Chapter 21

Mm versus Optical Interferometry: a qualitative comparison

A Panel Discussion by

Anne Dutrey[1,2], Fabien Malbet[2], Stéphane Guilloteau[1] Robert Lucas[1], Dennis Downes[1] and Roberto Neri[1]

[1] IRAM, 300 rue de la Piscine, F-38406 Saint Martin d'Hères, France

[2] LAOG, BP 53, F-38041 Grenoble cedex 9, France

This chapter is a brief summary of the panel discussion. The goal was to present the main differences concerning not only the instrumentation itself but also the language which is used by both community.

The summary does not appear as a standard panel discussion where several people interact because we have chosen to compare both techniques through three fundamental aspects:

- The expression of the interferometric equation
- The instrumental differences
- The atmospheric behaviour and the noise properties

21.1 The basic equation of interferometry

In a two element interferometer, the signal coming on the detectors from telescopes 1 and 2 is the sum of contributions from the background $B_{1,2}$ (either the atmosphere or the instrumentation itself) and from the astronomical source $I_{1,2}$.

21.1.1 Additive interferometry

For **direct detection (or additive) interferometry**, as in the optical domain, an interferometer measures *on-source* on the baseline $\mathcal{B}_{12}$:

$$I_{12} = I_1 + I_2 + 2\sqrt{I_1 I_2} V_o |\mathcal{V}_{12}| \cos\Phi_{12} + B_1 + B_2 \tag{21.1}$$

The term $I_1 + I_2 + B_1 + B_2$ is the continuum term while $2\sqrt{I_1 I_2} V_o |\mathcal{V}_{12}| \cos\Phi_{12}$ is the interferometric term.

After doing an *on-off* (also called the "sky calibration"), Eq.21.1 becomes:

$$I_{12} = I_1 + I_2 + 2\sqrt{I_1 I_2} V_o |\mathcal{V}_{12}| \cos\Phi_{12} \tag{21.2}$$

Where $\mathcal{V}_{12}$ is the visibility of the astronomical source measured on baseline $\mathcal{B}_{12}$ of amplitude $|\mathcal{V}_{12}|$ and phase Φ_{12}.

The visibility to calibrate can be expressed by:

$$V_{corr} = \frac{2\sqrt{I_1 I_2}}{I_1 + I_2} V_o |\mathcal{V}_{12}| \cos\Phi_{12} \tag{21.3}$$

V_o is the contrast which takes into account the calibration of all the system (instrumentation + atmosphere). The photometric term is given by $\frac{2\sqrt{I_1 I_2}}{I_1+I_2}$ (note that I_1 and I_2 are relatively easily measured).

The visibility $\mathcal{V}_{12} = |\mathcal{V}_{12}| \cos\Phi_{12}$ appears as a fringe contrast (which is flux calibrated), therefore it is normalized to unity. Note finally that in the optical case $B_{1,2} \ll I_{1,2}$.

21.1.2 Multiplicative interferometry

For **heterodyne or multiplicative detection**, the output of the interferometer (correlator) gives a correlation rate r_{12} which is a dimension less number (this uses a simple correlation between two antennas, not a "bi-spectrum").

The correlation corresponding to $\sqrt{I_1 I_2} V_o \mathcal{V}_{12}$ is the term of astronomical interest, and is related to r_{12} by:

$$\sqrt{I_1 I_2} V_o |\mathcal{V}_{12}| e^{i\Phi_{12}} = r_{12} \sqrt{(B_1 + I_1)(B_2 + I_2)} \tag{21.4}$$

Where $(B_1 + I_1)$ and $(B_2 + I_2)$ are the autocorrelations mesured on telescopes 1 and 2, respectively.

At mm waves, $B_{1,2} \gg I_{1,2}$ because the atmospheric thermal emission strongly dominates with typically $I_{1,2}/B_{1,2} \sim 10^{-3} - 10^{-4}$ (except for the Sun and bright planets). Therefore, Eq.21.3 simplifies as:

$$\sqrt{I_1 I_2} V_o |\mathcal{V}_{12}| e^{i\Phi_{12}} = r_{12} \sqrt{B_1 B_2} \tag{21.5}$$

The heterodyne technique does not allow to measure the continuum term but preserves the phase (thanks to the use of a complex correlator, see Chapter 2). V_o can be seen as the correlation efficiency of the interferometer (instrumental + atmospheric). The calibrated visibilities (as defined in previous chapters) $V_{12} = \sqrt{I_1 I_2} \mathcal{V}_{12}$ are expressed in unit of flux density (Jy) while $\sqrt{B_1 B_2}$ can by considered as the photometric term (including the photometric calibration of the atmosphere).

21.2 Getting the fringes

For details about both techniques, we invite the reader to read Chapters 2 and 4. We only focus here on some basic points.

Additive detection versus Heterodyne technique

An heterodyne system preserves the phase information, therefore one major interest of the heterodyne detection is to allow high resolution spectroscopy. Some interferometers working at 10μm such as ISI use heterodyne technique. However they have a low efficiency and can only observe very bright sources.

Electronic compensating delay versus delay lines

Direct detection at optical wavelengths uses delay lines which are well suited to the wavelengths and baseline lengths. In the mm range, due to the low wavelengths and the long baselines, the size of the mirrors would be prohibitive. To avoid losses due to diffraction in the delay lines, the mirror size must be larger than about $\sqrt{B \times \lambda}$. For example, at $\lambda = 3\,\mathrm{mm}$ and assuming a baseline of $B = 400\,\mathrm{meters}$ (which is of medium size), the mirror should be larger than 1.1 meters. For ALMA, assuming baselines of 14 km and a wavelength 3 mm, the required diameter goes up to 6 m. Using electronic compensating delay is definitely easier for the purpose of mm interferometry.

Note finally that the term *white fringe* in the optical is similar to the *fringe stopping*, at mm waves.

Phase calibration

Since t_o is typically of order several 10 minutes at $\lambda \sim 1.3$ mm, the atmospheric phase can be regularly calibrated by reference to a nearby source close to the astronomical source. This allows phase retrieval.

This is not possible in the optical because t_o is of order a few 10-100 milli seconds, and also because the angular scale over which the atmospheric phase is coherent (the isoplanetic patch) is too small. Instead as soon as optical arrays have three telescopes (or more), opticians use the phase closure relations in order to retrieve the astronomical phase.

Phase closure relations

In this sense, the phase closure relations *are not applied* in mm interferometry because individual visibilities are very noisy (dominated by the atmospheric noise, as explained above). Hence applying such a method does not really bring new constrains on the phase.

However a careful reader of Chapters 7, 9 and 12 should have noticed that mm interferometric data are mostly calibrated *per antenna* and not *per baseline*, the interest being to reduce the number of unknowns and therefore increase the SNR. This calibration technics implicitly assumes that the closure relations in phase and in amplitude are applied on the calibrators. This remains possible because the closure relations are indeed respected by the instrumentation.

21.3 Atmospheric behaviour and noise properties

Table 21.3 summarises the properties of the atmosphere and the resulting noise (including also the instrumentation) at both wavelengths.

Mm versus optical interferometry: Atmosphere & Noise properties

Item	Radio mm	Optical
λ ν	0.6mm to 1cm 30 to 450 GHz	0.4 to 30 μm 10 to 600 THz
Comparison given for	$\lambda \sim 1.3$mm	$\lambda \sim 1\mu$m
Noise sources Main instrumental noise Signal Detection	**background limited (gaussian)** Receiver (thermal) thermal sky emission $T_{signal}/T_{sys} \sim 10^{-2}.10^{-4}$	**photon limited (poisson)*** Detector (read-out) photon limited
Seeing origin Fried Parameter r_o (size of the coherence cell) Coherence Time t_o (time to reach $\Delta\Phi \approx 180^o$) **Equivalent to**	**Variation of W(H_2O)** $>$ antenna several 10 minutes **Single-speckle**	**Variation of T_{atm}** $\leq$ telescope $\sim$ 10 milli-seconds **Multi-speckle**
Atmospheric correction Photometry Seeing Phase Calibration	 monitoring of T_{sys} radiometric phase correction phase referenced on nearby sources	 "standard" photometry technics tip tilt adaptive optics t_o too short closure phase on dual interferometer
Measurements Information on	complex correlator rates: r_i,r_r complex visibility V $\mid V \mid$ & Φ_V	$V_{12}^{raw} = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}$ fringe contrast $\mid V \mid$, amplitude
Imaging Algorithms	Complex visibilities all standard imaging	Phase retrieval by closure relations + amplitude model fitting in the UV plane

* Note that for $\lambda \geq 2.5\mu$m, the atmosphere and the telescope are starting to contribute as main sources of noise (thermal emission), therefore the noise becomes background limited.