

OPTIMAL OPTICAL PHASE CLOSURE IMAGING: LESSONS FROM RADIO INTERFEROMETRY

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1 Introduction

This paper aims to discuss major effects from optical wavefront through the atmosphere based on lessons derived from long-baseline radio observations at the upper microwave band (10-100 GHz).

Some case examples are discussed in some detail as well as possible solutions from history lessons of radio interferometers operating at various frequencies and resolutions.

2 Point-like imaging

Often, it is of remarkable interest that astronomers chose to observe objects which are not resolved at all by each collecting area. In this case, the source angular sizes are far smaller than the diffraction limit of each individual telescope.

Guyon(2005) and Guyon & Roddier (2001) have discussed atmospheric errors and have shown that they are equivalent to baseline efficiency in the (u, v) coverage in the Fourier domain.

In this situation, one can expect the wavefronts to be tilted in phase and amplitude even if the baselines are as small as a couple of $10^3\lambda$, where λ is the observed wavelength. Moreover, for optical interferometry in the infrared, any decent baseline wavelength can fill up to 10^8 phase turns per unit length. During real observations, the atmospheric seeing and telescope pointing errors could well induce fluctuations in the recorded fringe rates which could not be easily corrected by regular phase-referencing technique.

Nevertheless, it is a lesson from radio interferometry with early VLA observations of strong jets such as 3C120 that differential phase offsets prevent high-contrast synthesis imaging techniques. Recently, Jörgens & Quirrenbach (2004) have produced a coarse modelling of closure phase measurements and effects of errors towards characterization of exoplanetary objects to be detected with AMBER instrument at the VLTI.

The self-calibration routine (Pearson & Readhead 1984; Wilkinson 1989 and non-linear deconvolution algorithm by Cornwell & Braun 1989) can be used in strong sources with simple brightness distributions but they will certainly fail for weak optical objects such as distant galaxy nuclei or planetary systems studies. It invokes the fact that while the relative phases for each telescope are varying with time due to the turbulence of the atmospheric refraction index, the closure phase over a set of three baselines is constant (Jennison 1958):

$$\Phi_{cl} = \phi_{12} + \phi_{23} + \phi_{13}$$

Recently, the selfcalibration has been proven to work even for optical interferometers with small reflecting surfaces ($d < 1$ meter) such as COAST (Baldwin et al. 2000).

For a telescope i , the amplitude correction is

$$a_i(t) = T_{sys}^K(t)G_i^K(t)\Gamma_i(t)$$

The (i, j) baseline-based telescope gains are:

$$G_{ij}^K = \delta_{ij}a_i(t)a_j(t)e^{i\phi_i-\phi_j}$$

Where the phase differences and $G_{i,j}(t)$ can be obtained by observing an unresolved calibrator source with known flux and polarization where the system gains $\Gamma_i(t)$ and system temperatures T_{sys}^K for radio telescopes can be obtained by direct signal strength comparison with standard noise sources.

As this has no equivalent calibration method in optical telescopes, an equivalent calibration scheme must be sought.

It is also known for millimetre interferometers that the signal phase fluctuations are due to different time varying water vapor content in the line-of-sight of each antenna telescope through the signal path in the atmosphere. At a given baseline (i, j) this introduces a decorrelation factor δ_{ij} on the optical fringes given by the Bayesian estimator averaged complex over K samples:

$$R_{i,j}(t) = \langle S_i(t)S_j(t + \tau) \rangle = \sum_{k=1}^{K=t/T} \hat{S}_{i,k} \otimes \hat{S}_{j,k}(t + \delta T)$$

With a likely quantum noise background given by a jointed Gaussian probability distribution, after the theoretical errors being removed:

$$P_{i,j} = \frac{N}{2\pi\sigma^2\sqrt{1-\rho^2}} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \exp \left[-\frac{(x^2 + y^2 - 2\rho xy)}{2\sigma^2(1-\rho^2)} \right] dx dy$$

This term, non-linear, cannot be factorized by antenna and can be seen as non-closing offsets. Fortunately, even for optical interferometers and due to the physical properties of the atmosphere, there are several timescales for this effect and they can be slow enough so that they can be corrected partially, but not altogether, unless strong signal-to-noise amplitude and phase calibrators are available.

3 Wide Field Imaging

If the angular size of the object to be imaged is comparable to the telescope diffraction limit, one must be aware that the interferometer might not collect a significant set of spatial frequencies from the gathered visibility data. In this case, the brightness distribution will not recover the due to missing interferometric (u, v) coverage. Hence the mosaicing technique developed through cold interstellar clouds observations with millimetre arrays could be applied to a handful of objects and ultracompact regions of star formation which are optimal targets for large interferometers such as the VLTI.

This effect is quite important when observing the central engines of AGNs at microarcsecond resolutions since the sizes of the optical jets can be in the order of 800-3000 beamwidths and if one expects to find synchrotron

optical emission from relativistic shocks or outflows in binary pairs containing accretion discs such as SS433-like objects which are likely to be found in radio surveys toward stars with variable magnetic activity.

4 Optical polarimetry

The polarization schemes for radio interferometry often invokes the parallactic angle method since the alt-azimuth mountings are available for large dishes. Fortunately, this allows a radio source with known polarization position angles to be tracked as function of elevation and the left minus right phase differences can be factored for each telescope by using a D-term model or ellipticity-orientation model for the feed horns.

Adaptive optics from coherent signal sources (Berger et al. 2001) could solve this problem as well as the phase-referencing scheme for weak sources as it has been doing for VLBI radio interferometers in the last 10 years (Muxlow, priv. comm.)

Artificially-generated stars by laser-heating techniques could provide reasonable unresolved sources to calibrate the left minus right phase differences, which are essential to optical polarization-sensitive interferometry. It can be stressed that radio polarimetry has been done with VLBI techniques at wavelengths longer than 2mm only for a couple of cases whereas it is quite standard nowadays for VLBI observations of synchrotron-emitting radio sources such as quasars, radio galaxies and water and OH maser sources. For millimeter-wavelength radio polarimetry, there is still a lack of successful scientific results mostly due to accurate calibration schemes for the obtained Stokes parameters.

5 Conclusions

The results presented in this paper are very preliminary and further simulations with actual VLTI data are required to produce better software solutions for planning observations of a range of celestial objects with strong astrophysical interest.

Meanwhile, I can conclude that:

- The effects of atmospheric turbulence and extinction in diminishing the coherence length can be hard even in dry atmosphere and observing

conditions;

- Adaptive optics can be a very helpful tool to help in polarization-sensitive optical interferometry, which is particularly interesting to understand the physics and dynamics of optical jet productions in AGN cores;
- Monitoring PSF using laser-produced stars can be useful to align the polarization offsets and to generate phase-referencing techniques for optical interferometric arrays;
- Imaging simulations over a range of possibilities for the ESO VLTI are being made with the telescope geometry and will be part of a future paper.
- Factorization of Möller matrix polarization crosstalks will not be as straightforward as it is in radioastronomy since feed horns are far easier to model than grooved plates or dielectric gratings (Cotton W.D., priv. comm.). Similar issue applies also for the removal of instrumental polarization from the true source Stokes parameters;
- Further studies must be under way for good polarization calibration in optical wavelengths where strongly polarized calibrators are not so abundant.

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6 References

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