Multibeam FPAs for MM-wave radio telescope: simulation and realisation

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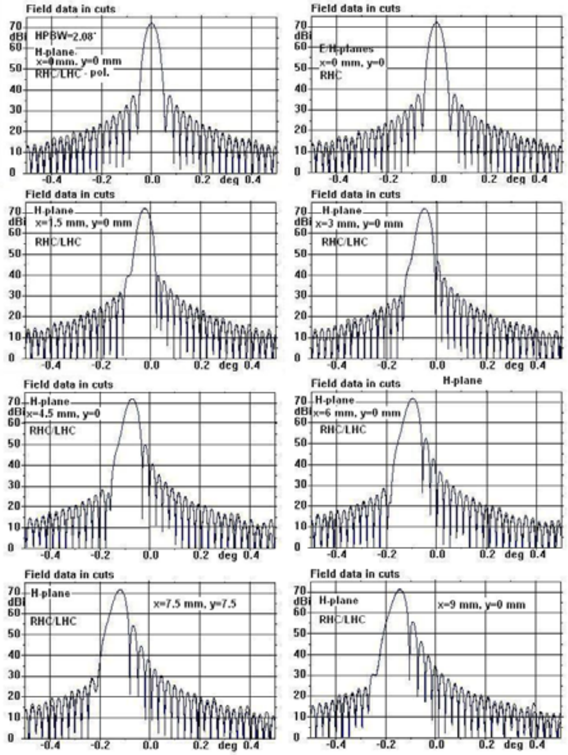
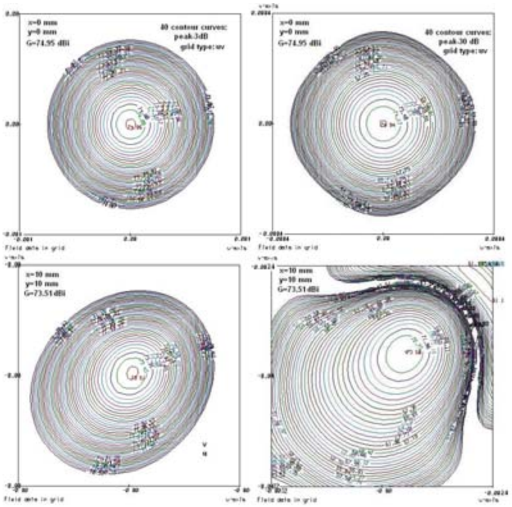
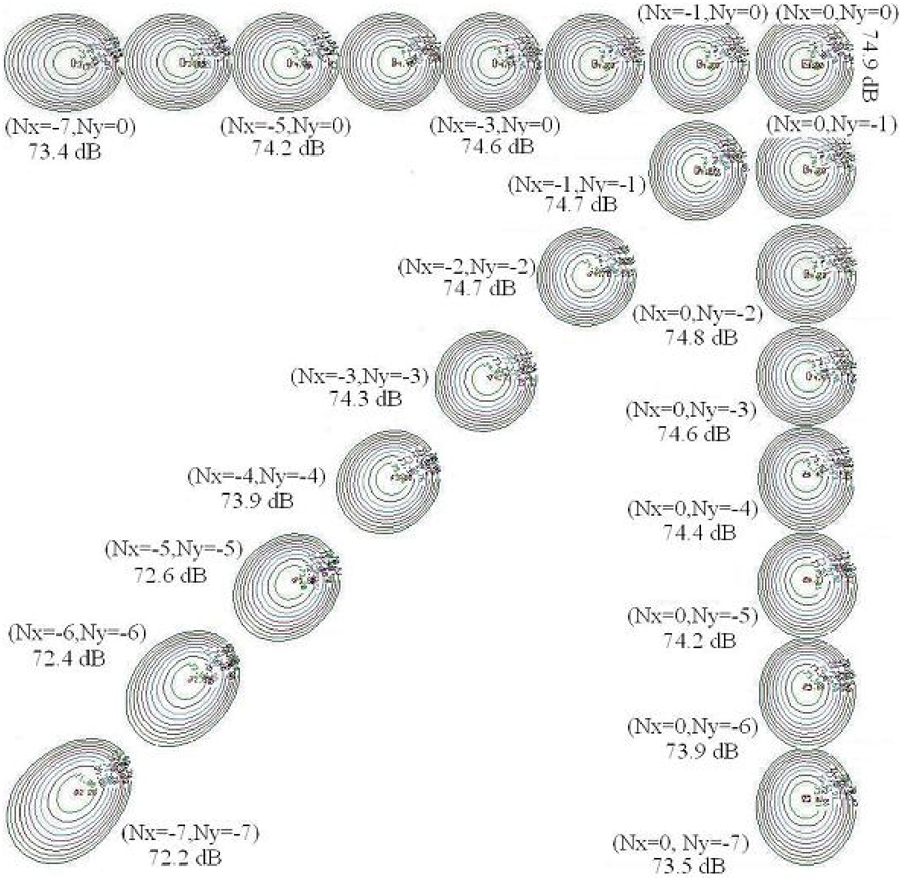
Second International FPA Workshop

- Multibeam FPAs may essentially widen the field of view, accelerate surveys, improve the integral sensitivity of a radio telescope, reduce atmospheric effects.
- Some peculiarities must be taken into account for reflector antenna modelling in MM band when the size of antenna may be very large in terms of the wavelength.
- Use of Physical Optics for simulation of beam pattern becomes impossible or very slow at high frequencies where GO and GTD have to be also used to calculate aperture distribution and edge-scattering effects at the main reflector, the subreflector and struts
- Radio telescope optics determines the aperture distribution, the feed flare angle, beam deviation and off-axis aberrations. Optimisation of radio telescope optics and FPA geometry help to find the best multibeam solution.







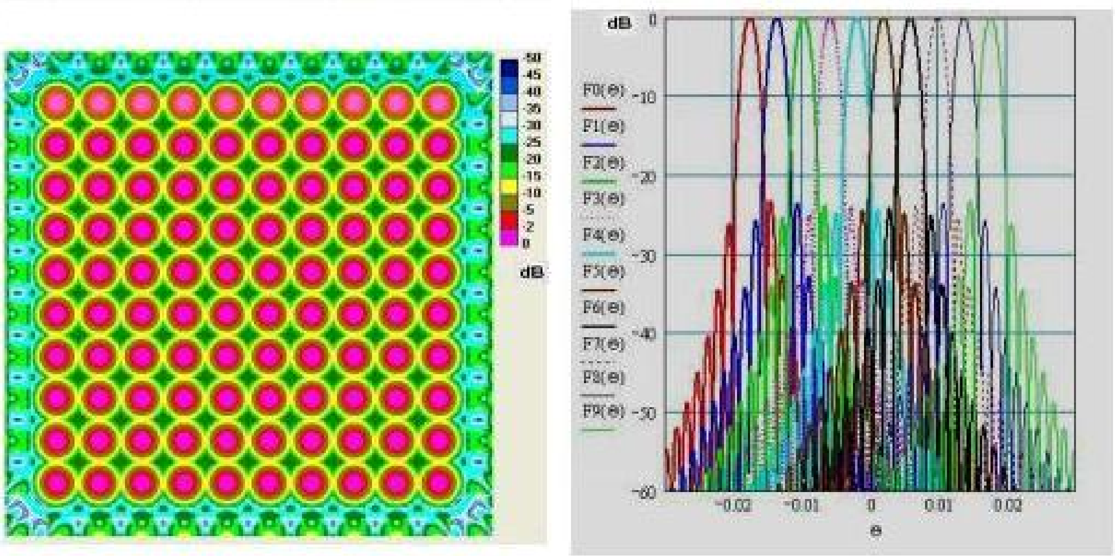
Multibeam FPA simulation of 8 m radio telescope at 100 GHz with GRASP8-SE

A projected aperture method determines aperture distribution from the feed BP with GO and the antenna BP in the far region (in transmitting mode) by integral transformation of the aperture field.

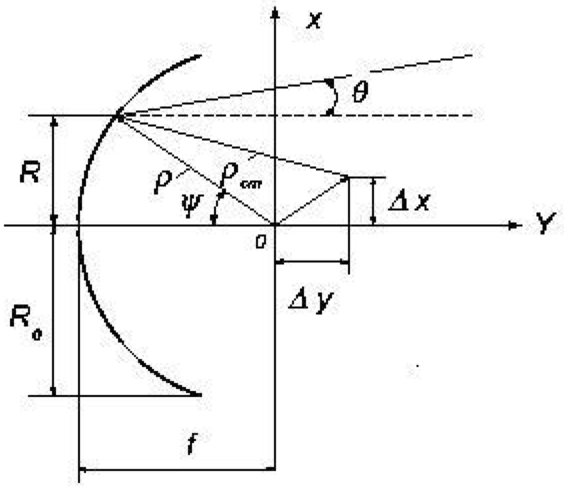
This method gives us good approximation for the main lobe and several nearest sidelobes in co-polarisation but it is not sensitive enough to cross-polarisation.

FOPAS - the software package developed for simulation and optimization of antenna characteristics in a multibeam mode. FOPAS calculates multibeam radiation patterns, illumination, sidelobe, spillover and aperture efficiency, beam overlapping level, optimal feed/beam spacing and other antenna characteristics with given antenna and FPA geometry, the aperture distribution or the feed BP, aperture blockage, RMS surface error etc.

FOPAS has been written in C++ code and successfully tested with the help of GRASP8-SE antenna simulation package. Simulation of 3 dimensional BP of 14 m MM-wave radio telescope with 10x10 beam FPA takes less than an hour with Pentium IV PC. .



Isolines of multibeam BP of 2 m Cassegrain radio telescope with 10x10 FPA at 3 mm (left), one-dimensional off-axis BP for m=11 (right), the feed taper – 10 dB.



$$F(\theta,\delta)=\int_0^{2\pi}\int_0^{R_0} E(R/R_0)e^{j\beta R\sin\theta\cos(\delta-\varphi)}\,R\,dR\,d\varphi$$

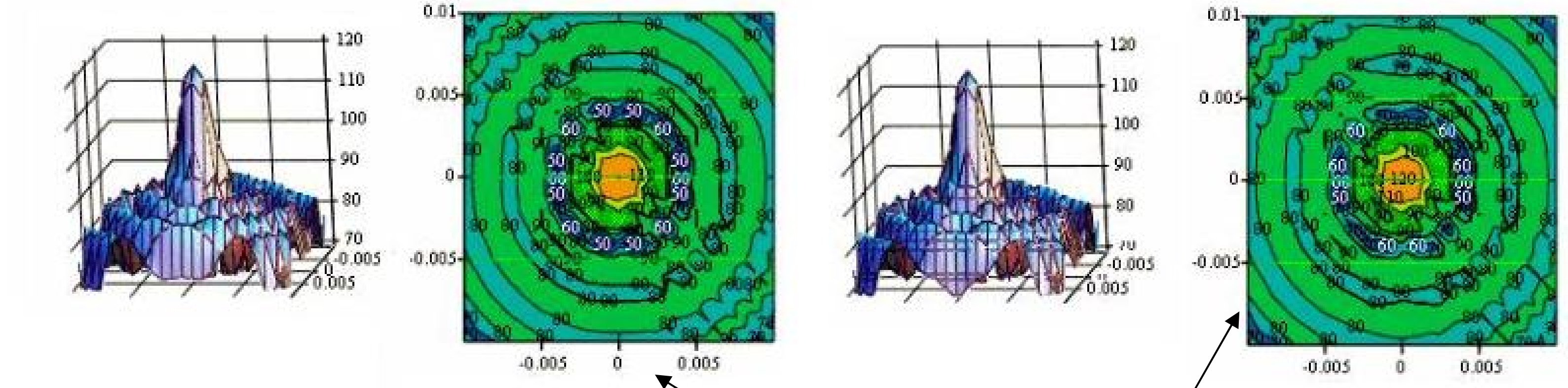
$$F(\theta,\delta)=\int_0^{2\pi}\int_0^{R_0} E(R/R_0)e^{j\beta R\sin\theta\cos(\delta-\varphi)+j\beta\Phi}\,R\,dR\,d\varphi$$

$$\Phi=\rho_{cm}-\rho,$$

$$\rho_{cm}=\sqrt{(R\cos\phi-\Delta x)^2+R^2\sin^2\phi+(F-R^2/4F+\Delta y)^2},\quad \rho=\sqrt{R^2+(F-R^2/4F)^2}$$

ϕ, R - polar coordinates of a point at aperture from the aperture center

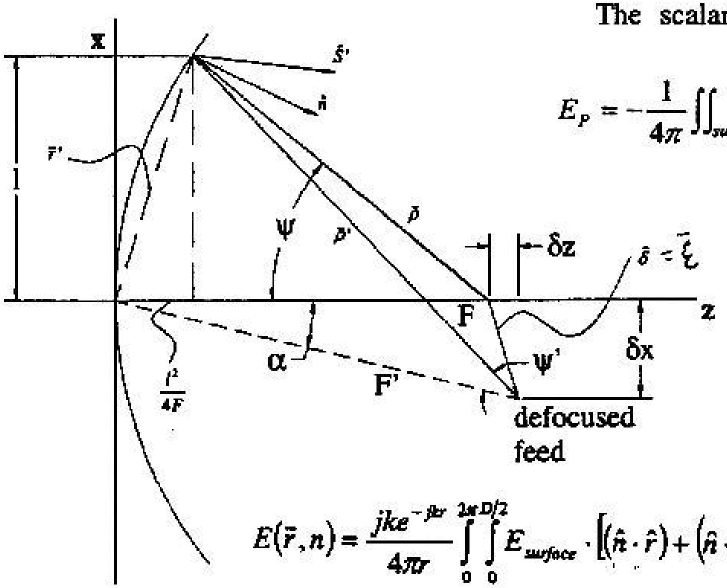
Δx, Δy - feed removal from the focus θ, δ - spherical coordinates of an observational point



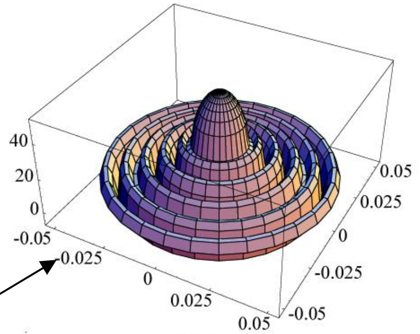
Examples of 3D BP simulation (focused and defocused)

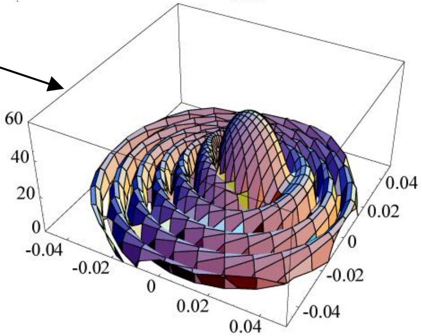
The scalar Kirchhoff Diffraction Integral

$$E_P = -\frac{1}{4\pi}\iint_{surface} E_{surface}\cdot jk\frac{e^{-jkR}}{R}\left[\left(\hat{n}\cdot\hat{R}\right)+\left(\hat{n}\cdot\hat{S}'\right)\right]dA_{surface}$$

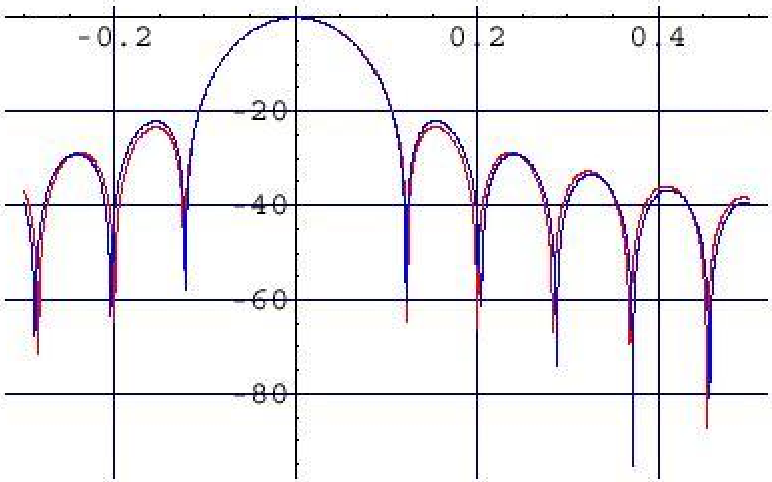


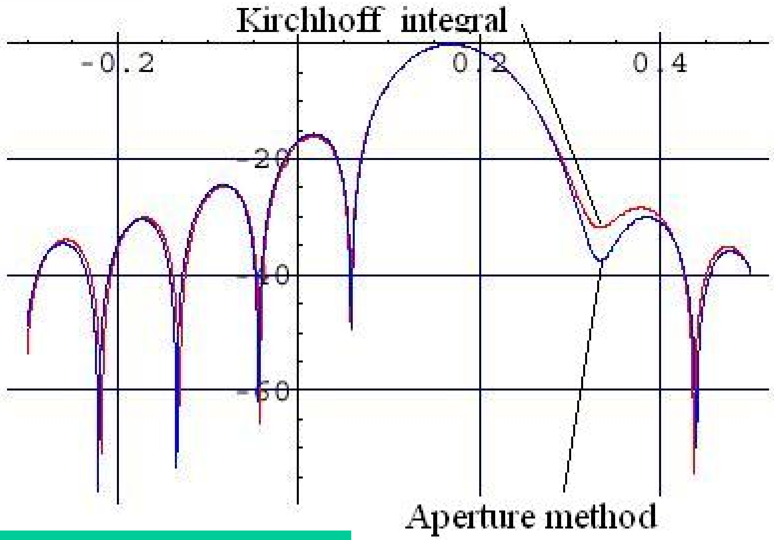
Examples of 3D BP simulation (focused and defocused)

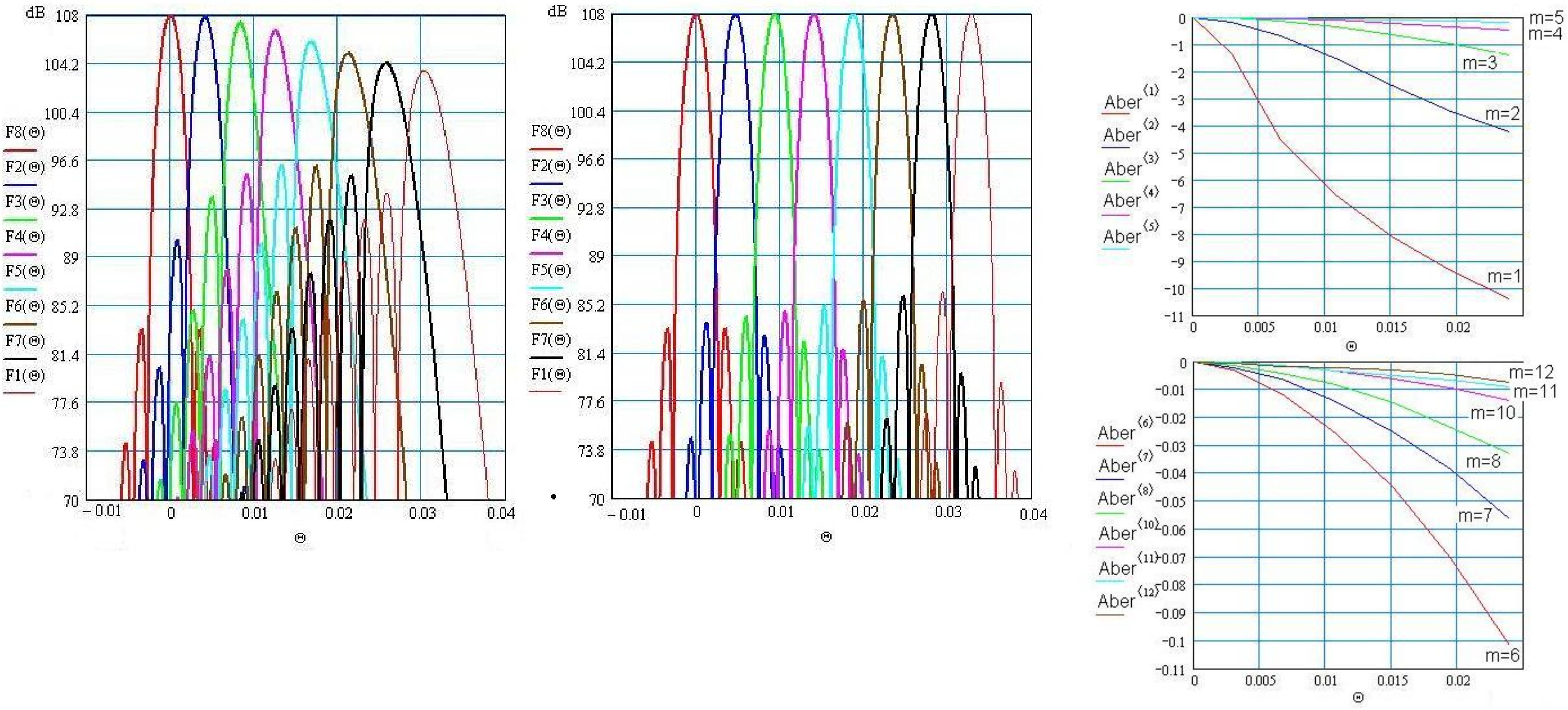




$$E(\bar{r},n)=\frac{jke^{-jkr}}{4\pi r}\int_0^{2\pi}\int_0^{D/2}E_{surface}\cdot\left[\left(\hat{n}\cdot\hat{r}\right)+\left(\hat{n}\cdot\hat{S}'\right)\right]\cdot\sqrt{1+\left(\frac{l}{2f}\right)^2}\cdot e^{jk\left(l\sin(\theta)\cos(\phi-\xi)+\frac{l^2\cos(\theta)}{4F}\right)}ldld\xi$$







On/Off-axis one-dimensional radiation patterns of a 2 m short-length focus (Cassegrain) radio telescope at 3 mm with m*f/D =0.87, m=(e+1)/(e-1), e-eccentricity of the secondary mirror(left) and a long-length focus radio telescope m*f/D=10 (middle), aberration curves for different m(right), the feed removal from the focus is 2mm*m*N, where N -number of array feed

Geometrical optics relationships for aperture field (E_a) and feed beam pattern (F_{feed}):

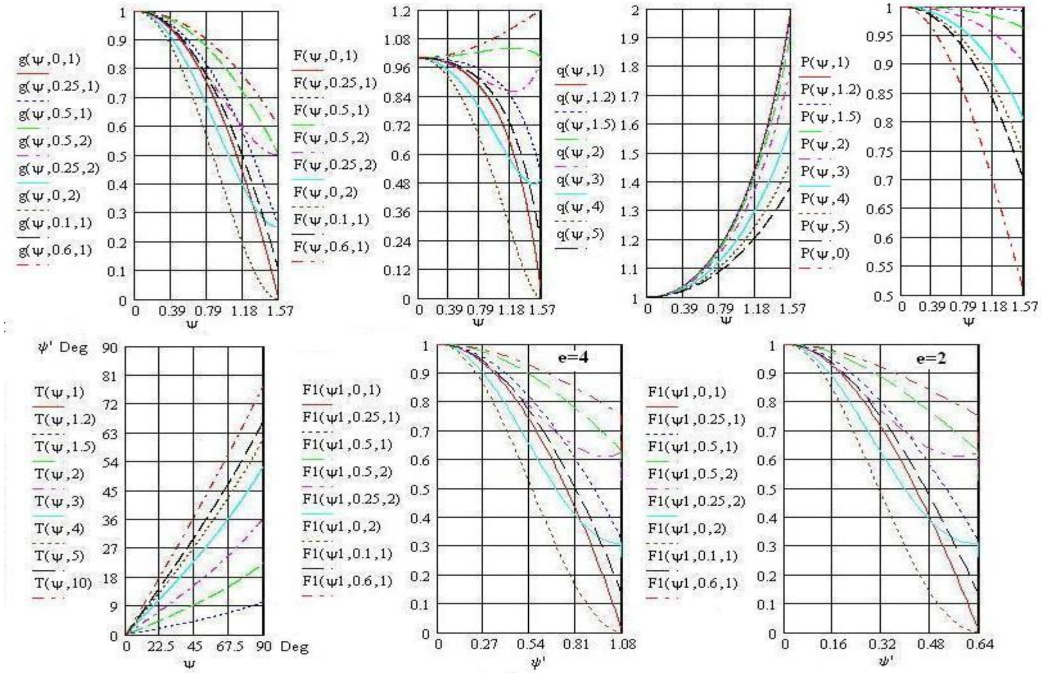
A single reflector: $E_a(\varphi,\psi)=\cos^2(\psi/2)\cdot F_{feed}(\varphi,\psi)/f$,

ψ - angle from primary parabolic dish focus to dish surface point M ($\psi=0-\psi_m$),

f-primary focal distance, $E_a(\varphi,\psi)$- aperture field distribution, $F_{feed}(\varphi,\psi)$ - feed beam pattern

A dual reflector: $E_a(\varphi,\psi)=\text{const}\cdot\cos^2(\psi/2)\cdot q(\psi)\cdot F_{feed}(\varphi,\psi')/f$,

ψ' - angle from secondary focus to correspondent point of the secondary mirror $M_1(\psi'=0-\psi'_m)$, $q(\psi)=(1+\mu)/(1+\mu\cdot\cos(\psi))$ - the field transformation coefficient for a dual reflector antenna, $\mu=2e/(1+e^2)$, e- eccentricity of the subreflector, $T(\psi,\psi')$ angle transformation, $G = E_a$



Calculation of radio telescope antenna efficiency by illumination, sidelobe, spillover, blockage, surface reflection and other efficiencies:

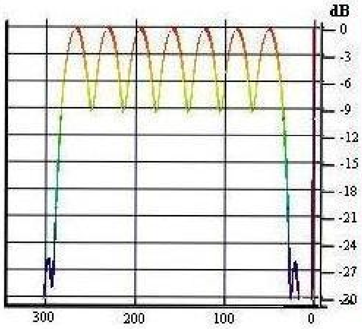
$$\eta_a = \eta_i \cdot \eta_{sp} \cdot \eta_{sl} \cdot \eta_b \cdot \cdot$$

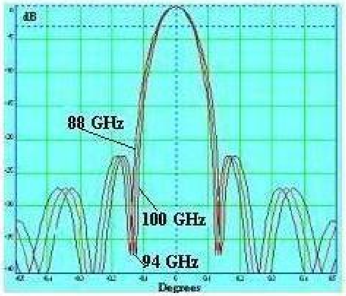
$$\eta_i = \frac{\left| \int_0^{2\pi} \int_0^{R_0} E(R,\phi)\, sin\theta dR d\phi \right|}{\pi R_0^2 \int_0^{2\pi} \int_0^{R_0} |E(R,\phi)|^2 R dR d\phi}$$

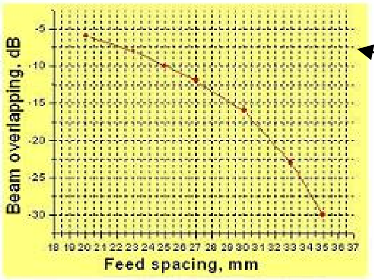
$$\eta_{sl} = 1 - \frac{\int_0^{2\pi} \int_{\theta_m}^{\pi} |F_n(\theta,\phi)|^2\, sin\theta d\theta d\phi}{\int_0^{2\pi} \int_0^{\pi} |F_n(\theta,\phi)|^2\, sin\theta d\theta d\phi}$$

$$\eta_{sp} = 1 - \frac{\left| \int_0^{2\pi} \int_{R_0}^{\infty} E(R,\phi) R dR d\phi \right|}{\pi R_0^2 \int_0^{2\pi} \int_0^{\infty} |E(R,\phi)|^2 R dR d\phi}$$

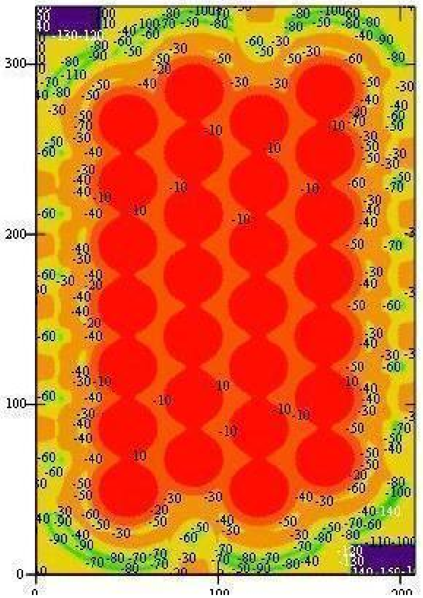
$$\eta_b = 1 - \frac{\left| \int_0^{2\pi} \int_0^{r_0} E(R,\phi) R dR d\phi \right|}{\pi R_0^2 \int_0^{2\pi} \int_0^{r_0} |E(R,\phi)|^2 R dR d\phi}$$

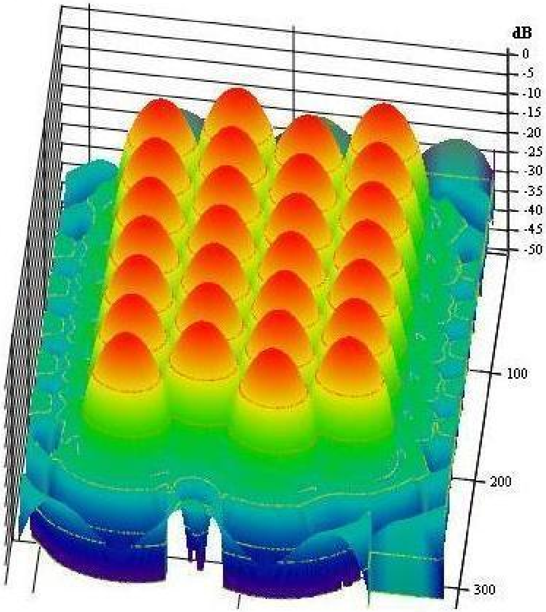






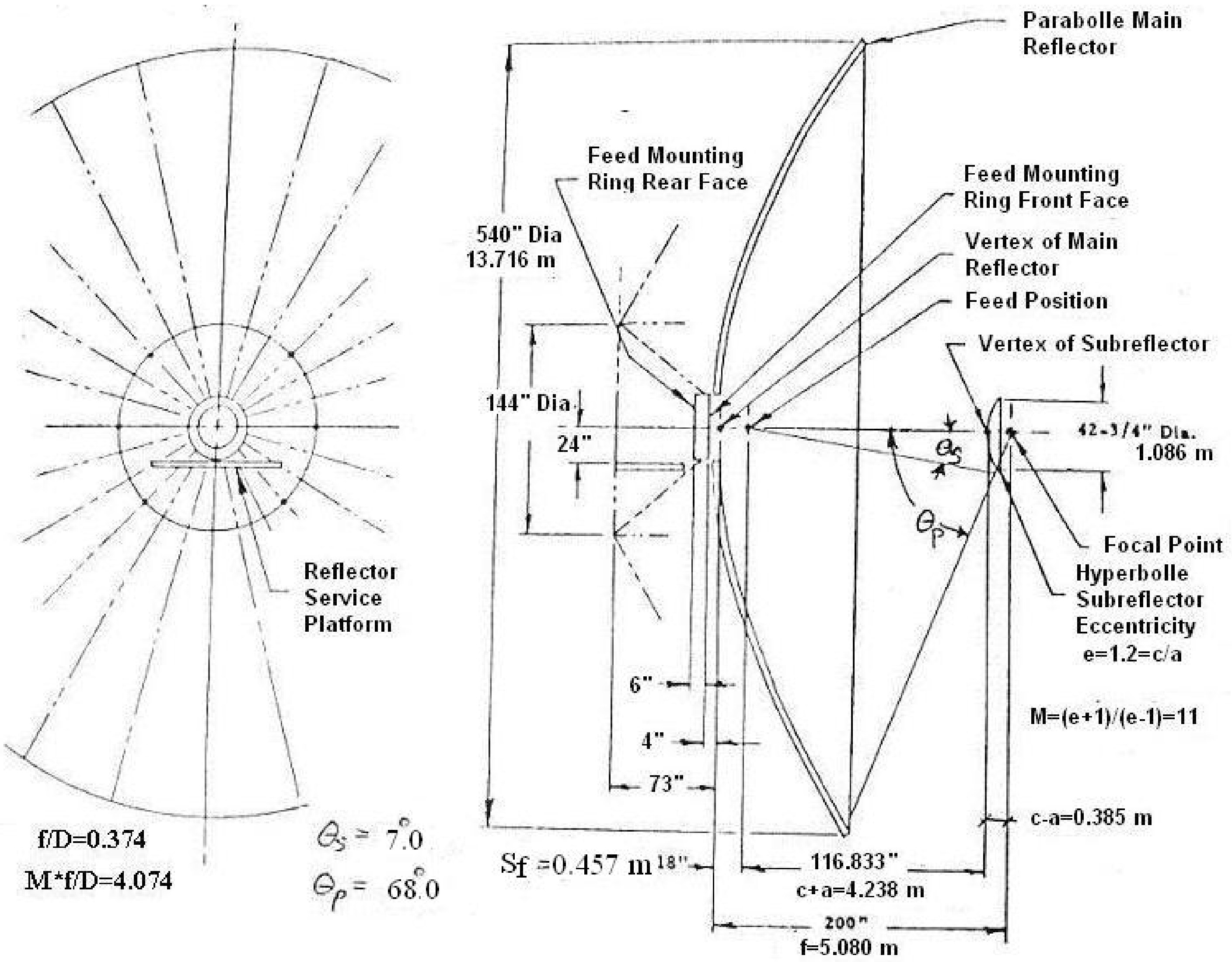
Simulated characteristics of Multibeam Solar Radio Telescope (MSRT) of Tuorla Observatory, Finland



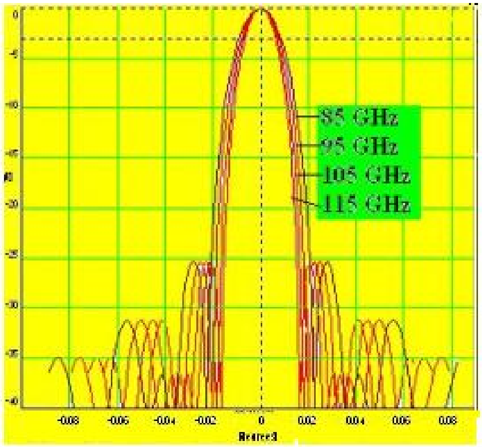


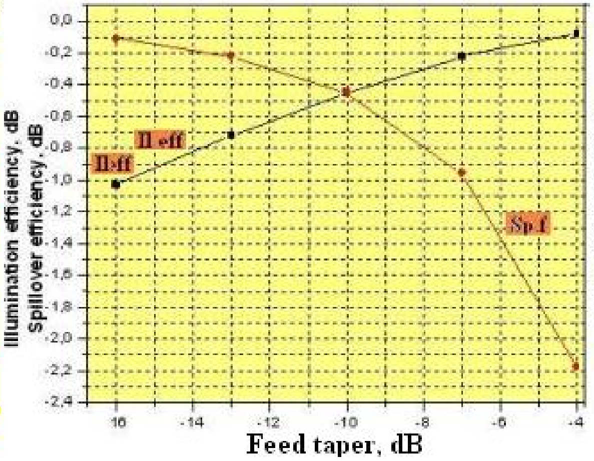
Frequency, GHz	Gain, dB	HPBW, arcmin	Beam overlapping, dB	Illumination efficiency, dB	Spillover efficiency, dB	Blockage efficiency, dB	Minimum beam spacing, arcmin	First sidelobe level, dB	Feed taper, dB
88	64.0	6.8	-9	-0.45	-0.46	-0.3	6	-22	-10
94	64.6	6.4	-10	-0.45	-0.46	-0.3	6	-22	-10
100	65.2	6.0	-11	-0.45	-0.46	-0.3	6	-22	-10

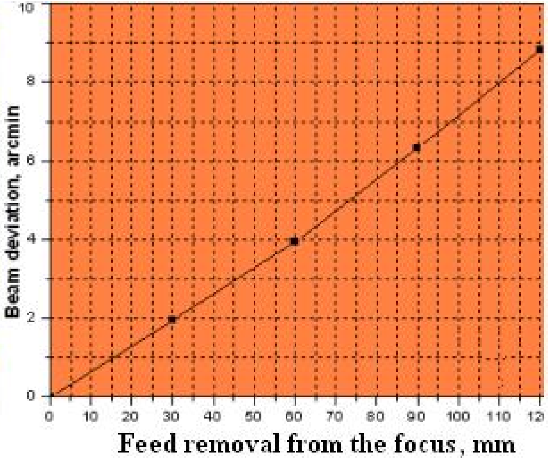
Geometry of 14 m MM telescope



Long-length focus design of a 14 m telescope (FCRAO, Metsahovi, TRAO) gives negligable aberrations with 10x10 and even 20x20 beam FPA



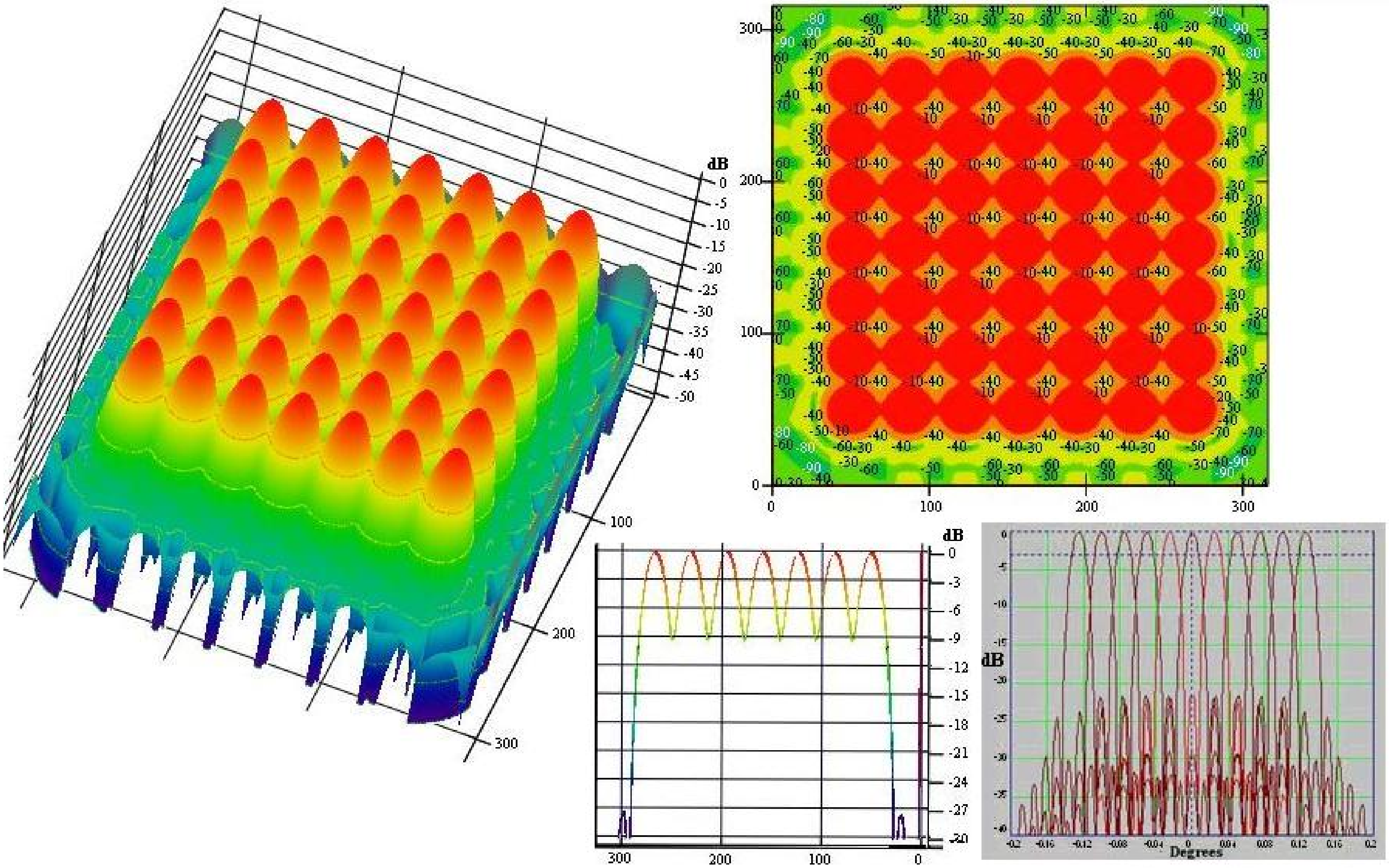




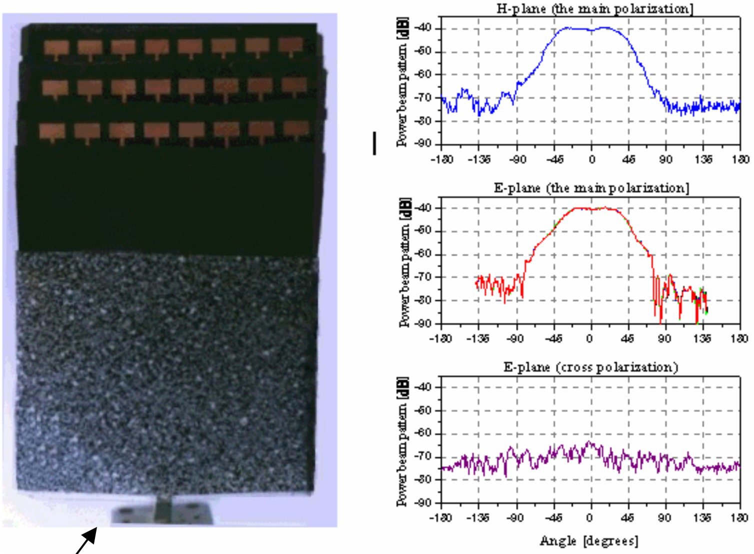
Removal from the focus, mm	Frequency, GHz	Gain, dB	First sidelobe level, dB	Beamwidth-3dB/-6 dB, arcsec/arcmin	Blockage efficiency, dB	Illumination efficiency, dB	Spillover efficiency, dB	Beam deviation, arcmin
0	95	81.54	-25.5	56.6/1.3	-0.11	-0.72	-0.22	0
30	95	81.55	-25.0	55.7/1.3	-0.10	-0.72	-0.22	1.94
60	95	81.57	-25.0	56.6/1.3	-0.09	-0.72	-0.22	3.93
90	95	81.61	-24.5	55.7/1.29	-0.08	-0.73	-0.22	6.33
120	95	81.62	-24.0	55.1/1.31	-0.07	-0.74	-0.22	8.82

Expected beam spacing is 1.5-2 HPBW and the field of view is up to 12’x12’ for 7x7 beam FPA

Multibeam simulation for 14 m MM wave radio telescope

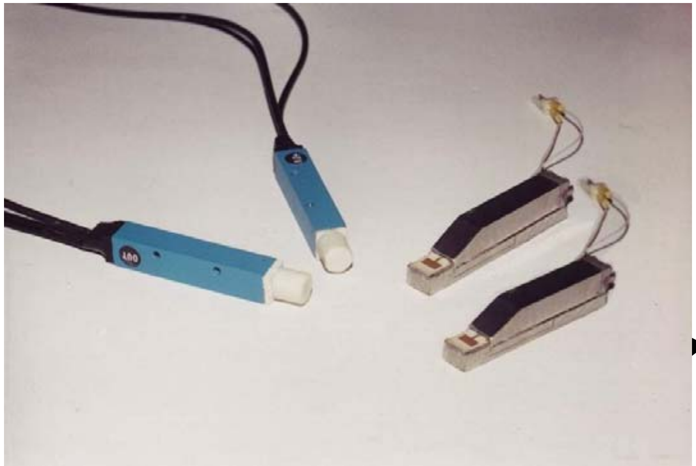


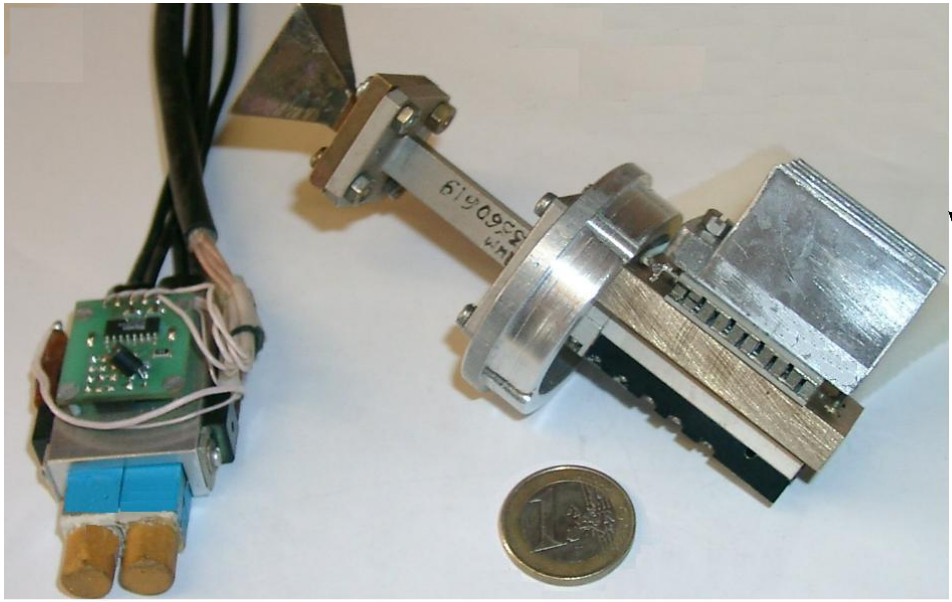
8-element MMIC focal array at 26-30 GHz



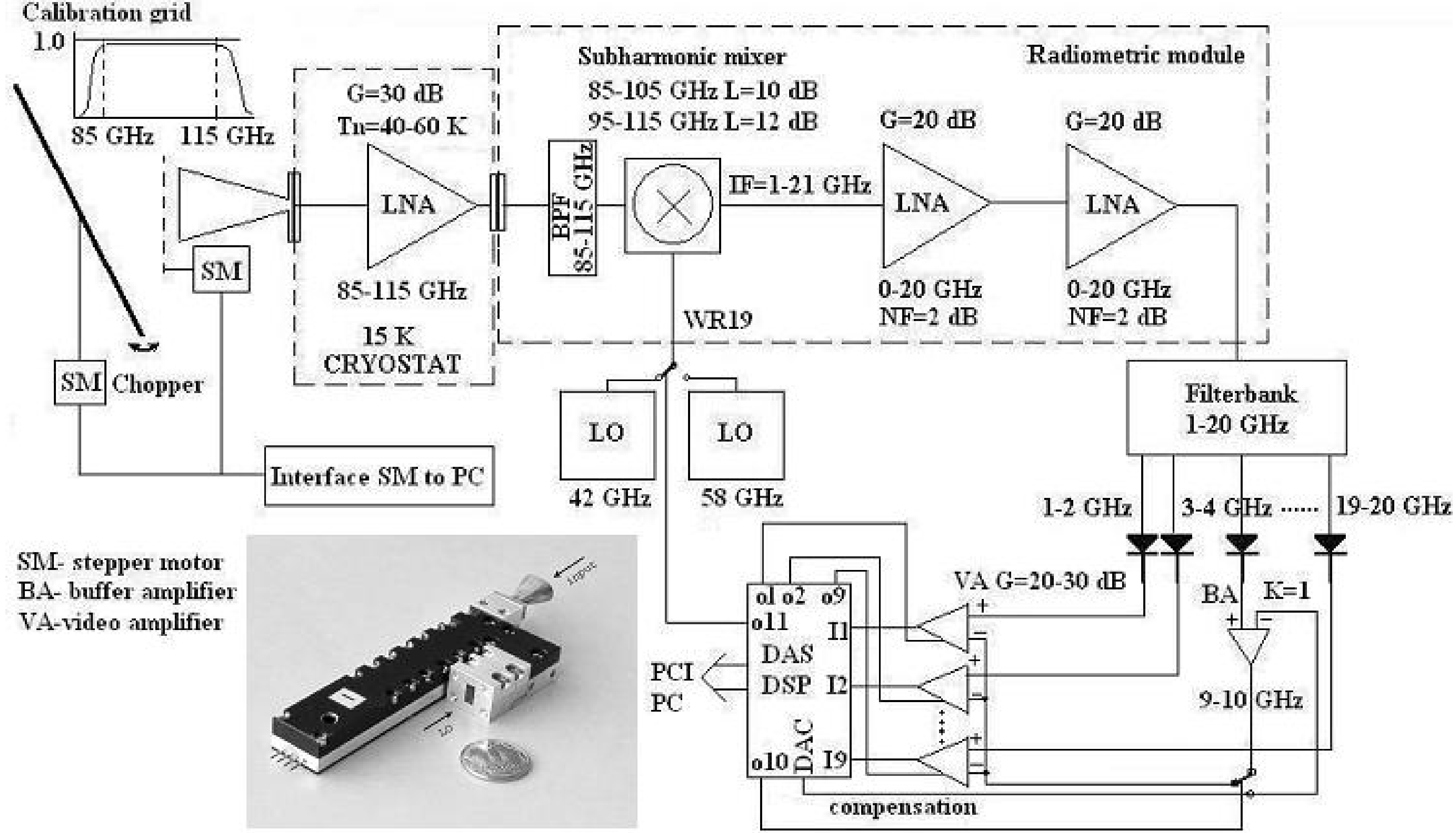
3x8 beam passive FPA prototype at 10 mm and one FPA element BP in the array

MMIC FPA receiver modules and array prototypes of 10 mm band





FPA receiver module prototypes with GaAs MMIC LNAs at 10 mm and 8 mm showed the sensitivity of 5-10 K/s^1/2 at room temperatures in 10%-20% bandwidth



SM- stepper motor
BA- buffer amplifier
VA-video amplifier

V.Khaikin, M-H.Chung, V.Radzikhovskij et al, in Proceed. of Cosmion-2004, in press.

Suggested scheme of 3 MM-wave FPA receiver module with a spectral filterbank. Expected sensitivity is 5-10 mK/s^1/2 per beam per channel (1 GHz) in 85-115 GHz band. A FPA receiver module prototype at 3 mm without LNA, measured sensitivity is 50 mK/s^1/2 in 5% bandwidth

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– Conclusion -

- Quick MM-wave imaging is the nearest goal for a single MM-wave radio telescope

- Developed software package FOPAS is useful instrument for simulation and optimisation of antenna characteristics of a MM-wave radio telescope

- Simulation shows that reachable beam spacing of 14 m MM-wave TRAO telescope with multibeam FPA is 1.5-2 HPBW, beam overlapping level is -9 dB, the expected field of view with 7x7 beam FPA at 3 mm is 12’x12’. Additional optics was recommended for 14 m MM telescope to reduce feed spacing and avoid undersampling.

- FPA receiver module prototypes with GaAs MMIC LNAs at 10 mm and 8 mm have showen sensitivity of 5-10 mK/s^1/2 at room temperatures in 10%-20% bandwidth.

- Expected FPA sensitivity with cryogenic InP MMIC LNAs is 5-10 mK/s$^{1/2}$ per beam per channel (1 GHz) in 85 GHz-115 GHz band.

- A single MM-wave telescope with multibeam FPA may be used for CMB mapping in continuum and with 1-20 GHz filterbank backends - for search of Spectral Spatial Fluctuations (SSF) of CMBR (V.Khaikin, V.Dubrovich. Mm-wave radio telescope with FPA for 3 K SSF search. In Proceedings of IRMMW-2004, Karlsruhe, Germany, Sept.2004.)

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