Developing a Phenomenological Model of Infrared Emissions from Detonation Fireballs for Explosives Identification

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Introduction

- Traditional battle space characterization
  - Classification of transient, infrared events
  - **Bomb detonations**, muzzle flashes, rocket and missile plumes

- Classifying explosives is difficult
  - No simple model exists for describing emissions from detonation fireballs
  - High-explosive detonations are non-reproducible
    - Inherent irreproducibility (age, mixture tolerances, casing design, impact angle, etc.)
    - Environmental interaction (soil type, atmospheric conditions, etc.)
  - Cost and safety concerns lead to small-scale tests with limited reproducibility
  - Broadband absolute radiometric signatures not *apparently* useful for classification
    - Roughly, variance within explosive class same size as variance between classes
Introduction

Framework for solving the explosives classification problem

- Collect data using spectrometers, radiometers, and several banded imagers
- Develop a *low-dimensional* phenomenological model for fireball emissions
  - Spectrometers: Chemistry
  - Imagers: Fluid dynamics
- Extract key features (fit model to data)
  - *Reproducible* within the same explosive class (small within-class scatter)
  - *Distinguishing* for different explosive classes (large variance between classes)
  - *Invariant* to uncontrollable factors
  - *Constrained* by physics
- Quantify classification potential of extracted features using pattern-recognition codes
Field Tests

- Radiant Brass III: Conventional Bomb
- Brilliant Flash II: Enhanced Novel Explosives (ENEs)
- Bronze Scorpio: IEDs

<table>
<thead>
<tr>
<th></th>
<th>RB3</th>
<th>BF2</th>
<th>BS</th>
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<tr>
<td>Events</td>
<td>56</td>
<td>44</td>
<td>58</td>
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<tr>
<td>Compositions</td>
<td>3 distinct</td>
<td>5 distinct</td>
<td>3 distinct</td>
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<tr>
<td>Sizes</td>
<td>4</td>
<td>4</td>
<td>2</td>
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<tr>
<td>Delivered by</td>
<td>aircraft</td>
<td>Uncased</td>
<td>Cased artillery</td>
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- ABB/Bomem MR Series FTS
  - RB3: 16 cm⁻¹ / 21 Hz (InSb: 1800–7100 cm⁻¹, MCT 500-6000 cm⁻¹)
  - BF2: 4 cm⁻¹ / 8 Hz (InSb: 1800–7100 cm⁻¹, MCT 500-6000 cm⁻¹)
  - BS: 4 cm⁻¹ / 38 Hz (InSb: 1800–7100 cm⁻¹, InGaAs 6000-11000 cm⁻¹)
- Radiometers (4 MWIR bands)
- Banded Imagers (Vis, NIR, MWIR)
Temporal Profile

Fast-scanning FTS collects time-resolved spectra

Temporal profiles reveal detonation and afterburn timescales
Typical Spectra

Uncased Explosive, 4 cm$^{-1}$, 8 Hz
Uncased Explosive, 4 cm\(^{-1}\), 8 Hz

\( t = 0.362 \text{ s} \)
At each frequency, assume spectrum’s temporal evolution is quadratic over the scan time of the interferometer

\[ I_1 = I_{\text{obs}}(\tilde{\nu}, x = 0) \quad I_2 = I_{\text{obs}}(\tilde{\nu}, x = L/2) \quad I_3 = I_{\text{obs}}(\tilde{\nu}, x = L) \]

\[ I_{\text{obs}}(\tilde{\nu}) = I_2 - \frac{1}{4\pi^2L^2} \frac{\partial^2 (2I_1 - 4I_2 + 2I_3)}{\partial \tilde{\nu}^2} + i \frac{1}{2\pi L} \frac{\partial (I_3 - I_1)}{\partial \tilde{\nu}} \]

\[ T = (T_H - T_L) e^{-k \Delta t} + T_L \quad T_H = 2000 \text{ K}, \quad T_L = 300 \text{ K}, \quad k = 1 \text{ s}^{-1} \]

\[ \Delta t = 0.1 \text{ s}, \quad \Delta \nu = 8 \text{ cm}^{-1} \]
Atmospheric Compensation

Find single set of absorber concentrations for entire data cube

\[ I_{obs}(\tilde{\nu}, t) = \tau(\tilde{\nu}) I_{src}(\tilde{\nu}, t) \]

\[ \tau(\tilde{\nu}) = e^{\sum_i \varepsilon_i(\tilde{\nu}) c_i l} \]

\[ I_{obs}(\tilde{\nu}, t) = \tau_i(\tilde{\nu}) \delta \tau_{j \neq i}(\tilde{\nu}) I_{src}(\tilde{\nu}, t) \]

\[ \delta = c / c_{old} \]

\[ \bar{I}_{obs} = \bar{\tau} \delta \bar{\tau}_r I_{src} \]

\[ \bar{I}_{obs} = I_{obs}(\tilde{\nu}_i, t_j) / I_{obs}(\tilde{\nu}_i + k \Delta \tilde{\nu}, t_j) \]
Weighted linear regression to estimate $\delta$

Atmospheric Compensation

Find single set of absorber concentrations for entire data cube

$$I_{obs}(\nu, t) = \tau(\nu) I_{src}(\nu, t)$$

$$\tau(\nu) = e^{\sum_i \varepsilon_i(\nu)c_i}$$

$$I_{obs}(\nu, t) = \tau_t(\nu)\delta \tau_{j \neq t}(\nu) I_{src}(\nu, t)$$

$$\delta = c/c_{old}$$

$$\bar{I}_{obs} = \bar{\tau}_m \bar{\tau}_r \bar{I}_{src}$$

$$\log \left( \frac{\bar{I}_{obs}}{\bar{\tau}_r \bar{I}_{src}} \right) = \delta \log(\bar{\tau}_m)$$

Estimate of $\log(\tau_m)$ which varies with time

Beer’s Law not strictly appropriate for moderate resolution spectra

$$\left( \int \tau(\nu) \text{ILS}(\nu - \nu') \, d\nu' \right)^\delta \neq \int \tau(\nu') \text{ILS}(\nu - \nu') \, d\nu'$$

Iteratively recompute $\tau_m$ with new concentration until $\delta = 1$

Weighted linear regression to estimate $\delta$
Atmospheric Compensation

Radiant Brass III Field Test

[H$_2$O] (ppm)

[CO$_2$] (ppm)

[CH$_4$] (ppm)

Test Number

5 10 15

5 10 15

5 10 15

305±7 ppb
310 ppb

371±9 ppm
366 ppm

1.59±0.04 ppm
1.70 ppm

371±9 ppm
366 ppm

1.59±0.04 ppm
1.70 ppm
Radiative Transfer

(Over-) Simplified RT for fireball

Local thermodynamic equilibrium

No gradients (uniform T, \( \rho \))

No sources except fireball

No scattering

Fireball parameters: \( \rho(\text{H}_2\text{O}, \text{CO}_2, \text{CO}, T_g), T_c \)

Rough approximation to full RT solution

Ignore geometry

Include continuum emitters additively

\[
I_{ap} = t_a \left[ A_c B(T_c) + A_g (1 - t_g) B(T_g) \right] + (1 - t_f) B(T_f)
\]

\[
t_g = t_g \left( T_g, [\text{H}_2\text{O}], [\text{CO}_2], [\text{CO}] \right)
\]

\[
t_g = \exp \left( -L \times \sum_i N_i \sigma_i(\tilde{\nu}, T_g) \right)
\]

H\(_2\)O & CO: HITEMP (HITRAN) database
CO\(_2\): CDSD
**Modeling Results**

\[ p = [1.96E-01 \ 2.01E+00 \ 1.31E+03 \ 1.90E+04 \ 7.04E+04 \ 9.16E+02] \]

**TNT (H\textsubscript{2}O/CO\textsubscript{2} \sim 0.4)**

SE = 4.20, RMS Err = 14.4\%, Median iRel Err = 7.2\%
Modeling Results

\[ p = [3.20E-01 \ 1.73E+00 \ 1.91E+03 \ 3.41E+04 \ 3.24E+04 \ 3.49E+03] \]

\[ \text{ENE (H}_2\text{O/CO}_2 \sim 9.5) \]

\[ I_{\text{obs}} - I_{\text{mdl}} \]

\[ \text{SE} = 9.25, \text{RMS Err} = 10.0\%, \text{Median |Rel Err|} = 6.5\% \]
Feature Extraction

TNT (L) vs ENE (R)

TNT ($\text{H}_2\text{O}/\text{CO}_2 \sim 0.4$)

ENE ($\text{H}_2\text{O}/\text{CO}_2 \sim 9.5$)
Conclusions

• Conventional munitions
  • Fireball emission well represented by a single-temperature Planckian distribution over most of the MWIR
  • Non-Planckian emission observed in 2000-2200 cm⁻¹ is likely due to hot CO₂
    • Accurate atmospheric correction key to connecting this residual to fireball phenomenology
  • Temperature decays exponentially (some fireballs exhibit secondary maxima)
  • Area dynamics can be determined without imagery (awaiting confirmation from MWIR camera)

• Enhanced novel explosives
  • Substantial non-Planckian component is a function of H₂O and CO₂ concentrations
  • Extracted concentration ratio [H₂O]/[CO₂] connected to explosive stoichiometry
  • Simple model enables the study of fireball kinetics

• Explosives classification from optical signatures promising