The unlikely rise of masking interferometry: leading the way with 19th century technology.

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ABSTRACT
The exquisite precision delivered by interferometric techniques is rapidly being applied to more and more branches of optical astronomy. One particularly successful strategy to obtain structures at the scale of the diffraction limit is Aperture Masking Interferometry, which is presently experience a golden age with implementations at a host of large telescopes around the world. This startlingly durable technique, which turns 144 years old this year, presently sets the standard for the recovery of faint companions within a few resolution elements from the core of a stellar point spread function. This invited review will give a historical introduction and overview of the modern status of the technique, the science being delivered, and prospects for new advances and applications.

Keywords: Aperture Masking Interferometry

1. THE DAWN OF INTERFEROMETRY
The 19th century witnessed spectacular progress in our understanding of light. For more than 150 years debate had raged over whether light was composed of particles or waves. The proponents of the wave theory were given a dramatic boost in 1802 with Young’s double-slit experiment. The showdown between the corpuscular and wave theories of light came in 1817 with Fresnel’s victory over Poisson at the Académie des Sciences spectacularly confirming the wave predictions of a bright spot (variously called Arago’s or Poisson’s spot) on axis behind an opaque circular occulter. Although this victory proved ephemeral and the match was ultimately declared a draw with the advent of quantum mechanics a century later, for the remainder of the 19th century, the wave theory ruled supreme.

In the first half of the 19th century there were a number of optical devices and experiments constructed using interferometeric principles, however almost all were investigations into the wave nature of light itself, usually intended to support the case against the corpuscular theory. Very few of these could be described using the modern meaning of the word Interferometer – a device intended to make quantitative measurements on a physical system by exploiting the wave nature of light.

Perhaps characteristically, the first person to realize the potential for measurement of physical properties using light was the great polymath of the age, Thomas Young. Having a primary profession as a medical doctor, Young invented a device around 1813 that he termed an “Eriometer” and which was used to make the first measurements of the size of red blood cells. The device worked by measuring the angular extent of the scattering halo created by a screen of particles of unknown size, and using his eriometer Young recorded a diameter of 7.1 µm for red cells (quite close to the modern value of 7.8 µm), before going on to correctly identify various halos and “glories” as seen in nature around bright sources of light, such as the moon, as being due to the same basic physics.

On the continent a few years later in 1818, a device which would look remarkably familiar to a modern interferometrist was developed by François Arago (who had maintained a productive collaboration with Fresnel after confirming the wave theory by actually looking for and finding the counter-intuitive bright spot). Arago placed two long tubes behind each aperture in a double-slit, and by drying the air along the path of one of the tubes, was able to observe 1.5 fringes of phase shift over a 1 m path giving an exquisitely accurate measurement of the small (0.3%) difference in refractive index between humid and dry air.

It is testament to how far these pioneers were ahead of their time that 30 years elapsed before the world caught up with these revolutionary ideas, and the power of optical interferometry was again harnessed for physical...
science. The leading light of the new generation was Fizeau, and he constructed an interferometric device in 1852 which was to become a benchmark for all that was to follow. Fizeau’s interferometer addressed the leading scientific question of the day: aiming to measure the speed of the earth through the luminiferous aether. In his writings, Fizeau credits the earlier inspirational work of Arago: “We are indebted to M. Arago for a method based upon the phenomena of interference, which is capable of indicating the most minute variations in the indexes of refraction of bodies. The experiments of MM. Arago and Fresnel upon the difference between the refractions of dry and moist air, have proved the extraordinary sensibility of that means of observation.” A few years later in 1856, Jules Jamin made high precision measurements of refractive index using an “Interferential-Refractor” setup that bears his name, and which (after several refinements) evolved into the recognizable modern form of the Mach-Zehnder interferometer before the end of the century.

It is in this setting of the very first few scientific applications for interferometry, with the actual word “Interferometer” yet to be coined, that Fizeau suggested in 1868 that it might be possible to measure the angular diameters of distant stars. Experimental realization of this idea came 4 years later with Edouard Stéphan’s observations with the Marseilles 80 cm reflector. After another interval of 17 years, Albert Michelson mounted his comprehensive experimental campaign delivering the first actual stellar diameters from Mt Wilson, together with a description of the mathematical foundations of stellar interferometry. The history of this era is given with comprehensive clarity in Peter Lawson’s historical essay on stellar interferometry, and so I will not attempt to cover it here.

These early observations were made with what we would now call an aperture masking interferometer, and before finishing this digression into distant history, it is worth noting a few points. Masking was not only the first stellar interferometry, it was among the first few interferometric experiments of any kind. However in some senses, this was a false dawn for the field. As the more ambitious longer-baseline devices of Michelson and Pease in the 1920’s and 1930’s hit a host of technical problems, it was realized that precision measurements of stellar diameters were simply beyond the technology of the day. However despite the fact that it was 100 years before Fizeau’s original vision could be realized with modern electronic detectors and control systems, the challenge laid down by the fundamental science of astronomical observation helped to spur the development of interferometry in the late 19th and early 20th century, and the ideas went on to underpin methods now found in almost every branch of physics.

2. THE MODERN RENAISSANCE OF MASKING INTERFEROMETRY

After a lapse of more than 60 years, masking interferometry was separately and independently resurrected by two astronomers on opposite sides of the globe. Interestingly, both shared a common background in radio astronomy where ideas of aperture synthesis and closure phase were long established. John Baldwin of Cambridge University was the first to publish interferometric data demonstrating the recovery of visibility and closure phase signals in the optical using the University of Hawaii 88-inch telescope. The results from the Australian team, led by Bob Frater, were published only a few months later and described experiments at the 3.9 m AAT telescope some of which entailed a very large full size plywood mask on the top ring of the telescope which occulted the primary mirror. These results came in the context of burgeoning interest in high resolution techniques following the pioneering Narrabri Stellar Intensity Interferometer and subsequent development of Speckle Interferometry, with the first suggestions to implement optical closure phase all in the early 1970’s. The Cambridge and Sydney groups were soon joined by a third masking team on the 200 in Hale Telescope, again led by scientists with a strong radio pedigree, producing high dynamic range, resolved images of close binary stars and evolved giants. Around this time there were also variations entailing more complex setups, such as a Dutch sparse-aperture shearing interferometer trialled in La Palma, although few of these progressed past prototypes.

Both the Cambridge and Sydney groups continued to actively pursue the development of more advanced second-generation masking experiments into the 1990’s. Following from the first true image recovered from optical aperture synthesis, the Cambridge experiment was moved to the larger 4.2m WHT telescope and a novel readout mode implemented with the CCD which could deliver a continuous sequence of 1-D snapshot images rapid enough to effectively freeze the seeing for bright targets. After publishing the first resolved image...
of a stellar surface (Betelgeuse\textsuperscript{19}), the WHT experiment went on to deliver a series of highly productive studies of red giant atmospheres and surface structures\textsuperscript{20–23}.

Meanwhile, the Sydney group now led by Gordon Robertson took a different tack with the construction of their MAPPIT instrument. Maintaining a 2-D readout of their detector array, they took the ambitious step of building a cross-dispersed system in which simultaneous spectral and spatial information could be recorded\textsuperscript{24–26}. As for the WHT experiment, the snapshot 1-D Fourier coverage could be rotated on the sky to sample the uv plane. MAPPIT’s powerful combination of cross-dispersed fringe data also delivered scientifically valuable findings for binary stars\textsuperscript{27} and evolved giants\textsuperscript{28–31}.

The first of the new generation of 10 m class telescopes, the Keck 1, was fully operational by the mid 1990’s. Exploiting the factor of 2 increase in baseline, an aperture masking experiment originating from the University of California at Berkeley was commissioned at Keck in 1995\textsuperscript{32}. There were several factors beyond the longer baselines that contributed to the success of this project, which delivered continuing output of new science for more than a decade. Near-infrared array cameras were just becoming available with fast readout and enough pixels to sample the two-dimensional Fizeau diffraction patterns (yielding snapshot 2-D imaging). Operation in the near-IR not only exploits the more benign atmospheric seeing, it also opens a window of key astrophysical relevance. While the number of stellar targets with apparent diameters resolvable with a mask in the optical is only a dozen or so, there are an order of magnitude more systems exhibiting hot circumstellar dust which present a large enough angular extent be imaged in the near-IR. Not only was the experiment well suited to the traditionally-favored interferometric targets of evolved/dusty red giants\textsuperscript{33–39}; it also delivered unique new images of YSO\textsuperscript{40–43} and revealed spectacular plumes and wakes around colliding-wind binaries\textsuperscript{44–48}. Figure 1 depicts the two principal workhorse masks delivering this science: typically the 21-hole Golay mask (Kmag < 0) while the annulus mask was suited to fainter objects. In addition to these, there was also a 1-dimensional mask which could be used in concert with a cross-dispersing grism element to deliver simultaneous spatio-spectral\textsuperscript{39} data in a near-IR analogue of the MAPPIT setup described above.

### 3. Masking Goes Global

Over the last decade, masking interferometry has broadened to encompass wavelength regimes from the optical to the mid-IR, along the way adopting a host of advanced modes and improvements to maximize its scientific utility. Masking projects are now in progress or planned at almost every observatory with an 8 m telescope.

#### 3.1 Masking and Adaptive Optics

During the evolution of the experiments described above, of course there were also many alternate approaches to high angular resolution imaging which were implemented. One rapidly maturing technology over this interval was Adaptive Optics (AO). Although at first glance, this may appear to be a direct competitor to the masking interferometry experiments described, it turned out that the two methods could be combined into a powerful new form which exploited the strengths of both: \textit{sparse aperture adaptive optics}, or perhaps more simply, masking-behind-AO. Among the most persistent outstanding problems in AO has been the robust deconvolution of information contained within the of the core of the PSF: a realm within a few \( \lambda/D \) over which masking interferometry has been demonstrated to excel due to its emphasis on precision calibration of residual phase noise. On the other hand, seeing-limited aperture masking is strictly confined to bright-target science by the requirement to freeze the atmospheric turbulence in a single exposure, so that integration times can be no more than a hundred milliseconds or so. Combining masking and AO can be thought of as a Fizeau interferometer in which the AO system performs the role of a fast fringe tracker, locking the fringe on every baseline to a phase center now defined by the wavefront sensor. As long as the AO system is able to deliver some reasonable degree of correction on all baselines, the fringes are stabilized and one can perform arbitrarily long integrations with the science camera, thereby reaching a fainter class of target. The first experiments to place a mask into a large telescope equipped with an AO system were implemented on the Hale 200 inch on the PHARO camera in 2003 and the NIRC 2 camera at Keck 2 in 2004\textsuperscript{49,50} with a further masking experiment commissioned in the NACO instrument at the VLT a few years later in 2007\textsuperscript{51,52}. 
Figure 1. Upper Panels: the two most productive aperture mask configurations used for the original Keck-1 masking experiment, overplotted on an image of the Keck-1 primary mirror. The left side shows a strictly non-redundant Golay type sampling, while the right hand panel shows a thin annular ring. The Center panels show a corresponding single-frame interferogram recorded on the NIRC camera while observing a bright point source reference star. The bottom panels show the mean power spectra of such data, accumulated over 100 frames.
3.2 High Contrast detection at High Angular Resolution

With the faint target reach opened up by sparse-aperture AO, combined with the high-fidelity recovery of complex visibility data, masking interferometers could be turned to one of the key observational problems in contemporary astronomy: resolving high contrast companions in the immediate environs of bright stellar targets. In particular, it turned out that the self-calibrating properties of the Closure Phases – which could be recovered with errors better than one degree from masking interferometry experiments – was the key to opening a new realm of high contrast science. Using this powerful observable, unique new science campaigns delivered low-mass stellar binary systems and brown dwarfs\cite{53-56} while the relative efficiency of observational methods enabled large surveys which pushed the contrasts ever higher towards the planetary regime\cite{57-60}. Finally, in the last couple of years, compact high contrast detections in very young transitional disk systems have been reported\cite{61, 62}\footnote{It is these high-profile discoveries, perhaps more than anything else, that has motivated the adoption of masking interferometry so widely as a part of the instrumental capability modern large telescopes around the world.}

3.3 Mid-Infrared interferometry and segment tilting

Masks used for high contrast detection, as described in the previous section, tended to have a relatively small number (7–9) of large (~1 m) holes. Binary objects are relatively simple and do not require extensive Fourier coverage, while masks with a few large holes pass more total flux. Masks of similar design also turn out to be useful for mid-infrared implementations of masking experiments, although for somewhat different reasons. In the mid-IR, $r_0$ can be of order several meters in size, and when mask holes are scaled for this parameter they tend to the few-large-holes side. A 7-hole mask following these principles was installed in the TRECS camera in Gemini South, and has been available for masking interferometry since 2007\cite{63}.\footnote{With the realization that some large telescope mirrors are comprised of separately steerable segments, each about the right size to make a workable element in a sparse aperture interferometer, the innovative concept of segment tilting interferometry was born. A great advantage of segment tilting interferometry is that several different subsets of mirrors can be separately assigned a distinct pointing center on the science camera, so that the primary mirror is then fragmented into a number of completely independent non-redundant interferometer arrays. Although simple in principle, in practice it turned out to be challenging to maintain alignment not only of all the separate tilts, but each mirror sub-array also requires specific piston offsets to all segments (all mirrors in a sub-array must lie on their own distinct parabolic surface). The first – and so far only – segment tilting experiments were performed in 2004/5 at the Keck 1 telescope, delivering excellent mid-IR size measurements of YSOs\cite{64}\footnote{however this promising project was cut short with the decommissioning of the LWS instrument upon which it relied. However many new-generation large-aperture telescopes, including the JWST as indicated in Figure\ref{fig:2} are being built with segmented apertures making them suited to this elegant technique.} however this promising project was cut short with the decommissioning of the LWS instrument upon which it relied. However many new-generation large-aperture telescopes, including the JWST as indicated in Figure\ref{fig:2} are being built with segmented apertures making them suited to this elegant technique.}

3.4 SAMPol: Sparse Aperture Masking Polarimetry

One advanced masking mode which is presently enjoying growing scientific success is the combination of aperture masking with polarimetry enabled by a Wollaston Prism. In optical setups of this kind, two orthogonal linear polarization states are split and recorded simultaneously on the detector array. This results in a situation somewhat akin to Speckle Holography\cite{65}\footnote{where one can record differential observables between the two separate interferograms with high precision due to the fact that both beams traversed nearly identical optical paths (including identical instantaneous turbulence) before reaching the detector. This has been exploited to great effect with the NACO instrument\cite{51} in recovering small differences in visibility arising in orthogonal polarizations due to resolved structures in the target. The power of this unique observational window onto the scattered-light dust distribution surrounding evolved stars has been demonstrated with the very recent revelation of a new population of large scattering grains around Mira-type variables\cite{66} as described in further detail in the present volume (Norris et al., 8445-2). To date, these results have exploited only differential visibility amplitudes. The next step incorporating differential closure phases which should yield even higher levels of immunity to noise due to the inherently self-calibrating nature of the basic observable.} where one can record differential observables between the two separate interferograms with high precision due to the fact that both beams traversed nearly identical optical paths (including identical instantaneous turbulence) before reaching the detector. This has been exploited to great effect with the NACO instrument\cite{51} in recovering small differences in visibility arising in orthogonal polarizations due to resolved structures in the target. The power of this unique observational window onto the scattered-light dust distribution surrounding evolved stars has been demonstrated with the very recent revelation of a new population of large scattering grains around Mira-type variables\cite{66} as described in further detail in the present volume (Norris et al., 8445-2). To date, these results have exploited only differential visibility amplitudes. The next step incorporating differential closure phases which should yield even higher levels of immunity to noise due to the inherently self-calibrating nature of the basic observable.}
4. WHERE NOW FOR MASKING INTERFEROMETRY?

Although masking interferometry is presently enjoying a small “Belle Èpoque”, there are many refinements and new generation instruments which will no doubt result in a continual evolution away from the simplest forms of masking, which would be immediately recognizable to Fizeau himself, towards more advanced forms.

4.1 Advanced/Differential Experiments

Further development of advanced forms of differential masking interferometry is already at an advanced stage. Dedicated polarimetric masking experiments, designed for significantly greater levels of calibration stability are being considered for deployment within the SPHERE/ZIMPOL instrument and also at the Subaru telescope (The VAMPIRES instrument is described in this proceedings: Norris et al., 8445-2). These instruments also push masking interferometry back to shorter optical wavelengths where polarization signals are generally stronger.

Another area of rapid technological advance has been the implementation of integral field units (IFU) capable of delivering data cubes which record simultaneous cross-dispersed imaging data. The straightforward nature of aperture masking setups means that cost and effort to implement it, even in the context of a complex IFU setup, is usually minimal. Recent work detailed in a paper in this meeting (Zimmerman et al., 8445-87) has shown that exploiting the additional information content in the wavelength direction can deliver a factor of a few enhancement in final dynamic range obtained for a masking interferometer.

4.2 Developments with AO

As adaptive optics becomes ever more capable and ubiquitous at a host of the world’s large telescopes, the fundamental nature of problem confronting astronomers wishing to extract high fidelity imaging data has changed. We are rarely now confronted with a completely phase-unstable wavefront, but rather one with varying degrees of partial long-term coherence. This shift will only be amplified with the imminent arrival of extreme-AO systems which should be deployed at several telescopes worldwide within a year. Under conditions of weaker instability of the wavefront phases, alternate approaches to the imaging problem may prove themselves competitive or superior to classical aperture masking. One promising example of this class of algorithms is the Kernel Phase\textsuperscript{2}

\textsuperscript{2}Pires which is also described in this Proceedings (Martinache, 8445-3).
4.3 The James Webb Space Telescope Interferometer (JWST-I)

An aperture mask has also been accepted aboard the James Webb Space Telescope as a part of the NIRISS instrument. Although there is obviously no seeing to combat, telescope and instrument induced speckle noise still dominate the detection threshold for recovery of high contrast companions, and simulations show that non-redundant masking can still deliver a significant gain over conventional imaging methods even in space where wavefront quality and stability are excellent. A depiction of an aperture mask configuration for JWST is given in Figure 3, and further discussion is also given at this meeting by JWST-I lead, Anand Sivaramakrishnan (8442-98).

4.4 Masking Interferometry for Optical Surface Metrology

The concepts underlying masking’s success as a astronomical technique can also find utility in the context of a solution to the engineering challenge presented by the requirement to cophase a segmented primary mirror, such as the JWST. A non-redundant pupil, such as is formed by a mask, exhibits the remarkable property that each Fourier component in the image plane has a direct and unique mapping to a pair of subapertures in the telescope pupil. This key property disentangles the complexity in transforming focal plane images back to a knowledge of the pupil from which they arose. Using the full telescope pupil, this mapping is an ill-posed problem, but it reduces to a few straightforward Fourier measurements when a non-redundant mask is present. Simulations which incorporate real-world noise sources indicate that with a few simple snapshot images, all segments sampled by the mask can be cophased to nanometer precision in an essentially single-step (not multiply-iterated) process. The algorithms to accomplish this are described further in 8442-98 (this conference). Further exploration of this promising technique may also yield a useful method to assist with the coming generation of segmented large-aperture ground-based telescopes.

4.5 Pupil Remapping Interferometry

Dramatic advances in the control and manipulation of light have arisen from the new fields of photonics and guided-light optics where technology is strongly driven by applications from the communications industry. Astronomy has a history of exploiting these advances, and in particular several projects around the world have pursued the idea of implementing a non-redundant beam combiner array by using a photonic remapping of the highly redundant sub-pupils. Such a setup would reject wavefront phase noise both by way of non-redundancy and also by spatial filtering of the beams in single-mode waveguide optics; all the while enabling the full telescope pupil to contribute light to the interferometer. At least three groups worldwide have been in active development of such a photonic reformulation of a classical masking interferometer with papers in the present conference: 8845-4 and 8846-70. If the considerable technical issues with the stability and throughput of these challenging
devices can be resolved, then they may well inherit the mantle taking the interferometric data generated by masking interferometer to new levels of measurement precision.

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