# REPORT DOCUMENTATION PAGE

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| 19-05-2014 | Final Report | 20-Sep-2010 - 19-Feb-2014 |

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Final Report: Dynamic Models of Insurgent Activity

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**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**
611102

**6. AUTHORS**
Andrea L. Bertozzi, P. Jeffrey Brantingham, George Mohler

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAMES AND ADDRESSES**
University of California - Los Angeles
Office of Contract and Grant Administration
11000 Kinross Avenue, Suite 211
Los Angeles, CA 90095 -1406

**8. PERFORMING ORGANIZATION REPORT NUMBER**

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**14. ABSTRACT**
The purpose of this project was to develop the modeling and analysis of both PDE-based and statistical point process models for repeat activity in security applications. The research team has made great strides in applying such ideas to urban domestic crime applications, to the point where models developed in research papers several years ago are now in place in the field in over 30 cities worldwide. This project developed new basic research to extend many of these ideas beyond domestic crime applications to problems abroad involving insurgents and also to other areas of interest to the Army such as email traffic on social networks and to emotional contagion in crowds

**15. SUBJECT TERMS**
insurgents, agent based models, self-exciting point process models, security

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 15. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | Andrea Bertozzi |
| UU | UU | UU | UU | | 19b. TELEPHONE NUMBER 310-825-4340 |

## Report Title

Final Report: Dynamic Models of Insurgent Activity

## ABSTRACT

The purpose of this project was to develop the modeling and analysis of both PDE-based and statistical point process models for repeat activity in security applications. The research team has made great strides in applying such ideas to urban domestic crime applications, to the point where models developed in research papers several years ago are now in place in the field in over 30 cities worldwide. This project developed new basic research to extend many of these ideas beyond domestic crime applications to problems abroad involving insurgents and also to other areas of interest to the Army such as email traffic on social networks and to emotional contagion in crowds. The research project produced 15 journal publications and an additional 4 manuscripts still under review. Published and submitted journal papers included the work of two postdoctoral scholars, six PhD students and three undergraduates, in addition to the PIs.

**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

| Received | | Paper |
|---|---|---|
| 01/24/2012 | 4.00 | George Mohler, Martin Short, P. Jeffrey Brantingham, Frederick Schoenberg, George Tita. Self-Exciting Point Process Modeling of Crime, Journal of the American Statistical Association, (03 2011): 0. doi: 10.1198/jasa.2011.ap09546 |
| 05/18/2014 | 27.00 | Sorathan Chaturapruek, Jonah Breslau, Daniel Yazdi, Theodore Kolokolnikov, Scott G. McCalla. Crime Modeling with Lévy Flights, SIAM Journal on Applied Mathematics, (01 2013): 1703. doi: 10.1137/120895408 |
| 05/18/2014 | 26.00 | Joseph R. Zipkin, Martin B. Short, Andrea L. Bertozzi. Cops on the dots in a mathematical model of urban crime and police response, Discrete and Continuous Dynamical Systems - Series B, (04 2014): 1479. doi: 10.3934/dcdsb. 2014.19.1479 |
| 05/19/2014 | 32.00 | George Mohler. Marked point process hotspot maps for homicide and gun crime prediction in Chicago, International Journal of Forecasting, (07 2014): 491. doi: 10.1016/j.ijforecast.2014.01.004 |
| 05/19/2014 | 28.00 | George Mohler. Modeling and estimation of multi-source clustering in crime and security data, The Annals of Applied Statistics, (09 2013): 1525. doi: 10.1214/13-AOAS647 |
| 05/19/2014 | 29.00 | M. B. Short, G. O. Mohler, P. J. Brantingham, G. E. Tita. Gang rivalry dynamics via coupled point process networks, Discrete and Continuous Dynamical Systems - Series B, (04 2014): 1459. doi: 10.3934/dcdsb. 2014.19.1459 |
| 07/04/2013 | 18.00 | Austin Curtis Alleman. Geographic Profiling Through Six-Dimensional Nonparametric Density Estimation, SIAM Undergraduate Research Online, ( 2012): 0. doi: 10.1137/11S011274 |
| 07/04/2013 | 25.00 | Alethea B.T. Barbaro, Lincoln Chayes, Maria R. D'Orsogna. Territorial developments based on graffiti: A statistical mechanics approach, Physica A: Statistical Mechanics and its Applications, (1 2013): 0. doi: 10.1016/j.physa.2012.08.001 |
| 07/04/2013 | 20.00 | Tijana Kosti?, Andrea Bertozzi. Statistical Density Estimation Using Threshold Dynamics for Geometric Motion, Journal of Scientific Computing, (6 2012): 0. doi: 10.1007/s10915-012-9615-6 |
| 07/04/2013 | 19.00 | Rachel A Hegemann, Erik A Lewis, Andrea L Bertozzi. An "Estimate & Score Algorithm" for simultaneous parameter estimation and reconstruction of incomplete data on social networks, Security Informatics, ( 2013): 0. doi: 10.1186/2190-8532-2-1 |
| 07/10/2012 | 9.00 | Laura Smith, Andrea Bertozzi, P. Jeffrey Brantingham, George Tita, Matthew Valasik. ADAPTATION OF AN ECOLOGICAL TERRITORIAL MODEL TOSTREET GANG SPATIAL PATTERNS IN LOS ANGELES, Discrete and Continuous Dynamical Systems, (09 2012): 3223. doi: |
| 07/10/2012 | 14.00 | Erik Lewis, George Mohler, P. Jeffrey Brantingham, Andrea Bertozzi. Self-exciting point process models of civilian deathsin Iraq, Security Journal, (09 2011): 0. doi: |
| 07/10/2012 | 13.00 | Alexey Stomakhin, Martin Short, Andrea Bertozzi. Reconstruction of missing data in social networks based on temporal patterns of interactions , Inverse Problems, (11 2011): 115013. doi: |

| | | |
|---|---|---|
| 08/16/2011 | 2.00 | Rachel A. Hegemann, Laura M. Smith, Alethea B.T. Barbaro, Andrea L. Bertozzi, Shannon E. Reid, George E. Tita. Geographical influences of an emerging network of gang rivalries, Physica A: Statistical Mechanics and its Applications, (06 2011): 0. doi: 10.1016/j.physa.2011.05.040 |
| 08/16/2011 | 5.00 | M. Short, P. Brantingham, M. D'Orsogna. Cooperation and punishment in an adversarial game: How defectors pave the way to a peaceful society, Physical Review E, (12 2010): 0. doi: 10.1103/PhysRevE.82.066114 |
| **TOTAL:** | **15** | |

**Number of Papers published in peer-reviewed journals:**

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## (b) Papers published in non-peer-reviewed journals (N/A for none)

| Received | Paper |
|---|---|

**TOTAL:**

**Number of Papers published in non peer-reviewed journals:**

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## (c) Presentations

Andrea Bertozzi - last year:

Colloquium, Courant Institute of Mathematical Sciences, Feb. 5, 2013
Invited Talk, Animal Swarms Workshop, Kfar Blum Isreal, Feb. 20, 2013
Mathematics Colloquium, TU Berlin, Germany, Feb. 26, 2013
Colloquium, Mathematics Department, Florida Atlantic University, March 15, 2013
Keynote talk, Math Day (High School Students), Florida Atlantic University, March 16, 2013
T.G. Ostrom Lecture, Washington State University, March 27, 2013
Invited one hour talk, Banff International Research Station, Workshop
on Partial Differential Equations in the Social and Life Sciences, Emergent Challenges in Modeling Analysis, and Computing, April 2, 2013
Public Lecture, University of Alberta, Mathematics of Planet Earth Series, April 5, 2013
Invited talk, Rutgers Statistical Mechanics Meeting, May 13, 2013
Marschak Colloquium, Anderson School UCLA, May 31, 2013
Plenary Talk, Second Pacific Rim Mathematical Association Congress,
June 25, 2013, Shanghai China
Invited Talk, NGA NARP Symposium, Washington DC, Sept 10, 2013
Invited talk, Microsoft Research New England, October 11, 2013
PDE and Applied Mathematics Seminar, UC Davis Department of Mathematics, Oct. 15, 2013
Colloquium, Imperial College London, Dec 9, 2013
Invited talk, Workshop on Complex Systems, Ecole Centrale Paris,
Dec 11, 2013

**Number of Presentations:** 16.00

## Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | Paper |
|---|---|

**TOTAL:**

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | Paper |
|---|---|

**TOTAL:**

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## (d) Manuscripts

| Received | | Paper |
|---|---|---|
| 05/19/2014 | 31.00 | Eric W. Fox, Martin B. Short , Frederic P. Schoenberg, Kathryn D. Coronges,, Andrea L. Bertozzi. Modeling E-mail Networks and Inferring Leadership Using Self-Exciting Point Processes, Journal of the American Statistical Association (09 2013) |
| 05/19/2014 | 33.00 | Andrea L. Bertozzi ┌ Jesus Rosado ┌, Martin B. Short ┌ Li Wang. Contagion shocks in one dimension, Journal of Statistical Physics (01 2014) |
| 05/19/2014 | 30.00 | J. T. Woodworth, G. O. Mohler, A. L. Bertozzi, and P. J. Brantingham. Nonlocal Crime DensityEstimation IncorporatingHousing Information, Philosophical Transactions of the Royal Society - A (03 2014) |
| 07/04/2013 | 17.00 | . MODELING AND ESTIMATION OF MULTI-SOURCE CLUSTERING IN CRIME AND SECURITY DATA, ( ) |
| 07/04/2013 | 24.00 | George Mohler. Marked point process hotspot maps for homicide and gun crime prediction in Chicago, ( ) |
| 07/04/2013 | 23.00 | James H. von Brecht, Scott G. McCalla. Obtaining Nonlinear Stability through Algebraically Decaying Point Spectrum with Applications to Non-local Interaction Equations, ( ) |
| 07/04/2013 | 22.00 | Sorathan Chaturapruek, Jonah Breslau, Daniel Yazdi, Theodore Kolokolnikov, Scott G. McCalla. Crime Modeling with Levy Flights, SIAM Journal of Applied Mathematics (10 2012) |
| 07/04/2013 | 21.00 | Joseph R. Zipkin, Martin B. Short, Andrea L. Bertozzi. COPS ON THE DOTS IN A MATHEMATICAL MODEL OF URBAN CRIME AND POLICE RESPONSE, Discrete and Continuous Dynamical Systems - Series S (04 2013) |
| 07/10/2012 | 10.00 | Tijana Kostic, Andrea Bertozzi. Statistical Density Estimation using Threshold Dynamics forGeometric Motion, Journal of Scientific Computing (12 2011) |
| 07/10/2012 | 11.00 | Rachel Hegemann, Erik Lewis, Andrea Bertozzi. An \Estimate & Score Algorithm" for simultaneous parameter estimation and reconstruction of missing dataon social networks, Security Informatics (02 2012) |
| 07/13/2012 | 16.00 | Alethea Barbaro, Lincoln Chayes, Maria D'Orsogna. Territorial Development based on graffiti: a statistical mechanics approach, Physica A: Statistical Mechanics and its Applications (10 2011) |
| 08/16/2011 | 1.00 | . Reconstruction of Missing Data in Social Networks Based on Temporal Patterns of Interactions, (08 2011) |
| 08/16/2011 | 3.00 | Martin Short, George Mohler, P. Jeffrey Brantingham, George Tita. GANG RIVALRY DYNAMICS VIA COUPLED POINT PROCESS NETWORKS └, (08 2011) |
| 08/16/2011 | 6.00 | George Mohler, Erik Lewis. A Nonparametric EM algorithm for Multiscale HawkesProcesses, (05 2011) |

08/17/2011 7.00 Erik Lewis, George Mohler, P. Jeffrey Brantingham, Andrea L. Bertozzi. SELF-EXCITING POINT PROCESS MODELS OF CIVILIAN DEATHS IN IRAQ,
To appear in Security Journal (08 2011)

**TOTAL:** **15**

**Number of Manuscripts:**

## Books

Received Paper

**TOTAL:**

## Patents Submitted

## Patents Awarded

## Awards

Andrea Bertozzi: honorary degree Doctor of Humane Letters, honoris causa, Claremont Graduate University, May 2014
Beatrice Yormack Lecture, Stanford University, 2013
T. G. Ostrom Lecture, Washington State University, 2013
Fellow of the American Mathematical Society - inaugural class of 2013
Appointed Betsy Wood Knapp Chair for Innovation and Creativity, UCLA 2012

## Graduate Students

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Joseph Zipkin | 0.10 | |
| Eric Fox | 0.20 | |
| **FTE Equivalent:** | **0.30** | |
| **Total Number:** | **2** | |

## Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
|---|---|
| Scott McCalla | 0.30 |
| James von Brecht | 0.30 |
| **FTE Equivalent:** | **0.60** |
| **Total Number:** | **2** |

## Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
|---|---|---|
| Andrea Bertozzi | 0.10 | |
| P. Jeffrey Brantingham | 0.10 | |
| George Mohler | 0.10 | |
| Theodore Kolokolnikov | 0.10 | |
| **FTE Equivalent:** | **0.40** | |
| **Total Number:** | **4** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Sorathan Chaturapruek | 0.00 | Mathematics |
| Jonah Breslau | 0.00 | Mathematics |
| Daniel Yazdi | 0.00 | Mathematics |
| **FTE Equivalent:** | **0.00** | |
| **Total Number:** | **3** | |

## Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ..... 3.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:..... 3.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:..... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):..... 3.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ..... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ..... 2.00

## Names of Personnel receiving masters degrees

| NAME |
|---|
| **Total Number:** |

## Names of personnel receiving PHDs

| NAME |
|---|
| Joseph Zipkin |
| Erik Lewis |
| Laura Smith |
| Rachel Hegemann |
| **Total Number:** 4 |

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
| --- | --- |
| **FTE Equivalent:** | |
| **Total Number:** | |

## Sub Contractors (DD882)

## Inventions (DD882)

## Scientific Progress

see attachment

## Technology Transfer

The purpose of this project was to develop the modeling and analysis of both PDE-based and statistical point process models for repeat activity in security applications. The research team has made great strides in applying such ideas to urban domestic crime applications, to the point where models developed in research papers several years ago are now in place in the field in over 30 cities worldwide. This project developed new basic research to extend many of these ideas beyond domestic crime applications to problems abroad involving insurgents and also to other areas of interest to the Army such as email traffic on social networks and to emotional contagion in crowds. The research project produced 15 journal publications and an additional 4 manuscripts still under review. Published and submitted journal papers included the work of two postdoctoral scholars, six PhD students and three undergraduates, in addition to the PIs. For conciseness we report on those manuscripts that were published or submitted in the last year of the project. Additional manuscripts and publications are listed for this award.

**Point process models:**

Crime hotspot maps are a widely used and successful method of displaying spatial crime patterns and allocating police resources. However, hotspot maps are often created over a single timescale using only one crime type. In the case of short-term hotspot maps that utilize several weeks of crime data, risk estimates suffer from a high variance, especially for low frequency crimes such as homicide. Long-term hotspot maps that utilize several years of data fail to take into account near-repeat effects and emerging hotspot trends. We show how point process models of crime can be extended to include leading indicator crime types, while capturing both short-term and long-term patterns of risk, through a marked point process approach. Several years of data and many different crime types are systematically combined to yield accurate hotspot maps that can be used for the purpose of predictive policing of gun-related crime. We apply the methodology to a large, open source data set which has been made available to the general public online by the Chicago Police Department. This work was published in the *International Journal of Forecasting.*

We introduce a point process model for inter-gang violence driven by retaliation, a core feature of gang behavior, and multi-party inhibition. Here, a coupled system of state-dependent jump stochastic differential equations is used to model the conditional intensities of the directed network of gang rivalries. The system admits an exact simulation strategy based upon Poisson thinning. The model produces a wide variety of transient or stationary weighted network configurations and we investigate under what conditions each type of network forms in the continuum limit. We then fit the model to gang violence data provided by the Hollenbeck district of the Los Angeles Police Department to measure the levels of excitation and inhibition present in gang violence dynamics, as well as the stability of gang rivalries in Hollenbeck. This work was published in *Discrete and Continuous Dynamical Systems.*

While the presence of clustering in crime and security event data is well established, the mechanisms by which clustering arises is not fully understood. Both contagion models and history independent correlation models are applied, but not simultaneously. In an

attempt to disentagle contagion from other types of correlation, we consider a Hawkes process with background rate driven by a log Gaussian Cox process. Our inference methodology is an efficient Metropolis adjusted Langevin algorithm for filtering of the intensity and estimation of the model parameters. We apply the methodology to property and violent crime data from Chicago, terrorist attach data from Northern Ireland and Israel, and civilian casualty data from Iraq. For each data set we quantify the uncertainty in the levels of contagion vs. history independent correlation. This work was published in the *Annals of Applied Statistics.*

Of interest to ARO is the analysis of patterns in e-mail traffic. Our former program manager suggested we study the IKENET dataset from West Point. Using an EM-type approach, we fit Hawkes process models to both the IKENET and the Enron e-mail datasets. We show that the self-exciting models adequately capture major temporal clustering features in the data and perform better than traditional stationary Poisson models. We also investigate how accounting for diurnal and weekly trends in e-mail activity improves the overall fit to the observed network data. A motivation and application for fitting these self-exciting models is to use parameter estimates to characterize important e-mail communication behaviors such as the baseline sending rates, average reply rates, and average response times. A primary goal is to use these features, estimated from the self-exciting models, to infer the underlying leadership status of users in the West Point and Enron networks. This work is under review at J. Amer. Stat. Assoc.

**Agent based and PDE models (contagion, Levy flights, and optimal control):**

We consider an agent-based model of emotional contagion coupled with motion in one dimension that has recently been studied in the computer science community. The model involves movement with a speed proportional to a “fear" variable that undergoes a temporal consensus averaging based on distance to other agents. We study the effect of Riemann initial data for this problem, leading to shock dynamics that are studied both within the agent-based model as well as in a continuum limit. We examine the behavior of the model under distinguished limits as the characteristic contagion interaction distance and the interaction timescale both approach zero. The limiting behavior is related to a classical model for pressureless gas dynamics with “sticky" particles. In comparison, we observe a threshold for the interaction distance vs. interaction timescale that produce qualitatively different behavior for the system - in one case particle paths do not cross and there is a natural Eulerian limit involving nonlocal interactions and in the other case particle paths can cross and one may consider only a kinetic model in the continuum limit. This work has been accepted for publication in the *Journal of Statistical Physics.*

In earlier work we published a burglary hotspot model [M. B. Short, M. R. D’Orsogna, V. B. Pasour, G. E. Tita, P. J. Brantingham, A. L. Bertozzi, and L. B. Chayes, *Math. Models Methods Appl. Sci.*, 18 (2008), pp. 1249–1267]for the formation of hotspots of criminal activity. In new work, we extend the earlier model to incorporate a more realistic model of human locomotion. The movement of the criminal agents follows a biased Levy

flight with step sizes distributed according to a power-law distribution. The biased Brownian motion of the original model is then derived as a special case. Starting with an agent-based model, we derive its continuum limit. This consists of two equations and involves the fractional Laplacian operator. A numerical method based on the fast Fourier transform is used to simulate the continuum model; these simulations compare favorably with the direct numerical simulations of the agent-based model. A Turing-type analysis is performed to estimate how the instability of the homogeneous steady state, as well as the expected number of hotspots, depends on the system parameters and especially the exponent of the underlying power law. The assumptions of the underlying agent-based model naturally lead to a separation of scales of the diffusion coefficients in the continuum limit. Using these assumptions, we asymptotically construct the leading-order profile of the localized hotspot of criminal activity. This work was published in the *SIAM J. of Applied Math* and involved three undergraduate researchers as part of the project.

In the M3AS paper cited above (2008), the work used a static or otherwise suboptimal police response to crime hotspots. In new work, we introduce a program of police response to hotspots of crime in which the police adapt dynamically to changing crime patterns. In particular, we choose their deployment to solve an optimal control problem at every time. This gives rise to a free boundary problem for the police deployment's spatial support. We present an efficient algorithm for solving this problem numerically and show that police presence can prompt surprising interactions among adjacent hotspots. This work was published in *Discrete and Continuous Dynamical Systems*.

**Density Estimation Problem**

This work brings ideas from nonlocal means image processing to bear on the problem of statistical density estimation as applied to spatial mapping. Given a discrete sample of event locations, we wish to produce a probability density that models the relative probability of events occurring in a spatial domain. Standard density estimation techniques do not incorporate priors informed by spatial data. Such methods can result in assigning significant positive probability to locations where events cannot realistically occur. In particular, when modeling residential burglaries, standard density estimation can predict residential burglaries occurring where there are no residences. Incorporating the spatial data can inform the valid region for the density. When modeling very few events, additional priors can help to correctly fill in the gaps. Learning and enforcing correlation between spatial data and event data can yield better estimates from fewer events. We propose a nonlocal version of Maximum Penalized Likelihood Estimation based on the H1 Sobolev seminorm regularizer that computes nonlocal weights from spatial data to obtain more spatially accurate density estimates.We evaluate this method in application to a residential burglary data set from San Fernando Valley with the nonlocal weights informed by housing data or a satellite image. This work involved all three PIs and UCLA PhD student Joseph Woodworth. This work was submitted to Philosophical Transactions of the Royal Society A.