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Detecting Extrasolar Planets with Sparse Aperture Masking

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ABSTRACT

Extrasolar planets are directly detected most easily when they are young and can have contrasts only a few hundred times fainter than their host stars at near- and mid- infrared wavelengths. However, planets and other solar-system scale structures around solar-type stars in the nearest star forming regions require the full diffraction limit of the world's largest telescopes, and can not be detected with conventional AO imaging techniques. I will describe the recent successes of long-baseline interferometry in detecting planetary-mass companions, focusing on the transitional disk system LkCa 15. I will outline why aperture-masking has been so successful in its resolution and sensitivity niche, and will outline the algorithms needed to calibrate the primary observable of closure/kernel phase to the level needed for extrasolar planet detection..

Keywords: aperture mask interferometry, sparse aperture masking, extrasolar planets

1. INTRODUCTION

Aperture-mask interferometry has long been used as a technique to overcome the effects of seeing in speckle interferometry observations,[1] and has been applied for 15 years at infrared wavelengths on 10 m class telescopes.[2] In this technique, a mask with an array of holes with non-redundant spacing is placed in the pupil-plane of a large telescope. This means that each spatial frequency in the recorded image corresponds to a unique pair of holes. Given that the majority of the incident light is blocked, leaving a sparsely sampled pupil, this technique has also been called *sparse aperture masking*. However, it is only relatively recently that the technique has been applied to observations behind Adaptive Optics (AO) systems.[3–5] The reason for the technique's success is that the closure-phase observable is unbiased and uncorrupted by residual wavefront aberrations present in an adaptive optics system.

With the continual improvement of techniques such as angular-differential imaging, the niche for aperture-masking interferometry is firmly within a field of view of approximately 2–4 λ/D, with D the telescope diameter. This may seem an especially strong limitation, given the apparent simplicity of direct AO imaging. However, this niche is especially important for a small number of key science goals. One is the measurement of dynamical masses for binary systems too faint for long-baseline interferometry. Another is the study of young extrasolar planets soon after their formation,[6,7] arguably a particularly exciting niche given the explosion in the field of extrasolar planets in the past 15 years.

In this paper, I will present a brief review of characteristic luminosities, temperatures and distances to expected nearby extrasolar planets. I will then review sparse aperture masking behind adaptive optics with special emphasis on calibration of closure phase, with the aim to repeat as little as possible of previous work.[2,4] Finally, I will discuss the recent example of LkCa 15 and conclude by speculating on the future of the technique and full-pupil aperture-masking in general.

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2. YOUNG EXTRASOLAR GIANT PLANETS

At separations of less than a few astronomical units as probed by the radial-velocity technique, extrasolar giant planets are distinct from stellar binaries.[8] This is seen as a gap in the companion mass function between approximately 20 and 80 M_J (Jupiter masses), leading to an observational upper limit to a giant planet mass of approximately 20 M_J. This distinction may continue at larger separations,[9] but there is very limited data on the distribution of wider separation low-mass companions to stars. This knowledge-gap is particularly prominent in the 5–20 AU separation range, which is also the separation region where both proposed giant-planet formation mechanisms (core-accretion and gravitational instability) are thought to operate. This knowledge gap can not be filled by indirect techniques that rely on orbital motion, primarily due to the long orbital timescales involved. For this reason, techniques that directly detect emission from extrasolar giant planets are needed to probe these separation ranges.

The luminosity of a young extrasolar giant planet is dominated by a loss in gravitational contraction energy. The energy lost in forming a planet of mass M_p and radius R_p is:

$$L_p = \alpha \frac{GM^2}{R\tau_e} \quad (1)$$

$$\approx 3 \times 10^{-4} (\frac{M}{M_J})^2 (\frac{R}{R_J})^{-1} (\frac{\tau_e}{1\mathrm{Myr}})^{-1} L_\odot. \quad (2)$$

Here α is a parameter close to 1.0 that depends on the interior structure of the planet, and τ_e is the emission timescale. M_J and R_J correspond to Jupiter's mass and radius, and $L_\odot$ is the sun's luminosity. Contraction and re-radiation of energy lost occurs on all timescales - but the bulk of the planetary luminosity is radiated at early times.

There are two main timescales (τ_e) on which young planets are expected to radiate energy: the cooling timescale and the accretion timescale. The cooling timescale for a planet which has its radius determined by degeneracy pressure (planets older than about 10 Myr) is proportional to the fourth power of temperature by the Stefan-Boltzmann law. This means that characteristic cooling timescales are a few Myr at 2000 K and many tens of Myr at 1000 K. The accretion timescale is much shorter, of order 10^5 to 10^6 years, with details depending on viscous processes in the circumplanetary disk. Accretion luminosity is driven by a sudden loss in energy as material accreting onto a planet collides with the planet, possibly guided by planetary magnetic fields in a manner analogous to stars and brown dwarfs. This sudden loss in energy is enough to ionise Hydrogen for planets of mass $\sim$1 M_J or more, but it is uncertain how this energy is reprocessed prior to reaching an observer. The picture is further complicated by the need to lose angular momentum - a process that involves rotating winds carrying away $\sim$10% of the accretion luminosity in the case of young stars, and possibly carrying away a similar proportion of the accretion luminosity for young extrasolar planets. Clearly, this is a complex picture and one that can only be understood through observations. The key points are:

- Extrasolar giant planets can only be thought of as isolated, slowly cooling objects when they are aged ($\sim$100 Myr) and difficult to detect (contrasts exceeding 10^4).
- Understanding the formation of giant planets requires observations that probe 5–50 AU separation ranges around stars still young enough to have disks, or at least to have circumplanetary disks.

3. NEARBY YOUNG STARS

Planets with an age up to $\sim$100 Myr and with atmospheres at temperatures of order 1000 K or less should be abundant within a few tens of pc, so are the prime targets for new high contrast instruments such as the Gemini Planet Imager (GPI) or SPHERE. However, young stars still potentially containing some trace of disks (less than $\sim$8 MYr) are found almost exclusively in nearby star forming regions or young OB associations. Planets around these stars are much more luminous, are much more likely to be found at the orbital radii of their birth, and much more likely to be accreting than field stars. The closest associations are summarised in Table 1, which

Table 1. A summary of young star forming regions and associations near the sun (<8 Myr, <150 pc). The number of stars refers to the number of solar-type stars ($\sim$0.5-2 $M_\odot$), either known or extrapolated from high-mass members. Numbers are indicative only, with a rough mass cutoff based on spectral type

Name	Number of stars	Age (Myr)	Distance (pc)
Taurus SFR	100	2-3	145
Upper Sco (in Sco-Cen OB2)	500–1000	5-8	140
ρ Oph	100	<2	140
η Cha/ϵ Cha	20	3–10	100

more-or-less consists of the Taurus star forming region and star formation arguably associated with the Sco-Cen OB2 complex (and may not be quite complete given the uncertainties on age and precise membership[10]). At the distance to the majority of these stars, a 20 AU separation corresponds to 150 milli-arcsec, which is the inner working angle of extreme AO systems. Extreme AO systems with coronagraphy will therefore not be able to answer critical questions about planetary birth and formation mechanisms.

Perhaps more importantly, solar-type stars in these associations have R/I magnitudes of $\sim$10-12, meaning that they are too faint for extreme AO systems to be correctly operating (for example GPI aims to have a magnitude limit of I=9). Therefore, observations of the youngest planets, and planets in the process of formation, is something that can only be done with moderate ($\sim$0.7) Strehls in H or K bands, at separations of less than $\sim$150 milli-arcsec.

4. SPARSE APERTURE MASKING

Sparse aperture-masking is a form of high-resolution imaging where the amplitude and phase of the Fourier transform of the image are considered the primary observables, and the information contained in the Fourier domain is as carefully controlled as possible. Consider images formed by a complex pupil-plane aperture function $P(x, y)$. The Fourier-transform of the image formed by this pupil is the auto-correlation of the aperture-function:

$$F(u, v) = \int P(x + u, y + v)P^*(x, y)dxdy \tag{3}$$

For this to make sense dimensionally, if x and y have units of meters, u and v also have units of meters, and spatial frequency is converted to cycles per radian by dividing by wavelength. For a simple aperture function P that is simply zero where light is blocked and $\exp(i\phi(x, y))$ for some aberration function ϕ, we can simplify this integral to:

$$F(u, v) = \int \exp(i[\phi(x + u, y + v) - \phi(x, y)])S(x, y)dxdy, \tag{4}$$

where the support function S is 1 where baselines exist within the pupil, and 0 elsewhere (see Figure 1). We can simplify this further by considering the argument and modulus of F separately, in the case of small ϕ. In this case, we approximate to second order in ϕ and arrive at:

$$F(u, v) = \int (1 - \Delta_{u,v}\phi^2/2)Sdxdy + i \int \Delta_{u,v}\phi Sdxdy \text{ , where} \tag{5}$$

$$\Delta_{u,v}\phi(x, y) = \phi(x + u, y + v) - \phi(x, y) \tag{6}$$

$$\mathrm{Arg}(F(u, v)) = (\int \Delta_{u,v}\phi Sdxdy)/(\int Sdxdy) + O(\phi^3). \tag{7}$$

$$|F(u, v)|^2 = (\int Sdxdy)^2 - (\int Sdxdy)(\int \Delta_{u,v}\phi^2 Sdxdy) + (\int \Delta_{u,v}\phi Sdxdy)^2$$

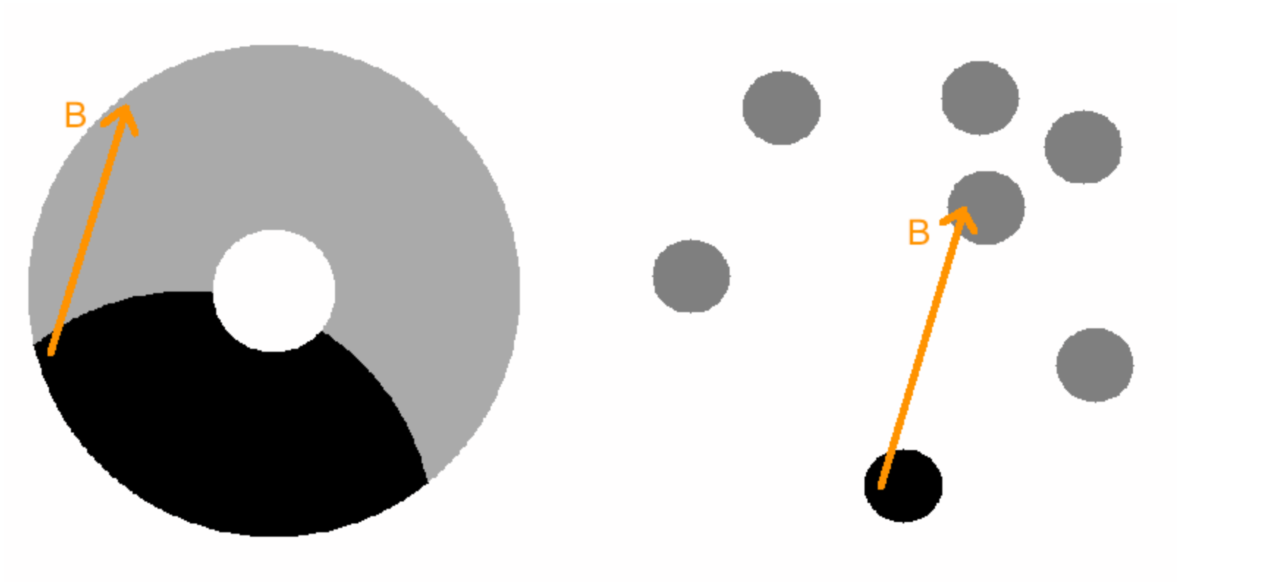

Figure 1. An illustration of the support function S (in black) for a baseline vector $B = (u, v)$ on a typical circular pupil with obstruction (left) and a sparse aperture mask (right). The sparse aperture is clearly less sensitive to large scale phase errors.

$$= \quad (\int S dx dy)^2 [1 - \langle (\Delta_{u,v}\phi - \langle \Delta_{u,v}\phi \rangle_S)^2 \rangle_S] + O(\phi^4), \tag{8}$$

where the square modulus is simplified by considering averages $\langle \cdot \rangle$ over the support S. The second-order errors in phase difference in Equation 8 may seem benign, but this analysis does not include the effects of exposure times much longer than atmospheric coherence times. Temporal errors in an adaptive optics system give both phase and amplitude errors, but phase errors average to zero, while amplitude errors do not. This means that Fourier amplitudes have typically not been used in sparse aperture masking, and when they have been used, calibration uncertainties of order 10% have to be included in the analysis. An exception to this general rule is data taken at wavelengths longer than 3 microns, where wavefront errors are small enough for amplitude errors to be at the level of a few percent or less in good conditions.

The Fourier phase in Equation 7 is to first order an integral of the phase differences over all baselines corresponding to the vector (u,v). Linear combinations of the Fourier phases $\theta(u, v) = \mathrm{Arg}(F(u, v))$ can be made that cancel out this effect of phase aberration to first order, called the *kernel-phase*, described in detail in Martinache (2010).[11] This is a very powerful technique, because the residuals are only third order in phase, while speckles that are calibrated with techniques such as Locally Optimized Combination of Images (LOCI)[12] have an amplitude that is first or second-order in phase.

The two pupil geometries illustrated in Figure 1 both share the same range of baseline lengths, and indeed their autocorrelations have similar areas (within a factor of a few) covered by non-zero elements (Figure 2). However, a much larger fraction of the circular aperture contributes to the signal at baseline B. Low-order wavefront errors therefore corrupt the kernel-phase for the full aperture data due to third order phase errors, but do not corrupt the kernel-phase in the case of a sparse aperture.

For readers familiar with interferometry, it is typical to make an approximation that each sub-aperture in a sparse aperture has a constant phase across it. Under this approximation, any closure-phase is a kernel-phase. Many past papers using aperture-masking data have created model fits directly to closure-phases. This has an obvious problem, however, in that with an n-subaperture sparse aperture, there are $n(n-1)(n-2)/6$ closure-phases, but only $(n-1)(n-2)/2$ kernel-phases (or linearly independent closure-phases). In general, closure-phase errors are correlated, due to effects such as dominant temporal tip/tilt errors in an adaptive optics system. These effects are overcome by fitting models to a statistically independent set of kernel-phases, rather

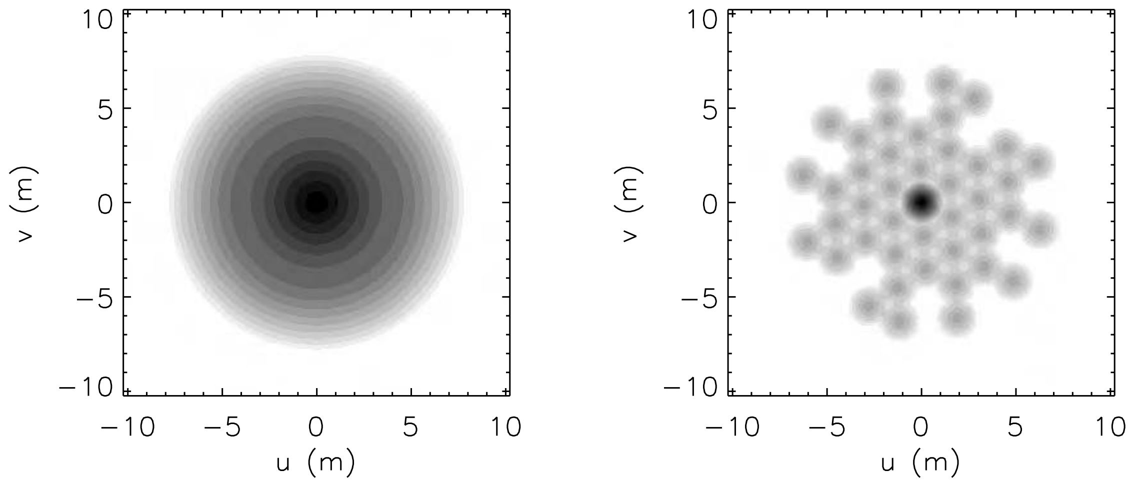

Figure 2. The autocorrelations of the aperture functions illustrated in Figure 1.

than closure-phases themselves.[7,13] For further details on phase errors in AO imaging, see the companion paper in the Adaptive Optics session.[14]

5. CALIBRATION TECHNIQUES

Like any other high-contrast technique, sparse aperture-masking is not perfect, and requires calibration. The fundamental reason for this is the third-order phase errors in Equation 7. Traditionally in speckle techniques, these effects are corrected by observing a *calibrator* star. Convolution of a science target brightness distribution with an aberrated PSF is equivalent to multiplication in the Fourier domain, which involves adding phases. Therefore, calibration of kernel or closure-phase is performed by subtracting the closure-phases of the calibrator star.

Calibration, however, is not perfect, and the kernel- or closure-phases of point sources observed subsequently are not in general the same, even with high signal-to-noise. An example of how phase errors come about is a variation in pupil-plane mask alignment against an aberrated optical element, due to thermal or gravity vector based changing stresses. In a similar manner to direct adaptive optics imaging, an ensemble of calibrators is better than a single calibrator. However, unlike the LOCI algorithm, in aperture-masking, the field of view is so narrow that any choice of linear combinations of calibrator stars has to be chosen globally. This can either be done by removing "bad" calibrator observations and averaging the rest, or by chosing an optimal linear combination of calibrators.

6. CASE STUDY: LKCA 15

The young star LkCa 15 is located in the Taurus star forming region. It appears to be associated with the young star HP Tau/G2 due to co-location on the sky (within a degree), which is a young star with a precise VLBA parallax.[15] The distance is therefore likely 161 pc, at the back side of Taurus (with an error of approximately 3 pc). The disk around LkCa 15 is a *transitional* disk, which means that it has an optically-thin inner disk, and an optically thick outer disk. This is known because of both the spectral energy distribution and direct sub-mm imaging.[16] This intermediate state of a protoplanetary disk is often thought to be a signpost of planetary formation, because disk clearing occurs during giant planet formation.

In order to maximize signal-to-noise for detecting faint structures around LkCa 15, it was necessary to both fit to kernel-phase (i.e. statistically independent linear combinations of closure-phase), and to optimally choose linear combinations of calibrator observations. As described in detail in Kraus and Ireland (2012),[7] a faint companion object was detected at 6.7 magnitudes contrast in a K-band filter at a 72 milli-arcsec separation, with a more extended structure detected with an integrated contrast of 5 magnitudes contrast in an L'-filter. The L'-band structure was detected in 3 separate epochs. More recent observations (from January 2012) in H-band have detected the companion at 7.2 magnitudes contrast at 6-σ near the location of the K-band detection. This required 6 hours of observing time, spread evenly between the target and several calibrators.

The most interesting part of the LkCa 15 detection is that unlike the expectation for older planetary systems, the detection in L-band was not of a point-source. Excluding an exotic scattering mechanism (giving emission of a red rather than blue color), the required temperature of the material ($\sim$500 K) is too warm to be directly heated by the central star. meaning that the cause of the extended L-band emission is local.

7. CONCLUSIONS AND FUTURE WORK

By being insensitive to pupil-plane phase errors to first-order, the kernel-phase technique is able to attain high-contrast at the full diffraction limit of a large telescope. When used with a sparse aperture mask, this technique (usually described as closure-phase) is especially insensitive to large-scale aberrations that are typical of varying non-common path errors in a AO system. In dedicated observations with many interspersed calibrator observations, 5-σ contrasts of 1000:1 have been obtained in the near-infrared at separations corresponding to $\sim 1\lambda/D$. Future adaptive optics systems with cutting-edge coronagraphy will be able to obtain exquisite contrasts on bright stars, but the majority of the most interesting young solar-type stars will remain beyond their reach for many years. The future of aperture-masking and kernel-phase techniques will involve an expansion to multi-wavelength simultaneous imaging with IFUs, in combination with more careful wavelength control and larger telescopes. As long as extrasolar planets can be discovered during or within 1 Myr of their formation, these techniques hold great promise for unravelling the secrets of giant planetary birth.

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Introduction

The chairs would like to share with you, in the next few pages, our view of the main highlights of this 2012 conference on *Optical and Infrared Interferometry*. This introduction summarizes the several panel discussions and awards that were handled during the conference but were not reported anywhere else in these proceedings.

1. CONFERENCE MAIN HIGHLIGHTS

This year 69 talks and 56 posters were presented over the 5.5 days of the conference. This number is slightly smaller than in previous years. The diminution of submissions was particularly striking in the field of space interferometry where only one project was represented, BETTII (Balloon Experimental Twin Telescope for Infrared Interferometry) by several interesting papers during the first afternoon. It reflects the fact that NASA has currently abandoned or postponed its former ambitious interferometric projects to concentrate on the JWST (James Webb Space Telescope). In contrast, aperture masking interferometry and its derivatives are on the rise. During the same afternoon, five talks highlighted the history, successes, and potential of this technique at the interface of interferometry and single dish imaging. Its synergy with adaptive optics could lead to direct observations of extra-solar planets at short angular distance from their stars.

Monday and Tuesday were devoted to a rather exhaustive review of the status and results of existing and planned facilities and instruments:

- Keck Interferometer with its Nuller (KIN) and its dual-feed facility ASTRA
- VLTI (Very Large Telescope Interferometer) including MIDI, AMBER, PIONIER, PRIMA and the second-generation instruments MATISSE and GRAVITY
- CHARA (Center for High Angular Resolution Astronomy) and its instruments VEGA, PAVO and MIRC
- NPOI (Navy Precision Optical Interferometer) and its next generation science camera
- SUSI (Sydney University Stellar Interferometer) with PAVO and MUSCA
- MROI (Magdalena Ridge Observatory Interferometer)
- LBT (Large Binocular Telescope) with its Interferometer (LBTI) and its future instrument LINC-NIRVANA.

From there we moved to the future, on Wednesday, with talks on recent achievements and future dreams on diluted pupils and hyper telescopes. A project of an astrometric satellite using interferometry and new technologies for producing integrated beam combiners were also presented. We finished the day with several papers on software and interferometric data reduction. This prepared the field for two invited talks on Thursday on interferometric imaging that introduced a related panel discussion chaired by Tom Herbst and John Monnier. The summary of the discussion is given in section 5 of this introduction. Then, on behalf of the IAU Working Group on Imaging Algorithms, Fabien Baron announced the winner of the 2012 Interferometry Imaging Beauty Contest, John Monnier (see section 4).

Science highlights of results obtained with interferometry were distributed all over the conference and used to introduce the various sessions. In particular we had 3 invited reviews on 3 of the main scientific objectives of interferometry (the Galactic Center, the Active Galactic Nuclei, and circumstellar disks). These talks introduced the panel discussion on the Future Directions chaired by Steve Ridgway. He engaged both panel and audience in a vigorous and wide ranging 90-minute tour of where we are and where we are going. This is summarized in section 6. The day was concluded with Hal McAlister announcing the award of the Michelson prize to Olivier Chesneau, and Denis Mourard announcing the Fizeau prize award to Charlie Townes. Both prizes are sponsored by the International Astronomical Union (see section 2).

The last and longest day of the conference was devoted to the description of critical sub-systems (fringe trackers on the various facilities, metrologies, beam stabilization, adaptive optics, and spectrometers) and to advanced observing techniques and calibration of the data (polarimetry, baseline solution degeneracy and closure phase calibration). This imposing program was complemented by 2 poster sessions held on Tuesday and Thursday evenings. Authors had the opportunity to highlight the main points of their posters in two-minutes-one-slide presentations on Tuesday and Wednesday.

Finally, the traditional award for the best presentation related to a PhD dissertation was given by the sponsor TNO (see section 3) to Dr. Johannes Sahlmann and closed this fruitful and full conference.

2. IAU INTERFEROMETRY PRIZES

In 2010, the IAU Commission 54 (Optical and Infrared Interferometry), The Observatoire de la Côte d'Azur (OCA), and the Mount Wilson Institute (MWI) announced the creation of two prizes in Interferometry, the Fizeau Prize and the Michelson Prize. The two prizes are similar but complementary, with the Michelson Prize emphasizing application of interferometry to astrophysical research, and the Fizeau Prize emphasizing innovative technical and theoretical work. In 2010, the winners of the Michelson and Fizeau were Michael Shao and Antoine Labeyrie, respectively. At this session of the SPIE conference, the winners for 2012 were announced.

Denis Mourard, OCA astronomer, announced that The **Fizeau Prize** for 2012 is awarded for lifetime achievement to **Prof. Charles Hard Townes** for his long-term commitment to and support of optical interferometry, especially in the mid-infrared, as evidenced by his work on the McMath prototype and Berkeley Infrared Spatial Interferometers. Professor Townes' development of heterodyne techniques, high-spectral resolution, and closure phases at the ISI has produced dozens of highly cited and transformative papers in the studies of dust production and time-evolution of evolved stars. Further, Professor Townes' support and mentoring of 27 doctoral students and dozens of postdoctoral and junior colleagues, many of whom are well-established interferometrists and active researchers today, will leave an enduring legacy for the field of optical/infrared interferometry.

Hal McAlister, CEO of the Mount Wilson Institute, announced that the **Michelson Prize** for 2012 is awarded to **Dr. Olivier Chesneau** for his recent contributions to stellar astrophysics. In the 10 years since his PhD, Olivier has vigorously exploited optical interferometry for the study of stellar environments—disks, winds, and nebulae—in young, early type and evolved stars through the latest stages of stellar evolution. In particular, he used a variety of interferometric data at very high resolution to model the close and dusty environment of the eta Car nebula, and recurrent novae RS Oph and T Pyx. Olivier has contributed as first author and as collaborator in more than 70 refereed publications in 10 years.

Additional information about the prizes can be found for the Fizeau at http://www.oca.eu/fizeau-prize, and for the Michelson at http://www.mtwilson.edu/michelson.php. Both prizes are administered jointly by the sponsors and the Commission, with the authorization of the IAU secretariat, and are offered in order to provide recognition within the community and to encourage contributors to the rapidly growing field of optical interferometry. The next opportunity to nominate candidates for these prizes is expected to be in early 2014.

3. BEST PhD DISSERTATION PRIZE

For the second time in the history of the Optical and Infrard Interferometry conference, a competition for the best presentation by a young researcher having presented his PhD in the last 2 years has been organised. In 2008 in Marseille, the prize, an initiative of John Monnier, was awarded jointly to Matthew Mutterspaugh and Antoine Mérand to recognise their contribution to interferometry both on the engineering and on the scientific side.

This year, there were 6 candidates: B. Norris (#8445-2), J. Sahlmann (#8445-26), A. La Camera (#8445-125 & 126), L. Burtscher (#8445-50), C. Paladini (#8445-61), and O. Pfuhl (#8445-64). All presentations were of very good quality, ranging from pure science to descriptions of critical instrument sub-systems. All candidates were clearly mastering their subjects. But a choice had to be made. The jury was composed of the Scientific Organising Committee joined by John Monnier. The evaluation was made both on the manuscript and on the oral/poster presentation during the conference, with a higher weight on the presentation side. Both the content (scientific interest, understanding of the field) and the way the topic was presented (clarity, structure, enthusiasm...) were taken into account.

The prize was sponsored this year by TNO Space and Science, a Dutch industry providing high-end opto-mechanical systems for space, astronomy, and science programmes (like GAIA, VLT and VLTI...).

The **Best PhD Dissertation Prize** was awarded and given by Ben Braam, TNO representative, to **Dr. Johannes Sahlmann** (Geneva Observatory, Switzerland) for his presentation "Narrow-angle astrometry with PRIMA."

4. IMAGING BEAUTY CONTEST PRIZE

The Imaging Beauty Contest is a long tradition in the SPIE interferometry meetings and this fifth edition enjoyed a record participation with 8 teams in competition. If in the first years, the competitors were mainly the authors of the data reduction software themselves. This year, several competitors were using general user software packages (CASA, BSMEM, MACIM, MiRA, MIROIRS, IRS). The contest is conducted by the Working Group on Image Reconstruction of IAU Commission 54.

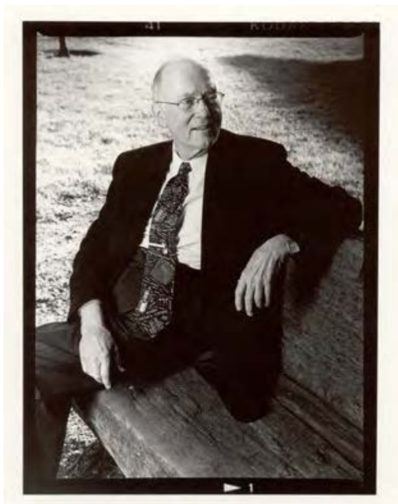
The principle of the contest is to provide simulated realistic interferometric data of an (unknown to the competitor) object in the standard OIFITS format. The competitors have to reconstruct the corresponding image. The reconstructed image is then compared to the original one and quantitative parameters are used to evaluate the quality of the reconstruction. The candidates have also to state their own confidence level in the features seen on their reconstructed images.

This year the data simulated two sources, a T-Tauri like object and a red super-giant, as if they were observed by MIRC-6T installed on CHARA with H-band low spectral resolution. Both objects proved very difficult to reconstruct, especially the T-Tauri object. Despite these difficulties, overall the reconstructions were convincing and with a decent image quality, but showed that one has to exercise caution when reconstructing spots from real data or when the object is very resolved.

After a quantitative scoring of the results, **John Monnier** (University of Michigan) was declared the winner of the contest for his MACIM entry and was awarded the **Imaging Beauty Contest Prize** by the jury composed of F. Baron, P. Lawson, and S. Ridgway.

xxx

Fizeau Prize 2012



Pr. Charles Townes[1]

Jointly sponsored by
IAU Commission 54
Observatoire de la Côte d'Azur

Michelson Prize 2012

Dr. Olivier Chesneau

Jointly sponsored by
IAU Commission 54
Mount Wilson Institute

Best PhD Dissertation Prize 2012

Dr. Johannes Sahlmann

Sponsored by

TNO innovation for life

Imaging Beauty Contest Prize 2012

Pr. John Monnier (2nd from left),
with jury members P. Lawson,
F. Baron, and S. Ridgway,
(President of IAU Commission 54)

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[1] Picture courtesy University of California, Berkeley - http://www.physics.berkeley.edu/research/faculty/townes.html

5. PANEL DISCUSSION ON INTERFEROMETRIC IMAGING SOFTWARE

The panel discussion on Interferometric Imaging Software took place on 5 July 2012, with Tom Herbst and John Monnier as moderators, and Fabien Baron, John Monnier (University Michigan), and Eric Thiébaut (CRAL, University of Lyon) as panel members. The discussion focused on two aspects of the present generation of software that will be critical for the future of image reconstruction: the limitations of current algorithms in terms of scientific prospects, and their ease of use by non-expert astronomers.

The shortcomings of current reconstruction packages had already been exposed in the imaging talks preceding the discussion. In the current paradigm, image reconstruction only deals with monochromatic snapshot images: the classic reconstruction procedures do not take spectral or temporal dependencies into account. The panel dispelled the notion that radio imaging packages in radio interferometry could be used for such purpose, as they are less advanced than their optical counterparts. From the discussion with the audience, it was concluded that current generic packages would provide these capabilities at medium term, but that in the near future they may have to be tailored for work on specific targets (e.g. spotted stars or young stellar objects).

The accessibility of reconstruction packages by non-expert interferometrists or even non-interferometrists was then debated. Image reconstruction currently requires a high level of expertise to set up the initial conditions of the reconstructions (regularization, regularization weights, priors). Many members of the audience expressed the desire to have reconstruction procedures much closer to black boxes, or at least to model-fitting software such as LITPro by the JMMC. The panel pointed out that while simple targets (such as binaries) may be reconstructed very easily in a black box manner, for more complex objects the scientific content of reconstructions can only be interpreted if the reconstruction procedure is well understood. This is the case in particular for committal choices of priors/regularizers that have to be made to reconstruct young stellar objects or spotted stars. It was also underlined that reconstruction algorithms do not produce useful error bars on images at the moment, though progress is being made toward this goal. Consequently the identification of artifacts is only possible through careful consideration of the reconstruction parameters.

Members of the audience then suggested creating a global library/repository of reconstruction packages similar to CASA in radio, or to the JMMC utilities for model-fitting and observation preparation. However the panel pointed out that the use of CASA itself is not widespread amongst radio astronomers that prefer to use packages tailored to their specific science cases. As noted previously, a similar trend can now be seen in optical interferometry. In addition, efforts going toward maintaining a global library infrastructure could be seen as diverting resources from actual algorithmic improvements. Moreover, the majority of current packages are already very accessible (free of charge or even free software), and official packages for 2nd generation VLTI instruments (MATISSE and GRAVITY) will soon be offered to astronomers as well.

The panel concluded the discussion by underlining again the growing interest for image reconstruction, a fact clearly visible as the size of the audience attending the imaging panel increases with each SPIE meeting.

6. PANEL DISCUSSION ON FUTURE DIRECTIONS

The panel discussion on Future Directions took place on 5 July 2012. It attracted approximately 50 people and lasted for 90 minutes. The format included a moderator (S. Ridgway) and a panel (C. Haniff, G. Perrin, P. Hinz, T. ten Brummelaar, and F. Delplancke). Approximately every 15 minutes the moderator posed a new question (see Table 1), inviting comment first from a member of the panel and then from the audience.

A *very abbreviated* paraphrasing of the discussion is given in Table 1. The scribe and editor apologize for any distortion or misattribution of contributions. Following the discussion the moderator came up with the following reflections and summary.

Our community has been holding discussions like these for more than 20 years, and we have seen a steady evolution of thinking. In the 1980's, we were very enthusiastic for ambitious interferometers in space, or even on the moon—of course it did not happen, and now we understand better the challenges of developing large baselines in space. In the 1990's, as prototype projects came into operation, we recognized that the essential technology was in place to build an optical VLA, and we touted the possibility at every opportunity. We did not succeed in raising such a project to high priority in the community, in spite of an initially sympathetic audience. For one reason, we could not present a compelling science case for a general purpose interferometric observatory of that scale. Entering the millennium, thinking turned towards the importance of amply demonstrating the capability of the facilities that were already operating or in the pipeline. In his introduction to the 2002 "Interferometry for Optical Astronomy II" (SPIE 4838) Wes Traub quoted a stark sound bite from that meeting's futures discussion: "We need to deliver good science this decade or we are dead."

Looking back from 10 years later, I think that we can take considerable satisfaction in our response to that challenge. Both prototypes and facility-class instruments were built and operated, inventing and demonstrating a wide variety of critical technology and exploring a lot of interferometry parameter space. Demonstration of scientific success may be partially subjective, but the count of 420 refereed astrophysics papers (including 12 in Nature and 4 in Science) since 2000 is a fact (easily verified thanks to the JMMC-Malbet-Mella publication engine on OLBIN). Expected contributions (e.g. YSO imaging) have been gratifying, and initially less familiar opportunities (e.g., asteroseismology) have blossomed.

Meanwhile the community has what are arguably the most impressive interferometer systems ever built in the queue for imminent deployment—namely, GRAVITY and LINC-NIRVANA—in addition to very impressive new combiners in MATISSE and LBTI. Remarkable new IR detectors are promised "real soon." There is every reason to expect a steady, if not accelerating, flow of innovative science as well as increasing productivity as we learn how to reduce, analyze, and interpret new kinds of data becoming available for the first time.

The 2012 SPIE session suggests several possible trends. The discussion returned several times to the merits of efficiency and simplicity (clearly a relative term here) as promoted in the MROI philosophy and as exemplified in the minimalist architecture of a CARLINA.

Interferometry flourishes at ESO, and while it does not have a mandate like ELT, it at least expects to compete for promised development resources on a level playing field with other Paranal facilities.

Support for interferometry in the U.S. is soft at the agency level, as demonstrated by the NASA decision to close Keck Interferometer. Space interferometry, which largely split from this conference a few years ago, had a low profile at this SPIE. It will take the community a while to recover from the heavy-handed termination of the Space Interferometer Mission (SIM), which seemingly had answered every challenge served to it. On the positive side, SIM/TPF/DARWIN studies mastered a lot of critical technology for space interferometry. Meanwhile, a highly productive ground-based program persists at CHARA thanks to a delicate balance of university funding, peer-reviewed opportunities, and international participation.

7. CONCLUSIONS

As this conference shows, the technical development and evolution of interferometry, and the impressive science production, continues unabated.

In spite of some hard knocks and setbacks—and there could be more—the field is in a vigorous state: young enough to be flush with opportunity, small enough for a new-comer to come to grips with, and successful enough to have earned respect. If only Michelson could have seen it happen!

Our deep thanks go to our SOC for the support in producing the conference programme, running the sessions and reviewing the proceedings, and to the panel members for driving the lively discussions. And thanks to all participants for an interesting conference. See you in two years in Montreal.

Françoise Delplancke
Jayadev K. Rajagopal
Fabien Malbet

Table 1. Minutes of the panel discussion on Future Directions

Participant	*Question / Comment / Answer*
Moderator	**What kinds of questions should we be looking at under the topic of Future Directions, and what is the current context?**
C. Haniff	Questions for today: 1) Where are we today? 2) What is missing, science-wise? 3) Rank the missing items. 4) Lay out how to get to this goal. My partial answers: - We need: 4-6 telescopes; no high precision astrometry; pectroscopic resolution of few tens to thousands; IR sensitivity 5th to10th mag at K band; baselines from 10m to 350m. - We have not enough telescopes. The community has become extremely cunning in milking a lot from very little. This is a pity. Resources should be spent in parallel on increasing telescope number.
T. ten Brummelaar	I agree. Images did wonders for CHARA. Before that, it was just another interferometer fitting things to strange plots.
Moderator	Is imaging critical at VLTI?
R. Petrov	I disagree with Haniff's statement that "sensitivity and accuracy have much lower priority" than increasing the number of telescopes. They are at least as important, in particular at the VLTI, where the enhancement of the imaging capability beyond 4T will be limited, even if adding small telescopes is very important, and where there is a lot of room for improvements in both sensitivity and accuracy.
C. Haniff	Very large telescopes are not key to sensitivity. CHARA is more than competitive with VLTI. In practice, sensitivity turns out to be as related to other design compromises as to size. 4 or 8m array is not a priority.
G. Perrin	Everything is connected. More telescopes means split light more ways and leads to lose sensitivity. We need large telescopes for faint sources, then more of those in flexible configurations and more efficient. But efforts must be made on efficiency to decrease the required size of telescope to build future affordable arrays (the goal should be to build sensitive facilities with 2-3 m telescopes that can be moved around). E.g. GRAVITY is optimized very carefully and still the throughput is only 1%. A fundamental look at the way we transport and detect photons is necessary. In IR the situation is improving thanks to IR APD with currently 3e- RON and possibly 1e- in the near future.
M. Mutterspaugh	Optimisation vs Versatility is a trade-off.
W. Jaffe	What is the killer app for this increased sensitivity?
J. Meisner	I disagree with Guy. With fringe-tracking and coherent integration, the effective SNR as integrated over multiple baselines does not suffer due to that division of light; there is no loss of information content. Also important is that the information content will be increased according to the logarithm of the precision of a visibility measurement relative to the a priori knowledge of that visibility.
G. Perrin	But practical matters mean that the more you split, the more difficulties you will have.

Moderator	Where can we hope to go with university-scale interferometer projects?
T. ten Brummelaar	The Decadal Review had a very negative effect. NSF, NASA reacted solely to the main report, whereas interferometry was highlighted in many of the secondary papers. University based projects are very important. All except VLTI (and excluding LBTI) are university class. All are on the hairy edge of survival. We should improve the capabilities and improve their access. We need to support existing capabilities.
Moderator	What is the biggest dream for CHARA?
T. ten Brummelaar	More telescopes and AO on all telescopes, in that order. Also a wider participation from the community.
C. Haniff	One should remember that UK is not all ESO. But there is no university support in UK. "We've paid for ESO" is the general attitude to all university projects, not limited to interferometry.
F. Delplancke	Even as ESO representative here, I am very supportive of university projects. VLTI is not the right platform for testing new technologies, ideas or experiments. Eg. PIONIER, a very successful visitor instrument, is based on IOTA experience (as VINCI was too) and it would need even more standardisation to become a general-user VLTI instrument. PIONIER success is the result of a long process that takes efforts and time before coming to the VLTI. If we want to test new concepts and be flexible, university based projects on smaller facilities are needed. ESO should not eat everything around interferometry in Europe.
H. McAlister	CHARA is 65% University funding. Today we could not do this. So universities cannot be expected to put a lot more money into interferometry.
Moderator	US and Europe were on the same path 10 years ago. Then Keck vs VLTI difference came about.
P. Hinz	Universities produce future builders, not just researchers today.
Moderator	**How should and can the VLTI evolve in the ELT era?**
F. Delplancke	The situation of interferometry in Europe is not as dark as in the US, but is not bright either. Astrometry and phase referencing are encountering difficulties, but there is still some hope for PRIMA. MATISSE and GRAVITY are being built and should be delivered by 2015 to the observatory. Beyond that new VLTI instrumentation will be on equal footing (and competition) with any other new VLT project of instrument. One instrument (or upgrade) every year for the next 10 years is the current perspective. But no investment on VLTI infrastructure is foreseen. So we could hope to get one additional VLTI instrument if the science case is interesting. ESO is preparing a white paper on the future of La Silla-Paranal observatory in the ELT era. All options are open from a tactical view (box thinking) to a new strategic view (breaking the operation paradigm) and from an evolution to a revolution. A first draft should be presented in October. So now is the moment to give feedback on what we would like to have on interferometry.
D. Mourard	VLTI and ELT are complementary
F. Delplancke	But a dedicated spectroscopic survey role for one VLT could kill VLTI, e.g. if a prime focus is installed.
S. Kraus	ALMA has similar science, so there is competition.

J. Monnier	ELT and Interferometry are completely different! Science cases are different. Lots of science is unique to interferometry (YSOs, etc.). Interferometry is more like a mid-scale program (e.g. wide-field capability). If you don't emphasize this, we end up in a very defensive posture. We should stop talking about ELTs in this context. We should compete with the right crowd. Stars vs Stars. Many reports agree on this.
C. Haniff	I agree with Monnier. But if the level playing field is VLTI vs VLTs, then the cosmologists will win. Like VLTI vs ELT. It is not a fair/helpful comparison.
Moderator	(To Delplancke) Is there any structure for community input to ESO?
F. Delplancke	The future VLTI Programme Scientist (to be hired soon) can be a medium. EII (European Interferometric Initiative) should participate to define VLTI future. ESO should be made well aware that the VLTI is now unique by the combination of several big telescopes. There are "plenty" of other single 8m telescopes in the world that could be used for surveys and the VLTI should not be sacrificed.
T. ten Brummelaar	We should co-opt stellar astronomy support. This means going to meetings and inspiring.
Moderator	**Is there a need for and potential for large-telescope interferometry in the ELT era and beyond, and what is it?**
P. Hinz	LBTI is a large aperture interferometer. Aperture Masking is an example of inteferometry with full apertures. One way for broader community to appreciate interferometry is using interferometric techniques in ELT calls. Aperture masking on the ELT is interferometry with 20-30 m baselines and a lot more sensitivity. That would cover e.g. the study of the evolution of planets and complex structures. So we should combine long baselines with the ELT.
Moderator	Do we need even larger unit telescopes?
G. Perrin	During the 2006 NOAO Workshop, one idea was large VLA-like Optical Array. Another was short baselines with 10 or 20 m telescopes. ELT would be confusion limited and this would go beyond that.
Moderator	This was a Roadmap meeting. The proceedings are on the NOAO web pages: http://www.noao.edu/meetings/interferometry/
C. Haniff	Getting a large number of 6-8m telescopes is difficult. The MRO is designed for 17% throughput. So good sensitivity can be obtained with smaller telescopes. Large UTs are not a sensible idea for the next 10 years.
D. Mozurkewich	My impression is that there is much more science coming out of the ATs than out of the UTs, in part due to competition with single-telescope observations but also due to intrinsic problems with big telescopes: vibrations and complicated delay paths. There is a knee in the cost-benefit curve at a few meters.
F. Delplancke	However the nice AGN results presented today were only possible thanks to the UTs. If we are not sensitive, we quickly run out of targets, like MIDI now. MIDI was quickly limited on ATs. Imaging with 4 ATs and PIONIER is complementary but does not replace UT observations.
A. Mérand	Big telescopes are not the final answer. Simple, better throughput, new detectors are also needed for sensitivity.
B. Mennesson	Outriggers might have saved Keck. VLTI is in good position with both small and large telescopes. Should we test on small telescopes and then go to the big ones?

G. Perrin	The UT's versatility means that they are not optimized for anything. Vibrations hurt interferometry.
M. Ireland	Vibrations are made much worse by long optical trains. Surely a fiber feed building on OHANA is a solution here?
G. Perrin	I have to say yes! 300 m of fiber at OHANA-Keck had still a 50% throughput in the K band (90% with J and H band fibers) (just fiber part). However out-of-fiber delays is a problem. Fibers with zero dispersion would be the key to build fibered delay lines (Asymmetric lengths for delay are impossible without zero-dispersion fibers unless at ultra-high angular resolution). We are getting into the next question here…
M. Ireland	I don't see delay as a problem. Going out and back into a fiber in an MROI-style vacuum delay line with tip/tilt internal metrology should provide a high efficiency solution.
Moderator	**What R&D is needed, where can it be done, who will do it, how can it be funded?**
G. Perrin	3 points. Sensitivity, fringe tracking and beam combination technologies. Sensitivity is the key in several respects including future large arrays: more sensitivity means smaller telescopes, longer baselines, more sources including reference sources for co-phasing. Smaller telescopes are important in several respects: better credibility for future large arrays in a very competitive funding context (E-ELT, SKA, CTA …) and possibility to build movable telescopes for high-fidelity imaging with 4-6 telescope arrays . Ways for better sensitivity: - Reduce detector noise: it is already the case in the visible, NIR APD detectors need to be improved to reach better than 1e- RON; - Efficiency: explore all-fiber approach and bulk optics approach; reduce number of optics; vacuum; better materials; - Beam combiners: explore design, materials, functions to improve integrated and bulk optics beam combiners. Fringe tracking: Shao - Colavita did this in the 80s. Now it is becoming common place. There is room for improvement: algorithms (to reduce vibration impact, using predictive commands, and optimizing loops as is done in AO, …), beam combiner design for fringe tracking, bootstrapping techniques… Beam Combination: - Improve current designs (integrated optics already mentioned); - All use same 2 types (multi-axial at camera focus or co-axial with beam splitter or equivalent); - Explore alternative beam combining schemes like the hypertelescope.
H. Le Coroller	The question is how best to recombine apertures in focal plane: pair-wise vs all in one, etc. Problem to build big Carlina (>200-300 m). In the future, is it possible to have (to attract) a large scientific community with numerous programs of observation for a 50-100 m dilute telescope?
W. Jaffe	As future R&D, I would recommend extremely high Dl/l, transport without dispersion, new recombiners.

V. Romero	How to fund all this? Military and commercial sources should be sought. E.g. DARPA is funding a fiber fed interferometer.
T. ten Brummelaar	They were not interested in our input. Fibers are essential as they would avoid vacuum tubes all over the place, and large mirrors for long transport.
C. Haniff	I disagree with some of you. I believe that the technology development has been amply demonstrated. Vacuum works. We do not need much R&D. AMOS builds low vibration telescopes. 8" beam tubes are trivial. CHARA MIRC combiners work. I think it is incorrect to suggest we don't know how to design multi-telescope beam combiners in an efficient way.
J. Meisner	One should forget the idea of fiber delay lines, as unequal fiber lengths will always entail huge dispersion; waveguides cannot ever be made non-dispersive. A delay line using mirror reflection works and is efficient! With laser metrology over beam width and low-order local AO, OPD vibrations and local seeing can be cancelled.
D. Mozurkewich	Fibers can work if we put small telescopes on a platform which points toward our target. There would be no delay to compensate, equal fiber lengths so no dispersion and therefore a simple system with high throughput.
Moderator	**While past technology demonstrations suffice for major projects, there are still important areas for development. Are there any concepts or technologies, not yet discussed today, that have the potential to be game-changing for the future of interferometry?**
R. Petrov	With the technology that can bring magnitude 13 at MROI we could be above magnitude 15 with the UTs, and then decisively change the sky coverage for off-axis fringe tracking. This would allow really going beyond stellar physics and the brighter AGNs. This needs R&D, and is a key goal at a 10 year timescale.
G. Perrin	We still need to improve combiners.
F. Malbet	The complexity of interferometers is the problem. We should increase the potential of current arrays, break the paradigm, simplify interferometry, go toward hypertelescopes, OHANA, delay in fiber, etc...