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Millimeter-Range Radiometric System for Perspective Problems of Meteorology and Telecommunication

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***Abstract*—Short description of new ground radiometric complex, working on 40 GHz and 94 GHz frequencies and providing remote continuous measurements of full vertical atmosphere attenuation, effective temperature values and liquid-water content of clouds, integral content of vaporous moisture in atmosphere. The feature of the complex is the availability of digital signal processing of detected signals mode.**

***Keywords*—radiometric complex, atmosphere research, millimeter wave range, vertical signal attenuation**

I. INTRODUCTION

At present, systems of continuous monitoring of thermo- and hydro-dynamical troposphere characteristics, such as effective cloud temperature, total content of water vapor and condensed moisture, are absent in Ukraine. Continuous measurements are important due to the fact that in the atmosphere, aside from sustained meteoformations, are also observed rapid processes, that influence on the quality of solving problems of meteorology [1], radioastronomy [2], perspective telecommunication systems [3-5] and others. Influence consideration of such rapid processes is impossible to obtain from discrete launches of technological radio-zondes and separate scientific experiments using remote acoustic and optic devices. As a part of the promising project of physical and radio-physical atmosphere properties joint researches, developed by National Aerospace University "Kharkiv Aviation Institute" (KhAI) and Kharkiv National University of Radioelectronics (KhNURE), it is supposed to complement the existing meteorological network of upper-air remote sensing devices, which provide the continuous measurements. Definition of statistical values and fluctuations of full vertical attenuation at millimeter waves band is important task, that can be solved using developed measuring complex. This information is important for development of terrestrial-space communication systems, including the introduction of a new world-developing generation of telecommunication technologies of 5G format in various regions of Ukraine [3, 4].

The necessity of assigned telecommunication and meteorological problems solution for Ukraine is confirmed by the ITU recommendations about the necessity of data accumulation of atmosphere of millimeter (MM) wave-band (WB) signals attenuation to mainstream the microclimatic regional features [6]. The fruitful usage same MM WB complexes in scientific organizations and organizations of hydrometeorological services in Germany, the Netherlands, Russia, the United States, Japan, and others confirms also the topicality of creating such apparatus.

In this regard, as well as with the need to ensure the round-the-clock monitoring and collection of radiophysical and meteorological data in automatic mode, KhAI together with KhNURE developed and constructed a prototype of dual-frequencies terrestrial radiometric complex. The complex includes designed and manufactured equipment of the superheterodyne type: modulation radiometer 40 GHz range (department of radio technologies of information and communication systems - RTIKS, KhNURE) and modulation radiometer 94 GHz range (Aircraft Radio Engineering Systems Design Department - ARESDD, KhAI). The main criteria for the selection of circuit and technical solutions, aside from the suitable sensitivity for the task providing (not worse than 0.3 K which corresponds to the ability to identify the variability of atmospheric attenuation less than 0.005 dB), preference was given to cost minimizing of the used element base, providing the reliability and ease of use of the measuring complex equipment (for the reasons of its widespread use in hydrometeorology).

II. DESCRIPTION OF MEASUREMENT COMPLEX INSTRUMENTS

Fig. 1 shows the block diagrams of developed measuring complex radiometers, consisting of two measuring channels of 3 mm and 8 mm bands. The 8 mm WB radiometer is constructed by the modulation scheme with the superheterodyne type receiver, in which two-band receiving mode is used.

In Fig. 1 following elements are illustrated: antenna (A), PIN diode modulator (PIN DM), ferrite circulator (FC), directional coupler (DC), mixer (M), Gunn oscillator (GO), intermediate frequency amplifier (IFA), square detector (SqD), synchronous detector (SD), DC amplifier (DCA), analog to digital convertor (ADC), personal computer (PC); field-programmable gate array (FPGA).

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Constructive elements used in radiometers construction are illustrated in the fig.2. Designed radiometric system provides the possibility of transferring the radiometer from radiobrightness measurement mode to polarization measurement mode, where the radiometer output releases signal which is proportional to the temperature brightness difference between the vertical and horizontal polarizations.

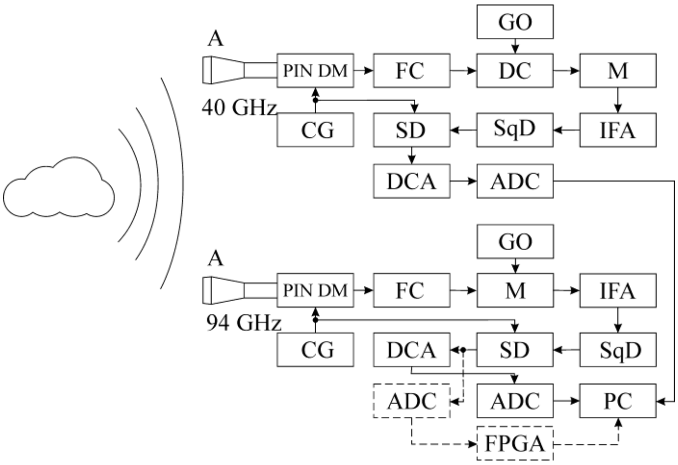


Fig. 1. Structural scheme of radiometric system.

This mode is of interest to remote research of thermal structure of clouds' crystal component or in studies of the Earth's surface and equipment objects polarization differences. Technical support of polarimetric mode is carried out by using as a modulator special ferrite Y-switches [7], loaded on the two antennas, which are configured to receive different polarizations. The output signal of the radiometer characterizes the differences between radiobrightness temperature of object with both antennas aimed at it.

As the auxiliary equipment of the two measuring complex radiometers there are included PC for data processing and calibration loads, made in the form of the original three-layer structure of high-efficiency radar absorbing material, comprised of a needle-mesh carpet structure of the type "Pile", radar absorbing layer of three-dimensional structure, made in the form of knitted fabric weaving, as well as non-cellulosic layer of (silicon-fiber) paper type APP with profiled surface.

As a radiometer antenna with a 40 GHz central frequency receiver configuration was used diagonal horn with aperture 50×50 mm^2, that provided the antenna pattern (AP) close to 5° with sidelobe level (SLL) -18 dB and cross-polarization level −14 dB [8]. PIN diode modulator U-7.2.242011 provides signal loss less than 0.5 dB in band 39-42 GHz, and a loss size of a switching ferrite Y-circulator [7] equals at the forward direction 0.4 dB with reverse loss close to 20dB. This circulator acts like a valve in a normal mode and like a signal modulator from two different similar antennas with different polarization in a radiometer-polarimeter mode.

After the Y-circulator, obtained signal goes to the input of waveguide-directional coupler, which has a signal channel loss 0.5 dB with directivity −18 dB and loss in the channel of heterodyne –14 dB. Mixer, containing a resonator camera with reduced section of the waveguide [7], where situates the mixer Schottky diode with cut-open packaging, is connected to the output of the directed coupler.

Fig. 2. Radiometers constructive elements: antenna (1), ferrite circulator (2), PIN diode modulator (3), mixer (4), Gunn oscillator (5).

Gunn oscillator with the output power close to 15 mW on the 40 Hz frequency is used as a heterodyne. The resonator oscillator chamber is a segment of the standard 8mm waveguide with a built-in diode "AAA 727V" type. The resonator camera is loaded on the cylindrical resonator from one side, and is connected with ferrite circulator, through which the oscillator signal passes to the directional coupler, from the other side.

From the mixer output the intermediate frequency signal goes to the low-noise preliminary amplifier and IFA cascades, which are constructed on standard UTR-5 modules. The IFA bandpass is 500-1000 MHz with the gain coefficient 60 dB.

To the output of IFA is connected the square detector, from which the noised low frequency (LF) signal of modulation frequency goes to the synchronous detector and integrator, and then it goes through DCA to the ADC and computer.

Cell stricter of without-body mixer diode with Schottky barrier, Gunn diode generator and ultrawideband PIN diode modulator with low loss level are manufactured in the Research Institute of Semiconductor Devices, (Tomsk, Russia). The rest UHF elements of tract were manufactured in the Pilot Manufacture of IRE NASU (Kharkiv, Ukraine).

Thus, we mention that total UHF signal loss in the predetection section is close to 2 dB. The estimated value of the mixer conversion loss is close to 7 dB.

Selected circuit and hardware solutions provided by the two-load measuring method [9] fluctuation sensitivity of the built radiometer about 0.2°K, which is in good agreement with the conducted calculation estimations of this basic radiometer parameter.

It should be mentioned, that if 40 GHz radiometer is constructed by the classical scheme for the superheterodyne modulation radiometer, structural construction of the 94 GHz radiometer differs from existing analogues (i.e. [9]) by the application in without-diplexers construction scheme of its UHF part. First of all, as the advantages of the proposed scheme [10, 11], in addition to the possibility of a more compact and cost-effective implementation, should be mentioned significantly reduced (by more than ten times of magnitude) requirements for the heterodyne output power. This decision allowed to use tunable in the band over 10 GHz Gunn oscillator, even with a resonance camera, configurable on heterodyne noise minimizing mode (instead of the traditionally used mode of the maximum output power). Such Gunn generator was developed by us on the basis of Barth construction [12, 13], by heuristic matching of resonance chamber geometry in relation to the use of the Gunn diode brand «AA 741». Trimmer short-trailing pistons of the generator also serve to adjust the optimum performance of the mixer, built on the base of cut-open packaging Schottky diode, located in full-high waveguide with section 1.2×2.4 mm^2 [14] (fig.2). The peculiarity of this radiometer is also the fact that it provides an opportunity to fundamentally new processing of radio emission signals [15−17] (watch channel, consisting two ADC and FPGA on fig. 1).

As in the previous radiometer, it is possible to implement the polarization measurements mode, wherein it highlights brightness temperature difference signal at the output of the radiometer between the vertical and horizontal polarizations.

Microwave channel element parameters of the radiometer are: horn antenna with breaks opening angle with 5° AP with SLL −18 dB and cross-polarization level −20 dB [18]. PIN diode modulator «PGV2.242» provides in the band 90-96 GHz signal loss less than 1.2 dB (locking 25dB), and the value of the ferrite Y-circulator [7] switching losses in the forward direction is less than 0.6 dB at a return loss more than 20 dB in range 92-97 GHz. This circulator functions as a valve when the system is operating in the normal mode of the radiometer and modulator signal function of the two identical antennas with different polarization at the operation mode of the radiometer-polarimeter.

After the Y-circulator, received signal reaches the mixer with a resonator camera of full waveguide section 1.2×2.4 mm2 [11], where the mixing diode with the Schottky diode with cut-open packaging is situated.

The Gunn generator with an output power of about 1 mW with the possibility of manual adjustment in the frequency range of 90-100 GHz was used as heterodyne.

From the output of the mixer intermediate frequency signal goes to low-noise preliminary amplifier and IFA and IFA cascades, which were constructed on "OGHASTA" modules. Bandpass of IFA is 1200-1700 MHz at noise coefficient close to 1 dB and gain coefficient close to 60 dB.

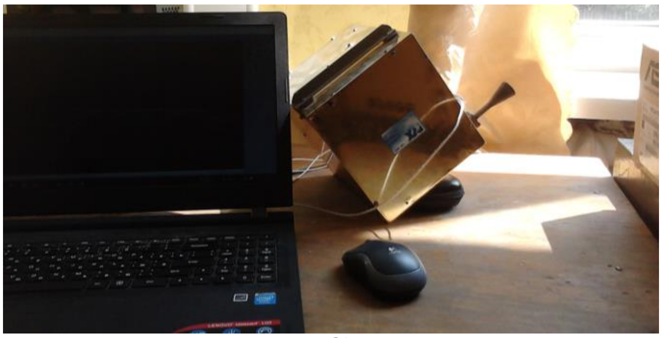
Square detector is connected to the output of IFA, from which the noised LF modulation frequency signal goes to ADC and computer.

Cell stricter of without-body mixer diode with Schottky barrier, Gunn diode generator and ultrawideband PIN diode modulator with low loss level are manufactured in Research Institute of Semiconductor Devices, (Tomsk, Russia). The rest UHF elements of tract were manufactured in the Pilot Manufacture of IRE NASU and ARESDD KhAI (Kharkiv, Ukraine).

Measuring sensitivity of radiometer is 0.25°K.

Fig. 3 shows the outer look of each radiometer.

(a)



(b)

Fig. 3. Photo of radiometers 40 GHz (a) and 94 GHz (b)

Microprocessor device for gathering and preliminary processing of measuring information also belongs to the end, LF part of measuring complex. Data obtain can be made as from output of square detector, so as, traditionally, from the output of radiometers synchronous detector. The first mode is used for speed changing improving of parameters of integration and modulation (demodulation) laws of radiometer input signal, and for realization of optimal processing modes [15−17].

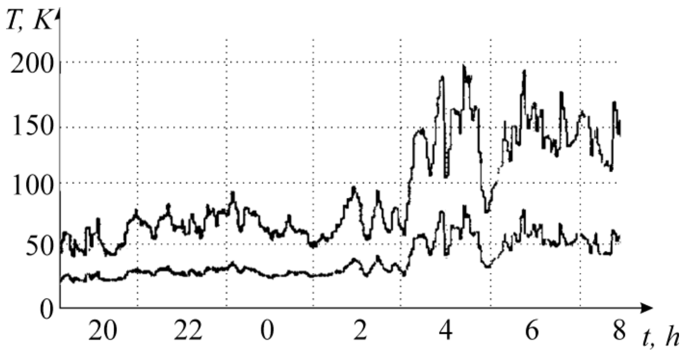


Fig. 4. Record fragment of sky radiobrightness change at 94 GHz (upper curve) and 40 GHz at passing through frontal zone of cloudiness from 7 p.m. to 8 a.m.

Developed measuring complex prototype successfully passed laboratory and natural tests. Fig. 4 shows the record fragment of sky radiobrightness change in 3mm and 8mm WB at passing through frontal zone of cloudiness. In [19] it was shown, that sky radiobrightness data, introduced in this figure, allows to restore the dynamics of full vertical attenuation value change in the atmosphere, values of effective temperature of condensed moisture in sky cover, values of water content and moisture content of clouds.

III. RADIOMETER DIGITAL PART

Two following channels of digital signal processing are provided in the complex:

- Feature of classical digital signal processing mode in both radiometers is that for providing of specified by apparatus parameters fluctuation sensitivity, the 16-bit ADC of brand Analog Device type ADS1115 is used, and reference voltage source with integrated amplifier allow to measure low voltages without the ADC resolution limit. The measurements can be made with frequency up to 800 SPS, and measurement results from ADC by sequence I2C interface reach the microprocessor block of preliminary processing. Developed interface provides the data transfer to PC and formation of Excel table with measurement results, that provide ease of accumulation and following processing of obtained data;
- Test mode (used only in the radiometer with central frequency of digital setting 94 GHz) envisages the signal processing algorithm that differs from used in classical modulation radiometer [20]. This algorithm, as it was proven in [15−17], provides unshifted radio-thermal radiation parameter estimation in the receiver with unstable gain coefficient and can be introduced in the next way:

$$T_A^\circ = \left(T_{ng}^\circ + T_n^\circ\right)\sum_{i=1}^{I} Q_i \left(\sum_{i=1}^{I} Z_i\right)^{-1} - T_n^\circ , \qquad (1)$$

where $Q_i = m(t_i)u^2(t_i)$ is the observation at the SD output at the time when $m(t_i)=1$, $Z_i = \left[1-m(t_i)\right]u^2(t_i)$ is the observation at the SD output at the time when $m(t_i)=0$, T_A° is the antenna temperature, T_{ng}° is the noise generator temperature, T_n° is the internal noise temperature, $m(t_i)$ is the digitalized modulation function (meander, which takes value of zero or one), $u(t_i)$ is the digitalized observation. Estimations of effective temperatures T_{ng}° and T_n° are obtained with first calibration.

Technical realization (1) is made in digital form in FPGA (fig. 1). Wherein, the observation is sampled after SD (the signal in band 1,2−1,6 GHz goes to SD input). For the signal from output SD sampling the low sampling frequency is required, but, despite this, ADC sampling frequency is chosen with significant reserve and equals 600 MHz (*Analog Device DL4A003*).

IV. MEASUREMENT AND RESTORING METHODIC

Measurement methodic supposes the continuous signal record with specified period of averaged sample and periodic radiometer calibration. Calibration procedure, from which in significant way depends the accuracy of atmosphere controlled parameters determining, has a couple of variants. The calibration variant chose depends on solved problems and requirements to atmosphere absorption measurements accuracy or atmosphere parameter retrieving. Problem investigation conducted by us showed that the biggest accuracy of absolute radiobrightness measurement accuracy (less than 3%) can be achieved at radiometer calibration by the method of two high-effective matched loads, at cooling of one of them to the liquid nitrogen boiling temperature (with the way of immersion into liquid nitrogen). Accuracy of absolute radiobrightness temperature measurements close to 6% can be achieved by the calibration of radiometer on zenith radiobrightness, value of which can be calculated on surface meteodata, for example, by the Liebe method [21]. Intermediate to this values 3-6% of accuracy can be obtained using calibration, based on determination of differences between the sum of differential signal from zenith direction composited with difference of the signals from zenith and direction 300 (from horizontal) and signal, received from matched antenna load or using a classical slice method [22].

Full vertical attenuation from the atmosphere value restoration is conducted at the basis of measured values of radiobrightness sky temperature in each channel separately. For the value restoration of integral moisture and water capacity and values of cloud layer effective temperature, data from synchronous double-frequencies measurements about values of full vertical attenuation is used.

The total absorption of the atmosphere in the vertical direction is evaluating from the measurements of the antenna temperature using the following equation:

$$\alpha_{total}^{\lambda} = \frac{ln\left[T_0 - \left(T_{ant} - T_{bground}\right)/(1-\beta)\right]/(T_0 - T_c)}{Sec\vartheta}, \qquad (2)$$

where: T_{ant} is the antenna temperature of atmosphere measured by radiometer; β is the dissipation factor of antenna outside of a main beam of AP of antennas; $T_{bground}$ is the effective temperature of background radiation received by back and side lobes of AP of antennas (experimentally obtained values); T_c is the relict cosmic radiation (2.75 K); ϑ is the zenith angle of sighting; λ is the wave length (millimeters); T_0 is the average temperature of atmosphere (was determined as $T_0 = bT^0$, where T^0 – temperature of near ground air, and b is the coefficient depending on wavelength and season (obtained from season-averaged profiles of meteo-fields). We use $b=0.98$ for summer and 0.96 for winter in 3-mm range, and $b=0.95$ for summer and 0.93 for winter in 8-mm range). For retrieving atmosphere vapor (Q) and liquid water content (W) values we uses a set of equations for 3mm and 8mm ranges:

$$\alpha_{total} = \alpha_{oxigen}(\lambda) + \Phi(\lambda)Q + k(\lambda, T_0)W \qquad (3)$$

where Φ and k – are the normalized coefficients of absorption in vapor and in liquid water accordingly. As a result of its solution:

$$W = \left\{\alpha_{total}{}^3 - \alpha_{oxigen}{}^3 - B(\alpha_{total}{}^8 - \alpha_{oxigen}{}^8)\right\}\left\{(1 - B/A)k_3\right\}^{-1},$$

$$Q = \left\{\alpha_{total}{}^3 - \alpha_{oxigen}{}^3 - A(\alpha_{total}{}^8 - \alpha_{oxigen}{}^8)\right\}\left\{(1 - A/B)\Phi_3\right\}^{-1},$$

where $\alpha_{oxigen}{}^{3,8}$ – values computed with meteorological data for 3 or 8 mm wavelength, respectively; $A{=}k_3/k_8$, $B{=}\Phi_3/\Phi_8$. As a rule the coefficient A has value between 3 and 6 (depended on droplet temperature) and $B = 6.8$ for our both frequencies.

V. Experimental results

The result of effective temperature retrieval of cloud layer from the dynamic of changes of sky radio-brightness depicted in Fig. 4 is shown in Fig. 5. The procedure of cloudiness effective temperature retrieval was based on well known formulas of double Debye [21].

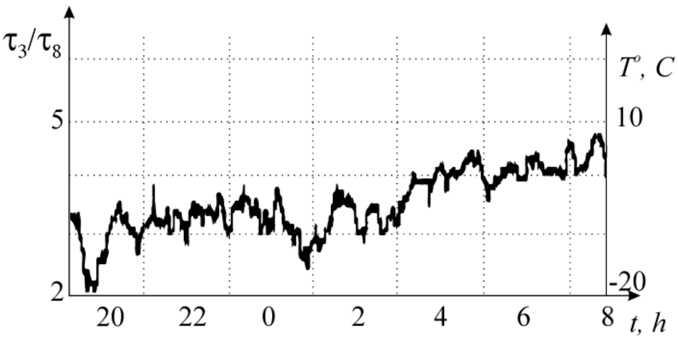


Fig. 5. The result of effective temperature retrieval of cloud layer

Retrieved atmosphere vapor (Q) and liquid (W) water content values of clouds are represented in Figs. 6(a) and 6(b).

Taking into account primary dates of two-wavelength radiometric measurements at 3 mm and 8 mm it is possible to determine clouds area that contains crystal moisture.

Thanks to polarization mode it is also possible to investigate morphological structure of crystals of frozen water [19, 23].

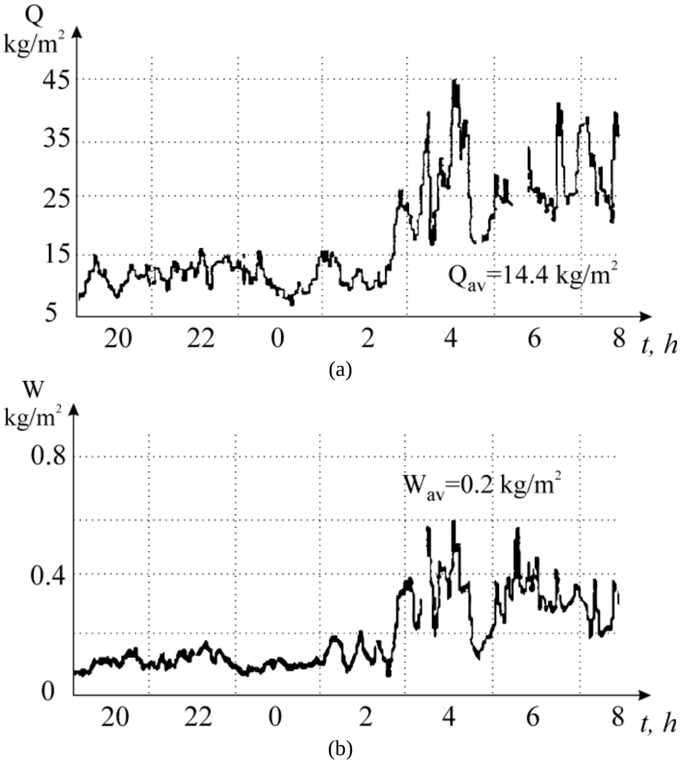


Fig. 6. Changes of clouds water content in the time

VI. Conclusion

The prototype of two-frequencies terrestrial measuring complex 40 GHz and 90 GHz range, which provides continuous measurement of atmosphere parameters (full vertical absorption in the atmosphere, effective temperature, crystal microstructure and clouds water capacity, total consistence of water vapor in the atmosphere) is developed and constructed practically in real-time.

Measuring complex provides:

- measurement of total water vapor consistence in the atmosphere zenith (integral vapor-water capacity) with estimative method error less than 2 kg/m2;
- measurement of integral cloud liquid-water content with estimative method error less than 0,05 kg/m2 (in the value interval 0 – 1.5 kg/m2);
- measurement of cloud cover effective temperature with the rate of data output about 300 s. in the range of real temperatures of droplet fraction and dependence of estimated error from value of negative supercooled drops temperature;
- identification of zones with crystal faction in cloud layer and with possibility of morphologic crystal forms estimation.

Wherein, the measurement procedure of moisture and water capacity are the main ones, and measurement procedure of cloud layer effective temperature with measurement of polarization differences of cloudiness crystal zone radiobrightness are auxiliary, allowing to improve the informativeness of main channels.

Installing of such complexes at the reference aerologic hydromet stations of Ukraine, allows to provide the continuous measurement from one side, and, from the other side, gives the possibility for additional calibrations using radio-probing data. Application of such two- or three- frequencies measuring MM WB systems is also effective it the scientific problems of climatology and problems of clouds' physics research. Usage of current system is expedient also in applied problems of artificial influence at the clouds in an effort to identify the most promising areas for clouds seeding at artificial stimulation or precipitation prevention.

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