Ivan PRUDYUS, Viktor TKACHENKO, Leonid LAZKO, Sergiy FABIROVSKYY

Lviv Polytechnic National University

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Sub-pixel Based Forming of High-Resolution Images

***Abstract**. The paper deals with considering the possibility of improving the image forming quality of the objects and scenes in remote sensing systems that works in visible range of waves. The analysis of the influence of the pixel shape aperture on the image formation quality and the ability to improve resolution by sub-pixel processing using inverse filtering and Tikhonov regularization, to enhance high spatial frequencies are conducted.*

Streszczenie.** W pracy rozważa się możliwość poprawy jakości obrazowania obiektów i scen z wykorzystaniem systemów zdalnego sondowanie Ziemi, które działają w widzialnym zakresie długości fal. Przeprowadzono analiza wpływu kształtu apertura piksela na jakość obrazu i zdolność do zwiększenia rozdzielczości przez subpikseli przetwarzanie z wykorzystanie filtracji odwrotnego oraz regularyzacji Tichonowa w celu wzmocnienia wysokich częstotliwości przestrzennych. **Formowanie obrazu wysokiej rozdzielczości przy przetwarzaniu subpikseli

Keywords: sub-pixel image processing, inverse problems, super-resolution, image restoration.
Słowa kluczowe: subpiksel przetwarzania obrazu, odwrotnymi problem, super rozdzielczość, przywrócenie obrazu.

Introduction

The radio and optoelectronic systems which work in radio and visible range of electromagnetic waves are widely used for objects and scenes monitoring [1,4,5,7,10].

Optoelectronic systems in comparison to radar systems are characterized by a high resolution of objects despite the fact that the quality of formed images depends on the weather conditions.

The quality of the formed image is primarily characterized by resolution that is determined by the spectrum width of a pixel aperture function with respect to the spectrum of the object [1,6], the number of formed pixels per unit to object area, by lens characteristics and digital sensor, parameters of the medium propagation of optic waves and by signal processing methods [1,4,6,11,12]. The further development of optoelectronic systems and improvement of the formed images quality are constrained by technological factors that arise in manufacturing light-signal converters and require new approaches and image formation methods by combining information from multiple spatially separated sensors [4,5,13,14].

Analysis of the impact of the forming system elements on image quality

The pixel shape of sensor effect on the impulse response of image forming system, which is a point spread function h(ξ,η) [5,9], that describes the dependence of the light distribution from the object coordinates (ξ, η) in the plane of formed image of a point object with coordinates (x,y). In an ideal optical system, free from the diffraction a point appears as point, but in a real optical system appears as scattering spot (for systems with a round aperture in look a disk Airy) [2,3].

Based on the spatial invariance conditions to shift [3] each point of two-dimensional image will be presented as a function h(ξ-Px, η-Py), where P – coefficient that characterizes the shift magnitude of the image element and the light intensity distribution of the image is determined by convolution function of input image I (x,y) with the point spread function h (ξ, η).

Optical transfer characteristics of system is an important to assess the object structure quality as described [2,5]:

$$D(\omega_\xi,\omega_\eta)=H(\omega_\xi,\omega_\eta)\cdot e^{[j\Phi(\omega_\xi,\omega_\eta)]} \quad (1)$$

where $H(\omega_\xi,\omega_\eta)$ – spatial spectrum function of optical system; $\Phi(\omega_\xi,\omega_\eta)$ – phase factor; $H(\omega_\xi,\omega_\eta)$ called modulation transfer function, determines the dependence of image contrast at spatial frequencies.

For an ideal optical system (without diffraction) modulation transfer function is | D | = 1 and looks like a parallel plane to the spatial frequencies plane. In the presence of diffraction modulation transfer function will take the form of convex surface at high spatial frequencies area.

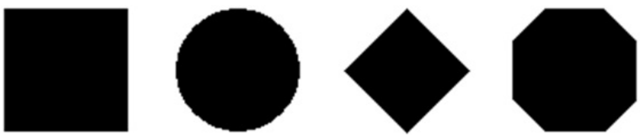
The line-filter model of image formation process, which is based on the consideration of the first kind Fredholm equation with convolution type core in the spectral band looks like prior application of low-frequency spatial filter, followed by spatial sampling initial image [2,5].

$$I(k,l)=S\cdot D\{I(x,y)\oplus h(\xi,\eta,x,y)+N(x,y)\} \quad (2)$$

where: *S* – sensitivity function, *N(x,y)* – noise, *D{−}* – discretization operator, *I(x,y)* – initial image, *h(ξ,η,x,y)* – function of pixel aperture, *x,y,ξ,η* – linear coordinates, *k,l* – discrete coordinates, $\oplus$ – convolution operator.

This model leads to process of high spatial frequencies suppression of the input image of the object, which leads to a decrease in its reproduction definition of fine details and deterioration of resolution.

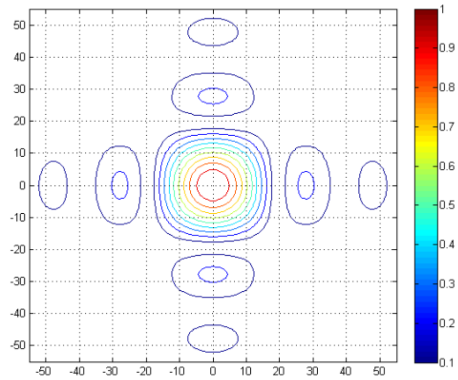
To assess the influence of aperture function h (ξ,η) on modulation transfer function and thus the quality of synthesized images four pixels apertures forms are formed (Fig. 1). The calculations of modulation transfer function are shown in Figure 2 and were made for each apertures.



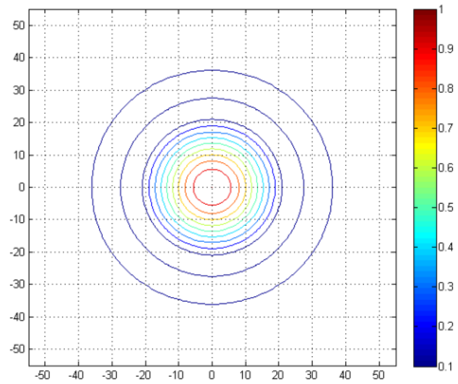
a) b) c) d)

Fig. 1. **Form of pixel aperture**: a) – square form, b) – round form, c) – rhomboid form, d) – square form with truncated corners

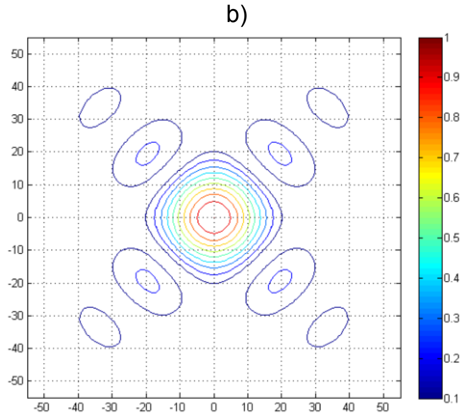
As evidently, for the chosen pixels apertures, except a round form, is available as a continuous central area of spatial spectral components and additional separate selections more high-frequency spectral components are presented. Since the resolution is limited by wide of spectral range of aperture pixel functions, then, obviously, the wider range of spatial aperture function and lower its anisotropy, for directions, the better is resolution. An isotropy after directions is characteristic only for the round of pixel aperture form (Fig. 2b). For other apertures forms, especially square (Fig. 2a) and rhomboid (Fig. 2c) are spatial angles, which lack the spatial spectral components, i.e. within these angles will be appeased spectral components of the objects.



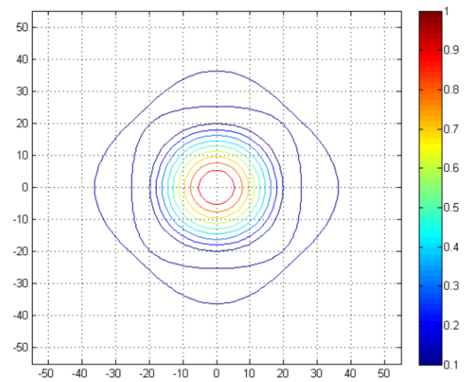
a)



b)



c)



d)

Fig. 2. Modulation transfer function: a) – square form of pixel; b) – round form; c) – rhomboid form; d) – form with truncated corners.

To assess the influence of the pixel aperture on the image formation quality, at pixel processing, calculation of mean square error of the image formation of test object depending on the signal to noise ratio was made. The calculation results are shown in Figure 3.

As shown in Fig. 3 formation error with this method is sufficiently large. The smallest error provides aperture with round pixel form and it is close to the aperture with truncated corners. The values of errors in both directions are the same scan. In addition, even at large signal to noise ratio observed distortion, causing of suppression the high-frequency spectral components that prevents image formation with high resolution.

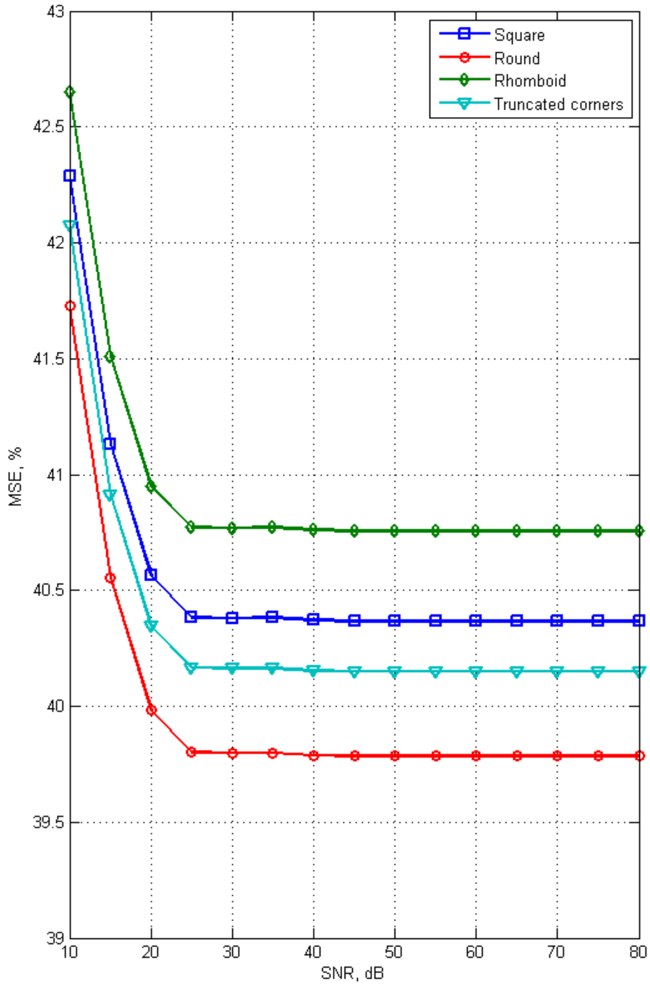


Fig. 3. The dependence of the mean square error of image formation for different values of the signal to noise ratio.

Sub-pixel image formation

Improve the quality of image formation is possible by increasing the number of pixels in the CCD matrix, but this leads to a reduction in their size, which creates technological problems of manufacturing and reduces their sensitivity.

A more rational use of sub-pixel image formation using multiple sensors shifted to sub-pixel distance [4,5]. Thus Fig. 4 shows the spatial arrangement of the two sensors (CCD-lines) shifted to sub-pixel distance R = 1/2 pixel.

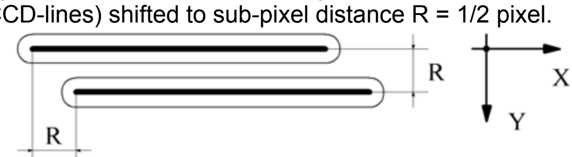


Fig. 4. The spatial arrangement of two CCD lines

As a result, sub-pixel formation discretized image with a higher sampling rate.

At sub-pixel formation, to image restore and reducing the pixel aperture influence additionally used the inverse filtration. The transfer function of this filter [6]:

(3) $$W\left(\omega_\xi,\omega_\eta\right)=\frac{1}{H\left(\omega_\xi,\omega_\eta\right)};$$

a spectrum of restored image:

(4) $$F_R\left(\omega_\xi,\omega_\eta\right)=F\left(\omega_\xi,\omega_\eta\right)+\frac{1}{H\left(\omega_\xi,\omega_\eta\right)}N\left(\omega_\xi,\omega_\eta\right).$$

In the absence of noise, i.e., $N(\omega_\xi,\omega_\eta)=0$, use of inverse filtering allows precise restore the original image, but when it is present, which is inevitable in real systems, the reduced image noise added that passed through the inverse filter that completely masks the restored image. Thus, inverse filtering has low noise stability, because this method does not consider noisy of the observed image. It is proposed to improve noise immunity use Tikhonov regularization. The transfer function of the filter with Tikhonov regularization [6]:

(5) $$W(\omega_\xi,\omega_\eta)=\frac{H(\omega_\xi,\omega_\eta)}{\left|H(\omega_\xi,\omega_\eta)\right|^2+\alpha Q(\omega_\xi,\omega_\eta)};$$

where $Q(\omega_\xi,\omega_\eta)$ – the stabilizing function, α – coefficient of regularization.

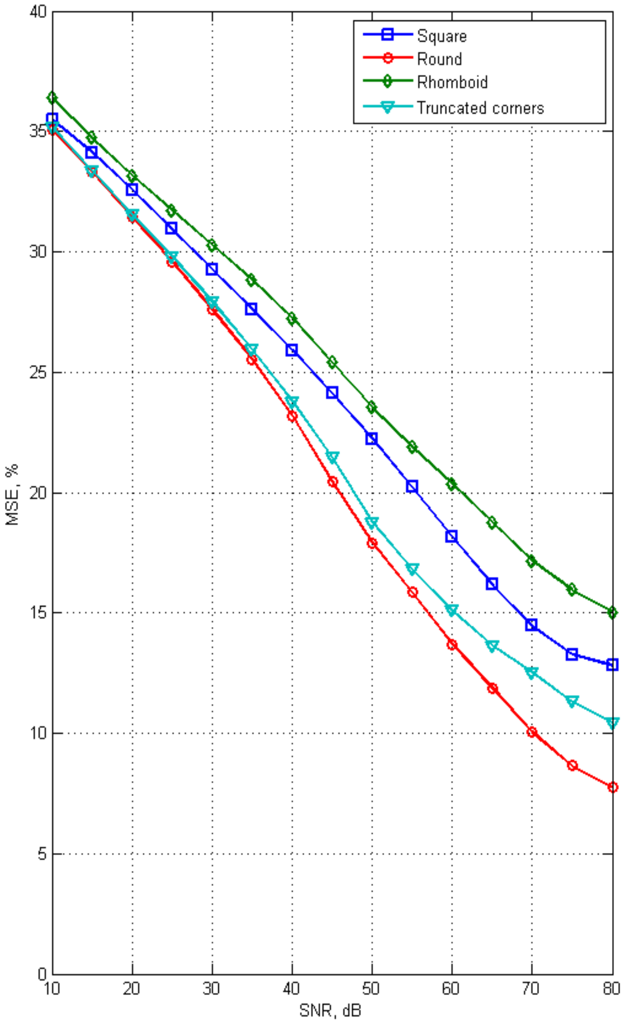


Fig. 5. The dependence of the mean square error of sub-pixel image formation for different values of the signal to noise ratio

The results of research of sub-pixel image formation quality at different values of the signal to noise ratio are shown in Fig. 5.

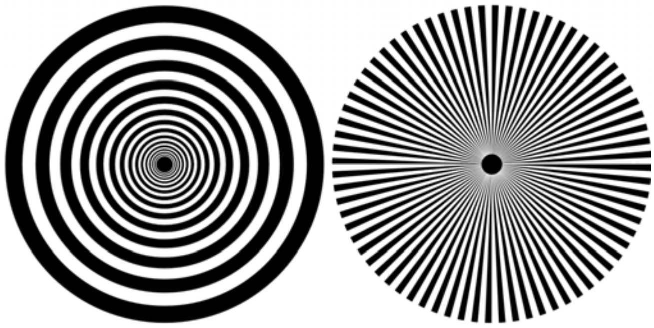
Comparing Fig. 3 and Fig. 5 it can be concluded that the use of sub-pixel forming and restoration of image with using invers filtration with Tikhonov regularization allows effectively improve restoration quality, especially at high signal to noise ratios. So in the case of a round aperture for the test image formation received error reduction from 39.8% to 7%, which is attributed to increase the resolution of formed image.

Calculation of resolution using test images for different pixel apertures

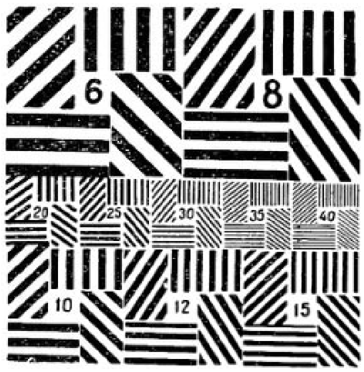
Resolution is a space-frequency characteristic of the photographic system and can be determined by visual decoding after photographing test objects - mir. Definition resolution data method is conducted in the laboratory and in real conditions. [7].

Mira - the general name of various test objects used for numerical characteristics of image quality in the study of lenses, and photographic materials. Measures consist of arrays of different frequencies parallel and radial strokes, printed text and other images made on a transparent or opaque material. [8].

Traditional test objects include specified achromatic contrast measure with uniform spectral characteristics: dashed measure radial measure, and others. [7].



a)



b)

Fig. 6. Test image: a) – radial; b) – dashed

To obtain numerical characteristics of evaluation image resolution used radial measure. This method can get systems resolutions r [mm^{-1}], finding the diameter of the circle scattering d [mm] [7].

(6) $$r=\frac{n}{\pi d};$$

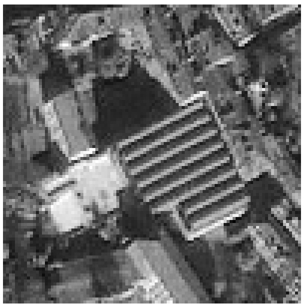
where: n – the number of sectors, while the diameter d of the scattering circle is calculated by Rayleigh criterion [3].

Calculation of the minimum size of image element L was carried out for capture height H = 1 km, focal length of optical system f = 6,5 mm, number of sectors of test image n = 144. The calculations were performed for four pixel apertures. The results are shown in Table 1.

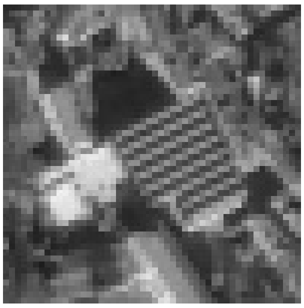
Table 1. The simulation results at SNR = 40 dB

Pixel aperture form	Parameter	Low resolution image	Subpixel image	Subpixel image with recovery
Square	d, mm	220	200	154
	R, mm^{-1}	0,208	0,229	0,298
	L, m	0,369	0,336	0,258
Rhomboid	d, mm	228	208	160
	R, mm^{-1}	0,201	0,22	0,287
	L, m	0,383	0,349	0,268
Round	d, mm	194	176	136
	R, mm^{-1}	0,236	0,26	0,337
	L, m	0,326	0,295	0,228
Truncated corners	d, mm	198	180	138
	R, mm^{-1}	0,232	0,255	0,332
	L, m	0,332	0,302	0,232

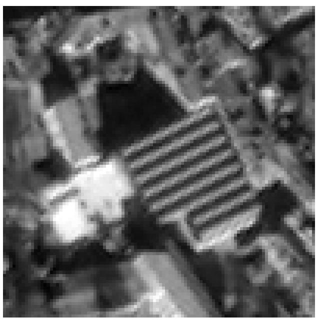
Based on the obtained results we may conclude that the use of sub-pixel image processing with inverse filtering increases the resolution of an average of 1.42 times and a simple sub-pixel image processing without recovery of 1.14 times towards to low resolution image. To illustrate the results of test image restore on fig.6c.



a)



b)



c)

Fig. 6. Simulation result: a) – test image; b) – low resolution image; c) – result after deconvolution.

Conclusions

The analysis of image formation process shows that the pixel aperture effects on him as a spatial low-pass filter and impairs spatial resolution at a pixel as in sub-pixel image formation. The proposed approach is based on the additional use of inverse filtering that can reduce the influence of the pixel aperture on the image formation quality.

Analysis of different pixels apertures shows that the smallest error and, therefore, the best resolution are provided by a round aperture. Another advantage of a round aperture is independent a concerning of the level of resolution scanning direction, unlike the square. Since the area of round pixels, compared with square is less under reduced sensitivity, it is proposed to use a square aperture pixels with truncated corners, giving some resolution improvement in the diagonal directions, compared with square form, as shown in Fig. 3. The proposed approach of sub-pixel image formation with decreasing of pixel aperture influence by inverse filtering with Tikhonov regularization, allows the use of all the advantages of sub-pixel processing and to increase the resolution and quality of image restoration. So for a test image, reduction of forming error turns out in 1,4 times compared with low resolution image.

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***Authors**: prof., Ivan Prudyus, Lviv Polytechnic National University, Electronic Devices and Systems Department, Profesorska Street 2, Lviv, 79013 Ukraine; PhD, Viktor Tkachenko, Lviv Polytechnic National University, Electronic Devices and Systems Department, Profesorska Street 2, Lviv, 79013 Ukraine; PhD, Leonid Lazko, Lviv Polytechnic National University, Electronic Devices and Systems Department, Profesorska Street 2, Lviv, 79013 Ukraine; postgraduate, Sergiy Fabirovskyy, Lviv Polytechnic National University, Electronic Devices and Systems Department, Profesorska Street 2, Lviv, 79013 Ukraine.*