Exceeding the resolving imaging power using environmental conditions

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We present two approaches that use the environmental conditions in order to exceed the classical Abbe's limit of resolution of an aperture-limited imaging system. At first we use water drops in order to improve the resolving capabilities of an imaging system using a time-multiplexing approach. The limit for the resolution improvement capabilities is equal to the size of the rain drops. The rain drops falling close to the imaged object act as a sparse and random high-resolution mask attached to it. By applying proper image processing, the center of each falling drop is located, and the parameters of the encoding grating are extracted from the captured set of images. The decoding is done digitally by applying the same mask and time averaging. In many cases urban environment includes periodic or other high-resolution objects such as fences. Actually urban environment includes many objects of this type since from an engineering point of view they are considered appealing. Those objects follow well known standards, and therefore their structure can be *a priori* known even without being fully capable of imaging them. We show experimentally how we use such objects in order to superresolve the contour of moving targets passing in front of them.

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1. Introduction

The field of superresolution addresses the capability of seeing beyond the physical limitations enforced by the optics and the detector of an imaging system. The limitation of the lenses is mainly related to the F-number of the optics, and the limitation of the detector is related to the size of the pixels and their number [1,2]. Overcoming those limitations or obtaining superresolution means achieving high-end system performance via use of low-end configuration. Therefore the applicability of this field is not only scientific but also industrial. The superresolution can be applied for remote imaging as well as for near-field, where seeing below the size of an optical wavelength is sometimes required as well. It can be used to overcome the limitations of the optical system itself and to exceed the imaging boundaries determined by the medium, as in, e.g., turbulence and scattering.

There are many approaches to overcome the limitations enforced by the imaging system or the medium, by applying polarization [3,4], wavelengths [5,6], space or field of view [7–10] or time [11–13] manipulations that encode the spatial information prior to its transmission through the band-limited optical system or medium, and then decoding the information and recovering the missing spatial content.

Emmett Leith had arrived to optics from the field of synthetic aperture radar (SAR), which at that time was using optical means to process and recover the radar information. The field of SAR is the evolutional prototype for the time-multiplexing superresolution that later was used in optical imaging. By being familiar with this approach, Leith was naturally acquainted with the field of superresolved imaging and knew how to implement his brilliant ideas in this field as well.

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During his extraordinary research career, Leith dealt with various topics of optical superresolution involving holography and interferometry [14,15], first-arriving-light (FAL) superresolution to deal with imaging through scattering media [15,16], developing of general concepts for time [17], wavelength and code encoding of optical wavefronts [18,19], and resolution improvement in confocal microscopy [20,21]. Leith pioneered some of those topics and made significant contributions that influenced more than one generation of scientists in those fields.

As previously mentioned, one of the most common approaches for increasing the resolution of an imaging setup being limited by diffraction is to use time multiplexing [11,22,25]. The basic concept involves attaching or projecting a high-resolution moving grating on top of the target that we aim to superresolve. This moving grating performs encoding of the spatial spectrum of the target. If a sequence of images is captured while each is multiplied at the camera plane by proper decoding grating and afterward summed, one may increase the imaging resolution up to the resolution at which he has the encoding grating.

In the first part of this paper we suggest using the time-multiplexing approach for superresolution, where instead of projecting a grating, we use the environmental conditions to generate it. We capture a set of images on a rainy day assuming that the rain is not very heavy and therefore its drops are relatively sparse. We assume that the rain is close to the object. By digital processing we allocate the centers of the drops, although they are smeared due to the low-resolution imaging. A decoding pattern is digitally generated by creating a set of points located at the centers of the drops. We multiply the decoding pattern by every captured image and integrate in time. Therefore, the encoding is made by a time-varying random pattern [24], with the main advantage that, due to the low fill factor, the pattern can be extracted from the captured images. A superresolved image is reconstructed having the resolution as fine as the small drops falling close to the object. The main advantage of this approach is the lack of need to project a grating, but rather, we use the environment in order to enhance our resolution. The superresolving approach fits to remote objects as well, and the distance to the object is no longer an obstacle in having its resolution enhanced.

In many urban cases, there is no need in projection or attaching gratings, since they exist as part of the environment [26]. In many cases, those gratings are known, since most of them have repeating structural patterns and well known standards for spatial periods. Also, instead of moving the grating, we superresolve the contour of a moving target that passes in front of such static grating. Since movement is relative, it is not really important which one is the moving one and which is the static one. In this paper we show experimentally how the contour of moving targets passing in front of urban environment typical objects such as a fence can be superresolved. In this case the urban objects are not known *a priori*, but since they have standards, the decoding can be done and the high-resolution object can be extracted.

In a more heuristic description, both approaches that are described in this manuscript deal with time-multiplexing superresolution. Structures containing small features (smaller than the optical-resolving capability of the imager) are positioned near the object. Those structures are either the rain droplets (the first approach) or the background (the second approach). Similar to what happens with the moire effect, those fine structures multiply the spatial distribution of the object and demodulate its high spatial frequencies into low frequencies that now can be resolved by the imager. The relative movement between the object and those fine structures (either the object is static and the rain droplets are falling or the background is static and the object is moving) generates Doppler shifts, i.e., a time-varying phase that allows the separation between the originally high spatial frequencies that were demodulated into low ones and the originally low spatial frequencies (despite the mixing between those two types of frequencies). Proper digital postprocessing performs the demodulation and the reconstruction of the original spectrum out of the mixed spectral slots.

The structure of the paper is as follows. In Section 2 we present a technical description of the rain drops related approach. Its experimental results are presented in Section 3. In Section 4 we present the theory for the urban background related technique. Preliminary experimental results are seen in Section 5. The paper is concluded in Section 6.

2. Theoretical Analysis of the Rain Drops Approach

In the following, we use one-dimensional notation; the extension to two dimensions is straightforward. The transparency function of the rain drops is denoted as $g(x, t)$. This function is space as well as time dependent. The image is designated as $s(x)$. The intensity point spread function of the imaging system is denoted by $p(x)$. Therefore the intensity of each captured frame equals to

$$I(x', t) = \int s(x)g(x, t)p(x' - x)\mathrm{d}x. \tag{1}$$

By allocating the peaks of the rain function, we manage to have approximate reconstruction of the encoding function $g(x, t)$. In order to extract the drops' locations in every frame we prepare an average of all captured frames, $\langle g(x, t)\rangle$. For a given frame, taken at time t, the subtraction of the average image gives a smoothed version of the rain drops alone. Assuming that I_m is the maximal gray level of $I(x, t)$, then the allocation of the maxima of the difference between each frame and the time average while creating a decoding grating based on that may be approximated mathematically as

$$d(x,\ t) = \left[\frac{I(x,\ t) - \langle I(x,\ t)\rangle}{I_m}\right]^K, \tag{2}$$

where $d(x, t)$ is the decoding grating and $K \gg 1$.

Since the rain drops constantly and randomly vary in time and space, one may assume that

$$\int g(x',\ t) d(x,\ t) \mathrm{d}t \approx \delta(x - x') + \kappa, \tag{3}$$

where κ is a constant. Applying the decoding grating $d(x, t)$ on the captured intensities of Eq. (1) and time averaging yields

$$r(x) = \int I(x,\ t) d(x,\ t) \mathrm{d}t = \int\int s(x') g(x',\ t) p(x - x') \times d(x,\ t) \mathrm{d}x' \mathrm{d}t. \tag{4}$$

Using the orthogonality of Eq. (3) yields

$$\begin{aligned} r(x) &= \int s(x') p(x - x') \left[\int g(x',\ t) d(x,\ t) \mathrm{d}t\right] \mathrm{d}x' \\ &= \int s(x') p(x - x') \delta(x - x') \mathrm{d}x' \\ &\quad + \kappa \int s(x') p(x - x') \mathrm{d}x' = s(x) p(0) + \kappa \cdot \mathrm{LRI}, \end{aligned} \tag{5}$$

where LRI is the-low resolution image. One may see that the reconstructed image $r(x)$ includes the high-resolution original image $s(x)$ multiplied by a constant and added to the low-resolution image obtained without applying the superresolved approach.

3. Experimental Results of the Rain Drops Approach

In the experiment that we have performed, a set of images was captured while a resolution target was placed near a water tap that was constantly spreading drops of water. By applying the algorithm that we have previously described, we have digitally extracted the decoding grating and applied it in the reconstruction process. From each captured frame we extracted the proper decoding mask and multiplied it by the frame. We added over more than 100 frames. Each one of the frames was captured at video rate with integration time of 1 ms in the camera. A conventional TV lens with a focal length of 16 mm and F-number of around 5.6 to 8 was used for the imaging. The camera was a Basler A312f with pixels of 8.3 μm × 8.3 μm. The camera was controlled with Matlab through a laptop computer.

In the experiment we positioned the camera about 3 meters away from the resolution target and splashed water droplets from a water pipe toward the target.

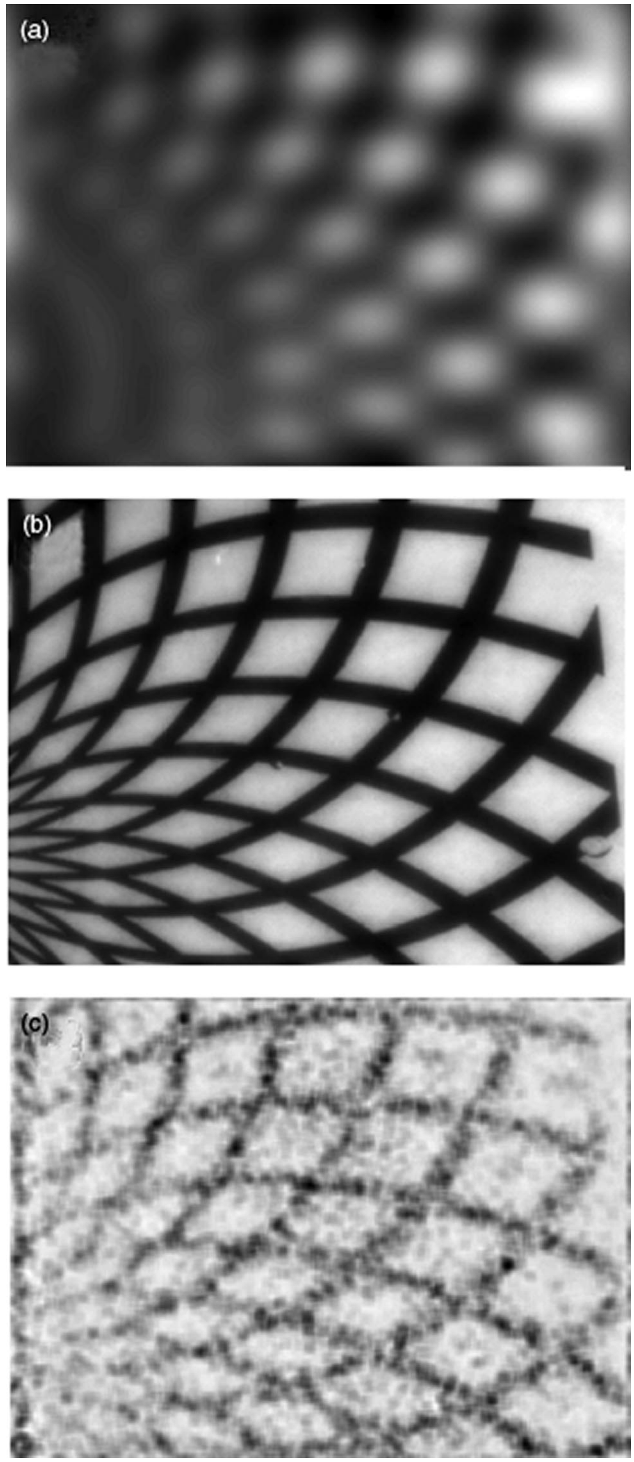

Fig. 1. Experimental results: (a) the low-resolution images; (b) the high-resolution target we used for the experiment; (c) the obtained reconstruction after averaging over more than 100 frames.

The obtained results can be seen in Fig. 1. In Fig. 1(a) we see one frame out of the low-resolution images. In Fig. 1(b) we present the high-resolution target we used for the experiment and that we aim to reconstruct. In Fig. 1(c) we present the obtained reconstruction after averaging over more than 100 frames. One may clearly see the reconstruction of the high-resolution features that are not seen in each individual member of the imaged low-resolution set of images.

4. Technical Description for the Urban Detection Approach

We denote by $s_1(x)$ the support of the object that is a binary function having the shape of the target but with gray level of one:

$$s_1(x) = \begin{cases} 1 & s(x) > 0 \\ 0 & s(x) = 0 \end{cases}. \tag{6}$$

Note that all the variables are optical intensities and the imaging system is operating under spatially incoherent illumination.

The intensity of the target that is moving in front of a periodic urban background (say, a fence) may be expressed mathematically as

$$t(x,\ t) = [1 - s_1(x - vt)]\Big[\sum_n A_n \exp(2\pi i n x \mu_0)\Big] + s(x - vt), \tag{7}$$

where v is the target's velocity and $\sum_n A_n \exp(2\pi i n x \mu_0)$ is the Fourier series of the urban periodic background (e.g., a fence). The blurred intensity $I(x, t)$ captured by the imaging camera equals to

$$I(x,\ t) = \int t(x',\ t)p(x - x')\mathrm{d}x'. \tag{8}$$

Substituting Eq. (7) into Eq. (8) yields

$$\begin{aligned} I(x,\ t) = {} & \sum_n A_n \int \exp(2\pi i n x' \mu_0)p(x - x')\mathrm{d}x' \\ & - \sum_n A_n \int s_1(x' - vt)\exp(2\pi i n x' \mu_0)p(x - x')\mathrm{d}x' \\ & + \int s(x' - vt)p(x - x')\mathrm{d}x'. \end{aligned} \tag{9}$$

The decoding process involves multiplication of $I(x, t)$ by the high-resolution urban object $\sum_n A_n \exp(2\pi i n x \mu_0)$ (which is known or can be extracted from the low-resolution images since such objects follow well known standards and formats), shifting the product back a distance of vt and summing all the images captured along the observation period (the sequence of images that we use for the superresolution) yields

$$R(x) = \sum_n A_n \int I(x + vt,\ t)\exp[2\pi i n(x + vt)\mu_0]\mathrm{d}t, \tag{10}$$

where $R(x)$ is the reconstructed image. Shifting back is required in order to obtain the reconstructed target always in the same spatial position; otherwise, blurred reconstruction will occur (due to bad registration of images). The relative shift of two images in the sequence can easily be found by correlating them with each other.

By substituting Eq. (9) into Eq. (10) and changing the integration variables from x' and t into $x'' = x' - vt$ and t, one obtains

$$\begin{aligned} R(x) = {} & \sum_n \sum_m A_n A_m \int \exp[2\pi i n(x + vt)\mu_0] \\ & \times \left\{ \int \exp[2\pi i m(x'' + vt)\mu_0]p(x - x'')\mathrm{d}x'' \right\}\mathrm{d}t \\ & - \sum_n \sum_m A_n A_m \int \exp[2\pi i n(x + vt)\mu_0] \\ & \times \left\{ \int s_1(x'')\exp[2\pi i m(x'' + vt)\mu_0]p(x - x'')\mathrm{d}x'' \right\}\mathrm{d}t \\ & + \sum_n A_n \int \exp[2\pi i n(x + vt)\mu_0] \\ & \times \left[\int s(x'')p(x - x'')\mathrm{d}x'' \right]\mathrm{d}t. \end{aligned} \tag{11}$$

Since mathematically one has

$$\int \exp(2\pi i n v \mu_0 t)\exp(2\pi i m v \mu_0 t)\mathrm{d}t = \delta(n - m),$$
$$\int \exp(2\pi i n v \mu_0 t)\mathrm{d}t = \delta(n), \tag{12}$$

we will assume that the urban grating can be approximated as

$$\sum_n \delta\left(x - \frac{n}{\mu_0}\right) \approx \sum_n A_n \exp(2\pi i n x \mu_0) \approx \sum_n A_n A_{-n} \exp(2\pi i n x \mu_0). \tag{13}$$

This is a good approximation since the fences have high duty cycle, and therefore their Fourier coefficients A_n are close to unity. Using this relation in Eq. (11) yields

$$R(x) = p(0) - \int s_1(x'')\sum_n \delta\left(x - x'' - \frac{n}{\mu_0}\right)p(x - x'')\mathrm{d}x'' + A_0 \int s(x'')p(x - x'')\mathrm{d}x''. \tag{14}$$

Since the width of the blurring function is smaller than the period of the urban grating, i.e., the width of p is smaller than I/μ_0, one obtains that, out of the summation in the second term, only one term remains, and therefore

$$
\begin{aligned}
R(x) &= p(0) - \int s_1(x'')\delta(x-x'')p(x-x'')\mathrm{d}x'' \\
&\quad + A_0\int s(x'')p(x-x'')\mathrm{d}x'' \\
&= p(0) + A_0\int s(x'')p(x-x'')\mathrm{d}x'' - s_1(x), \qquad (15)
\end{aligned}
$$

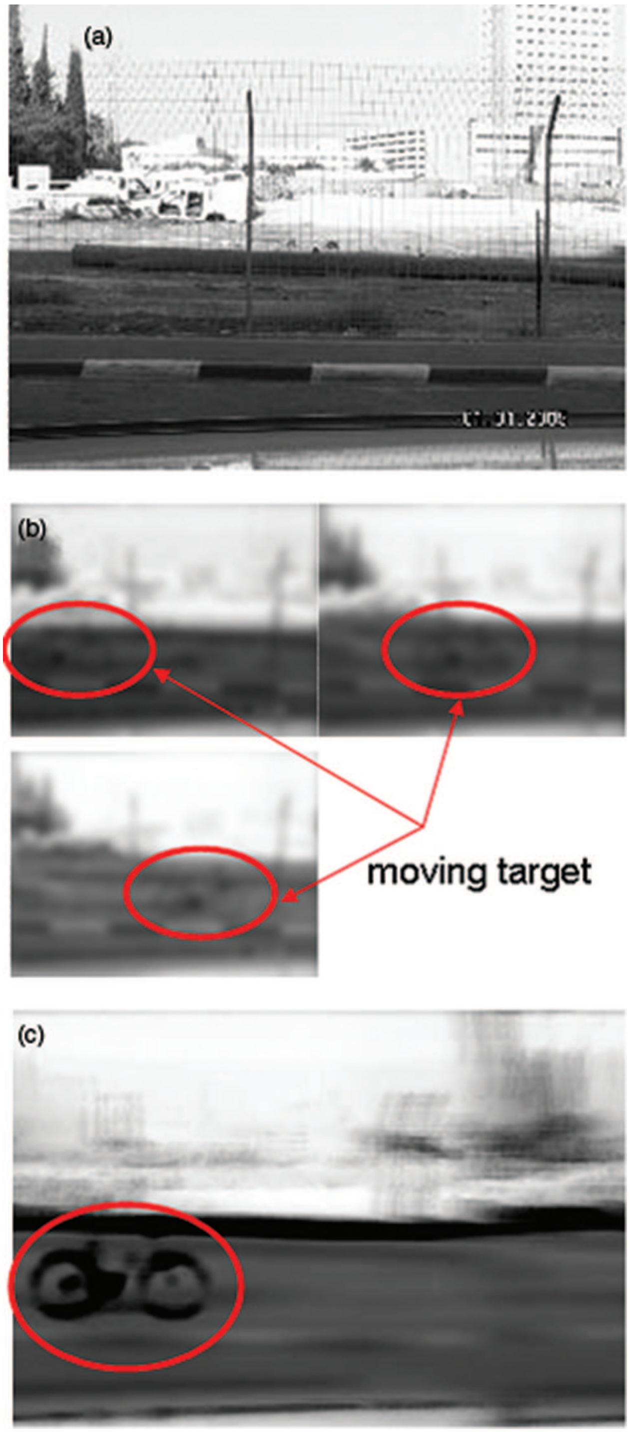

Fig. 2. (Color online) (a) High-resolution urban environment; (b) part of the sequence of low-resolution images containing moving target; (c) the superresolved moving target.

which means that the reconstructed image equals to a constant plus the low-resolution target image (i.e., the target blurred by the blurring point spread function) minus the high-resolution contour of the target (i.e., s_1). Thus, the suggested approach recovers the high-resolution contour of the moving target, and in order to extract it one should subtract from $R(x)$ the low resolution (i.e., blurred) target.

5. Experimental Results for the Urban Detection Approach

In Fig. 2 we present some experimental results demonstrating the described approach. In Fig. 2(a) one may see the high-resolution urban texture including the high-resolution fence. Such a fence, even if not resolved by the imaging setup, can be extracted from the low-resolution captured image since the spatial features of fences have standardized spacing, and therefore it can be anticipated and estimated even without being fully imaged. In Fig. 2(b) we capture a set of low-resolution images, including bicycles, as a moving target passing in front of the urban fence. The capturing of the sequence of images was done with digital camera Konica Minolta Z6 (has 6 megapixels), while the integration time was 1 ms. We used its lens with a focal length of 35 mm.

One may see that, due to the low resolution of the imaging system, the bicycles cannot be even identified. In Fig. 2(c) we apply our decoding algorithm, which includes multiplying each low-resolution image with the high-resolution coding fence, correlating in order to find the relative movement of the target between the sequential frames, backshifting of the target always to the same spatial position, and summation of all the decoded images in the sequence. The result may be seen in Fig. 2(c). As one can see, the moving target is superresolved. Now one can easily recognize that indeed the moving target was a bicycle.

6. Conclusions

In this paper we have experimentally demonstrated two applicable superresolving approaches allowing use of the environmental conditions in order to have better resolution imaging. In the first approach we have demonstrated how one may use the natural environment such as rain drops in order to be able to obtained superresolved imaging without the need to attach or to project anything on the observed object. By applying the proper digital decoding algorithm, we have experimentally demonstrated a resolution improvement of more than 3 times in comparison to the image quality obtained without applying the proposed approach. The method uses digital processing, and it does not require *a priori* knowledge of the encoding/decoding function that should be applied for the superresolved process.

In the second technique we have shown a way for reconstructing the contour of moving objects passing in front of periodic urban background. One need not have *a priori* knowledge of the structure of the periodic urban background since it usually follows well known fabrication standards and therefore can be estimated and used to decode the high-resolution image out of the sequence of low-resolution images.

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References

1. Z. Zalevsky and D. Mendlovic, *Optical Super Resolution* (Springer-Verlag, 2003).
2. Z. Zalevsky, D. Mendlovic, and A. W. Lohmann, "Optical systems with improved resolving power," in *Progress in Optics,* E. Wolf, ed. (Elsevier, 2000), Vol. 40, pp. 271–341.
3. W. Gartner and A. W. Lohmann, "An experiment going beyond Abbe's limit of diffraction," Z. Phys. **174,** 18 (1963).
4. A. Zlotnik, Z. Zalevsky, and E. Marom, "Superresolution with nonorthogonal polarization coding," Appl. Opt. **44,** 3705–3715 (2005).
5. A. I. Kartashev, "Optical systems with enhanced resolving power," Opt. Spectrosc. **9,** 204–206 (1960).
6. D. Mendlovic, J. Garcia, Z. Zalevsky, E. Marom, D. Mas, C. Ferreira, and A. W. Lohmann, "Wavelength multiplexing system for a single mode image transmission," Appl. Opt. **36,** 8474–8480 (1997).
7. M. A. Grimm and A. W. Lohmann, "Superresolution image for 1-D objects," J. Opt. Soc. Am. **56,** 1151–1156 (1966).
8. H. Bartelt and A. W. Lohmann, "Optical processing of 1-D signals," Opt. Commun. **42,** 87–91 (1982).
9. W. Lukosz, "Optical sytems with resolving powers exceeding the classical limits. II," J. Opt. Soc. Am. **57,** 932–941 (1967).
10. Z. Zalevsky, D. Mendlovic, and A. W. Lohmann, "Super resolution optical systems using fixed gratings," Opt. Commun. **163,** 79–85 (1999).
11. W. Lukosz, "Optical systems with resolving powers exceeding the classical limits," J. Opt. Soc. Am. **56,** 1463–1472 (1967).
12. M. Francon, "Amélioration de résolution d'optique," Nuovo Cimento Suppl. **9,** 283–290 (1952).
13. D. Mendlovic, I. Kiryuschev, Z. Zalevsky, A. W. Lohmann, and D. Farkas, "Two dimensional superresolution optical system for temporally restricted objects," Appl. Opt. **36,** 6687–6691 (1997).
14. P. Naulleau and E. Leith, "Imaging through optical fibers by spatial coherence encoding methods," J. Opt. Soc. Am. A **13,** 2096–2101 (1996).
15. K. Mills, Z. Zalevsky, and E. N. Leith, "Holographic generalized first-arriving light approach for resolving images viewed through a scattering medium," Appl. Opt. **41,** 2116–2121 (2002).
16. K. D. Mills, L. Deslaurier, D. S. Dilworth, S. M. Grannell, B. G. Hoover, B. D. Athey, and E. N. Leith, "Investigation of ultrafast time gating by spatial filtering," Appl. Opt. **40,** 2282–2289 (2001).
17. P. C. Sun and E. N. Leith, "Superresolution by spatial-temporal encoding methods," Appl. Opt. **31,** 4857–4862 (1992).
18. Z. Zalevsky, E. Leith, and K. Mills, "Optical implementation of code division multiplexing for super resolution. Part I. Spectroscopic method," Opt. Commun. **195,** 93–100 (2001).
19. Z. Zalevsky, E. Leith, and K. Mills, "Optical implementation of code division multiplexing for super resolution. Part II. Temporal method," Opt. Commun. **195,** 101–106 (2001).
20. W.-C. Chien, D. S. Dilworth, E. Liu, and E. N. Leith, "Synthetic-aperture chirp confocal imaging," Appl. Opt. **45,** 501–510 (2006).
21. E. N. Leith, K. D. Mills, P. P. Naulleau, D. S. Dilworth, I. Iglesias, and H. S. Chen, "Generalized confocal imaging and synthetic aperture imaging," J. Opt. Soc. Am. A **16,** 2880–2886 (1999).
22. A. Shemer, D. Mendlovic, Z. Zalevsky, J. Garcia, and P. G. Martinez, "Superresolving optical system with time multiplexing and computer decoding," Appl. Opt. **38,** 7245–7251 (1999).
23. A. Shemer, Z. Zalevsky, D. Mendlovic, N. Konforti, and E. Marom, "Time multiplexing superresolution based on interference grating projection," Appl. Opt. **41,** 7397–7404 (2002).
24. J. Garcia, Z. Zalevsky, and D. Fixler, "Synthetic aperture superresolution by speckle pattern projection," Opt. Express **13,** 6073–6078 (2005).
25. V. Mico, Z. Zalevsky, P. Garcia-Martinez, and J. Garcia, "Single-step superresolution by interferometric imaging," Opt. Express **12,** 2589–2596 (2004).
26. Z. Zalevsky, J. Garcia, and C. Ferreira, "Superresolved imaging of remote moving targets," Opt. Lett. **31,** 586–588 (2006).