Radio-Engineering Means of Transmission, Reception, and Processing of Signals

Comparison of Radio Interferometers with Analog and Digital Extraction of Recorded Signal

Nikolai E. Kol'tsov[1,2], Sergei A. Grenkov[2✉], Leonid V. Fedotov[2]

[1]Saint Petersburg Electrotechnical University, St Petersburg, Russia

[2]Institute of Applied Astronomy of Russian Academy of Sciences, St Petersburg, Russia

✉skynet81@yandex.ru

Abstract
Introduction. Radio telescopes incorporated in very long baseline interferometry (VLBI) networks are used to record several narrowband signals (up to 32 MHz), which are extracted by means of base band converters (BBC) from an analog noise signal of an intermediate frequency (IF) with bands up to 1 GHz. When processing the as-obtained data, the method of frequency band synthesis is used. Novel compact radio telescopes (e.g., RT-13) digitalize wideband IF signals. A digital narrowband signal extraction module developed in 2019 provides the possibility of integrating RT-13 radio telescopes with the Russian Quasar VLBI Network.
Aim. To assess the accuracy of measuring the interferometric group delay of a signal by a radio interferometer equipped with a digital narrow-band signal extraction module, as well as to compare the sensitivity of interferometers with analog and digital signal extraction systems.
Materials and methods. Sensitivity losses of interferometers with different systems for detecting recorded signals were calculated. The accuracy of a multi-channel interferometer with the synthesis of a frequency band and an interferometer with recording of digital broadband IF signals without band synthesis was compared. The results were confirmed by VLBI observations in the observatories of the Quasar VLBI Network.
Results. When replacing the analog system of signal extraction with the digital system, the sensitivity losses of the interferometer decreased slightly. The measurement accuracy of the interferometric group delay remained unchanged. An increase in accuracy was achieved when broadband IF signals were recorded digitally and when a frequency band significantly larger than the IF bandwidth was synthesized. Conditions and minimum synthesized bands were determined, under which the accuracy of the interferometer registering narrowband signals exceed that of the interferometer registering wideband IF signals.
Conclusion. The problem of integrating RT-13 radio telescopes with VLBI networks, which record video frequency signals, was solved. The feasibility of installing digital signal conversion systems on radio telescopes was shown.

Keywords: very long baseline interferometry, data acquisition systems, digital base band converters, accuracy of the interferometer, frequency band synthesis

Conflict of interest. Authors declare no conflict of interest.

Радиотехнические средства передачи, приема и обработки сигналов

Оригинальная статья

Сравнение радиоинтерферометров с аналоговыми и цифровыми системами выделения регистрируемых сигналов

Н. Е. Кольцов[1,2], С. А. Гренков[2✉], Л. В. Федотов[2]

[1]Санкт-Петербургский государственный электротехнический университет "ЛЭТИ" им. В. И. Ульянова (Ленина), Санкт-Петербург, Россия

[2]Институт прикладной астрономии Российской академии наук (ИПА РАН), Санкт-Петербург, Россия

✉ skynet81@yandex.ru

Аннотация

Введение. Радиотелескопами комплексов радиоинтерферометрии со сверхдлинными базами (РСДБ) обычно регистрируются несколько сигналов с относительно узкими (до 32 МГц) полосами, которые выделяются видеоконвертерами из аналогового шумового сигнала промежуточной частоты (ПЧ) с полосами до 1 ГГц. При обработке данных применяется синтез полосы частот. На новых небольших радиотелескопах (например, РТ-13) оцифровываются широкополосные сигналы ПЧ. Возможность подключения радиотелескопа РТ-13 к РСДБ-комплексу "Квазар-КВО" и к международным РСДБ-сетям обеспечивает модуль цифрового выделения узкополосных сигналов, разработанный в 2019 г.

Цель работы. Определение точности измерения интерферометрической групповой задержки сигнала радиоинтерферометром с цифровым модулем выделения регистрируемых сигналов и сравнение чувствительностей интерферометров с аналоговыми и цифровыми системами выделения сигналов.

Материалы и методы. Рассчитываются потери чувствительности интерферометров с разными системами выделения регистрируемых сигналов. Сравниваются точности многоканального интерферометра с синтезом полосы частот и интерферометра, регистрирующего цифровые широкополосные сигналы ПЧ без синтеза полосы. Результаты подтверждаются РСДБ-наблюдениями в обсерваториях комплекса "Квазар-КВО".

Результаты. При замене аналоговой системы выделения сигналов на цифровую потери чувствительности интерферометра немного снижаются. Точность измерения интерферометрической групповой задержки не меняется. Точность повышается при синтезе полосы частот, значительно превышающей ширину полосы ПЧ, и при цифровой регистрации широкополосных сигналов ПЧ. Определены условия и минимальные синтезируемые полосы, при которых точность интерферометра с регистрацией узкополосных сигналов может быть выше точности интерферометра с регистрацией широкополосных сигналов ПЧ.

Заключение. Решена задача совмещения радиотелескопов РТ-13 с РСДБ-сетями, где регистрируются сигналы видеочастот. Показана эффективность установки на радиотелескопах цифровых систем преобразования сигналов.

Ключевые слова: радиоинтерферометрия со сверхдлинными базами, системы преобразования сигналов, цифровые видеоконвертеры, точность интерферометра, синтез полосы частот

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Introduction. Data acquisition systems (DAS) are widely used in radio telescopes with very long baseline interferometry (VLBI) networks. These systems are capable to extract signals with relatively narrow (up to 32 MHz) ΔF bands from a wide (up to 1 GHz) band of intermediate frequencies (IF) that followed by their conversion to base band frequencies and digital recording [1, 2]. This class of system also includes R1002M 16-channel DAS [3] which are installed on RT-32 VLBI radio telescopes in the Quasar VLBI Network [4]. Signals with ΔF bands are extracted from a noise IF signal with a band of 0.1…1 GHz using analog quadrature frequency converters (QFC) and digital downconverter. The extracted signals are amplitude-quantized and formatted according to the international VDIF standard [5] or the VSI-H format [6], followed by the transmission of the received observation data for processing by VLBI correlators [7, 8]. For VLBI observations by astrometry and geodetic programs the signals of 5–8 frequency channels with bands of $\Delta F = 8$ or 16 MHz are extracted from the IF band and processed using the method of wide band frequency synthesis [9].

In recent years the transition to compact radio telescopes with digital systems for recording broadband signals (from 0.5 to 1 GHz) has become the main direction in of the development of VLBI [10, 11]. Such systems are essential both for the creation of new generation VLBI complexes [12, 13] and for the development of radiometry as a whole [14]. For example, the RT-13 13-meter VLBI radio telescopes was incorporated with digital systems for converting broadband signals that have eight channels and able to record IF signals with $B_0 = 512$ MHz bands at a sampling frequency of $F_d = 1024$ MHz [11]. Processing of high-speed data streams received by the system channels (2048 Mbit/s per channel) are carried out by specialized software VLBI correlators [15].

In order to integrate radio telescopes with broadband channels into existing VLBI networks, where narrowband signals of base band frequencies are recorded and processed, the signals with relatively narrow bands should be extracted from a high-speed digital IF signal and converted to base band frequencies $(0...\Delta F)$. This operation can be performed by digital modules on a field programmable gate array (FPGA) that containing polyphase filters (PPF) and base band converters (BBC) [16]. In terms of structure and clock frequency the data stream generated by such modules is similar to that received using R1002M DAS. As a result, it becomes possible to integrate RT-13 radio telescopes registering broadband signals with both the Quasar VLBI Network and international VLBI networks that recording narrowband signals.

In this regard, it is important to determine the effect of replacing analog DAS with digital signal extraction modules on the sensitivity of radio interferometers and the measurement accuracy of interferometric group delays of the τ received radiosignal. This information is essential both for the rational planning of VLBI observations using heterogeneous signal conversion systems and for the selection of reference sources for radiosignals. In addition, this information can be used for developing multifunctional digital systems for converting signals with $B_0 = 512$ MHz bands (sampling frequency of $F_d = 2048$ MHz with the aim of upgrading the existing RT-32 radio telescopes and equipping new compact radio telescopes.

In this article we set out to investigate the effect of the loss of instrumental sensitivity by radio interferometers equipped with different systems for extracting recorded narrowband signals from a wide IF band. To this end we compare the sensitivity and accuracy of measuring the interferometric group delays of signals using an interferometer with extracting registered narrowband signals digitally and an interferometer with an R1002M DAS.

In connection with the development of VLBI radio telescopes with ultra wide-band radio astronomy receivers (RR) [17, 18] and registration systems for broadband signals [10, 11], the possibility of synthesizing a frequency band exceeding the passband of the receiving channel (up to 1 GHz) is of particular significance. The receivers of RT-13 radio telescopes [19] have three receiving channels for each frequency range and for any of two circular wave polarizations, thus allowing the frequency bands up to 2.5 and 6 GHz wide to be synthesized in the X (7…9.5 GHz) and K range (28…34 GHz), respectively. Since the effectiveness of such an approach has not been clarified yet, it is of interest to compare the parameters of a multichannel interferometer that registering narrowband signals (up to 16 MHz) digitally for a subsequent synthesis of a broadband signal, with those of an interferometer recording in parallel (without synthesis) up to three broadband (0.5 or 1 GHz) signals.

Determination of the sensitivity of interferometers based on different systems for extracting

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recorded signals. The sensitivity of a radio interferometer is characterized by the ratio of the correlation response peak to the root mean square deviation (RMSD) of the residual noise at the output of the correlator. For a single-channel interferometer with the ΔF band of signal recording, the signal-to-noise ratio at the peak of the correlation response is defined as:

$$R_1 = \chi\sqrt{2q_1 q_2 \Delta F t_\text{o}},$$

where $\chi \le 1$ is the coefficient that taking into account the loss of sensitivity in the receiving and recording channels of radio telescopes and in the correlator of the interferometer; $q = T_\text{s}/T_\text{n}$ is the ratio of the T_s received signal noise temperature to the T_n temperature of the radio telescope set noise at the RR input; t_o is the source observation (scanning) time [8]. Subscripts 1 and 2 indicate the serial numbers of the interferometer radio telescopes. VLBI measurements are usually performed at $R_1 > 7$.

Let us represent the coefficient of hardware sensitivity loss by the $\chi = \chi_\text{E}\chi_0$ product, where the first term represents the losses in the broadband receiving and amplifying channels, as well as in the device for separating the recorded base band frequency signals, while the second term represents the losses in the digital processing and correlation devices of the extracted base band frequency signals.

The χ_0 value is determined mainly by losses arising during amplitude quantization of digital samples of the noise signal (12 or 36.3 % for four- or two-level quantization, respectively), as well as by losses involved with the correlation processing of base band frequency signals, accounting together for about 13 % [9]. For radio interferometers with narrowband channels, including those in the Quasar VLBI Network with R1002M systems, as a first approximation, $\chi_0 \approx 0.76$ or $\chi_0 \approx 0.55$ can be taken for four- or two-level quantization, respectively. These χ_0 values remain valid for an interferometer based on digital signal extraction systems, since the methods of amplitude quantization, formatting and correlation processing of narrowband signals remain the same.

For assessing the quality of signal extraction channels, it is sufficient to compare the χ_E loss coefficients for interferometers with digital signal extraction systems (χ_D) and those with analog R1002M DAS (χ_A).

In RT-32 radio telescopes the RR is connected to the DAS by a coaxial transmission line containing power amplifiers with corrections for the non-uniformity of attenuation in the 0.1…1 GHz IF band (Fig. 1). In the DAS IF signal is distributed over base band converters each of which comprises a quadrature frequency converter (QFC) equipped with diode mixers and ΔF band analog low-pass filters (LPF), a pair of analog-to-digital converters (ADC) and a digital phase signal splitter (PSS) separating the signals of the upper and lower side bands. After the four-level quantization of amplitudes the digital signals with ΔF bands are fed to the data formatter of the Mark 5B+ recording terminal [20] followed by transmission of the observation data to the correlation processing center.

When the χ_A coefficient is calculated using an interferometer with an DAS R1002M, account is taken of the losses associated with the distortion of signals in the receiving-amplifying channel from the input of the RR to the ADC in the DAS base band converter. In general,

$$\chi_\text{A} = \chi_0 \prod_i (1 - 0.01\eta_i),$$

where η_i are the losses related to the i-th factor (in
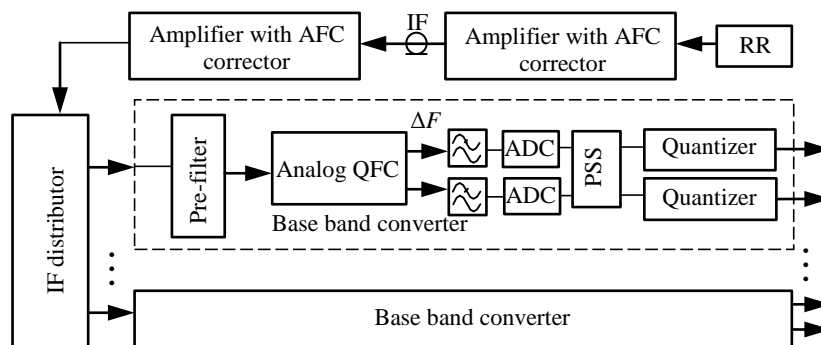
Fig. 1. A System for Extracting Narrowband Signals at the RT-32 Radiotelescope

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percent). Losses of about 3 % result from distorting the signal by the phase noise from super-high frequency heterodynes of the RR. Distortions of the narrowband signal in the RR with a wide passband can be neglected, since the amplitude-frequency characteristic (AFC) and phase-frequency characteristic (PFC) of the receiving channel are formed by the narrowband low-pass filter of the base band converter. In the IF signal transmission line, due to the non-uniform AFC of power amplifiers and the residual slope in the AFC of the coaxial cable (uncompensated attenuation nonuniformity), signals with ΔF bands in individual frequency channels are susceptible to distortion. The distortions of the channel AFC due to the slope of the spectrum leads to the loss of the interferometer sensitivity of up to 2 %.

A significant loss of the interferometer sensitivity may occur due to the non-identity of the AFC of analog filters in the base band converters of an interferometer radio telescope pair. Technological variation in the filter parameters, temperature changes and aging of circuit elements can also result in the oscillation and slope of the AFC in the channel passband. In R1002M DAS base band converters, the AFC identity and PFC linearity of the channels are significantly increased due to digital filters forming the ΔF band and digital PSS separating sideband signals with an isolation of more than 42 dB. The noise of the mirror channel is practically eliminated, while moire noise is suppressed by a pre-filter (switchable filters) at the input of the base band converter. Nonlinear distortion of signals in the channel with digital filters is also practically absent. The quantization noise of the analog signal can be neglected, when the number of ADC bits equal to at least 8. Losses arising for the aforementioned reasons account for about 2 %. Minor (about 1 %) sensitivity losses occur due to noise from heterodyne signals, the RMSD of which is reduced to 2° [3]. The loss of the interferometer sensitivity due to signal distortion in the R1002M DAS comprises about 3 % in total.

In general, for an interferometer with analog signal extraction channels of base band frequencies, the coefficient of hardware sensitivity loss can be taken as $\chi_A \approx 0.92\chi_0$.

In interferometers based on digital conversion systems for broadband signals, the ADC operates at the sampling frequencies of $F_d = 2048$ MHz (with the registration band of $B_0 = 1024$ MHz) or $F_d = 1024$ MHz (with the band of $B_0 = 512$ MHz). From the received high-speed (broadband) digital signal, narrowband signals are extracted using an FPGA-formed PPF module and BBC (Fig. 2). A digital input signal with a F_d sampling frequency is distributed by the demultiplexer (DM) over the N channels of PPF with decreasing frequency to the FPGA value of clock frequency $F_T \leq 550$ MHz. Complex signals at the PPF outputs are divided into N real signals with $B_s = B_0/N$ bands by the splitters (PSS) in phase-shifting filters. From the obtained band signals, signals with the ΔF specified bands are extracted by BBC. The selected signals are quantized in amplitude and formatted similar to those in the DAS R1002M channels.

In radio astronomy equipment that based on FPGA, it is convenient to use BBC operating with a clock frequency of $F_T = 128$ or 256 MHz [11] which are tuned by digital heterodynes [21] in the frequency bands up to 64 or 128 MHz, respectively. When using heterodynes with a clock frequency of 512 MHz [22], the tuning range of the BBC is expanded to 256 MHz. However, in the latter case, preliminary filtering of the input broadband signal is also necessary.

During polyphase filtering in the near-zero frequency range and at the frequencies multiple of F_T the signals are distorted. Distortions also occur near the frequencies multiple of $0.5F_T$ where the signal spectra partially overlap at the edges of adjacent B_s bands. Thus, in order to be capable of extracting signals of any frequencies without distortion, the mod-

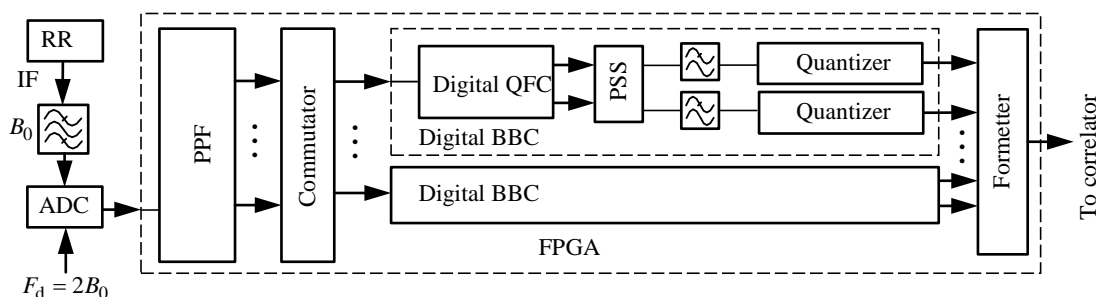*Fig. 2.* System for Extracting Narrowband Signals from a Digital IF Signal

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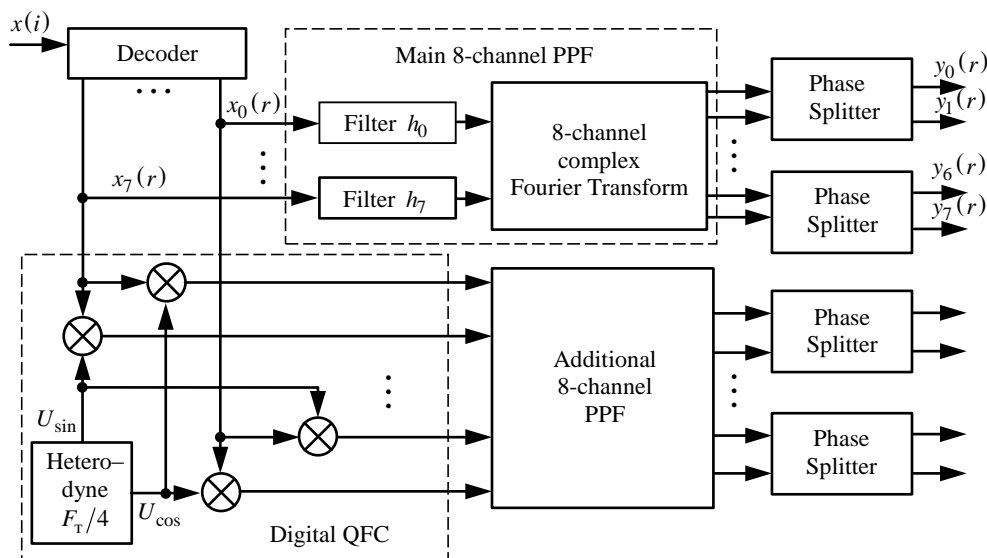
Fig. 3. IF Digital Signal Pre-filtering Module

ule is equipped with two (main and additional) N-channel PPFs (Fig. 3) [23]. In the channels of the additional PPF the input broadband signals enter through quadrature frequency converters. The $U_{\sin}$ and $U_{\cos}$ heterodyne quadrature signals have a frequency of $F_\text{T}/4$. In this case the signals at the outputs of the phase selectors in the channels of the additional PPF are shifted by half the band relative to the output signals in the channels of the main PPF.

At the outputs of the main N-channel PPF, complex signals are formed

$$y_n(r) = \sum_{i=0}^{N-1} \left\{ \sum_{l=0}^{L-1} x\big[L(r-l)-(L-1)n\big]h_n(l) \right\} \times$$
$$\times \exp(j2\pi ni/N), \qquad (1)$$

where n is the serial number of the output signal code; L is the order of the filters for the $h_n(r)$ weight functions; j is the imaginary unit. The weight function affecting the distribution of energy between the main and side lobes of the spectral function for the output signal has the form:

$$h_n(r) = 0.5\big[1 - \cos(2\pi r/LN)\operatorname{sinc}(r/L - 0.5N)\big],$$

where $\operatorname{sinc}(\varsigma) = \sin(\varsigma)/\varsigma$.

In RT-13 radio telescopes, a digital broadband IF converter is located next to the RR by means of a fixed short (less than 1.5 m) coaxial. The signal spectrum at the ADC input is formed by a broadband IF filter. Here, the sensitivity losses associated with distortions of signals in the IF signal transmission lines are eliminated; however, the losses (up to 3 %) due

to signal distortions in frequency converters by heterodyne phase noise are still present. All filters in the signal extraction channel are digital, thus ensuring a high stability of the receiving and recording channel parameters during the antenna movement and changes in external climatic conditions. Therefore, the PFC linearity is guaranteed, and distortions in the AFC shape of the receiving and recording channel are minimized (distortion and oscillation of AFC, deviations in the passband, frequency tuning shift). The loss of sensitivity due to the AFC nonidentity of the interferometer channels is lower than

0.3 %. The AFC side lobes of the PPF channel are attenuated by 30 dB. Due to out-of-band noise penetrating the side lobes, the signal-to-noise ratio in the 8-channel PPF decreases by about 0.7 %.

In digital signal extraction systems, insignificant losses appears due to the bit depth limitations (truncations) of the codes in the PPF, PSS and BBC. In calculations according to (1), 8-bit codes of the $x(i)$ input signal and 16-bit codes of the $h_n(r)$ weight function are multiplied, while $L = 16$ products are summed. The codes obtained at this stage are truncated to 9 bits. At the stage of multiplying these codes by 16-bit codes of the exponential function and adding the $N = 8$ obtained results, the output signal codes are truncated to 12 bits. As a result of code truncations, the signal-to-noise ratio in the PPF channel decreases by 0.16 %. A decrease in the bit depth of the codes to 14 in the band signal phase selector does not result in any noticeable loss of sensitivity. In the BBC heterodyne, the resolution of the current phase codes decreases to 10, corresponding

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to a RMS phase noise of the heterodyne signal of 0.1°. Losses associated with such a phase noise are negligible. Amplitude fluctuations of heterodyne signals represented by 10-bit codes have little effect on the signal-to-noise ratio in the frequency converter. Almost no change in the signals of the base band frequencies caused by signal-to-noise ratio is observed at the outputs of the QFC, while limiting their bit depth to 15. The total sensitivity loss introduced by the digital narrowband signal extraction module does not exceed 0.5 %.

In the digital module, the total decrease in the signal-to-noise ratio is significantly lower than the loss resulting from signal distortion by phase noise of the RR heterodynes. Taking into account all losses for an interferometer with digital narrowband signal extraction systems, the loss coefficient can be taken equal to $\chi_D \approx 0.96\chi_0$. For an interferometer with the same antennas and RR, but with different types of narrowband signal extraction systems, $\chi_A \approx 0.94\chi_0$.

The sensitivity of interferometers can be slightly increased (up to 4 %) by replacing the standard R1002M DAS in RT-32 radio telescopes with the considered modules for digital extraction of narrowband signals. A slight improvement in sensitivity has little effect on the accuracy of determining the τ interferometric group delay of the received radio signal. Under $R_1 > 7$, the greatest effect is produced by factors unrelated to the signal registration system, including errors in tracking systems for Doppler frequencies and ephemeris, errors in measuring group delays of signals in the receiving and recording channels of radio telescopes and discrepancies in the time scales of data formatters in radio telescopes. In addition, for angular and coordinate-time measurements by VLBI methods, account should be taken of the state of the atmosphere; however, the accuracy of such corrections may be insufficient.

A radio telescope with a digital signal extraction module can be operated both in a multichannel interferometer mode with registration of narrowband signals and in an interferometer mode registering broadband IF signals. During the VLBI observations conducted at the Zelenchukskaya and Badary observatories, the parameters of the Quasar standard radio interferometer (two RT-32 radio telescopes with R1002M DAS) and an interferometer with different types of radio telescopes (RT-32 with DAS and RT-13 with a digital signal extraction module) were compared. The tests confirmed the possibility of integration radio telescopes with different systems of signal conversion in the VLBI network and the possibility of operating a RT-13 radio telescope in the Quasar VLBI Network.

Accuracy assessment of a multichannel interferometer providing digital signal extraction. For an M-channel radio interferometer with the synthesis of a wide frequency band, the RMSD calculated by the interferometric delay correlator is defined as [8]:

$$\sigma_\tau(M) = \frac{1}{2\pi\chi q B_E \sqrt{2M\Delta F t_0}}, \qquad (2)$$

where $q = \sqrt{q_1 q_2}$; B_E is the effective frequency band; ΔF is the band of registered signals. In this case:

$$B_E = \sqrt{\frac{1}{M}\sum_{r=1}^{M}(f_{0r} + f_{av})^2},$$

where f_{0r} is the average frequency of the narrowband signal extracted by the channel with the r number; $f_{av} = 0.5(f_{01} + f_{0M})$. Formula (2) determining the potential accuracy of the interferometer is derived for an ideal interferometer having the same group delays of the signals in the receiving and recording channels of radio telescopes, precisely aligned time scales and an absolutely accurate correlator.

The frequencies of the extracted signals in the B_{synth} synthesized frequency band during VLBI observations are chosen such that it could be possible to extrapolate the signal phases from one frequency to another without 2π uncertainty and to construct a linear dependence of the recorded signal phases to the frequency with the greatest possible accuracy. In one of the recommended options, the frequency spacing between adjacent channels doubles as the r channel number increases [8]. The minimum frequency interval of $w = f_{02} - f_{01}$ is chosen such that the resolution function calculated by the correlator had no additional large-amplitude spikes, which could be confused with the main peak. Under a weak signal $(q < 1)$, it can be taken that $w \approx 4\Delta F$ and $B_E \approx 0.4 B_{synth}$ [9]. In this case, for synthesizing a digital signal in the $B_{synth} = 15w + \Delta F \approx 61\Delta F$ $(B_{synth} = 976\ \text{MHz}$ frequency band at $\Delta F = 16\ \text{MHz}$ or 488 MHz at $\Delta F = 8\ \text{MHz})$, it is sufficient to place 5 channels with the ΔF bands in the RR passband of $B_R \approx 1\ \text{GHz}$. In the RT-13 radio

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telescope, the former option can be implemented using one RR channel and two channels of the standard digital signal recording system with $B_0 = 512$ MHz bands. The latter option requires one channel with a 512 MHz band.

In the synthesis of a frequency band not exceeding the IF bandwidth $\left(B_{\text{synth}} \leq B_0 \right)$, the $\sigma_\tau (M)$ mean square error of the M-channel interferometer is always greater than that of a single-channel interferometer with a B_0 recording band defined in [9] as

$$\sqrt{12}\Big/\left[2\pi\chi q B_0 \sqrt{2 B_0 t_o} \right].$$

Provided that the interferometer contains m parallel channels registering broadband IF signals and after averaging m results, the RMSD of the calculated interference group delay will be

$$\sigma_{\tau B} (m) = \frac{\sqrt{3}}{\pi\chi q B_0 \sqrt{2 m B_0 t_o}}. \tag{3}$$

Based on (2) and (3), in the synthesis of the frequency band within the passband of the receiving channel $\left(B_{\text{synth}} \approx B_R \right)$, the relation is formed:

$$\frac{\sigma_\tau (M)}{\sigma_{\tau B} (M)} = \frac{B_0}{B_E} \sqrt{m B_0 / 12 M \Delta F} \approx$$
$$\approx \frac{B_0}{0.4 B_R} \sqrt{m B_0 / 12 M \Delta F}. \tag{4}$$

This formula can be used to determine the minimum value of the synthesized frequency band, under which the accuracy of determining the interferometric delay exceed that obtained by an interferometer with broadband channels without band synthesis.

Results. The use of the digital method for extracting narrowband signals at radio telescopes provides a minor (about 4%) reduction in the sensitivity loss of the radio interferometer, without affecting the accuracy of measuring the interference group delay of the signal. When replacing analog narrowband signal extraction systems with digital systems, the

accuracy of a multi-channel radio interferometer with frequency band synthesis remains unchanged.

As follows from (4), the accuracy of determining the signal interferometric delay by a five-channel interferometer with the bands of $\Delta F = 8$ MHz in the synthesis of the $B_{\text{synth}} = B_0 = 512$ MHz frequency band will be 2.5 times lower than the accuracy of a single-channel interferometer with a band of 512 MHz. The accuracy of a five-channel interferometer with the $\Delta F = 16$ MHz bands in the synthesis of the $B_{\text{synth}} \approx B_R \approx 1$ GHz frequency band will be 30 % lower than the accuracy of the interferometer with two broadband channels overlapping the passband of the RR $\left(2 B_0 \approx B_R \right)$.

One direction in the development of VLBI (international projects VLBI 2010 and VGOS) involves the synthesis of a frequency band significantly exceeding 1 GHz. The antenna irradiator and three-channel RR of the RT-13 radio telescope with the $B_R \approx 1$ GHz bandwidths [19] allow a frequency band of up to 2.5 and 6 GHz in the X and K wavelength range, respectively, to be synthesized. This task can be achieved by using three RR channels, four ADCs of a standard signal recording system with bands of 512 MHz and a module for digital extraction of narrowband signals (Fig. 4). The signal extraction device is realized in the FPGA of the XC7K325T type. After formatting the extracted signals with the ΔF bands according to the VDIF standard, an Ethernet 10G data stream is generated and transmitted through the X2 electron-optical transceiver to the radio telescope server and to the center of correlation data processing.

For synthesizing the B_{synth} frequency band exceeding the passband of the 1 GHz receiving channel, when working with the three-channel RR of the RT-13 radio telescope, the FPGA provides 4 PPF modules, 8 BBCs with four-level sample quantizers and a VDIF formatter with output to the fiber-optic data trans-
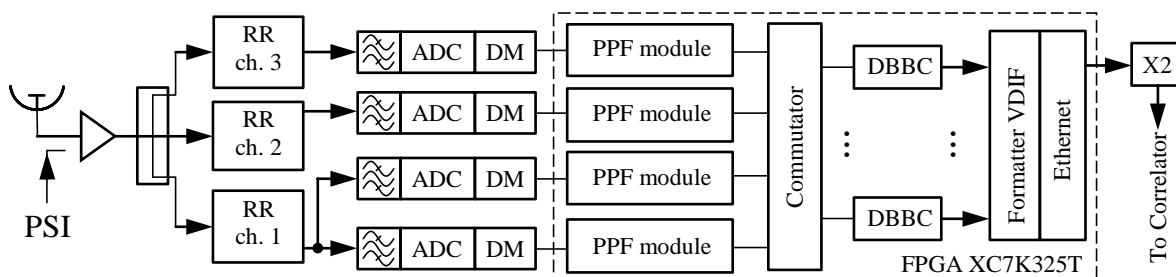

Fig. 4. System for Digitally Extracting Narrowband Signals from Output Broadband Signals of a Three Channel Receiver

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mission channel. The channel RR 1, extracting a broadband signal in the lower part of the operating frequency range, is connected to two ADCs through filters with adjacent passband (1024–1536 and 1536–2048 MHz). It is sufficient to connect one ADC with a filter of 1024–1536 MHz to the two remaining channels of the RR.

In the X frequency range, when synthesizing a frequency band up to 2.5 GHz, 2 RR channels with 1 GHz bandwidths, 3 ADCs digitizing signals with $B_0 = 512$ MHz bands, 3 PPF modules and 7 ADCs can be used (Fig. 5, *a*). Under $\Delta F = 8$ MHz and $w = f_{02} - f_{01} = 32$ MHz in the X band, up to seven signals with $f_{01}, \ldots f_{07}$ bands are extracted and recorded. In this case, the $f_x = f - f_{\min}$ frequency scale is counted from the lower boundary of the $f_{\min} = f_{01} - 0.5\Delta F$ received band. Under the previously mentioned doubling of the frequency interval, as the channel numbers of the registered signals increase, it is sufficient to use five BBCs for extracting the registered signals within the bandwidth of one RR channel $\left(B_{\mathrm{synth}} \leq 1\,\mathrm{GHz} \right)$ (Fig. 5, *a*)

Across the K frequency range, a frequency band of up to 6 GHz can be synthesized using three RR channels, four PPF modules and seven BBCs with the $\Delta F = 16$ MHz bands (Fig. 5, *b*). Under $w = 45$ MHz and a similar arrangement of signals in terms of frequency, the number of extracted signals can be potentially increased to 8. However, due to the absence of a fourth RR channel, the registration is limited to 7 signals (excluding the signal at a frequency of f_{06}) which is permissible during the frequency band synthesis.

A positive effect of the frequency band synthesis

can be obtained provided that $\sigma_{\tau 0}(M) < \sigma_{\tau B}(m)$ when

$$B_{\mathrm{synth}} > 0.72 B_0 \sqrt{\frac{mB_0}{M\,\Delta F}}. \qquad (6)$$

When using three receiver channels of the RR and four PPF modules, the synthesis of the frequency band in an eight-channel interferometer with the bands of $\Delta F = 8$ MHz can theoretically improve the accuracy of determining interferometric delays (compared with three autonomous broadband channels) in synthesizing the $B_{\mathrm{synth}} > 5.1$ GHz frequency band. This is possible in the K frequency range (28...34 GHz). When using two RR channels and three PPF modules, condition (6) for an eight-channel interferometer with $\Delta F = 8$ MHz bands is satisfied at $B_{\mathrm{synth}} > 1.8$ GHz. This mode can be implemented in any of the considered ranges (X or K).

When synthesizing an extremely wide frequency band $\left(B_{\mathrm{synth}} > B_{\mathrm{R}} \right)$ it becomes more difficult to align signal delays in the receiving channels of the radio telescope while providing a high accuracy of phase function linearization versus frequency during data correlation processing. Apparently, as compared to an interferometer recording broadband IF signals, no significant improvement in the accuracy of VLBI measurements by a narrowband multichannel interferometer with a frequency band synthesis should be expected.

When extracting narrowband signals exclusively from the RR passband $\left(B_{\mathrm{synth}} \leq B_{\mathrm{R}} \right)$ the interferometer sensitivity and the accuracy of determining the interferometric delay are reduced in comparison
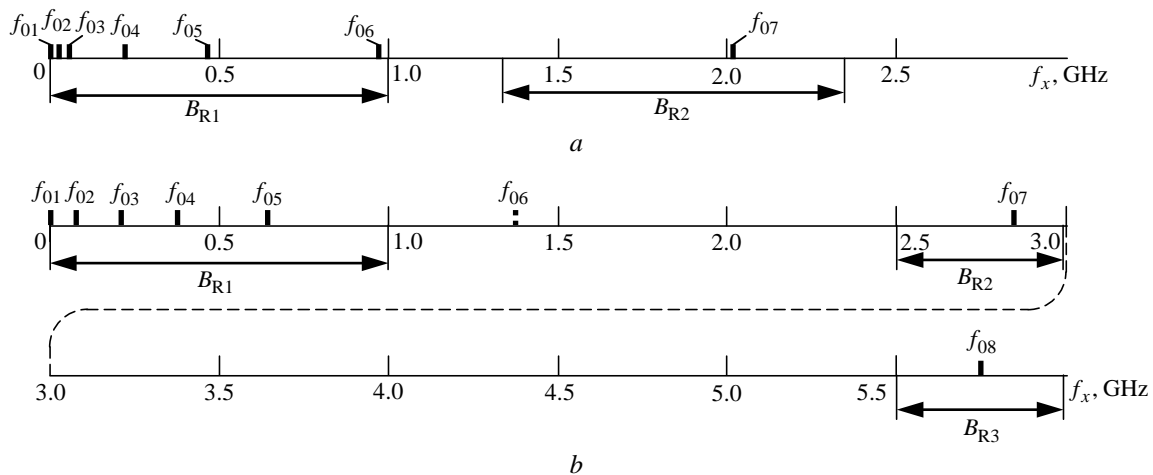
Fig. 5. Variants of the Frequency Distribution of the Recorded Signals in the Frequency Bands X (*a*) and K (*b*)

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with the interferometer operating in the registration mode of the broadband IF signals. However, in the mode of registering several ΔF narrowband signals, the total stream speed of data transmitted to the correlation data processing center decreases significantly, thus permitting the connection of the radio telescope to VLBI networks using narrowband signal correlators [8]. For example, in an interferometer recording 8 signals with 16 MHz bands (see Fig. 5, *b*), the total speed of the information stream under four-level quantization is 512 Mbit/s. An interferometer recording 4 signals with 512 MHz bands provides a stream with a total speed of 8192 Mbit/s. An increase in the speed of the data stream leads to stricter requirements for radio telescope servers, fiber-optic communication lines between radio telescopes and data processing centers, as well as VLBI correlators.

Discussion. According to the obtained results, a conclusion can be made about the advisability of installing digital signal conversion systems on the RT-32 and RT-70 (Ussuriysk) radio telescopes instead of the standard R1002M DAS with analogue extraction of narrowband signals. This replacement will improve slightly the sensitivity of the interferometer (approximately 4%), at the same time as leaving the accuracy of measuring the interferometric

group delays of the received signals practically unchanged. However, in digital systems, the complex channels for amplifying and transmitting broadband analog IF signals are replaced with fiber-optic digital signal transmission lines. Therefore, in terms of performance and reliability, digital systems provide distinct advantages.

In addition, the use of the developed digital system allows radio telescopes to be operated in the registration mode of broadband IF signals, thus significantly increasing the sensitivity of interferometers and expanding the list of available reference sources used in VLBI observations.

After completion of the ongoing development of antenna irradiators and ultra-wideband receivers for RT-32 radio telescopes, it will be possible to synthesize frequency bands wider than 1 GHz and to improve the accuracy of VLBI measurements.

The developed method for a digital extraction of narrowband signals from the IF bandwidth is applied in a new multifunctional signal conversion and registration system aimed at upgrading existing radio telescopes of the Russian Quasar VLBI Network and equipping novel compact radio telescopes [24]. This system is capable of rapidly switching the modes of radio astronomy observations.

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Information about the authors

Nikolai E. Kol'tsov, Dr. Sci. (Eng.) (1982), Professor (1985), Honored Scientist of RF (2001), the chief researcher of the Institute of Applied Astronomy of the RAS, Professor of the Department of Radio Astronomy of Saint Petersburg Electrotechnical University. The author of more than 140 scientific publications. Area of expertise: radio astronomy, instrumentation, radio interferometry and radiometry.
Address: Institute of Applied Astronomy of the Russian Academy of Sciences, Kutuzova Embankment, 10, St. Petersburg 191187, Russia
E-mail: reltaspb@yandex.ru
https://orcid.org/0000-0002-9961-1965

Sergei A. Grenkov, Cand. Sci. (Eng.) (2009), Researcher of the Institute of Applied Astronomy of the RAS. The author of more than 50 scientific publications. Area of expertise: processing techniques of radio astronomy signal; computer control systems.
Address: Institute of Applied Astronomy of the Russian Academy of Sciences, Kutuzova Embankment, 10, St. Petersburg 191187, Russia
E-mail: skynet81@yandex.ru
https://orcid.org/0000-0003-1577-9638

Leonid V. Fedotov, Dr. Sci. (Eng.) (2016), Leading Scientist of the Institute of Applied Astronomy of RAS. Author of more than 100 scientific publications. Area of expertise: very long base interferometry, data acquisition systems, design of radio astronomy instrumentation.
Address: Institute of Applied Astronomy of the Russian Academy of Sciences, Kutuzova Embankment, 10, St. Petersburg 191187, Russia
E-mail: lprsflv@mail.ru
https://orcid.org/0000-0001-9872-4215

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Информация об авторах

Кольцов Николай Ефимович – доктор технических наук (1982), профессор (1985) кафедры радиоастрономии Санкт-Петербургского государственного электротехнического университета "ЛЭТИ" им. В. И. Ульянова (Ленина), заслуженный деятель науки РФ (2003), главный научный сотрудник Института прикладной астрономии РАН. Автор более 140 научных работ. Сфера научных интересов – радиоастрономия; приборостроение; радиоинтерферометрия и радиометрия.
Адрес: Институт прикладной астрономии Российской академии наук (ИПА РАН), наб. Кутузова, д.10, Санкт-Петербург, 191187, Россия
E-mail: reltaspb@yandex.ru
https://orcid.org/0000-0002-9961-1965

Гренков Сергей Александрович – кандидат технических наук (2009), научный сотрудник Института прикладной астрономии РАН. Автор более 50 научных работ. Сфера научных интересов – цифровые системы обработки радиоастрономических сигналов; системы компьютерного управления.
Адрес: Институт прикладной астрономии Российской академии наук (ИПА РАН), наб. Кутузова, д.10, Санкт-Петербург, 191187, Россия
E-mail: skynet81@yandex.ru
https://orcid.org/0000-0003-1577-9638

Федотов Леонид Васильевич – доктор технических наук (2016), ведущий научный сотрудник Института прикладной астрономии РАН. Автор более 100 научных работ. Сфера научных интересов – радиоинтерферометрия со сверхдлинными базами, системы преобразования сигналов, проектирование радиоастрономической аппаратуры.
Адрес: Институт прикладной астрономии Российской академии наук (ИПА РАН), наб. Кутузова, д.10, Санкт-Петербург, 191187, Россия
E-mail: lprsflv@mail.ru
https://orcid.org/0000-0001-9872-4215

18   Сравнение радиоинтерферометров с аналоговыми и цифровыми системами
выделения регистрируемых сигналов
Comparison of Radio Interferometers with Analog and Digital Extraction of Recorded Signal