

Selected Publications of Lincoln Laboratory Technical Staff February 2009 to June 2009

FEBRUARY 2009

GMTI MIMO Radar

Bliss, Daniel W., Jr., Keith W. Forsythe, Shakti K. Davis, and Glenn S. Fawcett, *Proceedings of the 2009 IEEE International Waveform Diversity and Design Conference*: 118–122, 8–13 February 2009.

Multiple-input multiple-output (MIMO) extensions to radar systems enable a number of advantages compared to traditional approaches. These advantages include improved angle estimation and target detection. In this paper, MIMO ground moving target indication (GMTI) radar is addressed. The concept of coherent MIMO radar is introduced. Comparisons are presented comparing MIMO GMTI and traditional radar performance. Simulations and theoretical bounds for MIMO GMTI angle estimation and minimum detectable velocity are presented. The simulations are evaluated in the time domain, enabling waveform design studies. For some applications, these results indicate significant potential improvements in clutter mitigation SINR loss and reduction in angle-estimation error for slow-moving targets.

Photon-Number-Resolution with sub-30-ps Timing Using Multi-Element Superconducting Nanowire Single Photon Detectors

Dauler, Eric A., Andrew J. Kerman, Bryan S. Robinson, Joel K.W. Yang, Boris Voronov, Gregory Goltsman, Scott A. Hamilton, and Karl K. Berggren, *Journal of Modern Optics* **56(2 & 3)**: 364–373, January/February 2009.

A photon-number-resolving detector based on a four-element superconducting nanowire single photon detector is demonstrated to have sub-30-ps resolution in measuring the arrival time of individual photons. This detector can be used to characterize the photon statistics of non-pulsed light sources and to mitigate dead-time effects in high-speed photon-counting applications. Furthermore, a 25% system detection efficiency at 1550 nm was demonstrated, making the

detector useful for both low-flux source characterization and high-speed photon-counting and quantum communication applications. The design, fabrication, and testing of this detector are described, and a comparison between the measured and the theoretical performance is presented.

Extending the Dynamic Range of RF Receivers Using Nonlinear Equalization

Goodman, Joel I., Benjamin A. Miller, Matthew A. Herman, M. Michael Vai, and Paul Monticciolo, *Proceedings of the 2009 IEEE International Waveform Diversity and Design Conference*: 224–228, 8–13 February 2009.

Systems currently being developed to operate across wide bandwidths with high sensitivity requirements are limited by the inherent dynamic range of a receiver's analog and mixed-signal components. To increase a receiver's overall linearity, we have developed a digital NonLinear Equalization (NLEQ) processor, which is capable of extending a receiver's dynamic range from one to three orders of magnitude. In this paper, we describe the NLEQ architecture and present measurements of its performance.

High-Speed Analog-to-Digital Conversion with Silicon Photonics

Holzwarth, C.W., Steven Jay Spector, Theodore M. Lyszczarz, Michael W. Geis, Donna M. Lennon, Jung Uk Yoon, Matthew E. Grein, Robert T. Schulein et al., *Proceedings of SPIE* **7220**, "Silicon Photonics IV," 72200B-1–72200B-15, February 2009.

Sampling rates of high-performance electronic analog-to-digital converters (ADCs) are fundamentally limited by the timing jitter of the electronic clock. This limit is overcome in photonic ADCs by taking advantage of the ultra-low timing jitter of femtosecond lasers. We have developed designs and strategies for a

photonic ADC that is capable of 40 GSa/s at a resolution of 8 bits. This system requires a femtosecond laser with a repetition rate of 2 GHz and timing jitter less than 20 fs. In addition to a femtosecond laser, this system calls for the integration of a number of photonic components, including a broadband modulator, optical filter banks, and photodetectors. Using silicon-on-insulator (SOI) as the platform, we have fabricated these individual components. The silicon optical modulator is based on a Mach-Zehnder interferometer architecture and achieves a $V_{\pi}L$ of 2 Vcm. The filter banks comprise 40 second-order microring-resonator filters with a channel spacing of 80 GHz. For the photodetectors, we are exploring ion-bombarded silicon waveguide detectors and germanium films epitaxially grown on silicon, utilizing a process that minimizes the defect density.

Lithographically Directed Materials Assembly

Kingsborough, Richard P., Russell B. Goodman, Keith E. Krohn, and Theodore H. Fedynshyn, "Alternative Lithographic Technologies," ed. Richard P. Kingsborough, *Proceedings of SPIE 7271*: 72712D-1–72712D-10, February 2009.

We have developed a processing method that significantly reduces the number of steps necessary to yield a surface that directs block copolymer assembly. This methodology employs a single resistless lithography step that directly changes the surface energy without requiring subsequent material deposition or plasma etching steps. The lithographically defined difference in surface energies acts as a template to direct diblock polymer self-assembly into low-defect periodic structures. Our newly developed lithographically directed self-assembly technique can produce sub-45 nm half-pitch lines employing poly(styrene-*b*-methyl methacrylate) (PS-*b*-PMMA) and interference lithography. Once assembled into periodic lines of alternating materials, the PMMA block can be removed and the resulting polystyrene features can be used as an etch mask to transfer periodic lines and spaces into a silicon substrate.

MARCH 2009

Forensic Speaker Recognition: A Need for Caution

Campbell, Joseph P., Wade Shen, William M. Campbell, Reva Schwartz, Jean-Francois Bonastre, and Driss Matrouf, *IEEE Signal Processing Magazine* **26(2)**: 95–103, March 2009.

There has long been a desire to be able to identify a person on the basis of his or her voice. For many years, judges, lawyers, detectives, and law enforcement agencies have wanted to use forensic voice authentication to investigate a suspect or to confirm a judgment of guilt or innocence. Challenges, realities, and cautions regarding the use of speaker recognition applied to forensic-quality samples are presented.

The Effect of Amplitude (Power) Variations on Beam Combining Efficiency for Phased Arrays

Fan, Tso Yee, *IEEE Journal of Selected Topics in Quantum Electronics* **15(2)**: 291–293, March/April 2009.

In coherent beam combining (phased arrays), control of the relative amplitudes (powers) of array elements is needed to maximize the beam-combining efficiency. Here, simple expressions are derived for the efficiency in approaches that use interferometric combiners such as diffractive optical elements or fiber couplers. The beam-combining efficiency is relatively insensitive to small power errors. In the case of dropped elements, the efficiency is equal to the fraction of operating elements. The beam-combining efficiency is equivalent to the Strehl ratio for a tiled aperture.

Electrothermal Feedback in Superconducting Nanowire Single-Photon Detectors

Kerman, Andrew J., Joel K.W. Yang, Richard J. Molnar, Eric A. Dauler, and Karl K. Berggren, *Physical Review B, Condensed Matter* **79(10)**: 100509-1–100509-4, March 2009.

We investigate the role of electrothermal feedback in the operation of superconducting nanowire single-photon detectors (SNSPDs). It is found that the desired mode of operation for SNSPDs is only achieved if this feedback is unstable, which happens naturally through the slow electrical response associated with their relatively large kinetic inductance. If this

response is sped up in an effort to increase the device count rate, the electrothermal feedback becomes stable and results in an effect known as latching, where the device is locked in a resistive state and can no longer detect photons. We present a set of experiments which elucidate this effect and a simple model which quantitatively explains the results.

Ultrawideband Offset Bicone/Dipole Antenna: Simulations and Measurements

Sandora, John S. and Alan J. Fenn, *Annual Review of Progress in Applied Computational Electromagnetics*, March 2009.

An ultrawideband antenna has been developed for operation in the 60 MHz to 18 GHz frequency range. This antenna is a new type—an offset bicone/dipole design that allows for vertically polarized omnidirectional coverage over an instantaneous 300:1 bandwidth. Numerical electromagnetic simulations with the finite-element method were used to investigate the antenna concept and optimize geometry prior to fabrication. Measurements outdoors and in an anechoic chamber confirm the antenna's performance.

Modeling and Detection Techniques for Counter-Terror Social Network Analysis and Intent Recognition

Weinstein, Clifford J., William M. Campbell, Brian W. Delaney, and Gerald C. O'Leary, *Proceedings of 2009 IEEE Aerospace Conference*, 1–16, 7–14 March 2009.

In this paper, we describe our approach and initial results on modeling, detection, and tracking of terrorist groups and their intents based on multimedia data. While research on automated information extraction from multimedia data has yielded significant progress in areas such as the extraction of entities, links, and events, less progress has been made in the development of automated tools for analyzing the results of information extraction to “connect the dots.” Hence, our Counter-Terror Social Network Analysis and Intent Recognition (CT-SNAIR) work focuses on development of automated techniques and tools for detection and tracking of dynamically changing terrorist networks as well as recognition of capability and potential intent. In addition to obtaining and working with real data for algorithm development and test, we have a major focus on

modeling and simulation of terrorist attacks based on real information about past attacks.

APRIL 2009

Image-Based Querying of Urban Knowledge Databases

Cho, Peter L., Soonmin Bae, and Fredo Durand, *Proceedings of SPIE 7336*, “Signal Processing, Sensor Fusion, and Target Recognition XVIII,” 733614–733614-12, April 2009.

We extend recent automated computer vision algorithms to reconstruct the global three-dimensional structures for photos and videos shot at fixed points in outdoor city environments. Mosaics of digital stills and embedded videos are georegistered by matching a few of their 2D features with 3D counterparts in aerial lidar imagery. Once image planes are aligned with world maps, abstract urban knowledge can propagate from the latter into the former. We project geotagged annotations from a 3D map into a 2D video stream and demonstrate their tracking buildings and streets in a clip with significant panning motion. We also present an interactive tool which enables users to select city features of interest in video frames and retrieve their geocoordinates and ranges. Implications of this work for future augmented reality systems based upon mobile smart phones are discussed.

Magnetic Exchange Enhancement of Electron Spin Resonance

Dionne, Gerald F., *Journal of Applied Physics* **105(7)**: 07A525-1–07A525-3, April 2009.

Boltzmann probability theory applied to ferromagnets is adjusted to explain the coexistence of microwave and infrared exchange resonance. When paramagnetic systems become ferromagnetic, microwave resonance is greatly enhanced by the exchange energy. In a quantum mechanical analysis, an apparent paradox is revealed. The combination of Zeeman and exchange effects is modeled to produce approximate relations for the population of the magnetic ground state with the result that a reduced temperature of the spin system is defined. To illustrate these concepts, exchange-coupled $3d^1$ single-pair and $3d^5$ multi-spin pairs are examined.

Resist Roughness Bi-modality as Revealed by Two-Dimensional FFT 2D Analysis

Gotkis, Yehiel, Leonid Baranov, Theodore H. Fedynyshyn, and Susan G. Cann, *Proceedings of SPIE 7273*, "Advances in Resist Materials and Processing Technology XXVI," 727345-1-727345-10, April 2009.

LER/LWR performance is currently considered one of the major stumbling blocks complicating progress in the semiconductor technology. Line edge scans show that low-frequency components clearly dominate the LER Power Spectral Density (PSD), thus implying a large characteristic length (>100–500 nm) phenomenon as the major LER source. Most of the theoretical analyses aimed to identify the origin of the LER were focused on the combined effect of exposure and CAR action statistics, and failed to explain the origin of this limit, which resulted in suggestions that there is more than just one phenomenon involved in LER generation. Depth profiling experiments were performed for a broad set of Polymer-PAG-Base combinations. Depth profiling PSD spectra have demonstrated that higher RMS values and correspondingly higher PSD amplitudes are associated with tighter PSD spectrum shifted towards lower frequencies (larger sizes of roughness features), which is very typical for all the cases investigated. The set of the PSD spectra obtained exhibit a pronounced bi-modal structure, indicating that there are at least two clearly noticeable independent roughness-controlling mechanisms.

Lattice Thermal Conductivity of Nanostructured Thermoelectric Materials Based on PbTe

Koh, Yee Kan, Christopher J. Vineis, Stephen D. Calawa, Michael P. Walsh, and David G. Cahill, *Applied Physics Letters 94(15)*: 153101, April 2009.

We report the through-thickness lattice thermal conductivity Λ_l of $(\text{PbTe})_{1-x}/(\text{PbSe})_x$ nanodot superlattices (NDSLs) over a wide range of periods $5 \text{ nm} \leq h \leq 50 \text{ nm}$, compositions $0.15 \leq x \leq 0.25$, growth temperatures $550 \text{ K} \leq T_s \leq 620 \text{ K}$, and growth rates $1 \mu\text{m} h^{-1} \leq R \leq 4 \mu\text{m} h^{-1}$. All of our measurements approach Λ_l of bulk homogeneous $\text{PbTe}_{1-x}\text{Se}_x$ alloys with the same average composition. For $5 \text{ nm} \leq h \leq 50 \text{ nm}$, Λ_l is independent of h ; a result we attribute to short mean-free paths of phonons in PbTe and small acoustic impedance

mismatch between PbTe/PbSe. We alloyed the PbTe layers of four NDSLs with SnTe up to a mole fraction $y = 18\%$; Λ_l is reduced by <25%.

Sensitivity of EUV Resists to Out-of-Band Radiation

Roberts, Jeanette M., Robert L. Bristol, Todd R. Younkin, Theodore H. Fedynyshyn, David K. Astolfi, and Alberto Cabral, *Proceedings of SPIE 7273*, "Advances in Resist Materials and Processing Technology XXVI," 72731W-1-72731W-13, April 2009.

Here we present the relative sensitivity of extreme ultraviolet (EUV) resists to out-of-band radiation (OOB), specifically wavelengths in the range 157–400 nm. EUV light sources have specifications limiting the allowed energy output in that spectral range yet there is little data supporting the specified values. Filters might be required to meet the spectral purity specifications which will likely have the detrimental effect of reducing the in-band radiation at 13.5 nm and therefore negatively impact the cost of ownership of EUV lithography. To better quantify the effects of OOB, we obtained contrast curves and absorbance spectra for several EUV resist platforms at nine exposure wavelengths. The 2007 ITRS Roadmap suggests that resist thicknesses will be near 35–65 nm when EUV will be used.¹ We found that, in this optically thin regime, resist sensitivity increases with increasing absorbance. The sensitivity decreases dramatically for wavelengths approaching 300 nm, and is negligible for longer wavelengths. The OOB sensitivity of the resists examined can be estimated to within an order of magnitude using the resist absorbance value. For resists with absorbance values on the same order of magnitude, sensitivity is determined by other aspects of the resist formulation. Within the wavelength region explored, the greatest concern is near 160–240 nm, based on current resist sensitivity characteristics. However, there is a gap in data between 13.5–157 nm, and there may be other reasons to limit the source output in that wavelength range. The data presented here could be useful in setting or modifying the OOB specifications for EUV tools.

¹ <http://www.Itrs.Net/>

Deep UV Photon-Counting Detectors and Applications

Shaw, Gary A., Andrew M. Siegel, Joshua Model, Adam B. Geboff, Stanislav Soloviev, Alexy Vert, and Peter Sandvik, *Proceedings of SPIE 7320*, "Advanced Photon Counting Techniques III," 73200J-1–73200J-15, April 2009.

Photon-counting detectors are used in many diverse applications and are well suited to situations in which a weak signal is present in a relatively benign background. Examples of successful system applications of photon-counting detectors include lidar, bioaerosol detection, communication, and low-light imaging. A variety of practical photon-counting detectors have been developed employing materials and technologies that cover the waveband from deep ultraviolet (UV) to the near-infrared. However, until recently, photoemissive detectors (photomultiplier tubes (PMTs) and their variants) were the only viable technology for photon counting in the deep UV region of the spectrum. While PMTs exhibit extremely low dark count rates and large active area, they have other characteristics that make them unsuitable for certain applications. The characteristics and performance limitations of PMTs that prevent their use in some applications include bandwidth limitations, high bias voltages, sensitivity to magnetic fields, low quantum efficiency, large volume, and high cost. Recently, DARPA initiated a program called Deep UV Avalanche Photodiode (DUVAP) to develop semiconductor alternatives to PMTs for use in the deep UV. The higher quantum efficiency of Geiger-mode avalanche photodiode (GM-APD) detectors and the ability to fabricate arrays of individually addressable detectors will open up new applications in the deep UV. In this paper, we discuss the system design trades that must be considered in order to successfully replace low-dark count, large-area PMTs with high-dark count, small-area GM-APD detectors. We also discuss applications that will be enabled by the successful development of deep UV GM-APD arrays, and we present preliminary performance data for recently fabricated silicon carbide GM-APD arrays.

Analyzing Networks of Static and Dynamic Geospatial Entities for Urban Situational Awareness

Sherrill, Delsey M., Michael J. Yee, and Peter L. Cho, *Proceedings of SPIE 7346*, "Visual Analytics for Homeland Defense and Security," 734605-1–734605-12, April 2009.

Motivated by the problem of uncovering networks of illicit actors in complex urban environments, we present a prototype system for intuitive navigation of vehicle track data via interacting map and network views. Our system combines 3D geospatial visualization, social network display, and interactive track search software, and it provides a multi-touch interface for operators to navigate urban scenes and investigate potentially suspicious vehicle activity. We describe a case study to highlight the system's capabilities using ground truth vehicle data collected during a 2007 urban exercise. This data is most naturally viewed as tracks in space and time. But as cluttered track displays obscure potentially important actor relationships, our system provides a social network picture whose condensed format is easier to interpret. Through coordinated space-time/vehicle network searches, we demonstrate how analysts can uncover "Red" activities of tactical significance.

Reliable InP-Based Geiger-Mode Avalanche Photodiode Arrays

Smith, Gary M., K. Alexander McIntosh, Joseph P. Donnelly, Joseph E. Funk, Leonard J. Mahoney, and Simon Verghese, *Proceedings of SPIE 7320*, "Advanced Photon Counting Techniques III," 73200R–73200R-10, April 2009.

Arrays as large as 256×64 of single-photon-counting avalanche photodiodes have been developed for defense applications in free-space communication and laser radar. Focal plane arrays (FPAs) sensitive to both 1.06 and 1.55 μm wavelength have been fabricated for these applications. At 240 K and 4 V overbias, the dark-count rate (DCR) of 15 μm diameter devices is typically 250 Hz for 1.06 μm sensitive APDs and 1 kHz for 1.55 μm APDs. Photon-detection efficiencies (PDE) at 4 V overbias are about 45% for both types of APDs. Accounting for microlens losses, the full FPA has a PDE of 30%. The reset time needed for a pixel to avoid afterpulsing at 240 K is about 3–4 μsec . These devices have been used by system groups at

Lincoln Laboratory and other defense contractors for building operational systems. For these fielded systems, the device reliability is a strong concern. Individual APDs as well as full arrays have been run for over 1000 hours of accelerated testing to verify their stability. The reliability of these GM-APDs is shown to be under 10 FITs at operating temperatures of 250 K, which also corresponds to an MTTF of 17,100 years.

Arrays of 128 × 32 InP-based Geiger-Mode Avalanche Photodiodes

Verghese, Simon, K. Alexander McIntosh, Zong-Long Liao, Christopher J. Sataline, John D. Shelton, Joseph P. Donnelly, Joseph E. Funk, Richard D. Younger, Leonard J. Mahoney, Gary M. Smith, and Joseph M. Mahan, *Proceedings of SPIE 7320*, "Advanced Photon Counting Techniques III," 73200M-1–73200M-8, April 2009.

Arrays of InP-based avalanche photodiodes operating at 1.06 μm wavelength in the Geiger mode have been fabricated in the 128 × 32 format. The arrays have been hermetically packaged with precision-aligned lenslet arrays, bump-bonded read-out integrated circuits, and thermoelectric coolers. With the array cooled to –20C and voltage biased so that optical crosstalk is small, the median photon-detection efficiency is 23–25% and the median dark count rate is 2 kHz. With slightly higher voltage overbias, optical crosstalk increases, but the photon-detection efficiency increases to almost 30%. These values of photon-detection efficiency include the optical coupling losses of the microlens array and package window.

Analysis of Rapid C_n^2 Fluctuations Observed During a 5 km Communication Link Experiment

Yarnall, Timothy M., Steven S. Michael, John D. Moores, Ronald R. Parenti, and William E. Wilcox Jr., *Proceedings of SPIE 7324*, "Atmospheric Propagation VI," 73240B-1–73240B-1, April 2009.

The path-integrated turbulence strength is usually thought of as a parameter that varies slowly with time. In a recent free-space communications experiment the C_n^2 value over a 5 km horizontal path was monitored almost continuously for a period of nearly a month. In

addition to well-defined and repeatable diurnal fluctuations, strong short-term fluctuations were observed in which the turbulence strength changed by an order of magnitude within a period of minutes. These rapid changes were independently measured by a commercial scintillometer and the high-rate output from the communications transceiver. The characteristics and probable causes for these dynamic atmospheric events and their impact on the design of free-space communication systems are discussed in this article.

Crosstalk Analysis of Integrated Geiger-Mode Avalanche Photodiode Focal Plane Arrays

Younger, Richard D., K. Alexander McIntosh, Joseph W. Chludzinski, Douglas C. Oakley, Leonard J. Mahoney, Joseph E. Funk, Joseph P. Donnelly, and Simon Verghese, *Proceedings of SPIE 7320*, "Advanced Photon Counting Techniques III," 73200Q–73200Q-12, April 2009.

Arrays of photon-counting Geiger-mode avalanche photodiodes sensitive to 1.06 and 1.55 μm wavelengths and as large as 256 × 64 elements on 50 μm pitch have been fabricated for defense applications. As array size and element density increase, optical crosstalk becomes an increasingly limiting source of spurious counts. We characterize the crosstalk by measurement of emitted light and by extracting the spatial and temporal focal plane array (FPA) response to the light from FPA dark-count statistics. We discuss the physical and geometrical causes of FPA crosstalk, suggest metrics useful to system designers, then present measured crosstalk metrics for large FPAs as a function of their operating parameters. We then present FPA designs that suppress crosstalk effects and show more than 40 times reduction in crosstalk.

MAY 2009

Bit Error Rate Measurements of Diffraction by Non-True-Time-Delay, Holographic Optical Element

Tsui, Jing M. and Jeffrey M. Roth, *Electronics Letters* **45(11)**: 561–563, 21 May 2009.

The impact on digital communications performance from non-true-time-delay beam steering by a holographic optical element (HOE) is investigated. Free-space data transmission experiments were performed using an HOE

with a 5 mm diameter and 33° diffraction angle at the data rate of 10 Gbit/s with return-to-zero and non-return-to-zero formats. For this diffraction case, a small penalty of 0.7 dB at 10^{-9} bit error rate is observed for both formats. This penalty is smaller than the optical loss but would be expected to increase for larger diameters and data rates.

JUNE 2009

Polyphase Nonlinear Equalization of Time-Interleaved Analog-to-Digital Converters

Goodman, Joel I., Benjamin A. Miller, Matthew A. Herman, Gil Raz, and Jeffrey Jackson, *IEEE Journal of Selected Topics in Signal Processing* **3(3)**: 362–373, June 2009.

As the demand for higher data rates increases, commercial analog-to-digital converters (ADCs) are more commonly being implemented with multiple on-chip converters whose outputs are time-interleaved. The distortion generated by time-interleaved ADCs is now not only a function of the nonlinear behavior of the constituent circuitry, but also mismatches associated with interleaving multiple output streams. To mitigate distortion generated by time-interleaved ADCs, we have developed a polyphase NonLinear EQualizer (pNLEQ), which is capable of simultaneously mitigating distortion generated by both the on-chip circuitry and mismatches due to time interleaving. In this paper, we describe the pNLEQ architecture and present measurements of its performance.

Optical Techniques for Detecting and Identifying Biological-Warfare Agents

Greenwood, Darryl P., Thomas H. Jeys, Bernadette Johnson, Jonathan M. Richardson, and Michael P. Shatz, *Proceedings of the IEEE* **97(6)**: 971–989, June 2009.

Rapid and accurate detection and identification of biological agents is an objective of various national security programs. Detection in general is difficult owing to natural clutter and anticipated low concentrations of subject material. Typical detection architectures comprise a nonspecific trigger, a rapid identifier, and a confirming step, often in a laboratory. High-confidence identification must be made prior to taking action, though this must be

traded against regrets stemming from delay. Sensing requirements are best established by positing plausible scenarios, two of which are suggested herein. Modern technologies include the use of elastic scatter and ultraviolet laser-induced fluorescence for triggering and standoff detection. Optical and nonoptical techniques are used routinely in analyzing clinical samples to confirm infection and illness resulting from a biological attack. Today, environmental sensing serves at best as an alert to medical authorities for possible action, which would include sample collection and detailed analysis. This paper surveys the state of the art of sensing at all levels.

MIMO Radar Ambiguity Functions

San Antonio, Geoffrey, Daniel R. Fuhrmann, and Frank C. Robey, *IEEE Journal of Selected Topics in Signal Processing* **1(1)**: 167-177, June 2007.

Multiple-input multiple-output (MIMO) radar has been shown to provide enhanced performance in theory and in practice. MIMO radars are equipped with the ability to freely choose their transmitted waveforms at each aperture. In conventional radar systems, Woodward's ambiguity function is used to characterize waveform resolution performance. In this paper, we extend the idea of waveform ambiguity functions to MIMO radars. MIMO ambiguity functions are developed that simultaneously characterize the effects of array geometry and transmitted waveforms on resolution performance. Overall resolution performance is shown to be governed by a space-time covariance function that can be controlled by the system on transmit using waveform diversity. Visual examples are provided to illustrate the resolution enhancement possible using MIMO technology.