# THE TOMOGRAPHIC TECHNIQUE FOR RECONSTRUCTION OF THE COSMIC RADIO SOURCES IMAGES ON THE BASIS OF RADIO INTERFEROMETRIC DATA

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## ABSTRACT

Ionosphere influence practically excepts phase measurements at interferometric observations and leads to a "phase problem" in decameter radio astronomy. A tomographic approach to data processing based on use of the longitudinal correlation function as new information parameter at interferometric observations is proposed to solve an image reconstruction problem. It allows to reduce this problem up to a classical task of tomographic reconstruction on base of parallel projections. Such technique is less subject to influence of phase distortions. The developed tomographic procedure is being illustrated by results of numerical modeling with use of the experimental image of the CasA.

## INTRODUCTION

Urgent problem of modern radio astronomy is the construction of the radio images of cosmic radio sources. The given report is devoted to some aspects of this problem, which concern, first of all, of decametric waves. This problem is considered as applied to Ukrainian Decameter Very Large Base Interferometer (VLBI) Network URAN. However decision, offered in the report, can have wider application in radio astronomy.

Using the decameter wave band in radio astronomy allows to obtain a new astrophysical information. But it imposes a number of restrictions at images reconstruction. The purpose of the report is to show, that the decision of a problem of reconstruction of the cosmic radio sources images on decametric waves on the basis of interferometric data can be reduced to a classical problem of tomographic reconstruction of function under its Radon-image. Such techniques is more steady to phase distortions and influence of interferences which take place in a decametric range.

The questions considered in the report are the following: -the Ukrainian Decameter VLBI Network URAN; -classical approach to radio image reconstruction and phase problem in radio astronomy;-proposed approach to radio images reconstruction on the basis of the longitudinal correlation function; -numerical simulation of tomographic reconstruction procedure in decameter radio astronomy.

## PROBLEM STATE

### Ukrainian Decameter VLBI Network URAN

The Ukrainian Decameter VLBI Network URAN has been constructed in Ukraine. It consists of five decameter radio telescopes, located as is shown in Fig. 1, near cities Kharkiv (UTR-2, URAN-1), Poltava (URAN-2), Lviv (URAN-3), Odessa (URAN-4) [1]. They create the baselines from 42 to 957 km. The instrument is used for systematic surveys of the north sky, investigation of angular structure of radio sources and some other programs in the range 10 to 30 MHz.

In decametric waveband the minimum correlated flow approximately 7J at 25 MHz (quasar 3C216) have been experimentally registered by the VLBI UTR-2 - URAN-3 (baseline is 957 km). It opens unique opportunities of research of angular structure of decametric radio emission of a number of space sources with the resolution ~1 arcsec and the signal-to-noise ratio ~ 0.5. The result of one of last researches with use of the Network URAN is given in Fig. 2 [2]. The most suitable simple models of radio brightness distribution of the compact component of the quasar 3C216, determined with use of three interferometers of the Network URAN (baselines of 42.3 km, 152.3 km and 946.2 km; frequencies: 1 - 20 MHz, 2 - 25 MHz), against a background of a radio map of the Galaxy ([3], 4885 MHz) are represented. It is shown that the decameter radio image of source is essentially different from that at higher frequencies.

Unfortunately, a number of peculiarities of the VLBI Network URAN limits its possibilities concerning the reconstruction of radio images, including monochromatic approximation, the significant difference in sensitivities of the


Fig. 1. The elements locations of the VLBI Network URAN.

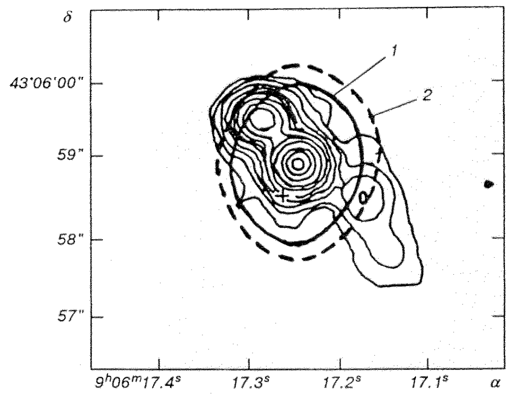


Fig. 2. The models of radio brightness distribution of the compact component of the quasar 3C216.

antennas, influence of the ionosphere, absence of phase measurements etc. Therefore it is necessary to find other ways to bypass these restrictions at reconstruction of the radio images.

**The classical approach to radio images reconstruction**

The classical approach to reconstruction of radio images in radio astronomy by interferometric technique is based on use of the Van Cittert-Zernike theorem [4]. As a first approximation, this theorem connects the sought angle distribution of radio brightness $I(\xi,\eta)$ and the lateral correlation function (mutual coherence function) $B_{\perp}(D)$, registered by an interferometer, by Fourier transformation.

Such reconstruction technique has two main limitations. First of all, use of the Van Cittert-Zernike theorem requires the monochromatic approximation. Therefore, the frequency range, which participates in the signal processing, should be much less than a center frequency of the interferometer band pass. In this case the use of a wide band pass leads to the radial blurring of the reconstructed image, or requires of the separation of a band pass on several ranges with separate processing of signals in everyone. Secondly, use of the Fourier transformation for the reconstruction procedure leads to increase of information usefulness of a phase of the visibility function.

At the same time, at decameter interferometry the amplitude of the visibility function is being confidently registered, but a phase undergoes considerable distortions by a propagation medium. In this wave band the ionosphere influence practically excepts the phase measurements at interferometric observations and creates in radio astronomy the so-called "phase problem" [4]. It is possible to note a number of effects from ionosphere influence on radio emission propagation [5]: ionospheric Faraday effect, group delay, additional path, phase change, phase instability, attenuation (in *D*- and *F*-regions), refraction. For example, the phase instability in the meter wave band may be hundreds and thousands radians. There are a number of techniques for overcoming this problem, which are usually being used in more high frequency radio astronomy: closure phase technique, point source method, Labeyrie method (speckle interferometry), Hilbert transform, integral equations, non-linear algebraic equations system, optimal solution method, Fienup algorithm, Herbert-Saxton algorithm, maximum entropy method, optimization (non-linear) methods, adaptive methods, Kalman filtering methods etc [4, 6]. But these techniques are not always effective on low frequencies (decametric).

**PROPOSED APPROACH TO RADIO IMAGE FORMATION**

**Terminology and tomographic procedure**

In author's opinion, it is possible to offer the tomographic approach for solution of a problem of images reconstruction of cosmic radio sources at a high level of interferences including the ionosphere influence. Technology of computerized tomography decides a problem of image formation of object on the basis of its projections [7]. Researches showed that the procedure of image formation of cosmic sources at interferometric observations it is possible to present as consequent procedures of data collection (the direct Radon conversion) and the next inverse Radon transformation. But in this case a measuring parameter at interferometric observations should not be the lateral correlation function used usually, but the longitudinal correlation function (LCF).

Let's consider the *AB*-interferometer (Fig. 3) for the plane case and assume that radiating *X*- and *Y*-elements of a radio source are placed on a surface of the sphere of the unit radius. Mutual time delay $\tau = D\sin(\varphi)$ between signals received by antennas *A* and *B*, is uniquely determined by an angular coordinate of a radiating element. Let also assume that all elements have an identical spectrum and its radiation is $\delta$-correlated. At such assumptions the following theorem is proved for a plane case: the LCF $R_{AB}(\tau)$ is being determined as a convolution of the normalized auto-correlation function $r(\tau)$ of radio source emission with its angle distribution of brightness $f(\tau)$. At transition from wideband radiation to quasi-monochromatic case this theorem is being reduced to Van Cittert-Zernike theorem. Thus, the solution of the convolution equation ensures solution of the inverse problem of reconstruction of angle distribution of radio emission intensity at one hour angle on the basis of the LCF.

Let's address to Fig. 4, which demonstrates what it means for the real interferometer observations. There are the celestial sphere and the cone. Cone's axis is a prolongation of the base-line vector of the *AB*-interferometer. On its intersection with celestial sphere the points with identical time delays are located on a circle. At rotation of the Earth the base-line vector describes a circle in the $u'v'$-plane. Let's consider a projection of the celestial sphere on the $u'v'$-plane. In this plane the circle, formed by the crossing of a celestial sphere by a cone, will be projected as a straight line. It is possible to determine this line as a Radon projection for the radiating elements located under angle $\varphi$. Other cones, appropriate to various angles $\varphi ... \varphi_n$ and time delays $\tau ... \tau_n$, form a number of parallel straight lines.

So, for the specific hour angle (time moment) on the basis of the LCF one can determine a number of parallel projections on the $u'v'$-plane of the angle distribution on the celestial sphere of radio source brightness. At rotation of the Earth the *AB*-interferometer is rotating concerning celestial sphere. At that sets of parallel projections of a radio source under diverse angles may be obtained in the $u'v'$-plane. During 12 hours one can obtain a full set of parallel Radon projections which are the basis for formation of a source image on the basis of the inverse Radon transformation. And it already - the classical tomographic problem, which can be solved by the various calculated methods.

Fig. 5 illustrates the proposed tomographic procedure at interferometry measurements with use of measured values of the LCF during *T* hours. Such procedure should include the next steps: registration of the LCF; determination of the parallel projections set on the basis of convolution equation; the obtaining of projection data sets for diverse hour angles at rotation of the Earth; the source image reconstruction in the plane $u'v'$ by the inverse Radon projection; formation of the source brightness angle distribution by the geometric inverse projection of the $u'v'$-image. This procedure is especially attractive for decameter interferometry, including the Ukrainian Decameter VLBI Network URAN, by the following reasons: absence of phase measurements; real possibility of use of the wideband receiving channel (it increases the sensitivity of an interferometer); increase of a band pass compensates the low coating of baseline space by decameter antennas.

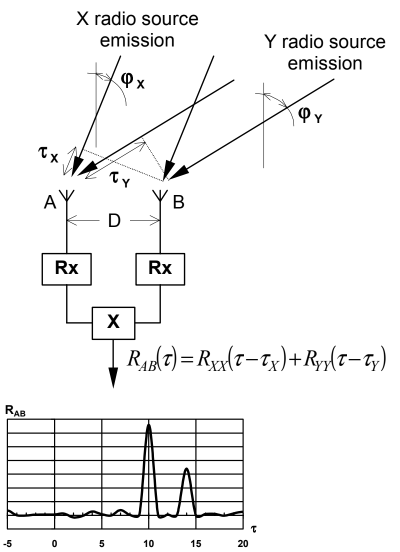


Fig 3. The correlation response of the AB-interferometer.

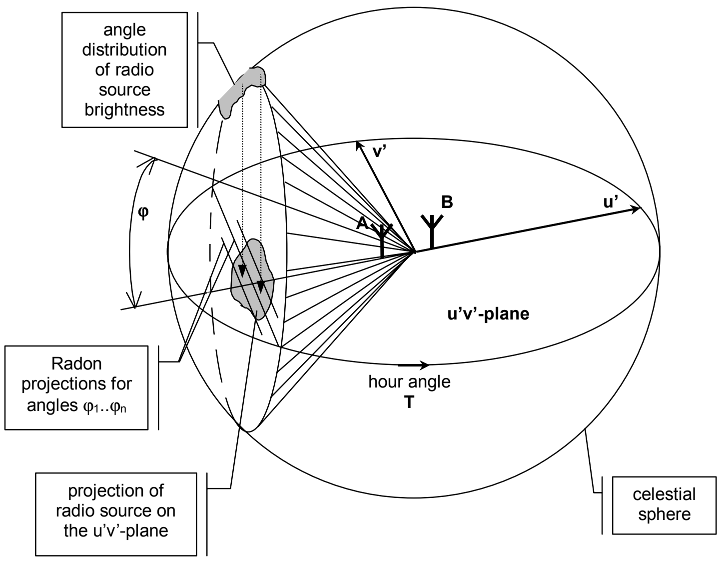


Fig. 4. Schematic presentation of the tomographic approach for interferometry observations in radio astronomy.

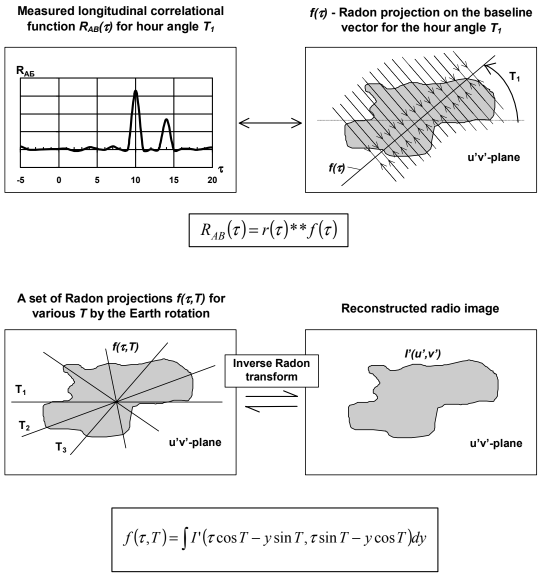


Fig. 5. Procedure of tomographic reconstruction at interferometry measurements.

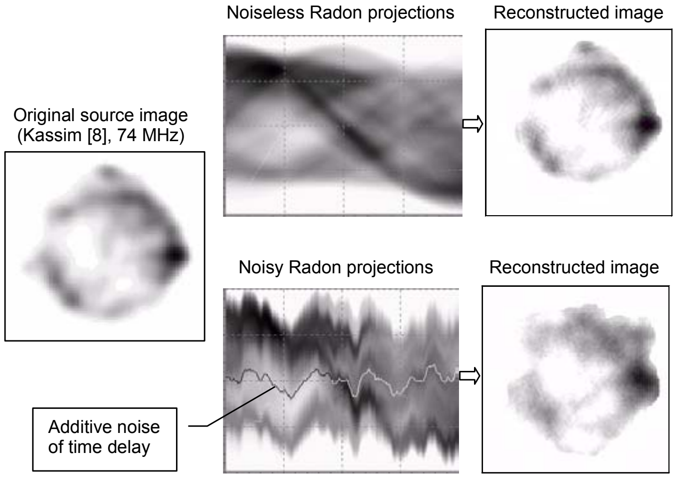


Fig. 6. The original experimental image of Cas A (74 MHz [8]) and reconstructed image on the Radon projections

**Numerical simulation**

Fig. 6 illustrates the results of numerical simulation: the original radio image of Cas A (Kassim, 74 MHz, [8]); the noiseless and noisy Radon projections of this image (additive noise; peak-to-peak of the introduced changes of time delays makes up to 30 % from maximal length of the projections, shown on figure); the reconstructed images of Cas A from the noiseless and noisy projections. The noise factor was selected correspondingly to phase delays, caused by the ionosphere influence. The reconstructed image conserves the main peculiarities of the original source image. Represented results have confirmed the availability of the proposed tomographic procedure and its stability to influence of the ionospheric noise.

**CONCLUSION**

The proposed tomographic approach to formation of radio images of cosmic sources on the basis of the measuring of the longitudinal correlation function at interferometric observations allows to realize the image reconstruction procedure in decameter interferometry only on the basis of amplitude measurements (without of phase measurements).

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