

---

---

# The Development of Superresolution at Lincoln Laboratory

Irvin G. Stiglitz

**T**HIS SPECIAL ISSUE focuses on a variety of superresolution-oriented adaptive-array processing efforts at Lincoln Laboratory. For more than two decades, the Laboratory has been responsible for applications in which the achievement of the performance benefits of superresolution was essential for truly effective system operation.

During this period, adaptive-array processing has made the transition from a technological curiosity with limited apparent potential for practical importance to a significant technology that has brought about paradigm shifts in sensor design rules. Today these superresolution processing capabilities are often a central component in the concept-formulation stage of a program. This special issue of the *Lincoln Laboratory Journal* includes examples of such efforts in the context of various application areas.

## Overview

The articles in this issue fit into the following two general application areas: (1) copy and/or geolocation of signals in cochannel interference and (2) radar imaging. These problems share a common goal, i.e., to achieve optimal resolution with fractional (Rayleigh) beamwidth separation between the desired output and the undesired interference.

For simple configurations the term beamwidth is easy to define; for a filled line array used with single-polarization narrowband waveforms, the beamwidth (measured in radians) is the reciprocal of the aperture (measured in wavelengths). More general situations with complications such as polarization variation, wideband waveforms, and large sparse aperture arrays require a more generalized definition of beamwidth,

which is presented in the sidebar entitled “Definition and Properties of Beamwidth” in the article by Keith W. Forsythe. Analogous definitions apply to bandwidth for time-of-arrival estimation and integration time for frequency estimation.

Representative goals of superresolution include copy of a desired signal in the presence of closely spaced cochannel interference, direction finding on a desired signal in the presence of cochannel interference, and estimation of radar cross section for each of a number of scatterers. Practical approaches to enhanced resolution should (1) avoid sensitivity to assumptions about modeling error, (2) limit dependence on precision calibration, and (3) limit the computational requirements.

The first two articles in this special issue address the problems of copy and direction finding on signals buried in cochannel interference, based on the use of multichannel adaptive-array processing for the suppression of cochannel interference at fractional beamwidth separations. The article by Larry L. Horowitz, entitled “Airborne Signal Intercept for Wide-Area Battlefield Surveillance,” describes the underlying theoretical problem, and highlights the results of an airborne flight-test program to evaluate the achievable performance envelope at wavelengths comparable to aircraft dimensions. Performance comparisons are provided between algorithms that exploit known waveform features versus generic algorithms whose performance depends on antenna-calibration residuals. The article shows that near-optimum signal copy can be achieved without antenna-array calibration by relying on known waveform features. In addition, the article describes array-

calibration techniques that achieve calibration residuals lower than  $-40$  dB.

The article by Keith W. Forsythe, entitled “Utilizing Waveform Features for Adaptive Beamforming and Direction Finding with Narrowband Signals,” complements the Horowitz article by providing a number of specific techniques that are designed to exploit waveform features and achieve improved performance and relaxed calibration requirements.

The article by Gary F. Hatke, entitled “Super-resolution Source Location with Planar Arrays,” focuses on the use of a constrained aperture for two-dimensional direction finding in the presence of cochannel interference with fractional beamwidth separation from the desired signal. Hatke presents two efficient algorithms that can deal with environments having both specular and diffuse cochannel interference.

The article by Gerald R. Benitz, entitled “High-Definition Vector Imaging,” describes the application of adaptive-array processing to the problem of improving performance in radar imaging for both manual image analysis and automated-target-recognition algorithms. The specific goals for high-definition vector imaging (HDVI) are subpixel resolution, suppression of sidelobes and clutter, and discrimination of scatterers on the basis of their underlying scattering signatures.

The processing techniques described in the Benitz article have a family resemblance to the techniques described in the articles written by Hatke and by Forsythe. In those two articles, the data samples required for determining the requisite second-order statistic—the covariance matrix—were acquired by taking successive time samples. By analogy, the weight vector required (to replace the conventional fast-Fourier-transform eigenvectors) for the radar imaging application depends on a covariance matrix that, in principle, could be obtained from multiple coincident synthetic apertures. The Benitz article describes a practical alternative, based on approximating the covariance matrix with the data from a single synthetic aperture.

The article by Thomas G. Moore, Brian W. Zuendorf, and Earl C. Burt, entitled “Enhanced Imagery Using Spectral-Estimation-Based Techniques,” de-

scribes a resolution-enhancement technique for inverse synthetic-aperture radar (ISAR) imagery, based on Berg’s linear-predictive model. Specifically, the linear-prediction-model parameters estimated from the in-band data are used in turn to estimate the data beyond the measured spectral region. The expanded data set composed of the measured in-band data and the estimated out-of-band data is then weighted and compressed by using fast Fourier transforms to provide improved range resolution. Cross-range resolution enhancement is achieved by similar techniques that extend the effective aspect-angle change. Finally, bandwidth-interpolation techniques are employed to fill in missing or garbled portions of the spectrum.

Superresolution processing techniques are often viewed as tools for niche applications rather than as procedures for routine—perhaps even unattended—processing. The article by Leslie M. Novak, Gregory J. Owirka, William S. Brower, and Alison L. Weaver, entitled “The Automatic Target-Recognition System in SAIP,” describes and evaluates an HDVI-based automated image processing system developed to explore the feasibility of automation aids that can address the operational challenge of large quantities of radar imagery. This problem arises from the desire for high-performance automated target recognition without a concomitant need for high radar resolution and wideband communications.

The Semi-Automated IMINT Processing (SAIP) system described in the article by Novak and his co-authors utilizes HDVI with a minimum mean-square error template-matching classifier to achieve automatic target recognition. In addition, the SAIP system contains a number of other target-recognition subsystems essential to providing an operationally significant capability. The article provides SAIP-system performance data along with an indication of the requisite image database necessary to construct the target-recognition templates.

The potential availability of multiple bands of ISAR data offers the appealing prospect of achieving the intrinsic temporal resolution of the full processing bandwidth. This goal is the focus of the article by Kevin M. Cuomo, Jean E. Piou, and Joseph T. Mayhan, entitled “Ultra-Wideband Coherent Processing.” The technique described in this article rep-

resents an extension of the bandwidth-expansion techniques described in the article by Moore and his coauthors.

The first step in the ultra-wideband resolution process is to achieve requisite coherence between multiple subbands. The ultra-wideband process assumes an all-pole model for each of the subbands, and adjusts subband-model amplitude and phase corrections to achieve self-consistence. A single all-pole model is then used to fit the mutually coherent data. Conventional pulse-compression techniques are employed to achieve the range-resolved profiles. These results offer evidence that enhanced resolution can be achieved without requiring a filled spectrum or aperture.

### **Summary**

The availability of low-cost, high-performance digital signal processing devices has provided the implementation stimulus for the development of practical techniques for achieving sensor performance substantially better than that predicted by the Rayleigh limit. The articles in this special issue on superresolution provide examples of this capability. These examples represent a few of the interesting applications of superresolution processing. No effort has been made to cover the full range of applications.

Because of the numerous technical contributors to this area at Lincoln Laboratory, it is not possible to enumerate all of the people who have made significant contributions. However, I do want to take this opportunity to acknowledge three individuals, specifically, David Goldfein, Ken Senne, and Jay Sklar, each of whom has provided unique technical leadership and vision at critical junctures in the development and demonstration of this technology.

Finally, it is fitting that this special issue on superresolution commemorate the retirement of Walter Morrow as Director of Lincoln Laboratory. Walter's persistent personal interest, support, guidance, and encouragement were an essential catalyst for success in each of the efforts described here.

---

*Irvin G. Stiglitz is leader of the Advanced Techniques group at Lincoln Laboratory.*