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RATAN-600 AS A MM-ARRAY

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ABSTRACT

It is shown that multi-elements surface of the Russian biggest reflector may be considered as a 1000-element array with limited freedom of motions of each element. This limitation may be compensated by selection of the proper "virtual sub-array" of elements at any given direction of observations. This approach is especially effective for mm-waves where field of view of 600-meter reflector in usual mode is less than 1 arcsec. The present stage of realization of that project is shortly discussed, including requirements for multi-feed system near the focal plane of the radio telescope, wavelength limitations and error budget, and near field zone 3-dimensional synthesis mode of observation.

INTRODUCTION

RATAN-600 radio telescope has no analog in Radio Astronomy. Being the world greatest (in size) reflector , it is also one of the first realizations of the multi-element NTT : homology, aperture synthesis, adaptive optics , holography — all these methods are in the every day use or in the test experiment phase. Here we describe some new suggestions which may be realized extending Fiso sub-aperture approach to its extremes variant with the help of phased array near the focal plane of the telescope Special attention will be given to the solution of the field of view problem at short wavelengths and to the possibilities of three-dimensional image in the near field zone of the RATAN-600.

FROM RING REFLECTOR TO THE ARRAY OF INDEPENDENT ELEMENTS

Flexibility and power of the Ryle Synthesis method made many original projects to incorporate it in many observational programs (e.g., transformation of the "Mills" and "Cris" crosses, "Wild" circle to Ryle synthesis arrays). RATAN-600 has now all 1000 panels under computer control and we are also ready to investigate the efficiency of the use of our reflector telescope as a usual array. Next step in this direction connected with construction of the small field phased array near the focal plane of the telescope. The first step was tested in 60^{th} (Esepkina et al., 1961). One-dimensional model is under way but two-dimensional multi-element small phased array approach is in the pilot design stage (Pinchuk et al., 1991). It is shown that limiting number of sub-elements which can operate independently is close to the

$$N = \frac{S}{\lambda R}$$

where S-geometrical surface of the radio telescope, R-radius of the circle. $\lambda R = S_f$, that is the surface of the first Frenel zone visible from the center of the circle. For the longest wavelength ($\lambda = H^2/R$, $H = 11.4$m , the height of the panel) we can have 150 elements with effective diameters $D = 13$m. For $\lambda = 3$mm Frenel zone is much smaller than the size of the panel and N is greater than 10000. Even with proper field phase array in the focal plane we are strongly limited by the azimuthal mechanical limitation in the movement of each panel (13 degrees only). But from 225 to 900 panels can see the same point on the sky at any R.A. and DEC. We can use the proper (and big enough) "virtual sub-array" to map the source in the snap-shot mode and in Earth rotation synthesis mode as well. The maximum possible field of view of this array is limited by

$$field\ of\ view = \lambda / S_f$$

which is by factor D/λ (close to $G^{1/2}$ where G is Gain-factor) greater in this mode of operation than in the simplest reflector-type mode.

FROM CM- TO MM-WAVELENGTHS

Last few years we improved quality of the main surface. In our case we have at least sources of errors: r.m.s. accuracy of the panels, geometrical deviations of the shape of panels from the theoretical local shape of the elliptical cone , errors of panel adjustment and the secondary mirror errors. More than 100 panel was resurfaced recently with r.m.s. error 0.08 mm for the central 5.5 m and 0.18 mm for the 7.4 m. Holography correction gives us about 0.08 mm accuracy of the mutial panel alignment process. Some applications of holography for surface testing are given in the work (Khaikin, 1992). Without secondary mirror problems random surface errors can be decreased to 0.1 mm. Two main geometrical errors depend on elevation of the source. With the identical geometry of the panels r.m.s. error connected with deviations of the local curvature of the elliptical cone from real (mean) curvature of panels is about 0.25 mm at the horizon and decreases to zero at Zenith. "Diagonal" error connected with deviation of the guiding lines of the cylindrical surface of the real panel from the guiding lines of the local theoretical elliptical cone guiding lines is maximal at the medium elevations (up to .25 mm, r.m.s. even for central 5.5 m of the panel) but is zero for Zenith and horizon. Error budget analysis shows us that the best situation appears at high elevations where only random errors exist depressed by $\cos(h/2)$, h-elevation of the source. It means that maximum gain-factor may be reached at wavelength

$$\lambda = 4\pi\varepsilon_{rms}\cos(h/2) = 1mm$$

for high h if we ignore secondary mirror problems and many other small problems. For safety, we shall take $\lambda_{min} = 3$mm. in discussions below.

ARRAY

Using recommendations of NRAO group (Hjelming, 1990) we list below most important parameters of the array which may be constructed on the base of the existing construction of RATAN-600. To compare RATAN-600 in array mode with mm array of the NRAO group we begin with the sub-array of 21 elements each having 10-meter dish collecting surface at 3mm operating wavelength.

TABLE I Some antenna design parameters

Number of elements N	21
Maximum antenna separation B (meters)	576
Effective diameter of the single element (meters)	10
Geometrical area (meters^2)	1649
System temperature (K)	200
Wavelength (mm)	3
Bandwidth (GHz)	1
Observation time (min)	2
Maximum possible number of the occupied UV-cells	10423
Real number of the occupied cells	416
Mean number of the data points per occupied UV-cell	1
Side-lobe r.m.s. level, natural weighting,	0.048
Side-lobe r.m.s. level, uniform weighting,	0.048
Solid angle of synthesized beam, natural weighting (arcsec.)	0.23
Solid angle of synthesized beam, uniform weighting (arcsec.)	0.23
R.m.s. sensitivity of 1 pair of elements (mJy)	19.43
Point source sensitivity, natural weighting (mJy)	0.946
Point source sensitivity, uniform weighting (mJy)	0.948
R.m.s. brightness temperature sensitivity, nat.weight. (mK)	67.6
R.m.s. brightness temperature sensitivity, unif.weight.(mK)	67.6
Percents of the holes on UV-plane	0.993

For one-hour tracking time (maximum possible time for the Zenith mode of operation with all 900 elements) we have the following table (first 7 parameters are the same as in the TABLE 1)

In the most powerful zenith mode we can have array of 174 elements with 10-m class elements , that is about 8 independently operating sub-arrays of VLA type. For about 3 steradians of the sky the following parameters may be reached:

We listed the parameters of the RATAN-600 in the array mode using 21 × 10 m sub-array terminology just to compare with NRAO first version of mm-array (Hjelming, 1990). Unusual feature of RATAN-600 is high flexibility of the proposed array. Introducing "virtual array " or "virtual two-element" concept

TABLE II Some antenna disign parameters

Observing time (hours)	1
Maximum possible number of the occupied UV-cells	10423
Real number of occupied cells	1905
Mean number of the data points in occupied cell	1.17
R.m.s. side-lobe level, natural weighting,	0.025
R.m.s. side-lobe level, uniform weighting,	0.023
Solid angle of the synthesized beam, arcsec/λmm,	0.18
Solid angle of the Synthesized beam, arcsec/λmm	0.19
R.m.s. point source sensitivity for 1 pair of elements (mJy)	3.55
R.m.s. point source sensitivity of array, nat. weight. (mJy)	0.24
R.m.s. point source sensitivity of array, unif.weight. (mJy)	0.25
R.m.s. surface brightness sensitivity, natural weight. (mK)	48.4
R.m.s. surface brightness sensitivity, uniform weighting (mK)	31.9
Percent of the holes on UV-plane	0.81

TABLE III Some antenna disign parameters

Geometrical area, (meters^2),	13665
Observing time (hours)	1
Side-lobe level, natural weighting,	0.010
Side lobe level, uniform weighting,	0.009
R.m.s. point source sensitivity, natural weighting (mJy)	0.003
R.m.s. point source sensitivity, uniform weighting (mJy)	0.004
R.m.s. surface brightness sensitivity, nat.weight. (mK)	0.27
R.m.s. surface brightness sensitivity, unif.weight. (mK)	0.32

we can match array UV-sensitivity with a priori information about UV -image of the object, we change the track of the "virtual two-element interferometer" pixel on the UV- plane (normally it is ellipse with fixed parameters). It is easy to optimize different "mosaic" modes (Cornwell, 1989) of observations to extend the field of view much above the λ/S_f limit. "FAST"-project of the US may be incorporated by RATAN-600 array mode.

FROM TWO- TO THREE-DIMENSIONAL IMAGING

As we pointed out in 1969 (Parijskij,, 1969), great expansion of the arrays sizes expend the near field zone (up to the cosmological horizon for ecliptic size array). Recent increase of interest to the nearby black body objects makes us to estimate RATAN-600 array abilities in three-dimensional patrolling of the near field zone. It is possible to obtain x, y, z coordinates of any point object with accuracy depending on the distance :

$$\varepsilon X = \lambda/D \cdot R \cdot N/S$$

$$\varepsilon Y = \lambda/D \cdot R \cdot N/S$$

$$\varepsilon Z = \frac{\lambda}{2\sin^2(\frac{D}{R}) \cdot \frac{N}{S}} = 2\lambda \cdot (\frac{R}{D})^2 \cdot N/S$$

Here D is a diameter of the RATAN-600, R — a distance to the object, N/S — signal-to-noise ratio. Near field zone for RATAN-600 extending up to the Moon at mm-wavelengths and to 10.000 km at decimeters. In principal, it is possible to extend Bracewell formalism for 3-dimensional u, v, w case . Triple interferometer with base D can operate as filter on Z-axis which is sensitive to the space frequency

$$w = \frac{D^2}{2\lambda R}$$

Parabolic dish with proper phase mask can operate in the near field zone as 3-dimensional space frequency filter in ranges

$$0 < u < D/\lambda$$

$$0 < v < D/\lambda$$

$$0 < w < \frac{D^2}{2\lambda R}$$

and convolution theorem may be written as

$$T_a(x_0, y_0, z_0) = f(x - x_0, y - y_0, z - z_0) * e(x, y, z)$$

where T_a is an antenna temperature, f – "three dimensional beam", and e – emissivity of the object. With the multi-element phase array in the focal plane and multi-channel mode of operation after each front-end receiver of the array elements we can have many $3D$-beams inside the near field zone simultaneously. Refocusing in the near field zone can greatly improve the signal as far as the size of the beam, $(\lambda R/D)^2$, is less than aperture of the radio telescope.

CONCLUSION

It is possible to use RATAN-600 as an array with high gain in the field of view. We hope, that (some times) this project may be realized. Computation and some technical phased array problems are out of the scope of present discussion.

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DISCUSSION

M. Ishiguro You showed the 21-element randomly spaced array. Where the limitation in the number of array comes from?

Y. Parijskij Just to compare with early VLA-mm. project (21 10m dishes). But with flexible focal array every changes may be done just by programming.

R. Brown What is the elevation of the site? How much of the year do you expect to be able to operate at 3mm?

Y. Parijskij The elevation is 974m above sea level. There are no problem during night winter time. With over-redundant aperture we have there is also strong averaging effect.