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Testing of the Ground-Based VLBI Stations Yevpatoria–Simeiz–Pushchino of the RadioAstron Mission

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Abstract—Results are presented of the ground-based VLBI experiments conducted at RadioAstron frequencies between the VLBI sites Simeiz (RT-22)–Yevpatoria (RT-70) and Simeiz (RT-22)–Pushchino (RT-22).

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1. INTRODUCTION

In 2009–2010, ground-based VLBI experiments were organized within the RadioAstron mission. The experiments were conducted at different frequency and spectral modes of the mission, namely, in the upper and lower sidebands and two circular polarizations (right and left) at wavelengths of 1.35 and 6 cm using the Pushchino and Simeiz interferometric sites.

In September 2011, the Astro Space Center, Lebedev Physical Institute (Moscow), Crimean Astrophysical Observatory (CrAO, Simeiz), Institute of Radio Astronomy (Kharkiv), and National Space Facilities Control and Testing Center (Yevpatoria) jointly conducted ground-based VLBI experiments using the antennas RT-22 in Simeiz and RT-70 in Evpatoria at wavelengths of 6 and 18 cm. The Simeiz interferometric site was previously fitted with the necessary instruments and participated in many radio interferometric experiments as part of the global VLBI network and European EVN network. It could be used as a reference site for the Simeiz–Yevpatoria baseline. The length of the Simeiz–Yevpatoria baseline is about 110 km. The maximum angular resolution at 18 and 6 cm is 0.33 and 0.18 arcsec in the north–south direction and 1.2 and 0.7 arcsec in the east–west direction. The length of the Pushchino–Simeiz baseline is 1100 km, and the maximum resolution in the north–south direction at a wavelength of 1.35 cm is about one millisecond of arc.

2. GENERAL PARAMETERS OF THE GROUND-BASED VLBI TESTS

The parameters of the RT-22 radio telescope at Pushchino (effective area and receiving equipment noise) were worse than at Simeiz; therefore, in terms of effectiveness, the former could simulate the onboard radio telescope of *Spektr-R.* RT-22 at Pushchino was fitted with receiving equipment, digital video converters, RDR-1 (RadioAstron Data Recorder), and a hydrogen frequency and time standard.

The equipment of RT-22 (Simeiz) was upgraded, and modern observation techniques were developed for working in the global VLBI network. The RT-22 radio telescope was fitted with equipment necessary for VLBI studies of space objects in the centimeter and millimeter spectral regions using specialized Mark 5A and Mark 5B+ high-speed digital data recorders.

RT-70 at Yevpatoria had high-sensitive receiving equipment at wavelengths of 6 and 18 cm, digital video converter, and RDR-1. In addition, the Simeiz and Yevpatoria VLBI sites were equipped with highly stable hydrogen frequency standards with a relative frequency stability of 10^{-14} and pegging of the local time scales to the GPS scale with an accuracy better than 10^{-8} s.

3. SIMEIZ–PUSHCHINO INTERFEROMETERS

3.1. Experiment at 6 cm Wavelength. The first VLBI observation session was conduced in October 2009 at a wavelength of 6 cm. Data were recorded in the 4 MHz band using Mark 5A disk-based recorders at Simeiz and RDR-1 (Astro Space Center; ASC) at Pushchino (in the PDF format). The two systems were synchronized using hydrogen frequency and time standards and a time synchronization system. Two sources—3C 454.3 and S 0528+134 (Nimfa)—were selected for observation. The first one, a stronger source, was used to refine the phase characteristics and offset parameters at each observation site. The second one, a fainter object, was used to assess the coherent averaging interval. The parameters of the radio telescopes are given in Table 1.

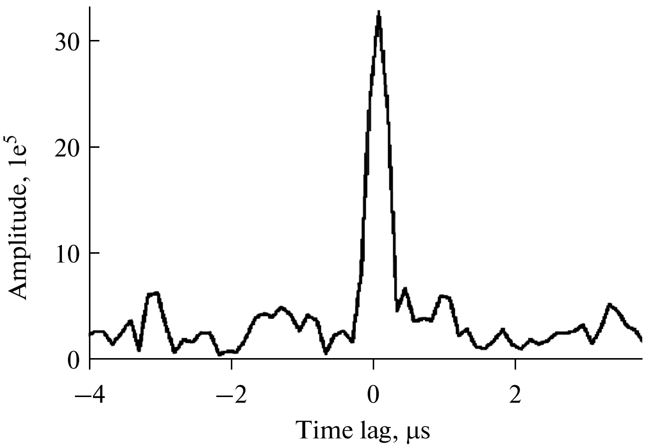

Fig. 1. Simeiz–Pushchino interferometer: implementation of coherent integration time. The signal-to-noise ratio is about 30. Correlated flux density is about 100 mJy.

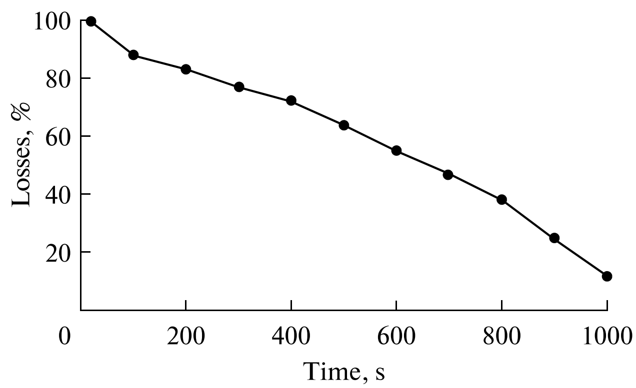

Fig. 2. Integration losses over the Simeiz–Pushchino baseline at 6 cm wavelength.

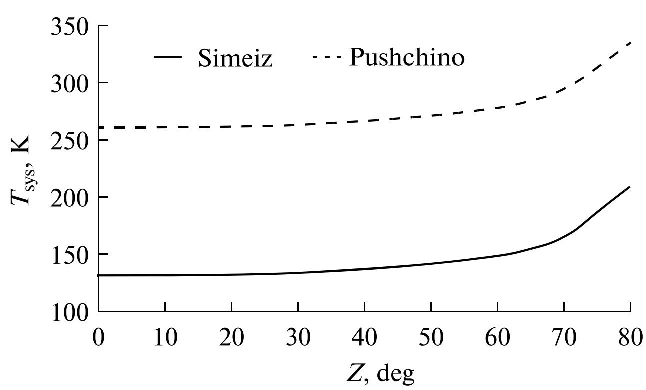

Fig. 3. Dependence of the system temperature on the site angle for the Simeiz and Pushchino stations.

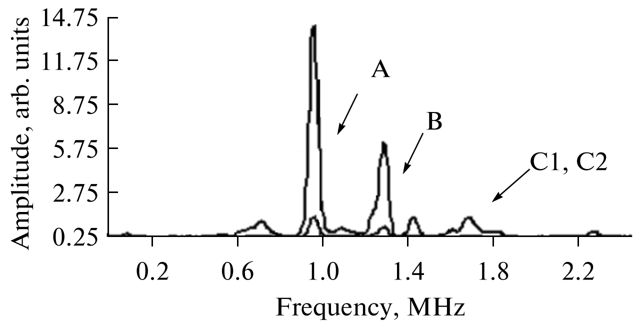

Fig. 4. Autocorrelation spectra at Simeiz and Pushchino for the source Orion KL.

During the second VLBI session at a wavelength of 6 cm, which was conducted in July 2010 using the modernized equipment of RT-22 at Pushchino, scientists estimated the coherent integration time under a project task within the RadioAstron mission. The observations were focused on the sources 3C 273 and 1055 + 018. The latter, a fainter source, was used to estimate the maximum achievable coherent averaging interval for interferometric observations.

Figure 1 shows the response for the radio source 1055 + 018 over the Simeiz–Pushchino baseline with a coherent integration time of 400 s.

During this VLBI session, the radio telescope at Pushchino simulated the sensitivity of the space antenna aboard the RadioAstron mission. The coherence interval of the Simeiz–Pushchino interferometer at a wavelength of 6 cm was about 700 s (Fig. 2 shows signal integration losses depending on time over the Simeiz–Pushchino baseline).

3.2. Experiment at 1.35 cm Wavelength. The minimum wavelength for observations planned within the RadioAstron was 1.35 cm. To verify the model parameters of the ground-based segment in this wavelength range, a radio interferometry session was conducted in March 2010 between the said radio telescopes in the continuous spectrum and in the H_2O line near the frequency 22.235 GHz.

The parameters of the stations are given in Table 2. The system's temperature T_{sys} takes into account the contribution of the Earth's atmospheric temperature toward the zenith. The dependence of T_{sys} on the site angle Z for the Simeiz and Pushchino stations is shown in Fig. 3.

Figure 4 shows the autocorrelation spectra for the source Orion KL, which was recorded at Simeiz and Pushchino for the date May 8, 2010 and 13:00 UTC. The band of the single spectral channel $\Delta F = 3.9$ kHz; the accumulation time was 1 min.

The radial velocities and frequencies of the components were:

Component A: $v = +12.2$ km/s (0.97 MHz);

Component B: $v = +7.7$ km/s (1.30 MHz);

Table 1

Antenna	Recording system	A_{eff}, m^2	T_{sys}, K	SEFD, Jy
Pushchino	RDR-1	100	170	4680
Simeiz	Mark 5A	230	80	950
Space telescope	RDR-1	40	70	4800

Components C1 and C2: v = +2.5 km/s and 0.5 km/s, respectively (1.7 and 1.85 MHz, respectively).

Figure 5 shows the cross-correlation spectrum for the source Orion KL and date May 8, 2010, 13:15 UTC, taking into account data processing losses and atmospheric absorption.

It is evident from Fig. 5 that correlated responses were recorded with high reliability from components C1 and C2 with amplitudes of 0.018 and 0.009 at frequencies of approximately 1.7 and 1.85 MHz.

Table 3 presents the data on the correlated amplitude for the spectral components A and B, which were corrected for atmospheric absorption, for three observation days.

Table 4 shows the antenna temperature, correlated flux, and luminosity function for the spectral components A, B, C1, and C2 of Orion KL.

The values of the luminosity function suggest that the size of the said spectral components in the H_2O radio emission spectrum in Orion KL exceed 20 ms.

3.3. Spectral and Polarization Observations of Orion KL in the Water Vapor Line at a Wavelength of 1.35 cm at the Simeiz Station. After completing the VLBI observation sessions over the Simeiz–Pushchino baseline, spectral polarization observations of Orion KL were conducted in the single mode at the Simeiz station at a wavelength of 1.35 cm. The observations used the recently developed and implemented receiver with a frequency resolution of 0.5 kHz based on the parallel-type Fourier spectrum analyzer. A distinctive feature of the receiver is a polarizer operating on the basis of the Faraday effect. The polarizer is controlled automatically.

The parameters of the radio telescope–radiometer system were measured using a Mark 5B+ recording system and the software designed at the CrAO Laboratory of Radio Astronomy. The system's noise temperature was determined for the sources with known fluxes in the given range (DR 21, Vir-A, Cyg-A, and Tau-A) and calibration steps.

Figure 6 presents the measured spectra of Orion KL for polarizer settings at the (a) maximum and (b) minimum of the polarized signal.

It is evident from Fig. 6 that at present the source's spectrum consists of seven main components. The emission of the component with the radial velocity of 7.7 km/s shows linear polarization of about 70% with a polarization plane position angle of about –20°. The spectral components A (12.2 km/s), C1 (2.5 km/s), and C2 (0.5 km/s) show no linear polarization.

Table 2

Name	Simeiz	Pushchino
Antenna, m	$D = 22$	$D = 22$
A_{eff}, m^2	230	90
Aperture efficiency (%)	50	20
T_{sys} ($z = 0^{\circ}$), K	130 (with atmosphere)	260 (with atmosphere)

Table 3

	Corr. amplitude (corrected for atmosphere and 1-bit quantization)		(B–A), Hz
Observation day	A	B	
83	0.0410	0.0129	0.232
84	0.0380	0.0154	0.243
85	0.0420	0.0146	0.254
Average	0.040	0.014	0.243

In the first activity epoch (1979–1987), the degree of source emission polarization was 60–70%, and the polarization plane position angles ranged from ~–15 for high-velocity details to ~–40 for low-velocity ones, but was virtually stable over time for each individual detail [2]. In November 1991, the source was in a low-

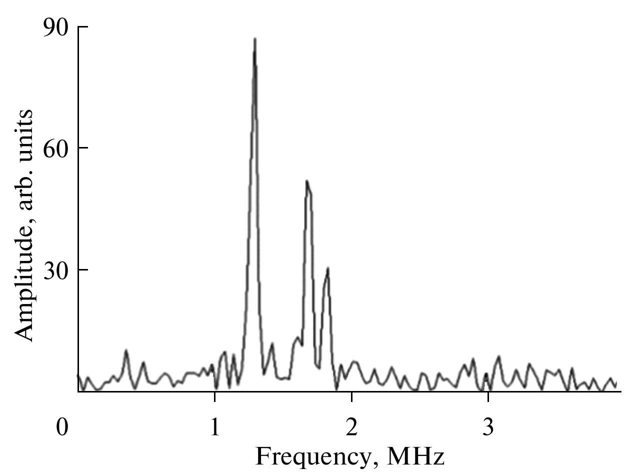

Fig. 5. Cross-spectrum of the radio source Orion KL.

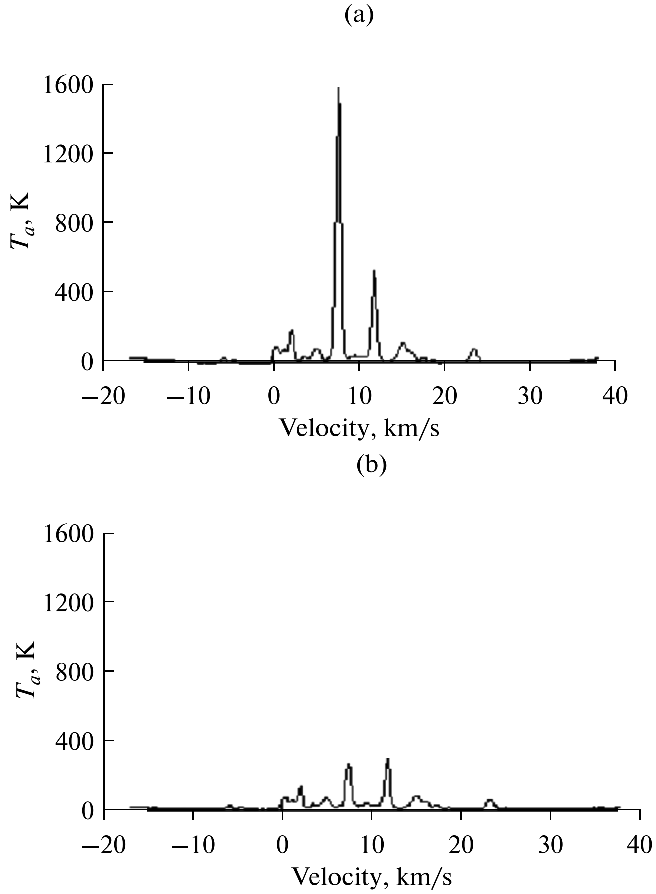

Fig. 6. Spectra of Orion KL.

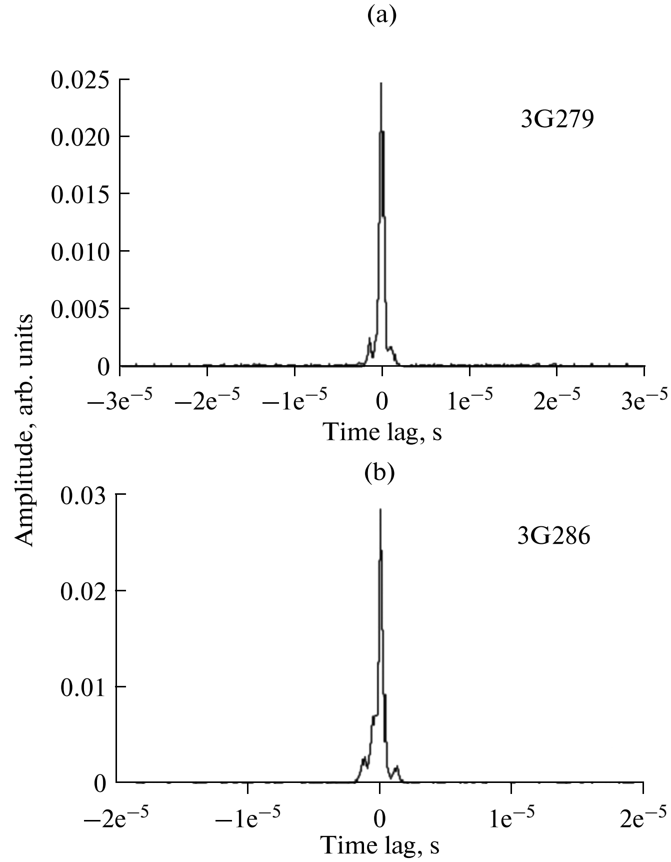

Fig. 7. Cross-correlation responses for the radio sources 3C279 and 3C286.

activity state. The degree of linear polarization at the maximum of the line with a radial velocity of 7.2 km/s decreased to 43%. The polarization plane position angle was −28° [3].

The VLBI observations conducted in a close epoch over the Simeiz–Pushchino baseline were used to identify a number of active zones in the Orion KL gas–dust complex. The sizes of the spectral components in the H_2O radio emission spectrum of Orion KL exceed 20 ms.

4. YEVPATORIA–SIMEIZ INTERFEROMETER

4.1. VLBI Experiment at 6 cm Wavelength. The observations over the Simeiz–Yevpatoria baseline were conducted in 2011 at a wavelength of 6 cm. The data were recorded using Mark 5A disk-based recorders at Simeiz and ASC RDR-1 (in the PDF format) in Yevpatoria. The systems at the two sites were synchronized using hydrogen frequency and time standards and time synchronization system. Six sources were selected for observation: 3C286, 3C279, 3C454.3, DA193, 0420-014, and DR21 (for calibration). The said objects allowed researchers to assess the coherence time of the Simeiz–Yevpatoria interferometer and calibrate the complex amplification coefficients for antenna elements. The averaged parameters of the radio telescopes at 6 cm wavelength are given in Table 5.

Figures 7 and 8 show the correlation responses at 6 cm wavelength for the sources 3C279, 3C286, and 3C454.3, respectively, with a time averaging constant

Table 4

Spectral component	T_a, K correlated temperature in 16 kHz band	Correlated flux, Jy	Luminosity function
A	19.3	370	0.015
B	17.4	330	0.025
C1	8.7	170	0.060
C2	4.4	80	0.060

Table 5

Antenna	Recording system	A_{eff}, m^2	T_{sys}, K	SEFD, Jy
Yevpatoria (RT-70)	RDR-1	2300	40	50
Simeiz (RT-22)	Mark 5A	230	70	840
RadioAstron (SRT-10)	RDR-1	40	70	4800

Table 6

Radio source	Correlation amplitude	Correlated flux density, Jy	Full flux density at 6 cm wavelength, Jy
3C279	4.44e^{-2}	9.90	13.0
3C286	2.35e^{-2}	5.3	6.3
3C454.3	3.16e^{-2}	7.1	16.0
DA193	2.52e^{-2}	5.7	6.1

Table 7

Antenna	Recording system	A_{eff}, m^2	T_{sys}, K	SEFD, Jy
Yevpatoria	RDR-1	2300	40	50
Simei	Mark 5A	230	70	840
Space telescope	RDR-1	40	50	3400

of 300 to 440 s. The resulting signal-to-noise ratio was above 400. The high coherence time of the interferometer allowed complex integration at intervals larger than 400 s and ensured a low noise level. Moreover, these parameters of the interferometer allowed researchers to estimate, with high accuracy, the complex amplitude of interference.

Table 6 shows the estimates for the correlated flux densities at 6 cm wavelength, which were calculated from the measured amplitudes of correlated response at SEFD (Simeiz–Yevpatoria) of 225 Jy.

4.2. Experiment at 18 cm Wavelength. To measure the model parameters of the ground-based segment in this wavelength range, an interferometric session was conducted in September 2011 between the radio telescopes RT-70 (Yevpatoria) and RT-22 (Simeiz) at a wavelength of 18 cm.

Six sources were selected for observation: 3C286, 3C279, W75N, W3(OH), PSR0329, and 19DR21. Apart from the tasks for 6 cm wavelength, adding the sources W75 and W3(OH) to the observation program allowed researchers to estimate the systems' parameters in observations of hydroxyl OH spectral lines. The parameters of the stations at 18 cm wavelength are given in Table 7.

The measured results for the autospectrum of W3(OH) in Yevpatoria in the right circular polarization are shown in Fig. 9a and at a frequency of 1665.5 MHz in the left circular polarization (Fig. 9b). The cross-spectrum of W3(OH) Yevpatoria–Simeiz is shown in Figs. 9c (left circular polarization) and 9d (right circular polarization).

It is evident from the figures that the sensitivity allowed for reliable assessment of the W3(OH) spectra, including in the circular polarization.

Figure 10 shows, as an example of the processing of data at 18 cm wavelength in continuum, a correlated response depending on the time lag for the source 3C279 in LCP. The time averaging constant is $\tau = 600$ s.

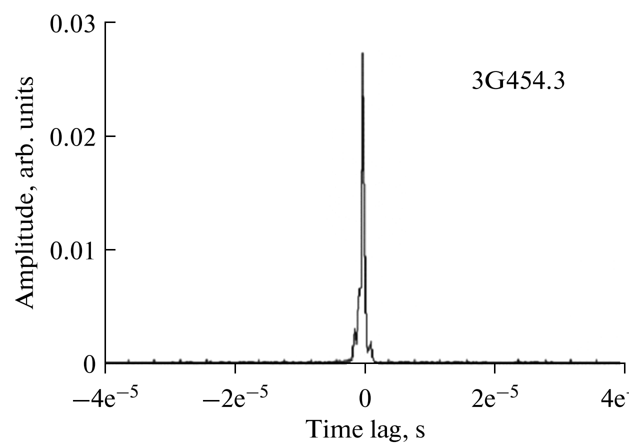

Fig. 8. Cross-correlation response for the radio source 3C454.3.

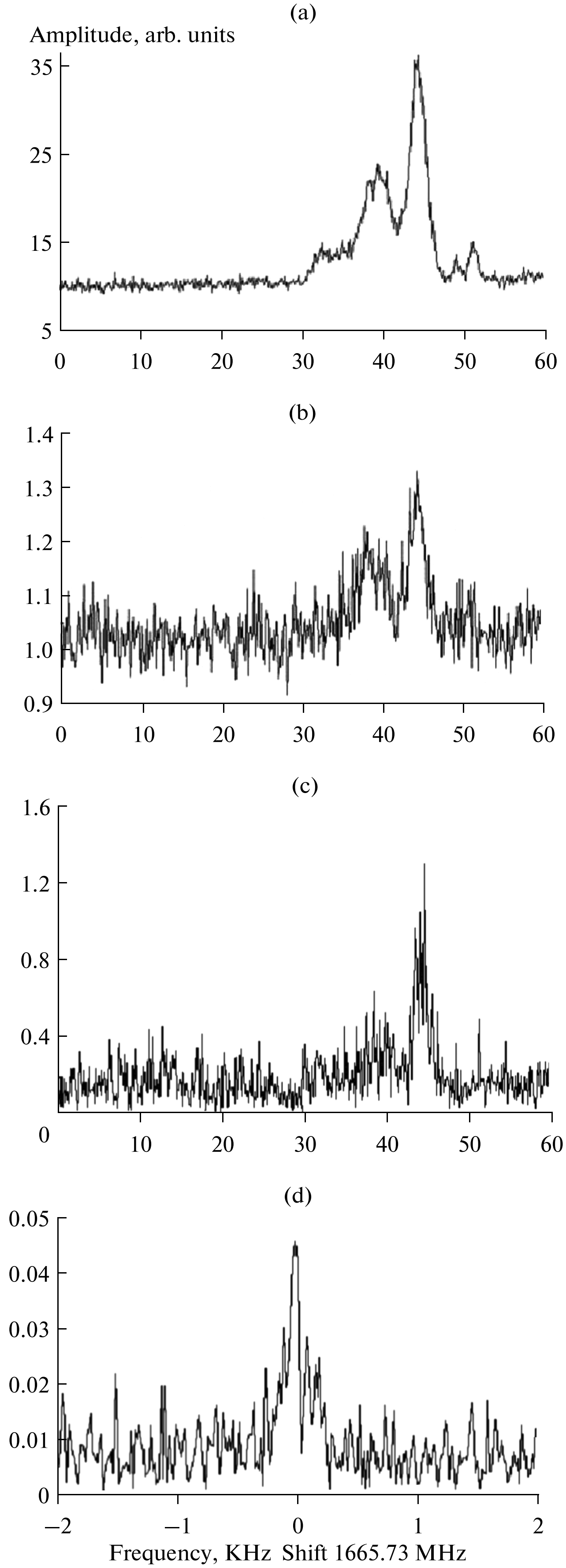

Fig. 9. Autocorrelation spectra and cross spectra of W3(OH) at Yevpatoria.

The correlated flux is about 1.5 Jy provided that the full density of the flux is 11 Jy. The position of the response peak for a time lag of 0 μs shows the high accuracy of the lag used in the processing of the model lag for the interferometric stations.

Analysis of the correlated data in continuum showed a high degree of coherence of the Simeiz–Yevpatoria interferometer (the so-called coherence time), which allows coherent integration at accumulation times under 600 s at a wavelength of 6 cm and above 900 s at a wavelength of 18 cm, making use of the high sensitivity. Thus, at a 6-cm wavelength, the fluctuation sensitivity (standard deviation) at a maximum coherent integration time (600 s) is approximately 3 mJy.

CONCLUSIONS

The ground-based tests within the RadioAstron at wavelengths of 18, 6, and 1.35 cm allowed us to obtain and calibrate the amplitudes and phases of cross-correlation functions and their time dependences. The tests showed consistency between the calculated parameters of the radio telescope's equipment and their suitability for further interferometric sessions. The following conclusions were drawn from the results of data processing with the ASC correlator (Lebedev Physical Institute):

(1) The sensitivity parameters and coherence properties of the interferometers implemented at wavelengths of 18, 6, and 1.35 cm are consistent with the calculated results for the technical parameters of the antenna systems used in the project.

(2) The interferometric sessions suggest that RT-70 (Yevpatoria) is suitable for participation in ground–space experiments at wavelengths of 6 and 18 cm.

(3) The experiment emulating the parameters of the onboard radio astronomy complex suggests that the Simeiz-SRT10 interferometer can detect signals with a correlated flux of about 100 mJy at a coherent integration time of around 10 s, signal-to-noise ratio of around 10, and signal band of 4 MHz.

(4) The LVBI experiment at a 1.35-cm wavelength between the Simeiz and Pushchino stations revealed the possibility of the further use of the said interferometer for spectral observations in the water vapor line.

(5) The implementation of a spectral polarimetric Fourier analyzer at the Simeiz station allowed systematic comprehensive polarization studies of star forming regions.

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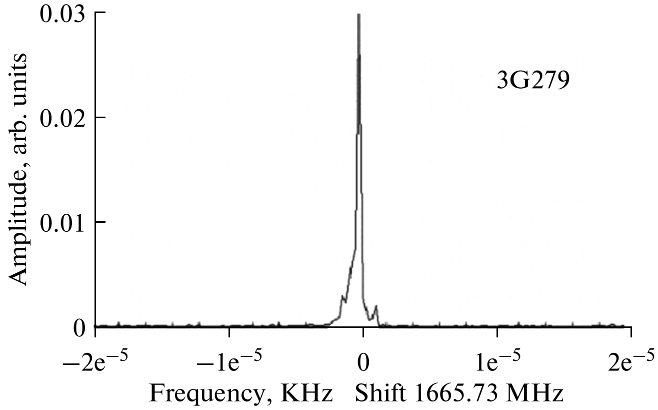

Fig. 10. Cross-correlation spectrum of the radio source 3C279, 18 cm.

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