Aquerre Technologies

# Advanced MIMO Capabilities for Gotcha Spiral II and Future SAR Imaging Systems

A TECHNICAL PROPOSAL

Submitted to the

Air Force Research Laboratory

Broad Agency Announcement No. FA8650-17-S-1005:
Research to Advance Comprehensive Exploitation of RF (RACER)

by

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## 1. Introduction

The Government has expressed the need for basic research and development in the field of Synthetic Aperture Radar (SAR) leading into new commercial products to advance the capabilities of the Gotcha Spiral II radar imaging system and next generation SAR imaging systems. In the Broad Agency Announcement (BAA) FA8650-17-S-1005, “Research to Advance Comprehensive Exploitation of RF (RACER)”, three strategic objectives to advance SAR imaging system capabilities are requested: 1. research and data, 2. software, and 3. hardware. In this technical proposal, Aquerre Technologies LLC will outline a strategic R&D roadmap for delivering solutions for the three objectives of the RACER BAA pertaining to the Gotcha Spiral II radar imaging system and beyond.

Aquerre Technologies LLC is focused on developing evolutionary and revolutionary approaches for advancing state of the art of Radio Frequency (RF) exploitation for Gotcha Spiral II and next generation radar sensing systems, for the RACER program. Our innovative methods will maximize RF sensing and exploitation performance using all available information from the RF signal space. Our methods are based on advanced theoretical models in concert with high performance signal processing and custom algorithm development for optimized for efficient RF sensing and awareness capabilities. We not only leverage modern results in the field of Synthetic Aperture Radar, we lead the state of the art through the development of innovative new technologies customized to meet the Government's performance requirements. Aquerre Technologies is founded by a Ph.D. expert in the field of RF communications and systems and will further be staffed by Ph.D. experts hand selected for the RACER program. Our strong expertise base and prior experience with big industry developing custom products and solutions for Government customers makes Aquerre Technologies the winning partner for the AFRL RACER BAA.

Our key technical contribution will focus on the use of new Multi-Input Multi-Output (MIMO) technologies to achieve new performance gains over conventional SAR imaging systems. We will implement innovative methods for utilizing centralized and distributed MIMO configurations, including multi-antenna array processing techniques per frequency band and multi-band array processing techniques.  In the RACER contract we implement innovative algorithmic approaches to MIMO SAR signal processing and data visualization. We further develop a distributed SAR application based on multiple platforms flying in formation and MIMO signal processing techniques.

### 1.1 RACER Deliverables

Major deliverables to the Government resulting from execution of the RACER contract will include the SARPVE (Synthetic Aperture Radar Processing and Visualization Engine) which is a software took kit implementing the advanced signal processing and visualization methodologies developed by Aquerre Technologies. The SARPVE will extend conventional SAR implementations leveraging enhanced MIMO signal processing. We further plan the development and delivery of a SAR Data Simulation and Interface Program for generating artificial data for algorithm studies as well as interfacing with online data sets for testing and evaluation of the methods developed in SARPVE. Performance data, detailed description of implemented methods, and software documentation shall be delivered to the Government as part of the RACER program.

The primary focus will be on software deliverables, however we envision the possible need for new antenna designs to facilitate MIMO processing methodologies. If custom antenna hardware is required, related hardware prototypes will be delivered to the Government as part of this contract. Furthermore, our proposed work program includes the option for in-house development of custom UAV based SAR radar platform for evaluating the potential of distributed SAR methodologies for future radar imaging systems. This is subject to approval by Government sponsor and any in-house developed radar components/systems will be furnished to the Government in the form of hardware prototypes.

## 2. Strategic Roadmap

The RACER program comprises a 5 year (60 month) work program for advancing RF sensing and exploitation capabilities for next generation SAR systems, specifically including advanced capabilities for theAFRL Gotcha Spiral II radar system. The Government intends to deliver the Gotcha Spiral II as part of the contract(s) awarded for this BAA. In this technical proposal, we propose to collaborate with the Government and appropriate industry partner, possibly through an Associate Contract Agreement (ACA), to obtain access to the Gotcha Spiral II Testbed, for developing and testing our proprietary technologies. Thereby, this technical proposal will focus primarily on the development of advanced models, algorithms and software, and to a lesser extent hardware, pertaining to Gotcha Spiral II and other future radar systems. We further omit details of ground and airborne operation of the Gotcha Spiral II Testbed to a later more appropriate context such as the negotiation of the ACA or direct interactions with a partnering contractor.

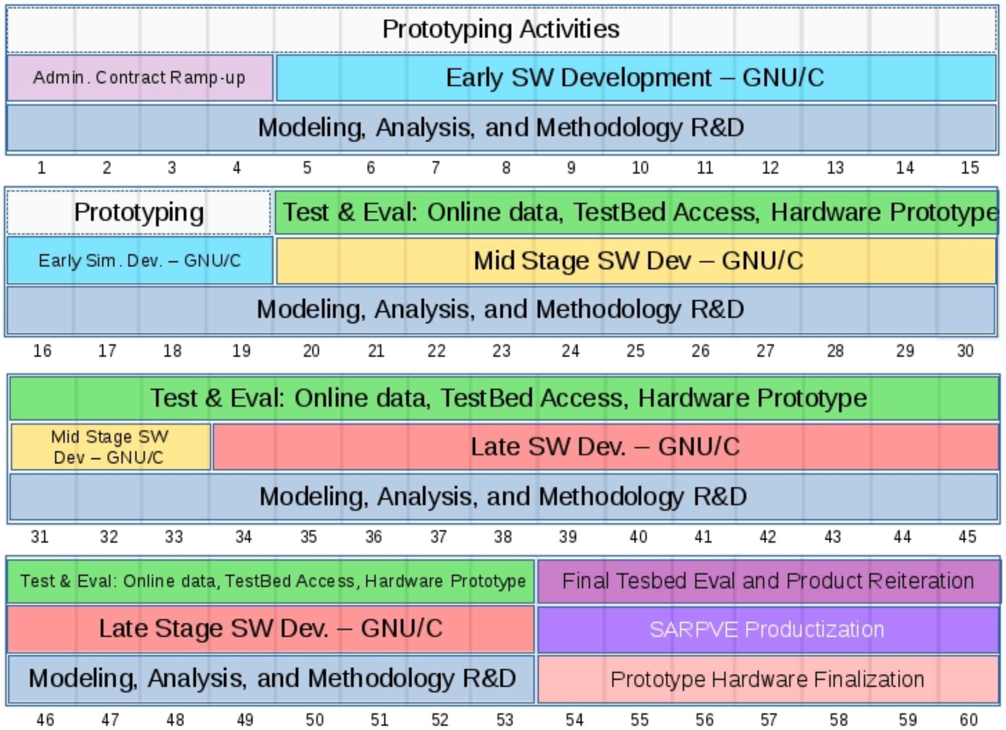


**Figure 1.** Sketch of Project Timeline

Figure 1 shows a graphical timeline of our proposed work program for the RACER contract. The x-axis represents the project-month and the y-axis represents the task allocation. Note that the ratio of time spent on each task is not drawn to scale, rather a flexible time allocation policy will be implemented in such a way to focus work effort on the most critical project components to eliminate any bottleneck issues that may arise and to ensure the most efficient transition toward the final goal of productization of advanced SAR technologies.

The proposed work plan is divided into three main tasks: (1) Modeling, Analysis and Methodology Development, (2) Computer Simulation and SAR Processing and Visualization Engine (SARPVE), and (3) Testing Activities via simulator runs of developed methods on computer generated and online data sets, Gotcha

Spiral II TestBed access, and in-house prototype development and testing. The final six months of the project timeline is treated separate from the preceding workflow and is meant to finalize the delivered products and includes the airborne TestBed performance evaluation as described in the main BAA document.

Task (1) will commence at the very start of contract execution and last for a duration of 54 months. Task (2) is sub-divided into three phases, early-, mid- and late-stage simulator platform development, spanning 16 months each. Task (3) is a testing work flow that is meant to provide realistic performance based feedback for the product development workflows during their intermediate phases of readiness. The specific implementation details of these tasks are provided in greater detail in the next section.

### 2.1 Task Workflow Details

In this section, we will treat the detailed description of three main work tasks outlined above and the fourth descriptive component will comprise the final six month work activities.

#### *2.1.1 Taks (1): Modeling, Analysis and Methodology Development*

The modeling, analysis and methodology development workflow is a fundamental component of Aquerre Technologies overall contribution to the RACER program. Our strength in the areas of mathematical analysis, signals and systems theory, probability theory, detection and estimation theory, and wireless communication systems will enable us make a key impact towards advancing the state of the art of SAR imaging systems by means of proprietary algorithms, advanced signal processing and new methodology/technology development. U.S. patent rights may be pursued here but the Government retains full unlimited rights to any technology innovations developed as part of this work effort. We plan to generate our own complete modeling and analysis tool-set specially geared for Government applications of interest, for example SAR imaging via penetration through dense foliage cover environment. Specific applications like this require specialized mathematical models (and joint testing/calibration activities) to accurately detect and estimate hidden targets beyond the capability of existing SAR systems.

We have extended this workflow throughout the overall project timeline up until the final six months with the goal of continuously building, adapting and refining our models, analysis and methods. The proposed workflow structure will allow incorporation of intermediate testing results and data into the Task (1) workflow process dynamically, as further results from testing simulated data, simulated performance with online data sets, and testing activities with the Gotcha Spiral II and our own prototype equipment are generated in the parallel Task (2) workflow. Regular interactions with Government sponsor (AFRL) and with collaborating contractor shall be used to guide Task (1) workflow progress.

The primary deliverable obtained through the Task (1) workflow will consist of thorough documentation of the mathematical logic developed throughout the program with corresponding details of the R&D applications of focus—this will be made available for sponsor review at regular (eg. monthly) update intervals to enable close tracking of our R&D development progress.  Additional deliverable items from the Task (1) workflow include regular (eg. yearly) technical presentations of the R&D progress, including a summary the of the primary Task (1) technical document and ongoing testing and productization activities.

### *2.1.2 Task (2): SAR Data Server and SAR Processing and Visualization Engine (SARPVE) Development*

The Aquerre SAR Data Server and SAR Processing and Visualization Engine (SARPVE) are the primary products to be delivered as a result of RACER contract execution. The first, SAR Data Server, will implement computer generated SAR data for testing and validation of the in-house developed mathematical models and signal processing and visualization methods. Moreover, the SAR Data Server will be configurable to provide raw data obtained from online data repositories, such as the one listed in Table 1, and those furnished by the Government.  The SARPVE comprises the bulk of the advanced capabilities for next generation SAR imaging systems including Gotcha Spiral II based on our in-house research and development expertise and innovations arising through execution of the RACER contract. The SARPVE will work with supplied SAR data and implement an advanced suite of signal processing and display/visualization functions pertaining to our in-house developed methodologies. The SARPVE will provide advanced monostatic radar processing functionality as a baseline and will extend to Multi-Input Multi-Output (MIMO) configurations, advancing the state of the art of SAR radar techniques. MIMO techniques developed will utilize an antenna array at the radar transceiver for enhancing spatial directivity, resolution and filtering capability of the SAR waveform and enhanced radar cross section. Further R&D and productization efforts will be directed towards distributed SAR applications, where one or more

SAR transmitters are received by one or more SAR receivers on non-co-located platforms, eg. UAVs flying in formation with precise GPS and SAR processing capability. A detailed mathematical description of our R&D technical approach is provided in Section 3.

| **Repository Name** | **URL** |
|---|---|
| Alaska Satellite Facility (ASF) Distributed Active Archive Center (DAAC) | https://earthdata.nasa.gov/about/daacs/daac-asf |

**Table 1.** Online raw SAR data source.

Code development will be performed in the GNU Linux C/C++ development environment, easily portable to all other major operating systems and software defined radio platforms. The Task (2) workflow is segmented into three 16 month distinct phases (early-, mid- and late-stage) to facilitate efficient and timely R&D-to-product trajectory.  The SARPVE will consume the majority of work hours especially in the mid- and late-stages. The early stage SARPVE will focus on generating and implementing a feasible set of candidate methodologies in the SARPVE code project. During this initial phase, exploration of and proof of concept demonstration will occur with the primary signal processing and visualization functionalities, as well as those deemed forward looking (in terms of computational complexity or cost of communication resources). By start of Phase II of this workflow we will have identified our baseline suite of algorithms, processing and visualization functions and will progress further towards the implementation of a full featured software environment for advanced SAR processing and data visualization. This workflow will be closely aligned with the testing and validation workflow conducted in parallel with SARPVE development. In Phase III of the Task (2) workflow, SARPVE will be nearing its finalized state with well defined functionality and data processing capabilities and will be further subject to extensive testing and validation leading towards a “beta” releasable code base. In addition, the Phase II and Phase III components will include a focus on integrability with existing Government software and systems such as Gotcha Spiral II system.

*2.1.3 Task (3): Testing Activities via simulator runs of developed methods on computer generated and online data sets, Gotcha Spiral II TestBed access, and in-house prototype development and testing*

Task (3) comprises the testing and evaluation component of the Aquerre Technologies' implementation of the RACER contract. Task (3) workflow start coincides with Task (2) Phase II start date, at month 20, and has an overall duration of 35 months. By start of Task (2) Phase II, the Aquerre SAR Data Server and SARPVE will be in their initial workable states and ready for operational testing and evaluation for feedback in to the main code development and R&D workflow. In addition to synthesized data, the SAR Data Simulator will provide an interface to raw SAR data sets, including any available Government furnished data sets. Hence operational testing will consist of operation of preliminary SARPVE code instances on synthetic and raw SAR data sets. In addition, we will seek to incorporate any available access to the Gotcha Spiral II Testbed in our code testing and evaluation feedback cycle. This is subject to arrangement between sponsor and collaborating contractor. We thereby include the option of developing in-house low-power/light-weight SAR radar prototype equipment for use with with UAVs, based on Commercial Off The Shelf (COTS) components for conducting testing and evaluation of SARPVE technologies. In this option, a separate budget component for procuring COTS radar prototypic modules and UAVs will be exercised to facilitate execution of RACER contract testing and evaluation, and a functional prototype radar hardware/software system will be included as part of the final program deliverables to the Government.

*2.1.4 Final six months of RACER contract timeline*

The final six month Aquerre Technologies' RACER contract timeline are segmented from the main workflow to emphasize final productization activities of the development cycle. In this period, the TestBed demonstration of developed technologies (as described in the BAA) will occur with the Gotcha Spiral II Testbed and/or the UAV SAR Prototypes developed by Aquerre Technologies. The final six months will include any final DARPVE product reiterations, based on TestBed performance and other feedback, moving the code base to its “alpha” release state. Finally, the UAV SAR Prototypes, the DARPVE, and the SAR Data Server, and corresponding Technical R&D and Software Documents, will be prepared for final delivery to the Government.

## 3. Research and development technical approach and technical innovation

In this section we introduce our main R&D technical approach and describe some of the innovations planned for this contract. The Gotcha Spiral II is a dual band, UHF and X-band, monostatic SAR system. Thus radar transmitter and receiver are co-located. The main technical innovation brought by Aquerre Technologies is the introduction of Multi Input, Multi Output (MIMO) methods for enhancing radar imaging and sensing capabilities. Multiple antennas and MIMO signal processing can be used to enhance system performance per frequency band, and distributed MIMO techniques offer a revolutionary approach to SAR imaging via collection of reflected SAR waveforms form multiple platforms operated in formation. Hence our main innovation approach will be based on the exploration of centralized and distributed MIMO radar signal processing for next generation radar imaging systems.

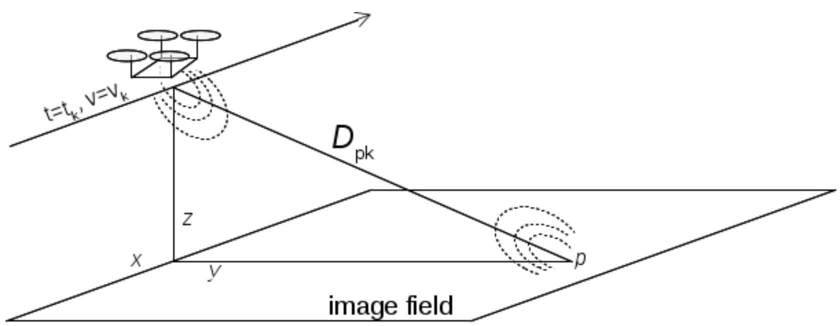


**Figure 2.** Monostatic SAR geometry.

### 3.1 Basic Mathematical Description of Single-Band, Single-Antenna Monostatic SAR Imaging System

First we describe a single element transmit and receive SAR system operating on a single frequency band and later extend to centralized and distributed MIMO implementations. Figure 2 depicts the basic system geometry, where SAR platform is moving along a certain path talking several “snapshots” of the imaging field, which will be combined by SAR processing methods to form the radar image. The SAR transmitter is assumed to emit a chirp waveform $x_k(t)$ every $P$ seconds. In complex baseband notation $x_k(t)$ is expressed as:

$$x_k(t) = G_{tx} * \exp\{i2\pi * f(t-t_k) * t\}, \quad t_0 + (k-1)P < t < t_0 + T_c + (k-1)P, \; k=1,\ldots,K \qquad (1)$$

where f(t) is typically a linear frequency ramp across bandwidth $B$ of length $0<t<T_c$ seconds, $G_{tx}$ denotes the transmitter gain coefficient, $t_0$ is time start of first chirp, $K$ is number of chirps, and $t_k = t_0 + (k-1)P$.

The return signal from chirp $k$ from the $n$th point reflector at distance $D_{nk}$ is given by:

$$y_{nk}(t) = G_{rx} * (2D_{nk})^{-2} * A_n * x(t - 2D_{nk}/c)$$

$$= G_{tx}*G_{rx}*(2D_{nk})^{-2}*A_n*\exp\{i2\pi*[f(t-2D_{nk}/c-t_0)-\Delta_{nk}]*(t-2D_{nk}/c)\},$$
$$t_k+2D_{nk}/c < t < t_k+T_c+2D_{nk}/c, \quad (2)$$

where $G_{rx}$ is the receiver gain coefficient, $A_n = \alpha_n \exp(i2\pi*\varphi_n)$ is the reflector induced amplitude ($\alpha_n$) and phase ($\varphi_n$) (here we assume $A_n$ is constant across the chirp bandwidth and angle to platform), $\Delta_{nk}$ is the Doppler shift corresponding to the *n*th reflector and the *k*th platform position and velocity, and the free space path loss exponent is assumed to equal 2.

The overall received signal from chirp *k* will include return signal contributions from all reflecting points in the radar illumination field:

$$y_k(t)=\sum_{n=1...N} y_{nk}(t)$$

We assume that *n*=1,...,*N* indexes each resolvable point (pixel) on a 2-dimensional image field. As the radar platform progresses along its flight path, the *n*th point reflector will move along a sequence of distances $D_{n1}$, $D_{n2}$, … $D_{nK}$, from the radar platform, where *K* denotes the number of transmitted chirps. The distance parameters $\{D_{nk}\}$ are assumed known by means of precise GPS location information and known platform geometry information relative to ground image field. Furthermore the Doppler shifts $\Delta_{n1}$, $\Delta_{n2}$, … $\Delta_{nK}$ are derived from platform to reflector geometry and platform velocity.

Given the collection of received signals $y_1(t)$ , $y_2(t)$, … , $y_K(t)$ the goal is determine the parameters $\alpha_1,...,\alpha_N$, i.e. the amplitude of the reflector located at each pixel. We suppose that the receiver samples the received signal above Nyquest frequency $2(B+2\Delta_m)$, where *B* denotes chirp bandwidth and $\Delta_m$ denotes max Doppler shift, and consider the receiver processing corresponding to a single pixel. The sampled received signal from the *k*th transmitted chirp is denoted as an $(N_s \times 1)$ vector

$$\mathbf{y}_k = [y_k[1]\ y_k[2]\ \dots\ y_k[N_s]]^T = \sum_{n=1...N} [y_{nk}[1]\ y_{nk}[2]\ \dots\ y_{nk}[N_s]]^T = \sum_{n=1...N} \mathbf{y}_{nk}$$
$$= \mathbf{y}_{pk} + \sum_{n=1...N,n\neq p} \mathbf{y}_{nk} = G_{tx}*G_{rx}*A_p*\bar{\mathbf{y}}_{pk} + \sum_{n=1...N,n\neq p} \mathbf{y}_{nk}$$

The second to last equality above separates the received contribution due to *p*th pixel from the main summation and the last equality factors out constant gain coefficients from *p*th received vector. We may further stack the received vectors from all *K* chirps into one long $(KN_s \times 1)$ vector

$$\mathbf{y} = [\mathbf{y}_1^T\ \mathbf{y}_2^T \dots \mathbf{y}_K^T]^T = G_{tx}*G_{rx}*A_p*[\bar{\mathbf{y}}_{p1}^T\ \bar{\mathbf{y}}_{p2}^T \dots \bar{\mathbf{y}}_{pK}^T]^T + \sum_{n=1...N,n\neq p} [\mathbf{y}_{n1}^T\ \mathbf{y}_{n2}^T \dots \mathbf{y}_{nK}^T]^T$$

$$= G_{tx}*G_{rx}*A_p*\bar{\mathbf{v}}_p + \sum_{n=1\ldots N, n\neq p} \mathbf{v}_n$$

where we have again separated the received signal corresponding to *p*th reflector and extracted the constant gain coefficients, and defined: $\mathbf{v}_n^T = [\mathbf{y}_{n1}^T\, \mathbf{y}_{n2}^T \ldots \mathbf{y}_{nK}^T]^T$ and $\bar{\mathbf{v}}_p = \mathbf{v}_p / ( G_{tx}*G_{rx}*A_p )$.

Next we approximate the summation of the second term above as a white Gaussian random vector by virtue of the Central Limit Theorem and argue that the matched filter is optimal, in terms of maximizing the Signal-to-Noise Ratio (SNR), for estimating $G_{tx}*G_{rx}*\alpha_p$ (since we will be normalizing the gain coefficients anyway, $G_{tx}$ and $G_{rx}$ are included in the parameter estimate). Thus the optimal receiver processing under the above assumptions for our model of monostatic SAR is a filter matched to the normalized received signal vector corresponding to *p*th reflector $\bar{\mathbf{v}}_p = [\bar{\mathbf{y}}_{p1}^T\, \bar{\mathbf{y}}_{p2}^T \ldots \bar{\mathbf{y}}_{pK}^T]^T$. Note that construction of this filter requires knowledge of the distance sequence (phase history) $D_{p1}, D_{p2}, \ldots D_{pK}$ and Doppler shift sequence $\Delta_{p1}\, \Delta_{p2} \ldots \Delta_{pK}$, which are determined by platform position and velocity relative pixel location in the imaging field. Hence an unnormalized max-SNR amplitude estimate corresponding to the *p*th pixel is given by:

$$\bar{\alpha}_p = \bar{\mathbf{v}}_p^H \mathbf{y},\ \ 1 < p < N. \tag{3}$$

The above model and derivation of optimal processor is based on the assumption that the reflector gain coefficient $A_p$ is approximately constant in frequency and angle. For dual band operation such as UHF and X-band, a separate coefficient per frequency band would be necessary due to different interactions with the reflector at widely separated frequencies. The impact of this approximation on performance is subject to further investigation.

In the case of non-white Gaussian noise, matched filter is no longer optimal and Minimum Mean Squared Estimate (MMSE) can be used to estimate parameter, as follows:

$$\bar{\alpha}_p = \bar{\mathbf{v}}_p^H \mathbf{R}^{-1} \mathbf{y},\ \ 1 < p < N, \tag{4}$$

where $\mathbf{R} = E[\mathbf{y}\mathbf{y}^H]$. Here we require an estimate of the correlation matrix **R**, which may be obtained by an empirical average of received signal vectors. An issue of complexity arises due to matrix inversion requirement of MMSE solution and further development of this approach is a topic for the R&D work program.

### *3.1.1 FFT based implementation*

The filter operation of Equation (3) is efficiently implemented with frequency domain processing provided by use of the Fast Fourier Transform (FFT). We observe that the steering vector, $\bar{\mathbf{v}}_p = [\bar{\mathbf{y}}_{p1}^T\, \bar{\mathbf{y}}_{p2}^T \ldots \bar{\mathbf{y}}_{pK}^T]^T$, which determines the matched filter for pixel $p$ is a composed of a concatenated sequence of scaled and time-shifted transmitter pulse signals. Letting $\mathbf{x}\{s\}$ denote the sampled transmitter pulse sequence time-shifted by $s$ samples, we can rewrite $\bar{\mathbf{v}}_p$ as

$$\bar{\mathbf{v}}_p = [\ \beta_{p1}\mathbf{x}\{s_{p1}\}^T\ \beta_{p2}\mathbf{x}\{s_{p2}\}^T \ldots \beta_{pK}\mathbf{x}\{s_{pK}\}^T]^T,$$

where $s_{pk}$ denotes the discrete time-shift corresponding to the $p$th reflector at snapshot $k$, and $\beta_{pk}=(2D_{pk})^{-2}$.

Rewriting Equation (3), we have

$$\bar{\alpha}_p = \bar{\mathbf{v}}_p^H\mathbf{y} = \sum_{k=1\ldots K} \beta_{pk}\, \mathbf{x}\{s_{pk}\}^H \mathbf{y}_k = \sum_{k=1\ldots K} \underline{\alpha_{pk}}.$$

We next invoke the Discrete Fourier Transformation (DFT) identity $\mathbf{D}^H\mathbf{D} = \mathbf{I}$, where $\mathbf{D}$ is the DFT matrix and $\mathbf{D}^H = \mathbf{D}^{-1}$ to obtain

$$\alpha_{pk} = \beta_{pk}\, (\mathbf{Dx}\{s_{pk}\})^H (\mathbf{Dy}_k)$$

Finally we use the fact that circular-time-shifted discrete time signal translates to multiplication by linearly rotating phasor in frequency, i.e.

$$\mathbf{Dx}\{s_{pk}\} = \mathbf{\Lambda}_{pk}\boldsymbol{\chi}_0\,,$$

where $\boldsymbol{\chi}_0 = \mathbf{Dx}\{0\}$ is the DFT of the unshifted transmitter pulse and

$$\mathbf{\Lambda}_{pk} = \text{diag}(\ [1\ \exp(-i2\pi s_{pk}/N_{DFT}) \ldots \exp(-i2\pi s_{pk}(N_{DFT}-1)/N_{DFT})\ ]\ ),$$

where $N_{DFT}$ is the DFT length. Hence, we have

$$\bar{\alpha}_p = \boldsymbol{\chi}_0^H \left(\sum_{k=1\ldots K} \beta_{pk}\, \mathbf{\Lambda}_{pk}^H\, \boldsymbol{\psi}_k\right) \qquad (5)$$

where $\boldsymbol{\psi}_k = \mathbf{Dy}_k$ is the DFT of the received signal corresponding to the $k$th snapshot. The complexity savings of Equation (5) lies in the construction of the matched filter corresponding to each pixel in the imaging field. The $\beta_{pk}$ $\mathbf{\Lambda}_{pk}$ matrix depends only on the delay shift corresponding to the distance range to pixel and not on the particular chirp pulse used by the radar. An implementation approach would be to quantize the set of ranges covering the image field and store the pre-computed $\beta_{pk}\mathbf{\Lambda}_{pk}$ matrices in a “filter bank” (only the diagonal elements need to be stored) allowing for efficient computation of Equation (5) based on FFT of received snapshot signals.

### 3.2 Monostatic MIMO SAR Mathematical Model

Addition of multiple transmit and multiple receive antennas to MIMO SAR systems offers the potential for enhanced spatial selectivity through electronic beam steering techniques, and recovery of greater radar cross section through parallel orthogonal channels such as multi-band coherent combining techniques. In this section we provide a brief description of MIMO SAR mathematical model and overview of basic processing methodology.

We assume the use of an *M*-element Uniform Linear Array (ULA) with antenna element spacing *d*, such as the one depicted in Figure 3. We assume that a single transmitted chirp pulse is emitted across the antenna array along a beemsteering vector directed towards imaging field. Beemsteering vector weights could be obtained by use of a suitable vector basis for the antenna steering space and calibration exercises do determine optimal steering coefficients for desired imaging area. Thus Equation (1) may be a suitable model for post-beamforming transmitted pulse with appropriately adjusted gain parameter to include transmit array beamforming gain. Alternatively, the system could be operated in Single Input Multiple Output (SIMO) mode, in which case beamforming gain will only be incurred at the receiver, and Equation (1) will again hold for transmitted pulse sequence.

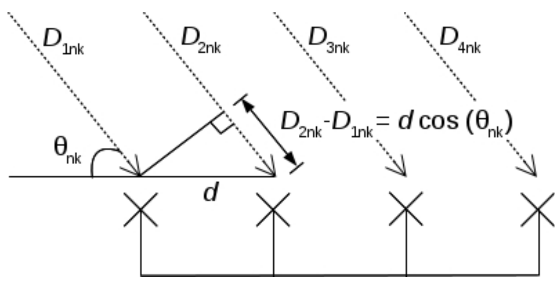


**Figure 3.** Uniform linear antenna array with inter-element spacing *d* and azimuth angel of arrival $\theta_{nk}$ for pixel *n* and snapshot *k*. Far-field approximation implies arriving RF radiation occurs along parallel lines.

We next define a detailed model of the receive array response to a point reflector in the imaging field. Figure 3 depicts a 4-element ULA with inter-element spacing *d*. A far-field propagation model is assumed wherein the return radiation arrives along parallel lines to each antenna element. Thus, the difference between range distances of adjacent antenna elements $D_{1nk}$, $D_{2nk}$, etc. depends only on the azimuth angle of arrival and the inter-element spacing. Analogous to Equation (2), the return signal from pulse *k* at the *m*th antenna element from the *n*th point reflector located at distance $D_{mnk}$ is given by:

$$y_{mnk}(t) = G_{rx}*(2D_{mnk})^{-2}*A_n*x(t-2D_{mnk}/c)$$

$$= G_{tx}*G_{rx}*(2D_{mnk})^{-2}*A_n*\exp\{i2\pi*[f(t-2D_{mnk}/c-t_0)-\Delta_{nk}]*(t-2D_{mnk}/c)\},$$

$$t_k+2D_{mnk}/c < t < t_k+T_c+2D_{mnk}/c.$$

where now we have $M$ return signals corresponding to the $M$ antenna elements. Note that Doppler shift $\Delta_{nk}$ depends only on the azimuth angle via the snapshot $k$ and pixel $n$ variables.

The max-SNR and MMSE style solutions of Equations (3) and (4) can be implemented given knowledge of the phase history sequence $D_{mp1}$, $D_{mp2}$, … $D_{mpK}$ , $m$=1,...M, and Doppler shift sequence $\Delta_{p1}\,\Delta_{p2}\ldots\Delta_{pK}$, for each pixel in the imaging field. The parameters are determined by platform position, antenna array orientation, and velocity relative to pixel location in the imaging field.

### *3.2.1 FFT based array combining approach*

We note that the sequence of distances to point reflector across antenna array, $D_{1nk}$, $D_{2nk}$,...,$D_{mnk}$, are uniquely determined by a single “anchor” distance, eg. $D_{1nk}$, and the azimuth angle $\theta_{nk}$ and the array spacing parameter $d$. This fact suggests the use of a pre-defined set of array combining filters (filter bank) corresponding to a quantized set of angles covering the imaging field. A possible implementation would use the FFT to decompose the received signal onto an orthogonal basis of frequency vectors, apply frequency dependent array combining, and then the remaining filtering operations (eg. Equations (3) and (4)) also in frequency domain, and then reconstruct time domain sequence with IFFT. This is analogous to the frequency domain implementation described in the previous section. Here we add details related to the multi-antenna receive array.

The frequency domain implementation of SIMO SAR matched filter solution is given by

$$\bar{\alpha}_p = \boldsymbol{\chi}_0^H \left(\sum_{k=1\ldots K} \sum_{m=1\ldots M} \beta_{mpk}\, \boldsymbol{\Lambda}_{mpk}^H\, \boldsymbol{\psi}_{mk}\right)$$

where we have added an additional sum over $m$=1,...,M corresponding to the array combining process. Implicit to this equation are the discrete time-shift delays, $s_{mpk}$ $m$=1,...,M which include the far-field “anchor” delay plus the delay incurred by angle of rotation of linear array. Leveraging the geometry in Figure 3, we may write

$$\bar{\alpha}_p = \boldsymbol{\chi}_0^H \left(\sum_{k=1\ldots K} \sum_{m=1\ldots M} \beta_{mpk}\, (\boldsymbol{\Lambda}_\theta^{(m-1)}\boldsymbol{\Lambda}_{1pk})^H\, \boldsymbol{\psi}_{mk}\right)$$

$$= \boldsymbol{\chi}_0^H \left(\sum_{k=1\ldots K} \boldsymbol{\Lambda}_{1pk}^H \left(\sum_{m=1\ldots M} \beta_{mpk} (\boldsymbol{\Lambda}_\theta^H)^{(m-1)}\, \boldsymbol{\psi}_{mk}\right)\right)$$

where the multiplication matrix $\boldsymbol{\Lambda}_{mpk}$ corresponding to time-delay operation is decomposed into commuting matrices $(\mathbf{\Lambda}_{\theta})^{(m-1)}\mathbf{\Lambda}_{1pk}$ corresponding to anchor delay and delay across antenna array. A simplification is obtained by approximating $\beta_{mpk} \approx \beta_{1pk}$, i.e. the path loss attenuation is roughly constant across the antenna array, in which case matched filter solution can be written as

$$\bar{\alpha}_p = \boldsymbol{\chi}_0^H \left(\sum_{k=1 \ldots K} \beta_{1pk} \mathbf{\Lambda}_{1pk}^H \mathbf{z}_k\right)$$

where $\mathbf{z}_k = \sum_{m=1 \ldots M} (\mathbf{\Lambda}_{\theta}^H)^{(m-1)} \boldsymbol{\psi}_{mk}$ is the array combined output depending only on the quantized azimuth angle and $\boldsymbol{\psi}_{mk}$ is the FFT of the received signal on antenna *m* from snapshot *k*. Hence SIMO SAR FFT domain matched filter may me achieved by quantizing azimuth angle of arrival θ and pre-combining array snapshot outputs per angle of arrival.

Investigation performance of this approach and alternative array combining techniques such as MMSE based filter approach is subject of our proposed RACER R&D work program.

### *3.2.2 MIMO SAR*

Multi-input Multi-Output (MIMO) SAR can be realized through multi-frequency band operation, in which multiple transmitters are operating simultaneously on separate frequency channels. Modeling per frequency band is the same as the above SIMO model since there will be no cross-talk between frequency channels. Our RACER work program includes development of innovative combining methodologies, including MIMO enhanced visualization of SAR image field, for obtaining MIMO performance gains using simultaneous multi-band radar operation.

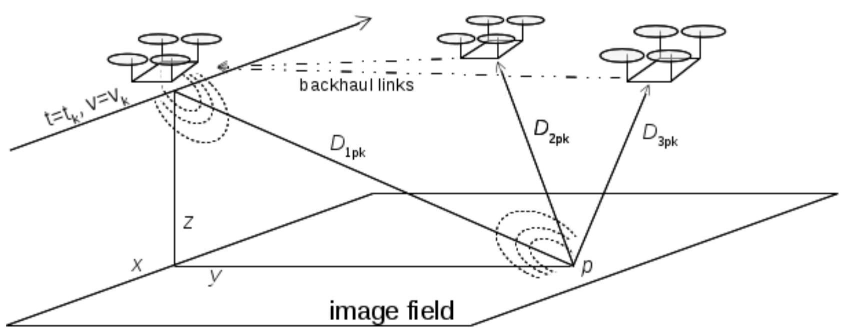


**Figure 4**. Multistatic SIMO distributed SAR system.

## 3.3 Multistatic Distributed MIMO SAR Mathematical Model

Finally we describe a multistatic distributed MIMO SAR imaging system which utilizes radar reflections captured from multiple airborne platforms. An advantage of the multistatic approach is that a high resolution image can be constructed from a single radar pulse collected from multiple distributed platforms, whereas the traditional SAR method relies on multiple radar pulses collected over the course of a flightpath of a single platform. A disadvantage of the multistatic approach is the high backhaul link communication requirement from the distributed platforms to Centralized Processing Unit (CPU). The backhaul requirement could be satisfied by microwave or optical communication links, with line of sight channels, between the distributed SAR platforms and CPU plaform.

We consider the case of a Single Input Multiple Output (SIMO) distributed SAR implementation as depicted in Figure 4. Letting Equation (1) denote the transmitted pulse sequence from transmitter platform, the reflected signal received by the *m*th platform is given by:

$$y_{mnk}(t) = G_{rx}*(D_{1nk}+D_{mnk})^{-2}*A_n*x(t-(D_{1nk}+D_{mnk})/c)$$

$$= G_{tx}*G_{rx}*(D_{1nk}+D_{mnk})^{-2}*A_n*\exp\{i2\pi*[f(t-(D_{1nk}+D_{mnk})/c-t_0)-\Delta_{nk}]*(t-(D_{1nk}+D_{mnk})/c)\},$$

$$t_k+(D_{1nk}+D_{mnk})/c < t < t_k+T_c+(D_{1nk}+D_{mnk})/c,$$

The difference between the above receiver model and the monostatic SIMO model is the distance traveled by the radar pulse is composed of the first path from transmitter to point reflector $D_{1nk}$ plus the second path from point reflector to *m*th platform $D_{mnk}$. This is illustrated in Figure 4. We have assumed that the point reflector complex gain coefficient $A_n = \alpha_n \exp(i2\pi*\varphi_n)$ is constant across the radar pulse bandwidth and across all *M* platforms.

As in the previous sections, we will implement space-time filtering approaches for the point reflector parameters base on standard estimation and detection techniques such as max-SNR filter, MMSE filter, Maximium Likelihood and Bayesian parameter estimation. Further methods of complexity reduction are required when optimal solution approach is computationally infeasible, such as simplified models and approximate solutions. In addition, FFT based implementations will leverage fast transform to frequency domain and back, and ease of implementing time-domain filters as frequency-domain multiplications.

Hence a major contribution of our proposed R&D approach is the development of centralized and distributed MIMO techniques for next generation SAR imaging systems. Our strong expertise in the fields of detection and estimation theory, digital signal processing, probability theory and linear systems, as well as wireless communication systems, will enable Aquerre Technologies to advance the state of the art in SAR MIMO processing and imaging systems and deliver superior product performance for Government applications.

## 4. Development of In-house UAV Based SAR System

In lieu of direct access to Gotcha Spiral II TestBed for testing and validation of our developed SAR processing and visualization technologies, we have included an optional component for in-house development of a UAV-based SAR prototype for testing and validation as well as demonstration of developed technologies to Government sponsor. The UAV SAR Prototype system will comprise a set of two basic UAV platforms equipped with low-power/light-weight radio-transmitter and receiver operating in unlicensed frequency spectrum, e.g. WiFi 2.4 GHz spectrum, as well as basic on-board micro-processors for processing, storing, and relaying SAR data. This option is subject to sponsor approval and negotiation of the final contract.

## 5. CV of Principal Investigator

Curriculum Vitae

Dr. Noah B. Jacobsen

### *5.1 Patents*

[1] N. B. Jacobsen and R. Soni. Method and system for encoding data using rate-compatible irregular LDPC codes based on edge growth and parity splitting. U.S. patent, No. 7,966,548, June 2011.

### *5.2 Ph.D. Dissertation*

[1] N. B. Jacobsen. Bayesian approaches to noncoherent communication: From Shannon theory to practical architectures. PhD thesis, University of California, Santa Barbara, Dept. of Electrical and Computer Engineering, 2005.

### *5.3 Standards Contributions*

[1] N. B. Jacobsen. “TDMA H-ARQ Code for Layer-2 Relay in LTE-Advanced”. 3GPP TSG RAN WG1 Long Term

Evolution (LTE) R1090775, Alcatel-Lucent, Murray Hill, NJ, Feb. 2009.

[2] Noah B. Jacobsen, Anthony Soong, Ji Wook Chung, Tom Richardson, Aamod Khandekar, Sung-Eun Park, Jun Xu, and Xin Yu. “LDPC Coding Proposal for LBC”. 3GPP2 Ultra Mobile Broadband (UMB) C30-20070315-003, Alcatel-Lucent, Huawei, LG Electronics, QUALCOMM Incorporated, RITT, Samsung, ZTE, Mar. 2007.

[3] N. B. Jacobsen. “Design of flexible rate-compatible LDPC codes”. 3GPP2 Ultra Mobile Broadband (UMB) C30-20070108-051, Alcatel-Lucent, Murray Hill, NJ, Jan. 2007.

### *5.4 Journal Papers*

[1] N. B. Jacobsen and U. Madhow. Coded noncoherent communication with amplitude/phase modulation: From Shannon theory to practical turbo architectures. IEEE Trans. Commun., 56(12), Dec. 2008.

[2] N. B. Jacobsen, G. Barriac, and U. Madhow. Noncoherent eigenbeamforming and interference suppression for outdoor OFDM systems. IEEE Trans. Commun., 56(6), June 2008.

[3] K. Solanki, N. B. Jacobsen, U. Madhow, B. S. Manjunath, and S. Chandrasekaran. Robust image-adaptive data hiding using erasure and error correction. IEEE Trans. Image Processing, 13(12):1627–1639, Dec. 2004.

### *5.5 Book Chapters*

[1] G. Barriac, N. B. Jacobsen, and U. Madhow. Space-time wireless systems: From array processing to MIMO communications, chapter 5: The role of feedback, CSI and coherence in MIMO systems. Cambridge University Press, 2006.

### *5.6 Conference Papers*

[1] N. B. Jacobsen. Practical cooperative coding for half-duplex relay channels. In Proc. Conf. on Inform. Sciences and Systems (CISS), Baltimore, MD, USA, Mar. 2009.

[2] N. B. Jacobsen and R. Soni. Design of rate-compatible irregular LDPC codes based on edge growth and parity splitting. In Proc. IEEE Veh. Tech. Conf. (VTC), Baltimore, MD, USA, Sept. 2007.

[3] N. B. Jacobsen, G. Barriac, and U. Madhow. Noncoherent eigenbeamforming for a wideband cellular uplink. In Proc. IEEE Intern. Symp. on Inform. Theory (ISIT), Chicago, IL, USA, June 2004.

[4] N. B. Jacobsen, G. Barriac, U. Madhow, R.-R. Chen, and R. Koetter. Towards Shannon-theoretic limits on wireless time-varying channels. In Proc. International Symp. on Control, Communications, and Signal Processing (ISCCSP), Hammamet, Tunisia, Mar. 2004.

[5] N. B. Jacobsen and U. Madhow. Code and constellation optimization for efficient noncoherent communication. In Proc. Asilomar Conf. on Signals, Systems, and Computers, Monterey, CA, USA, Nov. 2004.

[6] N. B. Jacobsen and U. Madhow. Reduced-complexity noncoherent communication with differential QAM and iterative receiver processing. In Proc. Conf. on Inform. Sciences and Systems (CISS), Baltimore, MD, USA, Mar. 2003.

[7] N. B. Jacobsen, K. Solanki, S. Chandrasekaran, U. Madhow, and B. S. Manjunath. Image adaptive high volume data hiding based on scalar quantization. In Proc. IEEE Military Comm. Conf. (MILCOM), Anaheim, CA, USA, Oct. 2002.

[8] K. Solanki, N. B. Jacobsen, S. Chandrasekaran, U. Madhow, and B. S. Manjunath. High-volume data hiding in images: Introducing perceptual criteria into quantization based embedding. In Proc. ICASSP, Orlando, FL, USA, May 2002.

[9] G. Barriac, N. B. Jacobsen, and U. Madhow. Beyond BAD: A parallel arbitration framework for low-complexity equalization. In Proc. 39th Annual Allerton Conf. on Communication, Control, and Computing, Oct. 2001.

### *5.7 Technical Reports*

[1] N. B. Jacobsen. “Detection of a coded signal”. Technical report, LGS Innovations, Florham Park, NJ, May 2011.

[2] N. B. Jacobsen. “On the dynamic re-use of satellite link spectrum with an active sensing cognitive radio network”. Technical report, Toyon Research Corp., Goleta, CA, July 2006.

[3] N. B. Jacobsen. “Fast detection of LO signal from heterodyne receivers”. Technical report, University of California, Santa Barbara, Santa Barbara, CA, Nov. 2005.

[4] N. B. Jacobsen. “Iterative APP interference cancellation for LDPC coded UWB communication”. Technical Report National Science Foundation (NSF) EASI 0310419, Yokohama National University, Yokohama, Japan,

Feb. 2004.

[5] N. B. Jacobsen. "Noncoherent Iterative Demodulation and Decoding for OFDM Systems". Technical report, Motorola Labs, Schaumburg, IL, Sept. 2002.

[6] N. B. Jacobsen and E. Chojnacki. "Infra-red propagation through various waveguide inner surface geometries". Technical Report SRF 990301-01, Floyd R. Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, NY, Mar. 1999.

### *5.8 Professional Experience*

[1] Founder/Owner/CEO/Principal Scientist/Janitor, Aquerre Technologies LLC, Sacramento, CA (05/2013–present). Highlights:

• "AQUERRE" is granted U.S. Trademark for "Computer programs for constructing, encoding, and decoding Error Control Codes (ECCs)" (03/29/2016). See https://aquerre-technologies.com/links.html for more information about our trademark and copyright pursuits

• Completed the 2016 California Dept. of Housing and Community Development Blue Books Contract (Standard Agreement #15-10-007)

- – Leveraged our data automation and information processing expertise as prime contractor for the State of California.
- – New product available for purchase from our web page, https://aquerre-media.com
- – Period of performance: 10/01/15–02/18/16
- – Total amount of contract $20,085.66

• Ongoing production work related to our subsidiary media unit, https://marsjazzproject.com

- – Produced the ten track audio recording "Beautiful.", released in Dec. 2014. Product was released for free on our web page, https://marsjazzproject.com/studio, with a multi-media web design featuring playable tracks with song composer data, visual art/photos about the project, and option to purchase a physical CD.
- – Live performance work comprising mainly open-mic venues and street performance with some shows announced on our twitter page, https://twitter.com/marsjazzproject, with the hashtag

#marsjazzprojectlive

[2] Sr. Operations Research Scientist, Dex One/Dex Media, Santa Monica, CA (09/2012–04/2013)

• Performed predictive analytics research and development work for Dex Media's local business advertisement search engine, DexKnows.com.

[3] Adjunct Associate Professor, Columbia University, New York, NY (Spring 2012)

• Developed curriculum (lectures, homeworks, exams) and taught graduate level Linear Systems Theory in the Electrical Engineering Department at Columbia University.

• Lectures, homeworks and solutions archived online at https://aquerre-technologies.com/teaching.html.

[4] R&D Engineer, Alcatel-Lucent, Bell Labs, Murray Hill, NJ (07/2006–10/2011)

• Performed research and development work for Alcatel-Lucent's Forward Looking Technology Group and Government Communications Laboratory

• Heavy focus on the development of new high-performance Error Correcting Codes (ECCs) with applications to commercial cellular systems and tactical radio systems. Work resulted in a U.S. Patent, multiple academic conference papers and multiple technical contributions to international wireless standards.

• Development of anti-jam technologies for tactical radio communication systems including satellite based systems. Transition of advanced algorithms to chip development team.

[5] Adjunct Lecturer, Polytechnic Institute of New York University, Brooklyn, NY (Fall 2010)

• Developed curriculum (lectures, homeworks, exams) and taught graduate level Probability Theory in the Electrical and Computer Engineering Department at Brooklyn Polytechnic University.

[6] Post-Doctoral Researcher, University of California, Santa Barbara, Santa Barbara, CA (09/2005–06/2006)

• Researched methods of detection and utilization of unused radio frequency (RF) spectrum for software-defined radio applications and for re-use of terrestrial digital broadcast television and satellite communication channels.

### *5.9 Education*

09/2005 Ph.D. University of California, Santa Barbara, Electrical and Computer Engineering

06/2002 M.S. University of California, Santa Barbara, Electrical and Computer Engineering

06/2000 B.S. Cornell University, Electrical Engineering

### *5.10 Software Fluency*

• GNU Linux (expert), Debian, C/C++, Bash Shell Scripting, OpenOffice (Writer/Calc/Impress), Microsoft Office (Word/Excel/PowerPoint), LaTeX, Octave, MatLab, Java, BASIC, HTML, Emacs, Vi, Gimp, Ardour, Audacity, Mozilla

### *5.11 Recent Conferences*

• Presenter, 2016 Air Force Space and Missile Systems Center (SMC) Small Business Industry Days (SBID), Los Angeles, California, Oct. 18-20, 2016

• Attendee, 2014 National SBIR/STTR Conference and Short Course “How To Develop An Acceptable Accounting System for Government Grants and Contracts”, Washington, DC, Jun. 16-18, 2014

### *5.12 Teaching Certifications*

• California Basic Educational Skills Test (CBEST) Completed, December 2013

### *5.13 Professional Societies*

• Institute of Electronic and Electrical Engineers (IEEE)

### *5.14 Notable Achievements*

• “AQUERRE” granted U.S. Trademark for “Computer programs for constructing, encoding, and decoding Error Control Codes (ECCs)”, March 2016

• Session Chair, “Wireless Networks and Communications,” 43rd Conference on Information Sciences and Systems (CISS), Johns Hopkins University, Baltimore, MD, March 18-20, 2009

• 3GPP2 Ultra Mobile Broadband (UMB) Air Interface Specification: Recognition of Contribution, Low Density Parity Check (LDPC) Ad Hoc Group, 2007

- National Science Foundation (NSF) and Japan Society for the Promotion of Science (JSPS) East Asia Summer Institutes Fellowship, Yokohama National University, Japan, 2003
- California Microelectronics Innovation and Computer Research Opportunities (MICRO) Fellowship, University of California, Santa Barbara, 2000–2001
- Theodore C. Ohart Scholarship in Engineering, Cornell University, 1999–2000
- Cornell University College of Engineering Cooperative Education Program, with Floyd R. Newman Laboratory of Nuclear Studies, Cornell University, 1998–1999
- Cornell University Dean of Students Service Award for service as Selections Director of the Cornell Concert Commission, 1998 and 1999