# Chapter 21

# Mm versus Optical Interferometry: a qualitative comparison

## A Panel Discussion by

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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 $\Phi_{12}$.

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 10$\mu$m 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 $\lambda = 3\,\text{mm}$ and assuming a baseline of $B = 400$ 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 |
|---|---|---|
| $\lambda$ | 0.6mm to 1cm | 0.4 to 30 $\mu$m |
| $\nu$ | 30 to 450 GHz | 10 to 600 THz |
| Comparison given for | $\lambda \sim 1.3$mm | $\lambda \sim 1\mu$m |
| **Noise sources** | **background limited (gaussian)** | **photon limited (poisson)**$^*$ |
| Main instrumental noise | Receiver (thermal)<br>thermal sky emission | Detector (read-out) |
| Signal Detection | $T_{signal}/T_{sys} \sim 10^{-2}.10^{-4}$ | photon limited |
| **Seeing origin** | **Variation of W(H$_2$O)** | **Variation of $T_{atm}$** |
| Fried Parameter $r_o$ (size of the coherence cell) | $>$ antenna | $\leq$ telescope |
| Coherence Time $t_o$ (time to reach $\Delta\Phi \approx 180^o$) | several 10 minutes | $\sim$ 10 milli-seconds |
| **Equivalent to** | **Single-speckle** | **Multi-speckle** |
| **Atmospheric correction** | | |
| Photometry | monitoring of T$_{sys}$ | “standard” photometry technics |
| Seeing | radiometric phase correction | tip tilt<br>adaptive optics |
| Phase Calibration | phase referenced on nearby sources | $t_o$ too short<br>closure phase on dual interferometer |
| **Measurements** | complex correlator rates: $r_i$,$r_r$ | $V_{12}^{raw} = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}$ |
| | complex visibility $V$ | fringe contrast |
| Information on | $\mid V \mid$ & $\Phi_V$ | $\mid V \mid$, amplitude |
| **Imaging** | Complex visibilities | Phase retrieval by closure relations |
| Algorithms | all standard imaging | + 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.