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Letter to the Editor

Point spread function in a confocal microscope with trigonometric pupil filters

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In this paper the distribution of point spread function was examined versus the spatial frequencies of the filters of $\cos(N\rho)$ type modulating the aperture of the confocal CSM for different values of numerical aperture. In particular, the following relations were determined: i) PSF as dependent on the pupil modulating spatial frequency r for $N = 1, 2, 3, 4, 5, 6, 7, 9, 11$ and numerical aperture NA = 0.8; ii) PSF for filters of $\cos(4\rho)$, $\cos(10\rho)$ type and NA = 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4; iii) cut-off spatial frequences r_c for the aperture modulated by $\cos(N\rho)$ for $N = 0, \ldots, 20$, NA = 0.2, 0.5, 1.0 and $\lambda = 0.6328$ μm.

In paper [1], the point spread function (PSF) was determined as a function of spatial frequency r in a CSM microscope of apertures modulated by ρ^n for $n = 2, 4, 6, 8, 10, 12, 14, 16$ and for NA = 0.5 and NA = 0.8. Also a characteristic of the cut-off spatial frequency $r_c(n)$ was examined as dependent on parameters n for NA = 0.5.

In the present paper, the distribution of the PSF is examined as a function of spatial frequency r in a confocal CSM microscope of aperture modulated by the filters of $\cos(N\rho)$ type (for $N = 1, 2, 3, 4, 5, 6, 7, 9, 11$) and NA = 0.8. Here, ρ is the absolute value of the radius-vector in the pupil plane. Additionally, the PSF has been examined for different r and $\cos(4\rho)$, $\cos(10\rho)$ and for NA = 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4. The characteristic of the cut-off frequency r_c has been determined for the aperture modulated by filters of $\cos(N\rho)$ type (for $N = 0, 1, \ldots, 20$) and NA = 0.2, 0.5, 1.0, with $\lambda = 0.6328$ μm.

The resultant point spread function (RPSF) h_r in a confocal microscope is defined by the PSFs h_1, h_2 of the first and second objectives, respectively, *i.e.*

$$h_r = h_1 h_2.$$

For the case of two identical nonmodulated circular objectives the image of the point object is defined by

$$I(w) = \left[\frac{2J_1(w)}{w}\right]^4$$

where: J_1 – Bessel function of the first kind and first order, $w = k\rho r/f$ – reduced coordinate in the image plane, $k = 2\pi/\lambda$ – propagation constant (wave number).

The PSF is a Fourier transform of the pupil function

$$\mathrm{PSF} = \mathrm{FT}\{P(\rho)\}.$$

For apertures modulated by the trigonometric filters we obtain [1]

$$h_N(r) = 2\pi \int_0^{\rho_0} \cos(N\rho)\rho J_0(k\rho r/f)\mathrm{d}\rho$$

where: J_0 – Bessel function of the first kind and zero order, ρ_0 – rim value of ρ. In the numerical calculations $f = 1$ μm and $\lambda = 0.6328$ μm have been assumed.

In Figure 1, the pupil function modulated by $\cos(N\rho)$ for $N = 1$, 4, 10 and 20 is shown. In Figure 2, the PSF is presented as a function of spatial frequencies

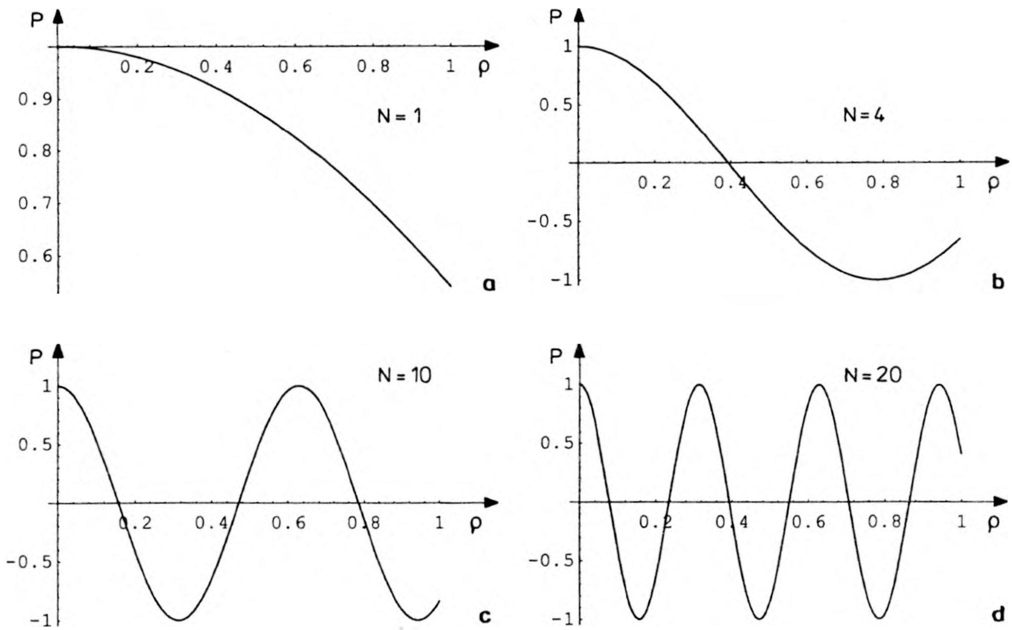

Fig. 1. Distribution of the pupil function $\cos(N\rho)$ for: $N = 1$ (a), $N = 4$ (b), $N = 10$ (c), $N = 20$ (d).

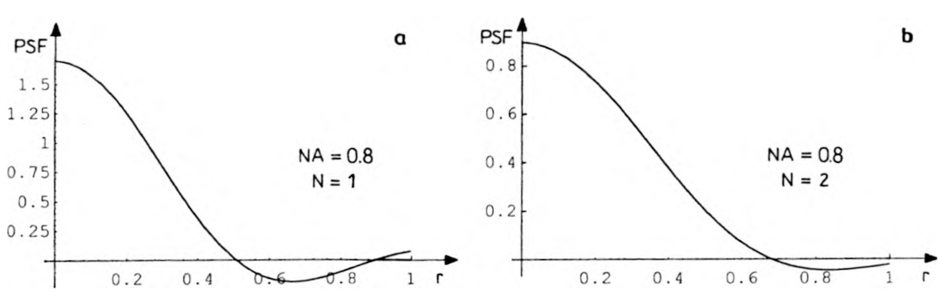

Fig. 2a,b

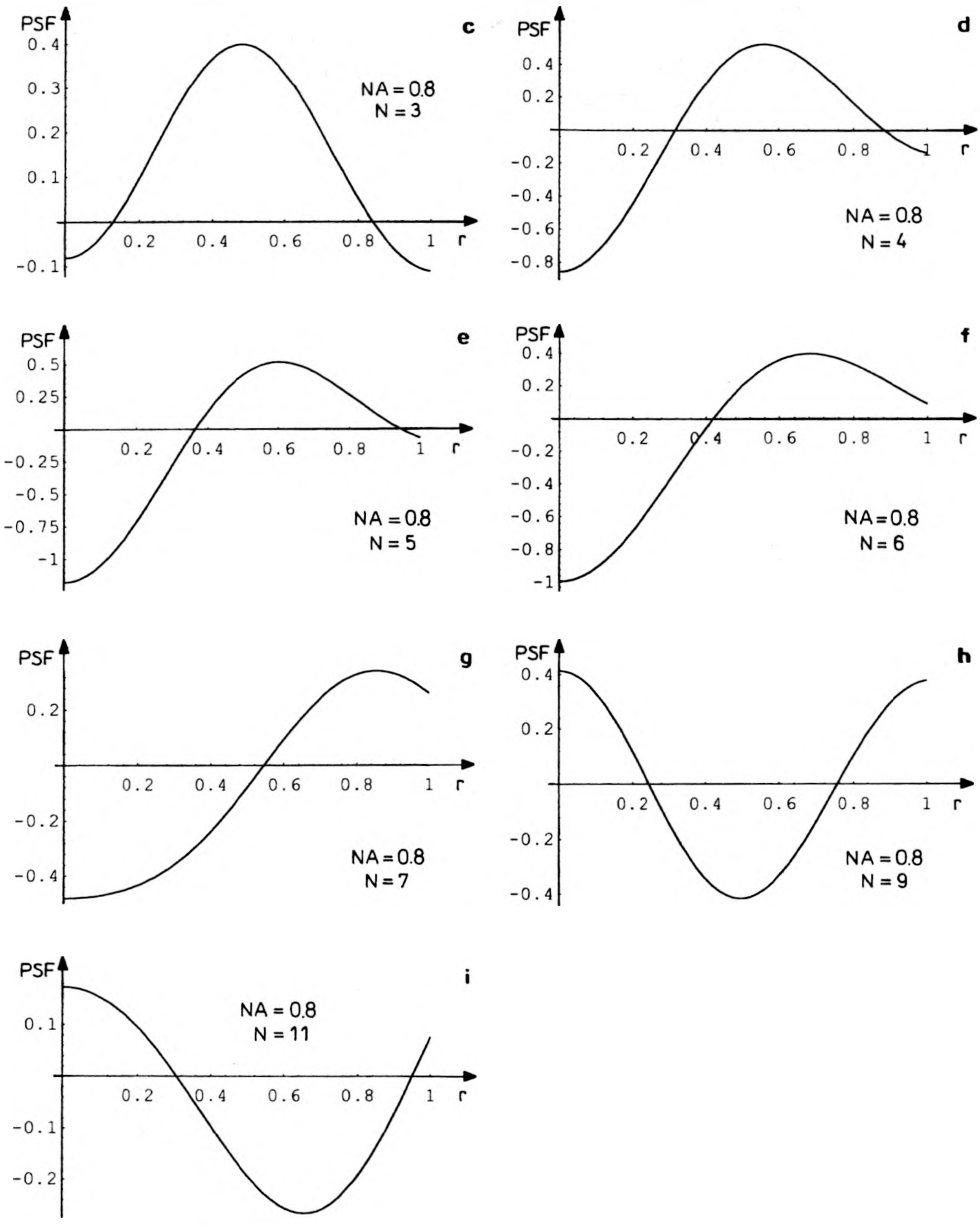

Fig. 2. Point spread function versus the spatial frequencies r [μm] for the pupil filter $\cos(N\rho)$ and the numerical apertures NA = 0.8 for: $N = 1$ (a), $N = 2$ (b), $N = 3$ (c), $N = 4$ (d), $N = 5$ (e), $N = 6$ (f), $N = 7$ (g), $N = 9$ (h), $N = 11$ (i).

r for pupil filters of $\cos(N\rho)$ type in CSM and for NA = 0.8, while N takes the values: 1, 2, 3, 4, 5, 6, 7, 9, 11.

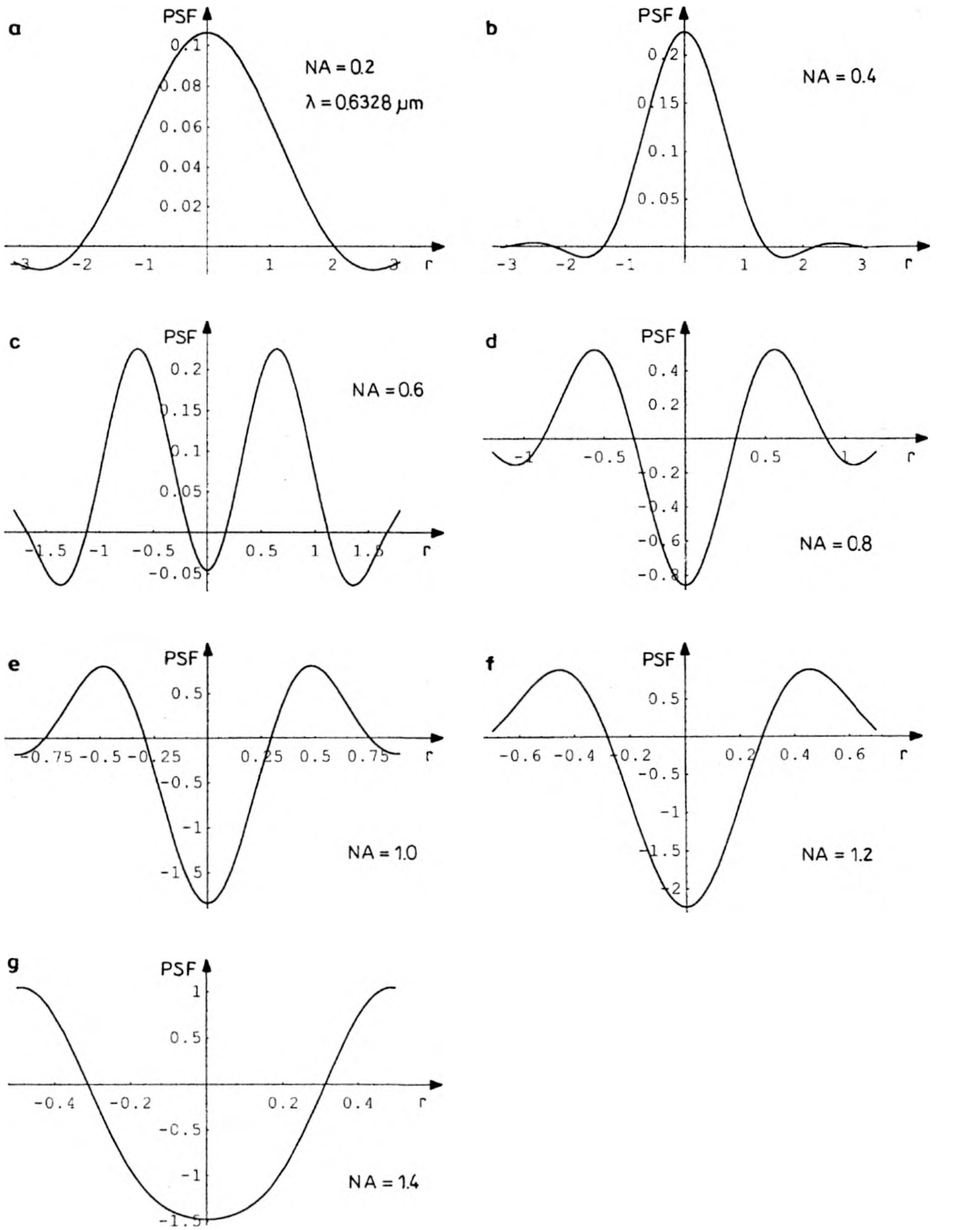

Fig. 3. Point spread function versus the spatial frequencies r [μm] for the pupil filter $\cos(4\rho)$ and the numerical apertures NA = 0.2 (a), 0.4 (b), 0.6 (c), 0.8 (d), 1.0 (e), 1.2 (f), 1.4 (g).

In Figure 3, the PSF is presented as a function of spatial frequencies r for the pupil filter $\cos(4\rho)$ and the following values of the numerical aperture: NA = 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4. In Figure 4, the PSF is presented as a function of spatial

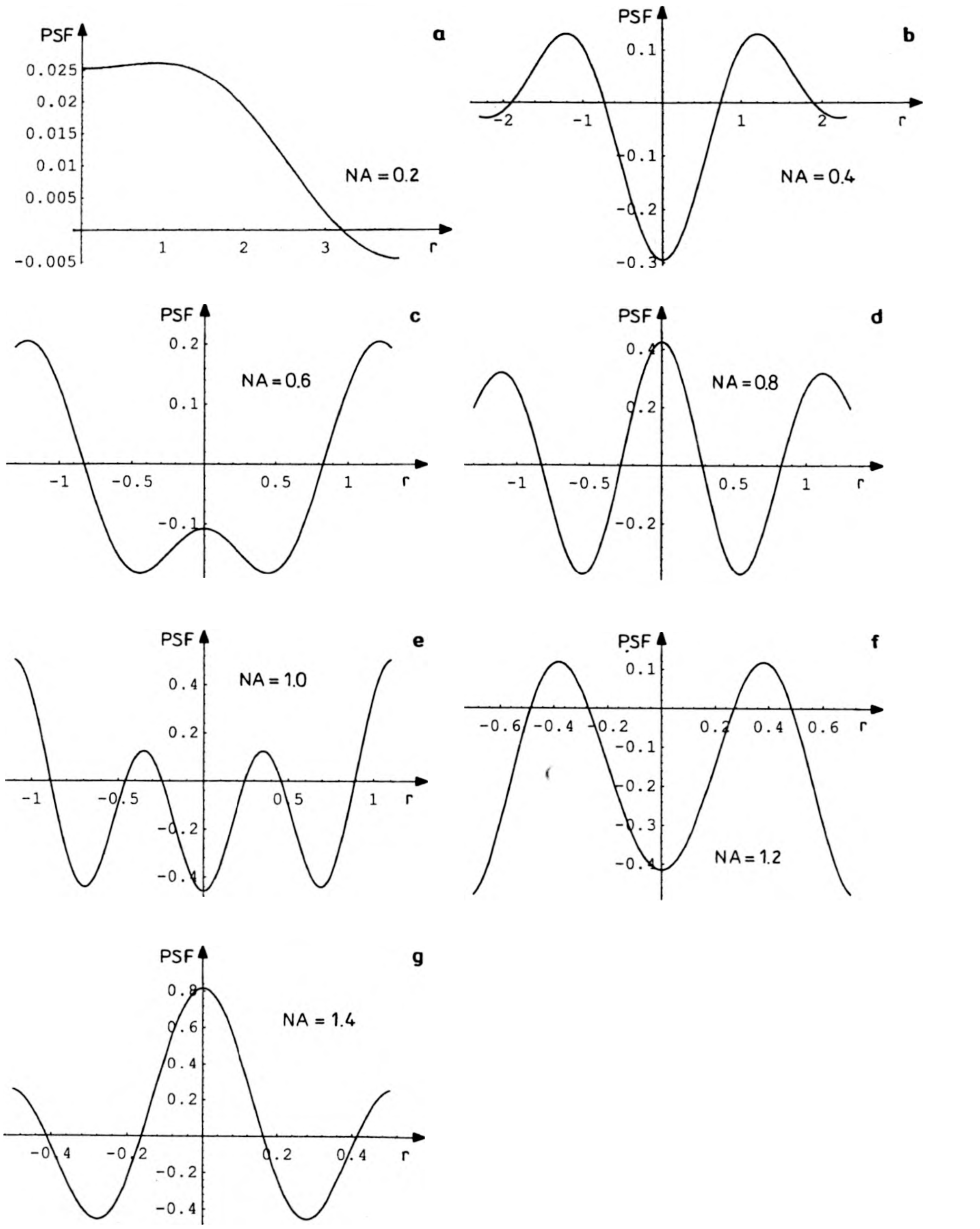

Fig. 4. Point spread function versus the spatial frequencies r [μm] for the pupil filter $\cos(10\rho)$ and the numerical apertures NA = 0.2 (a), 0.4 (b), 0.6 (c), 0.8 (d), 1.0 (e), 1.2 (f), 1.4 (g).

frequencies r for the pupil filter of $\cos(10\rho)$ for numerical apertures: NA = 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4. In Figure 5, the characteristic of the cut-off frequency r_c [μm] versus the parameter N ($N = 0$, 1, ... , 20) of the pupil filter $\cos(N\rho)$

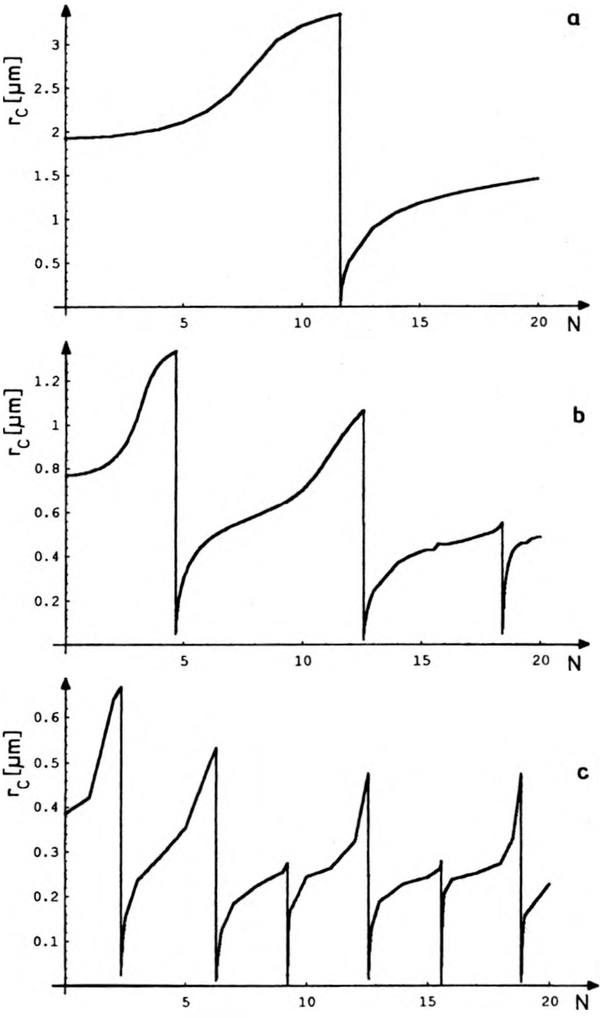

Fig. 5. Cut-off spatial frequencies r_c [μm] for different values of the parameter N of the pupil filters of $\cos(N\rho)$ type ($\lambda = 0.6328$ μm), $f = 1$ μm) for numerical apertures: NA = 0.2 (a), 0.5 (b), 1.0 (c).

has been determined for numerical apertures: NA = 0.2, 0.5, 1.0 and $\lambda = 0.6328$ μm. These frequencies have been determined by solving the equation

$$h_N = 0.$$

For a circular nonmodulated pupil ($N = 0$) and the numerical aperture of NA = 0.5, $\lambda = 0.6328$ μm, $f = 1$ μm, the cut-off frequency is equal to $r_c = 0.771807$ μm. For the aperture $P(\rho) = \rho^n$, as reported in [1], the cut-off frequency r_c ranges from $r_c = 0.772$ μm for the nonmodulated circular frequency ($n = 0$) to $r_c = 0.43$ μm for high values $n = 16$. In the case of aperture $P(\rho) = \cos(N\rho)$ and NA = 0.5 the characteristic $r_c(N)$ is shown in Fig. 5**b**. The results obtained are shown in the next page.

N	r_ε [μm]
0 (nonmodulated aperture)	0.7718
4.66	1.33425
4.66225	0.001351
12.56	1.06397
12.567	0.01034
18.41	0.5506
18.42	0.0488
20	0.487

For NA = 0.2, the characteristic $r_\varepsilon(N)$ is shown in Fig. 5a, while for NA = 1.0 in Fig. 5c.

Reference

[1] HAMED A. M., Optik **107** (1998), 161.

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