



NAVAL
POSTGRADUATE
SCHOOL

Optimizing a System of Threshold-based Sensors with Application to Biosurveillance

Ronald D. Fricker, Jr.

Third Annual Quantitative Methods in
Defense and National Security Conference

May 28, 2008

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the 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 this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 28 MAR 2008		2. REPORT TYPE		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE Optimizing a System of Threshold-based Sensors with Application to Biosurveillance				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School, Monterey, CA, 93943				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Presented at the Third Annual Quantitative Methods in Defense and National Security Conference, 28 May 2008, Durham, NC					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 22	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

What is Biosurveillance?

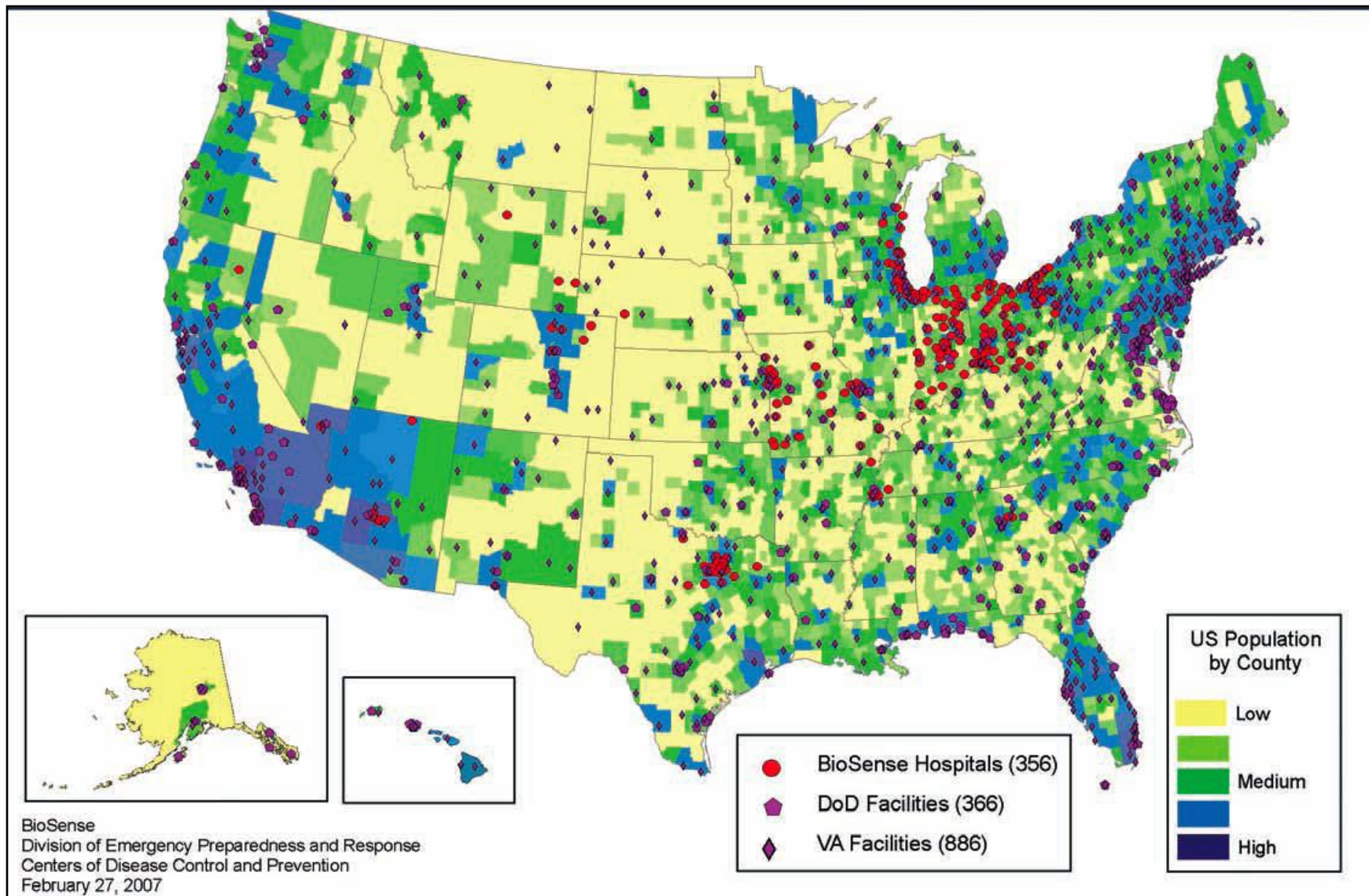
- Homeland Security Presidential Directive HSPD-21 (October 18, 2007):
 - “The term ‘biosurveillance’ means the process of active data-gathering ... of biosphere data ... in order to achieve early warning of health threats, early detection of health events, and overall situational awareness of disease activity.” ^[1]
 - “The Secretary of Health and Human Services shall establish an operational national epidemiologic surveillance system for human health...” ^[1]
- Epidemiologic surveillance:
 - “...surveillance using health-related data that precede diagnosis and signal a sufficient probability of a case or an outbreak to warrant further public health response.” ^[2]

[1] www.whitehouse.gov/news/releases/2007/10/20071018-10.html

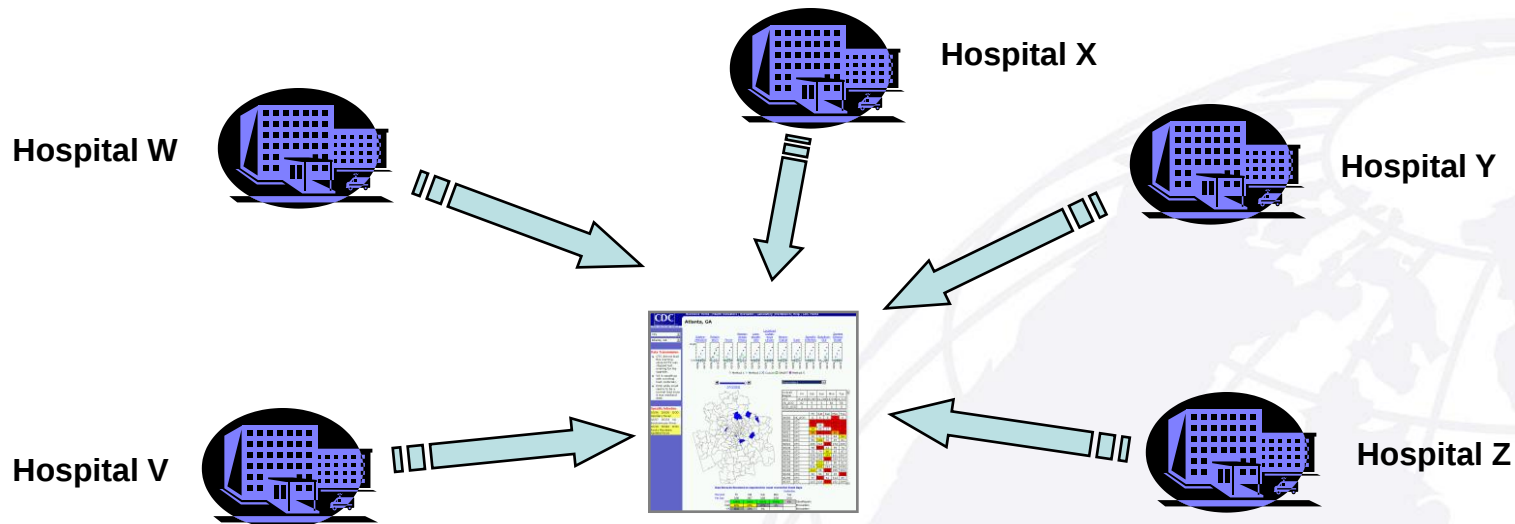
[2] CDC (www.cdc.gov/eпо/dphsi/syndromic.htm, accessed 5/29/07)



An Existing System: BioSense



Think of It Like a Large System of Sensors



- Issue: False alarms a serious problem
 - “...most health monitors... learned to ignore alarms triggered by their system. This is due to the excessive false alarm rate that is typical of most systems - there is nearly an alarm every day!” [1]

[1] <https://wiki.cirg.washington.edu/pub/bin/view/Isds/SurveillanceSystemsInPractice>

The Problem in Summary

- Goal: Early detection of disease outbreak and/or bioterrorism
- Issue: Currently detection thresholds set naively
 - Equally for all sensors
 - Ignores differential probability of attack
- Result:
 - High false alarm rates
 - Loss of credibility



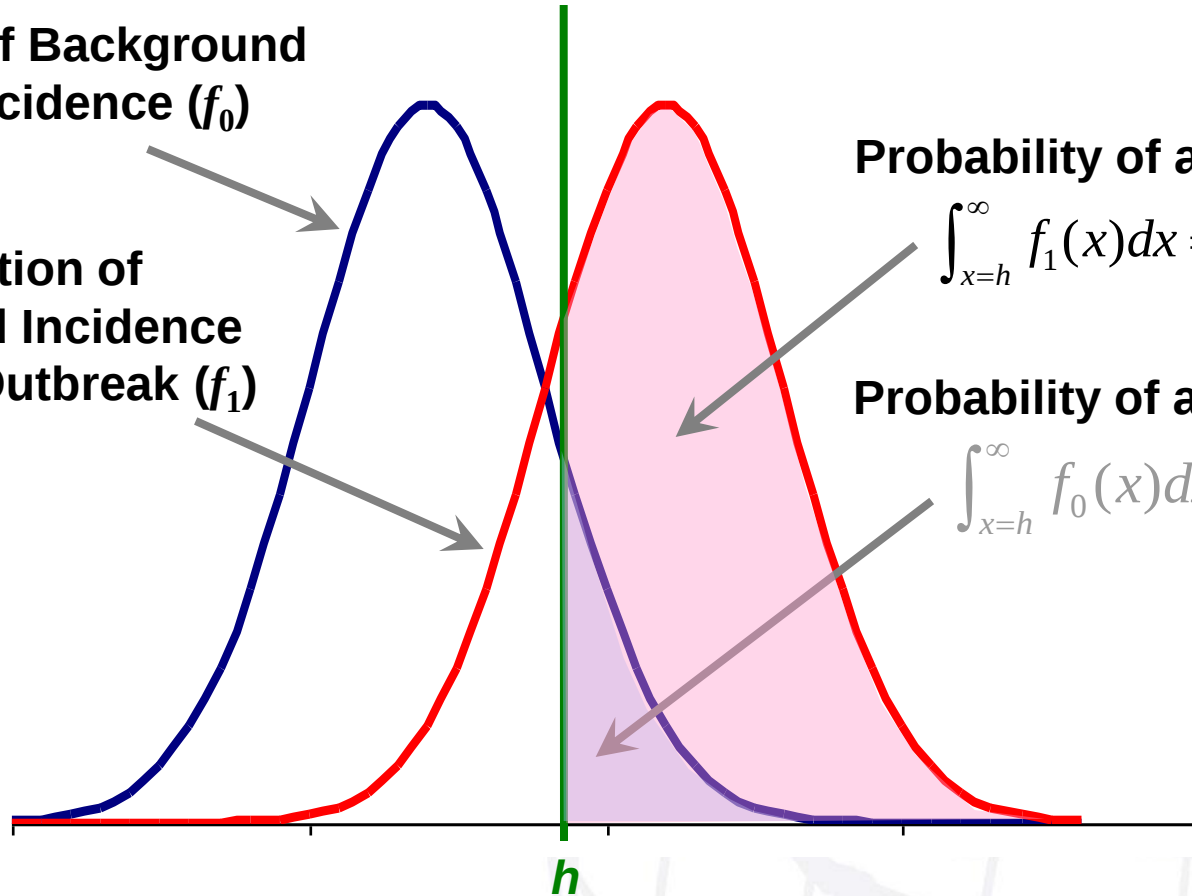
Formal Description of the System

- Let X_{it} denote the output from sensor i at time t , $i=1,\dots,n$, $t=1,2,\dots$
 - Each sensor / location has a probability of outbreak / attack: $p_1,\dots,p_n$, $\sum_i p_i = 1$
 - If no “event of interest” anywhere in the network, $X_{it} \sim F_0$ for all i and t
 - If an event of interest occurs at time τ , $X_{i\tau} \sim F_1$ for exactly one i
- A signal is generated at time τ^* when $X_{i\tau^*} \geq h_i$ for one or more i

Idea of Threshold Detection

Distribution of Background
Disease Incidence (f_0)

Distribution of
Background Incidence
and Attack/Outbreak (f_1)



Probability of a true signal:

$$\int_{x=h}^{\infty} f_1(x) dx = 1 - F_1(h)$$

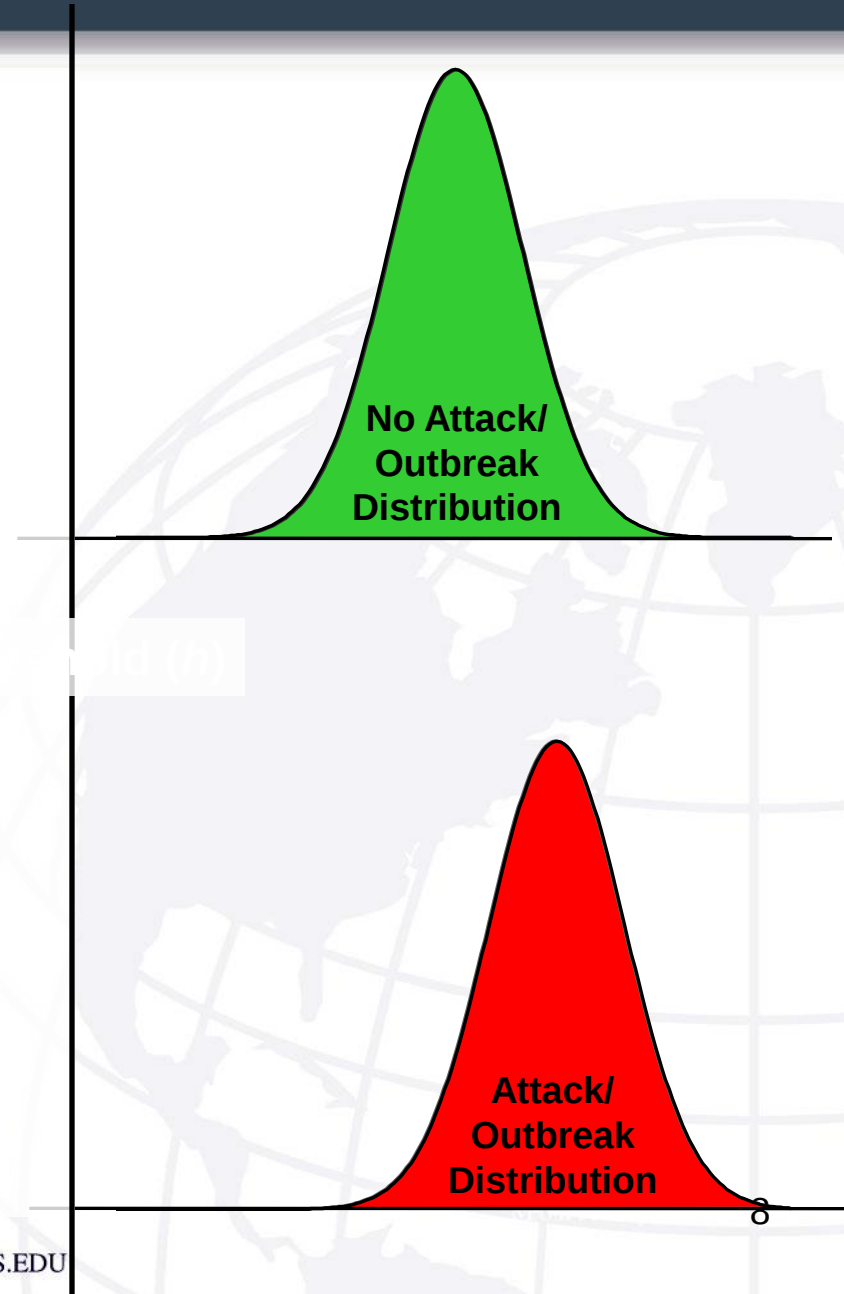
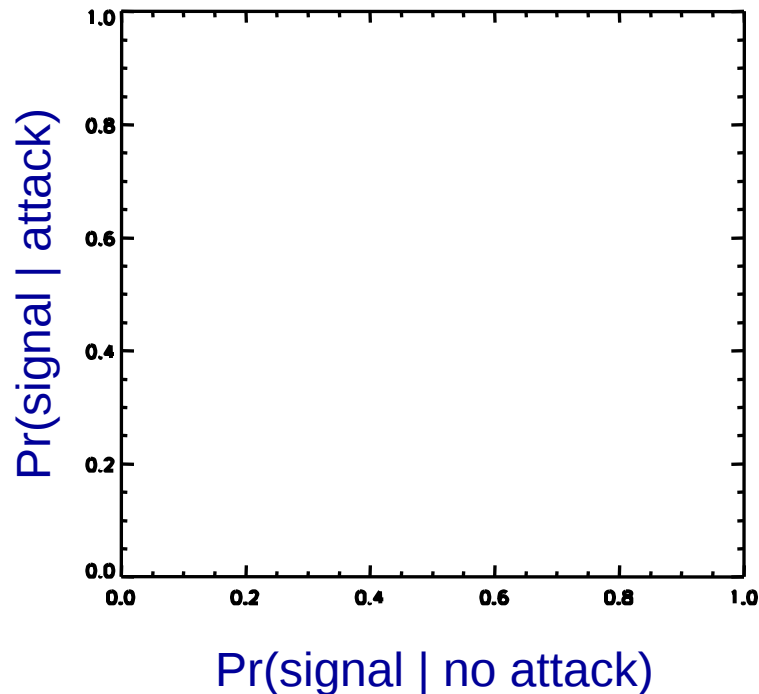
Probability of a false signal:

$$\int_{x=h}^{\infty} f_0(x) dx = 1 - F_0(h)$$

It's All About Choosing Thresholds

- For each sensor, choice of h is compromise between probability of true and false signals

ROC Curve



- It's simple to write out:

$$\Pr(\text{detection}) = \sum_i \Pr(\text{signal}|\text{attack}) \Pr(\text{attack})$$

$$E(\# \text{ false signals}) = \sum_i \Pr(\text{signal}|\text{no attack})$$

- Express it as an NLP optimization problem:

$$\begin{aligned} \max_{\vec{h}} \quad & \sum_i [1 - F_1(h_i)] p_i \\ \text{s.t.} \quad & \sum_i [1 - F_0(h_i)] \leq \kappa \end{aligned}$$

- Sensors are spatially independent
- Monitoring standardized residuals from an “adaptive regression” model
 - Model accounts for (and removes) systematic effects in the data
 - Result: Reasonable to assume $F_0 = N(0,1)$
- An attack will result in a 2-sigma increase in the mean of the residuals
 - Result: $F_1 = N(2,1)$
- Then, NLP is:
$$\min_{\vec{h}} \sum_i \Phi(h_i - 2)p_i$$
$$\text{s.t. } \sum_i \Phi(h_i) > n - \kappa$$

Ten Sensor Example

Sensor i	p_i	Common Threshold #1	Optimal Threshold (h_i)	Common Threshold #2
1	0.797	2.189	1.068	1.310
2	0.064	2.189	3.602	1.310
3	0.056	2.189	3.732	1.310
4	0.048	2.189	3.915	1.310
5	0.013	2.189	4.656	1.310
6	0.006	2.189	4.736	1.310
7	0.006	2.189	4.736	1.310
8	0.005	2.189	4.755	1.310
9	0.003	2.189	4.773	1.310
10	0.002	2.189	4.791	1.310
	P_d	0.117	0.378	0.378
	$\sum \alpha_i$	0.143	0.143	0.951



Simplifying to a One-dimensional Optimization Problem

- System of n hospitals (sensors) means optimization has n free parameters
 - Hard for to solve for large systems
- Can simplify to one-parameter problem:
 - *Theorem:* For $F_0=N(0,1)$ and $F_1=N(\gamma,1)$, the optimization simplifies to finding μ to satisfy

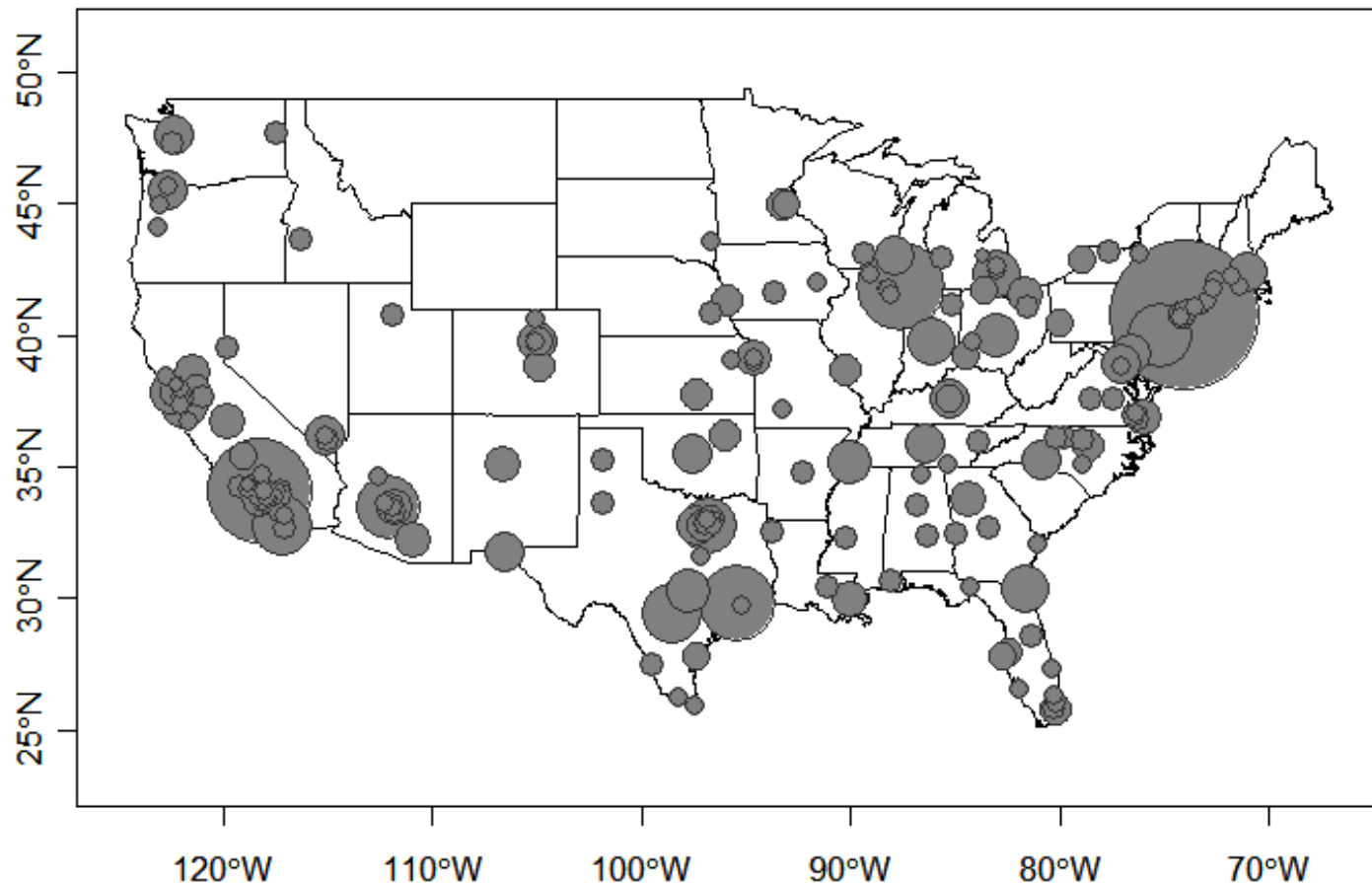
$$\sum_{i=1}^n \Phi \left(\mu - \frac{1}{\gamma} \ln(p_i) \right) = n - \kappa,$$

and the optimal thresholds are then

$$h_i = \mu - \frac{1}{\gamma} \ln(p_i).$$

Consider (Hypothetical) System to Monitor 200 Largest Cities in US

- Assume probability of attack is proportional to the population in a city: $p_i = m_i / \sum_i m_i$



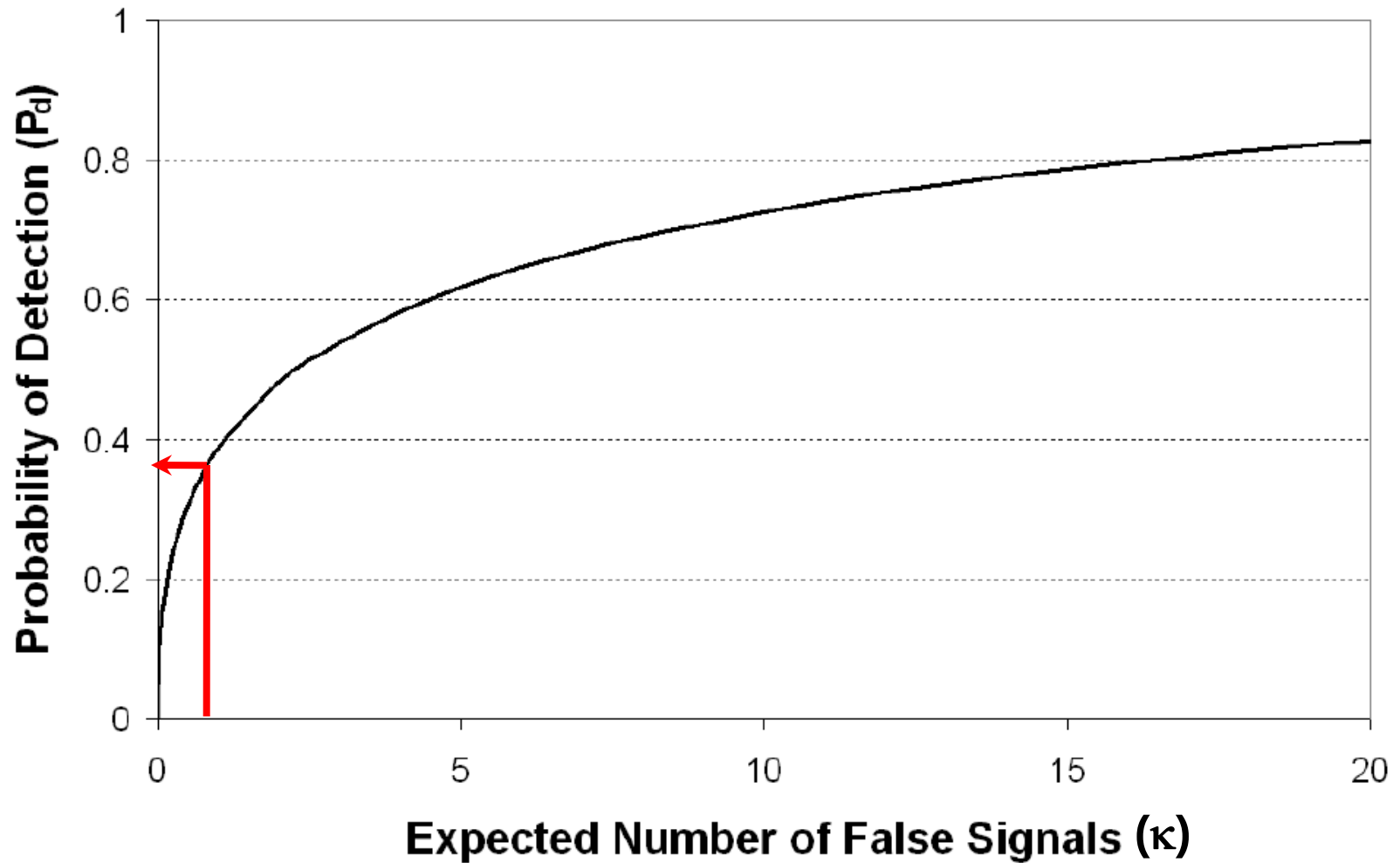
Optimal Solution for 200 Cities

- Assume
 - 2σ magnitude event
 - Constraint of 1 false signal system-wide / day

				Population	Pr(attack)	Threshold	Pr(signal attack)	Pr(signal no attack)
7	i	City	State	m_i	$p_i = m_i/M$	h_i	$1 - \Phi(h_i - \delta)$	$1 - \Phi(h_i)$
8	1	New York city	New York	8,214,426	0.1101	1.07	0.825	0.143
9	2	Los Angeles	California	3,849,378	0.0516	1.45	0.710	0.074
10	3	Chicago	Illinois	2,833,321	0.0380	1.60	0.656	0.055
11	4	Houston	Texas	2,144,491	0.0287	1.74	0.603	0.041
12	5	Phoenix	Arizona	1,512,986	0.0203	1.91	0.535	0.028
13	6	Philadelphia	Pennsylvania	1,448,394	0.0194	1.93	0.526	0.027
14	7	San Antonio	Texas	1,296,682	0.0174	1.99	0.504	0.023
15	8	San Diego	California	1,256,951	0.0168	2.01	0.498	0.022
16	9	Dallas	Texas	1,232,940	0.0165	2.01	0.494	0.022
17	10	San Jose	California	929,936	0.0125	2.16	0.438	0.016

- Result: $\Pr(\text{signal} \mid \text{attack}) = 0.388$
- Naïve result: $\Pr(\text{signal} \mid \text{attack}) = 0.283$

P_d – False Alarm Trade-Off



- Optimal probability of detection for various choices of γ and κ

$\mathbf{P}_d$	$\kappa = 1$	$\kappa = 2$	$\kappa = 3$	$\kappa = 4$	$\kappa = 5$
$\gamma = 1$	0.165	0.228	0.272	0.307	0.336
$\gamma = 2$	0.388	0.481	0.540	0.583	0.618
$\gamma = 3$	0.726	0.801	0.840	0.866	0.885
$\gamma = 4$	0.939	0.964	0.974	0.980	0.984

- Choice of κ depends on available resources
- Setting γ is subjective: what size mean increase important to detect?

- Optimal probability of detection

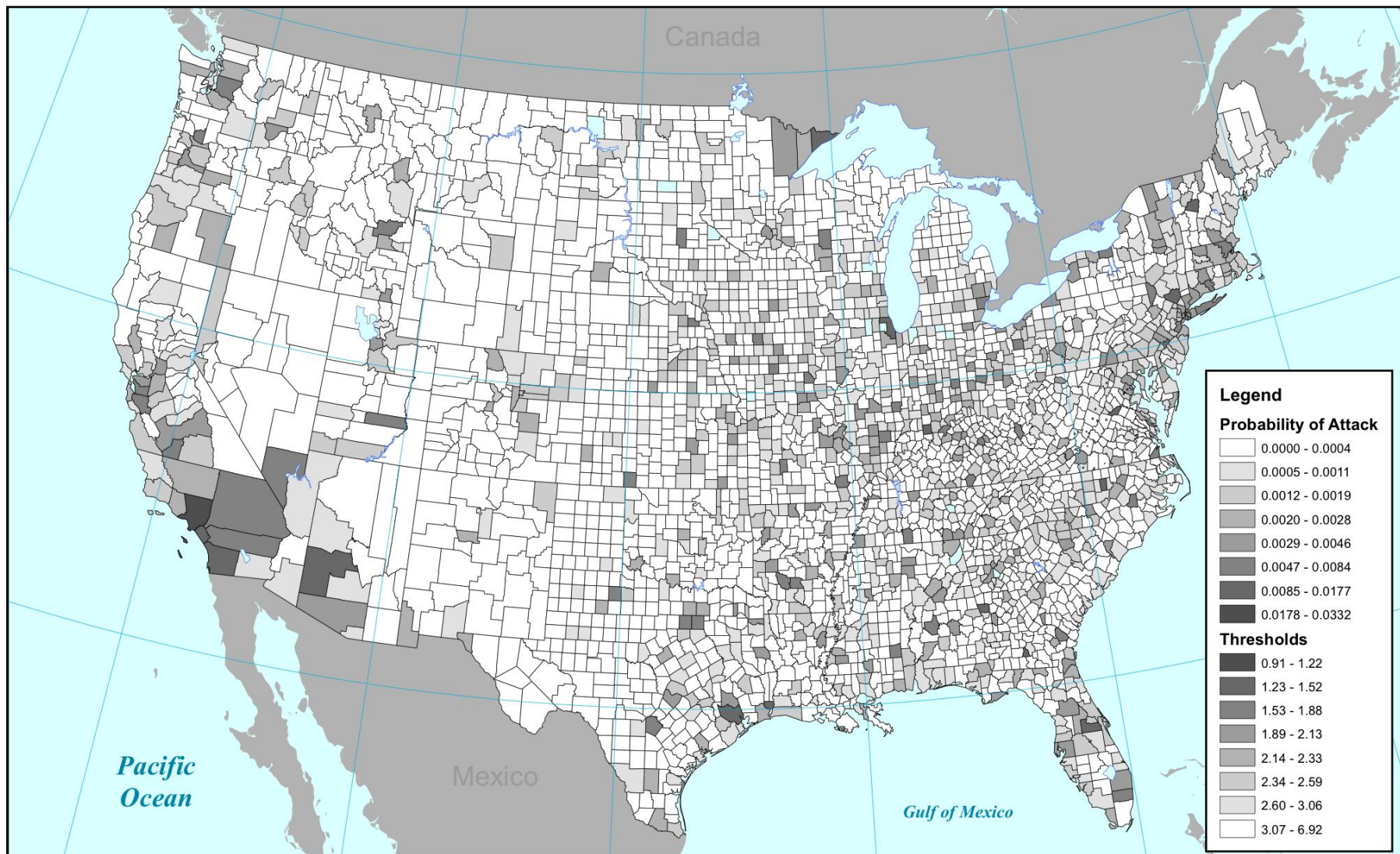
P_d	$\kappa = 1$	$\kappa = 2$	$\kappa = 3$	$\kappa = 4$	$\kappa = 5$
$\gamma = 1$	0.165	0.228	0.272	0.307	0.336
$\gamma = 2$	0.388	0.481	0.540	0.583	0.618
$\gamma = 3$	0.726	0.801	0.840	0.866	0.885
$\gamma = 4$	0.939	0.964	0.974	0.980	0.984

- Actual probability of detection

P_d	$\kappa = 1$	$\kappa = 2$	$\kappa = 3$	$\kappa = 4$	$\kappa = 5$
Observed $\gamma = 1$	0.137	0.193	0.235	0.269	0.298
Observed $\gamma = 2$	0.388	0.481	0.540	0.583	0.618
Observed $\gamma = 3$	0.711	0.790	0.832	0.859	0.879
Observed $\gamma = 4$	0.925	0.955	0.968	0.976	0.981

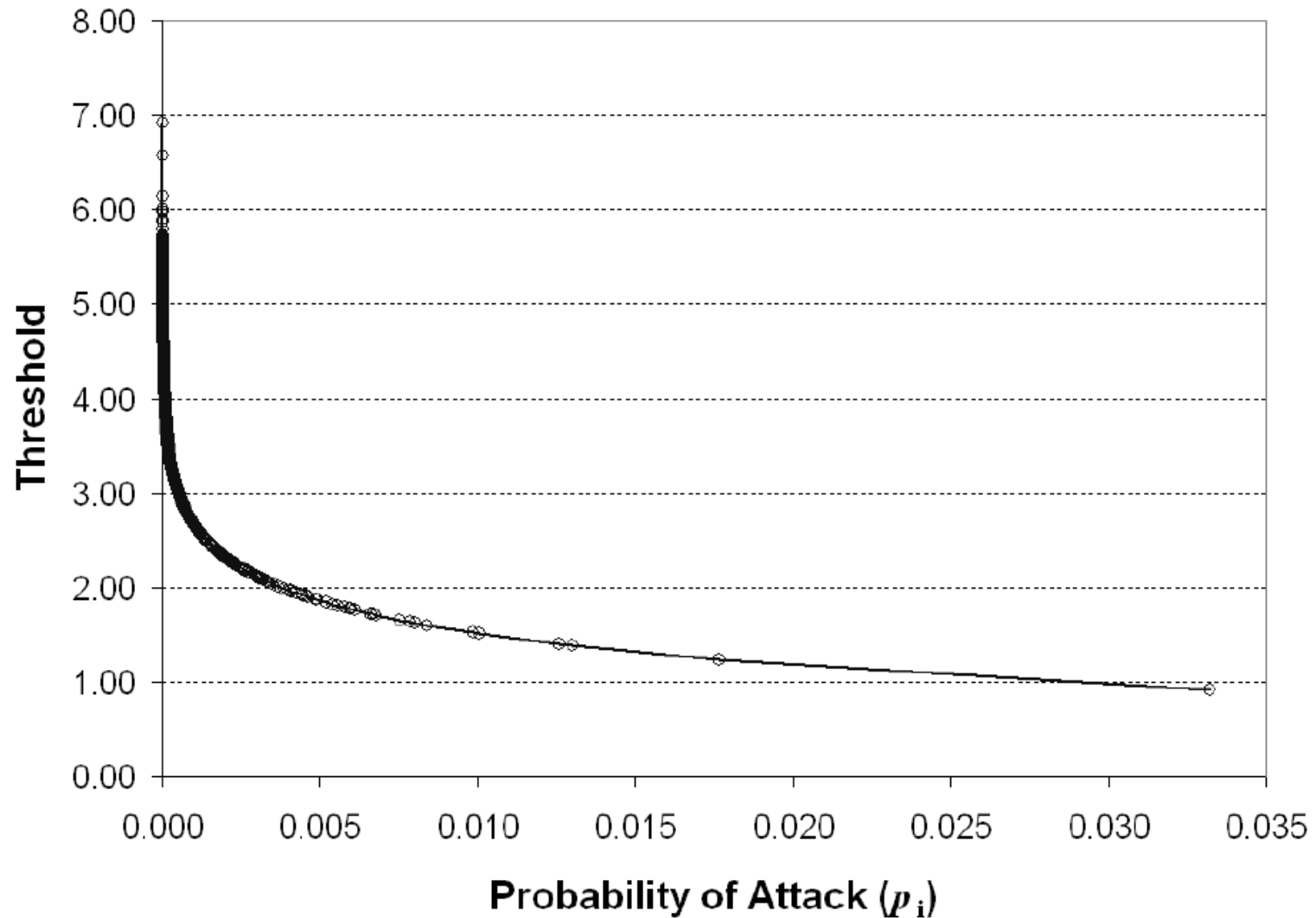


Optimizing a County-level System





Thresholds as a Function of Probability of Attack





- BioSense and other biosurveillance systems' performance can be improved now at no cost
- Approach allows for customization
 - E.g., increase in probability of detection at individual location or add additional constraint to minimize false signals
- Applies to other sensor system applications:
 - Port surveillance, radiation/chem detection systems, etc.
- Details in Fricker and Banschbach (2007)



- Assess data fusion techniques for use when multiple sensors in each region
 - I.e., relax sensor (spatial) independence assumption
- Generalize from threshold detection methods to other methods that use historical information
 - I.e., relax temporal independence assumption



Background Information:

- Fricker, R.D., Jr., and H. Rolka, Protecting Against Biological Terrorism: Statistical Issues in Electronic Biosurveillance, *Chance*, **91**, pp. 4-13, 2006
- Fricker, R.D., Jr., Syndromic Surveillance, *Encyclopedia of Quantitative Risk Assessment* (to appear).

Selected Research:

- Fricker, R.D., Jr., and D. Banschbach, Optimizing a System of Threshold Detection Sensors, in submission to *Operations Research*.
- Fricker, R.D., Jr., and J.T. Chang, A Spatio-temporal Method for Real-time Biosurveillance, *Quality Engineering*, (to appear).
- Fricker, R.D., Jr., Knitt, M.C., and C.X. Hu, Comparing Directionally Sensitive MCUSUM and MEWMA Procedures with Application to Biosurveillance, *Quality Engineering* (to appear).
- Jones, M.D., Jr., Woodall, W.H., Reynolds, M.R., Jr., and R.D. Fricker, Jr., A One-Sided MEWMA Chart for Health Surveillance, *Quality and Reliability Engineering International* (to appear).
- Fricker, R.D., Jr., Hegler, B.L., and D.A. Dunfee, Assessing the Performance of the Early Aberration Reporting System (EARS) Syndromic Surveillance Algorithms, *Statistics in Medicine*, 2008.
- Fricker, R.D., Jr., Directionally Sensitive Multivariate Statistical Process Control Methods with Application to Syndromic Surveillance, *Advances in Disease Surveillance*, **3**:1, 2007.