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Frequency scanning with RATAN-600 as a radioheliograph

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Abstract. An analysis of variations of the RATAN-600 antenna patterns (AP) with variation of frequency in antenna settings with difference of ray paths is presented in the paper. Such settings are expected to be used in a special mode of mapping based on "frequency scanning" of sources with multilobe antenna patterns. Methods of estimating the bandwidth and the separation of the central frequencies of the radiometer channels necessary for the implementation of the "frequency scanning method" are given. To determine the type of variations of the antenna patterns with frequency, the theory of aberrations is applied. It is shown that in certain positions of the source and the focus, the variation of the antenna pattern with frequency consists in its spatial displacement without distortion of the AP shape. Expressions have been derived for these cases, which determine the rate and direction of displacement.

Key words: telescopes: radio – instrumentation: radioheliograph

1. Introduction

The radioheliograph mode of the RATAN-600, the idea and the main features of which are stated in the papers by Bogod et al. (1988); Gelfreikh, Opeikina (1992); Bogod, Grebinsky (1997), is being developed for the purpose of fast two-dimensional imaging of the Sun and other radio sources. To solve this problem, "frequency scanning" technique is used, that is, obtaining of independent scans due to substantial change of the shape or the position of the antenna pattern at a small ($\frac{df}{f} \sim 0.1\%$) frequency variation of the received radiation. The antenna pattern varies with frequency if there is difference of ray paths in the antenna system. The antenna settings with the necessary difference of ray paths can be attained by changing the focus position.

In the radioheliograph mode, antenna patterns of different structure can be formed at a chosen central frequency. A single-lobe AP can be obtained at a given frequency by way of zoning — equalization of differences of ray paths of antenna elements to be integer of wavelengths. A multilobe pattern is obtained by specifying a non-cophasal field distribution in the antenna aperture. Single-lobe and multilobe APs will also be called "zoned" and "non-cophasal", respectively. In the majority of antenna settings single-lobe APs "break up" with changing frequency and become multilobe, while the change of multilobe antenna patterns consists in variation of spatial distribution of the lobes. The "frequency scanning" by multilobe antenna patterns was suggested as the main method of "frequency scanning" in the radioheliograph mode (Bogod et al., 1988; Bogod, Grebinsky, 1997). The use of such APs makes it possible to additionally speed up imaging owing to the fact that the field of view of each AP can cover the whole source at once. In this case the information derived in a great number of frequency channels at a single moment of time may turn out to be sufficient for "instantaneous" two-dimensional imaging. As it will be shown in this paper, the "frequency scanning" by single-lobe APs is also possible in some special antenna settings.

The application of "frequency scanning" calls for a detailed knowledge of in what manner and how fast the antenna pattern structure changes with varying frequency, how these changes depend on the parameters of antenna setting — the source and focus position, the initial phase distribution, the number of panels of the circular reflector, etc. In order to choose the optimum settings for observations, to define the frequency bandwidth (Δf) and the frequency spacing between the channels (δf) of the recording devices, analysis of all possible antenna settings should be made. Because of their great variety, the obtaining of the desired information by means of calculation and comparison of antenna patterns at different frequencies for each of the settings would lead to bulky computations. For this reason, it is necessary to find

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ways of evaluation which use easily computable characteristics of the radioheliograph setting. Such ways will be discussed and analysis of changes of the APs with frequency for some versions of settings will be made in this paper.

The type of variations of APs with varying frequency is determined on the basis of the general approach to the analysis of aberrations, according to which the dependence of the function describing phase distortions (aberration function) on the coordinates in the aperture plane is considered. The analysis of expression for the aberration function reveals several variants of antenna settings, the APs of which displace practically without distortions as the frequency changes. This is mainly determined by the focus position of the setting. For the given settings, expressions have been derived which relate the value of the spatial displacement of the AP to the value of the displacement in frequency and the parameters of the setting. This makes it possible to additionally substantiate the estimate of Δf and relate it to the estimate of δf. The validity of the conclusions and estimates made in this paper is justified by the computer modeling of antenna patterns.

2. Evaluation of the frequency bandwidth

The frequency bandwidth of one channel of the radiometer is estimated proceeding from the requirement that the variations of the antenna pattern within the band should be negligibly small. Consider a two-element antenna. The phase difference variation of the two waves arriving from the given direction, which arises because of the frequency variation, is $\delta\phi = 2\pi\Delta D\Delta f/c$, where ΔD is the difference in the optical paths of these waves, c is the speed of light. The variation of the AP in this direction can be neglected if $\delta\phi$ is a small fraction (α) of the total period. Allowing for the symmetry about the central frequency, obtain the bandwidth estimate:

$$\Delta f = \frac{2\alpha c}{\Delta D} \approx \frac{75}{\Delta D}\ MHz\ , \qquad (1)$$

where $[\Delta D]$ is expressed in metres, and $\alpha = 0.125$ (here we take the same value of α as in the paper by Parijskij and Shivris (1972)).

To estimate the bandwidth in the multielement settings of the radioheliograph, one can take the maximum difference of ray paths, ΔD_{max}, which corresponds to one of the pairs of elements (panels) that form the reflecting surface. Such a bandwidth may be considered to be rather narrow for the rest of the pairs. The variation of ΔD_{max} within the large field of view of non-cophasal APs, which can contain hundreds of lobes, should also be taken into account. For the centimetre wavelengths, this corresponds to a variation of the path difference of the order of several metres, and for some settings may prove to be comparable to the path difference in the main direction of the AP. The value of ΔD_{max} in the main direction can easily be found when computing the antenna setting (Gelfreikh, Opeikina, 2000). In a manner similar to the calculation for the main direction, it can be computed in the whole region of the angles that define the field of view. Examples of antenna settings and their associated functions $\Delta D_{max}(x^s, y^s) = D_{max}(x^s, y^s) - D_{min}(x^s, y^s)$ are shown in Fig. 1, where (x^s, y^s) is the rectangular coordinate system in the picture plane on the sky, which is oriented along the declination circle and the diurnal parallel of the source. The functions $\Delta D_k = D_k - D_{min}$ corresponding to the given settings and representing examples of aberration functions that will be discussed in the next Section are also shown in this figure (k is the number of the panel).

Now we need to distinguish between the notions of antenna setting and antenna configuration. The antenna configuration is a collection of settings for the given position of the source, which have the same position of the focus, the number of panels and their arrangement in a circle. The settings of one configuration will differ from one another by the radial shifts of the panels with respect to the initial circle, and by the distribution of the field phase in the aperture of the antenna at a central wavelength (Φ^0). In this paper we shall deal with configurations for which the characteristics ΔD_{max} and ΔD_k only slightly change from setting to setting, since ΔD_{max} and ΔD_k in these settings make tens of metres, which is much greater than the optical path variations introduced for specifying Φ^0 providing for the necessary structure of the antenna pattern. Note that for RATAN-600 the value of the optical path variations of each ray cannot be > 2 m (the maximum radial shift is 1 m), and for radioheliograph settings it, generally, does not exceed one wavelength — several centimetres (Gelfreikh, Opeikina, 2000). So, all settings of such configurations can be characterized by one pair of functions ΔD_{max} and ΔD_k.

Let us test the validity of estimation of the bandwidth by formula (1), comparing the antenna patterns computed with different intervals of integration by frequency. The APs were computed for the settings belonging to the configurations displayed in Fig. 1. It can be seen that the value of ΔD_{max} for these configurations varies comparatively slightly within the field of view. For this reason, one can take its value in the middle of the field. Denote the bandwidth computed by formula (1) as Δf_0, then for configuration 1 $\Delta f_0 \sim 3.125$ MHz, for configuration 2 it is ~ 3.42 MHz. Fig. 2 shows the APs at 8 cm with intervals of integration by frequency of 0, Δf_0, $2\Delta f_0$ and

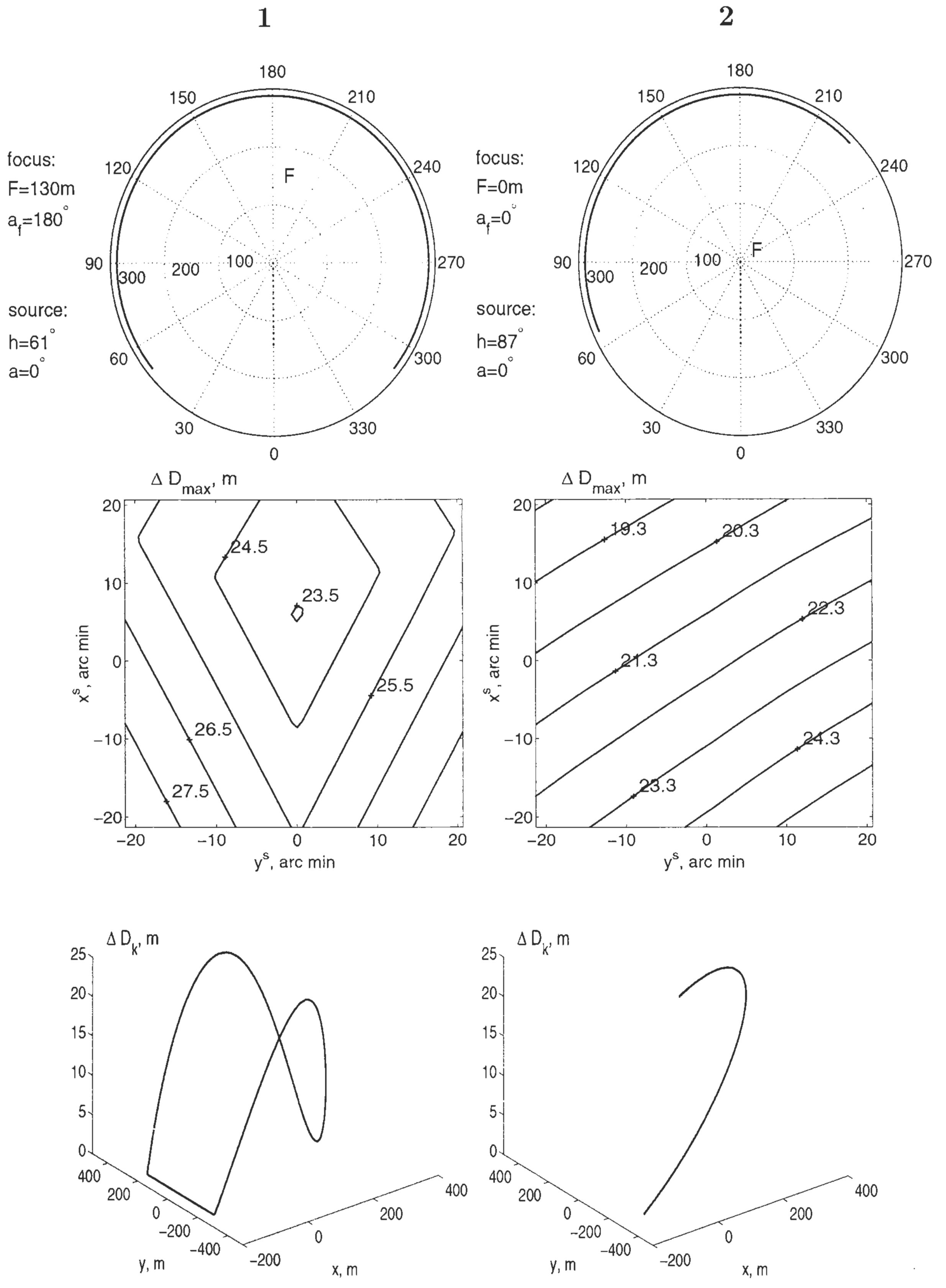

Figure 1: *Examples of antenna configurations and their characteristics:* ΔD_{max} *is the maximum difference of ray paths vrs the direction on the sky.* ΔD_k *— the aberration function vrs the coordinates in the aperture plane. The function values are given in metres.*

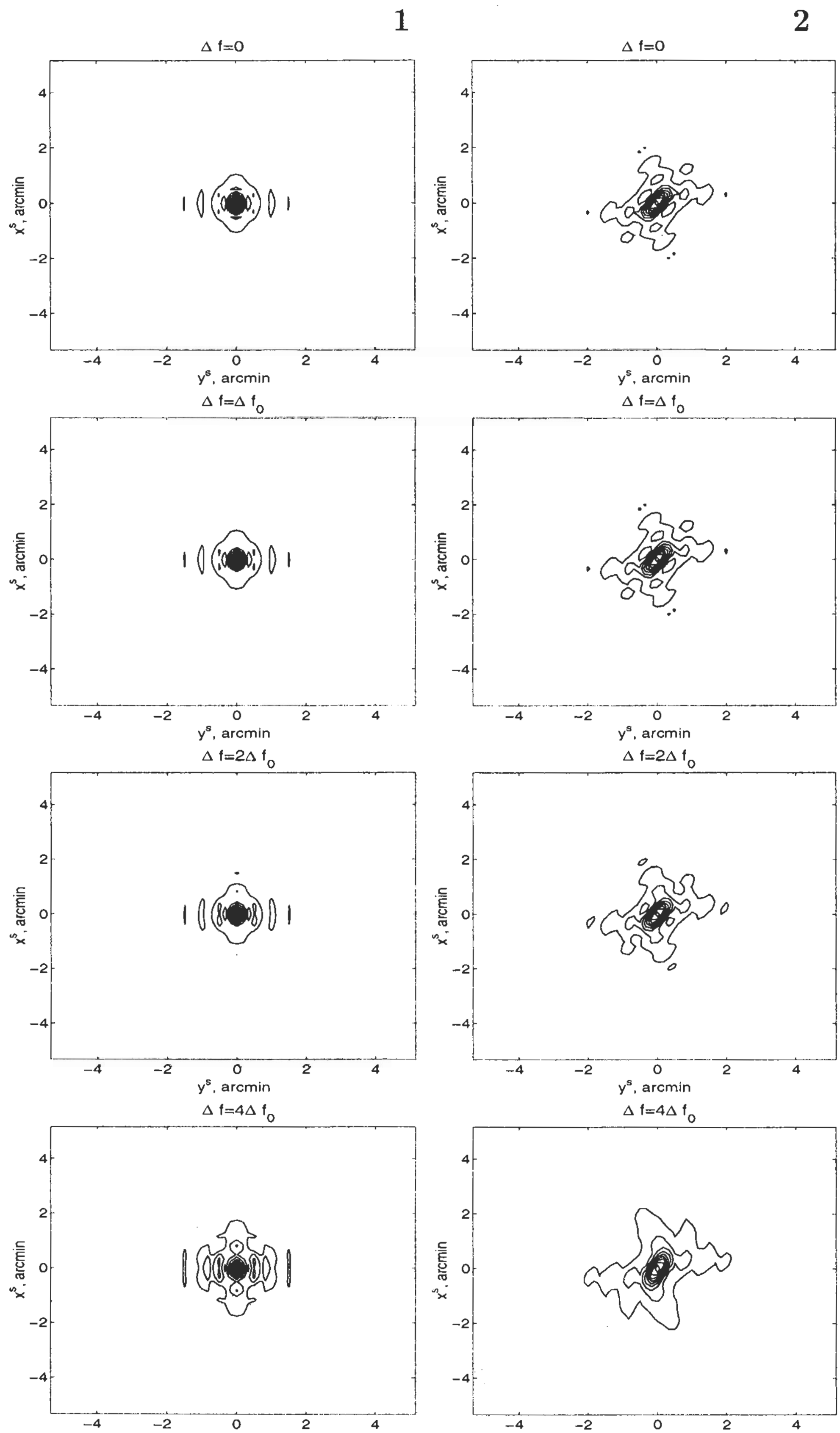

Figure 2: *Variations of the "zoned" antenna pattern with increasing frequency bandwidth for configurations 1 and 2.*

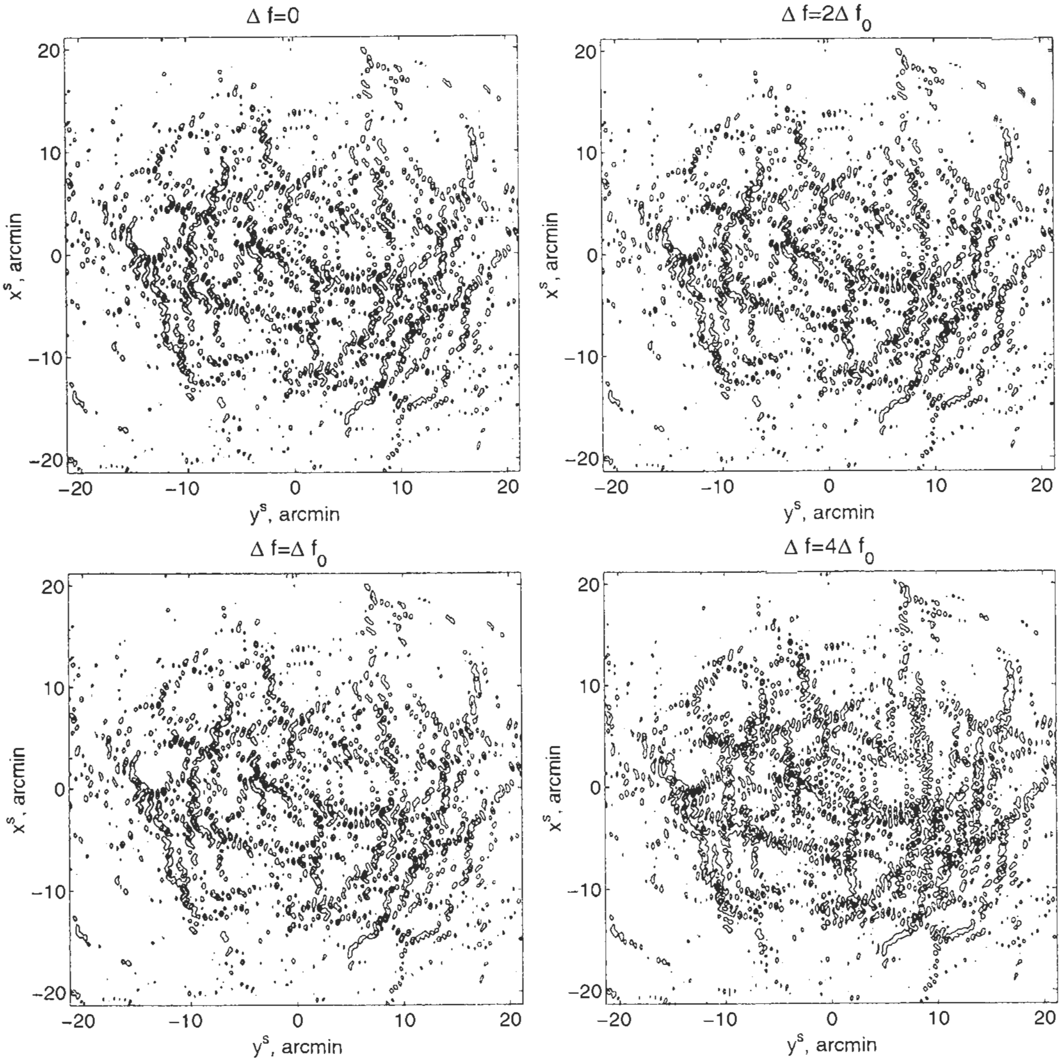

Figure 3: *Variations of the "non-cophasal" antenna pattern with increasing frequency bandwidth for configuration 1.*

$4\Delta f_0$ for the settings with zoning. The lobes the amplitude of which exceeds 10% of the maximum value are shown. It is seen that the antenna patterns with the band Δf_0 are nearly the same as the APs at the central frequency; in the band $2\Delta f_0$ the distortions of the APs are also negligibly small, and only when integrating in the band $4\Delta f_0$, noticeable variations arise. Figs. 3–4 show the antenna patterns for the same configurations and bandwidth values, but these APs are for the settings with the non-cophasal field distribution in the aperture. Here the isolines are given with a step of 20% and therefore the differences between the APs with the bands Δf_0 and $2\Delta f_0$ and the corresponding antenna patterns at the central frequency are still less visible. The lobes in the band $4\Delta f_0$ are markedly "blurred". Thus, the computations confirm that the frequency band can be estimated by formula (1), the parameters α and ΔD being selected so that the value of Δf_0 turns out to be underestimated and guarantees that the AP lobes will not be "blurred".

The values of Δf_0 for different settings of RATAN-600 may vary from ∞ to tenth fractions of a MHz. To select the optimum value of Δf_0, it is necessary to analyse all the settings that can be used in the radioheliograph mode with allowance made for requirements placed upon other parameters of settings (number of panels, distribution of panels in a circle, etc.) Such investigations have not been carried out to the full extent, however, computations of some radioheliograph settings show that the value of ray path difference makes tens of metres, and the bandwidth is a few MHz. It should also be noted that when resetting the antenna in the course of diurnal motion of the source, a bound set of configurations in which the bandwidth may differ a few times is formed. This involves additional difficulties in choosing the value of Δf_0.

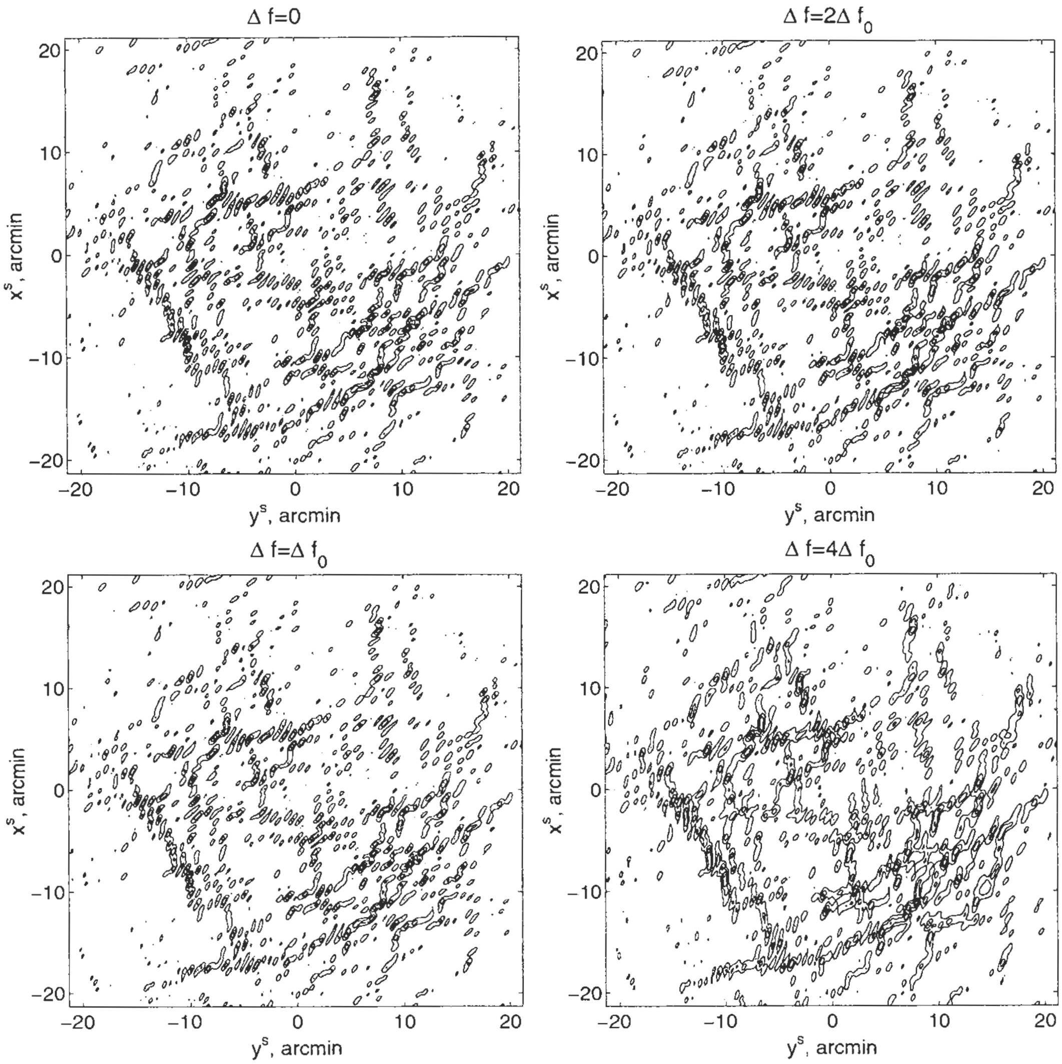

Figure 4: *Variations of the "non-cophasal" antenna pattern with increasing frequency bandwidth for configuration 2.*

3. Variations of antenna patterns with frequency

The variation of the phase function of the field in the antenna aperture brings about variations of the antenna pattern. The type of variations will be defined by the form of the functional dependence of the additional phase function component on the coordinates in the aperture plane (De Size, Ramsay, 1966; Stotskij, 1972). In the case considered here the phase function variation is caused by the frequency variation. Using the formula for computation of the radioheliograph antenna pattern $E = \sum_k E_k \exp(2\pi i D_k/\lambda)$ (Gelfreikh, 1977), write the phase function for the frequency $f + df$:

$$\Phi_k = \frac{2\pi}{c} D_k (1 + \frac{df}{f}) f = \frac{2\pi}{c} D_k f + \frac{2\pi}{c} (D_k \frac{df}{f}) f = \Phi^0{}_k + \delta\Phi_k, \quad (2)$$

where the variation of k (number of panel) corresponds to the variation of the coordinates in the aperture plane. The phase distortions are defined by the term $\delta\Phi_k$. To examine the form of the relation between this term and the coordinates, one has to consider the optical path function D_k:

$$D_k = R_k \cos(h) \cos(\pi + a - a_f - \phi_k) + \sqrt{R_k{}^2 + F^2 - 2R_k F \cos(\phi_k)} = D_k^{(1)} + D_k^{(2)}, \quad (3)$$

where (h, a) are the altitude and azimuth of the source, F is the distance between the antenna centre and the focus, a_f is the focus azimuth, R_k is the distance from the antenna centre to the centre of the kth panel (panel radius), ϕ_k is the panel azimuth with respect to the "centre–focus" direction, $D_k^{(1)}$ is the distance from the aperture plane to the panel centre, $D_k^{(2)}$ is the distance from the panel centre to the focus.

Choose rectangular coordinate systems in space, which are connected with the antenna plane (x^h, y^h, z^h) and the aperture plane (x, y, z) in such a way as shown in Fig. 5. The centres of the systems coincide and are located at the centre of the antenna. The x^h, y^h axes are in the antenna plane, the x, y axes are in the aperture plane. The antenna plane coincides with the horizontal plane, the x^h axis is oriented along the "centre–focus" line. The aperture plane is perpendicular to the direction to the source. The coordinate system in this plane is chosen so that the y axis coincides with the intersection line of the horizontal plane and the aperture plane. Thus, the (x, y) axes are oriented along tangents to the circle of altitude and almucantar of the source (h, a). The z axis is directed so that $D_k^{(1)} = -z$. The coordinates of the systems relate to one another as follows:

$$\begin{aligned} x &= \sin(h)\cos(\gamma)x^h + \sin(h)\sin(\gamma)y^h + \cos(h)z^h \\ y &= -\sin(\gamma)x^h + \cos(\gamma)y^h \\ z &= -\cos(h)\cos(\gamma)x^h - \cos(h)\sin(\gamma)y^h + \sin(h)z^h \end{aligned} \quad (4)$$

and

$$\begin{aligned} x^h &= \sin(h)\cos(\gamma)x - \sin(\gamma)y - \cos(h)\cos(\gamma)z \\ y^h &= \sin(h)\sin(\gamma)x + \cos(\gamma)y - \cos(h)\sin(\gamma)z \\ z^h &= \cos(h)x + \sin(h)z, \end{aligned} \quad (5)$$

where $\gamma = \pi + a - a_f$.

Since $R_k\cos(\phi_k) = x_k^h$, $R_k\sin(\phi_k) = y_k^h$, the expression for D_k in the horizontal coordinate system will be written as

$$D_k = \cos(h)\cos(\gamma)x_k^h + \cos(h)\sin(\gamma)y_k^h + \sqrt{\left(x_k^h\right)^2 + \left(y_k^h\right)^2 + F^2 - 2Fx_k^h}\ , \quad (6)$$

while in the coordinate system of the aperture plane, taking into account that for the antenna points $z^h = 0$, we derive

$$D_k = ctg(h)x_k + \sqrt{\left(\frac{x_k}{\sin(h)} - F\cos(\gamma)\right)^2 + \left(y_k + F\sin(\gamma)\right)^2}. \quad (7)$$

Thus, $D_k^{(1)} = ctg(h)x$ for any antenna settings is a linear function of the Cartesian coordinates in the aperture plane. A possible non-linearity of D_k is defined only by the term $D_k^{(2)}$. Note that the form of $D_k^{(1)}$ is not associated with the geometry of RATAN-600 and is the same for any positions of the antenna elements in the plane. If the term $D_k^{(2)}$ is absent, which is generally satisfied for antenna arrays, the type of variation of antenna patterns with frequency will then be the same for all such antennae and represent a displacement of the AP along the circle of altitudes (axis x) without changing its structure.

In the radioheliograph operation the type of aberrations of the antenna pattern depends on the term $D_k^{(2)}$, which is not equal to zero at any settings of RATAN-600. Below we shall discuss examples of antenna configurations in which $D_k^{(2)}$ can approximately be regarded as a constant quantity or a linear function of coordinates. Because only variations of D_k are of importance, we will call $\Delta D_k = D_k - D_{min}$ the aberration function, where D_{min} is a minimum value of D_k for the given setting (accordingly, $\Delta D_k^{(1)} = D_k^{(1)} - D_{min}^{(1)}$ and $\Delta D_k^{(2)} = D_k^{(2)} - D_{min}^{(2)}$).

1. If the focus is at the antenna centre ($F = 0$), then $D_k^{(2)} = R_k$. One can form antenna settings with $R_k = const$ for any sources and derive a strictly linear function D_k. However, as said above, in the radioheliograph operation it is provided for varying the position of panels in the radial coordinate to obtain Φ^0 of required form. Here $R_k \neq const(x, y)$, but the panel radius variations are small as compared to the radius of the initial circle R_0 because they are minimized by choosing the panel position with a desired phase near the initial radius (Gelfreikh, Opeikina, 2000). In this case the radius of the panel may be written as

$$R_k = R_0 + \delta R_k\ , \quad (8)$$

where $R_0 \gg \delta R_k$ and $R_0 = const(x, y)$. In settings with a path difference of over 10 m, which are of interest to us, the condition

$$\delta R_k \ll \Delta D_k^{(1)} \quad (9)$$

is also satisfied. For this reason, the value of δR_k may be ignored, that is, still consider $D_k^{(2)} \approx const$. The phase distortions will then be defined only by the linear term $D_k^{(1)}$, and the antenna patterns will be displaced along the circle of altitudes with varying frequency. In the rest frame of the source (x^s, y^s), which is oriented along the declination circle and the diurnal parallel, the "fan" of the APs will be located at an angle q with respect to the x^s axis, where q is the parallactic angle (the angle at the source in the parallactic triangle).

One can assess the AP displacement at the given frequency variation df proceeding from the fact that the phase function variation is equal to

$$\delta\Phi_k = \frac{2\pi f}{c} D_k \frac{df}{f} = 2\pi\frac{x}{\lambda} ctg(h)\frac{df}{f}. \quad (10)$$

Taking into account that when calculating antenna patterns, integration is done with respect to the variables $x' = \frac{x}{\lambda}$ and $y' = \frac{y}{\lambda}$, then according to the shift theorem for the Fourier transform, the displacement is

$$d\theta = ctg(h)\frac{df}{f}. \quad (11)$$

In reference to the axes x^s and y^s of the source rest frame, the displacements are $ctg(h)\cos(q)\frac{df}{f}$ and $ctg(h)\sin(q)\frac{df}{f}$ radians, respectively.

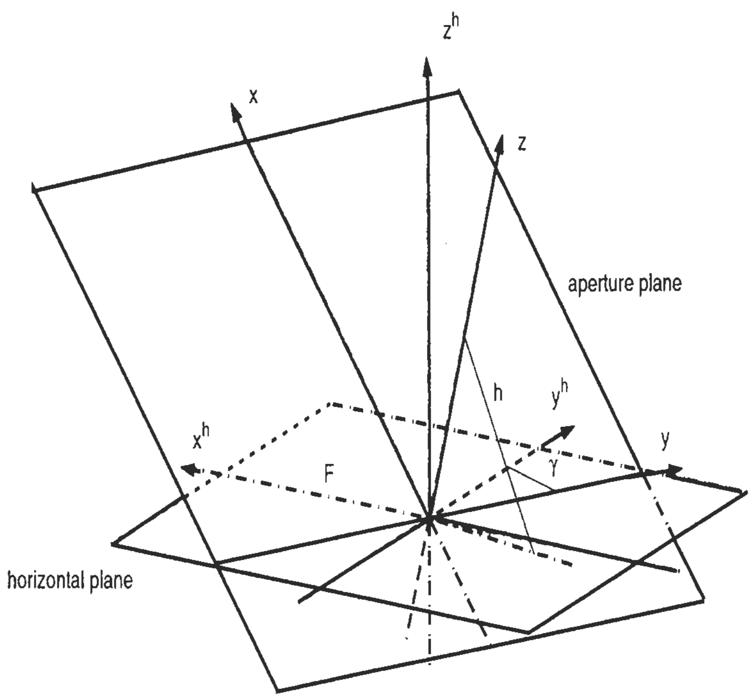

Figure 5: *Coordinate systems* (x^h, y^h, z^h) *and* (x, y, z).

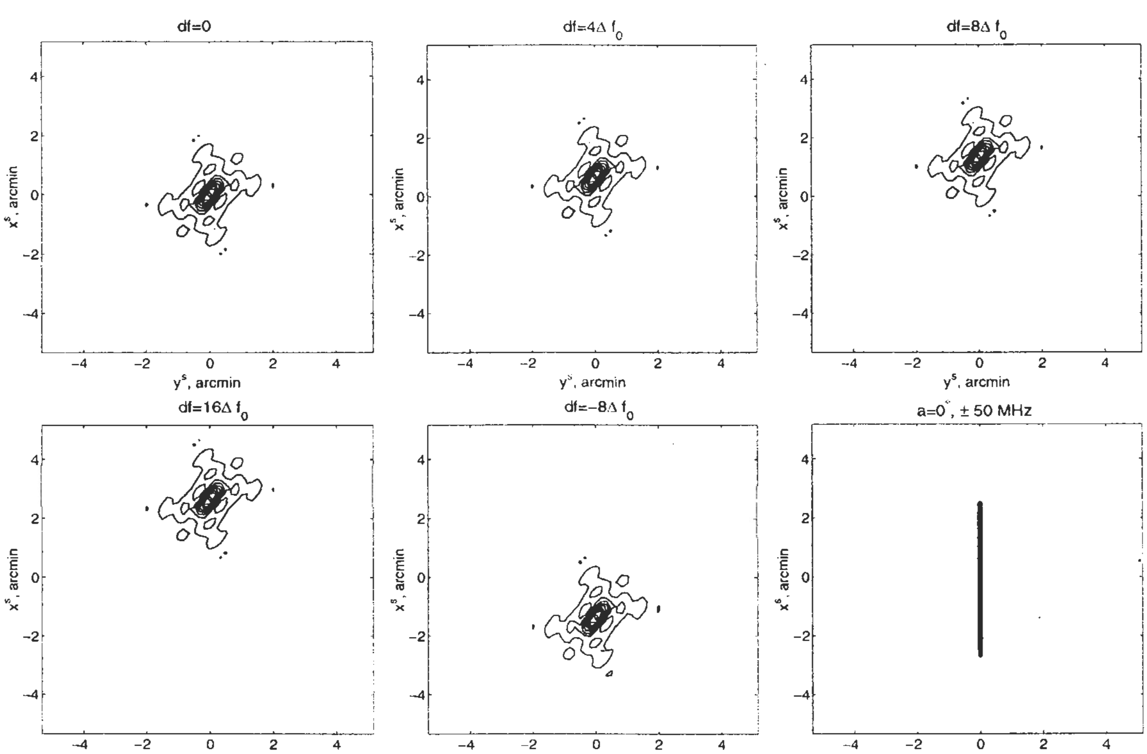

Figure 6: *Variations of the "zoned" antenna pattern with varying frequency* $(f' = f + df)$ *for configuration 2.*

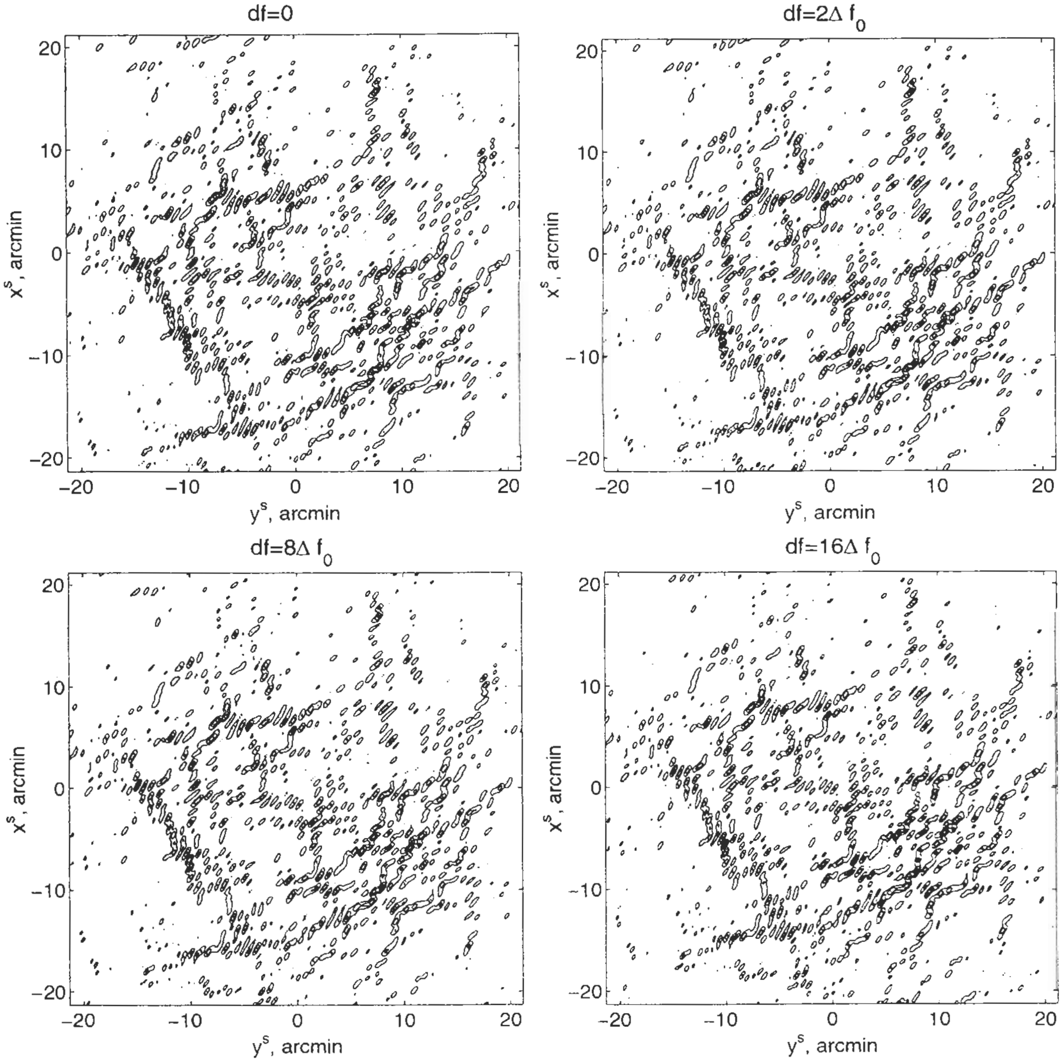

Figure 7: *Variations of the "non-cophasal" antenna pattern with variation of frequency for configuration 2.*

Such a type of antenna pattern variations with frequency is the same for all variants of the AP structure ("zoned", "non-cophasal", etc.) and practically independent of the number of panels in a setting and their arrangement in a circle.

The considerations presented are corroborated by the results of computer modeling. Figs. 6–7 show single-lobe and multilobe antenna patterns for antenna configuration 2 having $F = 0$. The antenna patterns are represented in the (x^s, y^s) coordinate system. One can see that as the frequency changes, they are displaced without distortion in both cases. Fig. 6 shows also the positions of the maxima of the antenna patterns computed in the range $df \pm 50$ MHz. In the given case, the source azimuth (a) is 0 and the direction of displacement is perpendicular to the direction of the source movement, that is, the y^s axis. Examples of how the direction of the AP displacement changes in relation to this source as its azimuth changes is displayed in Fig. 8. The angles between the directions of displacement, which are exhibited in the figures, and the x^s axis are equal to the parallactic angles for the corresponding positions of the source. The value of displacement of the computed antenna patterns agree with the value computed by formula (11). For instance, for $h = 87°$, $f = 3.751$ GHz and $df = 2.5$ MHz the antenna pattern is displaced by $7''\!.2$. The computed aberration function ΔD_k for configuration 2, which is shown in Fig. 1, is a linear function of (x, y) since the points of the curve by which it is represented lie in the same plane.

2. If $F \neq 0$, but the condition $F \ll R_k$ as well as conditions (8) and (9) is satisfied, the optical path may approximately be written as a linear function:

$$D_k \approx ctg(h)x - \frac{F}{\sqrt{R_0^2 + F^2}} \frac{\cos(\gamma)}{\sin(h)} x + \frac{F}{\sqrt{R_0^2 + F^2}} \sin(\gamma) y + \sqrt{R_0^2 + F^2}. \qquad (12)$$

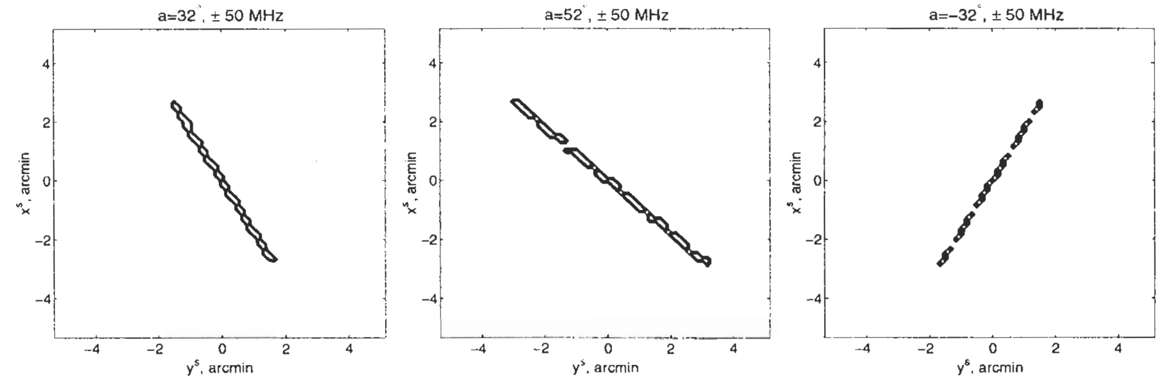

Figure 8: *Variation of the direction of displacement of the antenna pattern with variation of the source azimuth in the source rest frame for settings with $F = 0$.*

The direction and rate of displacement of the antenna pattern change as compared to the previous case. If $\sin(\gamma) = 0$, i.e. the focus azimuth is opposite or equal to the source azimuth, the displacement will still occur along the circle of altitudes, but at a rate proportional to

$$ctg(h) \mp \frac{F}{\sin(h)\sqrt{R_0^2 + F^2}}. \qquad (13)$$

3. Linear phase distortions arise also when the sources located near the meridian are observed with antenna settings having the same parameters (focus position, number of panels and their arrangement in a circle) as the so-called "standard" setting when the source is observed in the meridian without the optical path difference. Denote such settings by "$F = F_{st}$". The component $D_k^{(2)}$ is independent of the source position and is equal in the settings discussed. The linearity of D_k is explained here by the fact that the component $D_k^{(2)}$ remains compensated by the component $D_k^{(1)}$ long enough while the source moves away from the meridian. Let us write the summand $D_k^{(1)}$ in the coordinates (x^S, y^S) in the aperture plane, whose axes are parallel to those of the system (x^s, y^s):

$$D_k^{(1)} = ctg(h)(\cos(q)x^S - \sin(q)y^S) = A(t)x^S - B(t)y^S, \qquad (14)$$

where t is the hour angle of the source and

$$A(t) = \frac{\sin(\phi)\cos(\delta) - \cos(\phi)\sin(\delta)\cos(t)}{\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(t)}$$

$$B(t) = \frac{\cos(\phi)\sin(t)}{\sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(t)}, \qquad (15)$$

δ is the declination, ϕ is the local latitude.
At small departures from the meridian the function $A(t)$ varies slowly ($\sim \cos(t)$), while $B(t)$ varies fast ($\sim \sin(t)$). In the settings discussed here, the slow variation of $A(t)$ leads to the fact that at small $|t|$ the value of $A(t)x^S + D_k^{(2)} \approx const(k)$, as $A(0)x^S + D_k^{(2)} = const(k)$ ("standard setting"). In this case the aberration function is defined by the term $B(t)y^S$, and the displacement of the antenna patterns occurs along the line the source moves. This behaviour of the antenna patterns is presented in Fig. 9, and the direction of displacement for different azimuths is given in Fig. 10. The rate of variations of the functions $A(t)$ and $B(t)$ also explains the character of variation of the value of AP displacement in the case where $F = 0$ (Fig. 8): when the source azimuth changes the value of displacement along declination remains practically the same as in the meridian, while the value of displacement in hour angle changes significantly.

The settings with $F = 0$ and $F \ll R$ discussed in items 1 and 2 may be used for scanning the sources as they pass across the "fan" of similar antenna patterns since in these cases the axis of the "fan" is perpendicular to or makes an angle with the line of the source movement. Here it should be taken into account that although the behaviour of the patterns for settings with $F = 0$ is independent of the altitude of the source, only the settings for circumzenith objects with $h > 80°$ have quite a great number of panels in this case (Gelfreikh, Opeikina, 2000). Besides, settings with $F = 0$ are not suited to observation of sources with $h \sim 90°$, because the rate of displacement of the antenna patterns with frequency is very low. The rate of displacement (the bandwidth) and the number of panels can be manipulated by changing the focus position using the settings "$F \ll R$". Computations show that in this case the linearity of the phase function retains for F of about a few tens of metres. The settings dealt within item 3 are, on the contrary, unfit for scanning the sources in their diurnal movement since one and the same scan displaced in time will be recorded in different frequency channels. It should also be noted that in all the cases allowance made for the sizes of the co-phasal element will slightly affect the type of variation of the antenna pattern by narrowing the region of the angles at which the AP is displaced without aberrations. However, this may be disregarded at small frequency displace-

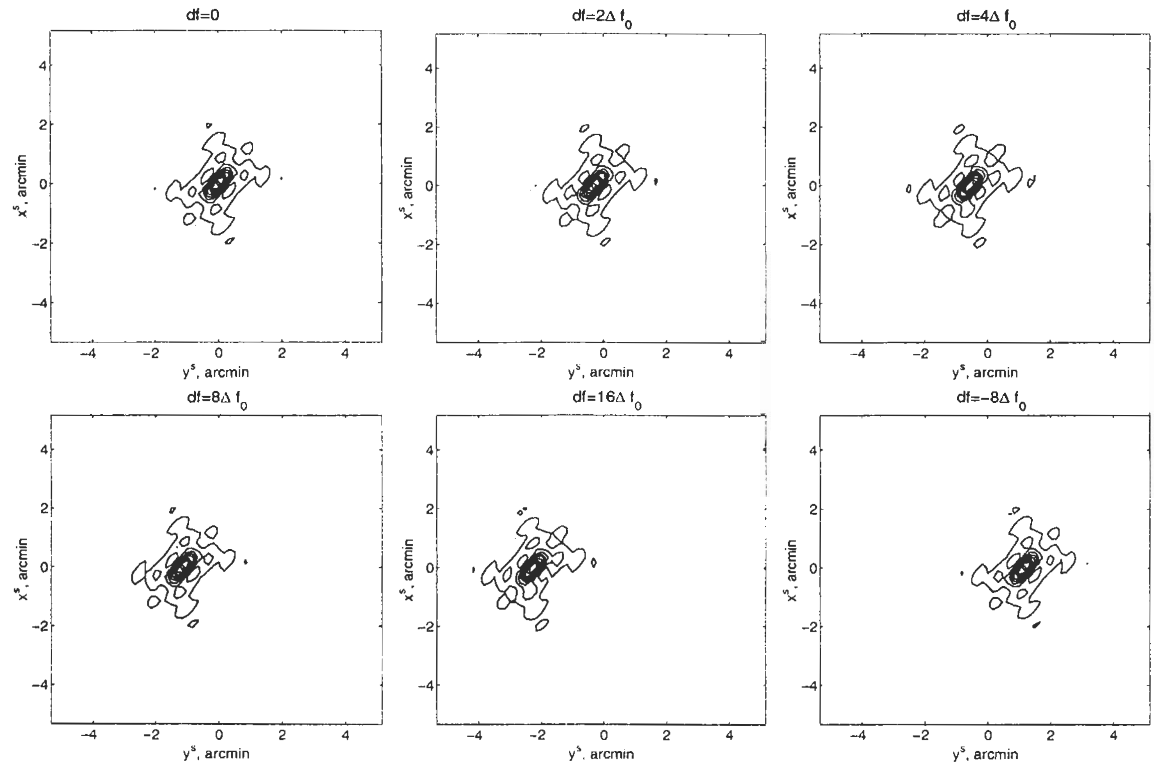

Figure 9: *Variations of the antenna pattern with varying frequency for the setting with $F = F_{st}$. The coordinates of the source $h = 85°, a = 52°$, the position of the panels is the same as in configuration 2.*

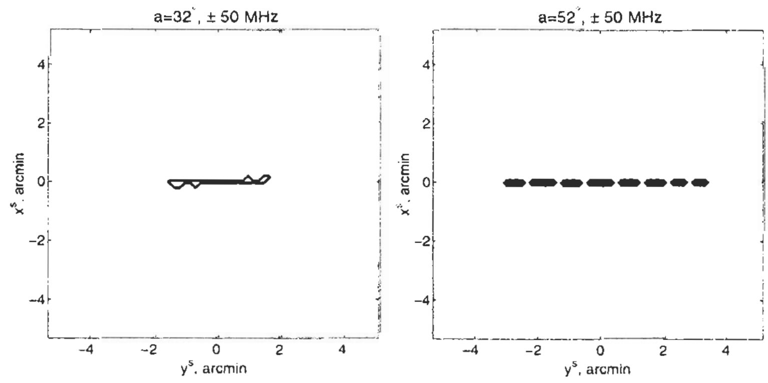

Figure 10: *Direction of displacement of the antenna patterns in the settings with $F = F_{st}$.*

ments for antenna patterns occupying a field of view smaller than the beam of one panel.

Examination of other antenna settings and selection of settings with the type of antenna pattern variation with frequency suitable for "frequency scanning" can be carried out by means of numerical calculation and analysis of their associated functions $\Delta D_k(x, y)$. This analysis is simplified owing to the fact that in settings with a large difference of ray paths the effect δR_k has on the form of the function $\Delta D_k(x, y)$ may be neglected (ignoring δR_k, we assume that *df* is sufficiently small too). Under these conditions the type of variation of the antenna pattern (type of aberrations) is defined by the antenna configuration parameters and is practically independent of the shape of phase distribution at the central frequency for the given setting. The functional dependence ΔD_k can then be estimated for only one of the settings of the given configuration, and it will hold true for the rest of the settings. This is confirmed by computer modeling for the configurations with the linear aberration function; it should be expected, however, that this holds true for configurations of more complex type of AP distortions. The examples of antenna patterns with complex distortions are given in Fig. 11.

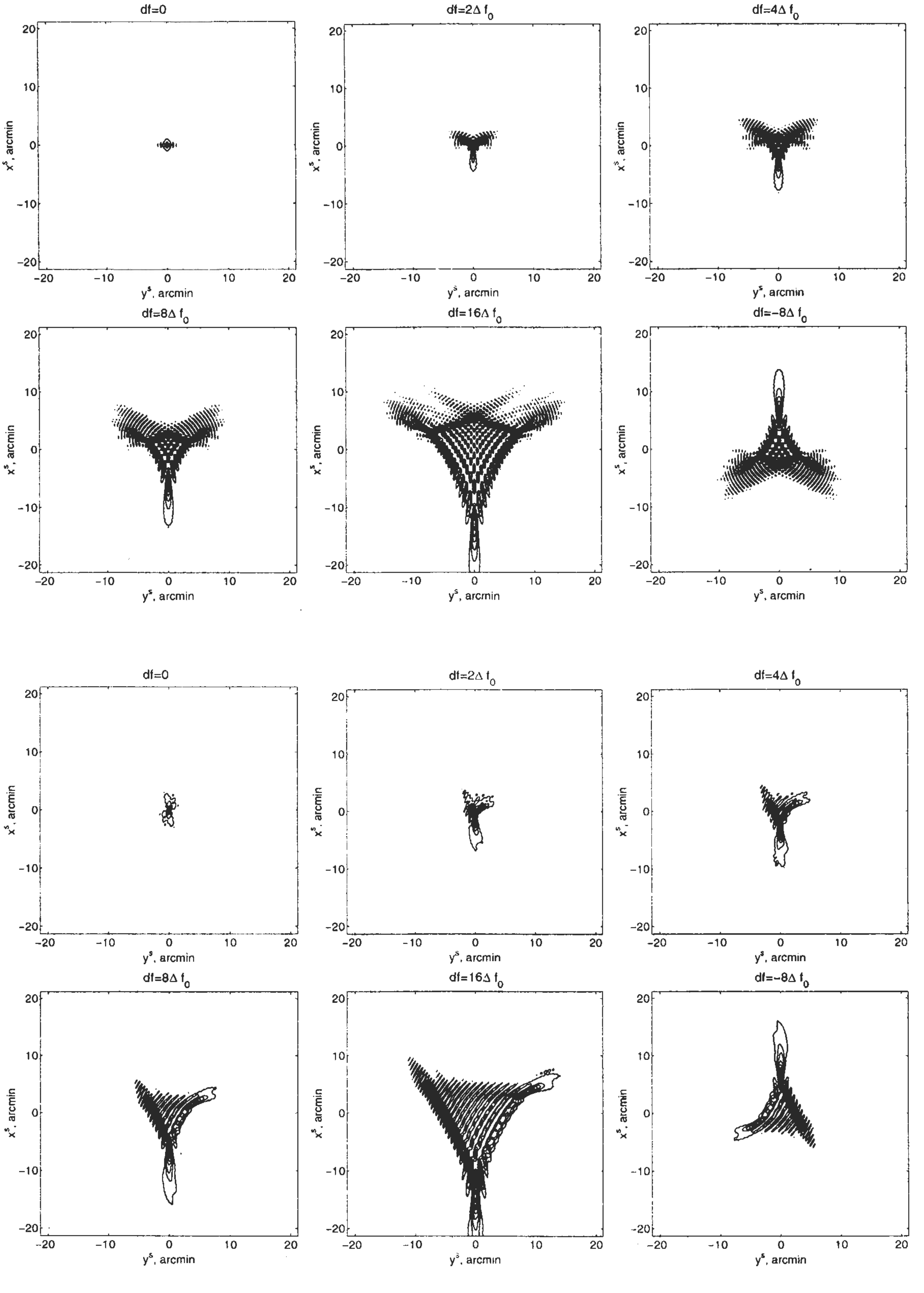

Figure 11: *Variations of the "zoned" antenna pattern with variation of frequency for configuration 1 (two upper rows) and for the configuration in which the position of the source and the focus coincides with configuration 1, while the number and positions of panels — with configuration 2 (two lower rows).*

4. Evaluation of spacing between channels

For "frequency scanning" to be implemented, the antenna pattern must vary significantly when changing from one frequency channel of the radiometer to another. This is the principal condition for choosing the spacing between channels. It is obvious that the spacing will be proportional to the frequency bandwidth and one can estimate the proportionality factor for the case of linear phase distortions.

Consider the case $F = 0$. The difference in ray paths here is determined by the distance from the aperture plane to the antenna panels. Examining any pair of panels, it can be seen that the path difference is $d_a \cos h$, where d_a is the projection of the baseline onto the azimuthal direction of the source in the horizontal plane (in Fig. 5 this direction is specified by the projection of the z axis onto the horizontal plane). To evaluate the bandwidth, a maximum path difference is taken, which corresponds to d_a^{max} — maximum of the projection of the baselines. Obtain the bandwidth by formula (1):

$$\Delta f = \frac{2c\alpha}{d_a^{max} \cos h}. \qquad (16)$$

According to formula (11), the value of displacement of the antenna pattern for $df = \Delta f/2$ is

$$d\theta = \frac{\alpha\lambda}{d_a^{max} \sin h}. \qquad (17)$$

Considering that the projection of the baseline onto the direction of displacement in the aperture plane (x axis) is $d_a \sin h$, derive that the AP displacement, as the frequency is displaced by the half-width of the band, is part α out of the AP beamwidth (width of one lobe) in the direction of displacement. Then, as the estimate of frequency spacing between channels one can then take the quantity

$$\delta f = \frac{\Delta f}{4\alpha}, \qquad (18)$$

which will provide a displacement by half a beamwidth, that is, quite significant AP variations.

It can be shown that the established relationship between the frequency variations expressed in terms of bandwidth and the spatial displacement of the antenna pattern expressed in terms of beamwidth is satisfied in all cases where D_k is a linear function (x, y). It should however be noted that if the number of panels in a setting is small and the antenna pattern is strongly dissimilar in different directions, the quantity δf may then prove to be insufficient for scanning towards the larger size of the AP because δf is consistent with the AP width only in the direction of displacement. For the case of more complex, than linear, phase distortions, the proportionality index of the bandwidth and the spacing in frequency may also turn out to be a different one.

5. Conclusion

The conclusions of this paper are as follows.

1. There are a number of antenna settings for which the variation of the antenna patterns with varying frequency is a displacement of the antenna pattern in space without aberrations. In particular, here belong the settings with the focus at the antenna centre ($F = 0$). In this case the type of variation of the antenna patterns with varying frequency is practically independent of the number of panels and their arrangement in the circle, neither does it depend on the altitude of the observed source. The antenna pattern is displaced along the circle of altitudes without distorting its structure. The AP displacement does not depend on the antenna parameters and equals $ctg(h)\frac{df}{f}$. Such a behaviour of antenna patterns is characteristic not only of the radio telescope RATAN-600 but also of other two-dimensional arrays with arbitrary positioning of elements in the plane if the phase differences between the elements are defined only by the ray paths from the wave front plane to the elements.
Displacement of the antenna pattern without distortion of its structure occurs also in the antenna settings with the focus near the antenna centre ($F/R \ll 1$) and in the settings close to standard ("$F = F_{st}$"). The direction and displacement value in them differ from the displacements in settings with $F = 0$. This makes it possible to choose settings with the direction and rate of displacement suitable for source scanning. One has to provide for the fact that in the settings "$F = F_{st}$" displacement occurs along the direction of movement of sources, which does not enable scanning of the source in its diurnal motion.

2. In the radioheliograph settings, which are characterized by the large difference of ray paths, the form of "chromatic" aberration functions depends only on the position of the source, focus and position of the panels. This leads to the same type of variations with frequency of APs of different forms (single-lobe, "non-cophasal") at the same antenna configurations. In the present paper, such a feature is demonstrated by the example of settings with linear aberration functions, in which the antenna patterns, at any phase distributions at the central frequency, are displaced without distortions with varying frequency. The same type of aberrations for all settings of the same configuration permits one not to take up each setting separately and simplify the procedure of choosing settings for observations.

3. The frequency bandwidth of one channel of a multichannel radiometer needed to realize the radio-

heliograph mode is determined by difference of ray paths in the antenna system. The maximum difference of ray paths in the main direction of the antenna pattern can be taken for bandwidth assessment. In settings with the linear aberration function, a displacement in frequency equal to bandwidth caused an AP displacement by a certain fraction of the beamwidth in the direction of this displacement. This permits the interval between the frequencies of the channels, which provides obtaining independent scans in "frequency scanning", to be expressed in terms of bandwidth (or maximum difference of ray paths in a setting).

In the antenna settings concerned within the paper, the form of the antenna pattern remains unaffected at varying frequency, which facilitates considerably the processing of images obtained with their aid. However, such settings are not suited for observations of the Sun because the number of panels in them will be small and the spatial resolution will be low. Nevertheless, one should examine with great thoroughness the settings for the utmost altitude of the Sun ($\sim 70°$) and the focus positions close to the antenna centre. The results of the paper point also to the fact that there are antenna settings that cannot be used for frequency scanning, irrespective of the antenna pattern structure (for instance, settings "$F = F_{st}$"). In order to exclude use of such settings in observations, it is needed either to inspect carefully the conditions under which such settings are formed or check preliminarily all the settings prior to observations. It is possible to study the variations of the antenna patterns with frequency in a great number of settings without resorting to computation of antenna patterns, which demands much computation. For this purpose an algorithm can be developed for evaluation of the type of variations of antenna patterns with frequency on the basis of analysis of the expression for the aberration function derived in this paper.

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