INTENSITY INTERFEROMETER EXPERIMENT WITH THE SYNCHRONOUS NETWORK OF TELESCOPES

B. Zhilyaev

Main Astronomical Observatory, NAS of Ukraine
27 Akademika Zabolotnoho St., 03680 Kyiv, Ukraine
e-mail: zhilyaev@mao.kiev.ua
International Centre for Astronomical, Medical and Ecological Research
27 Akademika Zabolotnoho St., 03680 Kyiv, Ukraine

ИНТЕРФЕРОМЕТР ИНТЕНСИВНОСТЕЙ С СИНХРОННОЙ СЕТЬЮ ТЕЛЕСКОПОВ, Жиляев Б. – Имеются две конкурирующие схемы для производства интерференции в астрономии. Одна объединяет апертуры нескольких телескопов, другая измеряет корреляции отсчетов от нескольких телескопов. Схема корреляции известна как интерферометр интенсивностей и будет рассматриваться в этой работе как предполагаемый проект. Он основан на Синхронной сети удаленных телескопов трех обсерваторий Украины, России и Болгарии. Почти все действующие интерферометры используют майкельсоновскую комбинацию лучей с базой в десятки метров. Интерферометр интенсивностей может потенциально давать те же результаты, что и интерферометры, основанные на майкельсоновской схеме, с базой континентального масштаба около 1500 км. Он состоит из нескольких удаленных телескопов, использующих синхронный счет фотонов. Синхронизация сети сбора данных основана на GPS-приемниках, дисциплинирующих локальные системы времени фотометров относительно UTC в пределах нескольких наносекунд. Ключевой компонент системы измерений включает оригинальную схему вероятностной идентификации совпадающих отсчетов. Научная программа включает: обнаружение переменности на сверх-высоких частотах путем измерений параметра вырождения Бозе–Эйнштейна, восстановление изображений, а также ряд других астрофизических задач.

There are two competing schemes producing interference in astronomy, one combining several telescopes as an interferometric array, the other capable of count correlation measurements with several telescopes. The correlation scheme is known as the Intensity Interferometer and will be considered in this work as the supposed project. It is based on the Synchronous Network of distant Telescopes (SNT) involving telescopes at three observatories in Ukraine, Russia and Bulgaria and called SNTI (the SNT Interferometer). Almost all of the interferometers of today use the Michelson beam combination among several phased pupils with the baseline of tens meters. The SNTI can potentially produce results like those of based on the classic Michelson scheme. The SNTI provides a baseline of continental scale about of 1500 km too. It consists of several fairly separated telescopes operating synchronously and equipped with photon counting photometers. The data network synchronization is based on GPS receivers to discipline local photometer timing systems relative to UTC within a few nanoseconds. Key component of the event measurement system includes an original scheme of the probabilistic identification of coincident counts. Science programs include: detection of the ultrahigh-frequency variability by consideration of the Bose–Einstein degeneracy, interferometric imaging, as well a variety of other astrophysical objectives.

INTRODUCTION

First interferometric measurements of objects outside the Solar System were performed in the 1920s using a Michelson interferometer. In the 1980s construction of a new generation of optical interferometers began. Among them there are the Cambridge Optical Aperture Synthesis Telescope (COAST), the CHARA project on Mt. Wilson, the Keck and VLTI interferometers based around groups of very large optical telescopes [5]. The latest will provide the milli-arcsec angular resolution. An area not covered in depth inscribes Intensity interferometers. At present only optical interferometers based on the Michelson scheme are planned or under construction. We will look at some basic principles underlying the operation of optical interferometers both the Amplitude and the Intensity One. The use of multiple telescopes to produce high-resolution images as well as ultrahigh-frequency stellar variability is the main goal of this work.

THE VAN CITTERT–ZERNIKE THEOREM

Any size-limited quasi-monochromatic source creates spatial coherent pattern in a projective plane. The coherence coefficient is equal to the Fourier transform of function describing the intensity distribution in the source:

$$\mu^{(1)}_{1,2} = e^{(-i\psi)} \frac{\int\int_{-\infty}^{+\infty} I(\xi,\eta) \exp[i\frac{2\pi}{\overline{\lambda} z}\Delta x\xi + \Delta y\eta] d\xi d\eta}{\int\int_{-\infty}^{+\infty} I(\xi,\eta) d\xi d\eta}, \tag{1}$$

$$D = 0.61\frac{\overline{\lambda}\, z}{a} = 0.61\frac{\overline{\lambda}}{\alpha}\ ,$$

where D is the diameter of coherence spot, $\overline{\lambda}$ is the mean wave length, α is the angular radius of a source.

$\alpha \approx 1''$	satellites of planets	$D \approx 2\,\mathrm{cm}$
$\alpha \approx 0.05''$	α Ori	$D \approx 40$ cm
$\alpha \approx 0.01''$	nearest-neighbor stars	$D \approx 2\,\mathrm{m}$
$\alpha \approx 10^{-8}{}''$	quasar	$D \approx 10^3\,\mathrm{km}$

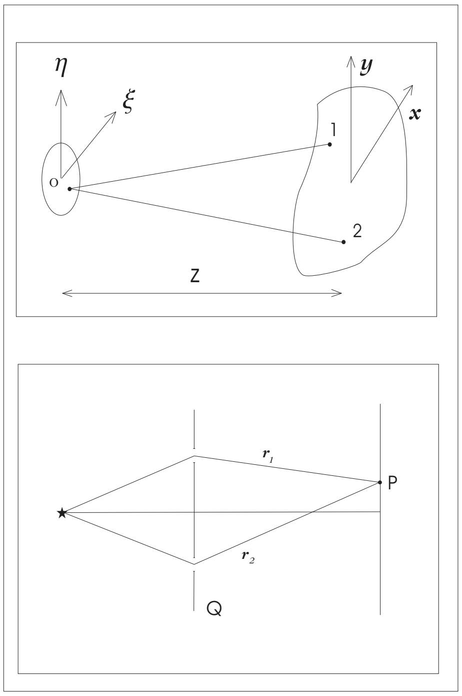

Figure 1. The top picture illustrates how coherence patterns rise from a finite size-limited quasi-monochromatic source. The bottom picture illustrates Young's Two-hole Experiment. The quantities measured in the P-plane are employed in an Amplitude interferometer. An Intensity interferometer operates with the quantities measured in the Q-plane

SOME QUANTUM OPTICS RELATIONS

Classical physics treats radiation in terms of "*intensity*", "*polarization*", "*spectrum*", *etc.* Quantum optics goes far beyond these quantities, describing one-, two-,... photon properties in terms of higher-order coherence functions and temporal correlations.

- The different quantities measured in experiments can be described in terms of the type

$$\langle E^*(r_1,t_1), E(r_2,t_2)...\rangle,$$

where E denotes a component of electric field, and $\langle\ \rangle$ time average, and * marks complex conjugate, in space r and time t.

- The measured light intensity can be defined as one-photon property

$$I = \beta \langle E^*(r_1,t_1), E(r_1,t_1)\rangle,$$

where β denotes the quantum efficiency. This is the very quantity, which a photomultiplier and a bolometer measure immediately.

- The spatial-temporal correlation function ("the second correlator")

$$\Gamma^{(1)}(r_1,r_2,t) \sim \langle E^*(r_1,t), E(r_2,t)\rangle$$

defines the first-order coherence function in the frame of classic Young's Two-hole experiment (Fig. 1). It is applied in astronomy for interferometric imaging. In most cases it can be factorized

$$\Gamma^{(1)}(r_1,r_2,t) \sim \mu^{(1)}(r_1,r_2)\gamma^{(1)}(t)$$

into two multipliers: the spatial coherence function $\mu^{(1)}(r_1,r_2) = \mu^{(1)}_{1,2}$ and the temporal one $\gamma^{(1)}(t)$.

- The spatial-temporal correlation function ("the fourth correlator")

$$\Gamma^{(2)}(r_1,r_2,t) \sim \langle E^*(r_1,t), E(r_1,t), E^*(r_2,t), E(r_2,t)\rangle$$

defines the second-order coherence function, which can be ascribed to two photon correlation. It can be given in terms of intensities too

$$\Gamma^{(2)}_{(1,2)}(t) \sim \langle I(r_1,t), I(r_2,t)\rangle.$$

The device capable of intensity correlation measurements is known as the Intensity Interferometer, first used by Hanbury Brown and Twiss in the 1950s.

- Producing interference requires high phase stability in the Amplitude Interferometer. In the case of Intensity Interferometer one needs an accurate timekeeping at both telescopes, which originates from the requirement $\gamma^1(t) \simeq 1$.

ONE-PHOTON INTERFEROMETRIC SCHEME. AMPLITUDE INTERFEROMETER

The foundation of all interferometric measurements in astronomy is the classic Young's Two-hole Experiment (Fig. 1). Almost all of the interferometers of today (if not all) use the Michelson beam combination among phased pupils with the baselines of up to tens meters.

- The intensity in the point P is equal

$$I(P) = I^{(1)}(P) + I^{(2)}(P) + 2\sqrt{I^{(1)}(P)I^{(2)}(P)} \cdot \mu^{(1)}_{1,2}$$

and can be used to determine $\mu^{(1)}_{1,2}$ in terms of intensities.

- Measuring $\mu^{(1)}_{1,2}$ from different baselines, it is possible to restore the intensity distribution on the source surface, which cannot be directly observed, using the inverse Fourier transform.
- Spatial fringle patterns have to be measured at an area of Airy disk in the focal plane. This requires small pixel size of some milli-arcsec and operations in the infrared.
- Interferometric instruments of this category require adjustment of pupil mirrors with μm precision, short exposure time, bright guide stars and Adaptive Optics to control atmospheric turbulence.

TWO-PHOTON INTERFEROMETRIC SCHEME. INTENSITY INTERFEROMETER

Operation of the Intensity Interferometer is founded on a quantum property of light called "the bunching of photons". Because of a photon gas follows a Bose–Einstein distribution the effect of temporal correlation between light quantum becomes significant. It is characterized by the quantity of Bose–Einstein degeneracy

$$\delta = \frac{1}{e^{\frac{h\overline{\nu}}{kT}} - 1}.$$

For the black body radiation at $T \approx 20\,000\,K$ $\delta \simeq 1$, for the Sun it equals $\sim 10^{-3}$.

- The normalized correlation function is

$$g^{(2)}_{(1,2)}(t) = \frac{\Gamma^{(2)}_{(1,2)}(t)}{\bar{I}_1 \bar{I}_2} = 1 + \frac{\langle \Delta I_1 \Delta I_2 \rangle}{\bar{I}_1 \bar{I}_2}.$$

For gaussian light, the Siegert relation between the first- and second-order correlation functions is true [3]

$$g^{(2)}_{(1,2)}(t) = 1 + |g^{(1)}_{(1,2)}(t)|^2.$$

- Measuring the intensity $I(t)$ in the photon counting mode, $n(t) = \beta I(t)\tau$, where $n(t)$ is counts per sampling time τ, one may obtain

$$r(n_1, n_2) = |\mu^{(1)}_{1,2}|^2.$$

Here r is the correlation coefficient between the readings at two distant telescopes. Thus, the Intensity Interferometer can potentially produce results like those of based on the classic Michelson scheme.

- The quantity

$$r\ \sqrt{N-2} = t_{N-2}$$

for a noise series of the length N has the Student t_{N-2} distribution with the $N-2$ degree of freedom. We may establish a threshold for detecting spatial coherence function at the confidence level α

$$r_\alpha = \frac{t_{N-2,\alpha}}{\sqrt{N-2}}.$$

- The signal-to-noise ratio with the Intensity Interferometer is less than with the Amplitude One by a factor of $\beta\delta$, other things being equal. The basic requirements for its construction are, however, less strong.
- The Amplitude Interferometer measures the intensity of light combined among several phased pupils in one point P (Fig. 1). The Intensity Interferometer measures the intensity fluctuations correlation between distant pupils operating independently at different points in the Q plane (Fig. 1). Both devices measure in various ways the same quantity $\mu^{(1)}_{1,2}$, to restore the source image in the end.
- To illustrate how sensitive the algorithm is to the image features, an example in Fig. 2 performs two 2-D Fourier transforms. The example simulates the images, which include a single star as well as a close binary system. We convert the images to Fourier space. The plot constrains the image transforms only in one dimension. As one can see, result "a binary star" is practically identical to result "a single star" if the image amplitude information is used only. For display purposes, we present the plot of the amplitude spectrum, which was determined after subtraction of both complex Fourier spectra. As it is easy to see, the account of the phase information allows restoring tenuous features of the initial image. The demo shown in Fig. 2 convinces us that an Amplitude Interferometer has doubtless advantages in comparison with an Intensity One in interferometric imaging. However, the last can besides effectively carry out a role of the spectral device.

APPLICATION OF INTERFEROMETRIC TECHNIQUE FOR DETECTION OF ULTRAHIGH-FREQUENCY VARIABILITY

We want to point out that the study of fast varying sources can be put into practice with an Intensity Interferometer. First references on super-fast photometry date back to Bonazzola and Chevreton [1], Pimonov and Terebizh [4], who were looking for time varying phenomena whose characteristic time scale is much less than the mean time between two photons.

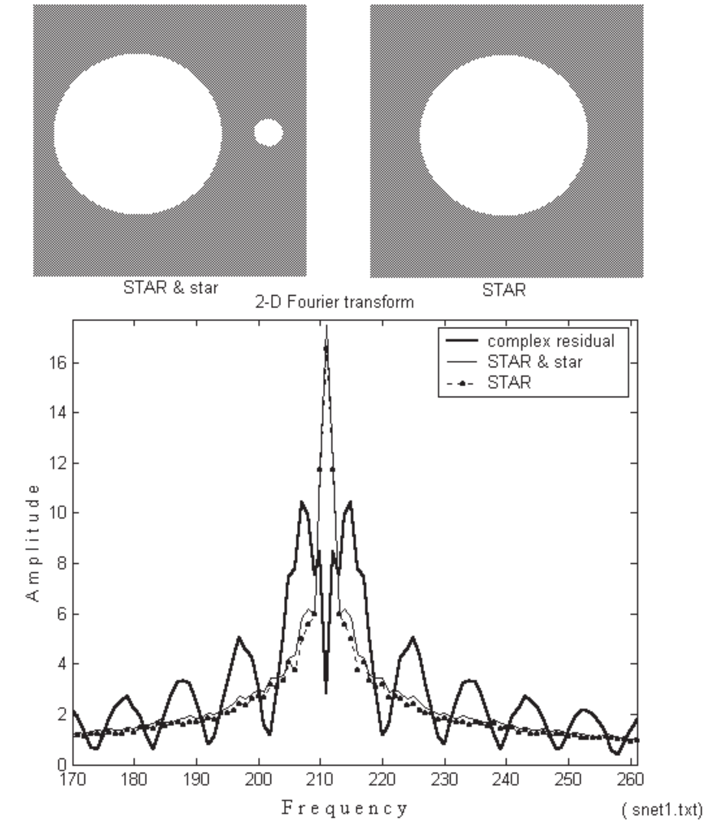

Figure 2. Computer-generated images of a single star and a star with small companion, showing sharp distinction in their spectral characteristics (see text)

Emission variations on timescales down to $1\mu s$ might be encountered 1) in objects far from thermodynamic equilibrium, 2) in the X and γ-ray sources, 3) in accretion discs around compact objects, *etc.* [2].

Any point-like source is characterized by a limitless spatial coherence. The same is true with respect to any size-limited coherently variable source. This means that their spatial coherence $\mu^{(1)}(r_1, r_2) \equiv 1$. The temporal term $\gamma^{(1)}(t)$ may be treated as an inverse Fourier transform of the source visible spectrum $F^{-1}G(\nu)$ in a Michelson interferometer. In the case of Intensity Interferometer this term may relate to the power spectrum density of variable source too. Because of Intensity Interferometer is an in-line correlation detector by nature, it can be utilized as a spectrointerferometer. An obvious advantage of this kind interferometric approach, utilizing the cross-correlation technique, over single-site monitoring is that atmosphere fluctuations do not significantly affect its performance. Tracking the source with two distant telescopes can also eliminate instrumental faults.

As it would seem, the light quantum deficiency puts obstacles in the way of fast photometry. For sparse quantum fluxes, light curves are of little use. This gives the false impression of an almost insurmountable problem when we have dealings with fast varying phenomena. However, this problem may be exactly soluble in Fourier space. We may obtain formal expressions for the harmonic frequency, amplitude and phase starting with only two photons in the measurement series. By Fourier theorem there is no restriction absolute values of the mean intensity, frequency of sampling, *etc.* However, the minimum detectable amplitude of signal depends on the total number of arrived photons [1].

The Synchronous Network of distant Telescopes (SNT) involving telescopes at three observatories in Ukraine, Russia and Bulgaria, is called SNTI (the SNT Interferometer). The SNTI provides a baseline of continental scale (about of 1500 km). It consists of several fairly separated telescopes operating synchronously and equipped with photon counting photometers. To integrate some apertures we need to synchronize distant telescopes to UTC within the sampling time. The data network synchroniza-

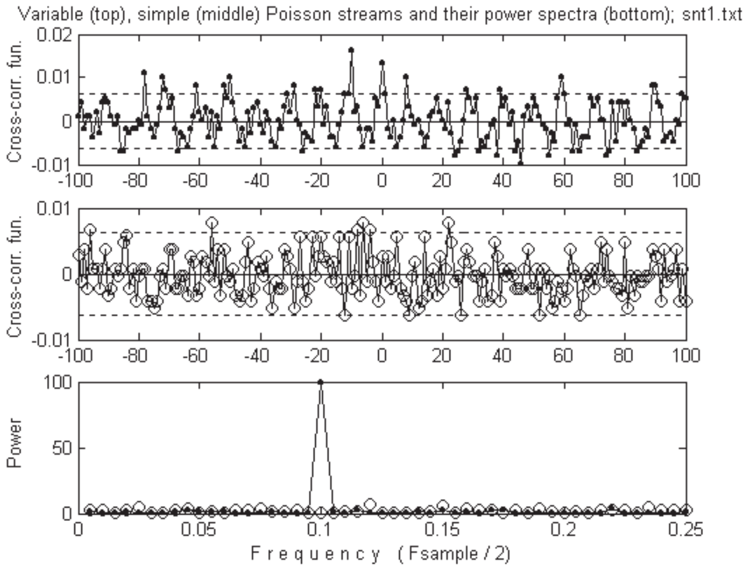

Figure 3. Computer-generated noise plus sinusoidal wave signal, showing sharp distinction from noise data (see text)

tion is based on GPS receivers Acutime 2000 to discipline local photometer timing systems relative to UTC.

At present time we can set the sampling time $\simeq 20\,\mu s$ as a typical value. Different telescopes can be synchronized to UTC within better than $\simeq 1\,\mu s$. Thus, shortest detectable temporal variations are of 25 kHz.

Fig. 3 shows the cross-correlation functions (CCF) and the cross-spectrum for two runs of generated noise as well as sum of noise and sinusoidal wave with amplitude equal to noise standard deviation. Noise is Poisson-distributed random integers. The computer simulation conditions are such that the mean interval between photons is hundred times greater than the sampling time. The total number of measurements and photons that have arrived are of 10^5 and $\sim 10^3$, respectively. The photoefficiency was chosen equal to 10 %.

The middle panel in Fig. 3 shows CCF calculated from the noise runs. The 95 % confidence levels for noise peaks are shown as the horizontal lines. The experimental data are in good agreement with the theoretical value given above for the correlation coefficient for noise series. The upper panel shows CCF calculated from sets of computer-generated noise plus sinusoidal wave signal, showing sharp distinction from the noise data. The bottom panel shows the cross-spectrum obtained as the Fourier transform of CCF. There is the striking peak at the actual frequency used in the computer-generated set.

To summarize, the results obtained here give some evidence that there is completely reliable opportunity to study the ultrahigh-frequency variability with the Synchronous Network of Distant Telescopes.

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