single-mode waveguides for interferometry and many combiners today now are based on this breakthrough (NPOI/VISION, CHARA/FLUOR+SPICA+MIRCX+MYSTIC, VLTI/PIONIER+GRAVITY). In §4.2 we discuss how the miniaturization made possible by telecommunication technologies have enabled new generation of sophisticated instruments.

3.5. Closure phases, phase-referencing, and fringe-tracking

While a fringe measurement reveals an amplitude and a phase, the fringe phase is initially corrupted by atmospheric turbulence. A time delay $\Delta\tau$ above one telescope due to

change in air density along the path of the photons will shift the phase of the fringe by $\phi_{\text{rad}} = 2\pi \frac{c\Delta\tau}{\lambda}$ and this changes by 1 radian every coherence time $\tau_0 \ll 1$ s. The phase excursions are too large and the statistics not sufficiently stationary to allow long term averaging. Two-telescope interferometers only average the $|\tilde{V}|^2$ and fit models to estimate stellar diameters or binary parameters. Complex astrophysical objects encode much information in the Fourier phases and so there is the need to calibrate these atmospheric fluctuations in order to carry-out true imaging with interferometers.

Radio interferometry encountered this phase instability problem first and introduced the concept of *closure phase* (Jennison 1958), which is an observable quantity for a triangle of baselines and which is immune to phase instabilities. Any fringe phase shift related to a single telescope (not baseline) can be removed by adding up fringe phases in a closed triangle. This can be seen by realizing that phase shift at telescope 2, for instance, will cause an equal but opposite-signed shift for baseline 1→2 and baseline 2→3. Closure phases thus reveal linear combinations of the true fringe phases we need for modeling and image reconstructions but not all the information. Numerically, the number of independent phases in an N telescope interferometer is $N(N - 1)/2$ while the number of independent closure phases is $(N - 1)(N - 2)/2$. For example, a 3-telescope array accesses one closure phase out of three phases, a 6-telescope array (CHARA) access ten out of 15 phases, and 50-telescope array (ALMA) measures 1176 out of 1225 phases. For more detailed explanations and examples, see the thorough treatment by Monnier (2000). Here we summarize a few important properties of closure phases compared to Fourier phases. Firstly, astrometric information is lost within closure phases since an image shift on the sky is equivalent to adding a planar geometrical delay above each telescope, thus cancels out in a triangle. Point-symmetric distributions (like uniform stars or simple inclined disks or rings) have phases of 0 or π when the origin is centered on the object, thus closure phases of point-symmetric objects also can only be 0 or π . Closure phases provide absolutely crucial information for asymmetric objects and can be interpreted with forward modeling (§4).

While closure phases allow recovery of phase information, their use does not extend the coherence time and thus not overcome the sensitivity limitations from short exposures. “Phase referencing” can be used to allow much greater sensitivity by using a bright nearby star as a phase-reference, a kind-of AO for interferometry that is used extensively in the radio. This technique has limits since one has to find a reference star within the “isopistonc” patch, which is the patch of sky that sees the same turbulence; the wavefronts from stars more than $\approx 30''$ away (in NIR) encounter different turbulence and thus the phase errors are mostly uncorrelated. While phase-referencing was demonstrated on the Keck Interferometer shortly before being shut down (Woillez et al. 2014), the VLTI/GRAVITY instrument was the first to make the technique practical and is leading us into a new era of high sensitivity observations – see science highlights in §2 along with more technical details in §5.

More common than dual-beam phase-referencing is fringe-tracking using self-referencing. Here, one uses part of the light of the target to track the fringes while reserving some of the light for “science” observations. For instance, at the Keck Interferometer, light from one side of the beamsplitter was sent to the low-resolution spectrograph for high sensitivity fringe tracking, while the light from the other side of beamsplitter was sent to a high resolution spectrometer (Woillez et al. 2012). Often one wavelength channel is used for real-time fringe-tracking to allow integration at another wavelength (e.g, Keck Nuller, VLTI/FINITO, CHARA/CHAMP; Serabyn et al. 2012, Gai et al. 2003, Monnier et al. 2012). The VLTI/GRAVITY fringe tracker (Lacour et al. 2019) allows long integrations

Closure Phase:

Phase observable immune to atmospheric turbulence, made from the sum of three fringe phases measured around a closed triangle of baselines

Group delay tracking:

Maintaining the optical path difference to within one fringe packet coherence length $R\lambda$

Phase tracking:

Maintaining the optical path difference to within 1 radian of phase delay $\frac{\lambda}{2\pi}$

Dual-beam phase referencing:

Technique to allow long coherent fringe integrations of a faint target by real-time fringe tracking of a bright nearby reference star

Baseline

bootstrapping: The technique of fringe tracking on two short baselines in order to coherently average on a longer baseline

at K-band or with the MATISSE instrument in L-, M- and N-bands. Note that the fringe phases do not need to be tracked on all baselines since a long-baseline fringe (say between telescopes 1 – 3) can be stabilized as long as fringes of two connecting shorter baselines (1 – 2 and 2 – 3) are available – a technique called “baseline bootstrapping.”

Homodyne interferometry:

Electric fields from two beams are mixed together before being measured by a square-law detector

Heterodyne interferometry:

Electric field is mixed with a laser local oscillator (LO) at each telescope, the output of the square-law detector maintains the original phase information. Signals can subsequently be interfered using standard radio techniques.

Quantum noise:

Heterodyne detection introduce extra noise related to Poisson fluctuations from the local oscillator signal

Quantum local oscillator (QLO):

Uses an entangled photon source to eliminate shotnoise in heterodyne interferometry

3.6. Homodyne, heterodyne, intensity, and quantum-enhanced interferometry

We conclude this section with a short summary of different kinds of interferometry under active development. In §1, we already introduced the main technique of “direct detection” or “homodyne” detection where the light from the different telescopes is interfered before detection by a square-law detector, which measures the intensity = $|\text{amplitude}|^2$. This is by far the most common way optical interferometry is carried out today.

A modified version of this method involves up-converting the light at each telescope to higher frequency using non-linear optics (e.g., Boyd & Townes 1977, Baudoin et al. 2016). This upconverted light can then be interfered using traditional direct detection methods, potentially with advantages in the thermal IR where fiber optics and detectors are inferior to shorter wavelength devices.

Heterodyne interferometry (Johnson et al. 1974, Hale et al. 2000) has been a practical method requiring only local measurements at the telescopes by mixing with a carrier signal and with interference happening separately. Often, the information can be recorded with correlation happening “in software,” or using special-built digital correlators. Heterodyne interferometry in the visible, NIR, and mid-infrared (MIR) is intrinsically much less sensitive than direct detection as it involves mixing the starlight with a bright laser as a local oscillator, introducing laser shot noise as a background that becomes severe shorter than $20\ \mu\text{m}$. See Ireland & Woillez (2018) for recent comparison of heterodyne and homodyne sensitivity in the context of the MIR Planet Formation Imager concept and Berger et al. (2020) for plans to radically increase bandwidths using multiplexing.

As already mentioned, intensity interferometry measures correlations in photon arrival times at different telescopes and is one of the earliest true “quantum optics” discoveries (Brown & Twiss 1956). This correlation requires two photon processes and thus is intrinsically less sensitive than homodyne methods, though again can be possibly practical for some applications. Attempts to revive this technique are underway taking advantage of the large collecting area and baselines from current and next-generation Cherenkov gamma ray telescopes (Nuñez et al. 2012, Cherenkov Telescope Array Consortium et al. 2019) and advances in detectors for extreme wavelength multiplexing (Horch et al. 2013)

The latest frontier in optical interferometry to open up is using quantum resources, such as entangled photons, to confer a “quantum advantage”. Using entangled photons as a quantum local oscillator (QLO), Gottesman et al. (2012) showed the laser shot noise of conventionally heterodyne interferometry can be side-stepped, recovering similar sensitivity of today’s “direct detection” methods but with potentially important practical advantages in the future. Brown et al. (2022) recently reported first lab demonstration of quantum advantage using heralded quantum-entangled photons, and others have speculated on advantages for quantum-enhanced interferometry in a future world with quantum networks and quantum hard drives (e.g., Bland-Hawthorn et al. 2021).

3.7. Software tools and resources

A host of community tools exist to help interferometrists prepare observations, analyze data, make images, and search archives. The Jean-Marie Mariotti Center (<http://jmcc.fr>) is a clearinghouse of essential software resources including *searchCal* for finding calibrators, *ASPRO* for planning observations at any facility, *LITpro* for fitting simple models, *OImaging* for image reconstruction tools, *Bad Cal* for bad calibrator list, and the *OIDB* for archiving and searching for reduced data. New python-based *PMOIRE* (Mérand 2022) also can fit a range of models as can julia-based *SQUEEZE*, *OITools* (<https://www.chara.gsu.edu/analysis-software/imaging-software>). All these tools use the OI-FITS Standard for exchanging calibrated optical interferometry data (Pauls et al. 2005, Duvert et al. 2017).

INTERFEROMETRY PRIMER - SUMMARY POINTS

1. A long-baseline interferometer is a Young's two-slit experiment, which measures Fourier components of the object brightness distributions.
2. Today's facilities have best angular resolution ranging from 0.5 to 5 mas.
3. Atmosphere turbulence poses fundamental limitations that can be overcome using closure phases, adaptive optics, fringe-tracking, and dual-beam phase-referencing.

uv coverage: Extent of the Fourier plane containing measured complex visibilities. The greater the uv coverage, the better quality images can be reconstructed.

4. ADVANCES IN INTERFEROMETRIC IMAGING

The past decade has not only seen a breakthrough in sensitivity but also in imaging power. It is striking that most of the results we highlight in §2 are *images* and not *visibility curves*, a huge change from previous reviews of O/IR interferometry. In this section we outline how this was made possible through effective use of 4- and 6-telescope arrays, new beam combiners that use all telescopes simultaneously, better beam combiner architectures to enhance calibration precision and data throughput, and also mature and proliferating image reconstruction software.

4.1. Filling the uv-plane

The O/IR interferometry field currently has three major imaging interferometers, NPOI (reconfigurable 6T), CHARA (fixed 6T), and VLTI-Auxiliary Telescopes (ATs, reconfigurable 4T) / VLTI-Unit telescopes (UTs, fixed 4T). This is reminiscent of the pre-ALMA age for millimeter-wave interferometers when many small arrays existed with < 10 telescopes (Sargent & Welch 1993). The number of baselines in an N telescope interferometer is $N(N - 1)/2$ (§3.5), thus even adding a few telescopes can substantially transform the imaging capabilities. Since each projected baseline is a single Fourier component of the true sky image, the imaging fidelity of an array is directly related to the ability to “fill the uv-plane.” In addition to simply increasing the number of telescopes, we can improve uv coverage by a) using earth rotation to sample different baseline projections, b) employing movable telescopes at the same site and combining configurations (as long as object does not change in time), c) combining data from geographically different interferometers at nearly the same time, d) observing over a wide wavelength range to sample different resolutions when coupled with a wavelength-dependent model of source. Figure 9 shows the evolution

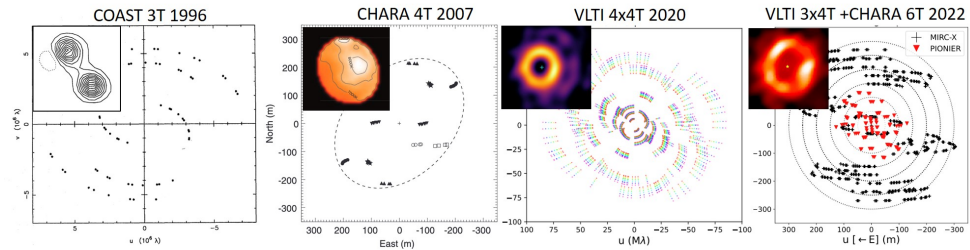


Figure 9

The uv plane can now be densely filled using multiple configurations of four- and six-telescope arrays. The evolution over the past 20 years has been dramatic and we show here actual published uv coverage along with the reconstructed images (Baldwin et al. 1996, Monnier et al. 2007, Kluska et al. 2020b, Ibrahim et al. 2022 submitted).

of uv coverage over past decades.

Even when arrays were built with 4+ telescopes, beam combiners did not yet exist to combine all the beams at the same time. This was the case for NPOI, VLTI and CHARA which did not possess combiners that could measure all baselines and closure phases simultaneously until the past decade, often a decade after first light. One part of the delay was caused by the cumbersome prospect of creating a 4+ beam combiner in bulk optics, which would take up large optical tables and require on-going tedious alignments. As already covered above, the classic “pairwise” beam combiner works well for two or three telescopes, however, scales poorly for large number of telescopes. Light from each of N telescopes must be split $N - 1$ ways and then combined with all other beams on $\binom{N}{2}$ beamsplitters leading to $N(N - 1)$ outputs. Further, bulk optics combiners historically have not produced as precise calibration as those using single-mode waveguides.

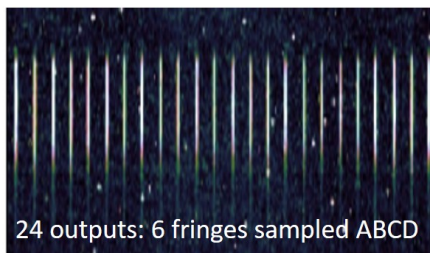
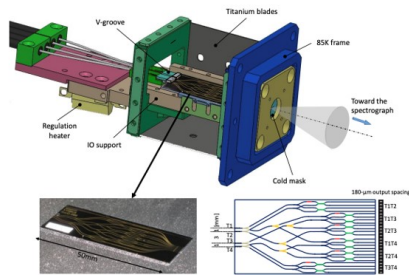
4.2. Better calibration and miniaturization with single-mode waveguides

We already mentioned the breakthrough in calibration from single-mode fibers and evanescent wave fused couplers (e.g., IOTA/FLUOR, Coudé du Foresto et al. 1998, Perrin et al. 1998) in the 1990s, but this architecture did not lead to all-fiber beam combiners for imaging. This was due to the difficulties in constructing a network of fiber-based splitters and couplers while maintaining better than millimeter internal path lengths and controlling for differential dispersion and birefringence.

This engineering problem was first solved using planar waveguide circuits (Kern et al. 1997), developed initially for telecommunications (see recent review, Righini & Chiappini 2014). In analogy to integrated circuits, integrated optics (IO) allows complex optical functions such as splitters, combiners, achromatized phase delays, and active phase modulation to be embedded in a thin dielectric slab using lithographic methods. The first IO device used for astronomy was IOTA/IONIC (Berger et al. 2001) and this technology has since matured with a basic form where the input beams are split, recombined to form all interference pairs and with internal delays to sample four equally-spaced fringe phases. The IO outputs are in a line that can then be dispersed on to an array detector. This so-called pairwise ABCD IO combiner is the basis for the H-band 4T combiner VLTI/PIONIER (Le Bouquin et al. 2011), the K-band 4T combiner VLTI/GRAVITY (Perraut et al. 2018),

Integrated Optics (IO): Optical equivalent to electronic integrated circuits (ICs). Dielectric chips implanted with optical waveguides providing beam splitters, combiners, delay lines, nulling, and more

Integrated Optics Combiner Pairwise ABCD



MIRC-style Combiner Image-plane combination with photometric outputs

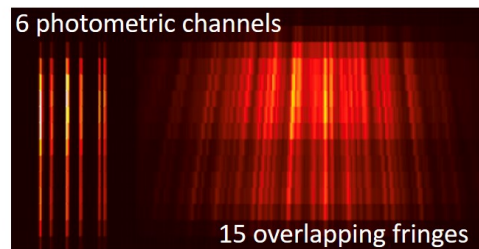
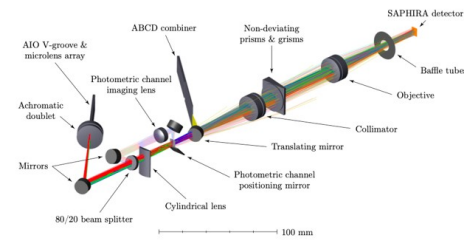


Figure 10

The imaging breakthroughs of the past decade required a new generation of “imaging” combiners. Today’s imaging instruments have all adopted either a pairwise ABCD combiner using an IO (left panel figures adapted from VLTI/GRAVITY instrument; Perraut et al. 2018) or a MIRC-style instrument using image-plane combination following single-mode fibers (right panel figures adapted from CHARA/MYSTIC instrument; Setterholm et al. 2022).

the K-band 4T combiner CHARA/MYSTIC-ABCD, and the new H-band 6T combiner for the CHARA/SPICA fringe-tracker. IO devices rarely can operate beyond about $\approx 30\%$ spectral bandwidth (due to the requirement to have low bending losses while maintain high single-mode purity), thus each astronomical band (J,H,K) needs its own device. Material absorption and scattering losses in the visible and thermal IR have limited IO use in these wavebands. Due to the need to minimize the curvature of waveguide bends, the chip length scales like N^2 , incurring significant propagation losses ($\approx 50\%$) for current devices. Better materials and new writing techniques continue to be developed in this active area, for instance see further discussion on nulling in §6.6 and the recent advances in 3-D laser writing (e.g., Labadie et al. 2018), which promises more compact combiners in more materials as the writing quality improves.

Another influential beam combiner architecture tailored for imaging with large N telescopes uses image-plane combination of light that has been spatially-filtered by fibers but with beam combination in the image-plane using conventional bulk optics. The CHARA/MIRC combiner pioneered this method, using conventional telecom fibers installed in a non-redundant linear array within a silicon v-groove mated with a microlens array. The interference fringes can then be focused onto a slit and dispersed, as for the IO devices. Bending losses tend to limit the usable bandwidth of IO devices, while single-mode fibers can have high transmission over $\approx 50\%$ spectral bandwidths, for instance including $1.1 - 1.8 \mu\text{m}$

using standard telecom fibers or $1.5 - 2.4 \mu\text{m}$ using special low-OH silica or fluoride fibers. This style of combiner is limited to wavelengths where good fibers exist. The image-plane combiner is also susceptible to cross-talk (Mortimer & Buscher 2022). So-called MIRC-style combiners lie at the heart of current instruments MIRC-X (Anugu et al. 2020), MYSTIC (Setterholm et al. 2022), SPICA (Mourard et al. 2018) and VISION (Garcia et al. 2016). Figure 10 show schematics of both IO and MIRC-style combiners and how the dispersed interference patterns look in practice.

4.3. Advanced image reconstruction algorithms

Many of the highest profile results in O/IR interferometry would not have been possible without advances in image reconstruction algorithms, beyond those developed by the radio community. Here we describe the current state-of-the-art but demur from detailed derivations or anything resembling a “how-to”. We refer interested readers to the review of methods by (Baron 2016, 2020), along with tutorial-like presentation by Thiébaud & Young (2017). Here you will find a brief overview of the current algorithms and future directions.

The radio community was first to attempt interferometric imaging and had initially been quite innovative in developing algorithms to account for the limited uv coverage of early facilities. The CLEAN (Högbom 1974) algorithm was tractable even with early computers and subsequently built into the standard radio packages AIPS and CASA. The basic principle behind CLEAN is to take a direct Fourier transform of the complex visibilities in the (mostly empty) uv plane, then to follow this with a deconvolution step to remove the large “sidelobes” that appear in the initial image. Since most of the artifacts come from the large *known* gaps in the uv-plane, this method works well for simple objects, especially when consisting of mainly point sources like binary or triple systems. Closure phases are incorporated using an iterative “self-calibration” scheme, applying positivity and limited field-of-view windows when carrying out the deconvolution (Readhead & Wilkinson 1978). Unfortunately, CLEAN does a poor job with reconstructing smooth extended emission, does not intrinsically deal with error bars or closure phases, and smooths away details as a way to minimize artifacts. The flaws of CLEAN are most severe with small $N < 10$ arrays like we have in O/IR interferometry.

Faster computers now allow a more mathematically rigorous approach. The “forward modeling” approach considers all possible astronomical images as hypotheses and then choose the best set of images based on a combination of the best-fit to the observables (χ^2) as well as any *prior* information, such as positivity, known field of view, etc. This is an example of an ill-posed inverse problem with no unique solution, so one must “regularize” the solution by introducing additional constraints. The first widely-adopted “regularizer” was the Maximum Entropy Method (MEM; Gull & Skilling 1984) which attempts to maximize the so-called Entropy S of the image: $S = -\sum_i f_i \log \frac{f_i}{p_i}$, where f_i is the fraction of flux in pixel i and p_i is the Bayesian prior (often taken as constant). Conceptually we expect this to find the “smoothest” possible image consistent with the data, which is attractive for the astronomical utility.

The panoply of codes now available now often incorporate alternative regularizers to entropy, that go by a variety of names such “total variation”, “uniform disk regularizer”, “dark energy”, some of which prefer sharp edges while other select smooth edges. Thus the astronomer is now expected to choose the regularizer appropriate to their target (Renard et al. 2011). Another way to approach image reconstruction is through “compressed sensing”

CLEAN: Traditional deconvolution technique for image reconstruction with interferometers

Regularizer: A mathematical metric that is optimized when fitting interferometric data with a model image

where one tries to find a good-fitting image that has the fewest number of “components”, where a component can be a something like a wavelet coefficient or derived from a dictionary of radiative transfer calculations.

Today’s image reconstruction frontier involves regularizing across time to track moving blobs in dust shells and disks, regularizing across wavelengths to improve uv coverage but accounting for smooth changes in images with wavelength, and even imaging with a (latitude, longitude) pixel grid projected onto a rotating spheroid to better image spots on spinning stars. Kluska et al. (2014) outlined a widely used approach where a central star with a known size and spectrum can be combined with a dust image which can have a different spectrum but which is otherwise “grey.” This SPARCO method is needed for imaging disks around young stars where the flux ratio between star and disk varies substantially across wavelength channels.

Radio work on imaging with sparse uv coverage radically slowed in the 1990s, and the IAU Working Group on O/IR Interferometry began a series of meetings around 2000 to address the need for better imaging as the modern facilities were building up. These meetings led to the OI-FITS data standard (Pauls et al. 2005, Duvert et al. 2017) for calibrated optical interferometry data as no appropriate standard from radio existed. In addition, a series of image reconstruction “contests” have been held during the SPIE astronomical instrumentation conference every two years since 2004 to encourage development of advanced imaging methods and to recognize excellent contributions. These double-blind contests typically used simulated data based on existing facilities and instruments with realistic noise (e.g., Lawson et al. 2004) or even were attempted on real data (Monnier et al. 2014). The result has been an innovative and dynamic subfield that has produced a range of community tools, usually publicly available: BSMEM (Buscher 1994), MACIM (Ireland et al. 2006), MiRA (Thiébaud 2008), IRBis (Hofmann et al. 2014), WISARD (Le Besnerais et al. 2008), SQUEEZE (Baron 2016), SURFing (Roettenbacher et al. 2016), ROTIR (Martinez et al. 2021), ORGANIC (Claes et al. 2020), G^R (Gravity Collaboration et al. 2022a). This work has now fed-back to radio interferometry, informing the imaging approach of the Event Horizon Telescope (EHT) project (e.g., Lu et al. 2014).

ADVANCES IN INTERFEROMETRIC IMAGING - SUMMARY POINTS

1. Interferometric imaging requires as many telescopes as possible to fill the uv-plane.
2. Within the past decade the major facilities have been able to combine all their available telescopes, with single-mode optics at the core of today’s beam combiners.
3. Specialized image reconstruction algorithms have been developed for O/IR interferometry, advancing the field over earlier work by radio astronomers.

5. BREAKTHROUGH IN SENSITIVITY

Initially, astronomical interferometers were made from small aperture telescopes or siderostats with a diameter less than a few times the atmospheric Fried parameter r_0 .

The sensitivity advantage of large telescopes for interferometry has been recognized early on, and both the VLT (Lena 1979, Beckers et al. 1990) and Keck telescopes (Colavita et al. 1998, 2013) have been designed and implemented to also operate as an interferometer. The use of AO then increases $r_0 \approx 0.1 \dots 1 \text{ m} \rightarrow D \approx 10 \text{ m}$, i.e. the “coherent volume” $r_0^2(c\tau_0)$

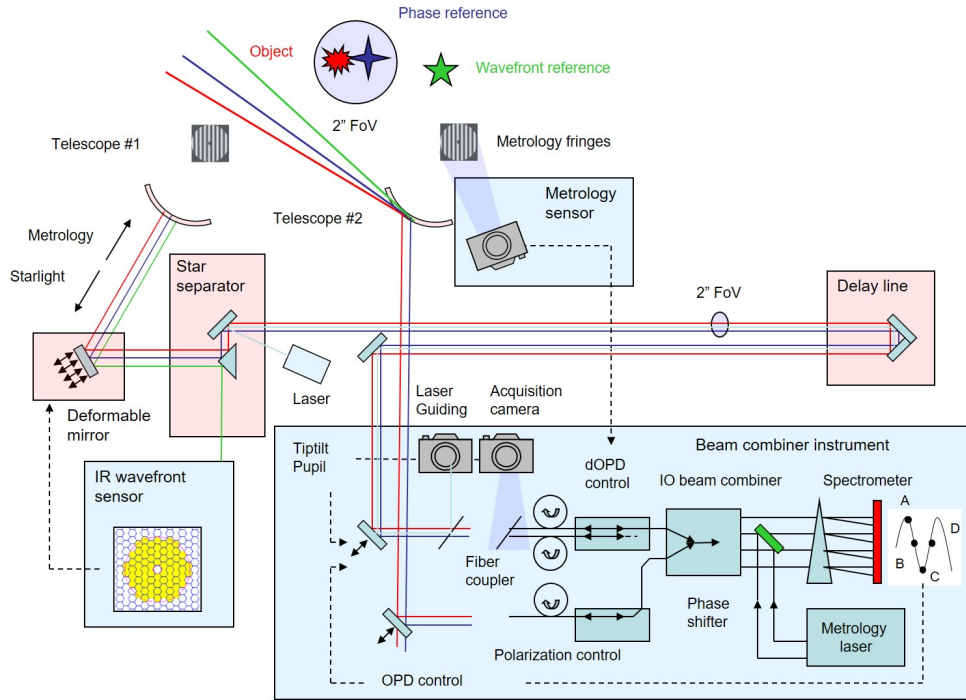


Figure 11

Overview and working principle of a modern, large telescope interferometer at the example of GRAVITY: each telescope is equipped with AO to provide a diffraction limited beam, which is then transported through mirrored delay lines to the beam combiner instrument. The instrument provides two beam combiners, one for fringe-tracking, the other optimized for long exposure, high spectral resolution interferometry of the science target. Off-axis fringe-tracking is done by either separating the phase-reference and science target at the instrument level (narrow field of view) or at the telescope level (wide field of view). In the latter case the two beams are propagated separately to the beam combiner instrument. The optical path length within the observatory is controlled via several laser metrology systems, delay lines and differential delay lines. The beams are stabilized through active field and pupil tracking, again taking advantage of laser metrology. For clarity, we show only two telescopes, and one AO, delay line, and beam combiner (Gravity Collaboration et al. 2017a).

(§3.3) increases by factor $\gg 100$, such that fringes of moderately faint objects $m_K \approx 10...11$ mag can be detected within the atmospheric coherence time $\tau_0 \approx$ few ms. This allows for stabilizing the fringes, and thereby opens up a factor 1000 - 100000 longer exposures times $\rightarrow T_{exp} \approx$ minutes - hours, and reaching out for yet another factor 1000 fainter objects $m_K \approx 19$ mag by dual-beam interferometry.

However, the technical hurdles were substantial, and it was only GRAVITY that brought all techniques together for routine science operation. Figure 11 illustrates the complexity and major subsystems of such a modern interferometer.

5.1. Sensitivity gain from large telescopes

On top of collecting area, there are more fundamental advantages of large telescopes for

Coherent volume:
Combination of Fried parameter and coherence time $r_0^2(c\tau_0)$ indicating sensitivity of an interferometer

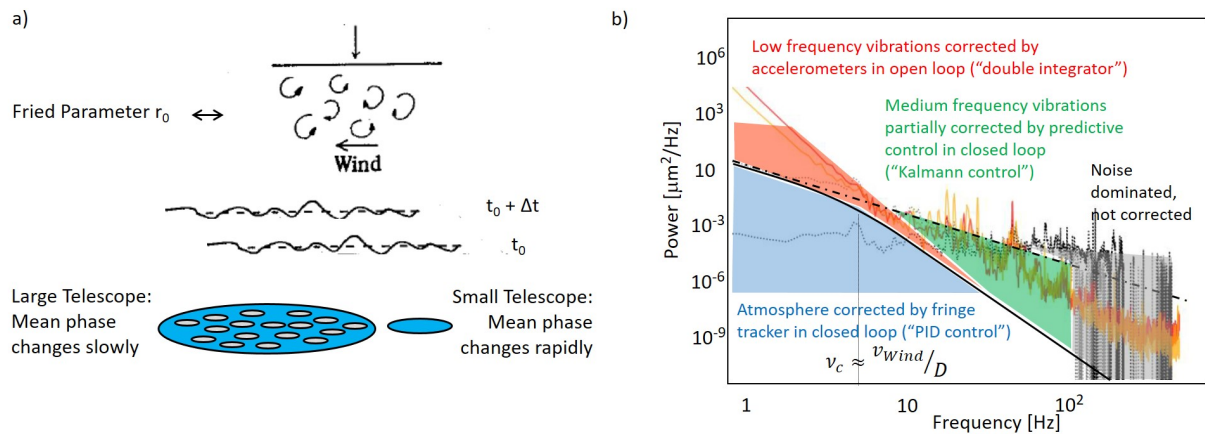


Figure 12

Interferometry with large telescopes. a) large apertures average out the small scale atmospheric perturbations, thereby increase the coherence time as compared to small telescope. The resulting temporal power spectrum (b) of the mean phase (black thick curve) exhibits a break around a typical frequency of $\approx \frac{v}{D}$, where v is the wind speed, and D the telescope diameter (adapted from Conan et al. (1995)). Vibrations (red/yellow lines) exceed the atmospheric path length fluctuations for large telescopes. They are corrected by a combination of accelerometers (open loop control) and fringe-tracking (closed loop) for low and intermediate frequencies up to few ten Hz. Vibrations at higher frequencies - especially from optics not monitored by accelerometers - can be partially corrected by predictive control with the fringe-tracker, but ultimately limit the current fringe-tracking residuals (black).

interferometry. They arise from phase averaging effects across the aperture, which increase the characteristic timescales for fringe-tracking, and from a smaller diffraction limit, thereby enabling the observations of crowded regions. In the following we quantify each respective advantage, which taken together yield a large telescope advantage $\propto D^{2\dots5}$.

The Signal-To-Noise (SNR) ratio in observations of point sources increases with the telescope diameter $\propto D^2$ for background limited, single-mode interferometric observations (Beckers et al. 1990). The reason is that the thermal background for diffraction limited observations is irrespective of telescope size (étendue = collecting area \times receiving solid angle = λ^2), while the signal increases $\propto D^2$, i.e. by factor 100 when going from one to ten meter telescopes. At the same time, the telescope primary beam shrinks in area with telescope diameter $\propto D^{-2}$. In the crowding limit, the number of objects in the observed field of view is reduced by a factor $\propto D^2$, and therefore the SNR per object increases accordingly $\propto D^2$, i.e. by another factor 100 when going from one to ten meter telescopes.

Taken together, the SNR increase for crowding limited observations in the IR is $\propto D^4$. This holds for interferometry as well as for diffraction limited observations with single telescopes. In O/IR interferometry with its comparably poor uv coverage, the smaller field of view can be even decisive for the observation of complex scenes. For the Galactic Center, e.g., the stellar density is about 70 stars brighter than 19.5 mag within the diffraction limited field of view of an 1 m diameter telescope, too many for the sparse uv coverage of a four telescope interferometer. It is the factor 100 smaller diffraction area of 10-m telescopes, which reduces the complexity to a few stars per pointing and thereby allows for the deep imaging and the accurate astrometry presented in §2.3.

Next, the coherence time increases with telescope diameter, because single-mode interferometers are probing the average phase of the pupil, thereby smoothing out the temporal

Outer scale of turbulence L_0 :

Distance, at which the phase structure function falls significantly below the Kolmogorov power spectrum

Cutoff frequency:

Frequency, above which the power spectrum falls significantly below the extrapolation from lower frequency

fluctuations (Figure 12a). The increase in coherence time is $\propto D^{1/6}$ for moderate size telescope $r_0 \ll D \ll L_0$ (Kellerer & Tokovinin 2007), and $\propto D^{7/6}$ when D approaches the outer scale of turbulence L_0 . However, current telescopes ($D \lesssim 10$ m) are smaller than L_0 (typically few 10 m for good astronomical sites (Ziad 2016)), and take only moderate advantage of the increased coherence time. The more relevant advantage comes from the shape of the phase power spectrum (Figure 12b): the averaging effect leads to the suppression of especially the high frequency perturbation, and results in a turnover of the atmospheric Kolmogorov power spectrum at a frequency $\approx 0.3 \frac{v}{D}$ (Conan et al. 1995), where v is the wind speed. This cutoff frequency will reflect in the required control bandwidth of the fringe-tracker, which in turn is ultimately set by the detector integration time. In the case of readnoise-limited short exposures, the SNR per exposure will therefore increase with the exposure time $\propto \frac{D}{v}$. In practice, the gain will be somewhere in between the above two regimes, i.e. $\propto D^{1/6 \dots 1}$.

While the sensitivity boost $\text{SNR} \propto D^{2 \dots 4}$ has already materialized with GRAVITY, it has not yet been able to take advantage of the increased coherence and fringe-tracking exposure times $\propto D^{1/6 \dots 1}$ because of excessive vibrations of large telescopes (§5.3).

5.2. Adaptive optics

AO is the technique to correct the wavefront distortion from the Earth’s turbulent atmosphere and to deliver diffraction limited images for large telescopes. A wavefront sensor measures the distorted wavefront of a bright star, which is then compensated in real-time with a deformable mirror, so that also the image from nearby objects will be sharpened. The original concept goes back to Babcock (1953) and was followed up independently and in parallel in military and astronomical applications. See e.g. Beckers (1993) and Davies & Kasper (2012) for reviews of its history, principle and applications in astronomy.

AO is also the prerequisite to efficiently interfere the light from telescopes with a diameter larger than the Fried parameter. Its decisive role was recognized already in the proposed implementation of the VLT interferometer (Beckers et al. 1990): while the sensitivity (SNR^2) - the faintest object detectable for a given observing time - of broad-band interferometric observations scales only moderately $\propto D^{1/3}$ with the diameter D of large telescopes in the case of seeing-limited (so-called multi-speckle) observations, the sensitivity increases $\propto D^4$ for diffraction-limited, single-mode interferometric observations. Therefore dedicated AO was implemented from the very beginning in the 8-m UTs for VLTI (Arsenault et al. 2003) and later upgraded with the GRAVITY IR AO (Hippler et al. 2020). The Keck interferometer took advantage of the multi-purpose Keck AO (Wizinowich et al. 2000). The smaller 1.8m diameter ESO ATs and the 1.0m CHARA telescopes are now also equipped with AO (Woillez et al. 2019, ten Brummelaar et al. 2012).

While the limiting magnitude of small telescope interferometers is set by fringe-tracking, large telescopes interferometers are limited by AO. The reason is that larger telescopes require ever higher order AO, because each atmosphere turbulence cell has to be corrected independently, and therefore the AO limiting magnitude is independent of the size of the telescope. Fringe-tracking, however, only measures and stabilizes a single (average) phase irrespective of telescope size, and the limiting magnitude thus increases with telescope diameter D . Because of additional light losses between the AO at the telescopes and the fringe-tracker in the interferometric laboratory, the limiting magnitude curves are shifted relative to each other, and the transition between the two regimes typically arises at 1–2 m

Adaptive optics

(AO): Technique to correct image blur from turbulent atmosphere and recover diffraction limited resolution of telescopes

Laser guide star

(LGS): Artificial star created with a laser, used for AO when no bright natural star is close to the observed object

telescope diameter as used in CHARA and the VLTI ATs.

Laser guide star (LGS) AO overcomes this limitation (e.g., Beckers 1993, Davies & Kasper 2012). Here the high order wavefront correction is done on an artificial star, created by a laser, and projected high up in the stratosphere. In this case the limiting magnitude of the AO is set by the need for a tip/tilt reference star (two degrees of freedom per telescope), which is comparable to the fringe-tracking limit (one degree of freedom per telescope, but reduced optical throughput). A first demonstration of LGS AO assisted interferometry was done at the Keck interferometer (Colavita et al. 2013) shortly before its shutdown. The GRAVITY+ project (Eisenhauer 2019) currently upgrades all VLT 8m telescopes with LGS and new AO (§7.2).

5.3. Fringe tracking and vibration control for minute long exposures

Fringe-tracking is the technique to track and correct the phase delay between telescopes which is introduced by the turbulent atmosphere. Among the first to propose and later implement an active tracking and stabilization of the fringe position using a servo-loop were Shao & Staelin (1977, 1980). A number of instruments followed the same path and implemented fringe-tracking to allow the interferometric observation of faint sources by actively stabilizing on a nearby bright source (Colavita & Wizinowich 2003, Gai et al. 2003, Delplancke 2008, Kok et al. 2013).

The first element of a fringe-tracker is the phase sensor, a beam combiner which measures the current fringe position (§4.2). A controller then compares the measured fringe position with a target position and commands an actuator (typically a fast piezo-mounted mirror) to correct the position. The different control-loop states (e.g. phase delay tracking close to the optical path zero, group delay tracking if the fringe is off by $> \lambda$ or fringe-search in case the fringe has been lost) are handled by a state machine.

An important limitation of fringe-tracking are vibrations from the telescopes, instruments, and infrastructure. They excite the mirrors along the optical train and result in optical path length fluctuations with pronounced peaks at the frequencies of the excitation and at the mechanical resonance frequencies of the mirror and mounts. The detailed power spectrum (Figure 12b) of the optical path variation is complex, with isolated peaks, forests of unresolved peaks, and a pseudo-continuum following a red power-law.

At frequencies below a few Hertz (Hz), the optical path fluctuations are completely dominated by vibrations, with an amplitude of order several to ten μm . At the VLTI and LBTI, e.g., they are measured by accelerometers placed on the primary, secondary and tertiary mirror, and corrected by piezo-driven mirrors in the main delay lines in feed-forward open loop (e.g. Di Lieto et al. 2008, Böhm et al. 2017). After the bulk of these vibrations have been corrected, the turbulence of the Earth's atmosphere dominates the optical path length fluctuations up to few ten Hertz. This is the primary domain of the fringe-tracker. At higher frequencies, the atmospheric perturbations have only little power, and on top, the averaging effect from large telescope aperture sets in (Figure 12a), damping the high turbulence frequencies even more.

For large telescopes, however, this high frequency range is again dominated by vibrations excited by, e.g., ventilators (around 48 Hz) and closed-cycle coolers of cryogenic instruments (around 80 Hz). The vibrations often come in the form of a forests of multiple, nearby frequencies, e.g. inductance motors with a slightly different frequency slip (typically few percent). With fringe-tracker frame rates of 100-500 Hz and corresponding closed-loop

Fringe tracking:

Technique to stabilize the interferogram of two telescopes for long exposures

Kalman filter:

Recursive algorithm, which estimates the internal state of a system from a series of noisy measurements.

Closed-loop bandwidth:

Maximum frequency up to which a control system can damp perturbations by a factor 2 (3dB) or better

Dual-beam interferometry:

Simultaneous interferometry of two objects. Allows observing of faint objects by fringe tracking on a bright, nearby reference star. Also used for astrometry and phase-referencing for improved aperture synthesis

Astrometry: Position measurement, here between two objects

Phase-referencing:

Technique, which optically links the fringe phase of two objects by an internal metrology.

bandwidth of a few ten Hz, most of these vibrations are beyond the control bandwidth. The vibrations are therefore corrected with predictive control, very much like in AO (e.g. Guesalaga et al. 2012, Kulcsár et al. 2012). One possibility are phase-locked oscillators to track and correct a small number of vibration peaks (Di Lieto et al. 2008, Colavita et al. 2010). An alternative approach is to compensate the vibration spectrum and the atmospheric turbulence at the same time.

This can be achieved with a Kalman (1960) controller, a predictive algorithm whose commands are based on a model of the identified disturbance components. Menu et al. (2012) successfully ported the Kalman filtering to four-baseline fringe-tracking, which was subsequently implemented in the GRAVITY fringe-tracker by Choquet et al. (2014) and Lacour et al. (2019). The Kalman filtering outperforms the classical PID control, reducing the (vibration-driven) fringe-tracking residual error on the VLTI UTs from 500 – 1000 nm rms to ~ 250 nm rms under typical conditions. On the small ATs, the fringe-tracking residuals reaches residuals < 100 nm rms (Lacour et al. 2019). Only the successful compensation of the telescope vibrations enabled minute long integration times in dual-field interferometry.

5.4. Dual-beam interferometry

Dual-beam interferometry refers to the simultaneous interferometric observation of two widely separated objects ($\theta \gg$ coherent field-of-view) contained inside the atmospheric turbulence isopiston patch (§3.3). The technique was first described by Shao & Colavita (1992) and later implemented by Colavita et al. (1999) at the Palomar Testbed Interferometer using star separators located at the focus of the telescope, which feed two independent beams to separate interferometric instruments. In the early 90s the interest in dual-field interferometry was primarily driven by the promise of high precision astrometry (§6.1) and its application in the detection of exoplanets through the reflex motion of their host stars (in preparation for space astrometry missions for exoplanets). The possibility to fringe-track on a bright object (§5.3) and to stabilize and observe fringes of a much fainter nearby target was tentatively explored by Lane & Colavita (2003), but was not pushed beyond the limiting magnitude of the interferometer around $m_K = 5$ mag.

The dual-field instrument PRIMA (Delplancke 2008) was designed to equip the VLTI with astrometric and phase-referencing capabilities. The main science interest in exoplanet detection put an emphasis on astrometry rather than pushing the sensitivity of the interferometer. Delays in the project and competition from GAIA (Gaia Collaboration et al. 2016) led to a stop of the astrometric efforts, while the dual field capability of the infrastructure was briefly explored. The first dual-field phase-referenced observations, which reached a magnitude of $m_K = 12.5$ pushing the sensitivity by a factor 10 compared to direct observations, were carried out by the ASTRA instrument (Willez et al. 2014). The emerging scientific capability of the Keck Interferometer was stopped from flourishing by the shut-down of the facility in 2012. It took another 5 years to unlock the full potential of phase-referenced imaging and to push the sensitivity limits by a factor 1000 compared to direct detection. The GRAVITY instrument (Gravity Collaboration et al. 2017a) routinely offers mas resolution imaging for objects fainter than $m_K = 19$ mag (§2.3).

5.5. Sub-electron readnoise infrared detector arrays

Irrespective of detailed implementation, the tracking and compensation of atmospheric perturbations with AO or fringe-tracking requires exposure times shorter than the atmospheric

coherence time. At typical frame rates of 1 kHz, i.e. exposure times of 1 ms, even bright objects are photon starved. This means that the performance of the sensor is limited by the readout noise of the detector (e.g. Finger et al. 2016). At the same time, the 1 kHz frame rate of typically a few thousand pixels requires a comparably high analog bandwidth of order MHz for reading the detector pixels.

The early IR fringe-tracking systems (e.g. PTI fringe-tracker, FINITO at VLTI, FAT-CAT at Keck) used NICMOS3, PICNIC or HAWAII arrays with typical readout noise for double correlated sampling of $\approx 20 - 30 e^-$ with exceptional systems reaching $\approx 5 - 10 e^-$ (Millan-Gabet et al. 1999, Colavita et al. 1999, Vasisht et al. 2003). Although the IR detectors grew enormously in size from 0.065 Mpixel to 16 Mpixel over the last three decades, the improvements in terms of read noise have been marginal.

In order to overcome the CMOS noise barrier, ESO started in 2007 a program together with SELEX (now LEONARDO) to develop HgCdTe based electron avalanche photodiode arrays (eAPD) for the NIR (Finger et al. 2010). An independent eAPD development under the name "RAPID" was started by SOFRADIR, CEA-LETI and a consortium of research institutes (Feautrier et al. 2014). HgCdTe is a well suited detector material for avalanche multiplication since the mass of the electron is much smaller than the mass of the holes and the APD process results in pure electron multiplication. HgCdTe is a direct semiconductor, i.e. electron-hole pairs are created without phonon interaction. This means that large avalanche gains with almost no excess noise are possible with HgCdTe based APDs (Finger et al. 2016). After several development cycles of solid state engineering, the eAPD arrays have matured and resulted in the 320×256 pixels SAPHIRA arrays. The first units were implemented in the GRAVITY fringe-tracker and Coudé Infrared AO units (CIAO). At short integration times (~ 1 ms) the SAPHIRA arrays achieve subelectron noise ($< 0.2 e^-$), high APD gain (up to 700), and an excess noise of only ≈ 1.3 (Finger et al. 2016, 2017). The introduction of the SAPHIRA arrays in AO and interferometry and the corresponding noise reduction from $\sim 10 e^-$ to $< 1 e^-$ has been revolutionary, and has played a considerable role in the success of VLTI/GRAVITY. A number of interferometer and AO facilities at observatories (e.g. Keck, Subaru, Kitt Peak, CHARA and Palomar) also adopted the SAPHIRA (e.g. Goebel et al. 2018).

The latest detector generation Mark14, grown by metal organic vapour phase epitaxy (MOVPE), has extended the sensitivity range to $0.8 - 2.5 \mu\text{m}$ (Finger et al. 2016). Current developments include high-speed 512×512 pixel eAPD array for AO applications on 30-40 m telescopes (Finger et al. 2019, 2022, in press), and large format science detectors (Claveau et al. 2022, Feautrier et al. 2022, both in press).

BREAKTHROUGH IN SENSITIVITY - SUMMARY POINTS

1. Sensitivity of O/IR interferometers scales with high powers of telescope size.
2. Adaptive optics, vibration control, and fringe-tracking allow for minute long exposures – a factor 1000 longer than the atmospheric coherence time.
3. Dual beam interferometry enables routine milli-arcsecond resolution imaging of objects fainter 19 magnitude.
4. eAPD detectors revolutionised the field of adaptive optics and interferometry.

Infrared detectors:

Detectors made from semiconductors with a smaller bandgap than Silicon (used for optical detectors), thereby sensitive to the lower energy IR photons

Complementary metal-oxide-semiconductor (CMOS) detector:

Detector array technology, which separates the photodiodes from the readout electronics (other than CCD detectors, which combine detection and readout in the pixels), utilized in IR detectors

Avalanche Photo Diode (APD):

Photodiode detector which amplifies the signal by a cascade of photo-electron multiplications, the semiconductor equivalent of a photomultiplier tube

Double correlated sampling:

Reading the voltage of the pixel in the beginning and end of an exposure to remove fixed pattern noise in CMOS detectors

Quantum efficiency:

Percentage of photons converted to photoelectrons

6. PRECISION INTERFEROMETRY

6.1. Narrow angle astrometry

Ground-based astrometry is fundamentally limited by Earth’s atmosphere. This limitation manifests itself in scintillation, image blurring and image motion in case of single dish imaging. In case of multiple apertures, astrometry is limited by the fringe jitter introduced by the atmospheric turbulence. The jitter of two stars however is correlated, depending on their separation and the aperture size (or baseline in case of an interferometer). With narrow-angle astrometry we denote the regime when the angular separation between two sources is small enough that their beams experience essentially the same atmospheric perturbations.

The narrow angle regime is defined by Shao & Colavita (1992) as the angular separation $\theta \ll B/h$, with the baseline B and the effective turbulence height h . The advantage of narrow-angle astrometry is that the atmospheric jitter of two sources is partially correlated and cancels in a differential measurement. Among the first to recognize the potential of narrow-angle astrometry was Lindgren (1980). The application in interferometry was later proposed by Shao & Colavita (1992). They realized the possibility of μas astrometry with long baseline interferometry. Using SCIDAR measurements of the atmospheric turbulence height profile at Mauna Kea, Shao & Colavita (1992) derived an expression of the differential astrometric error for $\theta \ll B/3000\text{ m}$. The residual error behaves as $\sigma \approx 1.45 \cdot 10^{-3} B^{-2/3} \theta t^{-1/2}$ [arcsec], with the source separation θ in arcseconds and the integration time t in seconds. Of particular importance in the narrow angle regime is the $\sigma \propto B^{-2/3}$ dependence, which explains why large interferometer arrays are key to high-precision astrometry. Assuming a baseline of 100 m and a separation of 2 arcsec, the residual atmospheric error averages to $\sim 10 \mu\text{as}$ within 5 min of integration time.

The principle of differential astrometry between two objects on sky relies on the measurement of the optical path difference ΔOPD of the two objects, which originates from the geometric delay introduced by the different projection of the baseline \vec{B} . The basic astrometric equation $\Delta\text{OPD} = \vec{B} \cdot \vec{s} + \Delta\text{OPD}_{\text{int}}$ relates the measured ΔOPD between the two objects, their differential optical path inside the interferometer $\Delta\text{OPD}_{\text{int}}$ and the object separation $\vec{s} = (\vec{\alpha} - \vec{\beta})$, where $\vec{\alpha}, \vec{\beta}$ are the positions of the two objects. A simple sensitivity analysis illustrates the required accuracies: $\delta s = \frac{\delta B}{B} \cdot s + \frac{\delta \Delta\text{OPD}}{B}$. Let’s assume the desired astrometric accuracy is $10 \mu\text{arcsec}$, the baseline is $B = 100\text{ m}$ and the source separation is $s = 1\text{ arcsec}$: this means that the baseline needs to be calibrated to millimeter accuracy, and the combined optical path delay error must be measured to few nm accuracy. The astrometric equation becomes significantly more complex when systematic uncertainties due to the residual atmosphere, baseline calibration, instrument and telescope alignment as well as metrology, polarisation and dispersion errors are considered. The following list gives an overview of major astrometric error sources: a) Baseline errors originate from the difficulty to measure and calibrate the B_{NAB} , which is physically realised by the end points of the metrology (§6.2). Depending on the location of the end points, B_{NAB} can be impacted by differential telescope flexure or runout. b) OPD errors ($\Delta\text{OPD}_{\text{S}} = \phi_{\text{FT}} \cdot \frac{\lambda_{\text{FT}}}{2\pi} - \phi_{\text{SC}} \cdot \frac{\lambda_{\text{SC}}}{2\pi}$) introduced by phase measurement and wavelength calibration errors in the fringe tracking or science channel. c) Metrology errors ($\text{OPD}_M = \phi_M \cdot \frac{\lambda_M}{2\pi}$), here most importantly the wavelength, because the metrology traces differential OPDs of the order few 10-100 mm. d) Dispersion errors $\Delta L_{\text{fib,air}} \left(\frac{n_{\text{fib,air}}(M)}{n_{\text{fib,air}}(S)} - 1 \right)$ from inaccurate calibration of the different refractive index between the metrology and the science wavelength in air or glass. e) Pupil mis-registration of the science and metrology beams in combination with pointing errors.

Narrow angle regime:

Angular separation $\theta \ll B/h$, with the baseline B and the effective turbulence height h , where the atmospheric tilt jitter of two objects is correlated.

SCIDAR:

Scintillation detection and ranging technique, to measure the atmospheric turbulence profile.

They lead to phase errors of the order $\Delta\vec{\alpha} \cdot (\vec{P}_S - \vec{P}_M)$. f) Polarisation induced astrometric errors from differential birefringence in the interferometer arms. Since the metrology laser is linearly polarised, birefringence can introduce an effective path difference between the laser and the unpolarised science objects.

These and more astrometric errors have been studied by Colavita (2009) and Woillez & Lacour (2013) as well as in particular for the GRAVITY instrument by Lacour et al. (2014a,b). The impact of polarisation has been studied by Lazareff et al. (2014).

6.2. Interferometric baselines revised

For infinitely small telescopes, the interferometric baseline is the separation vector between the apertures. It gives the optical path difference between the two telescopes when observing a point-like object (§3.1), sets the spatial frequency in interferometric imaging and the van-Cittert Zernike relation (§3.2), and results in the differential optical path difference between two neighboring objects in phase-reference observations (§5.3). For large telescopes, however, the baselines for the three cases are not identical, and each of them follows a different physical realization. The effects are often non-intuitive, especially for narrow-angle astrometry (§6.1). Woillez & Lacour (2013) and Lacour et al. (2014a) concisely reviewed the three concepts in preparation for the GRAVITY instrument, building on the learning from the earlier ASTRA (Woillez et al. 2010) and PRIMA (Delpiancke 2008) experiments.

The wide angle baseline is the separation between the pivot points of the telescopes. Since each telescope points towards the object, there is no phase gradient across the aperture, and all light rays have the same optical path length irrespective of their pupil position. The wide angle baseline tells where to preset the delay lines to find the fringes, and when precisely known, allows for measuring the absolute position of the star on the celestial sphere. The wide angle baseline is calibrated from stars with known coordinates, and for precision wide angle astrometry, the position of the telescopes pivot points are measured and monitored with dedicated laser metrology, e.g., at NPOI (Armstrong et al. 1998).

The imaging baseline sets the spatial frequency sampled by the interferometer. The observed complex visibility is then the Fourier transform of the objects intensity distribution (§3.2). The imaging baseline is given by the autocorrelation of the telescopes apertures as seen from the object (Thompson et al. 2017). More accurately, it includes the coupling of the electric field probed by the beam combiner instrument – i.e. the Gaussian mode of the instrument’s single-mode fiber – and the beam relay from the telescope to the beam combiner.

Finally, the narrow angle baseline links the distance of the interferograms of two separated objects, each measured with its own beam combiner. The differential optical path between the two interferograms is measured by laser metrology, probing the path length from each beam combiner to the telescopes (§6.1). More accurately, the narrow angle baseline is the separation between the end-points of the laser metrology, where the path length difference is measured, again, as seen from the object. The metrology endpoint for narrow angle astrometry are best placed in front of the telescope, e.g., for GRAVITY on the spider holding the secondary mirror (Lippa et al. 2016), because even small wobbles from the optical relay would alter the apparent position of internal end-points and thereby corrupt the narrow angle astrometry.

Baseline B and \vec{B} :

Separation and vector (3D) between a pair of telescopes

Projected baseline:

Separation between telescopes as seen from the observed target (2D)

Wide angle baseline:

Separation between pivot points of telescopes - delay equation

Imaging baseline:

Separation between telescope pupils, van Cittert - Zernike relation

Narrow angle

baseline: Separation between metrology end points - dual-beam astrometry

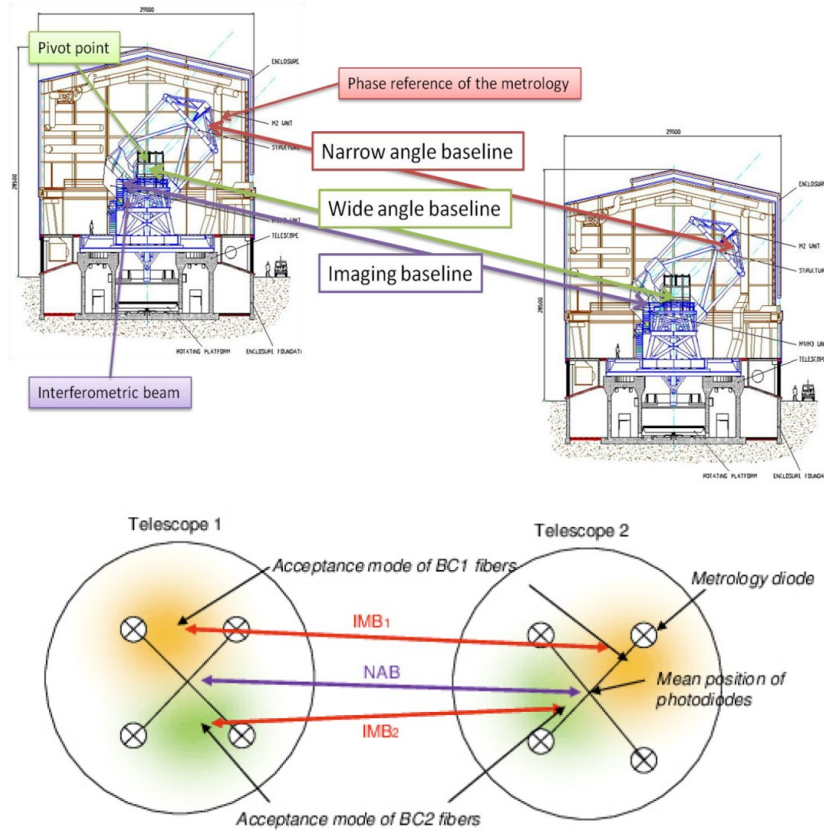


Figure 13

Baselines in O/IR interferometry: the separation between the telescopes of an interferometer is called baseline. In detail, we distinguish three types, each of them with a specific property and physical realization: the wide angle baseline (WAB) obeys the delay equation, and is realized by the pivot points of the telescopes. The imaging baseline (IMB) sets the spatial frequency in interferometric imaging, and is realized by the entrance pupil weighted by the Gaussian beam of the instrument single-mode fibers. For a dual-beam interferometer, the imaging baselines can be different for the two objects because of optical misalignment. The narrow angle baseline (NAB) is the separation between the endpoint of metrology system, which measured the internal path difference between two objects (adapted from (Lacour et al. 2014a)).

6.3. Laser metrology in interferometer

A key component of any dual-beam interferometers is a dedicated metrology system, which provides an optical link of the two beam combiners and their science interferograms. The metrology monitors the internal path length with nm accuracy to enable high precision astrometry. In some cases, the system also serves as a feedback for differential delay lines, which compensate the optical path difference of the two objects. As discussed in §6.2, the end points of the metrology, i.e. the points to which the internal optical paths are measured, define the narrow angle baseline B_{NAB} of the interferometer. Several metrology concepts have been developed for dual-field interferometers. The metrology systems implemented

in PTI (Colavita et al. 1999) and PRIMA (Leveque et al. 2003) rely on two heterodyne Michelson interferometers, which measure for each object the optical path change between the telescopes. The internal path difference between the objects $\Delta\text{OPD}_{\text{int}}$, corresponds to the difference between the path variations recorded by the two heterodyne interferometers.

The PRIMA metrology launches the lasers at the center of the pupil plane close to the beam combiners, and they are retro-reflected at the telescopes. The internal path difference $\Delta\text{OPD}_{\text{int}} = (T1 - T2)_{\text{FT}} - (T1 - T2)_{\text{SC}}$, i.e. the difference between the path variations, is recorded by photodiodes. The signal is filtered and the individual heterodyne signals are mixed such that the disturbance to be monitored is directly coded in the phase of the carrier signal. The GRAVITY metrology (Lippa et al. 2016) splits the laser light into three beams with fixed phase relations. Two of the beams are faint and injected backwards into the two beam combiner chips. The third, high-power beam is overlaid on top of the two faint ones after they have passed the fibers within the instrument, and acts as an phase-preserving amplifier for the detection. This approach minimizes the inelastic scattering of the metrology light in the instrument fibers. At each telescope, the three beams interfere in the pupil plane and form a fringe pattern. By temporal phase modulation of the two faint beams at different kHz frequencies the phase signal of the two light paths can be extracted using of lock-in amplifiers. The metrology measures the path variation between the objects to a single telescope. The difference of the variation between two telescopes provides the desired internal $\Delta\text{OPD}_{\text{int}} = (\text{FT} - \text{SC})_{\text{T1}} - (\text{FT} - \text{SC})_{\text{T2}}$ between the two objects.

A subtle but important distinction between the two metrology concepts originates from the way how the $\Delta\text{OPD}_{\text{int}}$ is measured. The PRIMA-like design allows to measure and correct vibrations occurring between the telescopes. However, a serious caveat of the PRIMA concept is that the metrology cannot trace the beam before the AO deformable mirror (DM), because it would imprint its deformation in the $(T1 - T2)$ path, thereby folding the atmospheric perturbations to the metrology signal. As a consequence, the metrology end points need to be downstream of the DM far away from the telescope primary mirror, which penalizes the B_{NAB} stability. In the GRAVITY concept, the two laser beams $(\text{FT} - \text{SC})$ go through the same DM, i.e. the difference signal does not see the deformation, which allows extending the metrology up to the telescope pupil, a decisive advantage for the stability of B_{NAB} . This comes at the cost that vibrations impacting the fringe-tracker and science beam, are not traced by the metrology.

Both metrology concepts have in common that they rely on frequency stabilised lasers, which operate at wavelengths shorter than the science band to minimize stray light. In both cases, the laser frequency $\nu = c/\lambda$ needs to be sufficiently stable such that the corresponding OPD error is less than 1 nm over a differential internal OPD of a few – 100 mm. This corresponds to a frequency stability of better than $10^{-7\dots-8}$.

6.4. Field- and pupil stabilization

The use of single-mode fibers mandates the accurate control of the star's position to better than the diffraction limit. This is typically achieved by a combination of AO (§5.2) and/or guider at the telescope, and a lab- or instrument provided secondary guiding on the object itself to correct the image motion from imperfect beam relay. This two stage approach provides the large field of view at the telescope for picking a bright, nearby star for telescope guiding, so that the secondary guider can run with longer exposure times and accordingly higher sensitivity. The lab guider (e.g. Gitton et al. 2004, Crawford et al. 2006) is typically

Lock-in amplifier: A type of amplifier that can extract a signal with a known carrier wave frequency from an extremely noisy environment.

Telescope guider:

Camera to track and stabilize the telescope on bright star

Secondary guiding:

Provides extra correction of perturbations between telescope and instrument

Variable curvature

mirror: A mirror for which the radius of curvature can be actively adjusted, e.g. by air pressure

a dedicated camera, operating at a different wavelength and serving several instruments. This comes with the disadvantage of non-common guiding errors, e.g., from atmospheric refraction. The field stabilization requirements are especially hard for narrow angle astrometry (§6.1), for which even small tilt errors (order 10 mas) reduce the astrometric accuracy through cross-terms with pupil errors. In this case the guiding is directly done on the fiber by slightly (radius few mas) modulating the tip/tilt at high frequency (few 10 Hz) and using the correlation between the measured flux and modulation signal (in analogy to a lockin amplifier) as feedback to the control loop (e.g. Bonnet et al. 2006). Some beam combiner instruments also provide internal wavefront sensors (Anugu et al. 2018) for secondary guiding of low order aberrations, in particular focus.

It is also the narrow angle astrometry which requires accurate pupil control, typically to well below a percent of the telescope diameter. Because of the difficulty to see and track the pupil on faint objects, pupil guiding is implemented by means of laser beacons, either taking advantage of the path length metrology (e.g., Woillez et al. 2014), or dedicated laser beacons launched from the spider arms holding the telescope’s secondary mirror (Anugu et al. 2018). Most interferometers do not re-image the telescope pupil, but transfer only a collimated beam to beam combiner instruments, and therefore have zero field of view. The VLTI is the only interferometer with variable curvature mirrors (Ferrari et al. 2003) in the retro-reflectors of its delay lines to dynamically transfer the telescope pupil and to provide a coherent field of view of 2–6” for the beam combiner. As the delay lines move to compensate the pathlength difference between the telescopes, the curvature of this mirror is adjusted either blindly, or in closed loop on the laser beacons launched at the telescope (Anugu et al. 2018).

6.5. The role of optical aberrations in interferometry

Optical aberrations:

Deviation from perfect optical image formation, typically described as wavefront error in the pupil plane, but also imprints on the phase of the electric field in the image plane

The introduction and implementation of single-mode fibers (Froehly 1981, Shaklan & Roddier 1987, Coudé du Foresto et al. 1998) and resulting improvements in the calibration was a breakthrough in O/IR interferometry. The spatial filtering from single-mode fibers converts phase errors across the telescope pupils in amplitude fluctuations, which can be monitored and then corrected in the calculation of the visibility (§4.2). It thus removes the random phase fluctuations of the turbulent atmosphere as the dominant calibration error (e.g., Perrin et al. 1998, for a first demonstration). Dynamic aberrations like atmospheric tip/tilt result in an increased field of view (Perrin & Woillez 2019). Static optical aberrations have a more subtle effect on the interferometric measurement. The phase of the electric field from a point source is then not constant anymore across the Airy peak of the telescope point spread function, but is a function of the position within the field of view.

In radio-interferometry, the effect is known as direction-dependent (complex) gains (Bhatnagar et al. 2008). For O/IR interferometry, it was for the first time described and corrected in Gravity Collaboration et al. (2021b). Even for diffraction limited optics the static aberrations are of order $\lambda/10$, translating to comparable signatures in the interferometric measurements, or when expressed in position errors on sky, $1/10$ the interferometric beam size for objects located at the edge of the interferometers field of view. In GRAVITY, e.g., the calibration of the field dependent phase errors is done by scanning the field of view with the instrument internal calibration unit. The correction is then applied via a modified van Cittert-Zernike theorem in the forward modelling as part of the model-fitting (e.g., when fitting the measured visibilities and closure phases with a binary star) or

image-reconstruction (Gravity Collaboration et al. 2022a).

6.6. Nulling

Perhaps the technique with potential to deliver the most extreme precision is *nulling interferometry*, with a goal of $\ll 10^6$ contrast to detect Earth-like planets in the MIR. Akin to phase-mask coronagraphy on single-apertures (see, e.g., review by Mawet et al. 2012), nulling uses destructive interference to remove host-star light while letting light from a faint nearby object to be detected. Nulling interferometry potentially has the combination of angular resolution and high contrast to characterize a large number of Earth-like planets around other stars, especially in the thermal IR where many molecular biomarkers can be seen in the planetary atmospheres (e.g., Quanz et al. 2022).

The principle behind nulling was laid out by Bracewell (1978) and Angel & Woolf (1997): if one interferes light from two telescopes onto a beamsplitter with a π relative phase shift, then the electric fields destructively interfere and one beamsplitter output is completely dark, except the light from a second object (e.g. exoplanet) slightly offset on sky. In practice though there are many difficulties, including chromaticity of phase delay, electric field amplitude and polarization matching, wavefront aberrations, stellar diameter leakage, and fringe-tracking stability. The first sky nulling was performed by Hinz et al. (1998) using sub-apertures from a single telescope, where a π phase shift was created using glass combinations, and achieved $\approx 4\%$ null depths at best in open loop. Long-baseline nulling at the Keck Interferometer (Serabyn et al. 2012, using a field inversion for nulling) and the LBTI measured the exozodiacal dust contributions around nearby stars: Colavita et al. (2009) reported raw null depths of 1.5 – 2% in the IR and Defrère et al. (2016) also achieved $\approx 1\%$ null depths at the LBTI. These surveys (Millan-Gabet et al. 2011, Defrère et al. 2016) concluded that exozodiacal dust is generally not large enough to interfere with future exoplanet searches. Due to the importance for nulling to the future of exoplanet studies, theoretical and experimental work remains active. We point the reader to recent explorations of the optimal nulling architectures (e.g., Guyon et al. 2013, Hansen et al. 2022), ways to combiner nulling with closure phases (Lacour et al. 2014b), nulling within IO (e.g., Hsiao et al. 2010, Errmann et al. 2015, Martinod et al. 2021), and development of better IR-friendly materials for IO, such as lithium niobate (Hsiao et al. 2009) and chalcogenides (Kenchington Goldsmith et al. 2017). There is a new exoplanet-focused instrument VLTI/HI-5 (Defrère et al. 2018) under construction that will push nulling down to L-band ($3.5\mu\text{m}$) for the first time, and there is an active consortium proposing a space nulling interferometer, the Large Interferometer for Exoplanets (LIFE; Quanz et al. 2022). More on nascent space interferometer efforts in §7.5. Space is indeed the place for nulling since ground-based interferometry is tragically limited by atmospheric turbulence and thermal emission that degrade the achievable contrast far from fundamental limits.

Nulling: Using destructive interference to cancel the light from a point source in one of the beam combiner outputs, thereby reducing the photon noise

Coronagraphy: Technique to blacken out the direct light from a star and to suppress its diffraction rings.

(Exo-)Zodiacal light: Glow of diffuse starlight scattered on interplanetary dust (in the solar system and around exoplanets)

PRECISION INTERFEROMETRY - SUMMARY POINTS

1. Interferometers provide much more accurate astrometry than single telescopes.
2. It is necessary to distinguish between three kind of baselines: wide angle baseline, imaging baseline, and narrow angle astrometry baseline.
3. Laser metrology measures path length differences to nanometer accuracy.

4. Active field- and pupil control is key to cancel second order astrometric error terms.
5. Aberrations introduce phase variations across the field of view and limit the astrometric and imaging accuracy, but can be corrected by forward modelling.
6. Nulling is the interferometry equivalent to coronagraphy to block out the star light.

7. FUTURE DIRECTIONS

So far we have concentrated our discussion of the breakthrough in sensitivity on the gain from large telescopes, AO, fringe-tracking, and dual-beam interferometry. But where do we stand in comparison to fundamental limits - quantum noise and background noise? How much to gain, and which directions to go?

7.1. Far from fundamental limits

The quantum limit for the measurement of the phase from a two telescope interference is given by the Heisenberg uncertainty principle $\Delta\phi\Delta N < \frac{1}{2}$, where $\Delta N = \sqrt{N}$ is the uncertainty in the number of photons N in the measurement (e.g., Townes 2000). The resulting SNR of the fringe contrast in the photon noise limit is given by $\text{SNR} = V\sqrt{N}$. The number of photons needed to detect fringes ($\text{SNR} = 5$) from a partially resolved object ($V = 0.5$) is ≈ 100 photons, which for the case of two 8-m diameter telescopes and observing at K-band translates to 31 mag for an one hour exposure. This is about 100,000 fainter than currently reached with GRAVITY. How far are we from the atmospheric and thermal background limit? In this case, the noise is dominated by the background, and the SNR of the fringe detection is $\text{SNR} = V \frac{N}{\sqrt{N+B}} \approx V \frac{N}{\sqrt{B}}$, where B is the number of background photons. For a single-mode instrument operating at the diffraction limit, the atmospheric background at K-band is $\approx 10^3$ photons/s. The thermal emission from a blackbody with the average temperature of the laboratory of 16 °C translates to $\approx 10^4$ photons/s, roughly a factor 10 more than the atmospheric background. The number of photons needed for the detection of a partially resolved object in one hour is then $\approx \text{few } 10^4$, corresponding to ≈ 25 mag, or factor few hundred fainter than currently possible.

7.2. Enhancing sensitivity

Why are current O/IR interferometers falling several orders of magnitudes behind the fundamental limit? It is throughput, detector noise, instrumental background, and coherence loss. Here we illustrate the situation on the example of GRAVITY, and sketch out possible improvements from the ongoing upgrade to GRAVITY+ (Eisenhauer 2019).

The worst offender is throughput: the total detective QE is $\approx 0.1 - 1\%$. The losses are dominated by AO performance (Strehl ratio typically 10 – 40%), the beamtrain from telescopes to instrument (throughput $T \approx 35\%$), IO ($T \approx 54\%$), and "traditional optics losses" (e.g., grism efficiency $\approx 25 - 50\%$). On top there is a factor 2 loss from splitting the light between fringe-tracker and science beam combiner, and a factor 3 from the pairwise combination of the 4T array. Some losses can be reduced with current technology: taken together, better LGS AO, improvements in traditional optics, and going to dual-beam interferometry, will bring a factor 10–20 better throughput, thereby increasing the detective QE up to $\approx 10\%$. The losses from the pairwise beam combination remains a fundamental

Quantum limit:

Resulting from the Heisenberg uncertainty relation, that energy (number of photons) and arrival time (phase) cannot be simultaneously measured to better than the Planck constant

Background limit:

Photon noise from thermal emission of the atmosphere, telescopes and warm optics

issue, because there is no noise-free amplification at O/IR wavelengths. Focal plane beam combination (e.g., the so-called hyper-telescope; Labeyrie 1996) can partly overcome this limitation, but face practical limitation from detector noise and difficult calibration.

The second worst offender is noise: for minute-long exposures, GRAVITY observations are limited by the laser background from the metrology. Reducing the laser power or the interleaved operation will bring the laser background to below the detector noise, improving the sensitivity by factor 1.5–5. At that stage “zero-noise” eAPD detectors (§5.5) can again revolutionize sensitivity. Their long-exposure noise is currently dominated by a high dark current, but revised diode structures, readout circuits and optimized operation have already led to a demonstration of dark current $0.025 \text{ e}^- \text{ s}^{-1} \text{ pix}^{-1}$ (Atkinson et al. 2018) and readnoise $\lesssim 3 \text{ e}^-$ in minute long exposures (Finger et al. 2019, 2022, in press). Also large format eAPD detectors are in the coming (Claveau et al. 2022, in press, Feautrier et al. 2022, in press). These detectors are then expected to reduce the noise of high-spectral resolution observations by another factor 2–10.

The last offender is coherence loss: while polarization mismatch between telescopes is typically well corrected, fringe-tracking residuals are catastrophic ($\gtrsim 500 \text{ nm}$ with frequent fringe losses) for observations at the sensitivity limit, when the fringe tracker control bandwidth is reduced. For large telescopes, the coherence loss is then dominated by vibrations (§5.3). Expanding accelerometers to the full coudé optical train (Bigioli et al. 2022, in press), together with further reducing the source of vibrations (Woillez et al. 2018), should allow for 100 nm fringe-tracking also for 8-m telescopes (e.g. for exoplanet work), as well as increase the coherence at the current sensitivity limit by factor 2 (e.g., extragalactic objects).

All together, higher throughput, reduced instrument background, zero-noise detectors, and better vibration control, will enhance the sensitivity of current interferometers by another 1–2 orders of magnitudes, with a limiting magnitude then beyond $m_K \approx 22 \text{ mag}$.

7.3. Enhancing sky coverage

GRAVITY’s leaps in sensitivity by factor 1000s resulted from dual-beam interferometry and fringe-tracking on a nearby reference star. Because it splits the light of the two objects in the instrument, the maximum separation is $2''$ for the UTs. GRAVITY Wide (GRAVITY+ Collaboration et al. 2022) has extended its dual-beam capability to also take advantage of the previously installed PRIMA dual-beam infrastructure. The maximum separation between the two objects can then be up to several $10''$, limited only by the Earth’s turbulent atmosphere. The limit is set by the isopistonc angle θ_P , at which the phase between the two objects become uncorrelated.

The sky coverage is ultimately given by the combination of the isopistonc angle and the limiting magnitude for fringe-tracking. Both increase with telescope diameter, and we will show below that the advantage of large telescopes for dual-beam interferometry even exceeds the SNR advantage outlined in §5.1. First, the isopistonc angle increases with telescope diameter $\theta_P \propto D^{1/6}(\text{const.} + D)$ (Elhalkouj et al. 2008, Boskri et al. 2021), because in this case the beams from the two stars partially overlap, and thereby see the same atmospheric perturbations (Figure 12). As a result, the isopistonc area for off-axis interferometry around a fringe-tracking star increases $\propto D^{1/3 \dots 7/3}$. For typical atmospheric conditions, the isopistonc angle increases from $\approx 12''$ to $\approx 50''$ when going from 1-m to 10-m telescopes. Second, the gain in SNR $\propto D^2$ and the reduced bandwidth requirement

Detective quantum efficiency: Product of optical transmission and detector quantum efficiency, including all losses

Worst offender: Term dominating sensitivity or error budget

Sky coverage: Fraction of sky area / objects in a certain direction, which can be observed with a given instrument

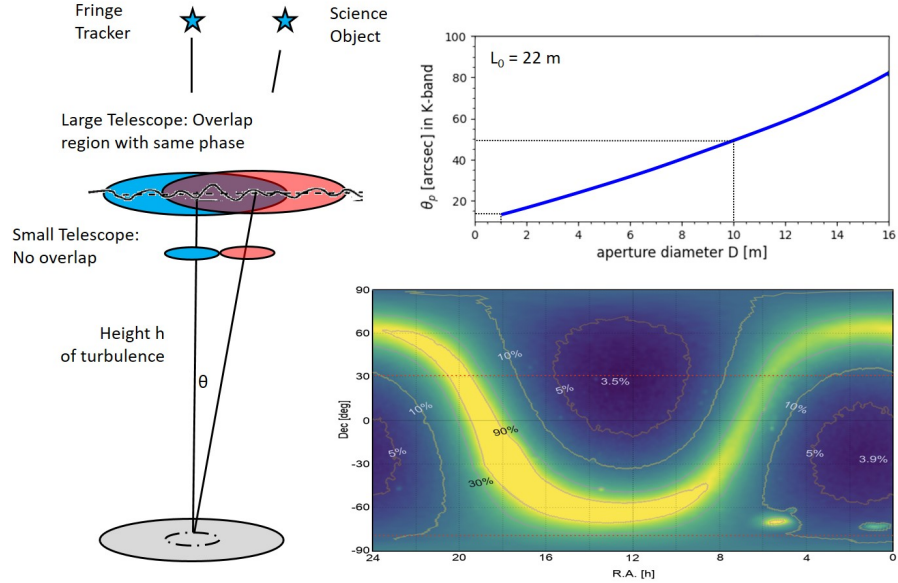


Figure 14

Enhanced sky coverage for large telescopes. Left: when observing two objects simultaneously, the two beams overlap for large telescopes, thereby increasing the isopistic angle with telescope diameter (top right, following Elhalkouj et al. (2008)). Bottom right: The resulting sky coverage for 8m telescopes with a fringe-tracking limiting magnitude $m_K = 13$ mag

for fringe-tracking $\propto D^{1/6 \dots 1}$ relax the brightness requirement by a factor $\propto D^{-2.2 \dots -3}$, which for a star luminosity function $N(\text{Stars brighter given flux } S) \propto S^{-3/2}$ increases the sky density of suitable stars $\propto D^{3.3 \dots 4.5}$.

Taken together, the larger isopistic area and the access to fainter fringe-tracking stars increases the sky coverage for dual-beam interferometry $\propto D^{3.6 \dots 6.8}$. Vibrations and imperfect AO will eat up some of the advantages of large apertures, but it is only the 10-m class telescopes, in combination with LGS AO, to provide full (in the galactic plane) and substantial (for extragalactic observations outside the galactic plane) sky-coverage for off-axis fringe-tracking (Figure 14).

7.4. Enhancing wavelength and baseline dynamic ranges

The wavelength range covered by O/IR interferometry is continuing to grow. MATISSE (Lopez et al. 2022) extended VLTI imaging capabilities to observe the L, M, N bands (3-12 μ m) simultaneously with 4 telescopes. Using the GRAVITY fringe-tracker will push limiting magnitudes especially for observations with higher spectral resolution, although only a few results are out as of this date. VLTI will also stretch to shorter wavelengths with the J-band BIFROST instrument, under construction (Kraus et al. 2022). Visible imaging with 0.3 mas angular resolution should now be possible at NPOI and CHARA, and we expect results in the near future for dwarf stars, interacting binaries, gaseous disks, and stellar surfaces. Visible imaging will be boosted as NPOI integrates new 1m telescopes with AO into the system. Improved imaging needs better uv coverage and this means

Dynamic range:

Maximum achievable contrast. In interferometric imaging driven by number of baseline, in model-fitting by signal-to-noise ratio

adding telescopes and baselines. While harder, there is progress here too as CHARA is adding a 7th mobile telescope that will be connected to the array with single-mode fibers, leading to potentially longer baselines as well as more dense uv coverage. Ultimately, new facilities are needed to make a breakthrough in imaging and the MROI hopes to do this with 10 movable telescopes. While MROI will not have substantially longer baselines than CHARA, the uv-plane will be radically better sampled with virtually no gaps in the uv-plane, making high fidelity imaging truly possible. This project is partially funded with first fringes expected in 2023. The Planet Formation Imager project (PFI; Monnier et al. 2018) explored the science potential of 12x3m array with 1.2km baselines and found an exciting science case for detecting giant exoplanets as they are forming in young disks using K and L band nulling, but also concluded that sensitivity was insufficient to go below a few Jupiter-masses. As the SNR for observations of point-sources scale $\sqrt{N_{\text{tel}}}D^2$ in the background-limit (§5.1), truly revolutionary capabilities await ground-based arrays of ten or more 8-m class telescopes (i.e, a scaled up VLTI-UT) rather than many small telescopes – or a move to space where the IR background is smaller by millions or even billions.

7.5. Space interferometry

O/IR interferometry is well-suited to space, as all the major difficulties from the ground are missing: atmospheric turbulence that limit coherent integration times, light losses from complex optics to transport and delay light as stars move across sky, and severe thermal IR backgrounds. The first attempts in 1990s and 2000s to build space interferometers were ultimately not pursued, namely the Space Interferometer Mission (SIM, aimed at precision astrometry) and two MIR nulling interferometers – DARWIN (ESA) and the Terrestrial Planet Finder Interferometer (TPFI) – designed to detect and characterize Earth-like planets. A new flagship mission called LIFE, the Large Interferometer for Exoplanets (e.g., Quanz et al. 2022) is being proposed. The nulling interferometer with 4x2m telescopes working in the thermal-IR aims at detecting 550 exoplanets, with 25-45 being rocky planets in their habitable zones (HZ). For 3.5m telescopes, the last number jumps to 60-80 planets that might harbor life. Recent technical advances make space interferometry more feasible, including successful formation flying missions (e.g., GRACE-FO, LISA Pathfinder), lower launch costs, and the maturation of cubeSats and commercial smallSats (see detailed overview by Monnier et al. 2019). The first space interferometer SunRISE (6-cubeSats in radio Kasper et al. 2019) will be launched in ~2024 and multiple optical designs using smallSats have been proposed (e.g., Matsuo et al. 2022). While the near-term political and technical outlook is still uncertain, the scientific potential of space nulling interferometry to measure the mid-IR spectra of Earth-like planets is still highly compelling and recognized as one of the most important long-term goals for Astronomy.

Formation flying:
Maintaining relative separation and orientation between multiple spacecrafts - prerequisite for large baseline interferometry in space

FUTURE DIRECTIONS

1. Current interferometers fall many orders of magnitude behind fundamental limits.
2. Worst offenders are adaptive optics performance, optical throughput, metrology laser background, detector noise, and vibrations.
3. Ongoing GRAVITY+ upgrade with laser guide star AO and wide-field dual-beam capability will boost sky coverage by order of magnitudes.
4. Current facilities continue to expand instrumentation to wider wavelength ranges

and offer a testbed for new technologies, such as nulling.

5. VLTI and CHARA will remain unique in the era of upcoming 30-40m extremely large telescopes (ELTs), not for sensitivity but for angular resolution.
6. New ground- and space-based interferometers are under construction (MROI) or proposed (PFI, LIFE).
7. Technologies to pursue include affordable 8-m telescopes, interferometric laser guide stars, formation flying space interferometry, and photon-counting IR detectors.

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LITERATURE CITED

- Akeson RL, Boden AF, Monnier JD, Millan-Gabet R, Beichman C, et al. 2005. *ApJ* 635:1173–1181
- Alexander T. 2005. *Phys.Rept.* 419:65–142
- Amorim A, Bauböck M, Berger JP, Brandner W, Clénet Y, et al. 2019. *Phys. Rev. Lett.* 122:101102
- Andrews SM, Huang J, Pérez LM, Isella A, Dullemond CP, et al. 2018. *ApJL* 869:L41
- Angel JRP, Woolf NJ. 1997. *ApJ* 475:373–379
- Antonucci RRJ, Miller JS. 1985. *ApJ* 297:621–632
- Anugu N, Amorim A, Gordo P, Eisenhauer F, Pfuhl O, et al. 2018. *MNRAS* 476:459–469
- Anugu N, Le Bouquin JB, Monnier JD, Kraus S, Setterholm BR, et al. 2020. *AJ* 160:158
- Armstrong JT, Mozurkewich D, Rickard LJ, Hutter DJ, Benson JA, et al. 1998. *ApJ* 496:550–571
- Arsenault R, Alonso J, Bonnet H, Brynnel J, Delabre B, et al. 2003. *SPIE Conf. Ser.* 4839:174–185
- Atkinson D, Hall D, Goebel S, Jacobson S, Baker I. 2018. *SPIE Conf. Ser.* 10709:107091H
- Babcock HW. 1953. *PASP* 65:229
- Baldwin JE, Beckett MG, Boysen RC, Burns D, Buscher DF, et al. 1996. *A&S* 306:L13
- Baldwin JE, Boysen RC, Cox GC, Haniff CA, Rogers J, et al. 1994. *SPIE Conf. Ser.* 2200:118–128
- Balick B, Brown RL. 1974. *ApJ* 194:265–270
- Baron F. 2016. In *Astronomy at High Angular Resolution*, vol. 439
- Baron FR. 2020. *SPIE Conf. Ser.* 11446:114461N
- Baudoin R, Darré P, Gomes JT, Fabert M, Grossard L, et al. 2016. *JAI* 5:1650006
- Beckers JM. 1993. *AnnRevA&S* 31:13–62
- Beckers JM, Enard D, Faucherre M, Merkle F, di Benedetto GP, et al. 1990. *SPIE Conf. Ser.* 1236:108–124
- Benisty M, Dominik C, Follette K, Garufi A, Ginski C, et al. 2022. *arXiv:2203.09991*

- Benisty M, Natta A, Isella A, Berger JP, Massi F, et al. 2010. *A&A* 511:A74
- Berger JP, Bourdarot G, Guillet de Chatellus H. 2020. *SPIE Conf. Ser.* 11446:1144613
- Berger JP, Haguenaier P, Kern P, Perraut K, Malbet F, et al. 2001. *A&A* 376:L31–L34
- Bhatnagar S, Cornwell TJ, Golap K, Uson JM. 2008. *A&A* 487:419–429
- Bland-Hawthorn J, Gerhard O. 2016. *AnnRevA&A* 54:529–596
- Bland-Hawthorn J, Sellars MJ, Bartholomew JG. 2021. *JOSA B Optical Physics* 38:A86
- Böhm M, Glück M, Keck A, Pott JU, Sawodny O. 2017. *JOSA A* 34:A10
- Bohn AJ, Benisty M, 2019 K, van der Marel N, Wölfer L, et al. 2022. *A&A* 658:A183
- Bonnet H, Bauvir B, Wallander A, Cantzler M, Carstens J, et al. 2006. *The Messenger* 126:37–40
- Born M, Wolf E. 1999. *Principles of Optics*
- Boskri A, Petrov RG, El Halkouj T, Hadjara M, Leftley J, et al. 2021. *MNRAS* 506:1364–1388
- Bouvier J, Perraut K, Le Bouquin JB, Duvert G, Dougados C, et al. 2020. *A&A* 636:A108
- Boyajian TS, von Braun K, van Belle G, McAlister HA, ten Brummelaar TA, et al. 2012. *ApJ* 757:112
- Boyd RW, Townes CH. 1977. *Applied Physics Letters* 31:440
- Bracewell RN. 1978. *Nature* 274:780–781
- Brown M, Thiel V, Allgaier M, Raymer M, Smith B, et al. 2022. *SPIE Conf. Ser.* 12015:120150E
- Brown RH, Twiss RQ. 1956. *Nature* 177:27–29
- Burtscher L, Meisenheimer K, Tristram KRW, Jaffe W, Höning SF, et al. 2013. *A&A* 558:A149
- Buscher DF. 1994. In *Very High Angular Resolution Imaging*, vol. 158
- Buscher DF, Creech-Eakman M, Farris A, Haniff CA, Young JS. 2013. *JAI* 2:1340001
- Buscher DF, Longair FbM. 2015. *Practical Optical Interferometry*
- Cassan A, Ranc C, Absil O, Wyrzykowski L, Rybicki KA, et al. 2022. *Nature Astronomy* 6:121–128
- Che X, Monnier JD, Zhao M, Pedretti E, Thureau N, et al. 2011. *ApJ* 732:68
- Cherenkov Telescope Array Consortium, Acharya BS, Agudo I, Al Samarai I, Alfaro R, et al. 2019. *Science with the Cherenkov Telescope Array*
- Chiavassa A, Kravchenko K, Montargès M, Millour F, Matter A, et al. 2022. *A&A* 658:A185
- Chiavassa A, Plez B, Josselin E, Freytag B. 2009. *A&A* 506:1351–1365
- Choquet É, Menu J, Perrin G, Cassaing F, Lacour S, Eisenhauer F. 2014. *A&A* 569:A2
- Claes R, Kluska J, Van Winckel H, Min M. 2020. *SPIE Conf. Ser.* 11446:114461U
- Colavita MM. 2009. *New Astron. Rev.* 53:344–352
- Colavita MM, Boden AF, Crawford SL, Meinel AB, Shao M, et al. 1998. *SPIE Conf. Ser.* 3350:776–784
- Colavita MM, Booth AJ, Garcia-Gathright JI, Vasisht G, Johnson RL, Summers KR. 2010. *PASP* 122:795
- Colavita MM, Serabyn E, Millan-Gabet R, Koresko CD, Akeson RL, et al. 2009. *PASP* 121:1120
- Colavita MM, Wallace JK, Hines BE, Gursel Y, Malbet F, et al. 1999. *ApJ* 510:505–521
- Colavita MM, Wizinowich PL. 2003. *SPIE Conf. Ser.* 4838:79–88
- Colavita MM, Wizinowich PL, Akeson RL, Ragland S, Woillez JM, et al. 2013. *PASP* 125:1226
- Conan JM, Rousset G, Madec PY. 1995. *JOSA A* 12:1559–1570
- Coudé du Foresto V, Perrin G, Ruilier C, Mennesson BP, Traub WA, Lacasse MG. 1998. *SPIE Conf. Ser.* 3350:856–863
- Crawford SL, Ragland S, Booth A, Colavita MM, Hovland E. 2006. *SPIE Conf. Ser.* 6268:62683W
- Davies R, Kasper M. 2012. *AnnRevA&A* 50:305–351
- Davis J, Tango WJ, Booth AJ, ten Brummelaar TA, Minard RA, Owens SM. 1999. *MNRAS* 303:773–782
- Defrère D, Absil O, Berger JP, Boulet T, Danchi WC, et al. 2018. *Exp. Ast.* 46:475–495
- Defrère D, Hinz PM, Mennesson B, Hoffmann WF, Millan-Gabet R, et al. 2016. *ApJ* 824:66
- Delplancke F. 2008. *New Astron. Rev.* 52:199–207
- di Benedetto GP, Conti G. 1983. *ApJ* 268:309–318
- Di Lieto N, Haguenaier P, Sahlmann J, Vasisht G. 2008. *SPIE Conf. Ser.* 7013:70130H

- Do T, Hees A, Ghez A, Martinez GD, Chu DS, et al. 2019. *Science* 365:664–668
- Dong S, Mérand A, Delplancke-Ströbele F, Gould A, Chen P, et al. 2019. *ApJ* 871:70
- Dullemond CP, Monnier JD. 2010. *AnnRevA&S* 48:205–239
- Duvert G, Young J, Hummel CA. 2017. *A&A* 597:A8
- Dyck HM, Benson JA, Ridgway ST. 1993. *PASP* 105:610
- Eisenhauer F. 2019. In *The Very Large Telescope in 2030 (VLT2030)*. 10.5281/zenodo.3356274
- Eisenhauer F, Perrin G, Rabien S, Eckart A, Léna P, et al. 2008. In *The Power of Optical/IR Interferometry: Recent Scientific Results and 2nd Generation*
- Eisner JA, Graham JR, Akeson RL, Najita J. 2009. *ApJ* 692:309–323
- Elhalkouj T, Ziad A, Petrov RG, Lazrek M, Elazhari Y, Benkhaldoun Z. 2008. *A&A* 477:337–344
- Errmann R, Minardi S, Labadie L, Muthusubramanian B, Dreisow F, et al. 2015. *App.Opt.* 54:7449
- Espinosa Lara F, Rieutord M. 2013. *A&A* 552:A35
- Event Horizon Telescope Collaboration, Akiyama K, Alberdi A, Alef W, Algaba JC, et al. 2022. *ApJL* 930:L12
- Feautrier P, Gach JL, Guieu S, Downing M, Jordan P, et al. 2014. *SPIE Conf. Ser.* 9148:914818
- Ferrari M, Lemaitre GR, Mazzanti SP, Derie F, Huxley A, et al. 2003. *SPIE Conf. Ser.* 4838:1155–1162
- Finger G, Baker I, Alvarez D, Dupuy C, Ives D, et al. 2016. *SPIE Conf. Ser.* 9909:990912
- Finger G, Baker I, Alvarez D, Eisenhauer F, Hechenblaikner G, et al. 2019. *SPIE Conf. Ser.* 11180:111806L
- Finger G, Baker I, Dorn R, Eschbaumer S, Ives D, et al. 2010. *SPIE Conf. Ser.* 7742:77421K
- Finger G, Baker I, Downing M, Alvarez D, Ives D, et al. 2017. *SPIE Conf. Ser.* 10563:1056311
- Fizeau H. 1868. *C. R. Acad. Sci.* 66:932–934
- Froehly C. 1981. In *Scientific Importance of High Angular Resolution at Infrared and Optical Wavelengths*
- Gai M, Corcione L, Lattanzi MG, Bauvir B, Bonino D, et al. 2003. *Memorie della Società Astronomica Italiana* 74:472
- Gaia Collaboration, Prusti T, de Bruijne JHJ, Brown AGA, Vallenari A, et al. 2016. *A&A* 595:A1
- Gallenne A, Mérand A, Kervella P, Monnier JD, Schaefer GH, et al. 2015. *A&A* 579:A68
- Gámez Rosas V, Isbell JW, Jaffe W, Petrov RG, Leftley JH, et al. 2022. *Nature* 602:403–407
- Garcia EV, Muterspaugh MW, van Belle G, Monnier JD, Stassun KG, et al. 2016. *PASP* 128:055004
- Gardner T, Monnier JD, Fekel FC, Le Bouquin JB, Scovira A, et al. 2022. *arXiv:2209.00669*
- Gardner T, Monnier JD, Fekel FC, Schaefer G, Johnson KJC, et al. 2021. *AJ* 161:40
- Genzel R, Eisenhauer F, Gillessen S. 2010. *Reviews of Modern Physics* 82:3121–3195
- Gitton PB, Leveque SA, Avila G, Phan Duc T. 2004. *SPIE Conf. Ser.* 5491:944
- Gлиндemann A. 2011. *Principles of Stellar Interferometry*
- Goebel SB, Hall DNB, Guyon O, Warmbier E, Jacobson SM. 2018. *JATIS* 4:026001
- Gottesman D, Jennewein T, Croke S. 2012. *PRL* 109:070503
- GRAVITY+ Collaboration, :, Abuter R, Allouche F, Amorim A, et al. 2022. *arXiv:2206.00684*
- Gravity Collaboration, Abuter R, Accardo M, Amorim A, Anugu N, et al. 2017a. *A&A* 602:A94
- Gravity Collaboration, Abuter R, Aimar N, Amorim A, Arras P, et al. 2022a. *A&A* 657:A82
- Gravity Collaboration, Abuter R, Aimar N, Amorim A, Ball J, et al. 2022b. *A&A* 657:L12
- Gravity Collaboration, Abuter R, Amorim A, Anugu N, Bauböck M, et al. 2018a. *A&A* 615:L15
- Gravity Collaboration, Abuter R, Amorim A, Bauböck M, Berger JB, et al. 2020a. *A&A* 638:A2
- Gravity Collaboration, Abuter R, Amorim A, Bauböck M, Berger JP, et al. 2018b. *A&A* 618:L10
- Gravity Collaboration, Abuter R, Amorim A, Bauböck M, Berger JP, et al. 2019a. *A&A* 625:L10
- Gravity Collaboration, Abuter R, Amorim A, Bauböck M, Berger JP, et al. 2020b. *A&A* 636:L5
- Gravity Collaboration, Abuter R, Amorim A, Bauböck M, Berger JP, et al. 2021a. *A&A* 645:A127
- Gravity Collaboration, Abuter R, Amorim A, Bauböck M, Berger JP, et al. 2021b. *A&A* 647:A59
- Gravity Collaboration, Amorim A, Bauböck M, Bentz MC, Brandner W, et al. 2021c. *A&A* 654:A85
- Gravity Collaboration, Amorim A, Bauböck M, Brandner W, Bolzer M, et al. 2021d. *A&A* 648:A117

- Gravity Collaboration, Amorim A, Bauböck M, Brandner W, Clénet Y, et al. 2020c. *A&A* 643:A154
- Gravity Collaboration, Caratti o Garatti A, Fedriani R, Garcia Lopez R, Koutoulaki M, et al. 2020d. *A&A* 635:L12
- Gravity Collaboration, Dexter J, Shangguan J, Hönig S, Kishimoto M, et al. 2020e. *A&A* 635:A92
- Gravity Collaboration, Garcia Lopez R, Natta A, Caratti o Garatti A, Ray TP, et al. 2020f. *Nature* 584:547–550
- Gravity Collaboration, Lacour S, Nowak M, Wang J, Pfuhl O, et al. 2019b. *A&A* 623:L11
- Gravity Collaboration, Nowak M, Lacour S, Mollière P, Wang J, et al. 2020g. *A&A* 633:A110
- Gravity Collaboration, Perraut K, Labadie L, Bouvier J, Ménard F, et al. 2021e. *A&A* 655:A73
- Gravity Collaboration, Perraut K, Labadie L, Lazareff B, Klarmann L, et al. 2019c. *A&A* 632:A53
- Gravity Collaboration, Petrucci PO, Waisberg I, Le Bouquin JB, Dexter J, et al. 2017b. *A&A* 602:L11
- Gravity Collaboration, Pfuhl O, Davies R, Dexter J, Netzer H, et al. 2020h. *A&A* 634:A1
- Gravity Collaboration, Sanchez-Bermudez J, Caratti O Garatti A, Garcia Lopez R, Perraut K, et al. 2021f. *A&A* 654:A97
- Gravity Collaboration, Sturm E, Dexter J, Pfuhl O, Stock MR, et al. 2018c. *Nature* 563:657–660
- Guesalaga A, Neichel B, Rigaut F, Osborn J, Guzman D. 2012. *Applied Optics* 51:4520
- Gull SF, Skilling J. 1984. In *Indirect Imaging. Measurement and Processing for Indirect Imaging*
- Guyon O, Mennesson B, Serabyn E, Martin S. 2013. *PASP* 125:951
- Hale DDS, Bester M, Danchi WC, Fitelson W, Hoss S, et al. 2000. *ApJ* 537:998–1012
- Hanbury Brown R, Davis J, Allen LR. 1967. *MNRAS* 137:375
- Hansen JT, Ireland MJ, LIFE Collaboration. 2022. *A&A* 664:A52
- Hartmann L, Kenyon SJ. 1985. *ApJ* 299:462–478
- Haubois X, Perrin G, Lacour S, Verhoelst T, Meimon S, et al. 2009. *A&A* 508:923–932
- Hillen M, Kluska J, Le Bouquin JB, Van Winckel H, Berger JP, et al. 2016. *A&A* 588:L1
- Hinkley S, Lacour S, Marleau GD, Lagrange AM, Wang JJ, et al. 2022. *arXiv:2208.04867*
- Hinz PM, Angel JRP, Hoffmann WF, McCarthy DW, McGuire PC, et al. 1998. *Nature* 395:251–253
- Hippler S, Brandner W, Scheithauer S, Kulas M, Panduro J, et al. 2020. *Instruments* 4:20
- Hofmann KH, Weigelt G, Schertl D. 2014. *A&A* 565:A48
- Högbom JA. 1974. *A&A Supp.* 15:417
- Hönig SF, Watson D, Kishimoto M, Hjorth J. 2014. *Nature* 515:528–530
- Horch EP, van Belle G, Genet RM, Holenstein BD. 2013. *JAI* 2:1340009
- Hsiao HK, Winick KA, Monnier JD. 2010. *App.Opt.* 49:6675
- Hsiao HK, Winick KA, Monnier JD, Berger JP. 2009. *Optics Express* 17:18489–18500
- Huber D, Ireland MJ, Bedding TR, Brandão IM, Piau L, et al. 2012. *ApJ* 760:32
- Ireland MJ, Mérand A, ten Brummelaar TA, Tuthill PG, Schaefer GH, et al. 2008. vol. 7013 of *SPIE Conf. Ser.*
- Ireland MJ, Monnier JD, Thureau N. 2006. *SPIE Conf. Ser.* 6268:62681T
- Ireland MJ, Woillez J. 2018. *arXiv:1812.02926*
- Jaffe W, Meisenheimer K, Röttgering HJA, Leinert C, Richichi A, et al. 2004. *Nature* 429:47–49
- Jennison RC. 1958. *MNRAS* 118:276
- Johnson MA, Betz AL, Townes CH. 1974. *Physical Review Letters* 33:1617–1620
- Kalman RE. 1960. *Transactions of the ASME—Journal of Basic Engineering* 82:35–45
- Kasper JC, Lazio J, Romero-Wolf A, Bain HM, Bastian T, et al. 2019 2019:SH33A–02
- Kellerer A, Tokovinin A. 2007. *A&A* 461:775–781
- Kenchington Goldsmith HD, Cvetojevic N, Ireland M, Madden S. 2017. *Optics Express* 25:3038
- Kern P, Malbet F, Schanen-Duport I, Benech P. 1997. In *Integrated Optics for Astronomical Interferometry*. 115
- Kishimoto M, Hönig SF, Antonucci R, Barvainis R, Kotani T, et al. 2011. *A&A* 527:A121
- Kloppenborg B, Stencel R, Monnier JD, Schaefer G, Zhao M, et al. 2010. *Nature* 464:870–872
- Kluska J, Berger JP, Malbet F, Lazareff B, Benisty M, et al. 2020a. *A&A* 636:A116

- Kluska J, Malbet F, Berger JP, Baron F, Lazareff B, et al. 2014. *A&A* 564:A80
- Kluska J, Olofsson H, Van Winckel H, Khouri T, Wittkowski M, et al. 2020b. *A&A* 642:A152
- Kobus J, Wolf S, Ratzka T, Brunngräber R. 2020. *A&A* 642:A104
- Koechlin L, Rabbia Y. 1985. *A&A* 153:91–98
- Kok Y, Ireland MJ, Tuthill PG, Robertson JG, Warrington BA, et al. 2013. *Journal of Astronomical Instrumentation* 2:1340011
- Koshida S, Minezaki T, Yoshii Y, Kobayashi Y, Sakata Y, et al. 2014. *ApJ* 788:159
- Kraus S, Hofmann KH, Benisty M, Berger JP, Chesneau O, et al. 2008. *A&A* 489:1157–1173
- Kraus S, Kreplin A, Young AK, Bate MR, Monnier JD, et al. 2020a. *Science* 369:1233–1238
- Kraus S, Le Bouquin JB, Kreplin A, Davies CL, Hone E, et al. 2020b. *ApJL* 897:L8
- Kraus S, Mortimer D, Chhabra S, Lu Y, Codron I, et al. 2022. *arXiv:2208.04959*
- Kulcsár C, Massioni P, Sivo G, Raynaud HFG. 2012. *SPIE Conf. Ser.* 8447:84470Z
- Labadie L, Minardi S, Martín G, Thomson RR. 2018. *Exp. Ast.* 46:433–445
- Labdon A, Kraus S, Davies CL, Kreplin A, Kluska J, et al. 2019. *A&A* 627:A36
- Labdon A, Kraus S, Davies CL, Kreplin A, Monnier JD, et al. 2021. *A&A* 646:A102
- Labeyrie A. 1975. *ApJL* 196:L71–L75
- Labeyrie A. 1996. *Astronomy and Astrophysics Supplement* 118:517–524
- Labeyrie A, Lipson SG, Nisenson P. 2014. *An Introduction to Optical Stellar Interferometry*
- Lacour S, Dembet R, Abuter R, Fédou P, Perrin G, et al. 2019. *A&A* 624:A99
- Lacour S, Eisenhauer F, Gillessen S, Pfuhl O, Kok Y, et al. 2014a. *SPIE Conf. Ser.* 9146:91462E
- Lacour S, Tuthill P, Monnier JD, Kotani T, Gauchet L, Labeye P. 2014b. *MNRAS* 439:4018–4029
- Lacour S, Wang JJ, Rodet L, Nowak M, Shangquan J, et al. 2021. *A&A* 654:L2
- Lagrange AM, Rubini P, Nowak M, Lacour S, Grandjean A, et al. 2020. *A&A* 642:A18
- Lane BF, Colavita MM. 2003. *AJ* 125:1623–1628
- Lawson PR. 2000. In *Principles of Long Baseline Stellar Interferometry*, ed. PR Lawson
- Lawson PR, Cotton WD, Hummel CA, Monnier JD, Zhao M, et al. 2004. *SPIE Conf. Ser.* 5491:886
- Lazareff B, Berger JP, Kluska J, Le Bouquin JB, Benisty M, et al. 2017. *A&A* 599:A85
- Lazareff B, Blind N, Jocou L, Eisenhauer F, Perraut K, et al. 2014 9146:91460X
- Le Besnerais G, Lacour S, Mugnier LM, Thiebaut E, Perrin G, Meimon S. 2008. *IEEE Journal of Selected Topics in Signal Processing* 2:767–780
- Le Bouquin JB, Berger JP, Lazareff B, Zins G, Hagenauer P, et al. 2011. *A&A* 535:A67
- Le Bouquin JB, Lacour S, Renard S, Thiébaut E, Merand A, Verhoelst T. 2009. *A&A* 496:L1–L4
- Leftley JH, Tristram KRW, Hönig SF, Asmus D, Kishimoto M, Gandhi P. 2021. *ApJ* 912:96
- Lena P. 1979. *Journal of Optics* 10:323–328
- Léna P. 2020. *Astronomy’s Quest for Sharp Images*
- Leveque SA, Wilhelm R, Salvade Y, Scherler O, Daendliker R. 2003. *SPIE Conf. Ser.* 4838:983–994
- Lindgren L. 1980. *A&A* 89:41–47
- Lippa M, Gillessen S, Blind N, Kok Y, Yazıcı Ş, et al. 2016. *SPIE Conf. Ser.* 9907:990722
- Lopez B, Lagarde S, Petrov RG, Jaffe W, Antonelli P, et al. 2022. *A&A* 659:A192
- Lu RS, Broderick AE, Baron F, Monnier JD, Fish VL, et al. 2014. *ApJ* 788:120
- Lynden-Bell D, Rees MJ. 1971. *MNRAS* 152:461
- Martinez AO, Baron FR, Monnier JD, Roettenbacher RM, Parks JR. 2021. *ApJ* 916:60
- Martinod MA, Tuthill P, Gross S, Norris B, Sweeney D, Withford MJ. 2021. *App. Opt.* 60:D100
- Matsuo T, Ikari S, Kondo H, Ishiwata S, Nakasuka S, Yamamuro T. 2022. *JATIS* 8:015001
- Mawet D, Pueyo L, Lawson P, Mugnier L, Traub W, et al. 2012. *SPIE Conf. Ser.* 8442:844204
- McAlister HA. 2020. *SPIE Conf. Ser.* 11446:1144604
- Menu J, Perrin G, Choquet E, Lacour S. 2012. *A&A* 541:A81
- Mérand A. 2022. PМОIRED. Astrophysics Source Code Library, record ascl:2205.001
- Michelson AA. 1891. *Nature* 45:160–161
- Michelson AA, Pease FG. 1921. *ApJ* 53
- Millan-Gabet R, Schloerb FP, Traub WA, Carleton NP. 1999. *PASP* 111:238–245

- Millan-Gabet R, Serabyn E, Mennesson B, Traub WA, Barry RK, et al. 2011. *ApJ* 734:67
- Mollière P, Stolker T, Lacour S, Otten GPPL, Shangguan J, et al. 2020. *A&A* 640:A131
- Monnier J, Aarnio A, Absil O, Anugu N, Baines E, et al. 2019. *BAAS* 51:153
- Monnier JD. 2000. In *Principles of Long Baseline Stellar Interferometry*, ed. PR Lawson
- Monnier JD. 2003. *Reports on Progress in Physics* 66:789–857
- Monnier JD, Baron F, Anderson M, Kraus S, Millan-Gabet R, et al. 2012. *SPIE Conf. Ser.* 8445:84451I
- Monnier JD, Berger JP, Le Bouquin JB, Tuthill PG, Wittkowski M, et al. 2014. *SPIE Conf. Ser.* 9146:91461Q
- Monnier JD, Ireland M, Kraus S, Alonso-Herrero A, Bonsor A, et al. 2018. *SPIE Conf. Ser.* 10701:1070118
- Monnier JD, Millan-Gabet R. 2002. *ApJ* 579:694–698
- Monnier JD, Zhao M, Pedretti E, Thureau N, Ireland M, et al. 2007. *Science* 317:342
- Montargès M, Cannon E, Lagadec E, de Koter A, Kervella P, et al. 2021. *Nature* 594:365–368
- Mortimer DJ, Buscher DF. 2022. *MNRAS* 511:4619–4632
- Mourard D, Monnier JD, Meilland A, Gies D, Millour F, et al. 2015. *A&A* 577:A51
- Mourard D, Nardetto N, ten Brummelaar T, Bailet C, Berio P, et al. 2018. *SPIE Conf. Ser.* 10701:1070120
- Mourard D, Tallon-Bosc I, Blazit A, Bonneau D, Merlin G, et al. 1994. *A&A* 283:705–713
- Muterspaugh MW, Lane BF, Konacki M, Wiktorowicz S, Burke BF, et al. 2006. *ApJ* 636:1020–1032
- Muterspaugh MW, Lane BF, Kulkarni SR, Konacki M, Burke BF, et al. 2010. *AJ* 140:1657–1671
- Netzer H. 2015. *AnnRevA&A* 53:365–408
- Nowak M, Lacour S, Lagrange AM, Rubini P, Wang J, et al. 2020. *A&A* 642:L2
- Núñez PD, Holmes R, Kieda D, Rou J, LeBohec S. 2012. *MNRAS* 424:1006–1011
- Ohnaka K, Weigelt G, Hofmann KH. 2017. *Nature* 548:310–312
- Paladini C, Baron F, Jorissen A, Le Bouquin JB, Freytag B, et al. 2018. *Nature* 553:310–312
- Pancoast A, Brewer BJ, Treu T, Park D, Barth AJ, et al. 2014. *MNRAS* 445:3073–3091
- Parks JR, White RJ, Baron F, Monnier JD, Kloppenborg B, et al. 2021. *ApJ* 913:54
- Pauls TA, Young JS, Cotton WD, Monnier JD. 2005. *PASP* 117:1255–1262
- Paumard T, Perrin G, Eckart A, Genzel R, Léna P, et al. 2008. In *The Power of Optical/IR Interferometry: Recent Scientific Results and 2nd Generation*
- Pease FG. 1930. *Scientific American* 143:290–293
- Perraut K, Dougados C, Lima GHRA, Benisty M, Mourard D, et al. 2016. *A&A* 596:A17
- Perraut K, Jocou L, Berger JP, Chabli A, Cardin V, et al. 2018. *A&A* 614:A70
- Perrin G, Coudé du Foresto V, Ridgway ST, Mariotti JM, Traub WA, et al. 1998 *ASP Conf. Ser.* 154:2021
- Perrin G, Ridgway ST, Lacour S, Haubois X, Thiébaud É, et al. 2020. *A&A* 642:A82
- Perrin G, Ridgway ST, Mennesson B, Cotton WD, Woillez J, et al. 2004. *A&A* 426:279–296
- Perrin G, Woillez J. 2019. *A&A* 625:A48
- Quanz SP, Ottiger M, Fontanet E, Kammerer J, Menti F, et al. 2022. *A&A* 664:A21
- Quirrenbach A. 2000. In *Principles of Long Baseline Stellar Interferometry*, ed. PR Lawson
- Quirrenbach A. 2001. *AnnRevA&A* 39:353–401
- Readhead ACS, Wilkinson PN. 1978. *ApJ* 223:25–36
- Renard S, Thiébaud E, Malbet F. 2011. *A&A* 533:A64
- Richardson ND, Lee L, Schaefer G, Shenar T, Sander AAC, et al. 2021. *ApJL* 908:L3
- Righini GC, Chiappini A. 2014. *Optical Engineering* 53:071819
- Roettenbacher RM, Monnier JD, Korhonen H, Aarnio AN, Baron F, et al. 2016. *Nature* 533:217–220
- Rubilar GF, Eckart A. 2001. *A&A* 374:95–104
- Ryle M, Hewish A. 1960. *MNRAS* 120:220
- Sana H, Le Bouquin JB, Lacour S, Berger JP, Duvert G, et al. 2014. *ApJS* 215:15
- Sargent AI, Welch WJ. 1993. *AnnRevA&A* 31:297–343

- Schaefer GH, Brummelaar TT, Gies DR, Farrington CD, Kloppenborg B, et al. 2014. *Nature* 515:234–236
- Schöller M. 2007. *New Astron. Rev.* 51:628–638
- Serabyn E, Mennesson B, Colavita MM, Koresko C, Kuchner MJ. 2012. *ApJ* 748:55
- Setterholm BR, Monnier JD, Davies CL, Kreplin A, Kraus S, et al. 2018. *ApJ* 869:164
- Shaklan SB, Roddier F. 1987. *App.Opt.* 26:2159–2163
- Shao M, Colavita MM. 1992. *A&A* 262:353–358
- Shao M, Colavita MM, Hines BE, Staelin DH, Hutter DJ, et al. 1988. *A&A* 193:357–371
- Shao M, Staelin DH. 1977. *JOSA (1917-1983)* 67:81–86
- Shao M, Staelin DH. 1980. *Applied Optics* 19:1519–1522
- Stephan ECR. 1874. *Compt. Rend. Acad. Sci. (Paris)* 78:1008–1012
- Swain M, Vasisht G, Akeson R, Monnier J, Millan-Gabet R, et al. 2003. *ApJL* 596:L163–L166
- ten Brummelaar TA, McAlister HA, Ridgway ST, Bagnuolo W. G. J, Turner NH, et al. 2005. *ApJ* 628:453–465
- ten Brummelaar TA, Sturmman L, Sturmman J, Ridgway ST, Monnier JD, et al. 2012. *SPIE Conf. Ser.* 8447:84473I
- Thiébaud E. 2008. *SPIE Conf. Ser.* 7013:70131I
- Thiébaud É, Young J. 2017. *JOSA A* 34:904
- Thompson AR, Moran JM, Swenson George W. J. 2017. *Interferometry and Synthesis in Radio Astronomy, 3rd Edition*
- Townes CH. 2000. In *Principles of Long Baseline Stellar Interferometry*, ed. PR Lawson
- Traub WA, Ahearn A, Carleton NP, Berger JP, Brewer MK, et al. 2003. *SPIE Conf. Ser.* 4838:45–52
- van Belle GT. 2012. *A&ARv* 20:51
- Vasisht G, Booth AJ, Colavita MM, Johnson Richard L. J, Ligon Edgar R. I, et al. 2003. *SPIE Conf. Ser.* 4838:824–834
- Waisberg I, Dexter J, Pfuhl O, Abuter R, Amorim A, et al. 2017. *ApJ* 844:72
- Wallace AL, Ireland MJ, Federrath C. 2021. *MNRAS* 508:2515–2523
- Wang JJ, Vigan A, Lacour S, Nowak M, Stolker T, et al. 2021. *AJ* 161:148
- Wang JM, Songsheng YY, Li YR, Du P, Zhang ZX. 2020. *Nature Astronomy* 4:517–525
- Wizinowich PL, Acton DS, Lai O, Gathright J, Lupton W, Stomski PJ. 2000. *SPIE Conf. Ser.* 4007:2–13
- Willez J, Abad JA, Abuter R, Aller Carpentier E, Alonso J, et al. 2019. *A&A* 629:A41
- Willez J, Akeson R, Colavita M, Eisner J, Ghez A, et al. 2010. *SPIE Conf. Ser.* 7734:773412
- Willez J, Akeson R, Colavita M, Eisner J, Millan-Gabet R, et al. 2012. *PASP* 124:51
- Willez J, Darré P, Egner S, Gonté F, Haubois X, et al. 2018. *SPIE Conf. Ser.* 10701:1070103
- Willez J, Lacour S. 2013. *ApJ* 764:109
- Willez J, Wizinowich P, Akeson R, Colavita M, Eisner J, et al. 2014. *ApJ* 783:104
- Wojtczak JA, Labadie L, Perraut K, Tessore B, Soulain A, et al. 2022. *arXiv:2210.13095*
- Zang W, Dong S, Gould A, Calchi Novati S, Chen P, et al. 2020. *ApJ* 897:180
- Zhao M, Gies D, Monnier JD, Thureau N, Pedretti E, et al. 2008. *ApJL* 684:L95
- Ziad A. 2016. *SPIE Conf. Ser.* 9909:99091K