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# Electromagnetic Remote Sensing of Sources and Scatterers

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This project developed methods to exploit data from active and passive sensors for the surveillance and localization of electromagnetic sources and scatterers. It addressed various Air Force and DoD needs for the development of future radar and sensor systems.
Specific projects included: target detection in wind turbine clutter, time-reversal and resonance enhancement, inclusion of realistic target and antenna models in simulations, extension of theory to moving targets, study of behavior in noise, target shape and motion from bistatic radar measurements, recovery of surface roughness information from SAR data, passive source localization, statistical approaches for detecting a coherent signal at spatially distributed antennas, geometrical understanding of frequency-difference-of-arrival (FDOA) curves and surfaces, and development and comparison of subspace detectors for first- and second-order statistical models.

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# Final Report

Electromagnetic Remote Sensing of Sources and Scatterers

AFOSR Grant FA9550-18-1-0087

February 1, 2018 – January 31, 2021

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## Abstract

This project developed methods to exploit data from active and passive sensors for the surveillance and localization of electromagnetic sources and scatterers. It addresses various Air Force and Department of Defense needs for the development of future radar and sensor systems.

# Chapter 1

# Project description

## 1.1 Objectives

This project developed methods to exploit data from active and passive sensors for the surveillance and localization of electromagnetic sources and scatterers. It addresses various Air Force and Department of Defense needs for the development of future radar and sensor systems.

Specific projects included:

- target detection in wind turbine clutter
- time-reversal and resonance enhancement
  - inclusion of realistic target and antenna models in simulations
  - extension of theory to moving targets
  - study of behavior in noise
- target shape and motion from bistatic radar measurements
- recovery of surface roughness information from SAR data
- passive source localization
  - statistical approaches for detecting a coherent signal at spatially distributed antennas
  - geometrical understanding of frequency-difference-of-arrival curves and surfaces

- development and comparison of subspace detectors for first- and second-order statistical models

## 1.2 Award

Alan Berman Research Publication Award, Naval Research Laboratory, 2018, for "Time-frequency synthetic aperture radar: a technique for adaptive imaging of regions containing weak and intermittent transmitters", J.A. Given and M. Cheney. 35 papers were chosen for this award out of 766 eligible ones.

## 1.3 Personnel supported on this contract

- Faculty:
  - Prof. Margaret Cheney (Principal Investigator). See Publications section below.
  - Prof. Louis Scharf, 2 months. See Publications section below.
  - Prof. Jeanne Duflot, 1 month, summer 2020. See Ongoing Work section below.
- Postdoc: Dr. Julien Chaput. See Ongoing Work section below. Dr. Chaput is now an assistant professor at the University of Texas El Paso.
- Graduate students supported on this contract, all supervised by Cheney
  - Chad Waddington (CSU Ph.D. 2018). He was hired by AFRL/RYMD and is doing very well there.
  - Sam Pine (CSU Ph.D. 2018). He has been hired by Matrix Research and is doing very well there.
  - Liam Coulter, CSU MS 2019. He is now in ECE grad school at the U. of Minnesota and is working for 3M.
  - Naomi Fahrner, CSU, MS, 2019. She is currently working at Ball Aerospace and making good progress on her dissertation on sensor resource allocation.
- Two ECE students, Jack Hall and Chris Robbiano, both supervised by Prof. Mo Azimi, were supported for a few days each to take acoustic data for the source localization problem.

# Chapter 2

# Technical Results

Technical work supported by this grant included the following journal papers, technical reports, conference papers, patent, dissertations, theses, and ongoing analysis.

## 2.1 Publications

### 2.1.1 Journal papers

- "Detection of Backscattered Waves from a Target in Clutter from a Rotating Scatterer", M. Cheney, L. Scharf, P. Pakrooh, A. Homan, M. Ferrara, SIAM J. Appl. Math., 2019, Vol. 79, Issue 5,
  URL: http://epubs.siam.org/toc/smjmap/79/5 ; DOI: 10.1137/19M1240496 .
  This paper includes physics-based modeling of the radar signal backscattered from an aircraft target and a rotating wind turbine at the same range. This physics-based model is combined with a statistical detection technique, and the result is a detector that is able to disentangle the target from the wind turbine clutter.

- "Synthetic Aperture Source Localization", C. Waddington, M. Cheney, J.A. Given, Inverse Problems 36 (2020) 015007 (31pp)
  DOI: 10.1088/1361-6420/ab50ab .
  This paper develops theory for a passive synthetic-aperture souce localization system that is able to form images of the locations of an unknown number of multiple sources in a scene. These sources may even be transmitting the same waveform. The system is assumed to consist of two spatially distributed, temporally synchronized receivers, one of which is moving. This system com-

putes the cross-correlation of the signals recived at the two receivers, and uses a filtered backprojection imaging algorithm to locate the sources. The paper, which is based on Chad Waddington's dissertation, provides resolution for the resulting system. It also shows that provided the moving sensor does not fly directly towards the stationary sensor, the process forms an image that focuses only at the correct emitter locations.

- "Scale-Invariant Subspace Detectors based on First- and Second-Order Statistical Models", I. Santamaria, L.L. Scharf, D. Ramírez, IEEE Transactions on Signal Processing 68 (2020): 6432-6443.
  The problem is to detect a multi-dimensional source transmitting an unknown sequence of complex-valued symbols to a multi-sensor array. In some cases the channel subspace is known, and in others only its dimension is known. Should the unknown transmissions be treated as unknowns in a first-order statistical model, or should they be assigned a prior distribution that is then used to marginalize a first-order model for a second-order statistical model? This question motivates the derivation of subspace detectors for cases where the subspace is known, and for cases where only the dimension of the subspace is known. For three of these four models the Generalized Likelihood Ratio (GLR) detectors are known, and they have been reported in the literature. But the GLR detector for the case of a known subspace and a second-order model for the measurements is derived for the first time in this paper.

  When the subspace is known, second-order GLR tests outperform first-order GLR tests when the spread of subspace eigenvalues is large, while first-order GLR tests outperform second-order GLR tests when the spread is small. When only the dimension of the subspace is known, second-order GLR tests outperform first-order GLR tests, regardless of the spread of signal subspace eigenvalues. For a dimension-1 source, first-order and second-order statistical models lead to equivalent GLR tests. This is a new finding.

### 2.1.2 Journal papers in review or in press

- "Correcting for motion in the time reversal operator", J. Kim, M. Cheney, and E. Mokole, submitted to IEEE Trans. Antennas & Propagation, 2020.
  It is well-known that an iterative time-reversal process can be used to produce a wavefield that focuses transmitted energy onto the strongest scatterer and hence maximizes the scattered energy. However, when scatterers are moving, this process breaks down. This paper shows how to modify the time-reversal

process in order to focus energy on a moving target.

- "Far-field passive source localization", K.J. (Cameron) Pine, S. Pine, M. Cheney, submitted to IEEE Trans. Aerospace & Electronic Systems, January 2021.
  Passive localization of acoustic or radio-frequency sources is often performed using time difference of arrival (TDOA) measurements and/or frequency difference of arrival (FDOA) measurements. TDOA localization has been thoroughly studied, but FDOA less so. This is largely because the TDOA level surfaces are hyperboloids, which are well-understood, whereas the FDOA level curves and surfaces are much more complicated. This paper addresses the case of known sensor positions and velocities and a stationary source. The paper shows examples of the FDOA level curves and surfaces, and shows that they simplify dramatically in the far field, *i.e.*, when the source is much farther from the origin than are the sensors. The far-field behavior is of two types, depending on whether the sensor velocities are equal or unequal. The far-field behavior gives insight into conditions needed for far-field TDOA-FDOA localization and FDOA-only localization. The paper includes a characterization of feasible far-field TDOA and unequal-velocity FDOA data.

### 2.1.3 Technical reports and papers in refereed conference proceedings

- G. Kristensson, M. Cheney, "Resonance Enhancement with Antenna Modeling", Lund University Technical Report LUTEDX/(TEAT-7261)/1-28/(2018); Vol. TEAT-7261. Jerry Kim is "reviewer".
  This technical report incorporated realistic target and antenna models into analysis of the iterative time-reversal process to identify electromagnetic resonance frequencies of a scattering object.

- L. Scharf, L.T. McWhorter, J.A. Given, and M. Cheney, "General First-Order Framework for Passive Detection with Two Sensor Arrays", Proceedings of Asilomar Conference on Signals, Systems, and Computers, 2019
  This is an announcement of work for which the main journal paper is still being written. See description of Ongoing Work below.

### 2.1.4 Patent

- "Technique for focusing waves on moving objects", Jerry Kim and Margaret Cheney, number US20180269982A1 , filed March 5, 2018, issued Feb. 11, 2020.

## 2.2 Theses supervised by Cheney

### 2.2.1 Ph.D. Dissertations

- Chad Waddington, CSU Ph.D. 2018, "Synthetic aperture source localization", now at AFRL/RYMD.
  This dissertation uses cross-correlations of signals from a moving receiver and a fixed one to determine the location of an unknown deterministic source. It uses a synthetic-aperture imaging approach, and includes resolution of the image and also shows that the cross terms focus only at the correct source locations.

- Sam Pine, CSU Ph.D. 2018, "Joint shape and motion estimation from echo-based sensor data", now at Matrix Research.
  This approach involved formulating the problem in terms of a system of polynomial equations. This work may form a foundation for GPS-denied navigation and for synthetic-aperture imaging that does not require precise knowledge of sensor positions.

- Nick Lorenzo, RPI Ph.D. 2019, "Inversion of rough-surface parameters via polarimetric synthetic aperture radar data".
  This dissertation shows how to recoveryof permittivity and surface roughness (RMS height and correlation length) from SAR data. This study focused on the Kirchhoff term of the Integral Equation Method, which is currently the best model for rough surface scattering. This approach allows the permittivity and surface roughness parameters to depend on frequency. The method was tested on publicly available AFRL Gotcha data.

  Nick has accepted a postdoctoral research position at the University of Dayton Research Institute.

- Laura Petto, Dartmouth Ph.D. expected spring 2021, statistical methods in inverse problems. The dissertation includes a study of optimization approaches involving radial basis functions and variance-based joint sparsity, statisical methods for inverse problems inlcuding Markov chain Monte Carlo and kernel density estimator methods, and statistical sampling based on the Stein

Variational Gradient Descent. She has accepted a job at Lincoln Lab in group 037.

- Naomi Fahrner, CSU grad student, hired by Ball Aerospace, currently working on a dissertation on sensor resource allocation. Applications are to optical sensing to support space domain awareness and to synthetic-aperture radar.

- Codie Lewis, CSU grad student, hired by NRL, currently working on dissertation on multiple-hypothesis tracking.

### 2.2.2 M.S. Papers

- Liam Coulter, CSU MS 2019, "Numerical Simulations for Synthetic Aperture Source Localization".

- Naomi Fahrner, CSU MS, 2019, "A MUSIC variant utilizing Hankel tensors and sliding QR windows".

- Saeid Ahmadinia, CSU ECE MS, 2020, "Acoustic Source Localization using Beamforming and Bayesian Updating"

## 2.3 Ongoing work

1. Resonance enhancement. Drs. Jerry Kim, Gerhard Kristensson, Ivars Kirsteins, and I are currently working on a project to study the performance in noise of the iterative time-reversal method for identifying resonances. We are comparing the performance of a time-reversal system to the performance of a system that simply averages many measurements obtained by repeatedly transmitting the same waveform. The time-reversal system is more complicated and expensive than the averaging system, so an understanding of possible advantages and limitations may inform system design.

2. Passive source localization. My colleagues and I are pursuing a number of approaches to passive source localization.

   - Statistical approaches.

     My colleague Prof. Louis Scharf, together with Dr. Todd McWhorter, has developed, from first principles, a method for detecting the presence of a common signal in the data at two different receiver arrays. The signal model allows the two arrays to be of different qualities in the sense of having different and possibly unknown noise levels, allows the sensor positions to be known only approximately, and applies even in the case when the receiver arrays are uncalibrated and do not have synchronized clocks. There are many different cases, corresponding to different model parameters being known or unknown, and different detectors for each case. In each case, the detector depends on how much the signal on one array needs to be time-delayed and Doppler-shifted in order to match with the signal on the other array. The idea is to scan through these possible relative time delays and relative Doppler shifts, compute the value of the detector for each, and choose the maximum value. If the maximum is larger than some pre-assigned threshhold, a common signal is declared to be present, and otherwise it is declared to be absent. When there is clock synchronization, the values of the time delays and Doppler shifts can be used to determine the source position.

This is an important advance for use in opportunistic distributed sensing, where the available sensors may be of very different quality and consequently have very different noise levels. Previous work has assumed that these noise levels are the same.

We are currently incorporating spatial information to create an imaging system.

- Geometry approaches.
  - Karleigh Cameron, a PhD student advised by my colleague Dan Bates, defended her dissertation on the use of frequency-difference-of-arrival (FDOA) measurements to determine the location of an unknown source. Her approach treated the problem in terms of a system of polynomial equations.
  - My colleague Prof. Jeanne Duflot, an expert on algebraic geometry, has been looking at geometrical aspects of FDOA level curves and surfaces. In particular, she has been working to identify the geometric objects that arise and then study this geometry using theoretical methods from algebraic geometry. This work, which involves characterizations of structures in complex projective space, is still ongoing.

3. GPS-based sensing. Former postdoc Dr. Julien Chaput has been collaborating with Dr. Frank Robey (Lincoln Lab) on a project to use GPS signals to do ionospheric sensing.

# Chapter 3

# Synergistic Activities of Cheney

Cheney regularly helps DoD labs and contractors make connections with the academic math community. This includes helping to connect DoD colleagues with potential academic collaborators with appropriate expertise. It also includes urging students to do internships, and matching graduating students with labs and contractors seeking to hire.

## 3.1 Interactions with DoD and government contractors

### 3.1.1 Visits to Government Laboratories and DoD contractors

visits to NUWC, Newport:
Dec. 17-21, 2018; Jan. 14-17, 2019;
ONR Summer Faculty Fellow, Summers 2018 and 2019
ONR Sabbatical, Sept. 2019 - June 2020
visits to NRL: Jan. 7 and 11, 2019; March 18-20, 2019; Nov. 11 and 14-15, 2019;
Jan. 6 and 10, 2020; March 10-13, 2020
visit to Ball Aerospace: Feb. 8, 2019
visits to AFRL and Matrix Research, Dayton: Dec. 10-13, 2018; March 12-16, 2018

Hosted Alan Lovell (AFRL/RV) visit to CSU, Feb. 6-7, 2019

### 3.1.2 Other work with DoD and DoD contractors

Some of Cheney's work with DoD personnel and DoD contractors was not supported by this contract:

- Consulting work with Matrx Research. This project involved development of theory for SAR from multiple transmitters for which the start-stop approximation is not valid.
- Work on underwater acoustic source localization with colleagues at NUWC.
- Work on narrowband imaging with colleague at NRL.

## 3.2 Efforts to bring the math community together with the radar signal-processing community

### 3.2.1 Organization of Conferences and Lecture Series

- 2018: Co-organized minisymposium "Underwater Sensing and Signal Processing", SIAM Computational Science & Engineering meeting, Spokane, Feb. 25 - March 1, 2019.
- 2019-2020: Co-organized special session on radar at SIAM Imaging Sciences conference, held remotely, July 2020

### 3.2.2 Invited Lectures

- Aug. 25, 2018, "Doppler-only imaging", Research and Applications of Photonics in Defense, Miramar Beach, FL.
- May 22, 2018, "Synthetic Aperture Radar Imaging", Summer School on Waves and Particles in Random Media, Colorado State University.
- May 3, 2018, "Radar Imaging", math colloquium, University of Denver.

### 3.2.3 Other conference participation

Participant: review of ONR program Unmanned Maritime Science and Technology: Feb. 28-29, 2020; Jan. 29 - Feb. 1, 2018, Miramar Beach, FL.
Presented talk, "Algebraic Geometry for Source Localization" at:

Acoustical Society of America conference, Dec. 2-6, 2019, San Diego
IEEE Underwater Acoustic Signal Processing, Oct. 16-18, 2019, Rhode Island
Participant: Acoustical Society of America conferences:
Nov. 5-8, 2018, Victoria, BC; May 7-9, 2018, Minneapolis.
Speaker at AFOSR Electromagnetics program reviews: 2019, 2020, 2021
Participant: Joh Tague's ONR program review, August 6-8, 2019

## 3.3 Other professional service

- 2015 - 2018: Scientific Advisory Board for Inverse Problems
- 2006 - present: Member of editorial board for AIMS journal Inverse Problems and Imaging
- 2009 - 2023: SIAM Committee on Science Policy, two meetings per year
- 2015 - 2020: IMA Board of Governors, one meeting per year.