PREDICTIONS OF OBSERVATIONS OF SHUTTLE ENGINE FIRINGS

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# Predictions of AMOS Observations of Space Shuttle Engine Firings

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**Unclassified**

<table>
<thead>
<tr>
<th>a. REPORT</th>
<th>b. ABSTRACT</th>
<th>c. THIS PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>unclassified</td>
<td>unclassified</td>
<td>unclassified</td>
</tr>
</tbody>
</table>
Outline

• Introduction
• Chemical Mechanisms
• Source and Apparent Signals
• Instrumentation
• Conclusions and Future Work
Acknowledgements

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Shuttle engine firing observation scenario. Engine exhaust, consisting mostly of H_2O, interacts with O-atom in the atmosphere to produce internally excited species, OH(v) and H_2O*. The radiative decay of these excited species is attenuated by the atmosphere and observed from AMOS in the 2-5 μm region.
Chemical Mechanisms

• Signal is due to two major chemical mechanisms

\[ \text{O}^{(3\text{P})} + \text{H}_2\text{O}(X,^{1}\text{A}_1) \rightarrow \text{OH}(X,^{2}\Pi) + \text{OH}(X,^{2}\Pi), \quad \Delta \text{H} = +16.9 \text{ kcal mol}^{-1}, \quad (1) \]

\[ \text{O}^{(3\text{P})} + \text{H}_2\text{O}(X,^{1}\text{A}_1, (\nu_1 \nu_2 \nu_3,JK)) \rightarrow \text{O}^{(3\text{P})} + \text{H}_2\text{O}(X,^{1}\text{A}_1(\nu_1' \nu_2' \nu_3',J'K')). \quad (2) \]

• Single collision models for total signal

\[
I_{\text{space}}^{\Delta \lambda} \approx \left[ \frac{\sigma^*}{\sigma_{\text{tot}}} \right] N_{H_2O} T_{\Delta \lambda} = \text{(Photon efficiency)} \ast (\text{H}_2\text{O engine flux}) \ast \text{(atmospheric transmittance)} = \# \text{ photons per second}
\]

\[
\left[ \frac{\sigma^*}{\sigma_{\text{tot}}} \right] = \frac{1}{\sigma_{\text{tot}}} \sum_{\text{species}} \sum_{v=1} \nu \sigma^{\text{species}}_v
\]
Energy level diagram for O + H₂O collisions

Transition States
Product States

O + H₂O

O(³P) H₂O(¹A₁)

O(¹D) H₂O(¹A₁)

O(²Σ⁺) H₂O(²Π)

H₂O*(¹Σ⁺)

H₂(¹Σ⁺) O₂(³Σ⁺)

ν₁ ν₂ ν₃

kcal/mol (km/s)

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Cross sections for the reaction, $\text{O} + \text{H}_2\text{O} \rightarrow \text{OH}(v) + \text{OH}(v)$, as a function of collision velocity

$\text{O} + \text{H}_2\text{O} \rightarrow \text{OH}(v) + \text{OH}(v)$

![Graph showing cross sections for various velocities](image-url)
Cross sections for the reaction, $O + H_2O \rightarrow O + H_2O^*$ as a function of collision velocity

$O + H_2O \rightarrow O + H_2O^*$

[Graph showing cross sections as a function of velocity]
Photon production efficiency per collision and total source signal in photons s\(^{-1}\) as a function of velocity for PRCS engine firings.

The H\(_2\)O\(^*\) contribution has been split into H\(_2\)O 2.7 \(\mu\)m and H\(_2\)O 6.3 \(\mu\)m contributions. The OH(v) contribution is here called ‘OH 2.8 \(\mu\)m’. The OH 2.8 \(\mu\)m and H\(_2\)O 2.7 \(\mu\)m curves contribute to the 2-5 \(\mu\)m pass-band.
Normalized spectral radiance from OH(v) (black curve) and H₂O* (blue curve) at 8 km s⁻¹ relative collision velocity.

Source and Apparent Signals

The OH(v) and H₂O* curves have been separately normalized to 1.0 and the H₂O* curve displaced for clarity. The atmospheric transmittance for a 60 degree zenith look angle from AMOS is shown in red. Spectral resolution is 5 cm⁻¹.
Source and apparent (atmospherically attenuated) O\(H(v) + H_2O^*\) relative spectral radiance at 8 km s\(^{-1}\) relative collision velocity.
The OH(ν) and H$_2$O* curves have been separately normalized to 1.0 and the H$_2$O* curve displaced for clarity. The atmospheric transmittance for a 60 degree zenith look angle from AMOS is shown in red. Spectral resolution is 5 cm$^{-1}$. 

Normalized spectral radiance from OH(ν) (black curve) and H$_2$O* (blue curve) at 11 km s$^{-1}$ relative collision velocity.
Source and apparent (atmospherically attenuated) OH(v) + H$_2$O$^*$
relative spectral radiance at 11 km s$^{-1}$ relative collision velocity

(a) Source OH(v) + H$_2$O$^*$

(b) Apparent OH(v) + H$_2$O$^*$

5.0 3.33 2.5 2.0 microns

Relative Radiance

Wavenumber (cm$^{-1}$)

11 km s$^{-1}$

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Space Shuttle Plume Measurement Analysis

• Utilize Total Signal Calculation to Estimate a Signal-to-Noise for Two Available Spectrometers – 3.76e04 W (11 km/s Case)
• Assume Both Integrable onto AMOS Telescope (Most Likely B37)
• 5 km Diameter Plume at 390 km Altitude and 60 Degree View From Zenith
• Expect Plume Radiance to Fill the FOV (B37 is Only 3 mrad Total)
• Calculate Average Radiance by Dividing by $4\pi$ Steradians and Estimated Plume Area
ABB (Bomem) FTIR Spectrometer Spec’s

- Two Simultaneous Non-Imaging Detectors
  - 1 - 6 \(\mu\)m InSb, 1.37e-09 RMS NESR at 1 \(cm^{-1}\) Resolution
  - 2 - 15 \(\mu\)m MCT, 1.4e-08 NESR at 1 \(cm^{-1}\)
  - Currently Use LN2 for Detector Cooling
- 5, 28, 75 mrad Telescopes Available as Attachments
- LN2 Cooled Cold Source
- Weight – 45 kg Nominal
- Scan Rate and Spectral Resolution Specifications:

<table>
<thead>
<tr>
<th>Resolution (cm(^{-1}))</th>
<th>16</th>
<th>8</th>
<th>4</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame Rate (scans/sec)</td>
<td>64.6</td>
<td>47.8</td>
<td>31.4</td>
<td>18.6</td>
<td>10.3</td>
</tr>
<tr>
<td>Maximum Acq Time (sec)</td>
<td>242</td>
<td>163</td>
<td>125</td>
<td>104</td>
<td>95</td>
</tr>
</tbody>
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ABB FTIR InSb Detector S/N Calculations

![Graph showing the relationship between spectral resolution and signal-to-noise ratio over different measurement times.](image)

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Broadband Array Spectrograph System (BASS)

- Aerospace Corporation Sensor (Dave Lynch)
- Wavelength Dispersive System – 2 Prisms
- 116 Total Detectors
- 3 – 13.5 μm Waveband
- Approximately 0.1 μm Resolution (Much Lower Than Desired)
- Noise Equivalent Power: 4.0e-14 W/Sqrt(Hz) (1 Sec Integration)
- Frame Rate: 0.1 – 200 Hz
- Estimate S/N = 1448 Over the 3 – 4.2 μm Region
  - Calculation Not Reviewed by Aerospace Corp. Personnel
Conclusions and Future Work

• Total Signal (Watts) =

\[(\text{Efficiency in photons per H}_2\text{O}) \times (\# \text{ H}_2\text{O from engine s}^{-1}) \times (3.33 \times 10^3 \text{ cm}^{-1} / \text{photon}) \times (1.9863 \times 10^{-23} \text{ Joules/cm}^{-1}) \times (\text{atmospheric attenuation factor})\]

8 km s\(^{-1}\) → 1.26e4 Watts
11 km s\(^{-1}\) → 3.76e4 Watts

• Results compare well with previous observations at 11 km s\(^{-1}\)
• OH(v) is the major contributor
• More source signal (and a little more attenuation) at higher velocities
• Need high angle of attack firing to see signal
• ABB FTIR spectrometer not sensitive enough with present configuration
• BASS sensor appears to have required sensitivity but at the expense of low spectral resolution

• Future Work
  – Better O + H\(_2\)O → O + H\(_2\)O* cross sections
  – Analyze spatial distribution of radiation
  – Additional instrument analysis required