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Statistical Framework for Assessing Trace Detection Methods for Air Cargo

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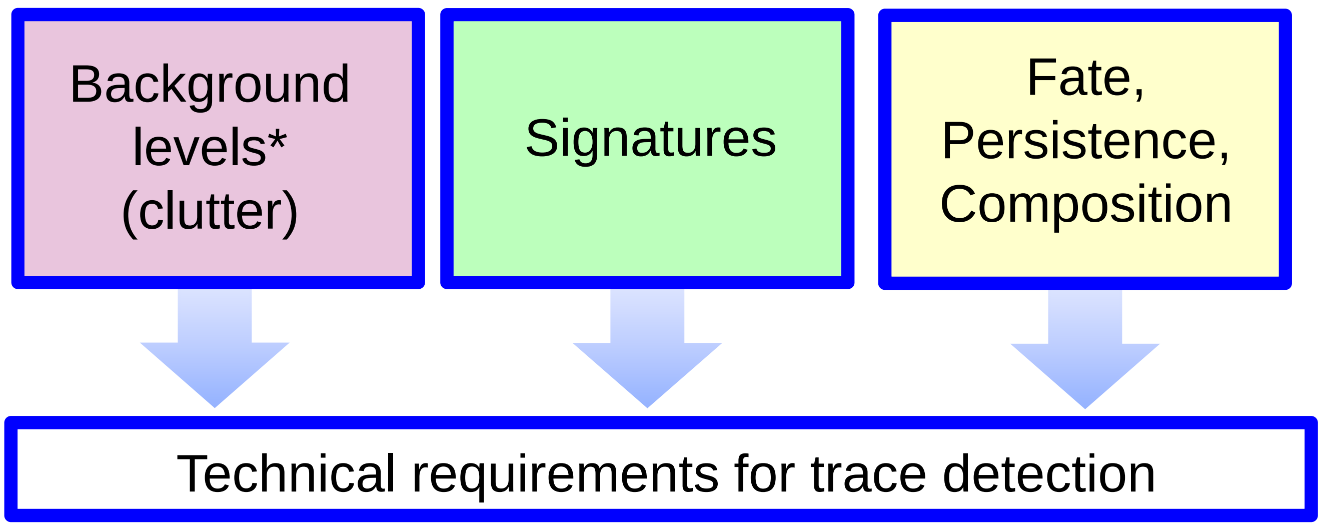
So What…Who Cares?

- Inform requirements for explosive trace detectors for cargo screening
- Estimate capabilities for specific ETD missions ***before*** technology investment decisions are made
  – Assess impact of background ETD false alarm and detection rates
- Developed a general framework to calculate idealized sensor-agnostic ROC curves for background limited scenarios
  – Based on measurements of background and threat signatures in air cargo
- Identify new CONOPs and detection strategies (correlations, etc.)
  – Instruments and algorithms that can simultaneously detect nitrate and ammonium will provide superior false alarm performance
- Current and future work focuses on measuring signatures associated with additional threats in air cargo scenarios

Phenomenology Overview

Measurements essential to determine if chemical sensing capabilities will be limited by the signature phenomenology



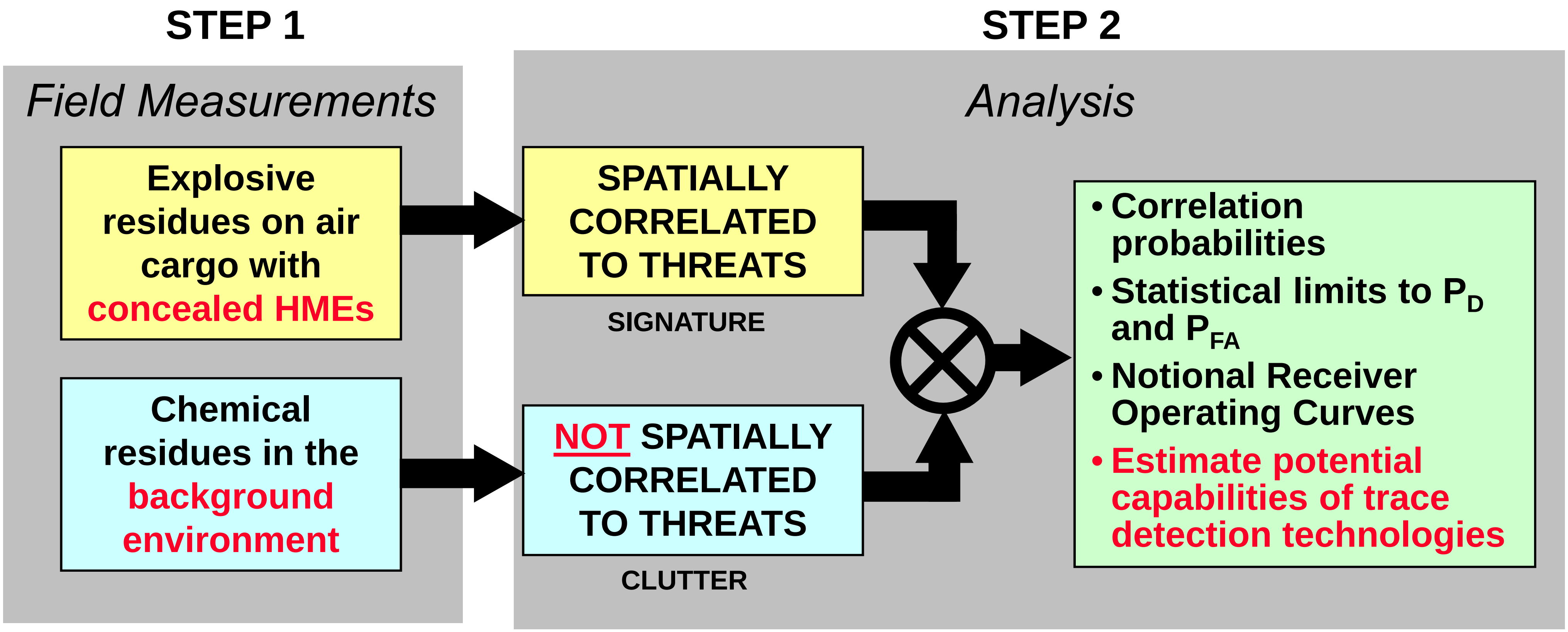
Goal: ***Project the efficacy of ETD approaches for ensuring air cargo safety***

Components of the "Signature"

SIGNATURE ATTRIBUTE	IMPACT	COMMENT
Abundance / Concentration	P_D	Absolute Amount of Signature Chemical Present
Form / Geometric Fill		Optical Coupling Efficiency
Fate, Persistence and Composition		Length of Time Signature Available Spectral Signature / Algorithm
Clutter	P_{FA}	Statistics of Backgrounds and Signature
All Listed Above	ROC Curve	Upper Limit on Projected Performance

Signature attributes directly impact P_D and P_{FA} rates of ETD technologies for detection

Approach



Use a two-step approach to project the efficacy of explosives trace detection for nitrate- and chlorate-based threats concealed in air cargo

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Outline

- Introduction
- Program Overview
  - Measurement Campaigns
- Results
  - Distributions
  - Correlations
  - Probability of False Alarm
- Method for Calculating ROC curves
- Conclusions

Program Overview

- **Objective:**
  - **Identify the potential performance capabilities ETD in air cargo terminals**

- **Program Elements:**
  - **Field measurements of background levels of AN and PC at air cargo facilities**
  - **Field measurements of threat levels associated with AN and PC based devices**
  - **Statistical data analysis to project operational impact of backgrounds**

- **Other Related Activities at MITLL :**
  - **Fate and persistence studies**
  - **Ionization reagent studies to broaden ETD system capabilities**

Analysis is technology independent, but mission specific

Measurement Environment

- **Background surface concentrations of ammonium, nitrate, potassium and chlorate determined via surface swipes of taken at designated air cargo terminals (1254 measurements, 4 seasons)**

→ P_{FA}

- **Threat signature measurements determined from multiple threat building exercises**

→ P_D

Notional ROC curve determined from signature measurements

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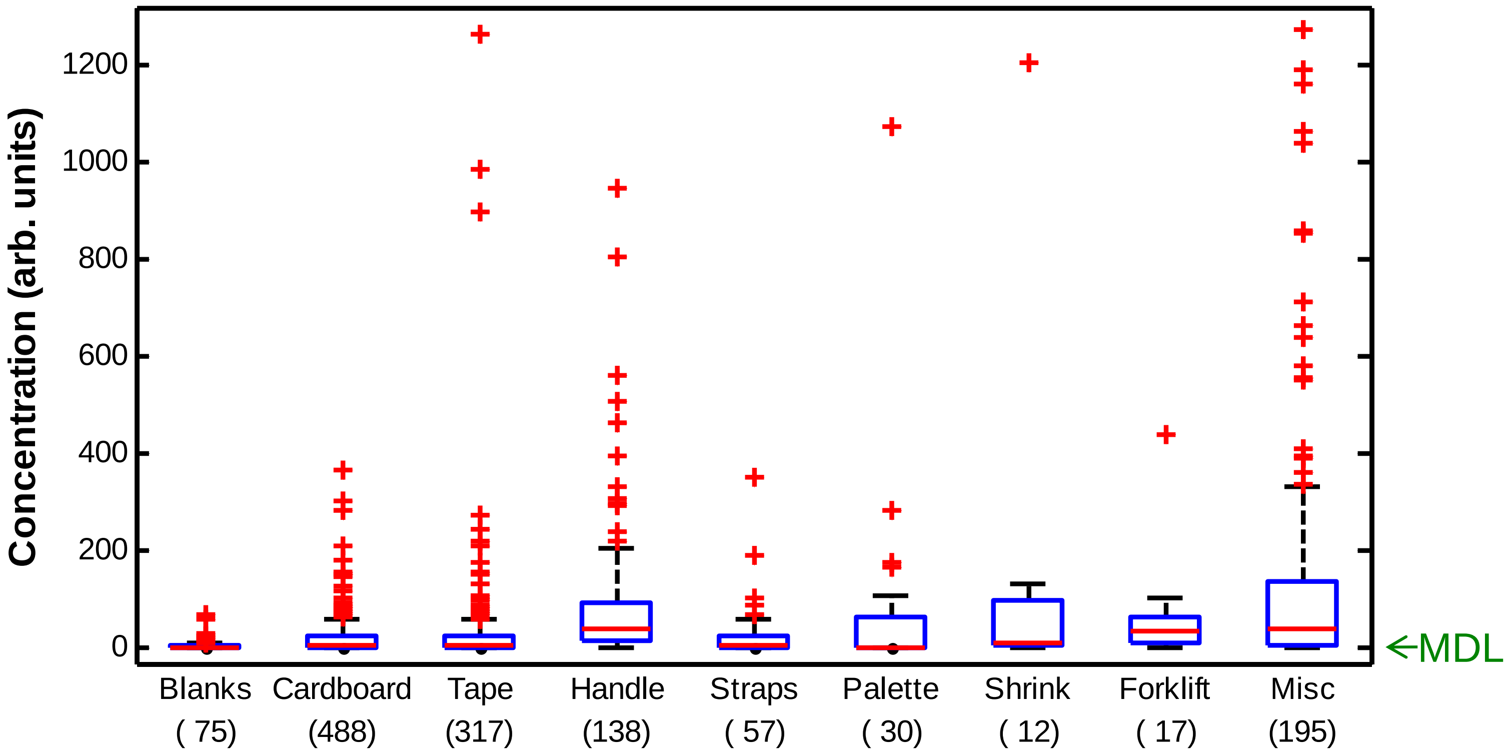
Results: Background Nitrate on Air Cargo



- Samples are sorted into nine categories
  - Most sample levels are well above method detection limits

No obvious nitrate patterns observed between sample types

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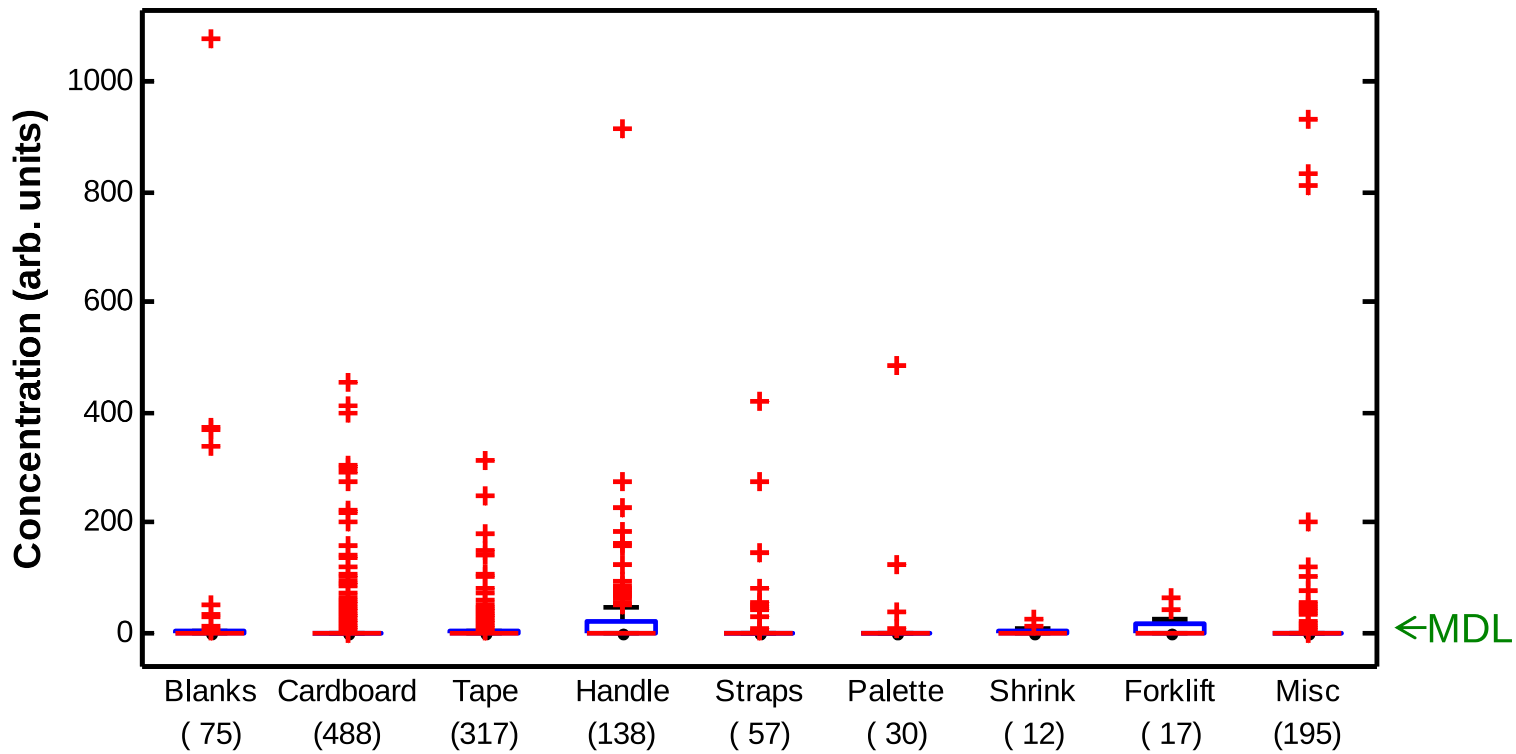
Results:
Background Ammonium on Air Cargo

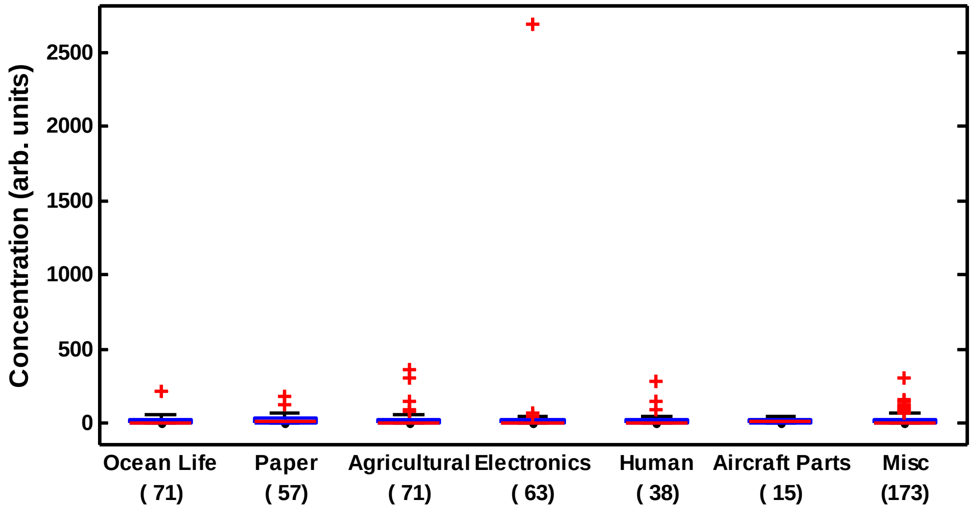


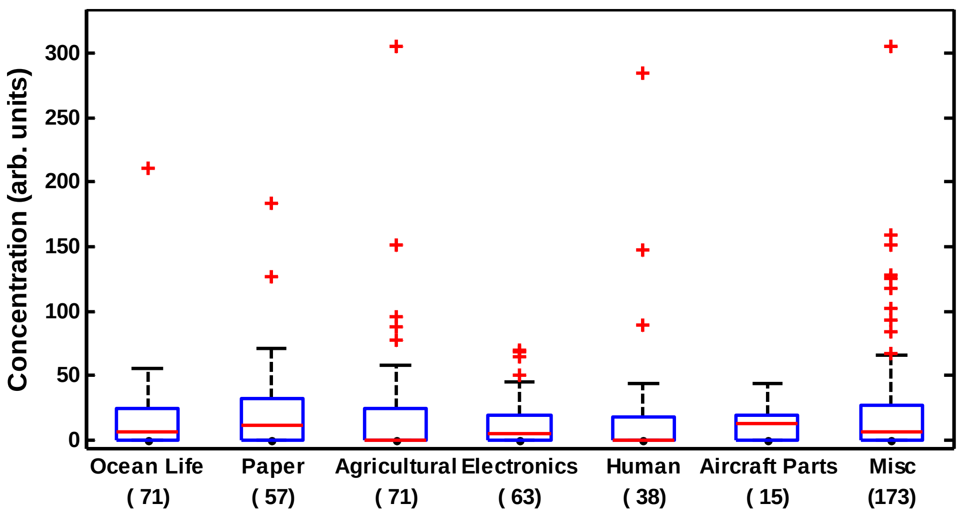
- Samples are sorted into nine categories
  - Median level for each category is near the minimum detectable limit of analytical method

No significant differences observed between sample types

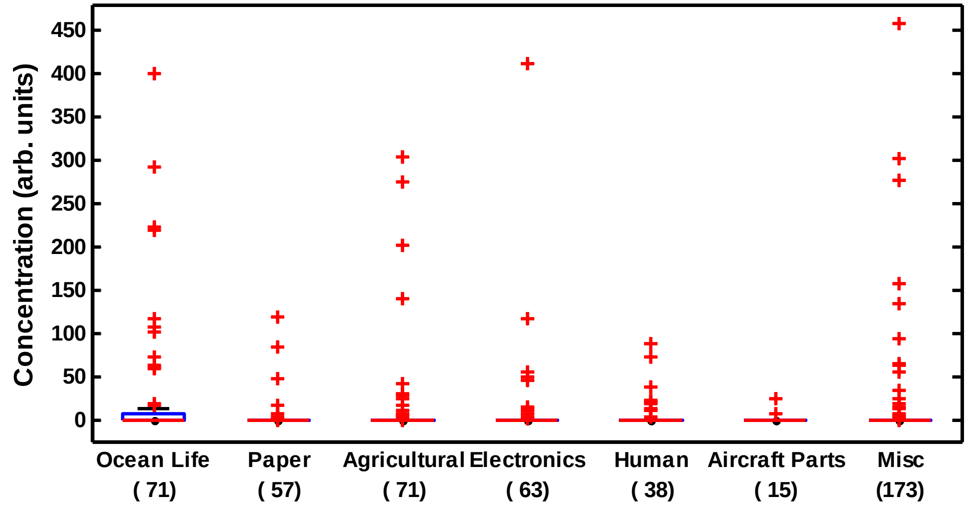
Nitrate and Ammonium Levels on Cardboard Boxes Categorized by Box Contents

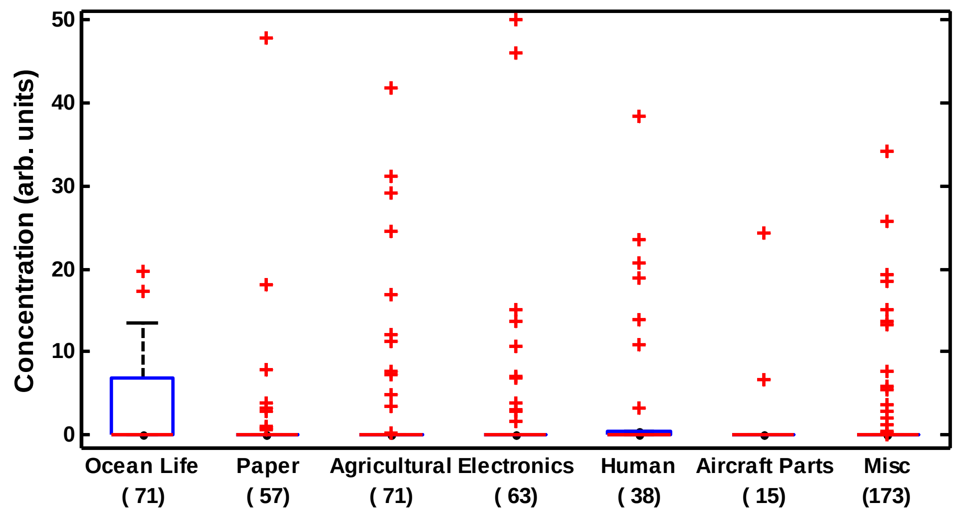
Nitrate





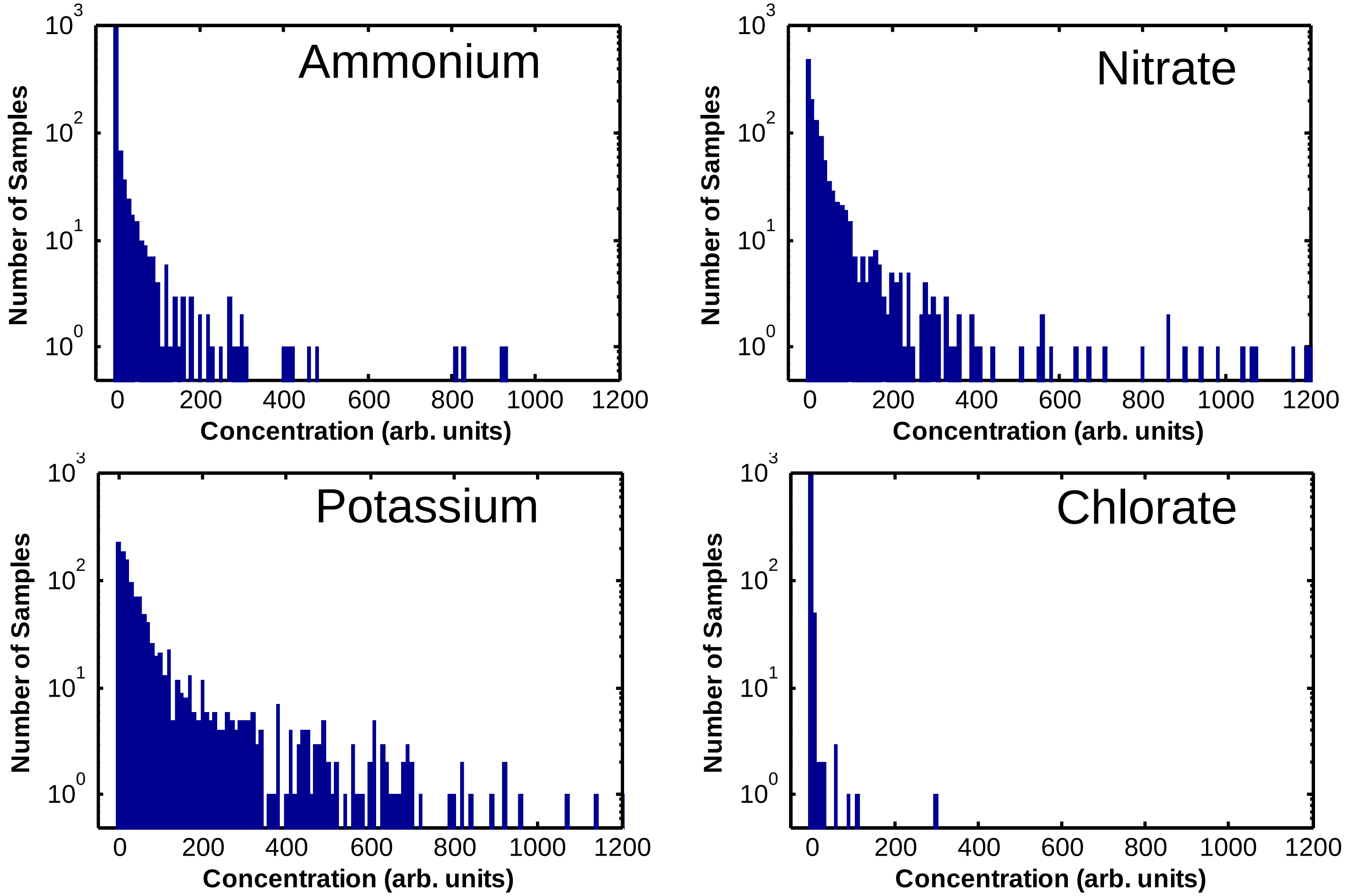
Ammonium





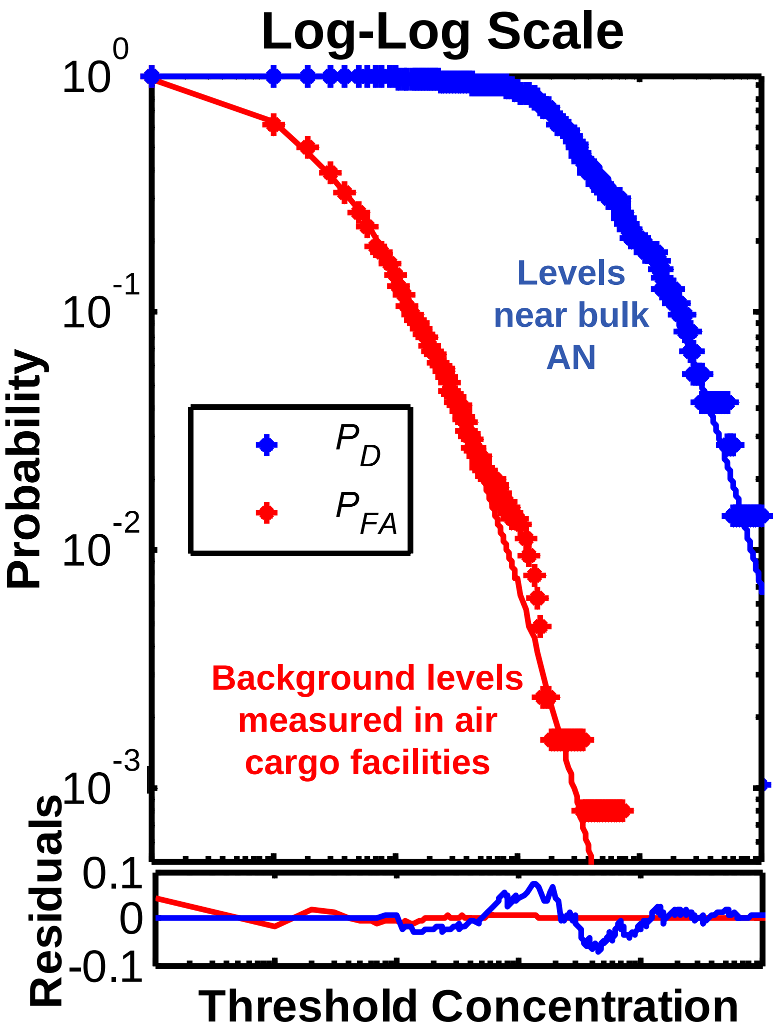
Nitrate levels are independent of cargo content

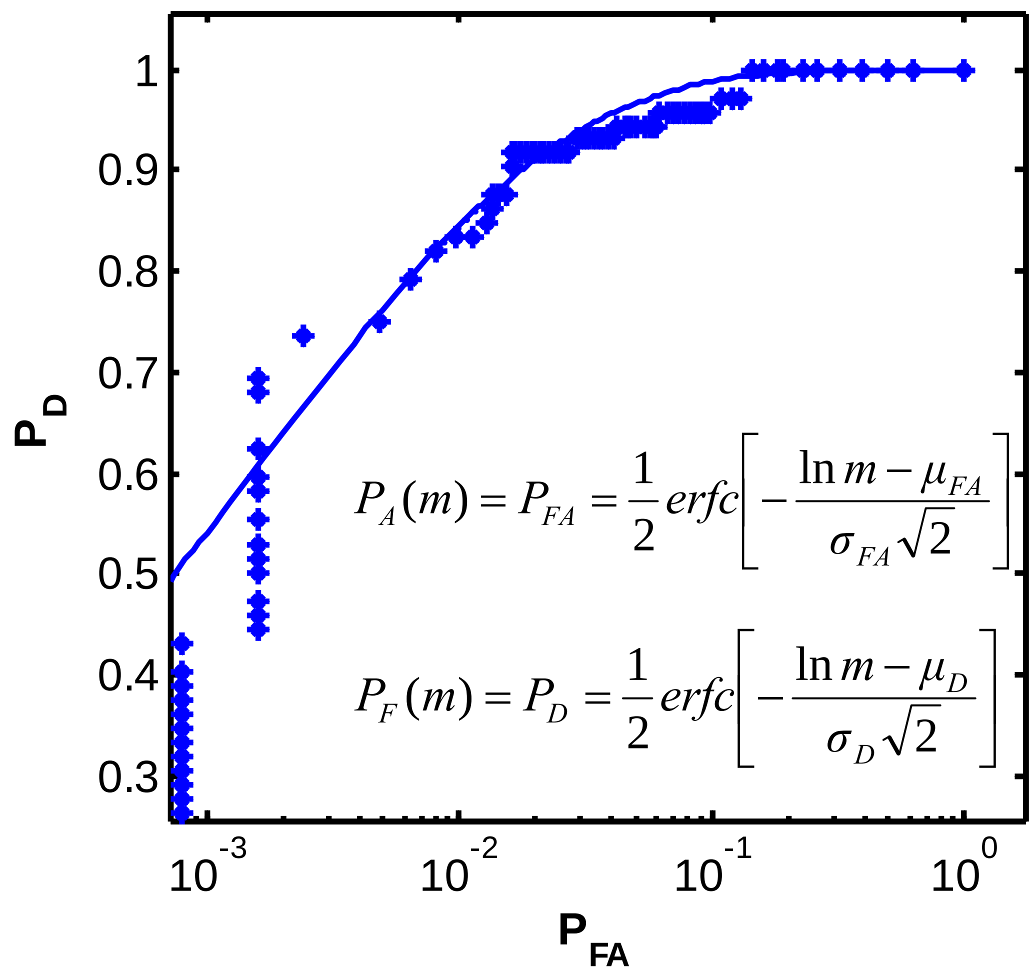
Measured Background Distributions



- **Aggregate analysis of nine fieldings to date**
- **Significant number of samples contain nitrate (61%) and/or potassium (82%)**
- **Only 19% of samples contain measurable levels of ammonium**
- **Only 5% of samples contain measurable levels of chlorate**

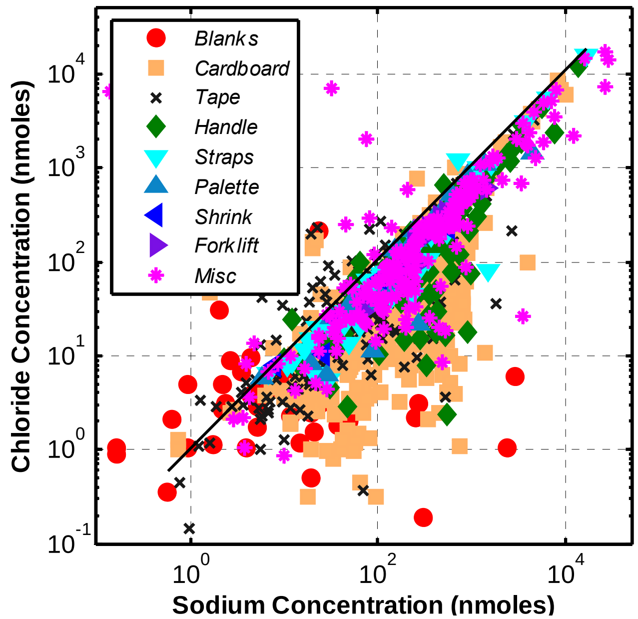
Curve Fits to the Signature and Background Nitrate Data

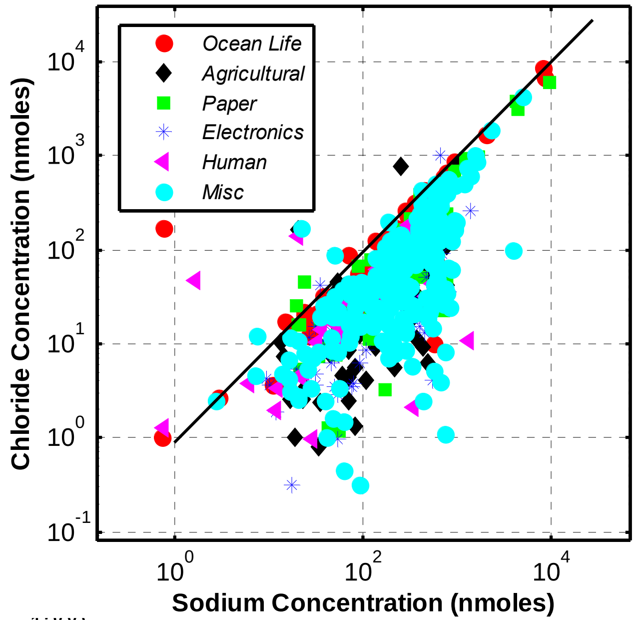


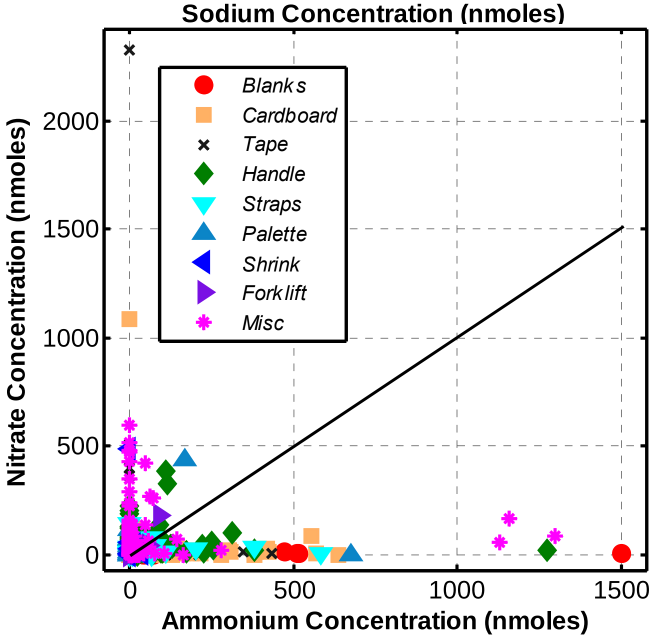


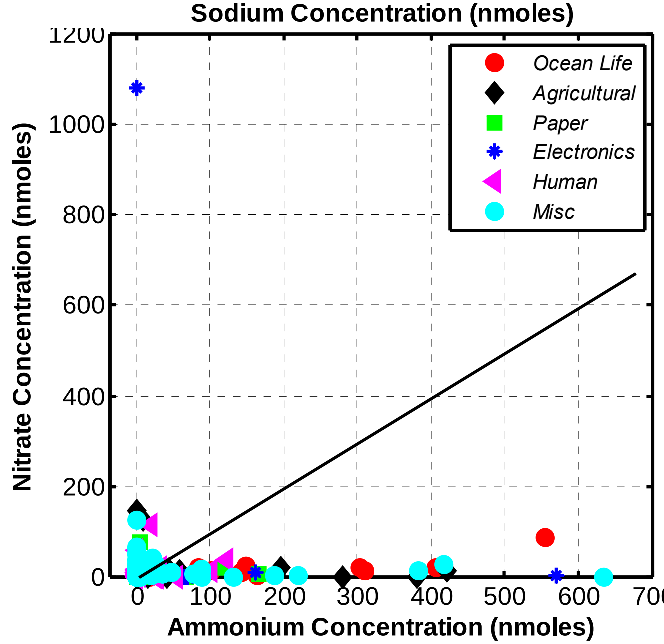
Nitrate background and threat distribution follows a lognormal probability distribution

Cation/Anion Correlations in Background: Air Cargo Samples









<u>Na^+ vs Cl^-</u>:
Na^+ scales with Cl^-, except for cardboard, where excess Na^+ exists

<u>NH_4^+ vs NO_3^-</u>:
In the background, there is no 1:1 correlation of NH_4^+ and NO_3^- at high levels, in fact they are *anti*-correlated

Ion clusters containing both NH_4^+ *and* NO_3^- may be highly selective indicators for ANFO

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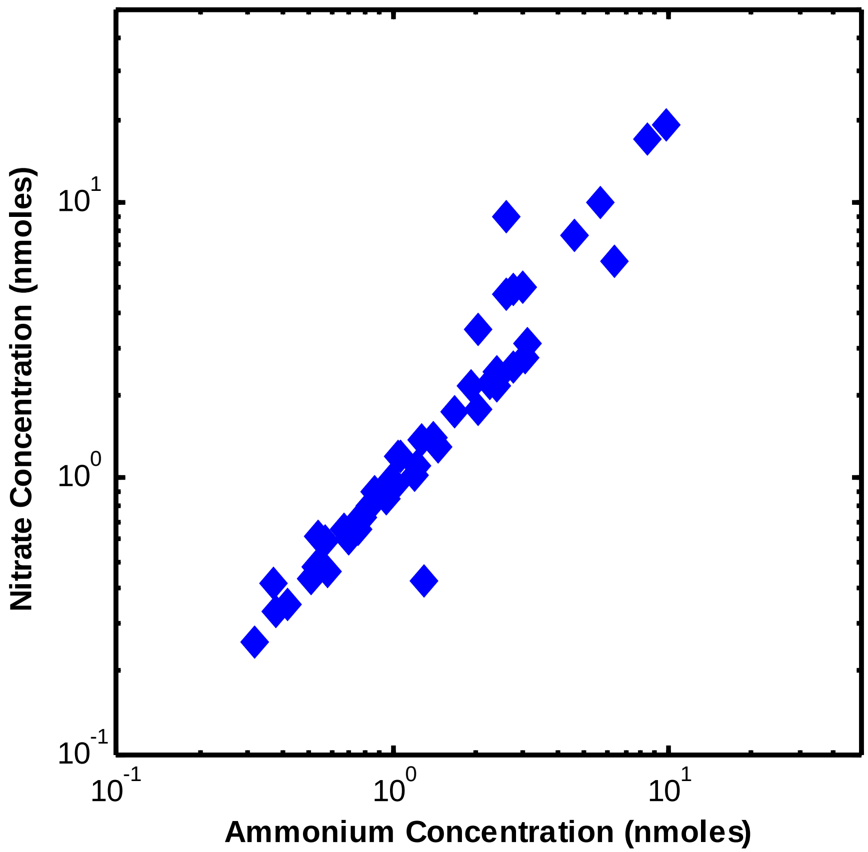
Ammonium Nitrate Fuel Oil: Correlation of Ammonium and Nitrate

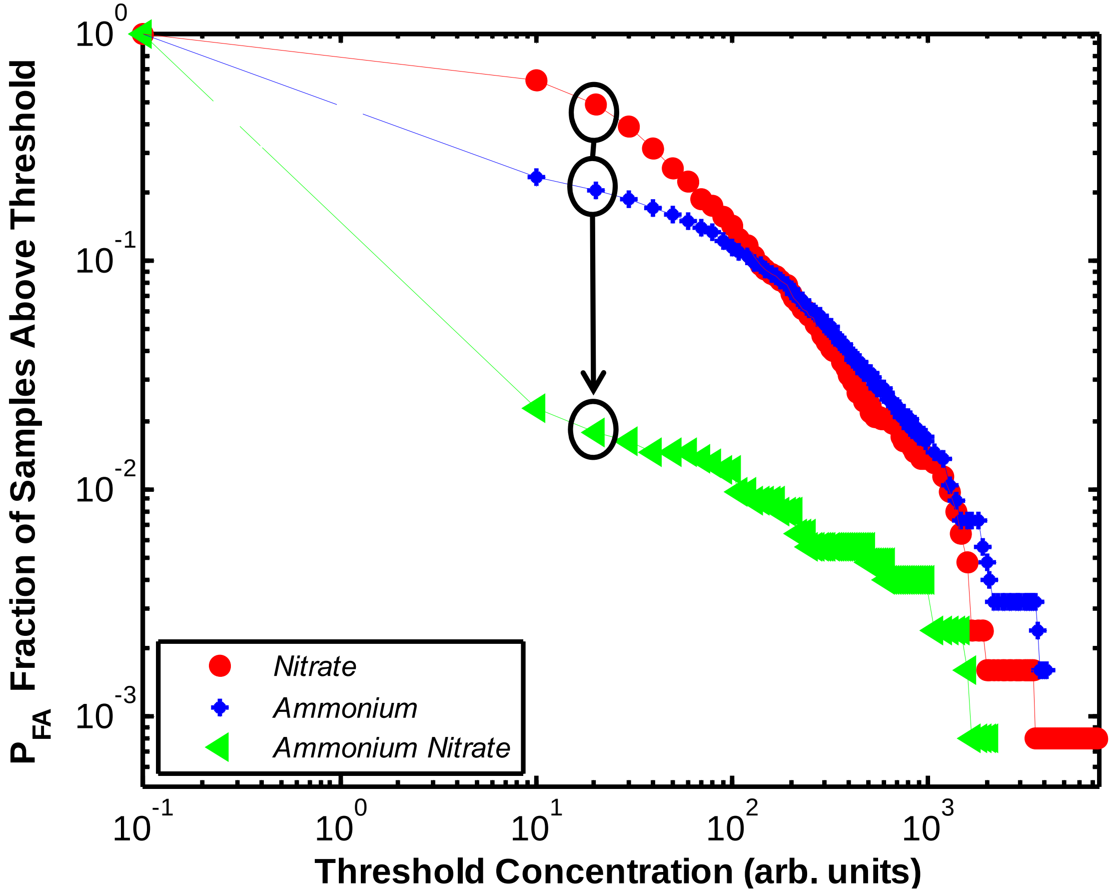


- **IC analysis of nitrate and ammonium for various fingerprints of ANFO on a silicon wafer**
- **Nitrate and ammonium are correlated for ANFO samples**

Correlation of nitrate and ammonium may indicate the presence of AN despite the occurrence of elevated background levels of nitrate

Probability of False Alarm for Ammonium Nitrate

- From the background levels on AN it is possible to determine a probability of false alarm solely due to the signature phenomenology



P_{FA} calculated by requiring Nitrate/Ammonium mole ratio for each sample to fall within a range of 0.7 to 1.3

Simultaneous detection of nitrate and ammonium lowers P_{FA} by an order of magnitude

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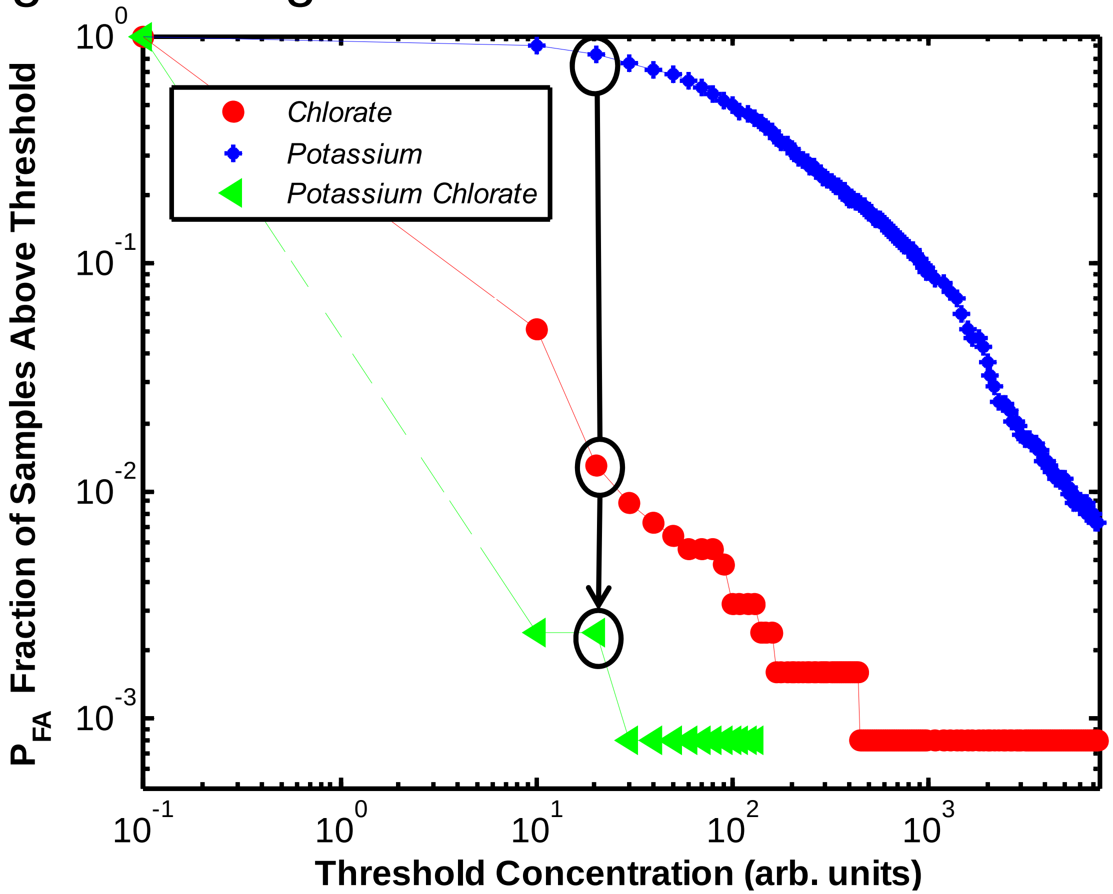
Probability of False Alarm for Potassium Chlorate

- False alarm rate for chlorate is low while potassium is orders of magnitude larger



◀ P_{FA} calculated by requiring Chlorate /Potassium mole ratio for each sample to fall within a range of 0.7 to 1.3

Simultaneous detection of chlorate and potassium lowers P_{FA} by an order of magnitude

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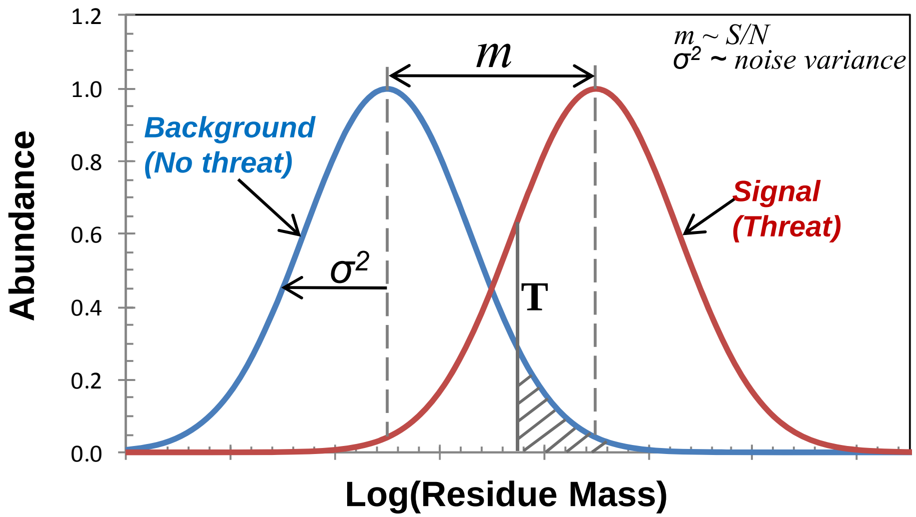
Statistical Analysis: ROC curves

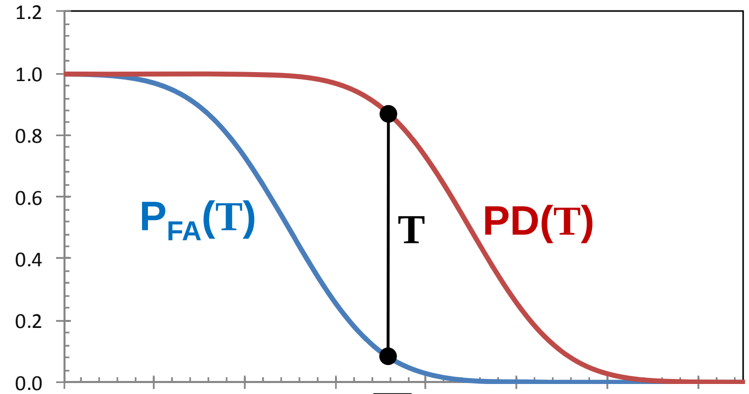
- **Combine background data and limited threat data set to generate ROC curve**
- **Background data provides estimates for P_{FA}**
  - **Assumes a unit (1 cm^2) sampling area, need to extend these results to larger swab area (>100 cm^2)**
- **Limited threat signature provides estimate for P_D**
  - **Additional measurements planned to get better statistics**
    - **Explosives expert will assemble authentic devices concealed in air cargo, made from AN and/or PC on an explosives range in South Carolina**
- **Develop computational framework to determine ROC curves as a function of swab area**

Deriving ROC Curves from Probability Distribution Functions

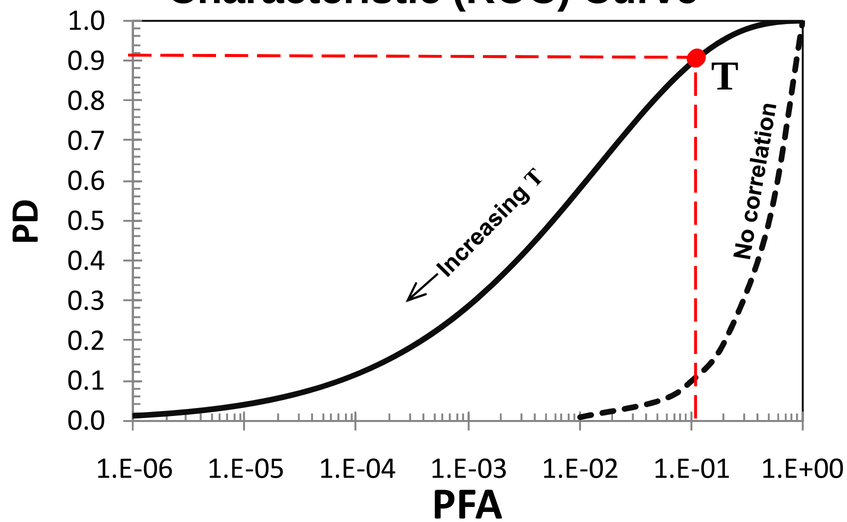
Response Histogram



Plotted *erfc* functions



Receiver Operating Characteristic (ROC) Curve



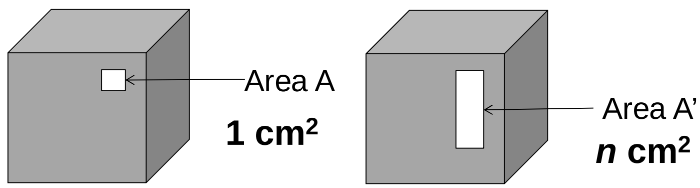
False alarm probability:

$$PFA = \left(\frac{1}{x\sqrt{2\pi\sigma^2}}\right)\int_T^{+\infty} e^{\left(-(\ln x)^2/2\sigma^2\right)}dx = \frac{1}{2}\,erfc\left(\frac{\ln(T)}{\sqrt{2\sigma^2}}\right)$$

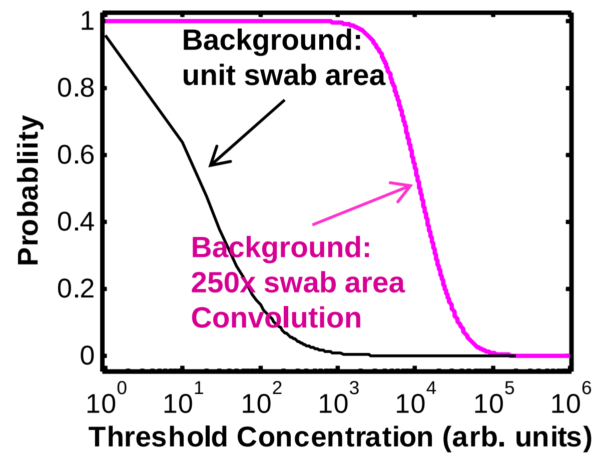
Detection probability:

$$PD = \left(\frac{1}{x\sqrt{2\pi\sigma^2}}\right)\int_T^{+\infty} e^{\left(-(\ln(x-m))^2/2\sigma^2\right)}dx = \frac{1}{2}\,erfc\left(\frac{\ln(T-m)}{\sqrt{2\sigma^2}}\right)$$

Model to Account for Different Swab Areas



For an area of *n* cm², calculate the probability that mass *m* of will exist in at least one of those *n* cm²



- **Signature data obtained for a small swab area**
- **Determine ROC curves for a larger arbitrary swab area based on convolution integrals**
- **Convolution Algorithm:**

If $X_1, X_2 \cdots X_n$ **are** n **random variables with the same probability distribution function, and their sum is** $S_n = X_1 + X_2 + \cdots + X_n$ **then**

$$f_{S_n}(x) = \left(f_{X_1} * f_{X_2} * \cdots * f_{X_n}\right)(x)$$

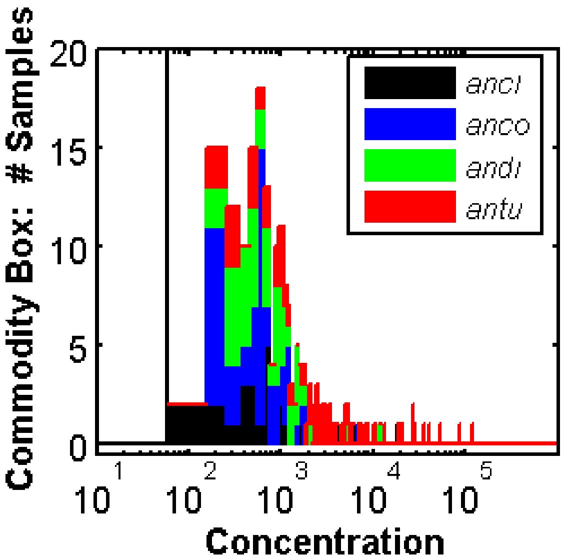
Where the definition of convolution is given by

$$(f * g)(z) = \int_{-\infty}^{+\infty} f(z-y)g(y)dy = \int_{-\infty}^{+\infty} f(z-x)g(x)dx$$

Probability of false alarm (and detection) increase as swab area increases for a given threshold

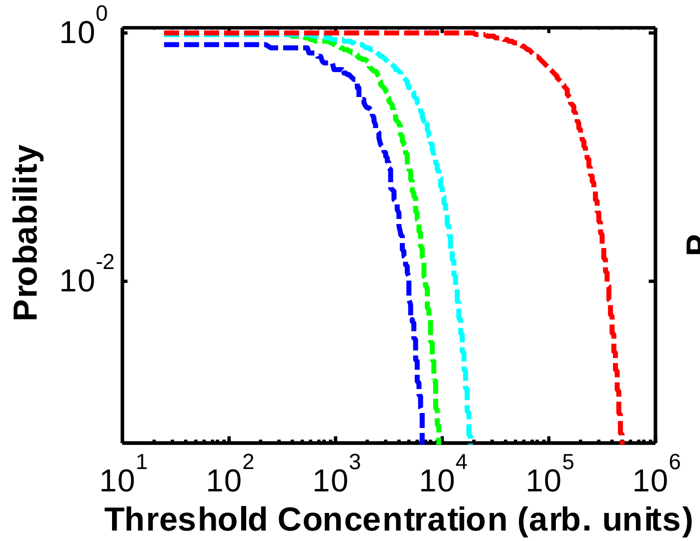
Statistical Analysis Example: Ammonium Nitrate Analysis Summary

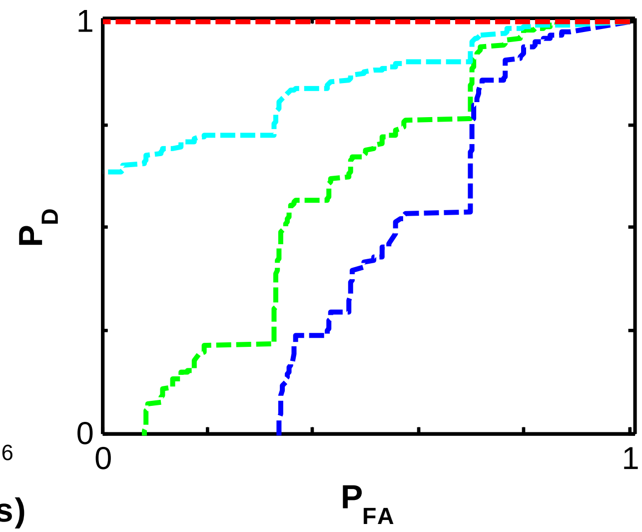
Threat Build Results



ROC Analysis

(Assumes Ideal Sensor – Best Case)





External Commodity Box

ROC performance can be individually calculated for each sampled surface, swab area, analyte, build type, container, and correlation algorithm

Conclusions

- **Developed a general framework to calculate idealized sensor-agnostic ROC curves for background limited scenarios**
  - **Based on measurements of background and threat signatures in air cargo**
- **Assess impact of background ETD false alarm and detection rates**
  - **Estimate capabilities for specific ETD missions *before* technology investment decisions are made**
- **Identify new CONOPs and detection strategies (correlations, etc.)**
  - **Instruments and algorithms that can simultaneously detect nitrate and ammonium will provide superior false alarm performance**
- **Inform requirements development for ETD for air cargo**
- **Current and future work focuses on measuring signatures associated with additional threats in air cargo scenarios**

Acknowledgements

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- **We would like to acknowledge: Department of Homeland Security, Science and Technology Directorate, Explosives Division and Department of Homeland Security, Transportation Security Administration**