Chemical Species Tomography of Carbon Dioxide

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The FLITES consortium

Academia:
- Edinburgh
- Manchester
- Strathclyde
- Southampton

Large Corporate:
- Rolls-Royce
- Royal Dutch Shell

Small to Medium Enterprise:
- Covesion
- Fianium
- OptoSci

Other Partners and Sponsors
- Stanford
- INTA
- Altium
  - Hydrocarbon Spectroscopy
  - Test and Development
  - PCB Software (CAD)

WC IPT8, 26-29 Sep 2016, Iguassu Falls, Brazil
Aims for Future Commercial Aviation

- **Engine Efficiency Optimisation**
  - Fuel Burning & Economic Efficiency
  - Thrust Maximisation

- **Fuel Mixture Optimisation**
  - Low-Emission Fuels
  - Combustion Science

- **Engine Production**
  - Maintenance / Sign-Off
  - Novel Engine Designs

- **Aviation Regulation & Legislation**
  - Green Aviation
  - Environmental Concerns

...By opening up exhaust plume chemistry as a window on engine and fuel performance
**Aims for Future Commercial Aviation**

...By opening up exhaust plume chemistry as a window on engine and fuel performance
Detecting CO₂ and other Exhaust Gas Species

**Beer-Lambert Law**

\[ I_d = I_0 \cdot e^{-\alpha CL} \]

- The absorption of a chemical species is given by its vibration-rotation spectrum.
- The absorption is proportional to the path length \( L \) and concentration \( C \).

\[ \alpha_v = -\ln\left( \frac{I_t}{I_0} \right)_v = \int P(l) X(l) S[T(l)] \phi_v dl \]

- \( v \) = optical frequency
- \( l \) = path length
- \( P \) = pressure
- \( X \) = mole fraction
- \( T \) = temperature
- \( S \) = transition line strength
- \( \Phi \) = line shape function

**Wavelength Modulation Spectroscopy:**

**2f/1f normalisation scheme:**
Aims of phantom tests

Prior to engine test cell installation:

- Verify correct operation of all electronic, mechanical and optical subsystems
- Test signal recovery, spectroscopic fitting and image reconstruction algorithms

✓ Emulate a jet engine exhaust using tomography test phantoms
CO$_2$ phantoms

- Synthetically introduce a deterministic CO$_2$ concentration distribution

Annular propane burner

Exhausts: quasi-homogeneous circular CO$_2$ distribution

- Achieved output of 6% CO$_2$ at 250 °C (verified with point probe)
CO₂ phantom experimental matrix

- Systematically test the tomography system
- 8 experimental conditions

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Description</th>
<th>Imaging space</th>
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<tbody>
<tr>
<td>1</td>
<td>40 cm phantom at centre of imaging space</td>
<td></td>
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<tr>
<td>2</td>
<td>60 cm phantom -/-</td>
<td>135° 90° 45°</td>
</tr>
<tr>
<td>3</td>
<td>40 cm phantom at 0°</td>
<td>180° 0°</td>
</tr>
<tr>
<td>4</td>
<td>40 cm phantom at 45°</td>
<td>60 cm</td>
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<tr>
<td>5</td>
<td>40 cm phantom at 90°</td>
<td>225° 1.4 m</td>
</tr>
<tr>
<td>6</td>
<td>40 cm phantom at 135°</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>40 cm phantom at 180°</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Dual phantom (see diagram on the right):</td>
<td></td>
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<tr>
<td></td>
<td>60 cm phantom at 45°, edge of imaging space</td>
<td></td>
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<tr>
<td></td>
<td>40 cm phantom at 225°, 20 cm separation</td>
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</tbody>
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- Exposed all sampling beams to the CO₂ plume for a thorough system test
Data acquisition and analysis

- Captured Background (CO$_2$ off) and Signal data (CO$_2$ on) for 10 s and averaged
- Lock-in detector demodulated the fundamental (1f) and 1$^{st}$ harmonic (2f) signals

Computed the 1f normalised 2f signal:

\[
\frac{2f}{1f} = \sqrt{\left(\frac{X2f}{R1f} - \frac{X2f_{bk}}{R1f_{bk}}\right)^2 + \left(\frac{Y2f}{R1f} - \frac{Y2f_{bk}}{R1f_{bk}}\right)^2}
\]
Example of processed signal

- 2f/1f signal for Wavelength-Modulation Spectroscopy
- Compensated for background CO$_2$

Highly sufficient SNR achieved
- 2f/1f signal then fitted to spectroscopy databases to yield CO$_2$ concentration
Image reconstruction

- Two reconstruction algorithms developed and used

1) **Smoothness-imposing algorithm**
   - Projects highly detailed version of image space onto a lower detail image subspace
   - Solve inverse problem numerically using Tikhonov regularisation

2) **Positivity-imposing algorithm**
   - Reformulate the forward problem to preclude negative solutions
   - Project to lower detail image subspace
   - Linearise around a point and compute solution iteratively

- Feature smoothing
- Computationally efficient
- 1-step solution (non-iterative)

- Ideal for sparse concentration distributions
- Computationally efficient, 8 iterations typically needed
Preliminary results

- Smoothness-imposing algorithm

40 cm phantom positioned at 0, 45, 90, 135 and 180 degrees

Phantom boundary
Imaging space

40 cm phantom
60 cm phantom
Dual phantom

streak artefact

Phantom boundary
Imaging space
Preliminary results

- Positivity-imposing algorithm

40 cm phantom

60 cm phantom

Phantom boundary

Imaging space

Dual phantom reconstruction convergence

8 iterations
9 iterations
10 iterations
Conclusions

✓ Presented the first results from the FLITES project, tomographically imaging CO$_2$
✓ Verified the reconstruction algorithms with experimental data
✓ Demonstrated the robustness of 1f-normalised Wavelength Modulation Spectroscopy
✓ Reconstructed images show excellent localisation of features
  • We are optimising the subspace basis functions to reduce common artefacts
  • and also enhancing the spectroscopic fitting to achieve near-zero background
✓ Verified correct operation of all front-end installed instrumentation subsystems

➢ Next planned stage is to gather data behind the jet engine