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13. ABSTRACT *(Maximum 200 words)*

In standard intensity imaging, the resolution is limited by the width of the aperture. The region of support of the autocorrelation of the pupil function is the measured spatial frequency bandwidth of the imaging system and thus determines the resolution limit. This relationship between the size of the pupil function and the resolution limit is generally taken to describe a fundamental limit for resolution. Contrary to conventional wisdom, the resolution is actually limited only for fields with zero higher-order cumulants. For fields with non-vanishing higher-order cumulants, higher resolution can be obtained by integrating higher powers of instantaneous intensity in the image plane and combining these images appropriately. The result is that resolution is limited only by the time required for the integral of the higher power of intensity to approximate the expected value. We demonstrate these claims and analyze the variance of the integrated intensity-squared image as a function of the temporal spectrum and integration time. Furthermore, various image restoration strategies are proposed to estimate the superresolved intensity image from the various measurements. Our simulations show imaging of spatial frequency information outside the support of the pupil function autocorrelation for non-Gaussian fields.

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Superresolution of Passive Millimeter-Wave Imaging
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Final Report

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AFOSR

Signal Processing, Probability, and Statistics

Superresolution of Passive Millimeter-Wave Imaging

Stanley J. Reeves

1 Objectives

This project develops a new method for image acquisition that will provide superresolution capability without the benefit of assumptions about the object intensity distribution. Superresolution is of particular interest in passive millimeter wave imaging, which has tremendous potential for imaging in adverse conditions but suffers from poor resolution. By integrating higher powers of instantaneous intensity, higher spatial frequencies are recorded in the image plane. Through appropriate image processing strategies, the measured spatial frequencies can be extracted from the measured image in a postprocessing step to obtain a superresolved image. The processing strategy is dependent upon the statistical characteristics of the recorded image. Therefore, this effort requires an integration of work in statistical optical analysis and digital image processing.

2 Technical Accomplishments

2.1 Method

Resolution in incoherent intensity imaging is proportional to aperture size and inversely proportional to wavelength. Restoration is strictly limited in its ability to improve resolution, since the spatial frequencies obtained in intensity imaging are strictly bandlimited in proportion to aperture size. Superresolution — extrapolation beyond the measured bandwidth — is sometimes achieved by incorporating prior information into the restoration process, but superresolution is impossible without this prior information. Without prior information, the restored bandwidth is limited to the measured bandwidth.

We have found that in the special case of non-Gaussian fields, this limit is not fundamental. It is well known that higher-order statistics of non-Gaussian processes contain information not found in second-order statistics. This extra information can be exploited to obtain higher spatial frequency information that is absent from standard intensity images and thereby increase the effective resolution.

Assume that the object radiation is both temporally and spatially incoherent. Let $c_i^x(p)$ be the ith-order moment of the random process, and $g(p)$ the inverse Fourier transform of the pupil function (the point-spread function of the amplitude image). Then by integrating the nth power of instantaneous amplitude in the image plane, we get the following images for $i \in 2, 4, 6$:

$$I_2(p) = \mu_2 |g(p)|^2 * m_2^x(p) \tag{1}$$
$$I_4(p) = 2[I_2(p)]^2 + \mu_4 |g(p)|^4 * [m_2^x(p)]^2 \tag{2}$$
$$I_6(p) = 6[I_2(p)]^3 + 9I_2(p)[I_4(p) - 2I_2(p)] + \mu_6 |g(p)|^6 * [m_2^x(p)]^3 \tag{3}$$

for constants μ_i. From these we can isolate the terms $J_i(p) = \mu_i |g(p)|^i * [m_i^x(p)]^{\frac{i}{2}}$.

2.2 Analysis

We have shown that higher spatial frequencies of the intensity image exist in the blurred intensity-squared image $J_4(p)$. Therefore, the spatial frequencies that pass through the filter $|g(p)|^4$ can be recovered to increase the spatial frequency content of the restored image, thus accomplishing superresolution. The same reasoning applies in theory to higher orders, so that the only limit to resolution is the time required to make the acquired random data approach the expected value. We also showed that the combination of higher- and lower-order images can achieve a higher degree of superresolution than a higher resolution image taken alone. Finally, we showed that in the presence of noise the highest useful spatial frequency that can be reconstructed increases as $\sqrt{n}$, where n is the power to which the instantaneous amplitude is raised before integrating.

A thorough understanding of the statistics of the measured higher-order image is essential for guiding the development of image processing algorithms to exploit the superresolution information. An integrated instantaneous squared intensity image contains within the time average both a blurred, then squared intensity image and a squared, then blurred intensity image, as well as self-noise. We have analyzed the blurred intensity image to determine the variance both as a function of integration time and spatial coordinates.

The blurred, squared intensity image is much more difficult to analyze. We have derived an expression for the variance in terms of the temporal impulse response of the system, the spatial point-spread function, and the cumulants of the emission process. Because of the complexity of the general expression, we have derived a simplified version under the assumption of a Gaussian-shaped impulse response.

2.3 Image Processing

We have considered two approaches to reconstructing a higher-resolution intensity image from the measured data. In the first approach, the fourth-order term $J_4(p)$ is isolated and restored. Since this yields an estimate of $[m_2^x(p)]^2$, we take the square root of the restored fourth-order image to obtain the final restoration. While this approach is simplistic, it works fairly well. A somewhat more sophisticated approach combines second- and fourth-order images by minimizing the following expression with respect to $m_2^x(p)$:

$$\sum\left\{\left[b_2(p) - |g(p)|^2 * m_2^x(p)\right]^2 + \alpha\left[b_4(p) - |g(p)|^4 * [m_2^x(p)]^2\right]^2 + \beta\left[|l(p)|^2 * m_2^x(p)\right]^2\right\} \quad (4)$$

where $b_i(p)$ is the appropriate scaled data term, $l(p)$ is a Laplacian operator, and α and β are scalars that control the relative emphasis on the various terms. The last term regularizes the estimate.

We have derived a criterion that estimates the optimal weights α and β in a multiple-image-dataset restoration context. This is a necessary step in deriving a suitable algorithm for restoration of images in the proposed algorithm, since we will have at least two datasets on hand with which to estimate the original image. The criterion is based on an extension of the concept of generalized cross-validation (GCV). GCV has been used successfully for regularization parameter estimation. Our preliminary simulations indicate that the extended criterion is effective in estimating the weighting parameter(s), although more analytical work remains to be done.

2.4 Conclusions

We have shown that superresolution is theoretically possible without prior knowledge of the spatial intensity distribution of the scene. However, an underlying requirement for superresolution in our imaging equations is that the random field be non-Gaussian. This assumption does not generally hold in the passive case. It remains to be seen whether practical imaging approaches can be designed to exploit these results.

3 Personnel Supported

Stanley J. Reeves, PI
Yunqing Li, Graduate Research Assistant

4 Technical Publications

[1] S. J. Reeves, "Superresolution imaging of non-Gaussian emitters," submitted to *Signal Processing.*

[2] S. J. Reeves, "Imaging a class of non-Gaussian fields beyond the diffraction limit," submitted to *Journal of the Optical Society of America A.*

[3] S. J. Reeves, "An analysis of the difficulties and possibilities for superresolution," in *SPIE Vol. 3064 — Passive Millimeter-Wave Imaging Technology*, (Orlando, FL), pp. 239–248, SPIE - Int. Soc. Opt. Eng. (US), April 1997.

5 Interactions/Transitions

Presentation/discussion at Wright Lab, Eglin AFB, March 18, 1998.

6 Patent Disclosures

None.