Affordable Reliable Precision Naviation and Timing
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1 Introduction

GPS is known to provide significant force enhancement capability. This force enhancement capability has been demonstrated in every U.S. military operation since and including the Gulf War. The success of GPS in these operations has led to an increasing DoD and Allied reliance on GPS. To date, over 200,000 GPS receivers have been delivered to the DoD and its Allies. GPS uses include navigation targeting, sensor aiding, weapons delivery, timing, and battlefield command/control.

The enemy threat is evolving in two areas: enemy use of GPS and the enemy's ability to deny GPS to the U.S. Worldwide military use of GPS is evolving due to the wide availability of commercial GPS receivers, and the widespread knowledge of the force enhancement capabilities offered by GPS, differential GPS, and satellite augmented GPS. The jamming threat is a concern because of the physical design of the GPS system. The received power from the GPS satellites is approximately -157 dBW. Many jammers available on the arms market today either already cover the GPS frequencies, or can be modified to do so. *The primary focus of this project is on the protection aspect.* The goal is to develop an affordable GPS system-level solution that protects the Department of Defense (DoD) and U.S. Allies operational use of GPS on a continual basis.

1.1 Problems, Difficulties, and Objectives

The success of GPS in Desert Storm and other operations has increased DoD's commitment to equipping weapon systems with GPS receivers. However, this commitment has been accompanied by a heightened awareness of the potential vulnerabilities of GPS to both intentional and unintentional RF interference. Limited Electronic Counter Counter Measures (ECCM's) have been developed over the past two decades primarily based on the null steering Controlled Reception Pattern Antenna (CRPA) and associated Antenna Electronics (AE). However, this spatial filter technology is limited in its ability to cancel jammers due to component, device, and technology limitations, as well as the increasing potential jamming threat. It is expected that the number of potential military and commercial interferers will increase along with more and new jamming threats that will likely be fielded in response to the U.S. fielding of numerous GPS equipped weapon systems.

The objective is to identify, evaluate, develop, and demonstrate innovative anti-jam (AJ) processors that are effective against intentional and unintentional interference to GPS user equipment. This will entail a system-level study of the trade-offs between protection performance versus hardware and computational complexity for various integrated levels of processing. The primary end objective is to build and test a programmable anti-jam processor brassboard to demonstrate higher, yet affordable AJ capabilities for GPS user equipment on navy cruisers, aircraft, and airborne weapons systems.

The AJ processor should be capable of suppressing a mixture of interferer types including multiple broadband Gaussian noise interferers. This type of interferer is a significant threat as it is possible to distribute the jammer power across the 20.46 MHz bandwidth of the standard military P(Y) code signal centered at the GPS L1 frequency, for example, at a low enough level that it is difficult to detect and identify, and yet the noise background is increased enough to disrupt tracking of the GPS signal. This is particularly true if the enemy distributes (spatially) a number of relatively low power broadband jammers over the combat arena.

The processor should also provide suppression capabilities against other types of interferers, both intentional and inadvertent. These include including continuous wave (CW), swept CW, pulsed CW, phase shift keying (PSK), pseudo-noise signals (20 MHZ bandwidth), and narrowband and wideband frequency modulated signals. The interferers may be located anywhere within or adjacent to the 20.46 MHz bandwidths centered at the GPS L1 frequency of 1575.42 MHz or the L2 frequency of 1227.60 MHz, and distributed anywhere over 2π steradians of solid angle centered at zenith relative to the local horizontal plane of a GPS receiving antenna.

In addition to providing interference suppression, the processor should allow reception of GPS satellite signals in a stressed environment by maximizing the signal power-to-interference plus noise power ratio (SINR) for acquisition and tracking of the GPS signal. Various user environments will be addressed. A top-down requirements study of the number of antennas and number of taps per antenna will be conducted under various user environments ranging from a foot soldier in the field to a navy cruiser to a high performance fighter aircraft.

2 Overview of Research Team

The proposal team consists of a synergistic group of researchers from academia, industry, and a government laboratory who have collaborated on pioneering research on space-time adaptive signal processing for applications in GPS, spread spectrum communications, and radar. The team members have strong ties to the Navy through both SPAWAR and the Office of Naval Research. Members of the research team are listed in Table 1 along with their respective affiliations and areas of expertise related to this project.

A brief overview of each team member is provided below. The overview emphasizes a small sampling of prior individual and collaborative contributions of the team members that will be utilized in the proposed research on enhancing the reliability and and robustness of GPS.

Team Member	Affiliation	Expertise Related to Project
Michael D. Zoltowski	Purdue University	Space-time adaptive interference cancellation for GPS; compact arrays with polarization diversity
Laurence B. Milstein	University of California, San Diego	interference cancellation for spread spectrum communications
Michael Honig	Northwestern University	Reduced-rank adaptive filtering for spread spectrum communications
J. Scott Goldstein	SAIC	Reduced-rank space-time adaptive processing (STAP) for radar and GPS
James R. Zeidler	SPAWAR Systems Center	Nonlinear effects in stochastic gradient methods and compact arrays
V. Balakrishnan	Purdue University	Optimal control, optimal subspace selection

Table 1: Research Team Composition and Areas of Expertise.

Dr. Michael Zoltowski, Professor of Electrical Engineering, Purdue University

Dr. Michael Zoltowski has been working on the problem of anti-jam protection for GPS since an industrial contract with E-Systems in 1995 [Zo1-Zo2]. E-Systems built one of the earliest anti-jam spatial filters for GPS, a seven element antenna array system. The principle used in the CRPA-AE system built by E-Systems (and deployed on F-16 fighters) to cancel interference is power minimization. That is, prior to correlation, the GPS signals are roughly 15 dB below the noise floor. Thus, a proven and widely used way to suppress interference is to set the weight for the reference antenna to unity and find that set of weights which when applied to the auxiliary antennas drives the output power of the beamformer as close to the noise floor as possible. This will adaptively steer nulls in the directions of those interferers whose power levels are above the noise floor.

The primary problem with the CRPA-AE system is that the weights applied to the auxiliary antennas were adjusted by analog means at RF. The vector modulators used did not allow precise control of the weight values. In addition, analog power measurements were used to drive the weight adaptations; this has problems dealing with pulsed jammers, among other things. Thus, the industry has moved towards digital solutions wherein the output of each antenna is down-converted and sampled at a rate at least twice the 20.46 MHz bandwidth.

Power minimization remains a popular means of canceling interference in a pre-processing mode of operation wherein standard GPS receivers are simply retro-fitted with a front-end device. With funding from the Air Force Office of Scientific Research (AFOSR) through the New World Vista (NWV) Program *Jam-Proof Area Deniable Propagation*, Dr. Zoltowski developed space-time extensions of the power minimization principle. These are discussed in detail in Section 3.1. Dr. Zoltowski also developed a low-cost post-correlation blind adaptive beamforming algorithm for GPS based on the cyclostationary nature of the BPSK signal obtained after despreading the signal received from a given GPS satellite. The nulling capabilities of the algorithm have been successfully demonstrated on a prototype GPS test-bed discussed in detail in Section 3.2.1.

Dr. Laurence Milstein, Professor of Electrical Engineering, University of California, San Diego

Dr. Milstein is a pioneering researcher and world renown expert in the area of spread-spectrum communications, in general, and interference suppression techniques for spread-spectrum communications, in particular. It should be noted that from a signaling viewpoint, the GPS system is a classical direct-sequence spread spectrum (DS-SS) or Code-Division Multiple Access (CDMA) communication system wherein each satellite is assigned a unique specific Pseudo-Noise (PN) sequence as a code. Some of the algorithms proposed herein for the GPS application have roots in interference suppression techniques developed for CDMA to effect reliable information transfer over a wireless link.

A very important difference between the commercial CDMA problem and the GPS application is that multipath pejoratively affects timing calculations and therefore should ideally be canceled. This is in contrast to commercial CDMA where the goal is to achieve diversity gains by adding the multipaths up in phase. In addition, the signals from the different GPS satellites arrive at the receiver roughly equal in strength. Thus, Multi-User Access Interference (MUAI) is not an issue as it is in cellular CDMA systems; there is not a near-far problem and the number of GPS satellites is far less than the length of the C/A code for a given GPS satellite. The protection problem for GPS is combating the interference types listed towards the end of Section 1.1.

Dr. Michael Honig, Professor of Electrical Engineering, Northwestern University

Dr. Honig has worked on interference suppression techniques for CDMA for over fifteen years. Consider the case of Minimum Mean Square Error (MMSE) estimation where the information symbols carried by the code are estimated by weighting and summing chip-spaced samples encompassing at least the length of the code. In [H3], Dr. Honig developed an adaptive algorithm for finding that weight vector which maximizes the post-correlation SINR for a given "user" knowing only the code of that "user", the P(Y) (or C/A) code for a given GPS satellite in the field of view in our case here. One very important aspect of Dr. Honig's algorithm is that also cancels any delayed replicas of the desired GPS satellite's signal caused by multipath propagation. This is very desirable in the GPS application as discussed previously.

Another very important aspect of the algorithm developed by Dr. Honig in [H3] is that adaptation towards the SINR maximizing weight vector is solely based on the known code for the desired "user." In terms of the GPS application, the point to be made is that the algorithm does not attempt to do beamforming through effecting phase shifts derived from the azimuth and elevation coordinates of a given GPS satellite. It is difficult and expensive to design antenna arrays calibrated well enough to achieve beamforming through geometrically derived phase shifts. There are nonlinear effects amongst the individual antennas comprising the array, mutual coupling, for example, and these nonlinear effects are generally time-varying. Thus, an adaptation scheme based solely on the known code is highly advantageous.

However, there are a couple of problems with applying Dr. Honig's algorithm in [H3] to the GPS problem. First, synchronization has to be acquired before it can be applied. This synchronization has to take into account the Doppler shift induced by the satellite motion. We will address the synchronization issue in the proposed research. Another important problem is that the weight vector has to be at least the length of the code which is on the order of thousands for either the C/A code (minimum length of 1023) or the P(Y) code portion of the signal arriving from a given GPS satellite. Such a large weight vector implies a large computational burden and very slow convergence to an operating point providing adequate interference suppression.

Dr. J. Scott Goldstein, Manager, Adaptive Signal Exploitation, SAIC

This is where the work of Dr. Goldstein comes into play. Over the past five years, Dr. Goldstein has worked on reduced-rank adaptive filtering schemes that constrain the adaptive weight vector to lie in a low-dimensional subspace. This substantially reduces the computational burden and dramatically speeds up convergence, if the subspace is chosen properly. In linear Minimum Mean Square Error (MMSE) estimation, the optimum weight vector is the solution to the Weiner-Hopf equation

$$\mathbf{R}_{xx}\mathbf{w} = \mathbf{r}_{dx} \tag{1}$$

where $\mathbf{R}_{xx}$ is the correlation matrix of the data and $\mathbf{r}_{dx}$ is the cross-correlation vector between the data and the desired signal. Prior work along the lines of dimensionality reduction restricted the weight vector $\mathbf{w}$ to lie in a subspace spanned by the Principal Components (PC) or dominant eigenvectors of $\mathbf{R}_{xx}$. Although this speeds up convergence, there is the intense computational burden of computing the dominant eigenvectors of $\mathbf{R}_{xx}$.

Dr. Goldstein formulated an alternative to Principal Components analysis referred to as the Multi-Stage Nested Weiner Filter (MSNWF) [G4]. The MSNWF represents a pioneering breakthrough in that it achieves a convergence speed-up substantially better than that achieved with Principal Components at a dramatically reduced computational burden relative to Principal Components. Intuitively speaking, achieving the best of both worlds – faster convergence AND reduced computation – is made possible by making use of the information inherently contained in both $\mathbf{R}_{xx}$ and $\mathbf{r}_{dx}$ in choosing the reduced-dimension subspace $\mathbf{w}$ is constrained to to lie within. In contrast, Principal Components only makes use of the information embedded in $\mathbf{R}_{xx}$.

In MSNWF, there is no computation of eigenvectors. Through collaboration with Dr. Honig [H1], it has been shown that MSNWF constrains the weight vector to lie in the Krylov subspace spanned by $\{\ \mathbf{r}_{dx}, \mathbf{R}_{xx}\mathbf{r}_{dx}, \mathbf{R}_{xx}^2\mathbf{r}_{dx}, \ldots, \mathbf{R}_{xx}^{D-1}\mathbf{r}_{dx}\ \}$. Through theoretical analysis and extensive supporting simulations, MSNWF has been shown to achieve near optimal SINR performance with a subspace of dimension roughly equal to $D = 8$ under diverse operating conditions for two different applications: (1) cancellation of multi-user access interference (MUAI) in asynchronous CDMA with flat fading [H1] and (2) cancellation of narrowband/wideband jammers for GPS employing a power minimization based space-time pre-processor [Zo7]. The latter application will be discussed in detail shortly. The fact that a subspace of dimension only equal to $D = 8$ provides near optimal SINR performance in two very different application areas is an astounding result that highly motivates further investigation into the efficacy of MSNWF.

Dr. James Zeidler, Senior Scientist, Communications and Information Systems, SPAWAR

The aforementioned interference canceling algorithm of Dr. Honig based on the code of the desired "user" can be implemented in terms of an LMS based adaptation which brings in the work of Dr. Zeidler. Dr. Zeidler has demonstrated and analyzed nonlinear effects inherent in LMS weight adaptations [Ze1]; LMS is a stochastic gradient descent algorithm. These nonlinear effects are actually advantageous for the GPS application. One result of these nonlinear effects is that they facilitate the formation of a sharper spectral notch to cancel a narrowband interferer, for example, than that achievable with purely linear processing. This is very important result: in the process of canceling interference, it is critical to minimize the resulting distortion to the GPS signal as best as possible. Dr. Zeidler discovered the nonlinear effects inherent in LMS weight adaptation and is to first researcher to analyze them. Dr. Zeidler has also researched nonlinear effects in compact arrays [Ze2]. This expertise is critical to the success of the project: it is important to be cognizant of the nonlinear effects that occur in real antenna array systems and to recognize that optimal estimation schemes should invariably involve nonlinear signal processing. Nonlinear quantization effects incurred in A/D conversion should also be factored into algorithm design. Along these lines, the project will benefit from the Dr. Milstein has conducted into finite word length effects on MMSE receiver performance for DS-CDMA [M7].

Dr. Venkataramanan Balakrishnan, Associate Professor of Electrical Engineering, Purdue University

Dr. Venkataramanan Balakrishnan has extensive experience in devising fast algorithms for large-scale principal component analysis for problems in optimal control [B1]. His contribution to the project will be to address real-time computational issues that are fundamental to implementation aspects. Dr. Balakrishnan has developed methods for computing a basis for a Krylov subspace, required for MSNWF as discussed previously, in an efficient and numerically stable manner. Dr. Balakrishnan has also made several contributions in applying optimization techniques, convex optimization in particular, to the efficient numerical solution of problems from systems, control, communications and signal processing [B2-B6].

Institution	**Annual Budget**	**Breakdown of Annual Costs**
Purdue University	\$205K	25% support of Michael Zoltowski 25% support of Venkataramanan Balakrishnan 50% support of 3 graduate research assistants
Northwestern University	\$100K	15% support of Michael Honig 50% support of 2 graduate research assistants
SAIC	\$200K	20% support for J. Scott Goldstein 1 man-year (mid-career) engineering support Use of Maui High Performance Computer Center
University of California, San Diego	\$100K	20% support of Laurence B. Milstein 50% support of 2 graduate research assistants
SPAWAR	\$145K	20% support for James Zeidler .75 man-year (mid-career) engineering support
Total	\$750K	**Proposed Annual Budget**

Table 2: Overview of Proposed Annual Budget.

3 Prior Work on Interference Cancellation for GPS

3.1 Power Minimization Based Space-Time Preprocessor

With funding from the Air Force Office of Scientific Research through the New World Vista Program *Jam-Proof Area Deniable Propagation* (NWV Topic 20), Dr. Zoltowski developed space-time extensions of the power minimization principle. The output of a space-time pre-processor is a weighted sum of chip-spaced samples across both space and time as depicted in Figure 1.

In order for the GPS receiver to provide accurate navigation information, it is necessary to track the signals from at least four different GPS satellites. Given the parallax error associated with GPS satellites near zenith relative to the plane of the receiver array, it is desirable to track the respective signals from a larger number of GPS satellites. It is desired then that the preprocessor "pass" unaltered as many GPS signals as possible. Mathematically, it is desired that the multidimensional Fourier Transform of the space-time weights be as flat in magnitude as possible.

A system based on space-only processing requires the placing of a spatial null in the direction of each narrowband interferer as well as each wideband interferer. This leads to two problems. First, the maximum number of interferers that can be spatially nulled is $M-1$, where M is the number of antennas. In the GPS application, M is small due to cost considerations, size limitations, power consumption, etc. Thus, cancellation of narrowband interferers through spatial nulling consumes precious degrees of freedom. Second, if a narrowband interferer and a GPS satellite are closely-spaced in angle, the formation of a null towards that interferer may drop the gain in the direction of the GPS satellite so low that it is rendered useless. Again, due to the aforementioned

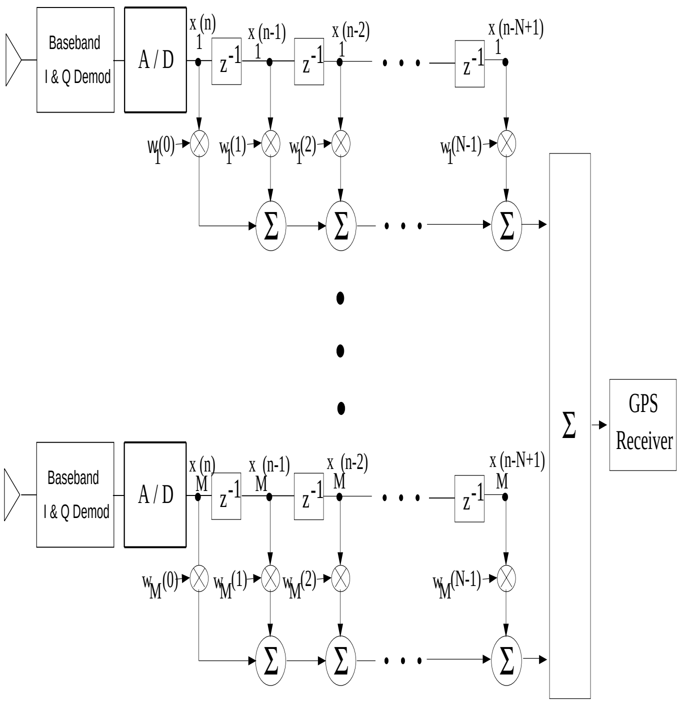


Figure 1. Power minimization based joint space-time preprocessor.

Jammer Type	SNR	AOA Ex.1	AOA Ex.2	Bandwidth
Wideband	-100 dBW	$20°$	$20°$	20 MHz
Wideband	-110 dBW	N/A	$0°$	20 MHz
Wideband	-100 dBW	N/A	$-20°$	20 MHz
Wideband	-100 dBW	N/A	$-40°$	20 MHz
Wideband	-110 dBW	N/A	$-60°$	20 MHz
Jammer Type	SNR	AOA	AOA	Freq. - L1
Narrowband	-100 dBW	$60°$	$60°$	-10 MHz
Narrowband	-100 dBW	$15°$	N/A	-5 MHz
Narrowband	-100 dBW	$-10°$	N/A	0 MHz
Narrowband	-100 dBW	$-30°$	N/A	5 MHz
Narrowband	-110 dBW	$-55°$	N/A	10 MHz

Table 3. Interference parameters for illustrative simulations presented in Figure 2.

economical considerations, the array aperture in the GPS application is typically on the order of one wavelength. Thus, the interferer and the GPS satellite may be widely-spaced in terms of physical angle but closely-spaced in terms of beamwidths.

In contrast, space-time processing only requires the formation of a “point-like” null in the multi-dimensional spectrum at the frequency-angle coordinates of each strong narrowband interferer. A sharp line null, i. e., a spatial null across the entire frequency band, is required along the angular coordinates of each broadband interferer. These nulling characteristics of power minimization based space-time pre-processing are illustrated in Figures 2(c) and 2(f), which will be discussed shortly.

The disadvantage of space-time processing relative to space-only processing is the large dimensionality of the space-time weight vector. This translates into a larger computational burden and slower convergence. As a result, Dr. Zoltowski collaborated with Dr. Goldstein in applying the MSNWF to the power minimization based space-time pre-processor [Zo3-Zo7]. MSNWF constrains the space-time weight vector to lie in a low-dimensional subspace, thereby speeding up convergence as well as reducing computational complexity. Illustrative simulation results are presented to demonstrate the impressive capabilities of the MSNWF.

3.1.1 Illustrative Simulation Results

The simulation study employed $N = 7$ taps at each of $M = 7$ antenna elements equi-spaced along a line. Although the prototype antenna system and GPS test-bed to be discussed shortly employs a circular array geometry, as do most practical anti-jam systems for GPS, a linear array was used in this illustrative simulation example in order to have only one angular variable. This allows the use of a single mesh or contour plot to display the multi-dimensional Fourier Transform of the space-time weights obtained from a given trial run.

Table 3 summarizes the parameters of the wideband and narrowband jammers simulated in each of two different scenarios. The angles-of-arrival (AOA's) listed are relative to broadside; the frequency listed for each narrowband jammer is its offset relative to L1. The first scenario involved 5 narrowband jammers and one wideband jammer. The attendant results are plotted in Figure 2(a) thru 2(c). The second scenario involved 1 narrowband jammer and five wideband jammers. The attendant results are plotted in Figure 2(d) thru 2(f). In all cases, the first tap at the first antenna was constrained to be unity. Given the $20MHz$ receiver bandwidth at each antenna, the noise floor was determined to be approximately -128 dBW. Recall the goal of power minimization is to drive the output power of the space-time beamformer as close to the noise floor as possible.

Figures 2(a) and 2(d) plot average power output of the MSNWF as a function of subspace dimension or rank of the dimensionality reducing matrix transformation. The subspace dimension at which MSNWF

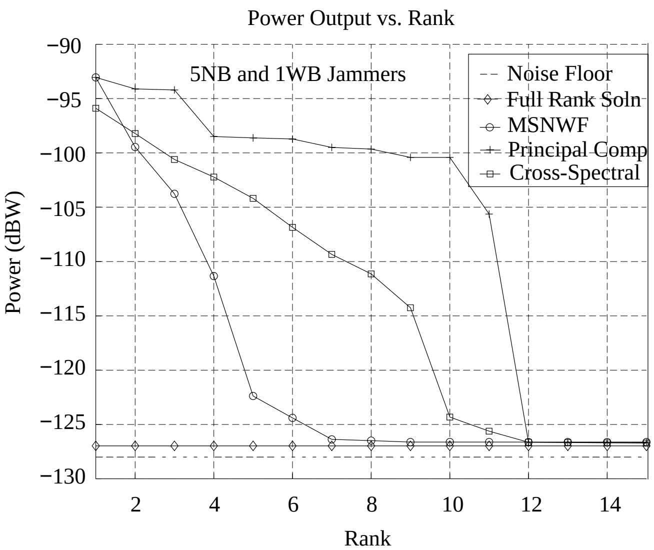


Fig. 2(a). Power Output vs Rank: 1 WB, 5 NB.

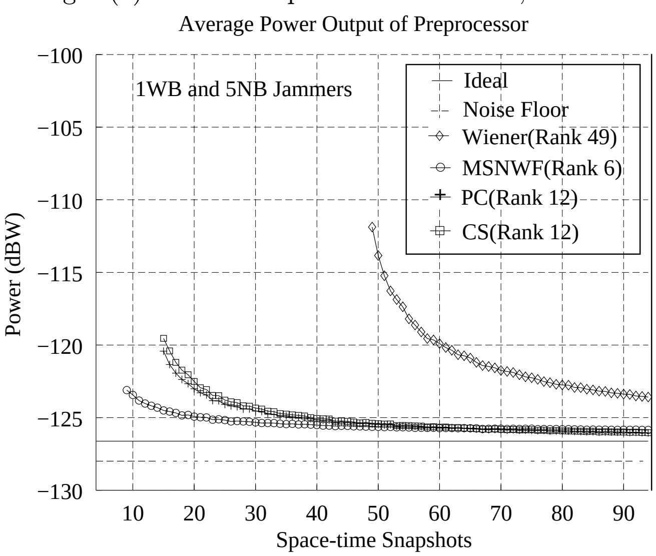


Fig. 2(b). Power Output vs Sample Support: 1 WB, 5 NB.

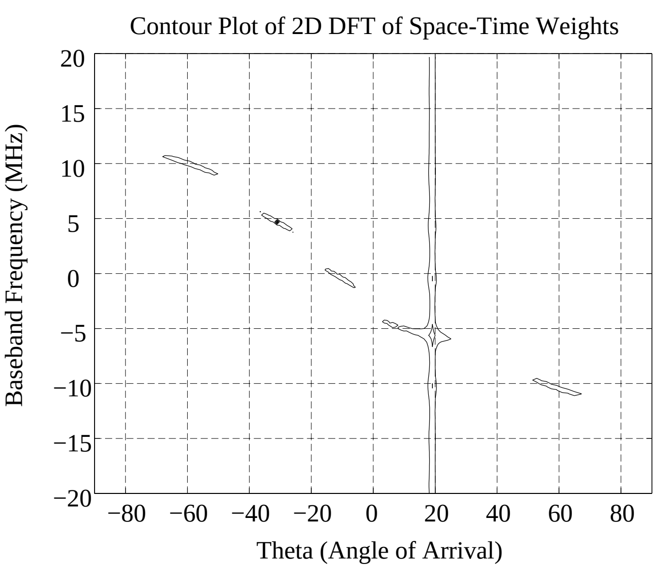


Fig. 2(c). STAP Angle-Frequency Response: 1 WB, 5 NB.

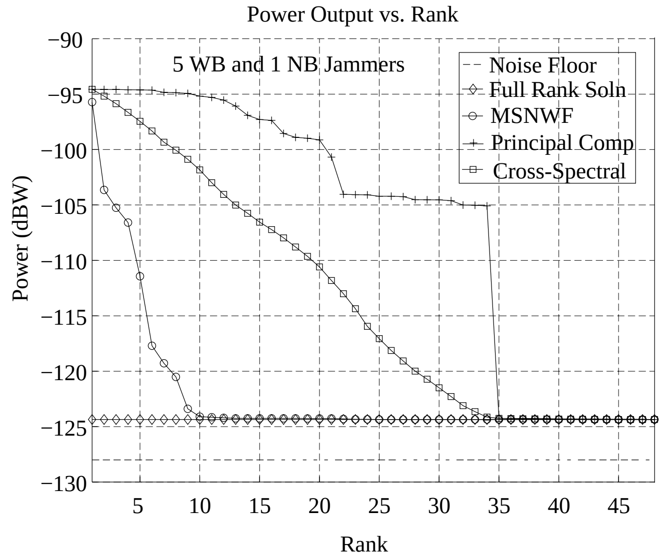


Fig. 2(d). Power Output vs Rank: 5 WB, 1 NB.

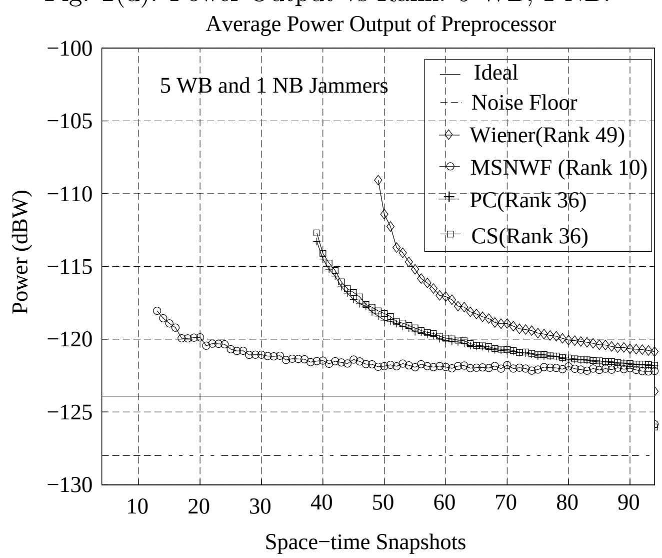


Fig. 2(e). Power Output vs Sample Support: 5 WB, 1 NB.

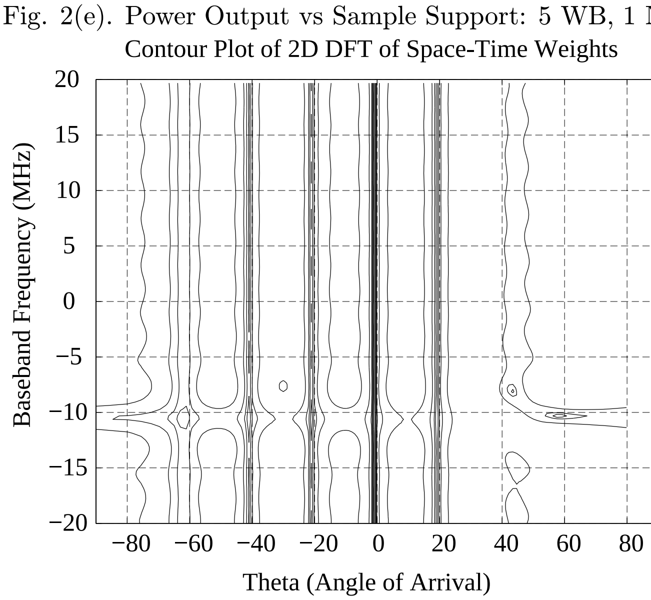


Fig. 2(f). STAP Angle-Frequency Response: 5 WB, 1 NB.

approximately achieves the performance of the full-dimension ideal (asymptotic) Weiner filter is roughly the same in both scenarios, around 8. In contrast, Principal Components (PC) generally requires a subspace dimension equal to the number of degrees of freedom taken up by the jammers to achieve the same output power level. Each narrowband jammer takes up one degree of freedom. Each wideband jammer takes up $N = 7$ degrees of freedom, where N is the number of taps per antenna. This is because the cancellation of a wideband jammer requires a spatial null, implying a null across the entire 20.46 MHz spectrum at its AOA. In Scenario 1, the jammers take up 5x1 + 1x7 = 12 degrees of freedom; in Scenario 2, the jammers take up 1x1 + 5x7 = 36 degrees of freedom.

Figures 2(b) and 2(e) examine the space-time snapshot sample support necessary to effectively null the jammers for each of the two scenarios simulated. The power output for each sample support level was averaged over 250 Monte Carlo trial runs. The greatest differential in performance between the MSNWF and PC based methods is observed in Figure 2(e) corresponding to Scenario 2. In this case, Figure 2(d) and the above calculation dictate that PC needs to adapt in a 36-dimensional subspace, while the MSNWF need only adapt in a 10-dimensional space. As a result, the MSNWF is able to converge more rapidly than PC.

At the same time, there is no computation of eigenvectors involved in the MSNWF. Only a small number of simple matrix-vector multiplications are needed to determine the required low-dimensional Krylov subspace. In contrast, the computation of the 36 eigenvectors needed by the PC method in Scenario 2 is a substantial computational burden. Note, though, that PC does indeed converge more quickly than the full-dimension (49), finite-sample Weiner filter. Note that Figure 2 also displays the performance of the Cross-Spectral Metric (CSM) method [G6]. Similar to the PC method, the CSM method constrains the space-time weight vector to lie in a subspace spanned by a subset of the eigenvectors of the space-time correlation matrix. The choice of eigenvectors is dictated by a cross-spectral metric derived from the cross-correlation vector, rather than simply choosing those eigenvectors associated with the largest eigenvalues. CSM yields improved performance relative to PC, but its performance is not nearly as good as MSNWF and it too requires the computation of eigenvectors.

Figures 2(c) and 2(f) display contour plots of the magnitude of the multi-dimensional Fourier Transform of the space-time weights obtained from the MSNWF with 40 space-time snapshots. For Scenario 1, Figure 2(c) displays a well-defined "point-null" at the angle-frequency coordinate of each narrowband jammer and a well-defined "line-null" along the arrival angle of the wideband jammer. For Scenario 2, Figure 2(f) displays a well-defined "point-null" at the angle-frequency coordinate of the one narrowband jammer and a well-defined "line-null" along the respective arrival angle of each of the five the wideband jammers. As important, in both cases the response of the space-time beamformer is observed to be relatively flat away from the null locations.

3.2 Post-Correlation Adaptive Beamforming

The advantage of the power minimization based space-time digital pre-processor is that it allows standard GPS receivers to be simply retro-fitted with a front-end device. However, there are at least two problems with this approach. First, as a practical matter, in order to truly avoid no modification to the GPS receiver itself, the output of the space-time pre-processor needs to undergo both D/A conversion followed by mixing back up to at least IF. Both Mitre and Mayflower market products that do just this. This is obviously counter-productive but necessary in cases where a simple retro-fit is the mandated solution.

Second, the space-time filter effected via power minimization is not optimized for any one GPS satellite signal in terms of maximizing the signal to interference plus noise ratio (SINR). The pre-processor simply attempts to pass as many GPS signals unaltered as best as possible while rejecting strong interference. Again, though, the GPS signals are very weak. It would certainly be nice to take advantage of the SNR gain possible with multiple antennas equal to the number of antennas in the case of simple co-phasal beamforming.

Another problem with the power minimization based space-time digital pre-processor is that it requires processing the data at the chip rate commensurate with the P(Y) code. As a low cost alternative, we have also developed an algorithm that operates on the antenna outputs after they have been de-spreaded [Zo2]. In this case, the spectrum is confined between DC and 50 Hz (after compensating for the Doppler shift due to the satellite motion) so that the data may be processed at at just several times the bit rate using a low-cost general purpose microprocessor or DSP chip. Recall that the 50 bits/sec data stream carriers the following information: ephemeris data, clock corrections, satellite status, Almanac data, HandOver Words, etc.

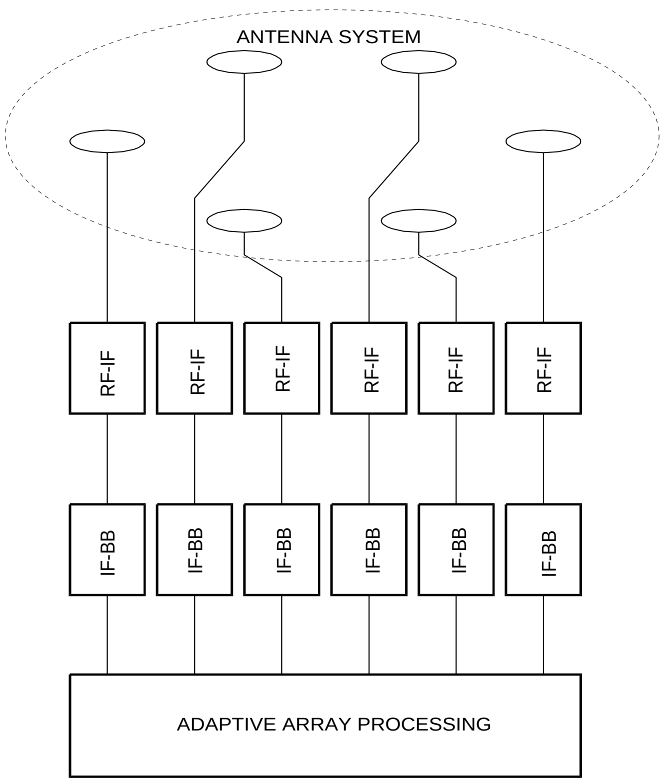
A post-correlation adaptive beamforming algorithm yielding the maximum SINR for each GPS satellite signal was developed in [Zo2]. The algorithm exploits the cyclostationarity of the aforementioned BPSK signal obtained after despreading. The algorithm forms one cyclic spatial correlation matrix at the bit rate and one at DC. It can be shown that the beamforming weight vector yielding the maximum SINR is equal to the largest eigenvector of the difference between these two matrices. This maybe easily computed via a few power iterations. Note that this represents a nonlinear signal processing algorithm.

A very important aspect of this algorithm is that it steers the beam and adapts the nulls based only on the known code for the desired "user." In terms of the GPS application, the point to be made is that the algorithm does not attempt to do beamforming through effecting phase shifts derived from the azimuth and elevation coordinates of a given GPS satellite. As discussed previously, it is difficult and expensive to design antenna arrays calibrated well enough to achieve beamforming through geometrically derived phase shifts. There are nonlinear effects amongst the individual antennas comprising the array, mutual coupling, for example, and these nonlinear effects are time-varying for a variety of reasons. Thus, an adaptation scheme based solely on the known code is highly advantageous.

Note that this algorithm does require a modified GPS receiver, not a simple retro-fit. Further, in its current form, it does not work in a cold start-up situation since it requires synchronization to effect interference cancellation. Finally, it also is currently formulated as a space-only scheme thereby placing spatial nulls in the direction of each strong interferer whether it is narrowband or wideband. Methodologies for removing these restrictions are part of the proposed research.

A prototype antenna array system was developed as a test-bed for demonstrating this algorithm. The prototype presented below was built at the Polytechnic University of Madrid through a collaboration between Dr. Zoltowski and an electromagnetics group there. A similar test-bed is being developed at Purdue University, but using TI DSP chips and polarization diversity amongst the antenna elements.

3.2.1 Description of Prototype/Test-bed



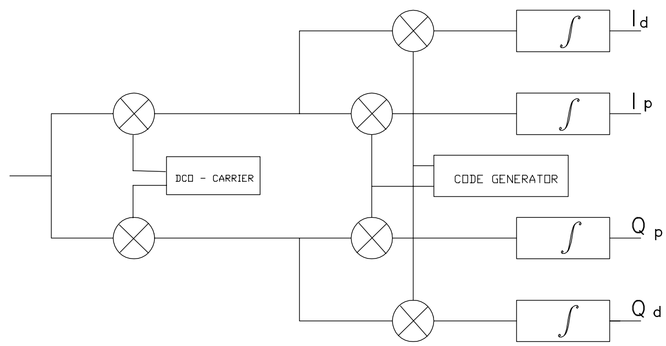


Figure 4. Structure of IF-BB Stage.

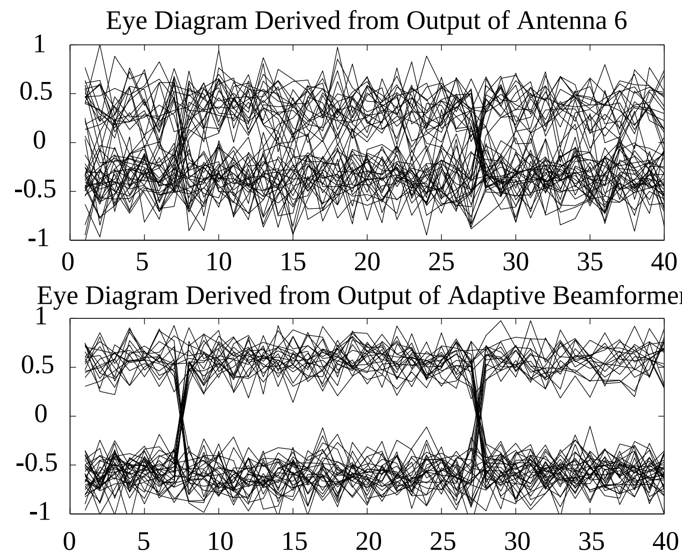


Figure 3. Block diagram of prototype/test-bed.

Figure 5. Eye diagrams derived from experimental data.

A block diagram of the receiver is shown in Figure 3. The antenna array consists of 6 elements equi-spaced along a circle of radius equal to roughly half the wavelength at L1. Each antenna element is a low cost *stacked patch antenna*. This configuration provides a wide bandwidth allowing the reception of INMARSAT as well as GPS. To achieve circular polarization, a 90^o hybrid is placed below each element. The antenna array subsystem is pictured in Figure 6. Following that are six Low Noise Amplifiers (LNA) in MMIC. The RF outputs of the six antennas are handed to six standard DS-SS receivers with the special feature that all of them are locked to the same Local Oscillator (LO). These six spread spectrum receivers are basically composed of two stages: downconversion from RF to IF, followed by digital down conversion from IF to BaseBand (BB). The design and implementation of each of these two stages are described below.

Two ASIC's are used in the implementation. The first one accomplishes the down conversion from RF to IF at 4.32 MHz. The output of the last mixer is sampled at 5.71 MHz and coded with only 2 bits. The second ASIC, a Digital Signal Processor (DSP), accomplishes the following tasks: down conversion to Base Band accounting for the Doppler offset, the correlation with the code corresponding to each satellite, bit synchronization, and the symbol decision relative to the BPSK constellation.

All the DSP involved in the IF-BB conversion is guided by a low cost microprocessor. The microprocessor serves the second integrated circuit asynchronously, i.e., on demand. The same microprocessor carries out the rest of the tasks needed in a GPS receiver which exceed that strictly necessary in a standard DS-SS receiver. This includes the estimation of the satellite-user distance, acquisition of the Universal Coordinated Time (UCT), decoding of the navigation message sent by the satellites and the computation of the users location. In addition to the aforementioned tasks, the microprocessor has to control the Digital ASIC and perform the beamforming using the weights computed from the aforementioned cyclostationarity based algorithm.

The digitalized signal is provided to the IF-BB stage at a rate of 5.71 MHz. Figure 3 outlines the structure of the parallel processing carried out on these signals. The processing gain in a DS-SS system is proportional to the ratio of the RF bandwidth to the bandwidth after the decorrelation with the desired GPS satellite code. The RF bandwidth is fixed by the chip rate. It has to be at least twice the chip rate. The minimum bandwidth the system should have after decorrelating or despreading is the bit rate (in base-band or twice that at IF). Thus, a narrowband filter has to be placed after decorrelation to achieve a high processing gain that permits a good suppression of low-level jammers and receiver noise, ideally having a bandwidth of 50 Hz.

On the other hand, the received frequency might be Doppler shifted up to $\pm$ 5KHz away from the nominal L1 (or L2) frequency due to GPS satellite motion. Therefore, the receiver has to have a very wide bandwidth relative to the bit rate. Similar comments hold relative to the code: in order to achieve high resolution in the location estimate provided by GPS, a very accurate estimation of the code delay is required. However, codes with a delay larger than (or equal to) half a chip are suppressed by the correlator. To balance these opposing requirements, the carrier and code recovery are done simultaneously in two stages: search and tracking.

The search stage consists of successive trials with different frequencies for the carrier and different delays for the code. After the search process, the worst case is a local oscillator 500Hz away from the actual received carrier and a generated code delayed less than half a chip with respect to the received code. Then the tracking stages begin for both carrier and code. Since the modulation for GPS is BPSK, the tracking of the carrier cannot be done with a regular PLL but with a Costas Loop. The tracking of the code delay is performed by a DLL (Delay Lock Loop). The Costas Loop estimates the phase error as the result of an iterative search. The phase error is measured by a phase detector which can be implemented in different ways in the digital receiver. Although the more reasonable phase detector would be to compute $\mathrm{atan}(Q_p/I_p)$, the prototype uses the lower cost approximation $sign(Q_p)I_p$. The design of the DLL follows a parallel optimization similar to the Costas Loop. In this case, the input to the loop is $I_p^2 + Q_p^2 - I_d^2 - Q_d^2$.

Both the tracking of the carrier and the code are governed by only one of the six receivers (Master) and the phase of the carrier and delay of the code are updated identically in the other five receivers (Slaves). At this point, the process in charge of the beamforming is fed with the $I_p + jQ_p$ complex envelope values at a rate of one sample per millisecond. The complex envelope is available for each of the six antennas.

3.2.2 Proof of Concept Experiment

An experiment was conducted in which the experimental GPS receiver was programmed to receive a GPS signal arriving at an elevation angle of 30 degrees with respect to the boresite axis of the array. After despreading, the SNR of the GPS signal was roughly 10 dB per element. In addition, interference was intentionally injected by a nearby radiating antenna at an angle of 20 degrees with respect to boresite, and at a power level 40 dB above the desired GPS signal (prior to despreading.) The beamforming weights were determined via the aforementioned cyclostationarity based post-correlation blind adaptive beamforming scheme. In order to give some idea of the improvement achieved, in Figure 5 the eye diagram at the antenna element with the best SNR is compared with that obtained at the beamformer output. It is clear that the jammer has been sufficiently rejected so as to "open up the eye."

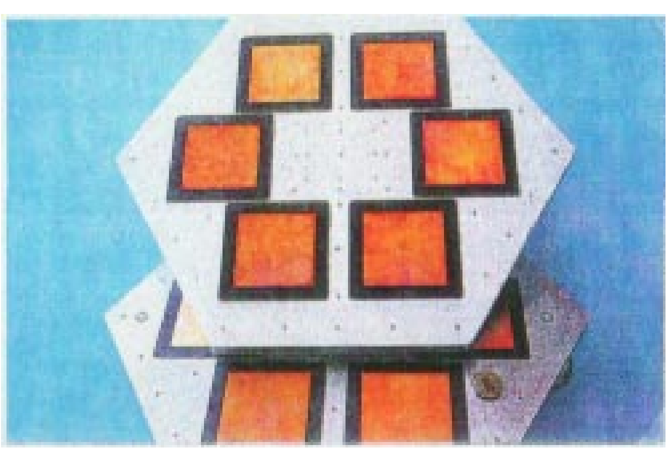


Figure 6. Prototype stacked patch antenna array.

Figure 7. Compact array used for DF at HF.

4 Preliminary Research Plan

Several innovative avenues of research were briefly discussed during the overview of the research team in Section 2. In particular, we propose to investigate the use of the algorithm developed by Dr. Honig in [H3] that adapts towards the SINR maximizing weight vector based solely on the known code for the desired "user." Recall that this algorithm cancels multipath reflections. This algorithm has not been applied to the GPS problem to date. The MSNWF of Dr. Goldstein will be used to make this algorithm amenable to real-time implementation. A small sampling of other innovative avenues of research to be pursued as part of this effort are briefly outlined below. Expanded discussion on these research themes along with additional innovations will be presented in the full proposal. All facets of these research will progress in an integrated fashion. In addition, all candidate algorithms will be tested in a prototype at Purdue as well as applied to GPS data obtained from other sources.

4.1 Space-Time Power Minimization & Post-Correlation Adaptive Beamforming

The problem with post-correlation adaptive beamforming based on cyclostationarity is that it requires synchronization which is not achievable if strong interference is present when the GPS receiver is first turned on. In the experimental result presented in Section 3.2.2, synchronization was achieved prior to turning on the interferer. To avert this restriction, we propose to investigate the efficacy of a hybrid combination of power minimization based pre-processing and cyclostationarity based post-correlation beamforming.

The idea is to create as many space-time power minimization based pre-processor outputs as there are antennas. The m-th one will be created by constraining the weight value of the first tap at the m-th antenna to be unity; the remaining weights are chosen as those which yield minimum output power. In practice, this may be effected via an LMS adaptation, which has advantageous nonlinear effects, by using the output of the first tap of the m-th antenna as a reference signal. This yields M linearly independent outputs, where M is the number of antennas, each of which reduces the interference well enough to at least achieve approximate synchronization, but none of which is optimized for any one GPS satellite. After correlating with the code of a given GPS satellite at EACH of these M outputs, the cyclostationarity based algorithm may be applied to find that linear combination of these M space-time power minimization based outputs yielding maximum SINR.

4.2 Beamforming with Polarization Diverse Arrays

As discussed previously, the formation of a null towards an interferer may drop the gain in the direction of a particular GPS satellite so low that it is rendered useless. Again, due to the small array aperture in the GPS application, an interferer and a GPS satellite may be widely-spaced in terms of physical angle but closely-spaced in terms of beamwidths. Polarization diversity amongst the antenna elements is a way to combat this problem.

For example, consider the compact array pictured in Figure 7 used for direction finding (DF) and beamforming at HF for electronic warfare applications. This vector sensor consists of three orthogonal loops and three orthogonal dipoles, all co-located but having mutually orthogonal orientations. Dr. Zoltowski has developed algorithms for DF and beamforming which exploit the polarization diversity inherent in this compact array [Zo6, Zo7]. For example, it has been demonstrated that two signals coming from exactly the same radial direction but with different polarization states may be extracted individually! In the GPS application, the beamforming weights that yield maximum SINR for a given GPS satellite have a complex dependence on on the polarization states and azimuth/elevation angles of both that satellite's signal and the interfering signals. However, all of the algorithms proposed for this project adapt either based on the known code of a given GPS satellite or on the power minimization principle if in a pre-processing mode. The optimal weights are achieved automatically without the need for estimating polarization states or azimuth/elevation angles.

The compact array pictured in Figure 7 was developed for operation at HF. What we primarily desire for the GPS application (operating around 1.5 GHz) is polarization diversity amongst the antenna elements. We will initially investigate a circular array geometry with adjacent antenna elements circularly polarized but in opposite directions, clock-wise followed by counter clock-wise in sequence. Compact array geometries and alternative realizations of polarization diversity will also be investigated exploiting the expertise of Dr. Zeidler.

4.3 Efficient and Numerically Stable Computation of Krylov Subspace for MSNWF

As discussed previously, Dr. Honig [H1] has shown that MSNWF constrains the weight vector to lie in the Krylov subspace generated by $\mathbf{R}_{xx}$ and $\mathbf{r}_{dx}$. The general problem of computing a basis for the span of the matrix $\begin{bmatrix} b & Ab & A^2b & \cdots & A^{r-1}b \end{bmatrix}$ directly from the vectors $\{b, Ab, A^2b, \ldots, A^{r-1}b\}$ becomes rapidly ill-conditioned, as the vectors A^ib become linearly dependent very quickly with i (this is simply a power iteration). Dr. Balakrishnan will address this issue by exploring numerically stable methods for computing a well-conditioned basis by applying Krylov subspace methods such as the Lanczos algorithm or the Arnoldi process. Another approach towards stably computing a basis relies on noting that span $\begin{bmatrix} b & Ab & A^2b & \cdots & A^{r-1}b \end{bmatrix} = \text{span}\, W_r$, where W_r is the solution to the Lyapunov equation $AW_rA^T - W_r = A^rbb^T(A^T)r - bb^T$.

BIOGRAPHICAL SKETCH

Michael D. Zoltowski, Purdue University

A: Brief Biography

Michael D. Zoltowski was born in Philadelphia, PA, on August 12, 1960. He received both the B.S. and M.S. degrees in Electrical Engineering with highest honors from Drexel University in 1983 and the Ph.D. in Systems Engineering from the University of Pennsylvania in 1986. ¿From 1982 to 1986, he was an Office of Naval Research Graduate Fellow. In Fall 1986, he joined the faculty of Purdue University where he currently holds the position of Professor of Electrical and Computer Engineering. During 1987, he held a position of Summer Faculty Research Fellow at the Naval Ocean Systems Center in San Diego, CA.

Dr. Zoltowski was the recipient of the IEEE Signal Processing Society's 1991 Paper Award (Statistical Signal and Array Processing Area) and "The Fred Ellersick MILCOM Award for Best Paper in the Unclassified Technical Program" at the IEEE Military Communications (MILCOM '98) Conference. He is a contributing author to *Adaptive Radar Detection and Estimation*, Wiley, 1991, *Advances in Spectrum Analysis and Array Processing, Vol. III*, Prentice-Hall, 1994, and *CRC Handbook on Digital Signal Processing*, CRC Press, 1996. He has served as an associate editor for both the *IEEE Transactions on Signal Processing* and the *IEEE Communications Letters.* Within the IEEE Signal Processing Society, he has been a member of the Technical Committee for the Statistical Signal and Array Processing Area, and is currently a member of both the Technical Committee for Communications and the Technical Committee on DSP Education. In addition, he is currently a Member-at-Large of the Board of Governors and Secretary of the IEEE Signal Processing Society. He is a Fellow of IEEE for "Contributions to the theory of antenna array signal processing and two-dimensional direction-of-arrival estimation". His present research interests include space-time adaptive processing for all areas of mobile and wireless communications, GPS, and radar.

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BIOGRAPHICAL SKETCH

Laurence B. Milstein, University of California, San Diego

A: Brief Biography

Laurence B. Milstein received the B.E.E. degree from the City College of New York, New York, NY, in 1964, and the M.S. and Ph.D. degrees in electrical engineering from the Polytechnic Institute of Brooklyn, Brooklyn, NY, in 1966 and 1968, respectively. ¿From 1968 to 1974, he was employed by the Space and Communications Group of Hughes Aircraft Company, and during 1974–1976, he was a member of the Department of Electrical and Systems Engineering, Rensselaer Polytechnic Institute, NY. Since 1976, he has been with the ECE department, UC San Diego where he is a Professor and former Department Chairman.

Dr. Milstein's research interests are in the area of digital communication theory with special emphasis on spread-spectrum communication systems. He has also been a consultant to both government and industry in radar and communications.

Dr. Milstein was an Associate Editor for Communication Theory for the IEEE Transactions on Communications, an Associate Editor for Book Reviews for the IEEE Transactions on Information Theory, and an Associate Technical Editor for the IEEE Communications Magazine, and is currently a Senior Editor for the IEEE Journal on Selected Areas in Communications. He was the Vice President for Technical Affairs in 1990 and 1991 of the IEEE Communications Society, and has been a member of the Board of Governors of both the IEEE Communications Society and the IEEE Information Theory Society. He is also a member of Eta Kappa Nu and Tau Beta Pi, and is a Fellow of the IEEE.

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Michael Honig, Northwestern University

A: Brief Biography

Michael L. Honig received the B.S. degree in electrical engineering from Stanford University in 1977, and the M.S. and Ph.D. degrees in electrical engineering from the University of California, Berkeley, in 1978 and 1981, respectively. He subsequently joined Bell Laboratories in Holmdel, NJ, where he worked on local area networks and voiceband data transmission. In 1983 he joined the Systems Principles Research Division at Bellcore, where he worked on Digital Subscriber Lines and wireless communications, including interference suppression for Code-Division Multiple Access (CDMA) systems. He was a visiting lecturer at Princeton University during the Fall of 1993. Since the Fall of 1994 he has been with Northwestern University where he is a Professor in the Electrical and Computer Engineering Department. In 1996 he was an ONR Summer Faculty Fellow at SPAWAR in San Diego, CA.

His recent work has focused on adaptive reduced-rank filtering techniques for interference suppression. This work includes the development of new high-performance algorithms, which require significantly fewer training samples than previously known adaptive filtering techniques. The performance of these and prior reduced-rank algorithms has been evaluated when used to suppress multiple-access interference in CDMA. He is an editor for the IEEE Transactions on Information Theory, and has served as an editor for the IEEE Transactions on Communications, and as a guest editor for the European Transactions on Telecommunications and Wireless Personal Communications. He has also served on the Digital Signal Processing Technical Committee for the IEEE Signal Processing Society. He is a Fellow of IEEE, and is currently serving as a member of the Board of Governors for the Information Theory Society.

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BIOGRAPHICAL SKETCH

Jay Scott Goldstein, SAIC

A: Brief Biography

J. Scott Goldstein is the Manager of Adaptive Signal Exploitation within the Sensor System Operation of SAIC's Technology Research Group. His responsibilities include program development, program management and technical leadership in advanced signal processing for detection, estimation, classification and recognition within the fields of radar, sonar and communications. He is also a reserve officer in the U.S. Air Force, assigned as the Senior Systems manager for Intelligence and Information Processing in the Multi-sensor Exploitation Branch, Air Force Research Laboratory. Dr. Goldstein received his Ph.D. in Electrical Engineering from the University of Southern California in 1997.

¿From 1998 to 1999, Dr. Goldstein was a staff member at MIT Lincoln Laboratory. From 1995 to 1997, he was with the University of Southern California. From 1993 to 1997, he was the Vice-President and Chief Scientist of Adaptronics, Inc. From 1992 to 1995, he was with the Radar Systems Division of the Sensors and Electromagnetic Applications Laboratory at the Georgia Tech Research Institute. From 1990 to 2000, he was a reserve officer in the United States Air Force assigned to R&D positions within Air Force Systems Command and Air Force Material Command. Prior to this, Dr. Goldstein served as a signal and infantry officer in the U.S. Army and was associated with both the George Mason University Center of Excellence in C3I and the Institute for Defense Analyses. He has also served as a consultant to the Army Research Laboratory and Adaptive Sensors, Inc.

Dr. Goldstein is the recipient of the IEEE Aerospace and Electronic Systems Society's EASCON Award, the Japanese Okawa Foundation Research Grant and the AFCEA Postgraduate Fellowship. In addition, Dr. Goldstein has received over 15 Air Force Awards for Scientific Achievement due to his research in radar and communications.

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James R. Zeidler, SPAWAR Systems Center

A: Brief Biography

James Zeidler is a Senior Scientist in the Communications and Information Systems Department of the Space and Naval Warfare Systems Center (SPAWAR), San Diego, CA. He received the Ph.D. degree in Physics from the University of Nebraska in 1972. Since 1974, he has been with SPAWAR. He was also a technical advisor in the Office of the Assistant Secretary of the Navy (Research, Engineering and Systems), Washington, DC from 1983-84.

Dr. Zeidler's research interests are in adaptive signal and array processing, wireless communications networks, compact antenna arrays, and interference suppression. He has published over 170 papers and has 10 patents in signal processing, communications systems, image processing, and electronic devices. He was an Associate Editor of the IEEE Transactions on Signal Processing from 1991-94 and is a member of the Editorial Board of the Journal of the Franklin Institute. He received an award for the best unclassified paper at the IEEE Military Communications Conference in 1995 and the Navy Meritorious Civilian Service Award in 1991. He was a Navy representative to the US/UK/Australia/Canada Technical Cooperation Panel on Satellite Communications. Dr. Zeidler was elected Fellow of the IEEE in 1995 for his technical contributions to adaptive signal processing and its applications. He received the 1996 Distinguished Alumni Award from the Physics Department, University of Nebraska.

Dr. Zeidler is also an Adjunct Professor of Electrical and Computer Engineering at the University of California, San Diego since 1989. He is affiliated with the National Science Association Industry/University Cooperative Research Center on Ultra-High Speed Integrated Circuits and Systems. He also initiated a joint research effort in imaging myocardial defects with the UCSD Medical School and the Nuclear Medicine Division of the Veterans Administration Hospital.

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Venkataramanan Balakrishnan, Purdue University

A: Brief Biography

Venkataramanan Balakrishnan received the B. Tech degree in Electronics and Communication Engineering, the President of India Gold Medal, and the Philips India silver medal, from the Indian Institute of Technology, Madras, India, in 1985. He then joined Stanford University, where he received an M.S. degree in Statistics and a Ph.D. degree in Electrical Engineering in 1992. From September 1992 to February 1993, he was a Post-Doctoral Scholar in the Department of Electrical Engineering at Stanford University. ¿From February 1993 to August 1993, he was a Post-Doctoral Scholar and a Lecturer at the California Institute of Technology. From September 1993 to August 1994 he was a Research Associate at the Institute for Systems Research, University of Maryland. In August 1994, he joined Purdue University, where he is currently an Associate Professor of Electrical and Computer Engineering. Dr. Balakrishnan was named an Office of Naval Research Young Investigator in 1997. He was also awarded the Ruth and Joel Spira Outstanding Teacher Award by the School of Electrical and Computer Engineering at Purdue University in 1997.

Dr. Balakrishnan's primary research areas are Systems and Control. In particular, he is interested in applying numerical techniques to problems in systems, control, communications and signal processing. His most recent contributions have been in the area of Linear Matrix Inequalities (LMIs), in which he has coauthored the book *Linear Matrix Inequalities in System and Control Theory*, Volume 15 of the Series in Applied Mathematics, SIAM, Philadelphia (item [B2] below). He has co-organized and co-chaired minisymposia, workshops, and invited sessions on LMI methods for control, at several control conferences over the past three years. He is a guest-editor for two issues of the *International Journal of Robust and Nonlinear Control* on *Linear Matrix Inequalities in Control Theory and Applications*, published in November–December of 1996. He is also the Chairperson of the IEEE CSS Technical Committee on Robust Control.

B: References: Selected Publications Related to Proposed Project

[B1] C-Y. Chang, A. A. Maciejewski, and V. Balakrishnan. "Fast Eigenspace Decomposition of Correlated Images." Accepted for publication in *IEEE Transactions on Image Processing*, 1999.

[B2] S. Boyd, L. El Ghaoui, E. Feron, and V. Balakrishnan. *Linear Matrix Inequalities in System and Control Theory*, volume 15 of *Studies in Applied Mathematics*. SIAM, Philadelphia, PA, June 1994.

[B3] M. L. Honig, K. Steiglitz, V. Balakrishnan, and E. Rantapaa. "Designing discrete-time amplitude limited signals for maximum amplitude separation". *IEEE Trans. Information Theory*, 41(1):164–170, January 1995.

[B4] V. Balakrishnan and A. Tits. Numerical optimization-based design. Chapter 47 of *The Control Handbook*, W. Levine, Editor, CRC Press, 1996.

[B5] T. F. Settle, M. D. Zoltowski, and V. Balakrishnan, "Design of Multichannel Equalizers Via Linear Matrix Inequalities: Trade-Offs Between SNR and ISI," *First Annual UCSD Conference on Wireless Communications,* 8-10 March 1998, San Diego, CA, pages 144–150.

[B6] V. Balakrishnan and S. Boyd. Global optimization in control system analysis and design. In C.T. Leondes, editor, *Control and Dynamic Systems: Advances in Theory and Applications*, volume 53, pages 1–55. Academic Press, New York, New York, 1992.