PROCEEDINGS OF SCIENCE

The Methods and a Hardware-Software Complex for Measuring the Stability of Radio Telescope Receiving Systems

Y.V. Vekshin[a,*]

[a] *Institute of Applied Astronomy of the Russian Academy of Sciences, St. Petersburg, Russia*

E-mail: yv.vekshin@iaaras.ru

Radio telescope sensitivity in radiometric observations and the accuracy of signal delay measurements in radio interferometric observations are largely determined by the amplitude and phase instability of the receiving equipment. To identify the sources of this instability, an urgent task is to create methods and equipment to measure the instability of the receiving system as a whole and its individual stages in particular. The paper presents a developed hardware-software complex, methods, and investigation of the amplitude and phase stability of the "Quasar" VLBI Network radio telescope receiving systems. The main sources of instability of the receiving systems and ways to improve their stability are determined. The measured RT-13 radio telescope characteristics obtained by the created hardware-software complex are presented. A method to determine the optimal signal averaging time of a radio interferometer has been developed, which reduces the error in determining the UT1−UTC corrections.

The Multifaceted Universe: Theory and Observations - 2022 (MUTO2022)
23-27 May 2022
SAO RAS, Nizhny Arkhyz, Russia

*Speaker

© Copyright owned by the author(s) under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (CC BY-NC-ND 4.0).

https://pos.sissa.it/

PoS(MUTO2022)003

1. Introduction

Radio telescope sensitivity and the accuracy of radio astronomical observations are determined by the instability of receiving system parameters. Fluctuations of receiver output signals have a power spectral density of the form $1/f^{\alpha}$, which limits noise reduction with increasing averaging time of the receiver output signal. A radio astronomical receiver is a multi-stage device with frequency conversion. To identify the sources of instability, it is necessary to create methods and equipment that allow us to measure the instability not only of the receiving system as a whole but also of its individual stages. So, recording of the signal is required not only in the intermediate frequency bands, in which regular recording systems operate, but also directly in the microwave frequency bands of the receiver input stages (in this case signal levels and frequency bands are greatly variable). Special equipment and software are needed to automate the measurements of different signals in different receiver stages at different time intervals and to process them. The identification and elimination of instability sources (or reduction of their influence) increase the sensitivity of a radio astronomical receiver. The aim of this work is to create a hardware-software complex and methods to determine the main sources of instabilities in the radio telescope receiving systems of the "Quasar" VLBI (Very Long Baseline Interferometry) Network and the ways to increase their sensitivity.

2. Requirements for the hardware-software complex

Three different types of the receiving systems of the "Quasar" VLBI Network [1] were investigated in the work: the S/X receiving systems of the RT-32 radio telescope and the tri-band (S/X/Ka) and broadband (3–16 GHz) receiving systems of the RT-13 radio telescope [2]. The receiving systems have a cryogenic unit, cooled to temperatures below 20 K, containing low-noise amplifiers, and for RT-13 the feed horn. Frequency converter units transfer the spectrum of a microwave signal to the intermediate frequency band. There are also additional amplification units. The receiving systems and their individual units differ significantly from each other: in terms of operating frequencies from 0.1 to 34 GHz, signal powers at the output of the units P_{out} from −60 dBm to +10 dBm, and also by the number of channels and design. To conduct the research, it is necessary to create a hardware-software complex that makes it possible to measure the stability of the output power, gain, phase, group delay of the receiving systems and their individual units.

The requirements for the amplitude stability measurement accuracy are based on the ratio of sensitivity ΔT to system noise temperature T_{sys}. For bandwidth $\Delta f = 1$ GHz and averaging time $\tau = 0.1$ s, $\Delta T/T$=10^{-4}. The gain instability $\Delta G/G$ should be measured with the same accuracy, while the relative error of the meter $\Delta P_{met}/P_{met}$ should be better than $3 \cdot 10^{-5}$ (in this case, the contribution of the meter error to the measurement result will be less than 5%).

$$\frac{\Delta T}{T_{sys}} = \frac{\Delta P_{out}}{P_{out}} = \sqrt{\frac{1}{\Delta f \cdot \tau} + \left(\frac{\Delta G}{G}\right)^2 + \left(\frac{\Delta P_{met}}{P_{met}}\right)^2}. \quad (1)$$

The measurement accuracy of the receiver group delay is determined by the required accuracy of the determination of UT1−UTC corrections by the interferometer with an RMS error less than

PoS(MUTO2022)003

20 μs. To achieve this, it can be shown that the RMS error of group delay of the interferometer signal should not exceed 20 ps.

The theoretical delay error σ_{tSNR} at the correlator output depends only on the *SNR* and bandwidth Δf [3].

$$\sigma_{tSNR} = \frac{\sqrt{12}}{2\pi \cdot \Delta f \cdot SNR}. \tag{2}$$

The real delay error σ_t depends on the signal delay instability in radio telescope equipment σ_{tEq_i}, $i = 1...N$, N=12, including 2 receivers, 2 acquisition systems, 2 syncronization systems, 2 cable sets, correlator, atmospheric fluctuations, and source structure.

$$\sigma_t = \sqrt{\sigma_{tSNR}^2 + \sum_{i=1}^{N} \sigma_{tEq_i}^2}. \tag{3}$$

The mean SNR at the correlator output, based on the RT-13 observed results, is about 100, bandwidth Δf = 512 MHz, then from (2) σ_{tSNR}=10 ps. Assuming the same and independent delay instabilities and taking into account the calculated σ_{tSNR}, in order to achieve the requirement of a group delay RMS error less than 20 ps, from (3) the receiver delay instability should be less than 5 ps. So, the measurement error of the meter should be better than 1.5 ps.

The SNR of a radio interferometer decreases depending on the phase instability of receiving systems: $SNR \propto 1 - 0.5 \cdot \sigma_{\Delta\phi}^2$ [3], where $\sigma_{\Delta\phi}$ is the standard deviation of the phase difference of two receiving systems. The SNR decrease is 1% when $\sigma_{\Delta\phi} = 8°$, or 5.7° for one receiving system. So, the phase meter error should be better than 2°.

3. Stability investigation method

The instability (deviation from the average value) is considered as noise with different spectral components. The Allan variance analysis [4] has been used to identify the noise types and their levels in output receiver signals.

The dependence of the Allan variance on averaging time $\sigma_A^2(\tau)$ is associated with the noise power spectral density $S(f) = h_\alpha / f^\alpha$: $\sigma_A^2(\tau) = K_\alpha \cdot \tau^{\alpha-1}$, where h_α, K_α are noise-type-dependent coefficients. The Allan variance plot in log-log scale allows you to determine the noise type by the slope: white noise (10 dB/decade decrease), flicker noise (constant), random walk noise (10 dB/decade increase), and drift (20 dB/decade increase). The Allan variance analysis also makes it possible to determine the stability interval of the receiver: the optimal averaging time of the output signal at which the minimum noise level is achieved.

The standard deviation of the relative fluctuations in the receiver output power P_{out} is determined by formula (1). In that formula G is the total receiver gain, which is the product of single stage gains: $G = G_1 \cdot G_2 \cdot G_3$; ΔG are gain fluctuations. It can be shown [5] that the total gain relative fluctuation is the sum of the relative fluctuations of individual stage gains:

$$\frac{\Delta G}{G} = \frac{\Delta G_1}{G_1} + \frac{\Delta G_2}{G_2} + \frac{\Delta G_3}{G_3}. \tag{4}$$

PoS(MUTO2022)003

The variance of the total gain relative fluctuation σ_G^2 is the sum of the variances of individual-stage gain relative fluctuations $\sigma_{G_i}^2$ and the mutual covariances K_{ij} of their fluctuations:

$$\sigma_G^2 = \sigma_{G_1}^2 + \sigma_{G_2}^2 + \sigma_{G_3}^2 + 2K_{12} + 2K_{23} + 2K_{13}. \tag{5}$$

The measurements of the gain fluctuations of receiving system stages were performed with the measurement setup, its scheme presented in Fig. 1. A harmonic signal from a generator was passed to a low-noise amplifier in the cryo unit through a directional coupler, wherein a special wide-aperture match load was mounted on the cryo unit input (horn feed). The input and output power of all units was controlled by power sensors connected to power meters. The power meter indications P_i (samples) were long-term recorded on a PC. The gain fluctuations of receiver stages were calculated as $G_i = P_{i+1}/P_i$. So, this measurement setup allows us to simultaneously measure the gain of all units, and it is important when studying correlations between units.

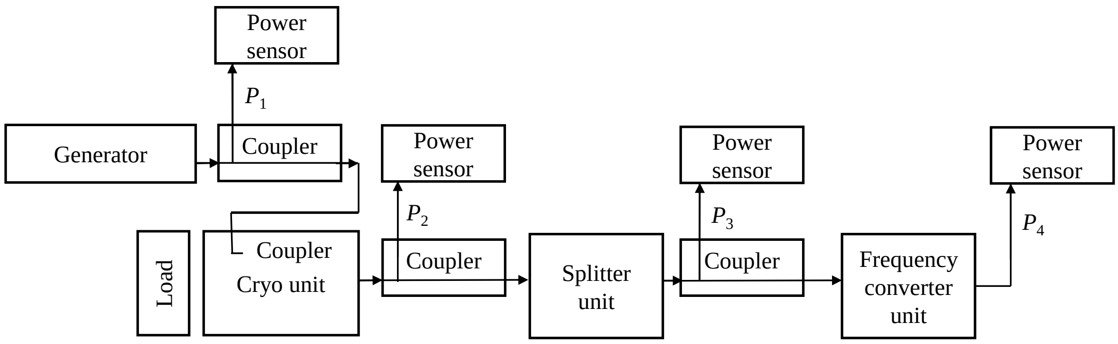

Figure 1: The amplitude stability measurement scheme of a broadband receiving system

4. The hardware-software complex

The hardware-software complex has been developed to study the stability of the output power, gain, phase, and group delay of the receiving system as a whole and its individual stages in particular. The operating characteristics of the laboratory instruments manufactured by the world leading companies were analyzed, and instruments were selected that met the requirements formulated in section 2. To automate the measurements, software has been developed that provides visualization, continuous long-term recording of measurement results on a PC, and their subsequent processing. The instrument control software has been developed in LabVIEW based on the VISA protocol.

To study the output power and gain stability, a power meter Keysight N1914A with 8487D power sensors was applied. The frequency range of the meter up to 50 GHz covers all operating bands of the studied receivers. In case of radio frequency interference (RFI) in the S band (e.g. from telecommunication systems), it is advisable to carry out spectral-selective power recording in a narrower frequency band that does not contain the RFI. The Keysight N9030A spectrum analyzer was used for this task. In this case, it is necessary to perform the Allan variance correction for signals with “dead time” [6].

The phase and group delay stability of receiving systems was analyzed with the vector network analyzer (VNA) Rohde&Schwarz ZVA 40. In the case of amplifying units, the measurements

PoS(MUTO2022)003

were carried out using the standard functions of the VNA, and measurement results were recorded on a PC using the software developed in LabVIEW. To measure the phase stability of devices with frequency conversion, the phase noise method is usually used. However, a typical spectrum analyzer allows phase noise measurements at a frequency offset more than 1 Hz from the carrier frequency, which allows measuring only short-term stability (less than 1 s time intervals). To study the long-term phase stability of a receiving system with frequency conversion, a measurement technique was developed using a multiport VNA: port 1 was used to generate an input microwave signal, port 2 was used to measure the output signal at an intermediate frequency, port 3 was used as a reference generator at the intermediate frequency. The VNA measured the phase difference between ports 2 and 3. All channels were synchronized between themselves and with the reference signal for the frequency converter unit. It has been experimentally verified that at frequencies above 1 Hz, the results obtained using the developed technique are similar to the results obtained by the phase noise measurement. To measure the group delay t_g of a device with frequency conversion, the two-tone method (patented by R&S) was used. The phase difference $\Delta\phi$ between two carriers with a frequency difference Δf at the input and output of the device was measured, and the group delay was calculated as $t_g = -\Delta\phi/2\pi\Delta f$.

The receiving systems of an RT-13 radio telescope (both tri-band and broadband) have 8 channels. To simultaneously measure the output power of these 8 channels, a special multichannel radiometric control device has been developed. The device consists of 8 diode power sensors R&S NRP8SN with a LAN interface, integrated into a single system by a PoE switch, data is transferred to a remote PC via an Ethernet interface. The control program for the device was developed in LabVIEW. The RT-13 parameters were measured using this device.

To control the stability of the output power, gain, and noise temperature of receiving system stages directly at the radio telescope, a special control device [7] was developed and manufactured. The device consists of a microwave unit and a data acquisition unit. The microwave unit implements amplification and band filtration necessary for independent measurement of individual receiver units and generation of a test noise signal. The data acquisition unit performs signal detection, digitization, and also modulation signal generation for the receiver modulation mode.

5. Laboratory results

Figure 2 shows the amplitude stability of the RT-13 radio telescope broadband receiving system (at 7.5 GHz) investigated according to the measurement scheme (Fig. 1). The Allan deviations (square root of Allan variance) are presented. Curve 1 in Fig. 2 is the relative Allan deviation of the ratio of the readings of two power sensors without a receiving system and characterizes the power meter relative instability $\Delta P_{met}/P_{met}$. The contribution of the cryo unit gain fluctuations $\Delta G_1/G_1$ (curve 2) to the whole receiver gain instability $\Delta G/G$ (curve 5) exceeds the contribution of the splitter unit $\Delta G_2/G_2$ (curve 3) and the frequency converter unit $\Delta G_3/G_3$ (curve 4), see formula (5). The mutual covariances K_{ij} between unit fluctuations are negligible. White noise (curve 7, the first term in formula (1)) dominates in the receiving system output power fluctuations (curve 6) at time intervals up to 0.3 s. This is the optimal averaging time of the broadband receiving system output signal, at which the minimum noise is achieved. At longer averaging time intervals, the flicker noise of the cryo unit prevails (the Allan deviation is constant).

PoS(MUTO2022)003

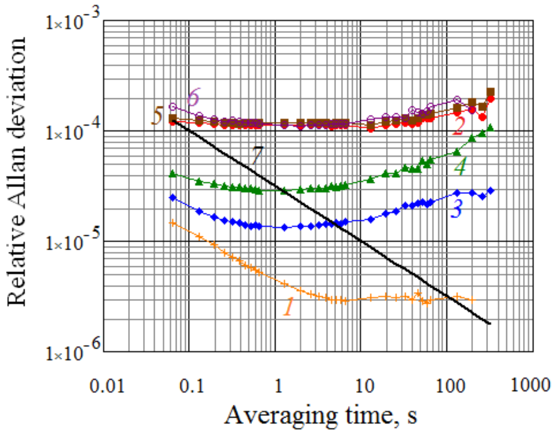

Figure 2: The amplitude stability of the RT-13 broadband receiving system: *1*—power meter, *2*—cryo unit gain, *3*—splitter unit gain, *4*—frequency converter unit gain, *5*—receiving system gain, *6*—receiving system total power, *7*—white noise: $\Delta T/T = 1/(\sqrt{\Delta f \cdot \tau})$

The amplitude stability of the S/X receiving system of the RT-32 radio telescope and the S/X/Ka receiving system of the RT-13 radio telescope was also studied. It was found that the main source of the amplitude instability in the "Quasar" VLBI Network receiving systems is the cryo unit. The standard deviations of $\Delta G/G$ fluctuations were calculated at τ = 1 s and 60 s measurement time (averaged value over the record): 0.9–2 $\cdot$ 10^{-4} for cryo units, 0.1–0.6 $\cdot$ 10^{-4} for frequency converter units, 0.1–0.3 $\cdot$ 10^{-4} for amplification units.

A similar technique was used to study the stability of phase and group delay of the "Quasar" VLBI Network receiving system units, and it was found that the main source of phase and group delay instability is the frequency converter unit. The phase stability is important over the source observation time in VLBI, which ranges from 10 to 120 s; the standard deviation of phase fluctuations measured at a 60-s interval with τ=0.1 s does not exceed 3 degrees, which reduces the radio interferometer SNR by 0.3% (see section 2). The delay stability is important throughout the duration of the entire one-hour VLBI-session. The standard deviation of the receiver delay instability measured at a 60-minute interval with τ=10 s does not exceed 0.6 ps, which meets the requirement of 5 ps formulated in section 2.

To improve the amplitude stability of the receiving systems, an adjustment with optimization by the sensitivity criterion (taking into account both the noise temperature and stability) is advisable to the transistor operating modes in the input cryogenic low-noise amplifiers. For the input amplifier of the broadband receiving system, it was possible to reduce gain fluctuations at 10–100 s averaging time intervals up to two times (up to 5 $\cdot$ 10^{-5}) by adjusting the drain voltage and drain current of the field-effect transistors of the amplifier.

The coefficients for the influence of the ambient temperature on the characteristics of the RT-13 tri-band receiving system and its individual units were measured in a thermal chamber. The temperature coefficient for the receiver gain ($-3.9 \cdot 10^{-3}$) is determined to the greatest extent by the frequency converter unit ($-2.6 \cdot 10^{-3}$), and that for the receiver group delay (−0.5 ps/K) by the cryo unit (−0.25 ps/K). The receiver stability is determined by temperature stability at long time intervals with 100–500 s averaging time.

6. Results at the radio telescopes

The characteristics of the RT-13 radio telescopes were measured for the first time using the created hardware-software complex at the "Badary," "Zelenchukskaya" and "Svetloe" observatories. The measured RT-13 characteristics (receiver T_{rec} and system T_{sys} noise temperatures, SEFD, aperture efficiency, half-power beamwidth $\Delta\theta_{-3dB}$) with the tri-band and broadband receiving

PoS(MUTO2022)003

Table 1: The radio telescope RT-13 characteristics at the "Svetloe" observatory

Receiver	Frequency, GHz	T_{rec}, K	T_{sys}, K	SEFD, Jn	Efficiency	$\Delta\theta_{-3dB}$, min
Tri-band	2.3	22	40	1120	0.72	34
	7.5	18	30	750	0.80	10
	28.5	48	65	1750	0.75	2.7
Wideband	4.0	31	47	1360	0.70	20
	9.0	21	34	1220	0.56	9
	15.0	25	44	1680	0.53	5

systems (Table 2) correspond to the calculated ones and to the characteristics of the best world radio telescopes.

The use of the developed multichannel radiometric control device increased the sensitivity of the RT-13 radio telescope (brought closer to the theoretical one). For example, for the Ka band the receiver sensitivity at τ = 1 s improved from 0.68 Jn to 0.18 Jn, which made it possible to more accurately focus the RT-13 radio telescope. The use of the developed parameter control device [7] increased the sensitivity of the RT-32 radio telescope up to 1.9 times at averaging times up to 10 seconds in the total power mode compared to the modulation mode (noise injection radiometer mode). For example, the X band receiver sensitivity at τ = 1 s improved from 0.077 Jn to 0.04 Jn.

A method for determining the optimal averaging time of a source signal in VLBI allowing for the receiver delay instability has been proposed [8]. A continuous 1-hour source tracking session using the RT-13 radio telescopes was carried out and the radio interferometer signal-to-noise ratio and the Allan deviation of delay were calculated depending on the averaging time.

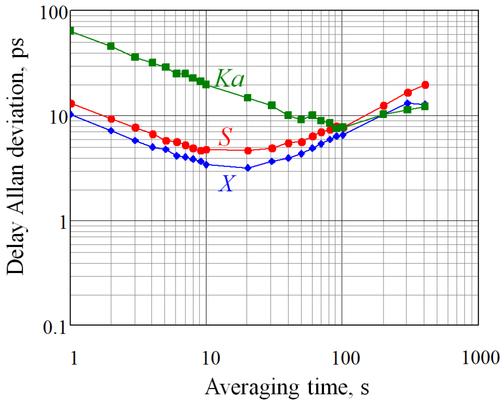

Figure 3: The Allan deviation of delay for the radio interferometer based on the RT-13 radio telescopes

The SNR increases proportionately to the square root of averaging time up to 3600 s for the S band, 1500 s for the X band, and 500 s for the Ka band, at longer averaging times the SNR decreases due to the instability of frequency standards. We have found that the delay error does not decrease with increasing averaging time (and SNR) according to theoretical formula (2), but delay instability appears at shorter time intervals (Fig. 3). The Allan deviation decreases like white noise up to 15 s averaging time in the S and X bands and up to 100 s averaging time in the Ka band (in the Ka band the SNR is smaller, so the averaging time needed to reach the instability is longer). This is the optimal averaging time at which the minimum Allan deviation of delay is achieved, delay instability prevails at longer averaging times. The minimum delay deviation is 5 ps in the S band, 3.5 ps in the X band and 8 ps in the Ka band. We propose to choose the averaging time of a source signal in such a way that the calculated standard deviation of the delay (by formula (2)) is more than the Allan deviation of delay instability, since further increase in averaging time will increase the delay measurement error (Fig. 3). Given this thesis, we recalculated the R-X sessions with 120-s scans and cut the averaging time into slices

PoS(MUTO2022)003

of 8 s for some intensive sources. We have found that the standard deviation of the Universal Time series reduced from 36 to 32 μs and the formal error reduced from 13 to 5 μs for the X/S combination [8].

7. Summary

The methods and a hardware-software complex have been developed which make it possible to study the amplitude and phase stability of radio telescope receiving systems and their individual stages. The contribution of the instability of the "Quasar" VLBI Network receiving system individual units is determined. It is shown that the cryo units are the predominant source of amplitude instability at time intervals up to 100 seconds, and the frequency converter units are the predominant source of phase and group delay instability. The ways to improve receiving system stability are determined: adjustment of the transistor modes of low-noise amplifiers with sensitivity optimization, voltage stabilization at the transistor electrodes of the amplifier, and improving the thermal stabilization of the frequency converter unit. Using the created hardware-software complex, adjustment and measurement of the main characteristics of the RT-13 radio telescopes with the tri-band and broadband receiving systems were carried out, which showed that the RT-13 characteristics correspond to those of the world best radio telescopes. The use of the created hardware-software complex increased the sensitivity of the RT-13 radio telescope and the RT-32 radio telescope in the total power mode. The method for determining the optimal averaging time of a source signal in VLBI has been developed, which makes it possible to reduce the UT1−UTC determination error.

8. Acknowledgements

I am grateful to Alexander Lavrov, Voytsekh Ken, Maxim Zotov, and Eugeniy Khvostov for their assistance and discussion of the results.

References

[1] N. Shuygina, D. Ivanov, A. Ipatov, I. Gayazov, D. Marshalov, A. Melnikov et al., *Russian VLBI network «Quasar»: Current status and outlook*, *Geodesy and Geodynamics* **10** (2019) 150.

[2] A.A. Evstigneev, V.K. Chernov, O.E. Evstigneeva, I.A. Ipatova, E.Y. Khvostov, A.P. Lavrov et al., *RT-13 VLBI Receivers*, *Transactions of IAA RAS* **55** (2020) 36.

[3] A. Thompson, J. Moran and G. Swenson, Jr, *Interferometry and Synthesis in Radio Astronomy*, Springer, Cham (2017), 10.1007/978-3-319-44431-4.

[4] J. Rutman, *Characterization of phase and frequency instabilities in precision frequency sources: Fifteen years of progress*, *Proceedings of the IEEE* **66** (1978) 1048.

[5] W. Shan, Z. Li, S. Shi and J. Yang, *Gain stability analysis of a millimeter wave superconducting heterodyne receiver for radio astronomy*, in *2010 Asia-Pacific Microwave Conference*, pp. 477–480, 2010.

PoS(MUTO2022)003

[6] Y.V. Vekshin and A.P. Lavrov, *The Allan Variance Usage for Stability Characterization of Weak Signal Receivers*, in *Internet of Things, Smart Spaces, and Next Generation Networks and Systems. Lecture Notes in Computer Science, vol 9870*, O. Galinina, S. Balandin and Y. Koucheryavy, eds., (Cham), pp. 648–657, Springer International Publishing, 2016, DOI.

[7] Y.V. Vekshin, M.B. Zotov and A.S. Lavrov, *A Control Device of S/X-bands Radio Astronomy Receivers Parameters*, *Transactions of IAA RAS* (2019) 32.

[8] Y.V. Vekshin, V.O. Ken, S.M. Mironova and S.L. Kurdubov, *Influence of signal delay instability in radio telescope equipment on optimal accumulation time of radio interferometer signal*, *Transactions of IAA RAS* (2022) 21.

PoS(MUTO2022)003