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EVALUATION OF ACCURACY OF RADIOMETRIC CORRELATION-EXTREME NAVIGATION SYSTEMS

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Background: The use of passive matrix radiometric sensors of the millimeter wave range in aircraft navigation systems, which make it possible to form a radiometric image of a ground navigation object under conditions of high-speed flight of aircraft, is one of the effective ways to ensure high accuracy in measuring the coordinates of objects and, ultimately, leads to an increase in the probability of positioning aircraft [1]. In work [2], analytical relationships were obtained and quantitative estimates of the accuracy of positioning of aircraft equipped with a matrix radiometric navigation system were made. It is shown that the use of matrix radiometric sensors makes it possible to realize the required high (up to units - tens of meters) positioning accuracy of high-speed aircraft.

Objectives: The purpose of this article is to develop a method for increasing the accuracy of a radiometric correlation - extreme system based on the use of a matrix radiometric millimeter-wave receiver with channel compaction.

Materials and methods: In this paper, we used the method of linear multiplexing with channel separation according to the waveform using orthogonal Walsh functions. In this case, the sensitivity for each channel corresponds to the sensitivity of the modulation radiometer, and in comparison with the sensitivity of the compensation radiometer, it decreases by about two times. Taking into account the orthonormality of the Walsh functions, the signal at the output of each channel is proportional to the intensity (power) of the signal at the input of this channel.

Results: In this work, it is shown that the optimal number of combined channels is a multiple $2^k - 1$. The analysis of the results of the calculations shows that the combination of 64 channels into one amplifier-conversion path leads to an increase in inter-channel interference and, as a consequence, to a deterioration in the sensitivity of each channel.

Conclusions: In this case, it is expedient to limit the number of channels to be sealed per one amplifying-converting path. So, when 16 channels are combined into one path, the sensitivity of each channel remains quite high: about 1 K – for a super heterodyne radiometric receiver, and less than 1 K – for a direct amplification radiometric receiver. In this case, the number of amplifying-conversion paths with the total number of channels in the matrix 64 is equal to four.

KEY WORDS: millimeter wave radiometric receiver, radiometric image.

ОЦІНКА ТОЧНОСТІ РАДІОМЕТРИЧНИХ КОРЕЛЯЦІЙНО-ЕКСТРЕМАЛЬНИХ СИСТЕМ НАВІГАЦІЇ

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Актуальність: Використання в системах навігації літальних апаратів пасивних матричних радіометричних датчиків міліметрового діапазону хвиль, що дозволяють формувати радіометричне зображення наземного об'єкта навігації в умовах високошвидкісного польоту літальних апаратів, є одним з ефективних шляхів забезпечення високої точності вимірювання координат об'єктів і веде до підвищення ймовірності місцезнаходження літальних апаратів [1]. В роботі [2] отримано аналітичні співвідношення і зроблені кількісні оцінки точності визначення місцезнаходження літальних апаратів, оснащеного матричної радіометричної системою навігації. Показано, що застосування матричних радіометричних датчиків дозволяє реалізувати необхідні високі (до одиниць – десятків метрів) точності визначення місцезнаходження високошвидкісних літальних апаратів.

Мета роботи: Метою даної статті є розробка способу підвищення точності радіометричної кореляційно - екстремальної системи на основі застосування матричного радіометричного приймача міліметрового діапазону з ущільненням каналів.

Матеріали та методи: У даній роботі використаний метод лінійного ущільнення з поділом каналів за формою сигналів з використанням ортогональних функцій Уолша. У цьому випадку чутливість по кожному каналу відповідає чутливості модуляційного радіометра, а в порівнянні з чутливістю компенсаційного радіометра падає приблизно в два рази. З урахуванням ортонормальности функцій Уолша сигнал на виході кожного каналу пропорційний інтенсивності (потужності) сигналу на вході цього каналу.

Результати: У даній роботі показано, що оптимальним є кількість поєднуваних каналів кратне 2^k-1. Аналіз результатів проведених розрахунків свідчить, що об'єднання 64 каналів на один підсилювально-перетворювальний тракт призводить до зростання міжканальних перешкод і, як наслідок до погіршення чутливості кожного каналу.

Висновки: Доцільно в даному випадку обмеження кількості каналів, що ущільняються на один підсилювально-перетворювальний тракт. Так, при об'єднанні 16 каналів на один тракт, чутливість кожного каналу залишається досить високою: близько 1 К – для супергетеродинного радіометричного приймача, і значно менше 1 К – для радіометричного приймача прямого підсилення. У цьому випадку кількість підсилювально-перетворювальних трактів при загальній кількості каналів в матриці 64, дорівнює чотирьом.
КЛЮЧОВІ СЛОВА: радіометричний приймач міліметрового діапазону хвиль, радіометричне зображення.

ОЦЕНКА ТОЧНОСТИ РАДИОМЕТРИЧЕСКИХ КОРРЕЛЯЦИОННО-ЭКСТРЕМАЛЬНЫХ СИСТЕМ НАВИГАЦИИ

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Актуальность. Использование в системах навигации летательных аппаратов пассивных матричных радиометрических датчиков миллиметрового диапазона волн, позволяющих формировать радиометрическое изображение наземного объекта навигации в условиях высокоскоростного полета летательных аппаратов, является одним из эффективных путей обеспечения высокой точности измерения координат объектов и, в конечном итоге, ведет к повышению вероятности местоопределения летательных аппаратов [1]. В работе [2] получены аналитические соотношения и произведены количественные оценки точности местоопределения летательных аппаратов, оснащенного матричной радиометрической системой навигации. Показано, что применение матричных радиометрических датчиков позволяет реализовать требуемые высокие (до единиц – десятков метров) точности местоопределения высокоскоростных летательных аппаратов.

Цель работы. Целью данной статьи является разработка способа повышения точности радиометрической корреляционно – экстремальной системы на основе применения матричного радиометрического приемника миллиметрового диапазона с уплотнением каналов.

Материалы и методы. В данной работе использован метод линейного уплотнения с разделением каналов по форме сигналов с использованием ортогональных функций Уолша. В этом случае чувствительность по каждому каналу соответствует чувствительности модуляционного радиометра, а по сравнению с чувствительностью компенсационного радиометра падает примерно в два раза. С учетом ортонормальности функций Уолша сигнал на выходе каждого канала пропорционален интенсивности (мощности) сигнала на входе этого канала.

Результаты. В данной работе показано, что оптимальным является количество объединяемых каналов кратное $2^k - 1$. Анализ результатов произведенных расчетов свидетельствует, что объединение 64 каналов на один усилительно-преобразовательный тракт приводит к возрастанию межканальных помех и, как следствие к ухудшению чувствительности каждого канала.

Выводы. Целесообразно в данном случае ограничение количества уплотняемых каналов на один усилительно-преобразовательный тракт. Так, при объединении 16 каналов на один тракт, чувствительность каждого канала остается достаточно высокой: порядка 1 К – для супергетеродинного радиометрического приемника, и менее 1 К – для радиометрического приемника прямого усиления. В этом случае количество усилительно-преобразовательных трактов при общем количестве каналов в матрице 64, равно четыре.
КЛЮЧЕВЫЕ СЛОВА: радиометрический приемник миллиметрового диапазона волн, радиометрическое изображение.

PROBLEM STATEMENT

The multichannel (matrix) radiometric sensor contains a multibeam antenna with a group feed and a multichannel radiometric (RM) receiver. As a focusing element of a multi-beam antenna, a parabolic one- or two-mirror antenna is used, or a lens (dielectric, metal-plate, waveguide) antenna.

Multichannel RM millimeter band (MMB) is made either in the form of a set of channel receivers (matrix of receivers), or according to the scheme of multiplexing channel signals to a common amplifier-converting path. The output of the receiver is an on-board computing device that generates a RM image (RMI).

The development of principles for constructing a matrix RM receiver is associated with the solution of a number of scientific and technical problems, the main of which are:

- selection of the optimal coefficient of overlapping of antenna radiation patterns of partial feeds, arrangement of channel feeds in a group feed, matching of a group feed with a focusing element of a multi-beam antenna;
- implementation of the synthesis of the optimal scheme of a multichannel RM receiver, elimination of the instability of the gain of individual channels;
- elimination of the mutual influence of local oscillators on the operation of adjacent channels.

The choice of the optimal value of the partial beam pattern overlap factor is decisive in the formation of a group pattern, for assessing the level of the side lobes of the pattern, the antenna directivity factor, amplitude, phase and other distortions of the pattern.

Analysis of the results of experimental studies [3, 4] aimed at the formation of RMI by scanning and matrix RM system MMB, allows us to conclude that the «half» overlap of the beam pattern of individual channels leads to an increase in the signal-to-noise ratio in the generated image due to additional accumulation of the signal in the RMI elements. In this case, the configuration of the image of the object, in contrast to the case without overlapping the beam pattern, is not violated [5].

The simplest option for constructing a multichannel RM is to create a RM matrix, the number of which is equal to the number of partial of the beam pattern. The output voltage of each RM is proportional to the brightness temperature of one resolved frame element. In this case, the maximum fluctuation sensitivity of each individual channel is realized. However, when performing RM receiver according to a super-heterodyne scheme, it becomes necessary to use a powerful local oscillator common for a large number of channels or to synchronize all local oscillators in frequency.

The use of one powerful local oscillator with dividing the signal power into a large number of channel RM in a matrix with a dimension 8×8 or more, or synchronization of the local oscillators of all channels leads to a significant increase in the power of the common local oscillator and, as a consequence, to an increase in the overall and mass characteristics of the onboard equipment. In addition, the «wiring» of signals from one local oscillator involves dividing the power of the local oscillator signal into all channels in the MMB, which is technically difficult to implement.

It should also be noted that the signals of neighboring local oscillators, which are sources of radio waves, can affect the quality of reception of the useful signal by a separate receiver in the matrix. The influence factors of the signals of neighboring local oscillators can be characterized as follows.

1. The signals of neighboring local oscillators are summed with the useful signal of a separate i–th channel, while the level of the useful signal changes.

2. In the frequency converter (mixer), beats occur between the signals of neighboring local oscillators and the signal of the local oscillator, that is, additional frequency components of the interfering signal appear at the mixer output.

3. In the event that the signals of neighboring local oscillators in the matrix are not synchronized in frequency, additional frequency components can fall into the frequency spectrum of the useful signal. It is impossible to filter out these frequency components without losing part of the useful signal power.

4. The harmful effect of frequency-converted signals of adjacent channels is manifested in a change in the level of the useful signal, i.e. signal level in a single pixel of the image. Thus, in a certain part of the image pixels, the signal level does not correspond to the actual one, and it is not possible to estimate this signal level.

5. In the case when the power of signals of neighboring local oscillators, converted in frequency and falling into the spectrum of the useful signal, exceeds a certain level, the amplifying cascades of the RM go into saturation mode and the process of receiving the useful signal is disrupted. In this case, part of the RMI pixels are lost, the current image of the surface (object) being sighted is distorted, which can lead to disruption of the RM operation of the navigation system as a whole.

The construction of a matrix of feeds on the principle of combining high-sensitivity low-noise direct amplification RM receivers eliminates the disadvantages inherent in heterodyne circuits. However, in this case, combining a large number of receivers into a matrix leads to the need to ensure the layout, power supply, heat removal, and other technical difficulties.

One of the most important is the issue of reducing the cost of a multichannel RM receiver. (According to the data of OAO NPP Saturn and the State Research Center «Iceberg», Kiev, the approximate cost of one RM channel of direct amplification is ~ 1 thousand cu, and its mass is 80 g. At the same time, the cost of the RM matrix (excluding the cost of the antenna, signal processing and image forming devices) with a dimension of 8x8 will be 64 thousand cu, and the mass of the matrix is 5.12 kg.

The listed factors, both for super heterodyne RM receivers and for RM receivers of direct amplification, to one degree or another lead to a decrease in the accuracy of measuring the coordinates of the sighted objects by the radiometric correlation – extreme system.

The aim of the research is to develop a method for increasing the accuracy of the RM of the correlation – extreme system based on the use of the matrix RM receivers of the millimeter range with channel compaction.

ANALYSIS OF THE PRINCIPLES OF CONSTRUCTING A MULTI-CHANNEL RM RECEIVER MMB

By analogy with information transmission systems [4], RM systems can also use the methods of frequency, time multiplexing and channel separation, as well as the multiplexing method with channel separation according to the waveform [4].

The method of frequency multiplexing in RM systems with large absolute values of the signal frequency band is difficult to implement technically.

The time division multiplexing method requires the use of high-speed interrogation switches (connection) of partial antenna feeds to a common receiving-amplifying path. The high speed of sequential polling is limited by the time of signal accumulation by the radiometer from each partial feed (channel), which is dictated by the need to implement the required sensitivity of the PM receiver. The method of temporal densification in terms of speed is similar to the method of sequential survey of space.

Analysis of existing methods of multiplexing and channel separation allows us to conclude that for multichannel RM receivers, the time-division multiplexing method and the linear multiplexing method with channel separation according to the waveform are the most appropriate [4]. In [2, 5], a functional diagram of a multichannel RM with linear multiplexing of channels according to the form of signals is proposed. This scheme can also be used to implement the time division multiplexing method.

In this work, the amplifier-conversion path of the receiver, common for all channel signals N, is represented by an intermediate frequency amplifier. This eliminates the influence of the non-stability of the gain of adjacent channels on the generated image. The instability of the gain of its own amplifying-converting tract is eliminated due to the modulation of channel signals by Walsh's orthogonal functions.

The disadvantage of this circuit is that the frequency converter (mixer and local oscillator) is placed at the input of each N of the channels (at N the outputs of the multi-beam antenna). In this case, the above factors of the harmful influence of the signals of neighboring local oscillators on the process of forming the RMI take place.

Figure 1 shows a functional diagram that implements the method of linear multiplexing with channel separation according to the waveform. This scheme is given in [2].

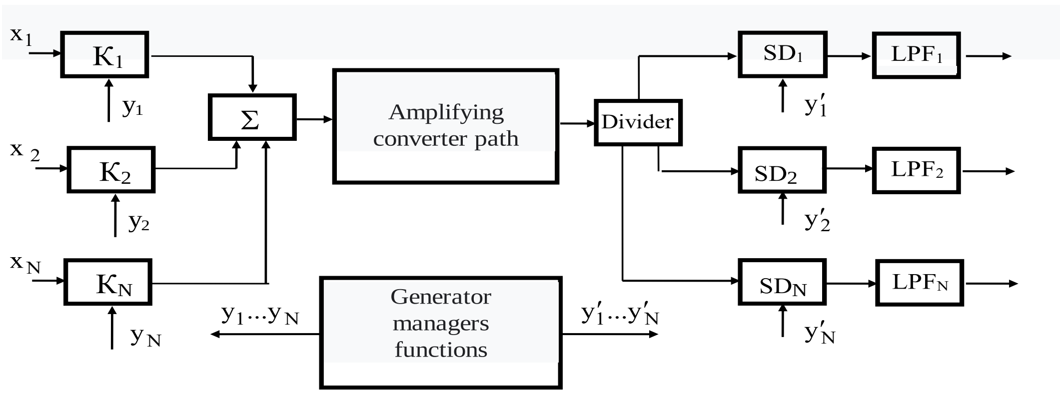

Fig. 1. Functional diagram of a multichannel RM with linear channel multiplexing and separation by waveform

The useful signal $x_i,\ i \in \overline{1, N}$ is a narrow-band normally distributed noise with a spectrum width Δf and a radio brightness temperature T_{ci} proportional to the intensity (power) of the radiation of the sighted area of the surface or an object at the input of the i-th channel.

With the help of switches $(K_1, K_2 \ldots, K_n)$, signals are modulated in each channel by signals (functions) $(y_1, \ldots y_n)$, which must be digital and belong to the family orthogonal on the interval $[0, \tau]$ [2, 5]. Further, the signals of all channels are fed to the input of the adder and to the general amplifying-converting path, where the noises of the RM with power are added to the signal T_N.

If the receiver is made according to a super heterodyne circuit, the amplifying-conversion path contains a frequency converter (mixer and local oscillator), an and a square-law detector. In the case of constructing a receiver according to a direct amplification scheme, this path contains several stages of low-noise high-frequency amplifiers and a square-law detector.

In both cases, there is one path for receiving, converting and amplifying the group signal, and thus there is no need to synchronize the local oscillators of individual channels. The source of the internal noise of the receiver is either the intermediate frequency amplifier or the high-frequency amplifiers of the common amplifying-converting path.

Further, the mixture of signal and noise, passing through the square-law detector, is divided by power into N channels and fed to synchronous detectors $(SD_1 \ldots SD_n)$, to the second inputs of which demodulating functions are received, similar to modulating functions $(y'_1, \ldots y'_n)$. The low-pass filter (low pass filter) integrates (statistical averaging) a signal with a noise structure over time τ.

In the particular case of time-division multiplexing of channels, the functional diagram (Fig. 1) does not change. The difference is that the switches $(K_1, K_2 \ldots, K_n)$ are connected to the adder in series.

With a small signal-to-noise ratio in each channel (which is typical for RM receivers), the optimal set of control functions is the family of Walsh functions [5]. In this case, the sensitivity for each channel corresponds to the sensitivity of the modulation RM, and in comparison with the sensitivity of the compensation RM, it drops by about a factor of two.

Taking into account the or the normality of the Walsh functions, the signal at the output of each channel is proportional to the intensity (power) of the signal at the input of this channel.

SIGNAL FLOW ANALYSIS IN A MULTIPLEXED RM RECEIVER

A multichannel radiometric receiver works as follows. Useful signals $u_{ci}(t)$, $i \in \overline{1,N}$ are fed to the inputs N of the corresponding switching devices (modulators) $(K_1, K_2 \ldots, K_N)$. With the help of switches $(K_1, K_2 \ldots, K_N)$, signals are modulated in each channel by orthogonal digital functions from the family $\left\{ y_i(t) = \frac{1}{2}\left[1 - wal_i(t)\right] \right\}_{i=1}^{N}$, which is built on the basis of the ensemble of Walsh functions [5]. Then the signals are fed to the inputs of the quasi-optical adder. The signal at the output of the adder can be written as follows:

$$u_c(t) = \sum_{i=1}^{N} \sqrt{T_{ci} y_i(t)}\, \tilde{U}_{ci}(t), \tag{1}$$

where $\tilde{U}_{ci}(t)$ – is the power (brightness temperature) normalized oscillation of the useful signal of the i-th channel, i.e. the power of the oscillations is always equal to one.

The signal from the output of the adder is fed to the input of the amplifying-converting path, where the internal noise of the RM of the receiver is added to the useful signal: the noise of the intermediate frequency amplifier in the case of a super heterodyne RM receiver, or the high-frequency amplifiers noise – in the case of constructing a receiver according to a direct amplification scheme without frequency conversion. The internal noise of the RM is completely identical to the useful signal and can be written in the form:

$$u_N(t) = \sqrt{T_N}\, \tilde{U}_N(t), \tag{2}$$

where T_N – is the power of the intrinsic noise of the RM of the receiver;

$\tilde{U}_N(t)$ – is the power-normalized oscillation of the receiver's own noise.

Further, the mixture of signal and noise, having passed the square-law detector, is divided by power into N channels and fed to synchronous detectors $(SD_1 ... SD_N)$, to the second inputs of which demodulating functions from the family are received:

$$\left\{ y_i'(t) = -\frac{1}{2} wal_i(t) \right\}_{i=1}^{N}. \tag{3}$$

We emphasize that the demodulating functions must be from the ensemble (3) of inverted Walsh functions, and the zero function is excluded. In this case, for a certain part of the period of the control functions, the modulators of all channels are simultaneously closed, and this interval is used to measure the intrinsic noise of the amplifying-converting path, as in the modulation receiver. A low-pass filter (low pass filter) integrates a signal with a noise structure over time τ.

In the particular case of time-division multiplexing of channels, the functional diagram (Fig. 1) does not change, and the switches $(K_1, K_2 \ldots, K_N)$ are connected to the adder in series.

At the output of each SD, the signal is determined by the expression:

$$u_c(t) = \frac{1}{N}\left[\sum_{i=1}^{N} \sqrt{T_{ci}\, y_i(t)}\, \tilde{U}_{ci}(t) + \sqrt{T_N}\, \tilde{U}_N(t) \right]^2 y_i'(t) \tag{4}$$

The average value of the signals at the output of the low-pass filter is:

$$\left\langle u_c(t) \right\rangle = \frac{1}{N}\left\langle \left[\sum_{i=1}^{N} \sqrt{T_{ci}\, y_i(t)}\, \tilde{U}_{ci}(t) + \sqrt{T_N}\, \tilde{U}_N(t) \right]^2 y_i'(t) \right\rangle. \tag{5}$$

The average value of the products $\left\langle \tilde{U}_{ci}(t) \tilde{U}_N(t) \right\rangle = 0$ of the type is equal to zero due to the uncorrelated signal and noise components. Taking into account the orthonormality of the Walsh functions:

$$\left\langle y_i(t)\, y_i'(t) \right\rangle = \begin{cases} 1, & i = \kappa \\ 0, & i \neq \kappa \end{cases}, \tag{6}$$

the signal at the output of each channel will be proportional T_{ci}, i.e. intensity (power) of the signal at the input of this channel.

Figure 2 shows a graphical illustration of a system of modulating Walsh functions from $N = 7$ functions $\left(N = 2^k - 1,\ k \in N\right)$ and an overlap factor $n = 4$ (four channels are simultaneously open).

To determine the sensitivity of each RM channel, it is necessary to find the ratio for the variance of fluctuations of the signal noise component.

Since the signals at the input of each channel of the radiometer are statistically independent, Gaussian random process, the variance of fluctuations of the noise component of the signal at the output of the radiometer (at the output of the common amplifying-converting path) can be represented as follows:

$$D=\sum_{i=1}^{n} D_i , \tag{7}$$

where $n=\Delta f\tau$ – is the number of independent samples according to Kotelnikov on the interval $[0,\tau]$, D_i – is the variance of fluctuations of the noise component of the signal at the output of the i–th channel.

Let us introduce into consideration the concept of the minimum time interval Δt during which the modulating Walsh functions retain their value.

It can be shown that for the case considered in Fig. 2, $\Delta t = \tau / p$, where $p=2^m$, and m – is the number of the maximum dyad of the Walsh functions used.

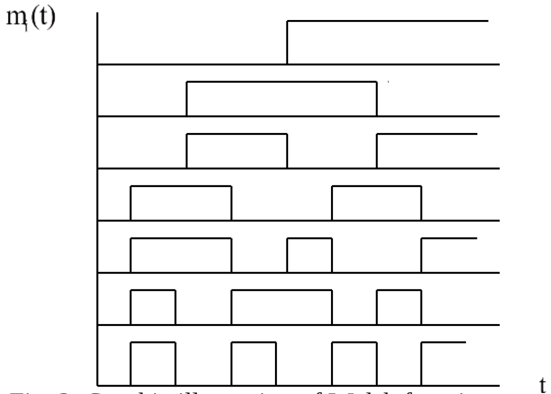

Fig. 2. Graphic illustration of Walsh functions

In the case under consideration, p = 8. Then expression (7) can be rewritten as:

$$D=\sum_{k=1}^{p}\left(\sum_{i=1}^{l} D_{ik}\right)=l\sum_{\kappa=1}^{p} D_{\Sigma k}=\frac{\Delta f\tau}{p}(T_{\Sigma k})^2 , \tag{8}$$

where $T_{\Sigma k}=\sum_{j=1}^{N} T_{ci}+T_N$ – is the total temperature of the signal at the k–th minimum time interval, Δt, $l=\Delta t\,\Delta l$.

In [6], an expression was obtained for the dispersion of a multichannel radiometer for the case of arbitrary N:

$$D_N=\frac{\Delta f\tau}{4}[N(N+1)T_c^2+4NT_cT_N+4T_N^2] . \tag{9}$$

The useful signal at the output of each PM channel is proportional to:

$$T_{c\,out}=T_c\frac{\Delta f\tau}{2} , \tag{10}$$

where T_c – is the signal temperature at the input of each channel.

Consider the worst case when the signals at all inputs are equal to the maximum value $T_{ci}=T_c$, $i\in\overline{1,N}$. Then the expression for the voltage signal-to-noise ratio at the output of each channel of the RM [2]:

$$Q_{out}=\frac{T_{c\,out}}{\sqrt{D_N}}=\frac{1}{2}q\sqrt{\Delta f\tau}\Big/\sqrt{1+Nq+\frac{N(N+1)}{4}q^2} , \tag{11}$$

where $q=\dfrac{T_c}{T_N}$ – is the signal-to-noise ratio at the input of each RM channel.

Understanding by the sensitivity δT of the radiometer the brightness temperature of the input signal, at which the value of the signal-to-noise ratio at the output is equal to unity, from expression (11) we find the ratio for the sensitivity of each channel of the RM:

$$\delta T=\frac{2T_N}{\sqrt{\Delta f\tau}}\sqrt{1+Nq+\frac{N(N+1)}{4}q^2} . \tag{12}$$

CONCLUSION

The results of calculations using formulas (11), (12) are shown in the graphs in Fig. 3.

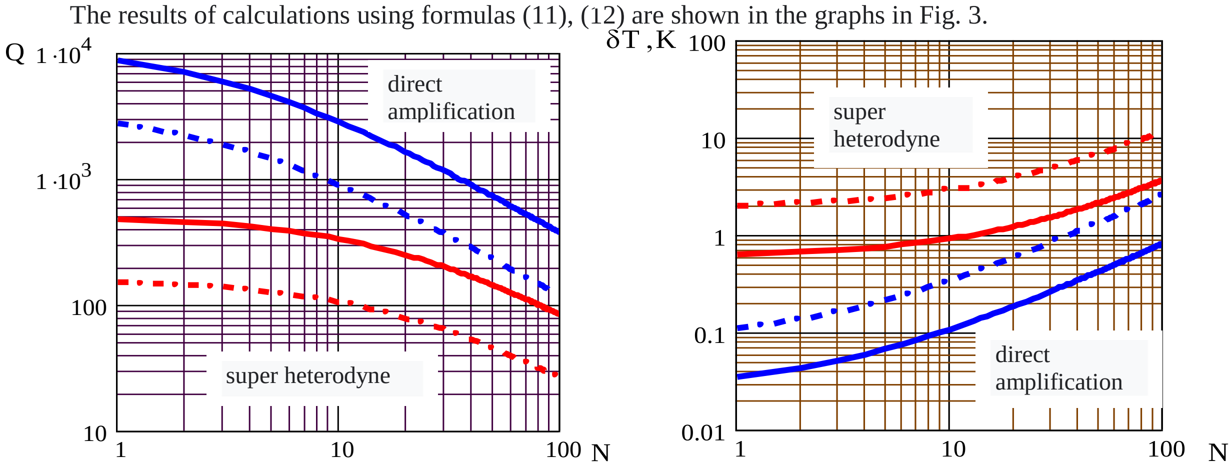

Fig. 3. Graphic of $Q = f(N)$, $\delta T = f(N)$

Analysis of the calculation results (Fig. 3) indicates that the combination of 64 channels into one amplifier-conversion path leads to an increase in inter-channel interference and, as a consequence, to a deterioration in the sensitivity of each channel.

For the super heterodyne RM, the degradation of the sensitivity in comparison with the single-channel modulation RM is ~ 6 times. The sensitivity of direct amplification RM (at $N = 64$) deteriorates 12 times compared to a single-channel modulation PM.

In this case, it is advisable to introduce a limitation on the number of combined channels per amplifier-conversion path. So, when combining, for example, 16 channels $\left(N = 2^4\right)$ per one path, the sensitivity of each channel remains high enough: $\delta T \cong 1K$ – for super heterodyne RM, $\delta T = 0{,}15K$ – for RM direct amplification $(\tau = 0{,}1s)$. In this case, the number of amplifying-conversion paths with the total number of channels in the matrix is $N = 64$, equal to four.

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