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A 20…25 GHZ RANGE RADIOMETER (λ = 1.35 CM) FOR INTEGRAL TROPOSPHERIC ABSORPTION MEASUREMENTS

Subject and Purpose. *The current research projects in astrophysics are in need of high-sensitivity scientific instruments. The accuracy and sensitivity of observations can be enhanced through the use of large radio telescopes and other radio frequency systems, as well as via application of diagnostic instruments intended for exploring the radio propagation conditions along the signal paths. The paths traverse all of the Earth's outer structural shells, from the atmosphere to remote layers of the magnetosphere. The present work is aimed at developing a highly sensitive off-set radiometer, operable in the frequency range of 20…25 GHz (1.35 cm waveband) and capable of monitoring the atmosphere above large centimeter-wavelength radio astronomical instruments, such as the recently developed radio telescope RT-32. The instruments like that should help making account of the integrated tropospheric absorption of the signals arriving from space radio sources and artificial objects in the near space.*

Methods and Methodology. *The modern software that is used for simulating operation of microwave circuits, and the high quality models of microwave units available on the market, allow analyzing various circuit options, thus enabling a full-fledged development of such devices. As long as the intended implementations of the radiometer suggest the use of exclusively standard, commercially available and preferably off-the-shelf components, the development was based on analyzing the parameters and layout of such units.*

Results. *An ultra-high sensitivity, broadband radiometer for the 1.35 cm range has been developed, which is intended for measuring integrated tropospheric absorption of the relevant radio waves. The calculated noise factor of the instrument is 2.3 dB. The extended bandwidth and high stability of the radiometer elements will provide for a sufficient sensitivity of the instrument as operated in conjunction with the receive system of the RT-32 radio telescope.*

Conclusions. *The high-sensitivity, broadband radiometer that has been developed will provide for a much greater operative accuracy of radio astronomical and radio physical research projects. The radiometer, which has potential for further modernization, has been designed for use with the multi-band, high-tech radio telescope RT-32 in the interests of radio astronomy and space science, in particular for monitoring and forecasting the state of atmospheric and space weather systems.*

Keywords: *radiometer, radio telescope RT-32, atmosphere, atmospheric and space weather systems.*

Introduction

The creation and commissioning in the year 2020 of the radio telescope RT-32 which is a world-class high-tech radio astronomical instrument, was assessed as one of the most significant achievements of the National Academy of Sciences of Ukraine over the 30 years of the country's independence, and noted in a special Resolution of the Academy's Presidium

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(No. 234 of 27.11.2020). The innovative technical solutions [1—5] implemented in the course of its creation have provided for parallel, simultaneous operation in all the frequency bands of the RT-32. The use of an advanced elemental base has made it possible to achieve a high stability of the receiving systems. The RT-32 provides ample opportunities for radio astronomy and radio physical research within the framework of international cooperation. The radio telescope can be exploited either in the single mirror or the Very Long Base Interferometry (VLBI) mode. It is well suited for solving geodetic problems within the International Earth Rotation and Reference Systems Service for the International Celestial Reference System, as well as the International Terrestrial Reference System. The filter based receiving system of the radio telescope [3—5] ensures separation of the signals in the frequency domain through the use of waveguides rather than sets of mirrors, or else through mechanical replacement of the receivers which operate in specific frequency bands. The system allows receiving signals in the bands of 4.7…6.8 GHz; 9.5…12 GHz, and 20…25 GHz in a parallel rather than series mode [6], thus making possible unique simultaneous observations in a variety of frequency bands. The switching system intended for controlling intermediate frequencies in all of the operating ranges, the possibility of tuning the local oscillators over a wide frequency range for obtaining suitable upper and lower sidebands [3], and the presence of several identical two-channel digital receivers — all these features enable us conducting simultaneous studies of different maser lines, either in three different ranges or in a single operating range of the RT-32. It proves possible to obtain both a high spectral resolution and information on flux density variations, thus having an additional powerful tool for radio astronomy and radio physical studies of the Earth's shells.

The level of the specialized hard- and software of the radio telescope itself, which was developed with due account of specific features of the RT-32 design, allows solving a wide range of tasks. The procedure and the hardware for automated analysis of the error matrix concerning the RT-32 telescope's orientation [7] allows drastically reducing the errors of pointing, in fact down to fractions of an arc minute for the antenna whose pattern width makes a few arc minutes. Thanks to this, the flux from a cosmic source is not modulated by the pattern's "jitter" when following the source. Still, from the point of provision for accuracy and completeness of our knowledge of the surrounding space, the specialize equipment which is currently available is absolutely insufficient. Monitoring the state of the Earth's environmental shells — from the atmosphere to the magnetosphere — which may produce passive interference to the measurements — as well as predicting their impact on the existing radio systems and developing adequate compensation methods are urgent and promising scientific and practical tasks.

The state of the environment, including the gas — plasma shells, is determined by a great number of regular and random external factors, such as moisture level in the atmosphere, variations in the total electron content in the ionosphere, variations of solar wind parameters, and the effects due to coronal mass ejections [4, 8, 9]. Taken together, they essentially prohibit creation of deterministic models of the atmosphere, ionosphere, magnetosphere and the interplanetary space — such that could meet the growing quantitative requirements. The currently known semi-empirical models are very crude. The specificity of ground-based radio astronomy research lies in the need of evaluating the impact of radio propagation conditions upon the resultant estimates of radiation sources' characteristics. In the operating range of the RT-32 the observational results are affected by the conditions in the interplanetary space and solar wind flows, variations of plasma parameters in the ionosphere and magnetosphere, as well as the heterogeneity and non-stationarity of the neutral atmosphere.

The high stability of the transmission coefficients of the receiving equipment [3, 5] has allowed detecting and compensating for the main mechanically produced effects of mis-adjustment of the RT-32 antenna during space source tracking. This enables studying the variability of astrophysical objects, as well as of physical processes in compact sources with a considerable level of energy release. (It is stressed again that all this is only possible with propagation effects taken into account, in particular, in the atmosphere along the radio wave propagation path).

That is why the development of a separate additional radiometer of high sensitivity, intended for monitoring the state of the atmosphere above the RT-32 telescope (with the aim of taking into account the integrated tropospheric absorption and its variations which may be capable of distorting the signals from space radio sources and artificial objects in the near space) is an urgent task for radio astronomy and radio physical instrumentation. Such a radiometer can be used either in conjunction with the RT-32 radio telescope or separately, for example at a different radio astronomy observatory.

1. Technical requirements for the radiometer

The formulation of technical requirements for the instrument is based on the results of previously performed studies on the RT-32 radio telescope. It is important to note that the highly stable receiving system of the new radio telescope ensured a several times better stability of reception of astronomical signals than the receivers of other centimeter waveband radio telescopes available in Ukraine, for example the RT-70. For comparison, let us refer to Fig. 1 presenting results of searching for the so-called intra-day variability effect during observations of the Perseus A (3C84) source [8, 9].

The intensity versus time records demonstrate three characteristic types of signal variability. First, these are the background noise and the intrinsic noise of the telescope's receiving system, the latter being the smallest component in terms of amplitude (see Fig. 1, the noise intensity never exceeds a few thousandths of the units shown in the graph). The variations attributable to the performance of the telescope's orientation system are of higher intensity (note the signal of a quasi-periodic ~410 s and an intensity of no more than 0.01 intensity units on the graph), which can be compensated for [7] during repeated observations. The highest intensity is demonstrated by the records of the sought for intra-day variability as obtained for the source 3C84 (periods ~15 000 s). Though, it might also be partially caused by changes in atmospheric absorption, say, through increased atmospheric moisture, which sometimes leads to an increase in noise by several degrees K even in the range of 4.7 to 6.8 GHz. It should also be noted that the level of instability and noise in the receiver that was developed 10 years ago (for use with the RT-70) did not allow detecting all of the above-mentioned types of variations (their correspondent range is also shown in Fig. 1, cf. the seg-

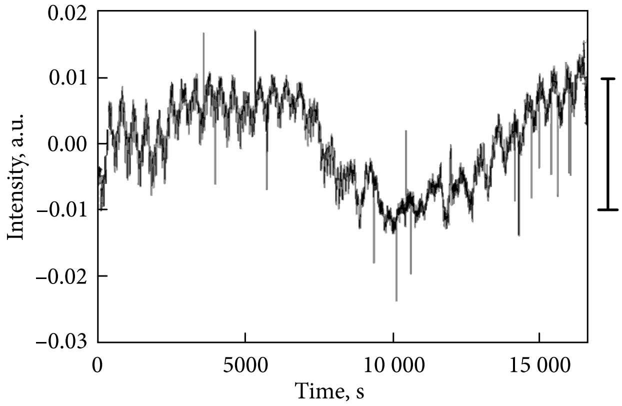

Fig. 1. Results of a multi-hour session of observations of the Perseus A source in the $\lambda = 5$ cm band (part of the study of the object's variability under the grant "Joint Latvian-Ukrainian study of peculiar radio galaxy "Perseus A" in radio and optical bands, No: lzp-2020/2-0121")

ment to the right of the graph). When studying the variability of such radio astronomy sources, the interfering effects should be eliminated or estimated and taken into account as completely as possible. The identification and elimination of extraneous (from the point of view of extragalactic astronomy) sources of signal variability, — such as effects due to the atmosphere, ionosphere, etc. — are the necessary measures for increasing the sensitivity of observations.

The operating frequency band of the RT-32 in this range is 20…25 GHz. To enable taking into account the effects arising from variations in tropospheric absorption and noise levels, the sensitivity of the radiometer should be close to that of the radio telescope's receiving system. The system noise temperature of the RT-32 receiving the choice of the central frequency of the radiometer is dictated by the presence of water lines, especially by the intense water vapor line at the wavelength $\lambda = 1.35$ cm ($f = 22.2$ GHz). Equipment in this range is 125…150 K [3]. Recalling that the receiver sensitivity is proportional to the square root of its frequency band width and the radiometer path bandwidth (≥ 5 GHz in our case) is at least an order of magnitude greater than that of the RT-32 receiver's broadband detector (0.5 GHz), an acceptable level of the radiometer sensitivity can be ensured by providing a noise factor of 2.6 to 3 dB (or ~250…300 K).

The radiometer should be amenable to further modernization, aimed at allowing performance of observational tasks either simultaneously with the radio telescope or in an autonomous mode. One may

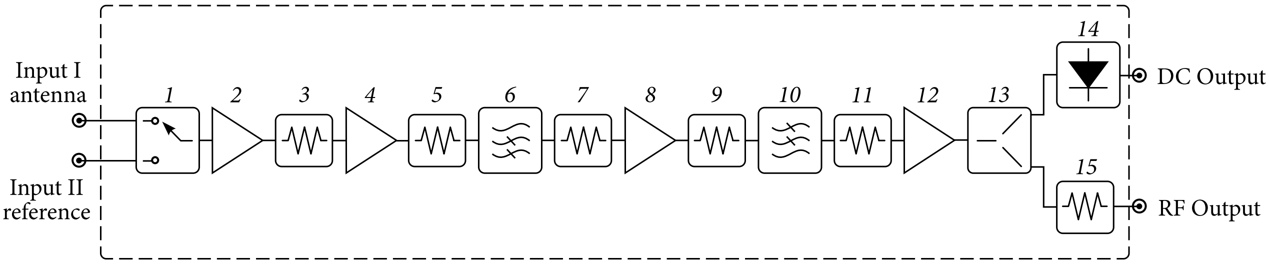

Fig. 2. Block-diagram of the radiometer: *1* — Input Switch (MASW-011197); *2* — LNA (CMD298C4); *3*, *5*, *7*, *9*, *11*, *15* — Attenuator 3 dB; *4* — LNA (ADL9005ACPZN); *6* — HPF (H160XHKS); *8* — LNA; *10* — LPF (L254XF3S); *12* — LNA (ADL9005ACPZN; *13* — Power Splitter; *14* — Power Detector (LTC5597HDC)

speak of obtaining kind of cross-sectional views of the atmosphere that would involve data for all elevation angles of the radio telescope's orientation for specific epochs of observations, and also provide possibilities for "coaxial" observations with the RT-32 radio telescope. That is, the instrument should be of a reasonably compact size to allow being installed on a platform with a possibility of synchronous pointing toward the source under study with the RT-32. Given that the observation program for the RT-32 may require pointing the telescope at dozens of radio astronomical sources and objects in the near space, it would be most efficient to develop a control program for parallel pointing of the radio telescope and the radiometer. It should be noted that the effects due to moisture and precipitation lead to a noticeable increase in the noise temperature even at 6 GHz, so the radiometer data should be useful for observations through the entire range of operating frequencies of the RT-32.

2. Development results and parameters of the radiometer

The block-diagram of the proposed radiometer is shown in Fig. 2. One of the goals pursued during technical implementation of the radiometer is the use of exclusively standard, commercially available circuit components.

In order to be able to implement a radiometer according to the Dicke scheme [10], the writers have selected a RF lineup with a single pole, double throw (SPDT) switch, choosing the recently announced monolithic, integrated microwave circuit (MMIC) of the MASW-011197 type [11]. This MMIC demonstrates such advantages as a low level of losses in the open state (specifically, below 1 dB) which are comparable with the figures for bare-die P—i—N based counterparts; high isolation in the closed state (over 45 dB); a low-voltage interface for CMOS logic control, and a fairly high switching speed (time below 1 μs).

The radiometer includes four amplification stages. The input low-noise amplifier (LNA) is based on a MMIC of the CMD298C4 type [12]. In the three other stages, MMIC's of type ADL9005ACPZN [13] are used. This type of amplifier is characterized by a relatively low gain (~17 dB) and a fair uniformity of the response function within the frequency range of 17…24 GHz, which increases the overall stability of the entire RF lineup. In addition, in order to ensure operation stability, a few 3 dB attenuators have been established between the amplification stages, with the aim of providing decoupling between the amplifiers. This measure tends to weaken the mutual influence of the amplification stages and to improve the overall stability. The amplifiers as described are characterized by a positive slope of the gain-vs-frequency dependence through the frequency range of interest (the amplification factor is increased by ~1 dB per amplification stage).This permits compensating, to some degree, the increase in signal losses with frequency that occurs in the passive components and the transmission lines.

The radiometer employs a broadband signal detector, so in order to limit the bandwidth and thus reduce the probability of interference from communication systems, the Internet and satellite television (the closest of which are located in the bands like 10.7…14.8 GHz and 26.5…40.0 GHz), standard low- and highpass filters of the types H160XHXS [14] and L254XF3S [15] are used in the radiometer.

Because of the fairly wide operating frequency band of the radiometer, individual filters are used instead of a single band-pass filtering unit. Besides, their specific allocation prohibits use of the standard filter products available on the market. This technical solution ensures a greater than 45 dB, nearly symmetrical rejection of the frequency offsets that are larger than 4.5 GHz. The radiometer involves an internal detector, retaining, at the same time, the possibility of using an external one that can be connected to the corresponding radio frequency output "RF" (See Fig. 2).

The internal detector is built using a MMIC of the type LTC5597HDC [16]. This MMIC is a wideband, linear response detector of root mean square power (represented in dB), optimized for the range of 35…0 dBm. The total mean gain factor of the RF lineup from the input of the first LNA to the input of the detector is about 59 dB (Fig. 3). As a result, the level of noise power is –15 dBm, which is an optimal value for the detector input at room temperature. This value is optimal for the indicated type of the detector as it provides for a minimum temperature drift of its transfer characteristics. In addition, all circuits of the RF lineup are to be placed in a simple cooling thermostat for automatically maintaining their temperature at the level of –20 °C. The solution is kind of a compromise between the necessity of reducing thermal noise in the RF circuits on the one hand and to economize on the thermostat's power supply on the other. It is expected to ensure a better stability of the measurements made by the radiometer, while offering some improvement in its sensitivity.

The design approaches proposed have been checked for validity via simulation of the radiometer's RF lineup with the use of the free QUCS studio software [17]. The essential results of the simulation (performed for room temperature conditions) are summarized in Table.

The presence in the circuit of an additional broadband output makes it possible to accurately measure spectral features of the received signals (with the use of a spectrum analyzer connected to that output), including the effects from water vapor in the atmosphere. By way of a comparative analysis of the highly sensitive spectral measurements with the RT-32 and broadband (accumulated over the frequency domain) radiometer data it should be possible to study temporal variations of the received signal and the degree of influence thereupon of a variety of factors. The use of integrated modules makes the design very compact, also providing the possibility of easy installation on any mobile platform for further control of radiometer pointing.

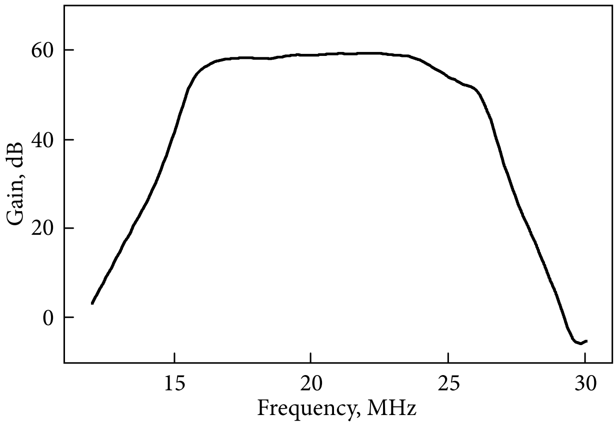

Fig. 3. Gain as a function of radiometer frequency

Results of simulating performance of the RF lineup

Parameter Name	Value
Operating Frequency Range	17…24 GHz
Noise Figure	< 2.3 dB
Gain factor (through to the connection point for an external detector)	55 dB
Slope of gain factor curve (at the output from the internal detector)	~18 000 V/dB
Gain Variation over Operating Frequency Range	< 1.7 dB
Stopbands<–45dB	< 12 500 MHz > 28 500 MHz

The use of low-noise amplifiers and input elements with a low level of signal losses ensures a smaller noise factor than 2.3 dB. Next, by placing the elements in a thermostat ensures stability of the transmission characteristics, which is necessary for fully implementing the capabilities of the RT-32 as a separate national instrument, as well as for its integration into global interferometric networks (like the EVN, VLBI, etc.).

On the other hand, since the radio telescope is an ultra-sensitive, multiband instrument capable of performing polarization measurements, it can be used, together with the radiometer that has been developed (as well as with other instruments) for monitoring the near space, the ionosphere, and atmosphere. Due to the presence in the near space of a large number of radio astronomical sources and artificial signal generators, combining these devices into a complex for remote sensing of the Earth's shells will help to significantly expand radio physical research of the surrounding space.

Conclusions

A high-sensitivity, broadband radiometer has been designed for performing integrated tropospheric absorption measurements in conjunction with the RT-32 radio telescope. The instrument shall allow for radio astronomical and radio physical research with greatly better measurement accuracies than before.

The broad spectrum of possibilities for using the radiometer may be achievable, should it be installed on the RT-32 observatory, with the guidance systems of the radiometer and the telescope having been co-developed and combined. Such a decision provides maximum opportunities for source tracking during radio astronomy observations, as well as for high accuracy spectral measurements of space signals against the noise background caused by water vapor in the atmosphere. Other ways of meaningful presentation of observational results include "cross-cutting" of the atmosphere for studying moisture distribution, as well as and other measurements with an ability of comparing the high-sensitivity spectral measurements of the RT-32 with the broadband (accumulated in the frequency domain) data from the radiometer. Simultaneous measurements with the use of the above mentioned equipment and methods allows us to separate the effects of various factors on the received signal.

The radiometer that has been developed should become an essential part of the complex for remotely sensing the near-Earth space through application of original methods of polarimetric and spectral observations, radio astronomical and physical investigation of both natural radio sources and the special radio frequency emitters operating from spacecraft. The radio sounding of the Earth's shells is done to investigate variations in the parameters of the magnetosphere, ionosphere, and neutral atmosphere, and to study weather and geocosmic disturbances.

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РАДІОМЕТР НА ДІАПАЗОН 20…25 ГГЦ (1.35 СМ) ДЛЯ ВИМІРЮВАННЯ
ІНТЕГРАЛЬНОГО ТРОПОСФЕРНОГО ПОГЛИНАННЯ

Предмет і мета роботи. Астрофізичні дослідження потребують все більш чутливих інструментів досліджень. Разом з великими радіотелескопами й системами радіофізичних досліджень підвищенню точності та чутливості спостережень сприяє використання приладів для діагностики шляхів поширення радіосигналів, якими є всі оболонки Землі — від атмосфери до віддалених шарів магнітосфери. Метою роботи є розробка окремого високочутливого радіометра на діапазон 20…25 ГГц (1.35 см) для моніторингу стану атмосфери над великими радіоастрономічними інструментами сантиметрового діапазону, такими, як розроблений нещодавно радіотелескоп РТ-32, для урахування інтегрального тропосферного поглинання сигналів космічних радіоджерел і штучних об'єктів у ближньому космосі.

Методи та методологія. Сучасне програмне забезпечення для моделювання роботи надвисокочастотних схем разом з високою точністю тих моделей обладнання, що є наявними на ринку НВЧ-блоків, дозволють проаналізувати різноманітні варіанти схем і виконати повноцінну розробку подібних пристроїв. Оскільки метою практичної реалізації радіометра є використання виключно стандартних, комерційно доступних і, зазвичай, готових компонентів, то розробку проведено шляхом аналізу параметрів і компонування таких наявних блоків.

Результати. Виконано розробку надвисокочутливого широкосмугового радіометра на діапазон довжини хвиль 1.35 см для вимірювання інтегрального тропосферного поглинання. Розрахований шум-фактор дорівнює 2.3 дБ. Широка смуга та стабільність параметрів елементів радіометра мають забезпечити достатню чутливість для роботи разом з приймальною системою радіотелескопа РТ-32.

Висновки. Розроблений високочутливий широкосмуговий радіометр сумісно з радіотелескопом РТ-32 надасть змогу проводити радіоастрономічні та радіофізичні дослідження зі значно більшою точністю. Радіометр, який має потенціал для подальшої модернізації, створено з метою використання разом з багатодіапазонним, високотехнологічним радіотелескопом РТ-32 в інтересах радіоастрономії та космічної галузі, а також для моніторингу й прогнозування стану атмосферної та космічної погодних систем.

***Ключові слова:** радіометр, радіотелескоп РТ-32, атмосфера, системи атмосферної та космічної погоди.*