Washington University in St. Louis
SCHOOL OF ENGINEERING & APPLIED SCIENCE

Preston M. Green Department of Electrical and Systems Engineering

June 20, 2018

Defense Technical Information Center
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Fort Belvoir, VA 22060-6218

Dear Sir/Madam,

Attached please find the final technical report and SF 298 form for ONR Grant No. N00014-13-1-0050 and No. N00014-17-1-2371.

I am thankful to ONR for the providing the support to work on this project.

Sincerely,

Arye Nehorai
The Eugene and Martha Lohman Professor of Electrical Engineering

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REPORT DOCUMENTATION PAGE

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1. REPORT DATE *(DD-MM-YYYY)*
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Co-Prime Sensor Array Signal Processing

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6. AUTHOR(S)
Arye Nehorai

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5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Washington University in St. Louis
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Green Hall, One Brookings Drive
St. Louis, MO 63130

8. PERFORMING ORGANIZATION REPORT NUMBER

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875 N. Randolph Street Suite 1425
Arlington VA 22203-1995

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12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION A. Approved for public release; distribution unlimited.

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14. ABSTRACT
We designed novel algorithms for various co-prime array signal processing problems. We developed new direction-of-arrival (DOA) estimators for wideband and distributed sources. We proposed a new tensor-based model for both electromagnetic and acoustic vector-sensor arrays. We developed high-resolution DOA estimators for off-grid sources using sparse modeling. We developed new approaches to calibrate sensor gain and phase errors. We conducted a comprehensive statistical performance analysis of coarray-based MUSIC, and analyzed the Cramér-Rao Bound for co-prime arrays. We investigated the statistical performance of co-prime arrays in the presence of sensor location errors.

15. SUBJECT TERMS
array signal processing, co-prime arrays, direction-of-arrival, parameter estimation, sparsity, performance analysis, Cramér-Rao Bound

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Arye Nehorai
					19b. TELEPHONE NUMBER *(Include area code)*
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Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

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3. DATE COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

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6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

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14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

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Co-prime Sensor Array Signal Processing
Final Report

Arye Nehorai
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Award Number: N00014-13-1-0050 and N00014-17-1-2371
http://www.ese.wustl.edu/~nehorai/index.html

LONG-TERM GOALS

We plan to develop a comprehensive statistical performance analysis and design algorithms for various co-prime array signal processing problems. We will develop methods to analyze co-prime sensing systems and to optimally design them. More specifically, we will analyze the sensitivity of co-prime sensing and nested sensing to modeling errors, extend nested and co-prime arrays to active radar sensing systems, employ multiple co-prime arrays simultaneously, and combine co-prime sensing with sparse modeling. We will show that co-prime arrays are capable of identifying large amount of sources using only a small collection of sensors under all the aforementioned scenarios.

OBJECTIVES

In this five-year project:

We will compute performance bounds on the number of sources that can be identified by co-prime arrays. We will also analyze the achievable estimation accuracy of co-prime arrays by computing bounds on estimation variance. We will analyze the sensitivity of estimation performed by co-prime arrays to modeling errors such as ambiguity in sensor locations, phase perturbations, noise covariance, etc. We will develop novel co-prime array processing methods that employ multiple spatially distributed co-prime arrays. We will compute the optimal deployment of multiple moving arrays by optimizing the posterior Cramér-Rao bound. We will formulate the problem of estimating parameters using co-prime arrays as a sparse signal reconstruction problem. We will extend our statistical data analysis of narrowband co-prime arrays to wideband signal models. We will formulate a new framework for performing statistical inference from the fusion of multi-modal and multi-sensor data obtained by employing co-prime arrays jointly with various other sensing modalities.

ACCOMPLISHMENTS

We developed a new method for improved source number detection and direction-of-arrival (DOA) estimation using nested arrays and uniform linear arrays (ULAs). We employed the strategy of jackknifing to detect the number of sources and estimate DOAs with both nested arrays and ULAs. We proved that by making full use of the data, jackknifing guarantees the performance improvement of source number detection and direction of arrival estimation for both nested arrays and uniform linear arrays, when the detection or estimation accuracy is greater than or equal to 50%. Our jackknifing work will help achieve more accurate detection and estimation performance using limited available data [1], [2].

We developed a new nested array based DOA estimation technique for wideband sources. We applied a nested array based strategy to each frequency obtained by narrowband decomposition for wideband signals. We then fused all the individual frequency results to conduct source number detection and DOA estimation. Our approach can estimate more wideband sources than the number of sensors [3], [4].

We developed new DOA estimation and source number detection approaches for nested vector-sensor arrays. We employed multilinear algebra and tensors to construct a novel signal model. We extended the nested-array strategy with scalar sensors to the case of vector-sensors: (a) we proposed a nested vector-sensor array model; (b) we constructed the analytical foundation of the proposed model for signal processing; (c) we proposed a novel spatial smoothing algorithm to exploit the increased degrees of freedom; (d) we conducted source number detection and DOA estimation based on tensor decomposition; (e) we considered the case of both acoustic and electromagnetic vector sensors. Based on the constructed signal model for nested vector-sensor arrays, we showed that the number of elements in the coarray model was increased to $O(N^2)$ with only N sensors. Our nested vector-sensor array model can be used in sonar, electromagnetic, and seismological applications [5], [6].

We developed several novel sparsity-based methods that can tackle the grid mismatch problem, and analyzed their statistical performance. We first designed and implemented a new joint-sparse recovery method that accounts for grid mismatches. Our joint sparsity method can be extended to a general case where structured mismatches exist in the dictionary of compressed sensing [8]-[10]. We then further extended the algorithm to the continuous parameter domain. We proposed to use semidefinite programming to solve the resulting optimziation problem. We showed that our algorithm can also achieve $O(MN)$ degrees of freedom with only $M+N$ sensors. We demonstrated that our algorithm can achieve higher resolution than MUSIC algorithm with spatial smoothing. We derived an analytical bound on compressed sensing with dictionary mismatch, and anlayzed the robustness of our algorithm. Our methods for grid mismatch problems not only apply to co-prime and nested arrays, they also fit wide applications of linear arrays and MIMO radar [11], [12].

We developed new approaches to calibrate gain and phase error for general non-uniform linear arrays. For non-uniform linear arrays with model errors, including nested arrays and co-prime arrays, we estimated the gain errors by exploiting a partial Toepliz structure of the covariance matrix. Then, rather than estimating the phase errors, we directly estimated the DOAs by solving a sparse total least-squares problem. Based on the estimated gain errors, the sparse total least-squares method achieved great calibrating performance for both nested arrays and co-prime arrays, improving the estimation accurarcy of DOAs efficiently. Our calibrating strategy is the first to consider non-uniform linear arrays with model errors. Our proposed sparse total least-squares strategy is a novel method for calibrating model errors [13], [14].

We developed a new method to estimate the DOAs of distributed sources inspired by our research on gain error estimation. We constructed a nested array signal model containing the distributed parameters, similar to the model error case with only gain errors. To increase the degrees of freedom, we proposed a new spatial smoothing strategy by exploiting *a priori* knowledge of the distributed parameters, and analytically proved its effectivenss. Our work about distributed sources can inspire further research about using nested arrays for real-world cases [15], [16].

We statistically analyzed the performance of coarray-based DOA estimators. More specificially, we considered two commonly used coarray-based MUltiple SIgnal Classification (MUSIC) estimators, namely the Direct Augmentation based MUSIC (DA-MUSIC), and the Spatial Smoothing based MUSIC (SS-MUSIC). We first derived the asymptotic (i.e., large number of snapshots) first-order statistics of the DOA estimation error for both MUSIC estimators. Based on their first-order statistics, we analytically derived a simplified asymptotic Mean-Square Error (MSE) expressions for both estimators by exploiting the coarray properties. We showed that both estimators have the same asymptotic MSE. This observation implies that given sufficient snapshots, we can replace SS-MUSIC with DA-MUSIC to reduce the computational complexity without sacrificing accuracy. In addition, we analyzed the asymptotic behavior of the derived MSE in high SNR regions. We concluded that when the number of sources is greater than or equal to the number of sensors, the MSE converges to a strictly positive value even if SNR goes to infinity. This conclusion analytically explained the "saturation" behavior observed in the numerical simulations in prior studies on co-prime arrays. We demonstrated that, given sufficient number of snapshots and SNR, our analytical MSE agreed very well with the empirical MSE obtained from Monte Carlo simulations. This is the first time such an MSE expression has been derived for DA-MUSIC and SS-MUSIC [17], [18].

We analyzed the Cramér-Rao Bound (CRB) for general non-uniform linear arrays, including co-prime and nested arrays. We first observed that the coarray manifold surprisingly appears in the final expression of the CRB. We then were able to show that the derived CRB is applicable when the number of sources is greater than the number of sensors, and less than or equal to the maximum number of identifiable sources. We also analytically showed that, when the number of sources is greater than or equal to the number of sensors, the CRB exhibits a different behavior in high SNR regions by converging to a strictly positive definite matrix as SNR goes to infinity. This observation implies that the similar behavior of the MSE is inherent in the problem, and not due to the algorithms. Our results on MSE and CRB have wide applications in resolution analysis and optimal array geometry design [17], [18].

We developed new DOA estimation algorithms using co-prime and nested arrays in the case of missing data. We introduced a signal model where sensor failures occur after taking certain number of snapshots. We proposed to first estimate a covariance matrix with enhanced degrees of freedom using the Toeplitz parameterization, and then apply the MUSIC algorithm to recover the DOAs. We introduced two structured covariance estimators. The first estimator is based on the idea of redundancy averaging, whereas the second is an iterative algorithm derived from the corresponding negative log-likelihood function. We also derived the CRB for our signal model. We used numerical examples show that our method can utilize the information in both complete and incomplete measurements, and achieve better estimation accuracy than the traditional method using only complete measurements [19].

We statistically analyzed the performance of SS-MUSIC in the presences of sensor location errors. We derived a closed-form expression of the asymptotic MSE of SS-MUSIC in the presence of small and deterministic sensor location errors. We gave an extension of our results to the stochastic error model, and analyzed the Gaussian case. We derived the CRB for joint estimation of DOAs and sensor location errors. Our results will benefit future research on the development of robust DOA estimators using sparse linear arrays and the optimal design of sparse linear arrays [20].

We further analyzed the CRB for general non-uniform linear arrays. We established the connection between our CRB and the classical stochastic CRB. By using the fact that co-prime and nested arrays consist of two ULAs, we analytically proved that the CRB of such arrays can decrease at a rate of O(M^{-5}) as the number of sensors, M, goes to infinity. For comparison, the CRB of an M-sensor ULA decreases at a rate of O(M^{-3}) as M goes to infinity. Our results for the first time analytically demonostrate that for a fixed number of sensors, co-prime and nested array can achieve better asymptotic DOA estimation performance with enhanced degrees of freedom than ULAs [21].

PUBLICATIONS

[1] K. Han and A. Nehorai, "Improved source number detection and direction estimation with nested arrays and ULAs using jackknifing, " *IEEE Transactions on Signal Processing*, Vol. 61, pp. 6118-6128, Dec. 2013.

[2] K. Han and A. Nehorai, "Source number detection with nested arrays and ULAs using jackkning," *5th IEEE Intl. Workshop on Comput. Adv. in Multi-Sensor Adapt. Proc.,* Saint Martin, Dec. 15-18, 2013, pp. 57-60 [Invited].

[3] K. Han and A. Nehorai, "Wideband Gaussian source processing using a linear nested array," *IEEE Signal Processing Letters*, Vol. 20, pp. 1110-1113, Nov. 2013.

[4] K. Han and A. Nehorai, "Wideband direction of arrival estimation using nested arrays," *5th IEEE Intl. Workshop on Comput. Adv. in Multi-Sensor Adapt. Proc.*, Saint Martin, Dec. 15-18, 2013, pp. 188-191 [Invited].

[5] K. Han and A. Nehorai, "Nested vector-sensor array processing via tensor modeling," *IEEE Transactions on Signal Processing*, Vol. 62, pp. 2542-2553, May 2014.

[6] K. Han and A. Nehorai, "Direction of arrival estimation using nested vector-sensor arrays via tensor modeling," *Proc. 8th IEEE Sensor Array and Multichannel Signal Processing (SAM) Workshop*, A Coruna, Spain, Jun. 22-25, 2014, pp. 429-432 [Invited].

[7] Z. Tan and A, Nehorai, "Sparse direction of arrival estimation using co-prime arrays with off-grid targets," *IEEE Signal Processing Letters*, Vol. 21, pp. 26-29, Jan. 2014.

[8] Z. Tan, P. Yang and A. Nehorai, "Joint-sparse recovery in compressed sensing with dictionary mismatch," *5th IEEE Intl. Workshop on Comput. Adv. in Multi-Sensor Adapt. Proc.,* Saint Martin, Dec. 15-18, 2013, pp. 248-251.

[9] Z. Tan, P. Yang and A. Nehorai, "Joint-sparse recovery in compressed sensing with dictionary mismatch," *5th IEEE Intl. Workshop on Comput. Adv. in Multi-Sensor Adapt. Proc. (CAMSAP),* Saint Martin, Dec. 15-18, 2013, pp. 468-471 (**Winner (third place) in the best student paper competition**).

[10] Z. Tan, P. Yang and A, Nehorai, "Joint sparse recovery method for compressed sensing with structured dictionary mismatch," *IEEE Transactions on Signal Processing*, Vol. 62, pp. 4997-5008, Oct. 2014.

[11] Z. Tan, Y. Eldar, and A. Nehorai, "Direction of arrival estimation using co-prime arrays: a super resolution viewpoint," *IEEE Transactions on Signal Processing*, Vol. 62, pp. 5565-5576, Nov. 2014.

[12] Z. Tan, Y. Eldar, and A. Nehorai, "Continuous sparse recovery for direction of arrival estimation with co-prime arrays," *Proc. 8th IEEE Sensor Array and Multichannel Signal Processing (SAM) Workshop*, A Coruna, Spain, Jun. 22-25, 2014, pp. 393-396 [Invited] **(Finalist in the best student paper competition)**.

[13] K. Han and A. Nehorai, "Calibrating nested sensor arrays with model errors," *Proc. 48th Asilomar Conf. Signals, Syst. Comput.*, Pacific Grove, CA, 5 pages, Nov. 2-5, 2014, pp. 368-372 **(Finalist and condidate for the best student paper competition)**.

[14] K. Han and A. Nehorai, “Calibrating nested sensor arrays with model errors," *IEEE Transactions on Antennas and Propagation*, Vol. 63, pp. 4739-4748, Nov. 2015.

[15] K. Han and A. Nehorai, “Nested array processing for distributed sources,” *IEEE Signal Processing Letters*, Vol. 21, pp. 1111-1114, Sep. 2014.

[16] K. Han and A. Nehorai, “Distributed source processing with linear nested arrays,” *Proc. 8th IEEE Sensor Array and Multichannel Signal Processing (SAM) Workshop,* A Coruna, Spain, Jun. 22-25, 2014, pp. 521-524 [Invited].

[17] M. Wang and A. Nehorai, “Coarrays, MUSIC, and the Cramér-Rao Bound,” *IEEE Transactions on Signal Processing*, vol. 65, no. 4, pp. 933–946, Feb. 2017.

[18] M. Wang, Z. Zhang, and A. Nehorai, “Performance analysis of coarray-based MUSIC and the Cramér-Rao bound,” *Proc. 42nd IEEE Int. Conf. Acoustics, Speech, Signal Processing (ICASSP)*, New Orleans, LA, Mar. 5-9, 2017, pp. 3061-3065.

[19] M. Wang, Z. Zhang, and A. Nehorai, “Direction finding using sparse linear arrays with missing data,” *Proc. 42nd IEEE Int. Conf. Acoustics, Speech, Signal Processing (ICASSP)*, New Orleans, LA, Mar. 5-9, 2017, pp. 3066-3070.

[20] M. Wang, Z. Zhang, and A. Nehorai, “Performance analysis of coarray-based MUSIC in the presence of sensor location errors,” *IEEE Transactions on Signal Processing*, Vol. 66, No. 12, pp. 3074-3085, June 2018.

[21] M. Wang, Z. Zhang, and A. Nehorai, “Further results on coarrays, MUSIC, and the Cramér-Rao Bound,” submitted.

HONORS/AWARDS/PRIZES

[1] Z. Tan, P. Yang and A. Nehorai, “Joint-sparse recovery in compressed sensing with dictionary mismatch,” *5th IEEE Intl. Workshop on Comput. Adv. in Multi-Sensor Adapt. Proc. (CAMSAP),* Saint Martin, Dec. 15-18, 2013, pp. 468-471 **(Winner (third place) in the best student paper competition**).

[2] Z. Tan, Y. Eldar, and A. Nehorai, “Continuous sparse recovery for direction of arrival estimation with co-prime arrays,” *Proc. 8th IEEE Sensor Array and Multichannel Signal Processing (SAM) Workshop*, A Coruna, Spain, Jun. 22-25, 2014, pp. 393-396 [Invited] **(Finalist in the best student paper competition).**

[3] K. Han and A. Nehorai, “Calibrating nested sensor arrays with model errors," *Proc. 48th Asilomar Conf. Signals, Syst. Comput.*, Pacific Grove, CA, 5 pages, Nov. 2-5, 2014, pp. 368-372 **(Finalist and condidate for the upcoming best student paper competition)**.

REPORT OF INVENTIONS AND SUBCONTRACTS

(Pursuant to "Patent Rights" Contract Clause) (See Instructions on back)

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b. ADDRESS *(Include ZIP Code)*:
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St. Louis, MO 63130-4862
d. AWARD DATE *(YYYYMMDD)*:

2.a. NAME OF GOVERNMENT PRIME CONTRACTOR: Office of Naval Research
c. CONTRACT NUMBER: N00014-13-1-0050
b. ADDRESS *(Include ZIP Code)*:
875 North Randolph Street
Arlington, VA 22203-1995
d. AWARD DATE *(YYYYMMDD)*: 6132013

3. TYPE OF REPORT *(X one)*: ☐ a. INTERIM ☒ b. FINAL

4. REPORTING PERIOD *(YYYYMMDD)*
a. FROM 1012013
b. TO 12312017

SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME(S) OF INVENTOR(S) *(Last, First, Middle Initial)* a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	ELECTION TO FILE PATENT APPLICATIONS (X) d. (1) UNITED STATES (a) YES	(1) UNITED STATES (b) NO	(2) FOREIGN (a) YES	(2) FOREIGN (b) NO	CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER (X) e. (a) YES	(b) NO
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f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR
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g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED
(1) TITLE OF INVENTION
(2) FOREIGN COUNTRIES OF PATENT APPLICATION

SECTION II - SUBCONTRACTS *(Containing a "Patent Rights" clause)*

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a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL *(Last, First, Middle Initial)*: Teri Medley
b. TITLE: Director of Grants
c. SIGNATURE: Tanya Sawyer
Acting for Teri Medley
d. DATE SIGNED: 5/15/18

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REPORT OF INVENTIONS AND SUBCONTRACTS

(Pursuant to "Patent Rights" Contract Clause) (See Instructions on back)

Form Approved
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The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to the Department of Defense, Executive Services Directorate (9000-0095). Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

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1.a. NAME OF CONTRACTOR/SUBCONTRACTOR Washington University	**c. CONTRACT NUMBER** N00014-17-1-2371	**2.a. NAME OF GOVERNMENT PRIME CONTRACTOR** Office of Naval Research	**c. CONTRACT NUMBER** N00014-17-1-2371	**3. TYPE OF REPORT** *(X one)* ☐ a. INTERIM ☒ b. FINAL
b. ADDRESS *(Include ZIP Code)* One Brooking Dr. St. Louis, MO 63130-4862	**d. AWARD DATE** *(YYYYMMDD)*	**b. ADDRESS** *(Include ZIP Code)* 875 North Randolph Street Arlington, VA 22203-1995	**d. AWARD DATE** *(YYYYMMDD)* 4132017	**4. REPORTING PERIOD** *(YYYYMMDD)* a. FROM 5012017 b. TO 3312018

SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME(S) OF INVENTOR(S) *(Last, First, Middle Initial)* a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	ELECTION TO FILE PATENT APPLICATIONS (X) d. (1) UNITED STATES (a) YES	(1) UNITED STATES (b) NO	(2) FOREIGN (a) YES	(2) FOREIGN (b) NO	CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER (X) e. (a) YES	(b) NO
N/A								

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR/SUBCONTRACTOR		**g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED**	
(1) (a) NAME OF INVENTOR *(Last, First, Middle Initial)*	(2) (a) NAME OF INVENTOR *(Last, First, Middle Initial)*	(1) TITLE OF INVENTION	(2) FOREIGN COUNTRIES OF PATENT APPLICATION
(b) NAME OF EMPLOYER	(b) NAME OF EMPLOYER		
(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*	(c) ADDRESS OF EMPLOYER *(Include ZIP Code)*		

SECTION II - SUBCONTRACTS *(Containing a "Patent Rights" clause)*

6. SUBCONTRACTS AWARDED BY CONTRACTOR/SUBCONTRACTOR *(If "None," so state)*

NAME OF SUBCONTRACTOR(S) a.	ADDRESS *(Include ZIP Code)* b.	SUBCONTRACT NUMBER(S) c.	FAR "PATENT RIGHTS" d. (1) CLAUSE NUMBER	(2) DATE *(YYYYMM)*	DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) e.	SUBCONTRACT DATES *(YYYYMMDD)* f. (1) AWARD	(2) ESTIMATED COMPLETION
N/A							

SECTION III - CERTIFICATION

7. CERTIFICATION OF REPORT BY CONTRACTOR/SUBCONTRACTOR *(Not required if: (X as appropriate))* ☐ SMALL BUSINESS or ☒ NONPROFIT ORGANIZATION

I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have been reported.

a. NAME OF AUTHORIZED CONTRACTOR/SUBCONTRACTOR OFFICIAL *(Last, First, Middle Initial)* Teri Medley	**b. TITLE** Director of Grants	**c. SIGNATURE**	**d. DATE SIGNED** 5/15/18

Acting for Teri Medley

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