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

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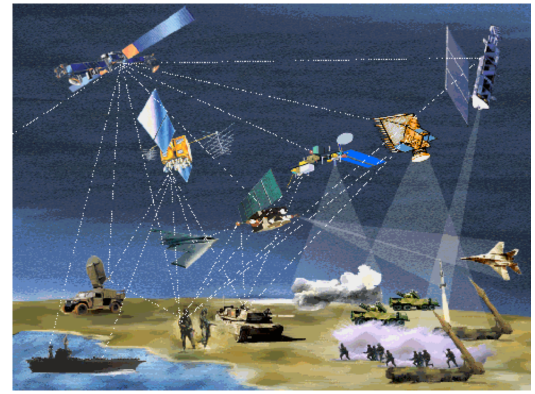
Introduction

- 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

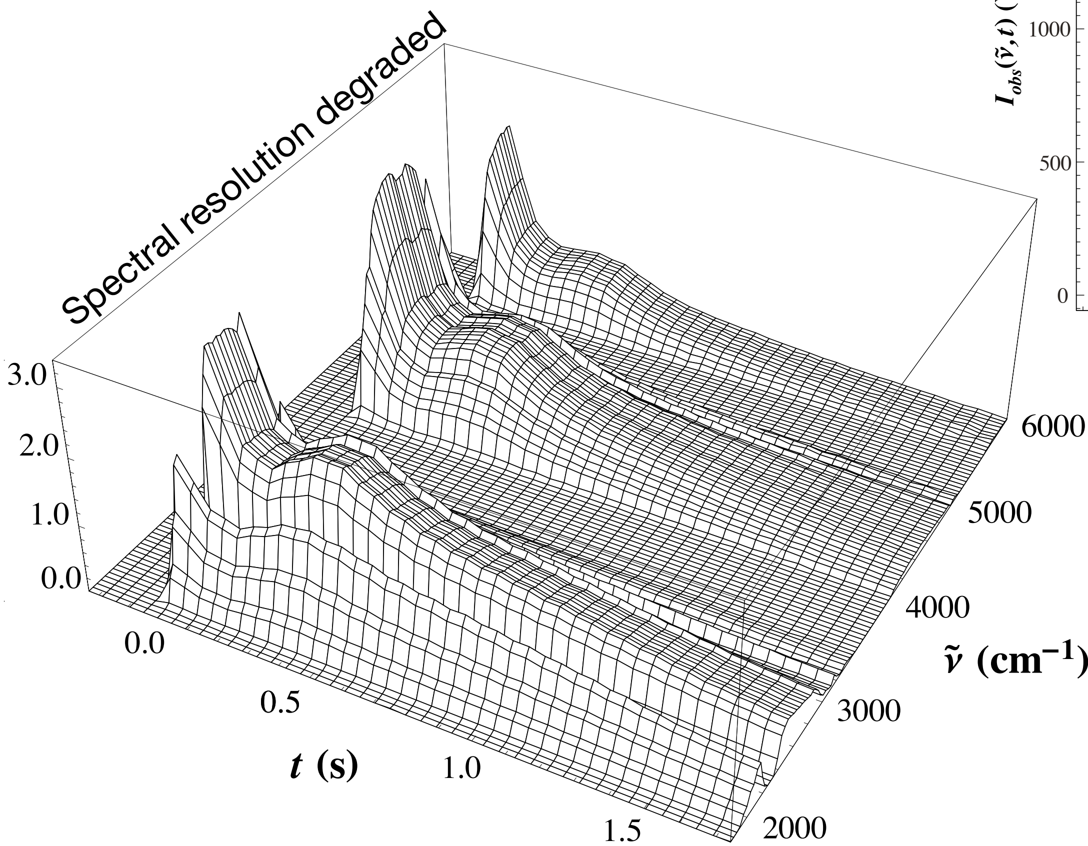
- Radiant Brass III: Conventional Bomb
- Brilliant Flash II: Enhanced Novel Explosives (ENEs)
- Bronze Scorpio: IEDs

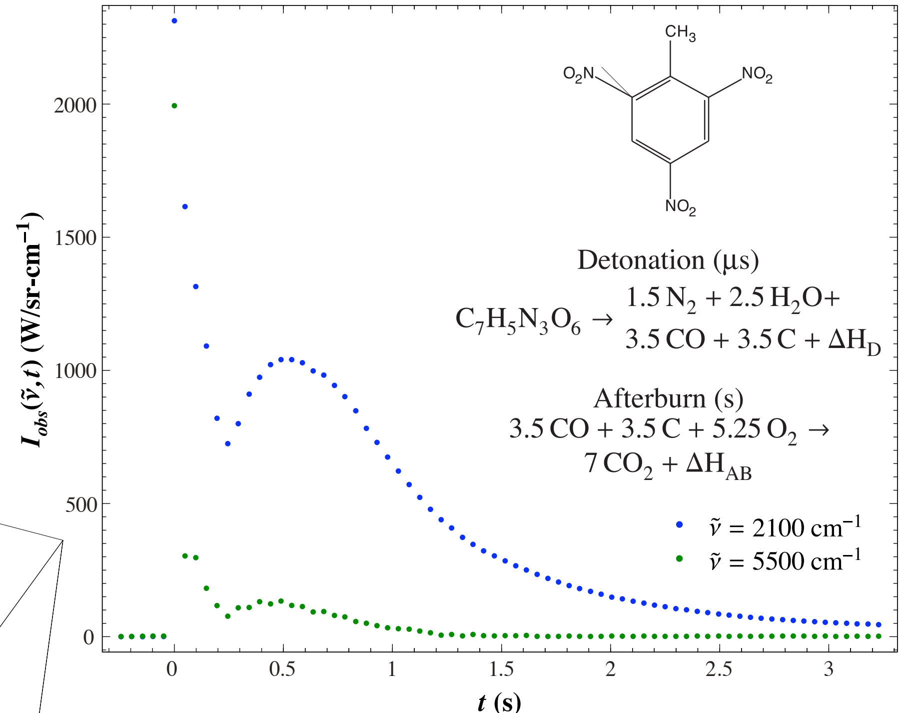
RB3	BF2	BS
56 Events	44 Events	58 Events
3 distinct compositions	5 distinct compositions	3 distinct compositions
4 sizes	4 sizes	2 sizes
Half delivered by aircraft	Uncased charges	Cased artillery shell

- 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

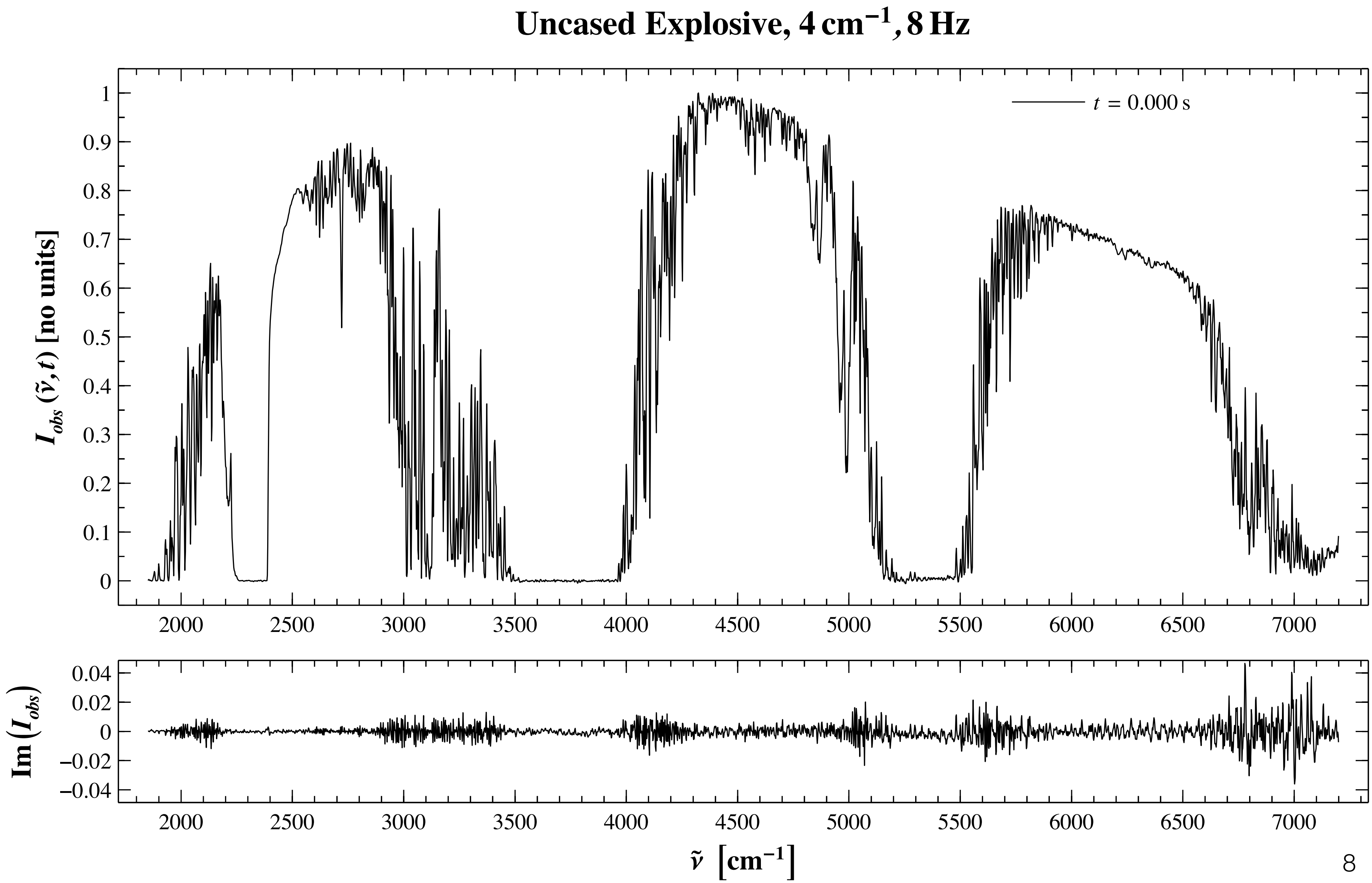
Fast-scanning FTS collects time-resolved spectra



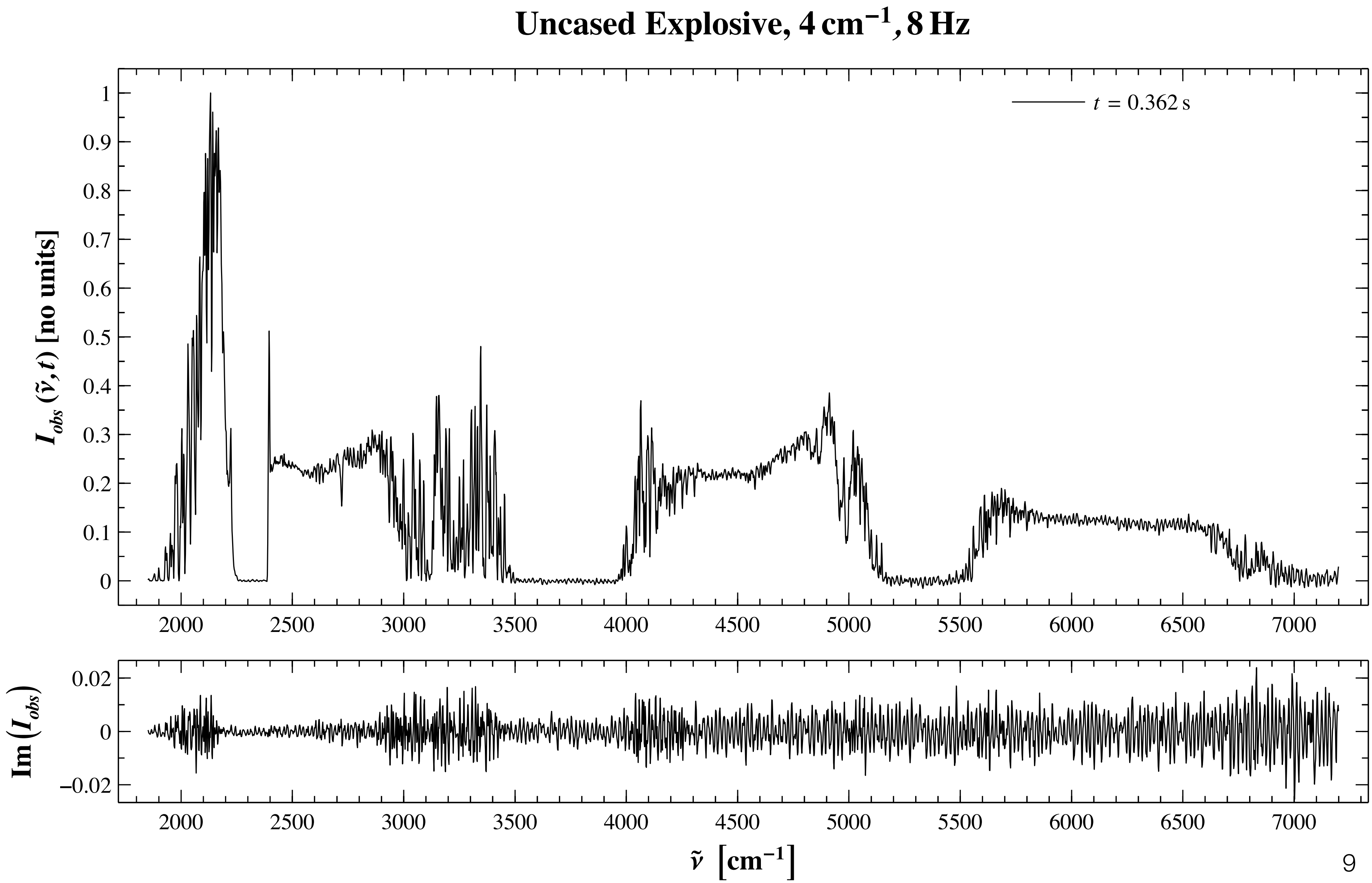


Temporal profiles reveal detonation and afterburn timescales

Typical Spectra



Typical Spectra

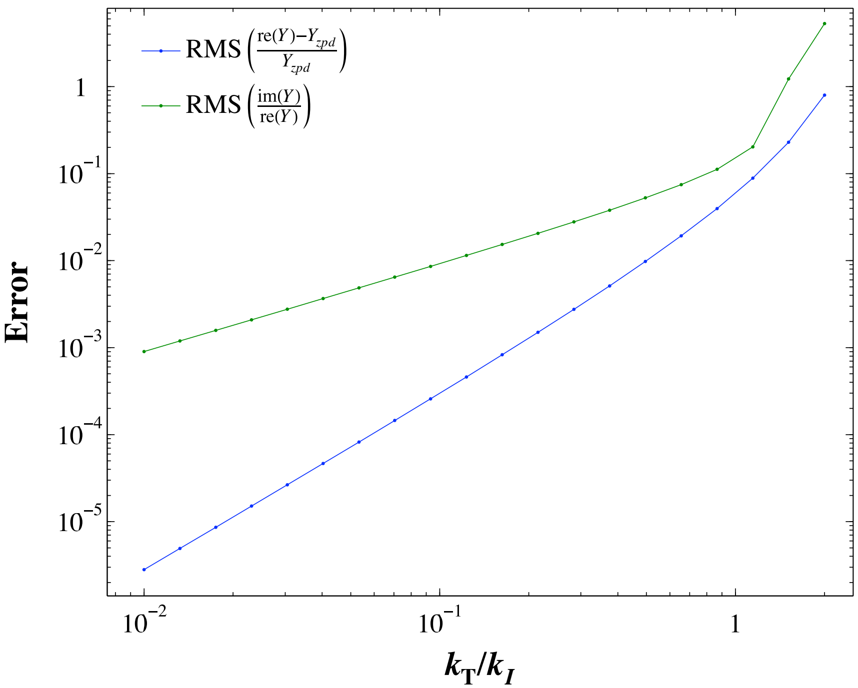


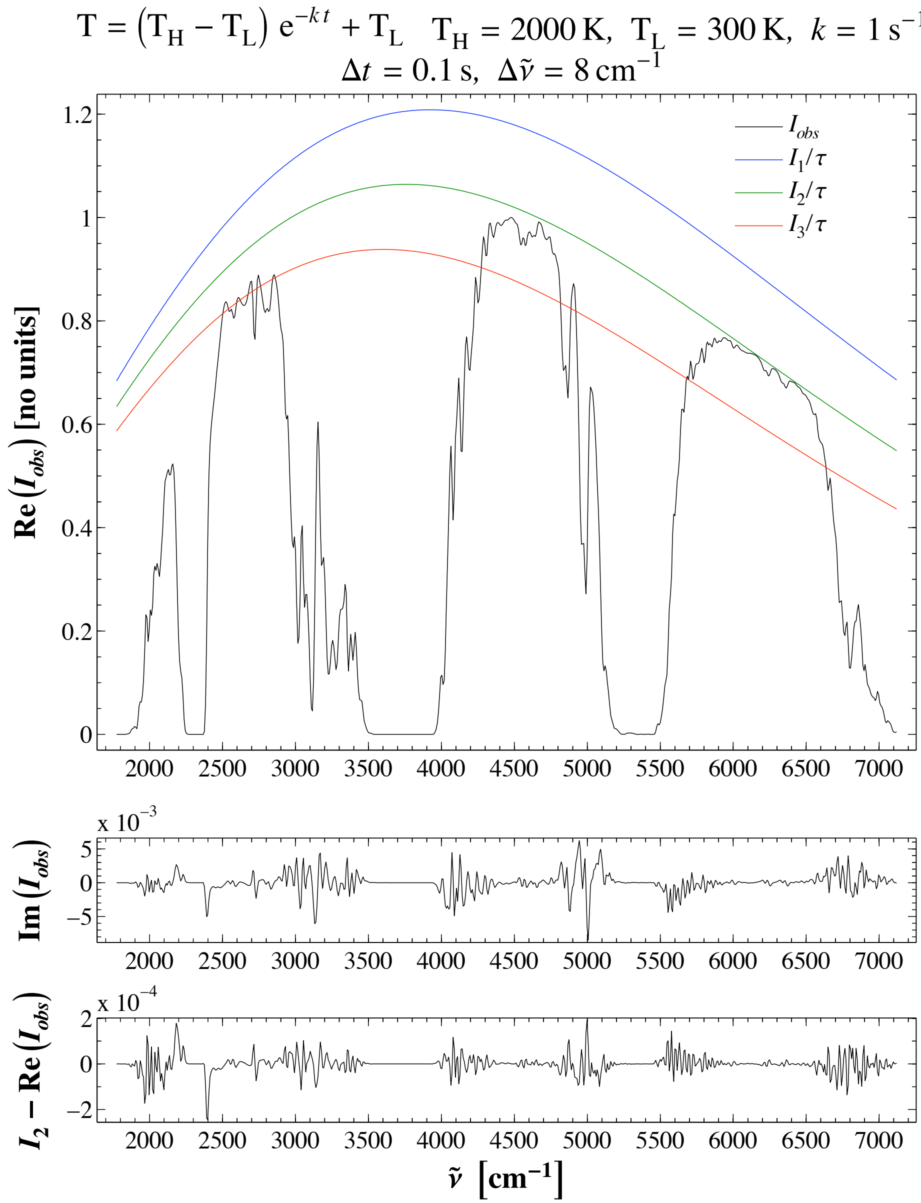
Scene-Change Artifacts

At each frequency, assume spectrum's temporal evolution is quadratic over the scan time of the interferometer

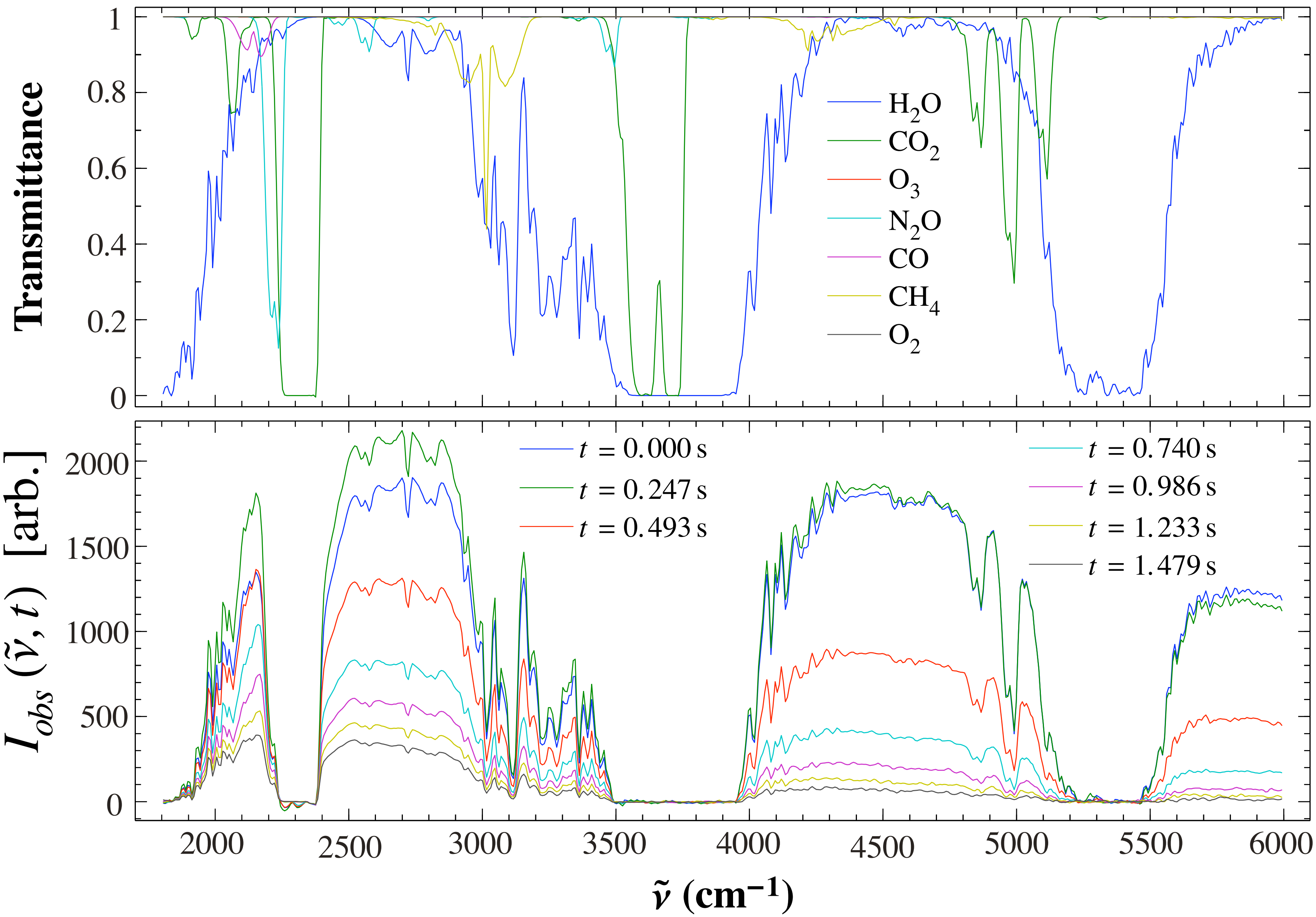
$$I_1 = \hat{I}_{obs}(\tilde{\nu}, x = 0) \quad I_2 = \hat{I}_{obs}(\tilde{\nu}, x = L/2) \quad I_3 = \hat{I}_{obs}(\tilde{\nu}, x = L)$$

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





Conventional (Cased) Munition



Atmospheric Compensation

Find single set of absorber concentrations for entire data cube

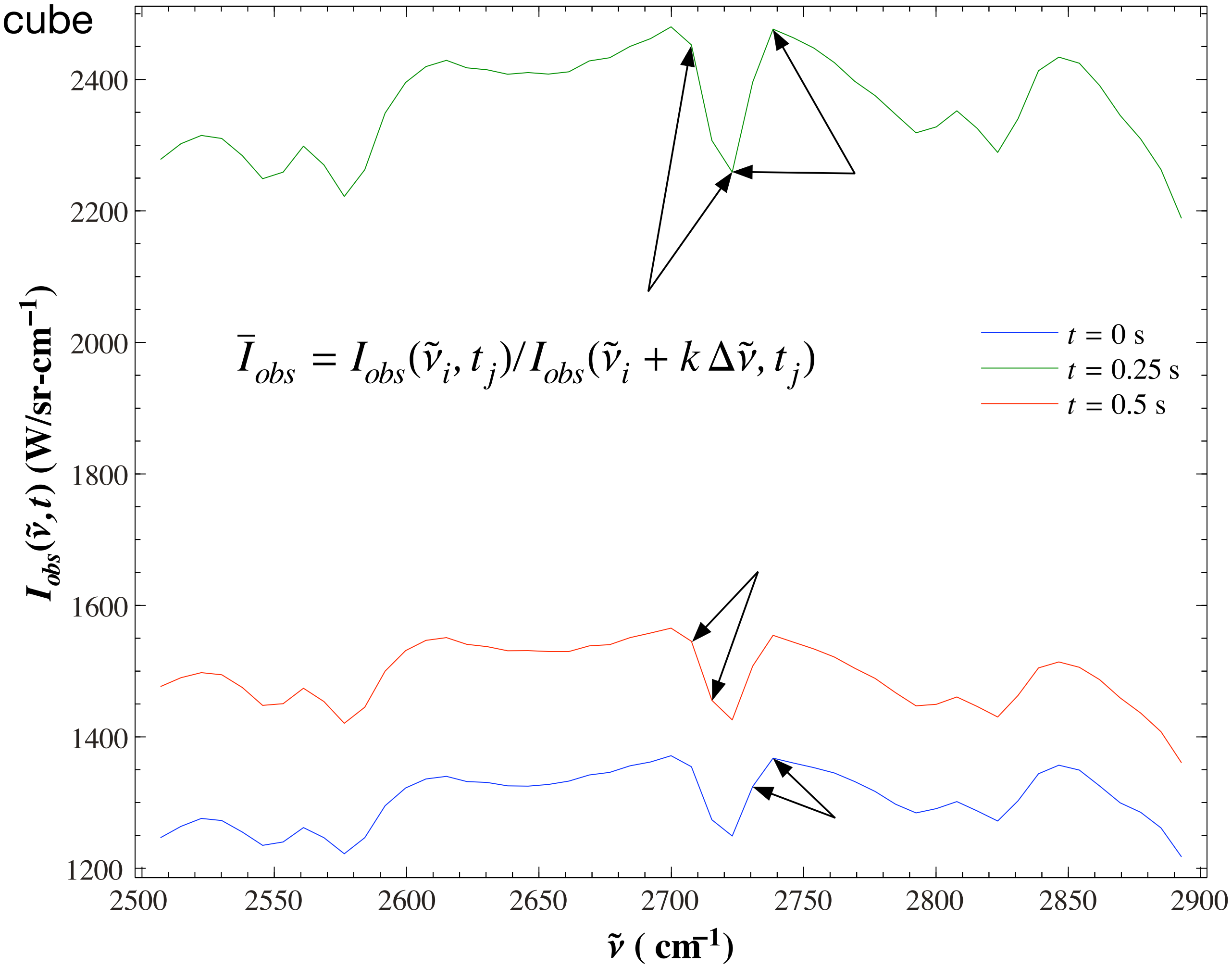
$$I_{obs}(\tilde{\nu}, t) = \tau(\tilde{\nu})\, I_{src}(\tilde{\nu}, t)$$

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

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

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

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



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

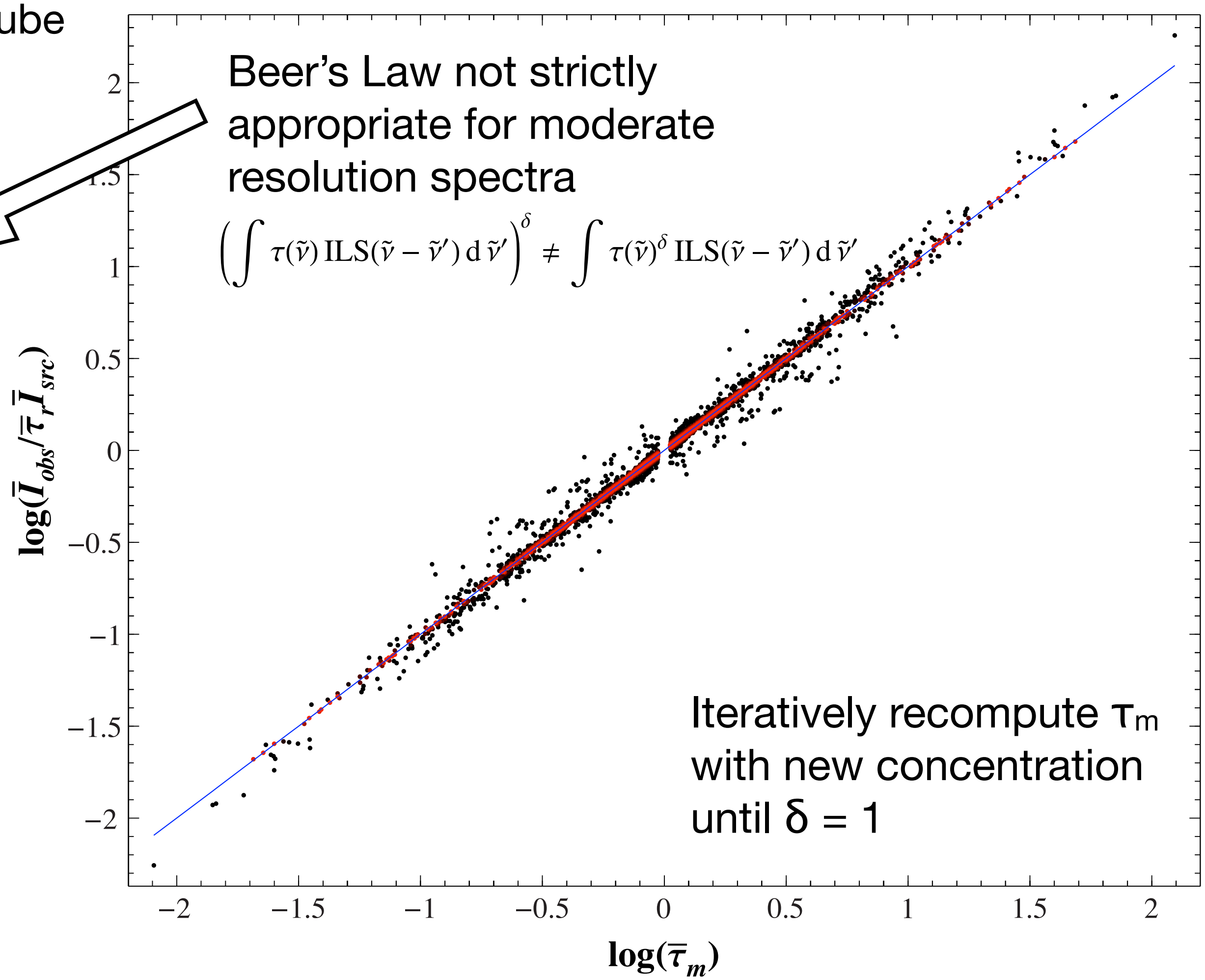
$$\bar{I}_{obs} = \bar{\tau}_m^{\delta}\, \bar{\tau}_r\, \bar{I}_{src}$$

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

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

Beer's Law not strictly appropriate for moderate resolution spectra

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

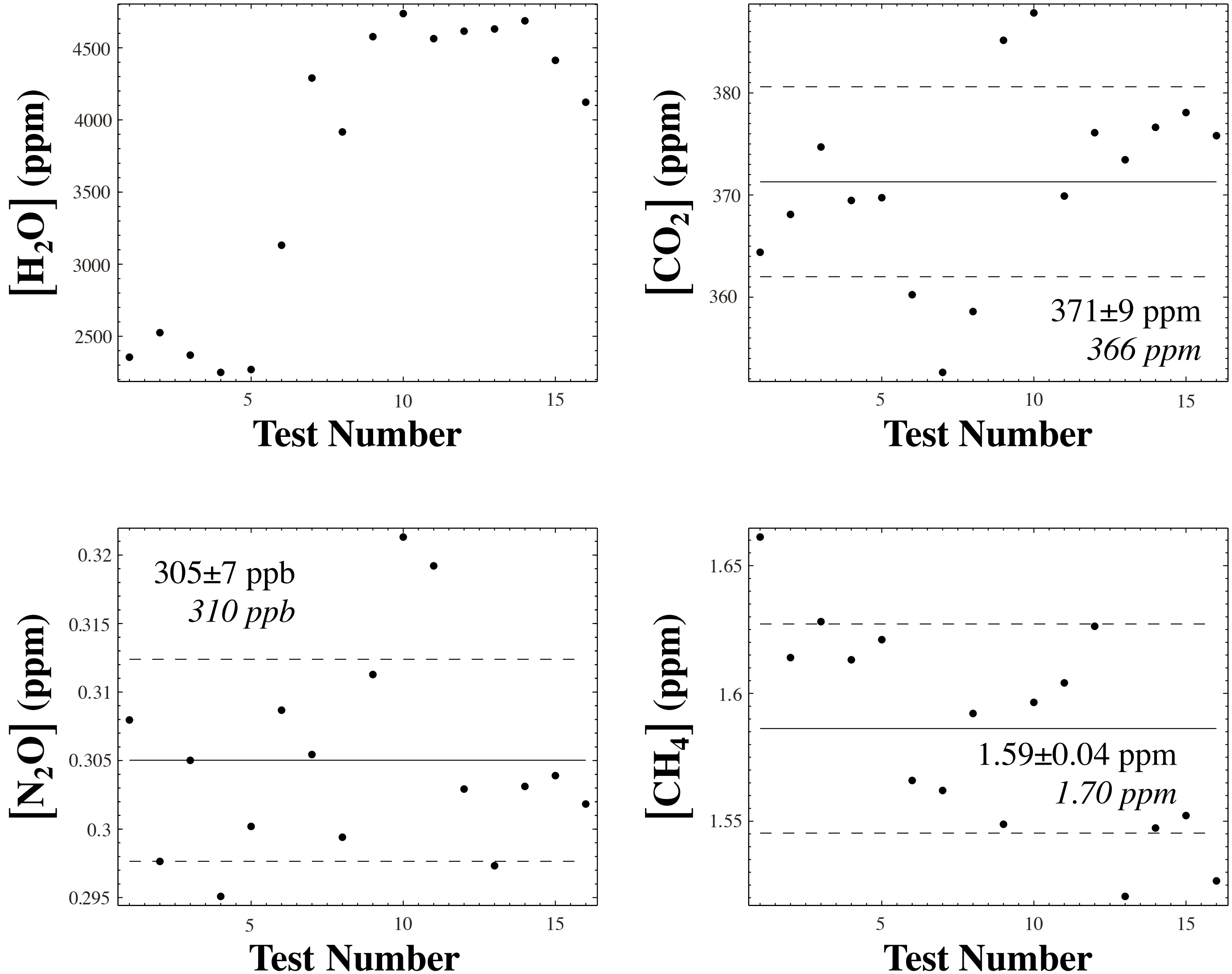


Iteratively recompute τ_m with new concentration until $\delta = 1$

Weighted linear regression to estimate δ

Atmospheric Compensation

Radiant Brass III Field Test



Radiative Transfer

(Over-) Simplified RT for fireball

$$I_{\tilde{\nu}}(s_i) = I_{\tilde{\nu}}(s_{i-1})\, e^{-\int_{s_{i-1}}^{s_i} \kappa_{\tilde{\nu}}(s')\, ds'} + \int_{s_{i-1}}^{s_i} \kappa_{\tilde{\nu}}(s')\, B_{\tilde{\nu}}\left(T(s')\right) e^{-\int_{s_{i-1}}^{s'} \kappa_{\tilde{\nu}}(s'')\, ds''}\, ds'$$

$$t_{\tilde{\nu}}\, I_{\tilde{\nu}}(s_{i-1}) + (1 - t_{\tilde{\nu}})\, B\left(T_i\right) \qquad t_{\tilde{\nu}} = e^{-(s_i - s_{i-1})\kappa_{\tilde{\nu}}}$$

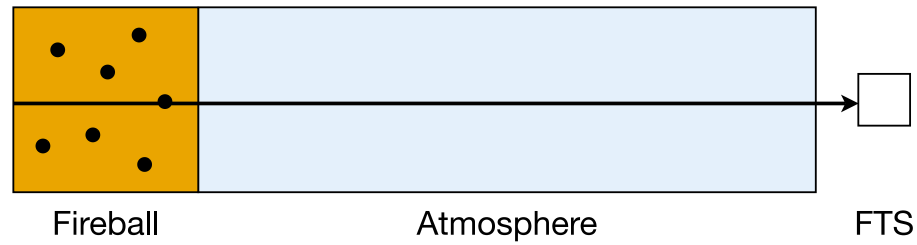
Local thermodynamic equilibrium

No gradients (uniform T, ρ)

No sources except fireball

No scattering

Fireball parameters: ρ(H_2O, CO_2, CO,T_g), T_c



Rough approximation to full RT solution

Ignore geometry

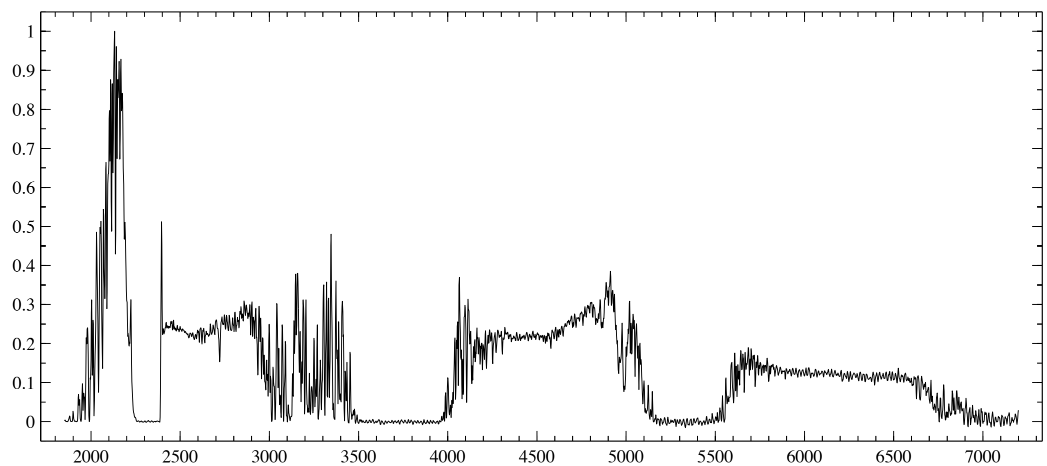
Include continuum emitters additively

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

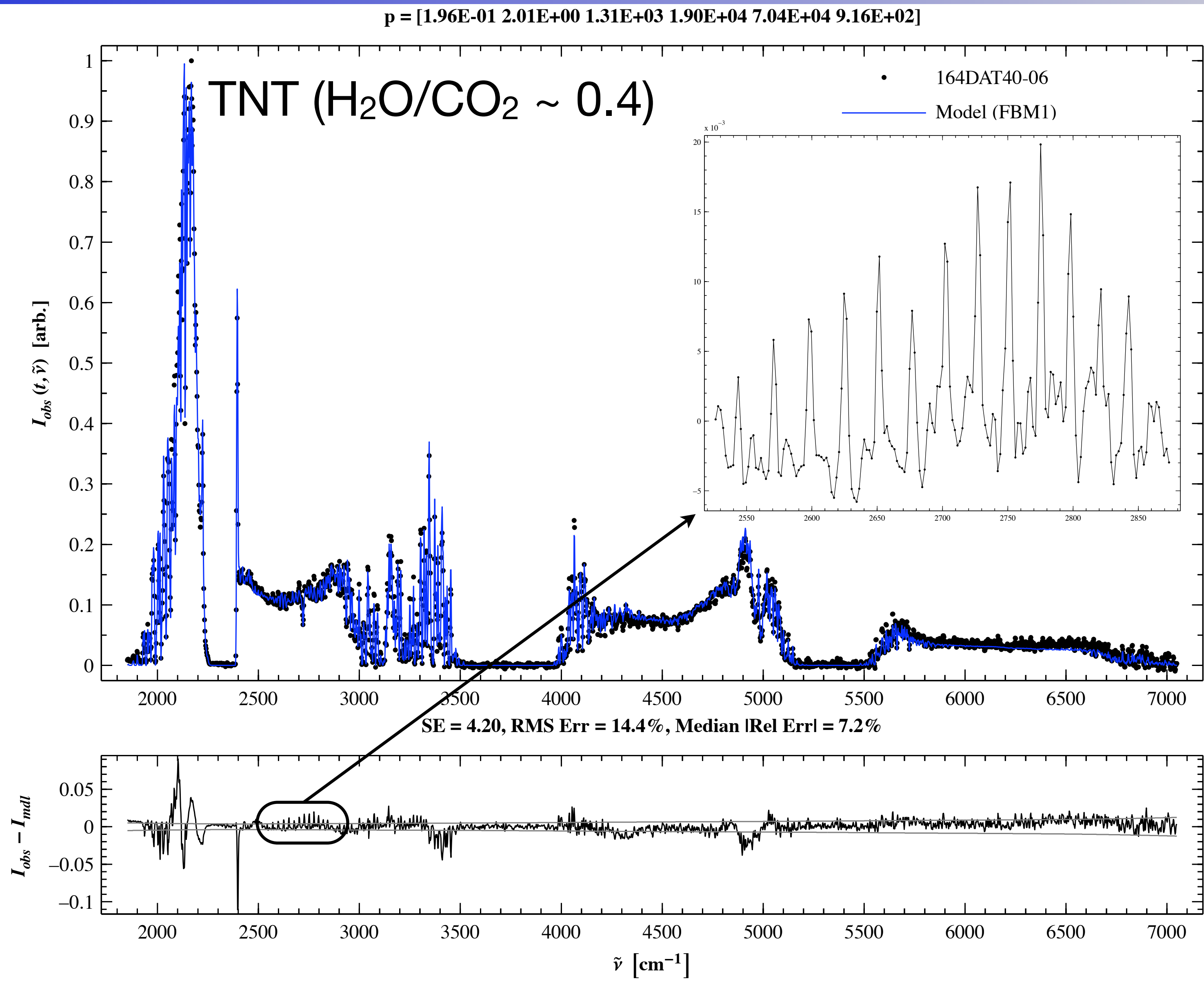
$$t_g = t_g\left(T_g, \left[H_2O\right], \left[CO_2\right], [CO]\right)$$

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

H_2O & CO: HITEMP (HITRAN) database
CO_2: CDSD



Modeling Results



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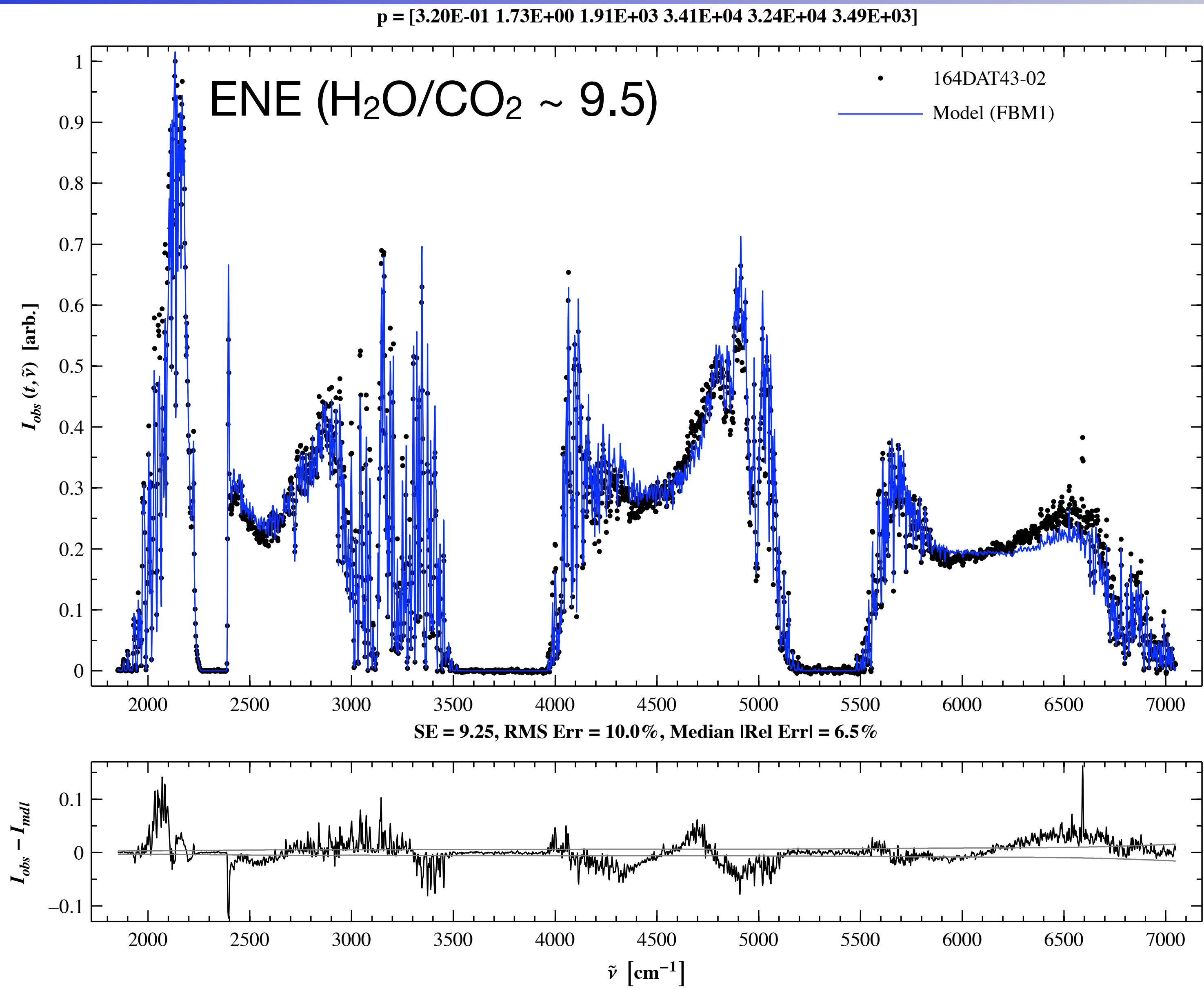
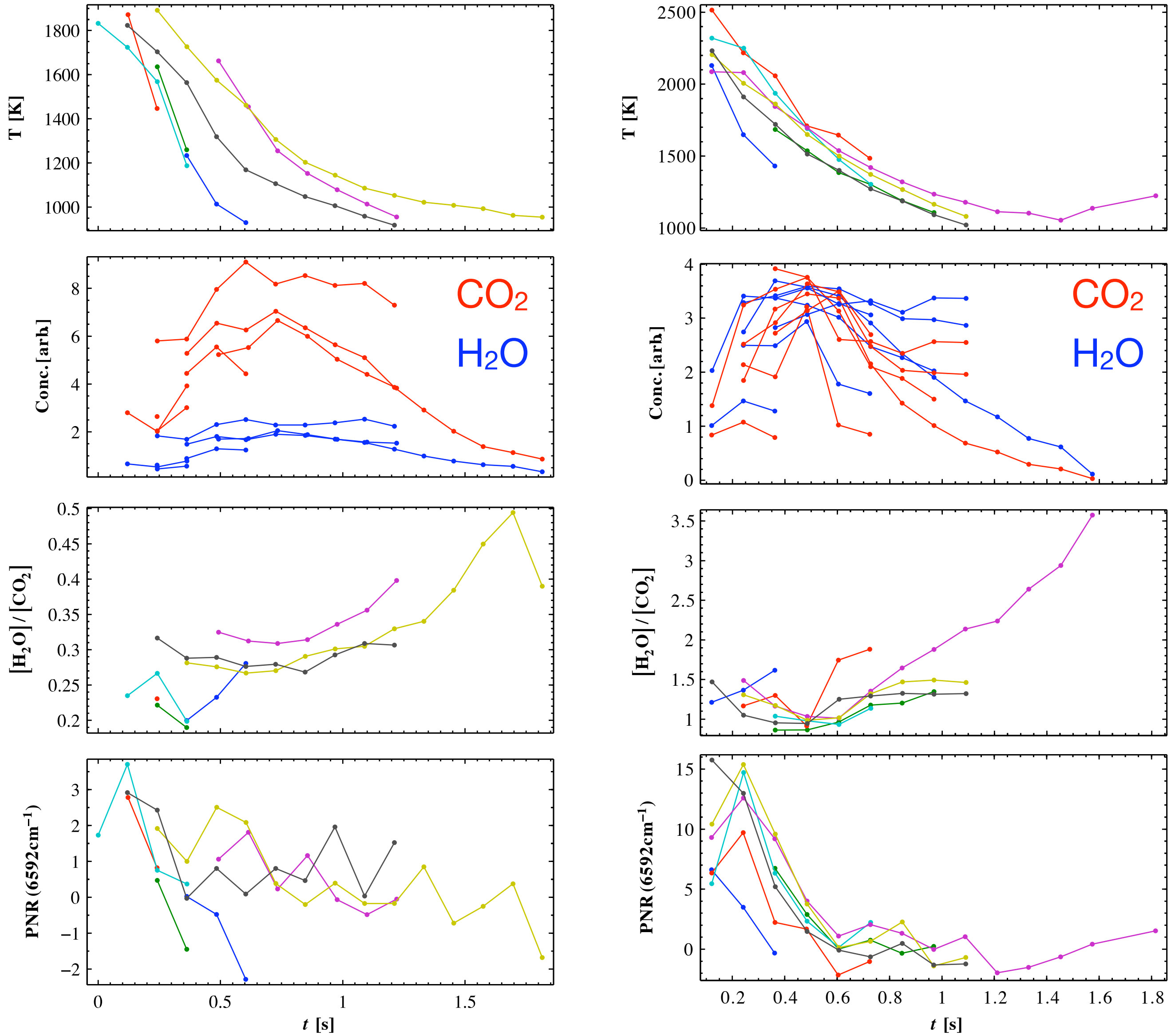


Feature Extraction



TNT (L) vs ENE (R)

TNT (H_2O/CO_2 ~ 0.4)

ENE (H_2O/CO_2 ~ 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 CO_2
    - 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 H_2O and CO_2 concentrations
  - Extracted concentration ratio [H2O]/[CO2] connected to explosive stoichiometry
  - Simple model enables the study of fireball kinetics
- Explosives classification from optical signatures promising