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THE PROBLEM OF APERTURE SYNTHESIS OF ANTENNAS WHICH ARE MOUNTED--ETC(U)
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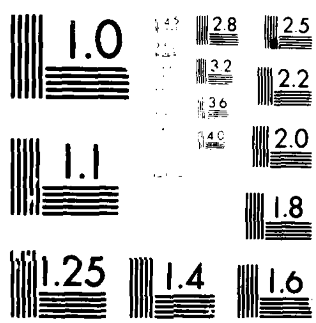
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FOREIGN TECHNOLOGY DIVISION

THE PROBLEM OF APERTURE SYNTHESIS OF ANTENNAS WHICH ARE MOUNTED ON MOVING OBJECTS

By

S. G. Rudneva

EDITED TRANSLATION

FTD-ID(RS)T-1036-79 12 July 1979

MICROFICHE NR: FTD-79-C-000940

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English pages: 17

Source: Sovremmennyye Problemy Antenno-Volnovodnoy Tekhniki, Izd-vo "Nauka", Moscow, 1967, pp. 176-188

Country of Origin: USSR
Translated by: Charles T. Ostertag, Jr.
Requester: FTD/SDED

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А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
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И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
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М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

THE PROBLEM OF APERTURE SYNTHESIS OF ANTENNAS WHICH ARE MOUNTED ON MOVING OBJECTS

S. G. Rudneva

The directional effect of a large receiving antenna, consisting of a number of identical elements, is the result of summation with the appropriate phases of signals which are received by the individual elements. The signal on the output of such an antenna can be viewed as the result of the simultaneous (parallel) processing of the information which is received by the elements of the antenna.

In the process of development of antenna technology a question was posed relative to the realization of a directional antenna at the expense of the sequential processing of information which is received by the individual elements of the antenna. In this case we gain the possibility of replacing a number of the identical elements, dipoles for example, with one movable element, fulfilling the role in sequence of each of the elements of the antenna [1, 2].

Such a synthesized antenna is very promising for moving objects (aircraft, satellites), on which it is not deemed possible to install antennas of large dimensions.

The problem of development of the described antenna has been solved at the present time for radar stations in which a high degree of stability of the frequency of the transmitter has been ensured. This stability is necessary for the sequential processing of the reflected signals which are received by the on-board antenna.

Such stations with a synthesized antenna which possess extremely high resolution are being used at present for making radar maps of the terrain.

Artificial Earth satellites and space rockets are opening up new possibilities for using the principle of an artificial antenna aperture. In particular the use of stations based on this principle has not been excluded for the investigation of the surface of planets which are covered with an atmosphere which is opaque for the eye (Venus, Jupiter).

In the present article we will consider a number of questions which are connected with the realization of this method.

1. Principle of formation of an artificial aperture

We will consider the process of realization of an artificial aperture, having accepted a number of initial assumptions.

We will assume that a station with a side-scanning antenna is mounted on an aircraft (or other flight vehicle) which is moving at a constant speed on a straight-line trajectory. The antenna emits the signals of the transmitter and receives signals which are reflected from objects located on the surface of the Earth. The transmitter operates in the pulsed mode and thus ensures the coherence of the radiated vibrations.

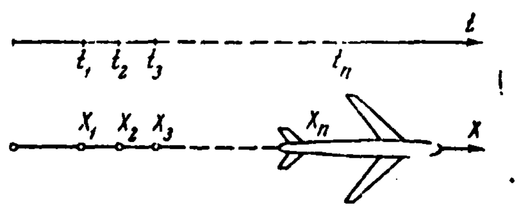


Figure 1. Axis of rotation and trajectory of movement of the aircraft.

Let us note that thanks to the use of the pulsed mode a resolution for range is realized.

For greater simplicity and clearness of discussions we will consider that there is one point reflecting object. The signals reflected from this object are received by the antenna at the moments of time t_1, t_2,..., t_n. At these moments the antenna occupies the positions on the trajectory which are noted in Figure 1 by points X_1, X_2,..., X_n. The distances between these points

$$d = \frac{V}{f_{\text{имп}}} \tag{1}$$

where V - speed of the aircraft, $f_{\text{имп}}$ - pulse repetition rate.

One of the component parts of the station should be a system which records the amplitude and phase of the high-frequency oscillations received by the antenna.

In the first approximation it can be considered that the amplitude of the signals reflected from a point object and received by the antenna is the same in all the points X_1, X_2,..., X_n. We determine the change in the phase of the signals which are received in different points of the trajectory. It is evident that with the assumptions made above the phases of these signals will be determined by the length of the path covered by each signal from the moment of radiation to the moment of reception.

We will place the beginning of the reading of coordinate X in the point of the trajectory X=0 (Figure 2), found at the least range R_0 from the target C. Then the phase of the signal received in any point of the trajectory

$$\Psi(X) = -kS(X), \tag{2}$$

where $k=(2\pi/\lambda)$ - wave number, $S(x)=2R(X)$ - length of path covered by the signal.

Since

$$S(X) = 2\sqrt{R_0^2 + X^2}, \tag{3}$$

then

$$\Psi(X) = -2k\sqrt{R_0^2 + X^2} \approx -2kR_0\left[1 + \frac{X^2}{2R_0^2}\right]. \tag{4}$$

Dropping the constant component in (4), it is possible to consider that along the trajectory the change in the phase of the signal reflected from a point object takes place according to quadratic law (Figure 3)

$$\Psi(X) = -\frac{k}{R_0} X^2. \qquad (5)$$

Processing of the data obtained includes the vector addition of the signals, described for a certain segment of the trajectory L, i.e., in essence is a process which takes place in any antenna, when its elements are excited by an incoming electromagnetic wave.

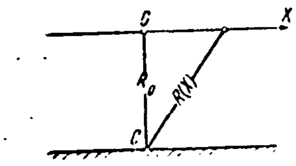


Figure 2. For determination of the phase relationships of signals received in different points of the trajectory.

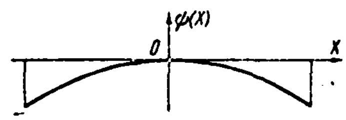


Figure 3. Change in the phase of signals reflected from a point object.

We will explain this in more detail.

We select the length of the sector of vector summation

$$L \ll R_0. \qquad (6)$$

Condition (6) makes it possible to consider the change of phase along the sector as linear in any position of this sector on the trajectory. Actually, on the basis of (4) we obtain the change of phase along the segment L:

$$\Psi(X, x) = \Psi(X + x) - \Psi(X) = \\ = -2kR_0\left[1 + \frac{(X+x)^2}{2R_0^2}\right] + 2kR_0\left[1 + \frac{X^2}{2R_0^2}\right] \approx -2k\frac{Xx}{R_0}, \qquad (7)$$

where X - coordinate of the beginning of segment L, x - current coordinate of the point on the segment, counted off from its origin (see Figure 4).

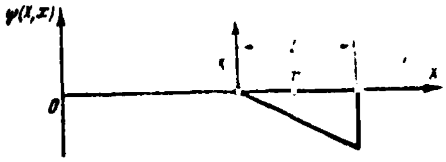


Figure 4. Change in the phase of signals received on the sector $L \ll R_0$.

Considering only the values of x corresponding to the positions of the antenna at the moment of reception of the reflected signals

$$x=d(n-1),$$

where n - number of position of antenna on the segment, we convert (7) to the form

$$\Psi(X,n) = -2\cdot\frac{kXd(n-1)}{R_0}, \tag{8}$$

where d is determined by expression (1).

The number of positions occupied by the antenna on the sector L,

$$N=\frac{L}{d}. \tag{9}$$

The total signal on the segment L

$$F_L(X)=\sum_{n=1}^{N}\exp[j\Psi(X,n)]=\sum_{n=1}^{N}\exp j\frac{2kdX(n-1)}{R_0}. \tag{10}$$

The modulus of expression (10)

$$|F_L(X)|=\frac{\sin\frac{NkdX}{R_0}}{\sin\frac{kdX}{R_0}}. \tag{11}$$

characterizes the amplitude of the total signal on the sector L.

The total process of processing the data obtained during operation of the station on one point object amounts to the determination of the amplitude of the total signal for a large number of positions of segment L on the trajectory. Each following position of segment L differs from the previous one by rejection from the left and addition from the right, this means that the beginning of segment L is shifted each time by one position (i.e., by $d = \frac{V}{F_{\text{имп}}}$).

We convert (11), introducing the substitution $\frac{X}{R_0} \approx \sin\vartheta$ and using the normalized multiplier $\frac{1}{N}$, and we obtain

$$|F_L(\vartheta)| = \frac{\sin Nkd \sin\vartheta}{N \sin(kd \sin\vartheta)}. \qquad (12)$$

Function 12 determines the dependence of total signal on the angle ϑ between a normal to sector L and the direction to the point object C.

Expression (12) can be considered an effective diagram of a synthesized aperture with a length L. It has the same form as the expression for a diagram of a cophasal antenna array made out of N nondirectional elements with a distance of 2d between them.

The artificial antenna obtained in this manner is equivalent to a linear array with a distance between elements equal to 2d.

Why does the distance between elements of an equivalent array turn out to be double the distance between the points in which the signals are received?

The fact is that the elements of the artificial aperture function independent of each other, and the signal emitted by an individual element is returned to this same element, covering a path equal to the doubled distance from the point of the aperture to the object. This circumstance found reflection in the derivation of the function of phase distribution (7). In a conventional antenna the signals are emitted by all the elements simultaneously, and as a result of the interference of these signals the radiation pattern is formed already in the mode of transmission. Therefore the phase distribution, caused by the reflected wave, is determined by the lengths of the paths covered by the signals in one direction (from the object to the elements of the aperture).

In connection with this the function of phase distribution for an artificial aperture has a doubled characteristic slope in comparison with a conventional antenna, and the effective pattern of the artificial aperture is narrower than the pattern of a conventional antenna of the same length.

The width of the pattern for the artificial aperture on a level of 0.7 from the maximum level for the field is equal to

$$\theta_c = \frac{\lambda}{2L}. \tag{13}$$

2. Linear resolution on coordinate X and its limiting value

Thus we obtained a pattern with a width θ_c, stipulated by the length of the synthesized aperture L. In this case the linear resolution on coordinate X

$$\Delta X = \theta_c R_0 = \frac{\lambda R_0}{2L}, \tag{14}$$

here R_0 - distance to the object being resolved.

The length of sector L we selected from the condition that the resolved object was found in the far zone of the antenna. However, such a case of realization of an artificial aperture is quite rare and not very interesting, since in this case the possibilities of the method are not revealed completely. With a considerable increase of the dimension L, when condition (6) ceases to be fulfilled, the phase distribution along L acquires a quadratic component.

Actually in this case the change of phase along the sector L

$$\Psi(X, x) - \Psi(X) = -2kR_0\left[1 + \frac{(X+x)^2}{2R_0^2}\right]^2 +$$
$$+ 2kR_0\left[1 + \frac{X^2}{2R_0^2}\right] \approx \frac{2kXx}{R_0} - \frac{kx^2}{R_0}. \qquad (15)$$

In the case of vector addition of the signals the quadratic component eliminates the effect of the increase in the dimensions of the artificial aperture, but the influence of the quadratic component can be compensated for, if during the processing the corresponding quadratic function of the reverse sign is introduced.

Under the condition of introduction of a compensating function there is a basic possibility of realizing such a large dimension of the artificial aperture, when the object is found practically in the near zone.

We will appraise the limiting possibilities of an antenna with an artificial aperture. First of all we determine the maximum size of the artificial aperture. We will consider that the area of positive reception of the signals of an antenna which is mounted on board an aircraft is limited by the aperture of its radiation pattern θ_a on the 0.5 power level. Then the process of recording the signals which are arriving from a point object continues for the course of the period when the target is found in the aperture of the pattern of the airborne antenna. This process begins in point A and terminates in point B of the trajectory (Figure 5).

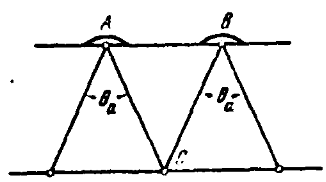


Figure 5. For determining the maximum value of the artificial aperture.

Segment $AB=\theta_a R_0$ can be considered the maximum dimension of the artificial aperture. Thus

$$L_{max} = \theta_a R_0. \quad (16)$$

If in the case of addition of signals which are recorded on the sector L_{max} the quadratic component of phase distribution is compensated for, then the effective width of the radiation pattern of the artificial aperture

$$\theta_{C\,min} = \frac{\lambda}{2L_{max}}. \quad (17)$$

From here it is possible to obtain the value of the extreme linear resolution

$$\Delta X_{min} = \theta_{C\,min} R_0. \quad (18)$$

Using (17) and (16), we obtain

$$\Delta X_{min} = \frac{\lambda R_0}{2L_{max}} = \frac{\lambda R_0}{2\theta_a R_0} = \frac{\lambda}{2\theta_a}. \quad (19)$$

Considering that $\theta_a \approx \left(\frac{\lambda}{d_a}\right)$ (where d_a - length of airborne antenna), we have

$$\Delta X = \frac{d_a}{2}. \quad (20)$$

It follows to turn attention to two remarkable features of an artificial aperture.

First of all, the extreme value of linear resolution (ΔX_{min}) does not depend on the distance to the object being resolved, and, secondly, the extreme linear resolution is improved with a lessening of the size of the antenna which is mounted on board the aircraft.

The first peculiarity is explained by the fact that with an increase in range according to (16) there is an increase in the magnitude of L_{max}, consequently in the corresponding manner the effective pattern of the artificial aperture is narrowed.

The second feature is connected with the fact that with a reduction in the size of the airborne antenna d_a its pattern is expanded, and, as a result of this, the sector L_{max} on which the recording of signals takes place is increased.

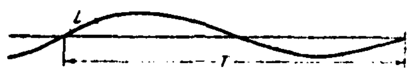


Figure 6. For determining the maximum magnitude of artificial aperture.

It is necessary to note that the maximum realization of an artificial aperture encounters a number of obstacles of a technical nature. Very strict requirements should be met for the stability of many parameters relating to the conditions of flight of the flight vehicle, to the parameters of the medium in which the radiowaves are being propagated, and to the electrical parameters of the station. Any type of deviations of the indicated parameters are perceived by the system for recording and processing of signals as phase errors, and this reduces the effective dimensions of the antenna [3, 4]. Trajectory instabilities are especially destructive. The dispersion of phase errors, developing due to deviations of the aircraft from the calculated trajectory, is great, it can be greater than the wavelength. Therefore the sufficiently effective utilization of an artificial aperture is possible only under the condition that the dimension of L is sufficiently less than the period of more or less regular deviations of the aircraft from the assigned trajectory (Figure 6).

In general the practical realization of an artificial aperture usually differs considerably from maximum. But in spite of this the method of artificial aperture gives a very significant gain in resolution in comparison with the resolution which is provided by the airborne antenna. In practice it is possible to obtain a resolution which exceeds by one hundred times the resolution which is provided by the station antenna.

3. Condition of unambiguous determination of coordinates with the help of an artificial aperture

It was shown above that a synthesized antenna can be considered as a linear array with a distance between elements equal to $2 \cdot V/f_{\text{имп}}$. This distance, as a rule, is considerably greater than wavelength, as a result of which a many-lobed pattern (12) is obtained with interference maximums in the direction ϑ, for which $kd \sin\vartheta = m\pi$, ($m=0$; ± 1; ± 2;...), see Figure 7.

The disposition of these maximums on the ϑ axis depends on the variable d/λ. With an increase of this ratio the distances between the interference maximums is reduced. The presence of a large number of maximums in the pattern of a synthesized antenna is extremely undesirable. They are the cause of ambiguity in the determination of coordinates. The suppression of secondary maximums (directed not on a normal to the linear array) is one of the most important problems which develop in the realization of the principle of an artificial aperture.

We will dwell on it in more detail.

In the derivation of (12) it was assumed that the synthesized array consists of point (nondirectional) elements. Actually the elements of this array possess directivity. The beam pattern of an element is nothing but the pattern of the airborne antenna of the station - $F_a(\theta)$.

It has been accepted to call function (12), describing the beam pattern of the array, consisting of point emitters, the array multiplier. The array radiation pattern, consisting of similar directional elements, represents the product of the array multiplier (12) by the radiation pattern of the individual element

$$F_c(\vartheta) = \frac{\sin Nkd \sin\vartheta}{N \sin kd \sin\vartheta} \cdot F_a(\vartheta). \qquad (21)$$

In many cases of realization of an artificial aperture the problem of suppression of secondary interference maximums is solved thanks to the directional properties of the elements, i.e., with the help of the pattern of of the airborne antenna. For the effective suppression of the maximums it is necessary to demand that in the case of the coincidence of the maximum of the pattern with the main maximum of function (12) its nulls would coincide with the nearest secondary maximums (Figure 7). This requirement can be fulfilled if the dimensions of the airborne antenna d_a in the azimuth cross-section satisfy the condition

$$d_a \geqslant \frac{2V}{f_{\text{имп}}}, \tag{22}$$

i.e., the size of the airborne antenna should be no less than the distance between the elements of the equivalent array or, in other words, should at least double the path covered by the aircraft between two pulses.

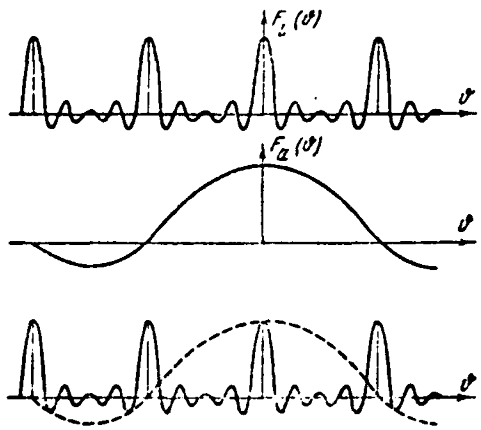


Figure 7. Suppression of secondary interference maximums with the the help of the pattern of the airborne antenna.

In the solution of the problem of suppression of secondary maximums it is necessary to take into account still another special feature of the synthesized array, amounting to the fact that the pattern of an individual element of an array does not have a strictly constant orientation of the maximum relative to the array itself. As a result of random turnings of the maximum of the pattern of the airborne antenna relative to the line of flight ambiguity develops in the determination of coordinates.

In connection with this, in addition to the fulfillment of condition (22), stabilization of the pattern of the airborne antenna relative to the vector of ground speed mainly in an azimuth plane should be ensured.

Thus the suppression of the secondary interference maximums of a synthesized array can be carried out with the help of the radiation pattern of the airborne antenna of the radar, if its dimensions are twice those of the segment of path flown over by the aircraft in the time between two pulses, and if the pattern is stabilized relative to the vector of ground speed.

But it has to be stated that such a path is not always feasible. Thus in the case of a very high speed of the flight vehicle and a sufficiently low pulse repetition rate for the suppression of inter ference maximums it may require antenna dimensions which in practice are difficult to realize. Thus with the mounting of a station on a satellite (or space ship) the antenna dimensions must be 50-80 m. In such cases it is expedient to make use of the possibility of the principle, which is known in antenna theory, of non-equidistant arrays. It is known that interference maximums develop due to the periodicity of the array, i.e., due to the equality of the distances between elements. If this periodicity is disrupted, then the secondary maximums (not coinciding with a normal to the array) are broken up.

The practical realization of a synthesized antenna based on a model of a non-equidistant array means that the sounding pulses of the transmitter are emitted not regularly, but according to a specific law. The law of distribution of sounding pulses on the axis of time is the same as the law of distribution of elements of the synthesized array. The problem is reduced to a search for the law of spacing of the elements of the array which would ensure a sufficient lowering of the level of interference maximums. In this case it is required, first of all, that the condition of suppression of maximums be preserved for any realization (i.e., for any position of the aperture on the X axis), and, secondly, that the distances between elements of the array satisfy the inequality

$$d_i > d_{min} - VT_{max}, \qquad (23)$$

where T_{max} - the time, necessary for propagation of the radiated signal to the object which is furthest away and back.

Due to the fact that a synthesized array contains a very large number of elements it becomes possible to use the method of mathematical statistics for its calculation. This means that the non--equidistant position of the elements on the axis of the array is realized according to a certain law of random distribution. It is necessary to find such a law, according to which the suppression of secondary interference maximums in the array pattern is ensured, and which is averaged on a large number of realizations, and, furthermore, it is necessary to determine the number of elements in the aperture which would guarantee a sufficiently low probability of the appearance of secondary interference maximums in an individual realization.

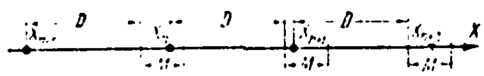


Figure 8. Layout of antenna array with random distribution of elements.

In order that condition (23) would be fulfilled, it is possible to realize such a construction of the array in which the element with the number n is located in a random manner on the interval M, but not closer than D in respect to the previous (n-1) element (Figure 8).

4. Problems of processing the signals which are received by a station with a synthesized aperture

In a coherent radar station with a high angular (on azimuth) resolution, obtained due to the creation of an artificial aperture, the accumulation (recording) of incoming signals takes place.

We recall that resolution for range is realized in such a station due to the time lag of signals which are reflected from objects which are at different distances away. Therefore each pulse of the transmitter is recorded on reception in the form of a series of signals arriving from different points of the Earth's surface along the beam of the airborne antenna. The following pulse gives the corresponding series of signals for the antenna beam which is displaced in parallel, etc. Thus the problem is reduced to the recording and processing of signals which are arriving at the receiver from a large area. This requirement is satisfied by the optical processing of signals, since optical devices by their nature are two-dimensional [5-7].

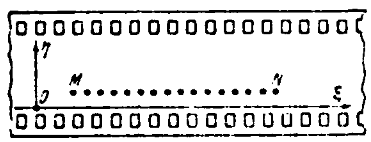


Figure 8. Arrangement for reading of coordinates on film.

In the case of optical processing it is assumed that the recording of incoming signals is done on film. On the film (Fig. 9) coordinate ξ corresponds to coordinate X of the point of the artificial aperture, and the sweep for range is made on the film along coordinate η. Then on the film a series of points, located along vertical lines, will correspond to each individual pulse. The points, found on a straight line (MN for example) parallel to the ξ axis, will correspond to the signals arriving with each pulse from sectors which are located at the same range.

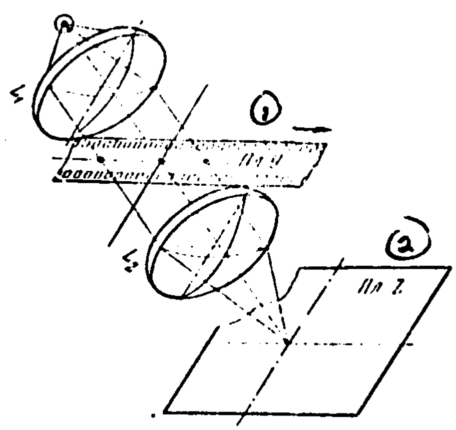
Just what do signals recorded along such a line represent?

It is evident that with each pulse the signals from all the elementary sectors of the surface, falling in the beam of the airborne antenna, which are equidistant from point X of the artificial aperture, arrive at the receiver simultaneously. At point X a total signal is received, the combined amplitude of which

$$M(X)=\int_{-\frac{\vartheta_d}{2}}^{\frac{\vartheta_d}{2}} A(\vartheta)\exp(jkX\sin\vartheta)\,d\vartheta, \quad (24)$$

where A (ϑ) - intensity of reflection from an object, located at a given distance at an angle of ϑ relative to the artificial aperture.

The signal (24) arrives at the input of the phase detector. The signal which is obtained on the output of the phase detector represents the real part of (24). The brightness of exposure of the film in the corresponding point ξ is proportional to the magnitude of the signal on the output of the phase detector.



Key:
(1) Plane Y;
(2) Plane Z.

Figure 10. Layout for optical processing.

The task of the subsequent optical processing is the restoration, based on the data recorded on the film, of a picture of distribution of intensity of reflections along the band of the Earth's surface being investigated. In other words, we have to find the function A (ϑ), which is the spectrum of function M(X). Mathematically this problem is solved by means of a Fourier transformation.

In practice this can be realized by the appropriate optical processing, in the process of which it is required to switch from radar signals, recorded through the variable brightness of the film, to light [signals].

The light signals are obtained as a result of modulation of light flux by the variable brightness of the film. For this the film is illuminated with a pl^ne wave of monochromatic light. If in this case the film is placed in the focal plane Y of converging lens L_2 (Figure 10), then in the other focal plane Z of this same lens the Fourier transform of the function, recorded on the film. will be reflected:

$$A(z) = \int_{\frac{-L_2}{2}}^{\frac{L_2}{2}} K(\xi) \exp(-jp\xi z)\, d\xi, \qquad (25)$$

where $K(\xi)=\mathrm{Re}M(X)$, L_2- lens opening. Then in the corresponding points of plane Z the signals, proportional to the intensity of reflections from the elementary sectors of the terrain, will be reproduced.

The circumstance that the Fourier transformation was applied to the active part of the signal M(X) creates the necessity of certain additional operations for the purpose of obtaining an unambiguous and correct picture of the terrain on the film. We will not consider these operations here.

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