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RADIOPHYSICS

IMPROVING THE SENSITIVITY OF RADIOMETRIC SYSTEMS BY SIGNAL POSTDETECTOR DIGITAL PROCESSING

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A digital method is described for processing the postdetector signal that makes it possible to maximize the sensitivity of radiometric systems. The method also allows for adapting radiometric systems to operation in microwave imaging devices using phased antenna arrays in scanning the scenes observed in real time.

To detect small power changes in thermal radiation by means of a radiometer, it is necessary to suppress the effect of the radiometric receiver noise, which is in most cases much stronger than the signal being measured. This problem is materially complicated by the presence of low-frequency flicker noise. In order to prevent the deviation of the radiometer readings from the true value, the popular radiometer circuits with analog signal integration usually use additional devices increasing the receiver noise (correlation radiometers), or the receiver therein is calibrated by a reference signal in the course of measurement, the signal channel being switched off for the calibration time, which leads to a loss of the signal intake power (modulation circuits), or else it is but a narrow band in the frequency response of the receiver that is exactly calibrated, the accuracy of measurement thus being impaired because of the unaccounted for fluctuations in the rest of the spectrum (circuits with a pilot signal). The result is that the sensitivity of such systems is several times lower than that of the ideal radiometers.

We have managed to use the input signal power and to improve the accuracy of measurement more effectively by integrating signal fluctuations rather than the signal itself. This is implemented by digitizing the amplified and detected signal and processing it in a digital fashion. In this case, the number of analog units in the circuit is reduced, and the potential sensitivity of a radiometer using such a circuit is ultimate [1]

$$\Delta T = \sqrt{2}T_n\sqrt{\frac{\Delta F}{\Delta f}}. \tag{1}$$

Here Δf is the receiver bandwidth and ΔF is the transmission band of the output filter. To find the functional relationship between the fluctuations being measured and the input temperature, we consider the effect of the nonlinear element, the square-law detector, in the radiometer circuit. The signal at the input of the detector is the sum of random signals of thermal origin: the amplified input signal and the receiver noise. Since these components do not correlate, the sum of their variances is the variance of the signal being detected

$$D_{\text{in.det}} = D_s + D_n. \tag{2}$$

According to the Wiener–Khinchin theorem [2], the variances of these signals are proportional to their spectral density integrals, and so the variance of the signal being detected is directly proportional to temperature

$$(T_s + T_n) \sim \int (S_s + S_n)d\omega = D_s + D_n = D_{\text{in.det}}. \tag{3}$$

Taking into account the fact that no direct component is present in the signal arriving at the detector having a volt-ampere characteristic with slope β, the variance of the signal being detected and that of the postdetector signal can be related

$$D_{\text{out.det}} = 2\beta^2 (D_{\text{in.det}})^2. \tag{4}$$

The sought-for value of the input signal temperature, T_s, can be found from expressions (3) and (4), provided that T_n is known

$$T_s - T_n \sim D_{\text{in.det}} = \sqrt{\frac{D_{\text{out.det}}}{2\beta^2}}. \tag{5}$$

Thus, to measure a thermal signal by the method suggested, it is necessary to digitize the detected signal, to cut off the low-frequency end of the spectrum containing flicker noise by means of a digital filter, to estimate the variance of the signal sequence obtained, and to compute the signal temperature by formula (5). As can be seen from this formula, the accuracy of the result depends on that of determining the variance of the signal. The consistent unbiased estimate of the variance of the sequence N of reading the signal x with zero mean is given by the expression [3]

$$\hat{D} = \frac{1}{N-1} \sum_{i=1}^{N} x_i^2. \tag{6}$$

By virtue of the consistency of this estimate, one can reduce the error of the computed variance by increasing the number of readings. To this end, it is necessary to increase either the signal integration time or the data reading rate. Therefore, the use of fast-acting analog-to-digital converters to digitize the postdetector signal makes it possible to reduce the error of determining the temperature of the input radiation in the course of a limited measurement time. Thanks to the absence of low-frequency units with relatively long relaxation time in the postdetector part of the radiometer, this approach to the determination of the temperature of the signal being received allows one to receive nonstationary signals. This is advantageous in forming radiometric images of thermal scenes on a real time basis. When applying the given measurement method, account should be taken of the special conditions imposed on the discretization frequency and digitization accuracy. The effective reading sampling frequency can be limited from above either by the bandwidth of the digitized signal or by the high-speed operation of the analog-to-digital converter and computational devices used. The number of readings sampled should be great enough in order that variance estimate (6) can more precisely correspond to its true value. But on the other hand, the reading integration time limits the period of the lowest flicker noise components that have not been paid heed in the course of digital filtration. Both these limits can be determined from the spectral analysis of the digitized signal sequence. It should be noted that in actual radiometers a great deal of the detected signal power in the high-frequency region of the spectrum is blocked by the limited bandwidth of the low-frequency amplifier placed immediately before the analog-to-digital converter. For this reason, the actual sensitivity of a radiometer is always lower than that calculated by formula (1) which fails to allow for the restriction of the output power spectrum. The method suggested was experimentally studied using a setup, whose schematic diagram is presented in Fig. 1. The elements in the diagram bear the following designations: NG-6 is the NG-6 noise generator which generates a noise signal with a temperature of 18 000 K in the frequency band of from 26 to 37.5 GHz; AT is the D3-36A polarization waveguide attenuator; R is a superheterodyne receiver, which amplifies the signal in a frequency band of 2 GHz; SLD is a square-law detector; ADC is the L-1250 analog-to-digital converter with the ADSP-2105 built-in controller; and PC is a personal computer. The input signal is digitized at a frequency of 450 kHz by means of a 12-digit array. Under continuous data sampling conditions, it proved possible to process an array of 32 760 readings.

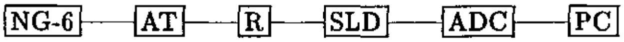

Fig. 1

Schematic diagram of the experimental setup.

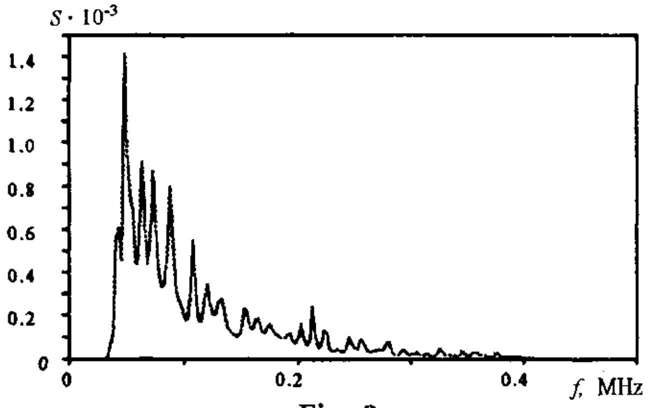

Fig. 2

Spectral density $S(t)$ of the signal after filtration.

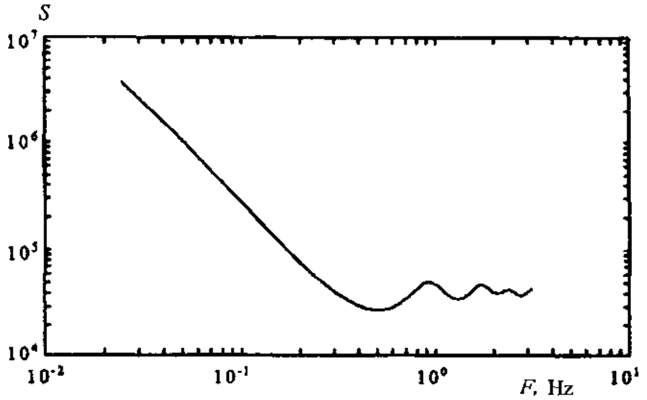

Fig. 3

Spectrum $S(F)$ of a sequence of implementations.

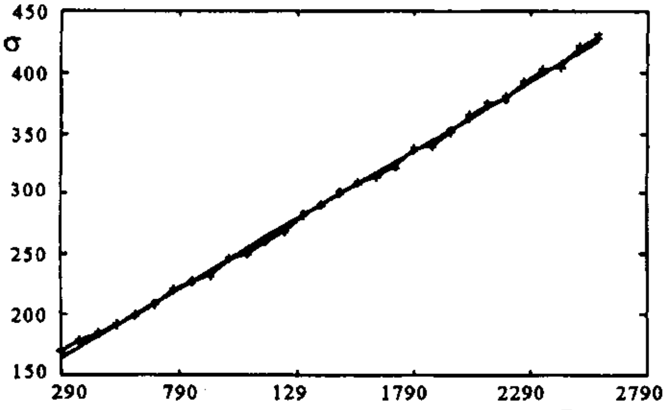

Fig. 4

Radiometer calibration curve: standard deviation as a function of temperature, $\sigma(T_s)$.

Figure 2 presents as an example the spectrum of a sequence of 2048 readings measured and filtered off at a frequency of 1 MHz (note that the starting data in this experiment were obtained with the aid of the C9-8 digital storage oscilloscope serving as an analog-to-digital converter: it provided for a high signal digitization rate but had a shortcoming of being incapable of measuring the implementations of more than

2048 readings). In the given case (Fig. 2), one can see that the detected signal is in the region below 400 kHz, and so the upper limit of the effective discretization frequency is close to 800 kHz. Figure 3 presents the result of expansion into a spectrum of a sequence of 1920 filtered off implementations from 30 720 readings digitized at a frequency of 450 kHz. The dip of the curve at a frequency of 0.2 Hz shows that the digital filter used effectively eliminates flicker noise at signal integration time of no longer than 5 s. The necessary reading digitization accuracy can be found from the relationship between the discretization error [4] and the random error in measuring the signal power. The repeated processing of measured and stored implementation, with the accuracy of readings being varied every time by rounding it off to a certain number of digits, helped to find the number of digits used for which the discretization error did not exceed the random error (in the given case, it proved necessary to have no less than 10 digits). To determine the brightness temperature of the radiation received, the radiometer should be pre-calibrated. The calibration result — the root-mean-square deviation of the filtered off postdetector signal versus the input signal temperature — is shown in Fig. 4. The approximation of the obtained curve by a linear function made it possible to find the noise temperature of the radiometer (see (2), (3), and (4))

$$T_n = \sqrt{\frac{D_{\text{out.det}}}{2\beta^2}}\,\Bigg|_{T_n\,=\,0}.$$

For our setup, it amounted to 1440 K. In the above example, the radiometer sensitivity, i. e., the spread of radiometer readings relative to the approximating line, came to 5 K (a relative error of 0.3%). Considering the loss of power outside the bandwidth of the low-frequency amplifier, which, as can be seen from Fig. 2, is 150–200 kHz wide, the results obtained may be considered as agreeing well with radiometric formula (1). Thus, if the bandwidth of the postdetector amplifier is increased to be twice the double frequency band of the external signal being received [1] and the digitization frequency of the analog-to-digital converter is raised to be 4 times as high as the upper frequency of the band, the detection limit will tend to 0.05 K (for a signal bandwidth of 2 GHz, signal integration time of 1 s, and receiver noise temperature of 1500 K).

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