Chemical Species Tomography of Carbon Dioxide

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Altium	PCB Software (CAD)

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- Fianium
- OptoSci

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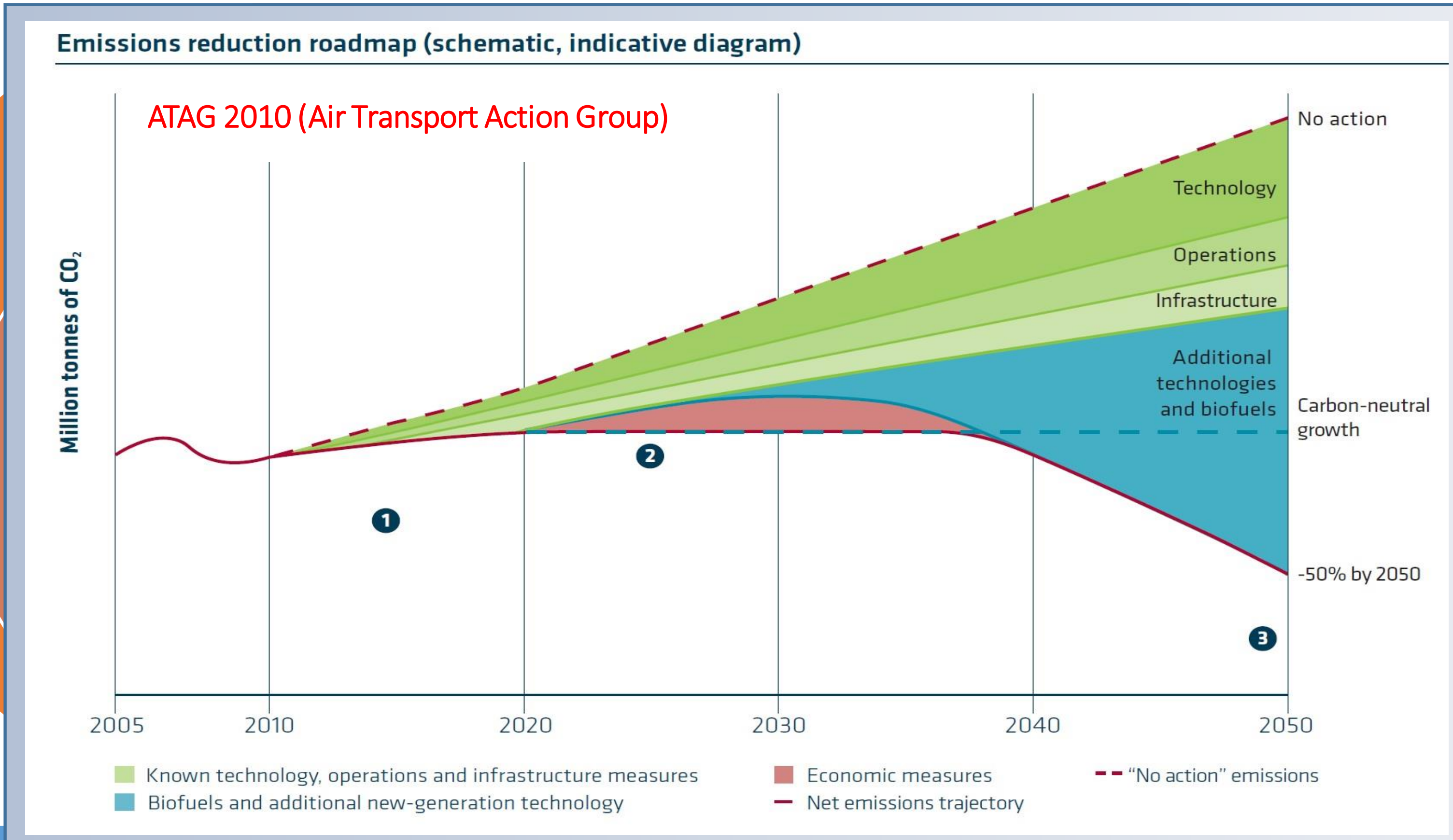
Aims for Future Commercial Aviation

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

EU ETS
Emissions Trading System

…By opening up exhaust plume chemistry as a window on engine and fuel performance

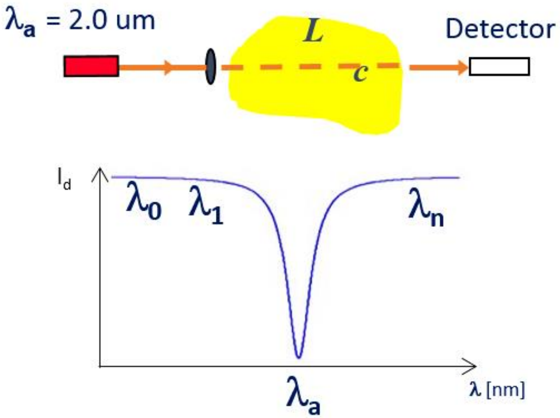
Aims for Future Commercial Aviation



…By opening up exhaust plume chemistry as a window on engine and fuel performance

Detecting CO_2 and other Exhaust Gas Species

Beer-Lambert Law



Path concentration integral:

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

- 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

$$\alpha_\nu = -\ln\left(\frac{I_t}{I_0}\right)_\nu = \int_l P(l)X(l)S[T(l)]\phi_\nu dl$$

- ν = optical frequency
- l = path length
- P = pressure
- X = mole fraction
- T = temperature
- S = transition line strength
- Φ = line shape function

<u>Wavelength Modulation Spectroscopy:</u>

Stewart G, Johnstone W, Bain J, Ruxton K, Duffin K (2011), Recovery of absolute gas absorption line shapes using tunable diode laser spectroscopy with wavelength modulation, *J Lightwave Technol*, 29, **6**

<u>2f/1f normalisation scheme:</u>

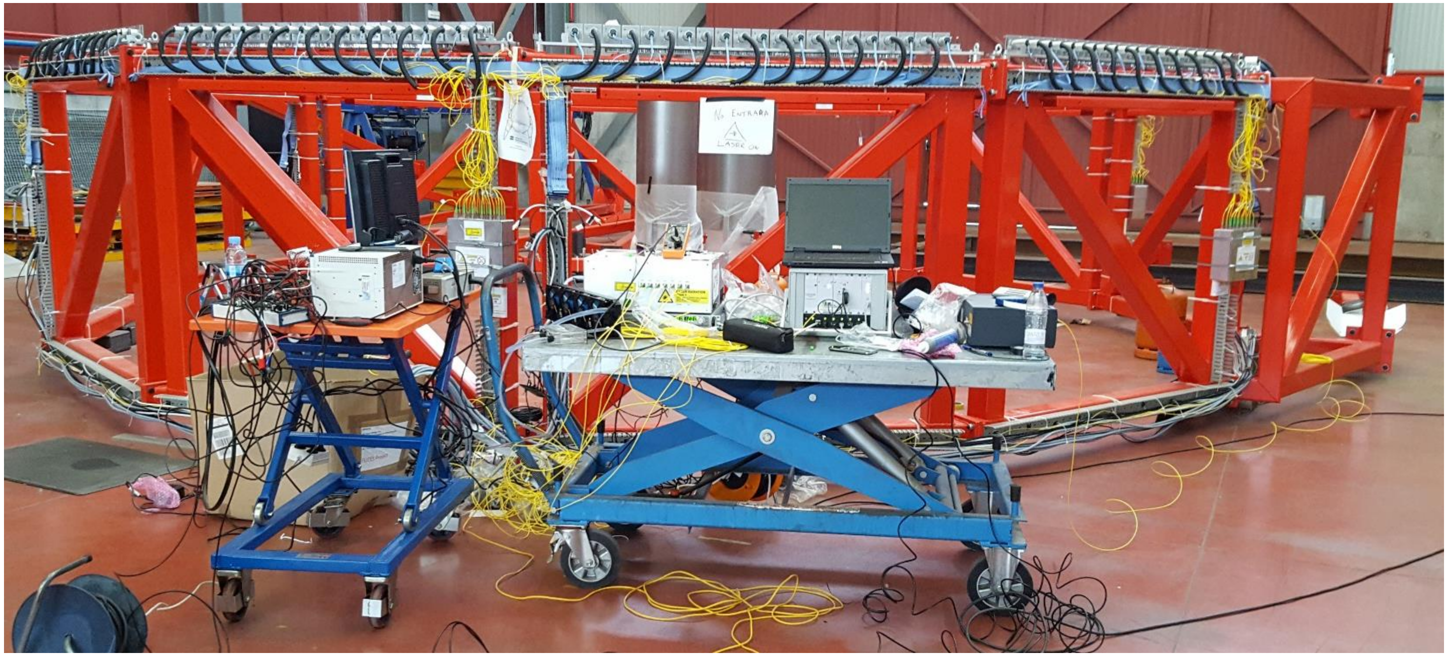
Rieker G, Jeffries J, Hanson R (2009), Calibration-free wavelength-modulation spectroscopy for measurements of gas temperature and concentration in harsh environments, Appl Optics, 48, **29**

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**

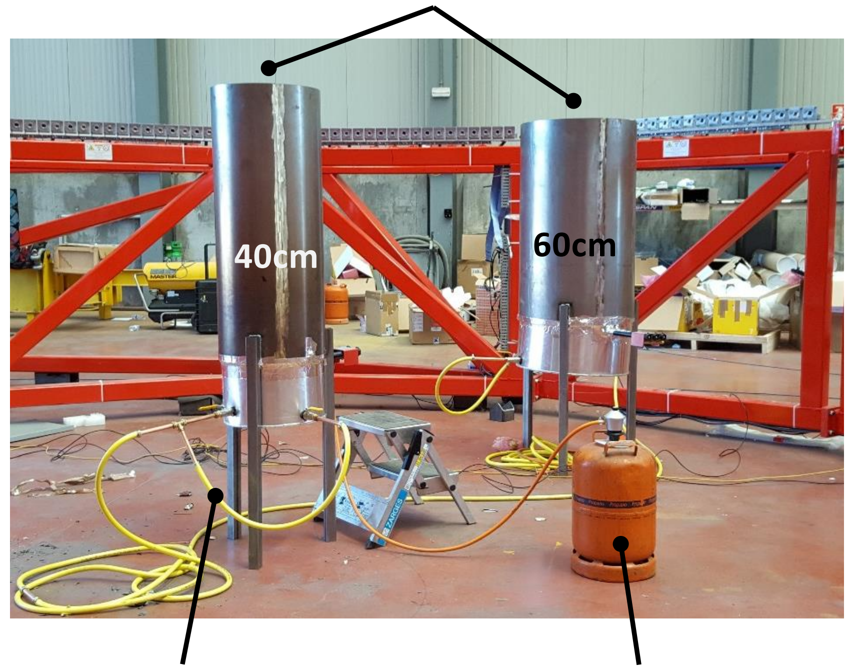


CO_2 phantoms

- Synthetically introduce a deterministic CO_2 concentration distribution

Annular propane burner

Exhausts: quasi-homogeneous circular CO_2 distribution



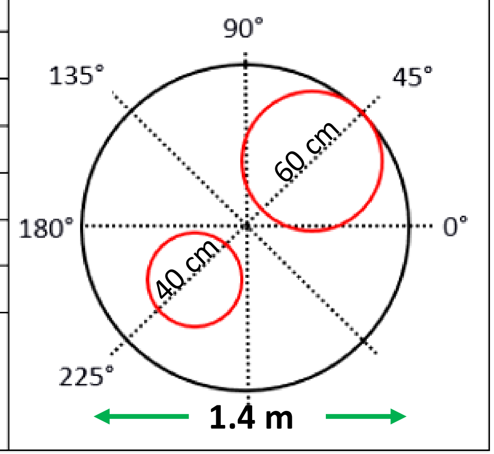
Aux CO_2 gas line

Propane tank

- Achieved output of 6% CO_2 at 250 °C (verified with point probe)

CO_2 phantom experimental matrix

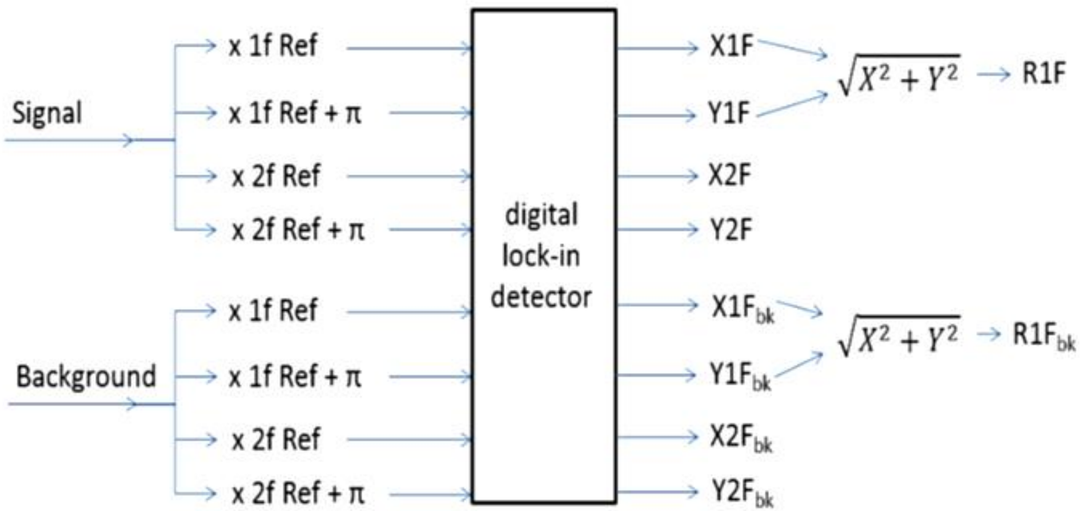
- Systematically test the tomography system
- 8 experimental conditions

<table>
<tr><th>Dataset</th><th>Description</th><th>Imaging space</th></tr>
<tr><td>1</td><td>40 cm phantom at centre of imaging space</td><td rowspan="8">
</td></tr>
<tr><td>2</td><td>60 cm phantom -//-</td></tr>
<tr><td>3</td><td>40 cm phantom at 0°</td></tr>
<tr><td>4</td><td>40 cm phantom at 45°</td></tr>
<tr><td>5</td><td>40 cm phantom at 90°</td></tr>
<tr><td>6</td><td>40 cm phantom at 135°</td></tr>
<tr><td>7</td><td>40 cm phantom at 180°</td></tr>
<tr><td>8</td><td><u>Dual phantom (see diagram on the right):</u>
60 cm phantom at 45°, edge of imaging space
40 cm phantom at 225°, 20 cm separation</td></tr>
</table>

- Exposed all sampling beams to the CO_2 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 1st harmonic (2f) signals



- Computed the 1f normalised 2f signal:

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

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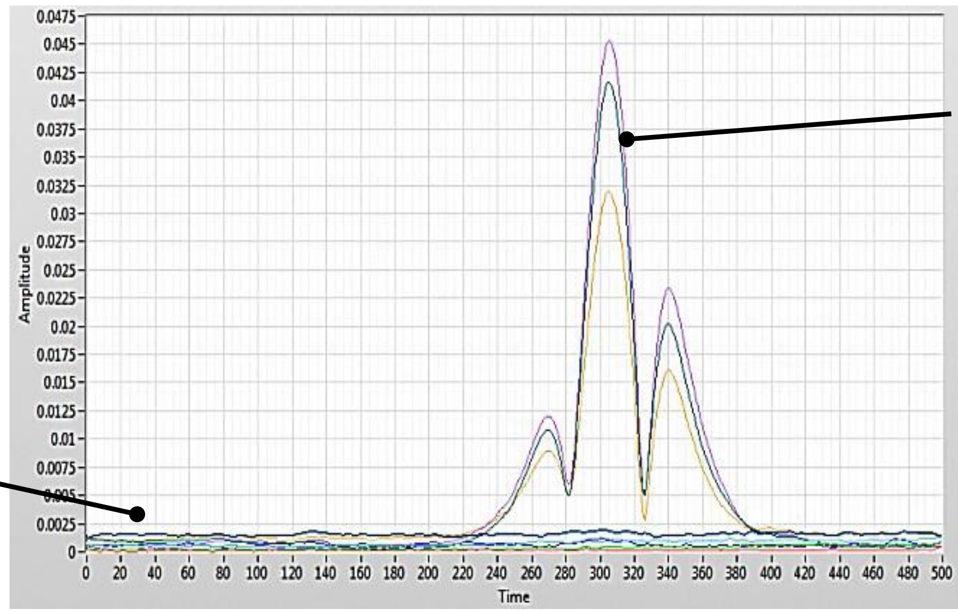
Example of processed signal

- 2f/1f signal for Wavelength-Modulation Spectroscopy
- Compensated for background CO_2



3 beams crossing the CO_2 plume (Dataset 1)

Background of beams outside of CO_2 plume

- 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*

$$c^* \xrightarrow[\text{error}]{\text{approximation}} \Pi c^* = \Phi r^* \xrightarrow[\text{error}]{\text{computational}} \Phi \hat{r}$$

High-dimensional space — Low-dimensional space — Inverse solution

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

  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*

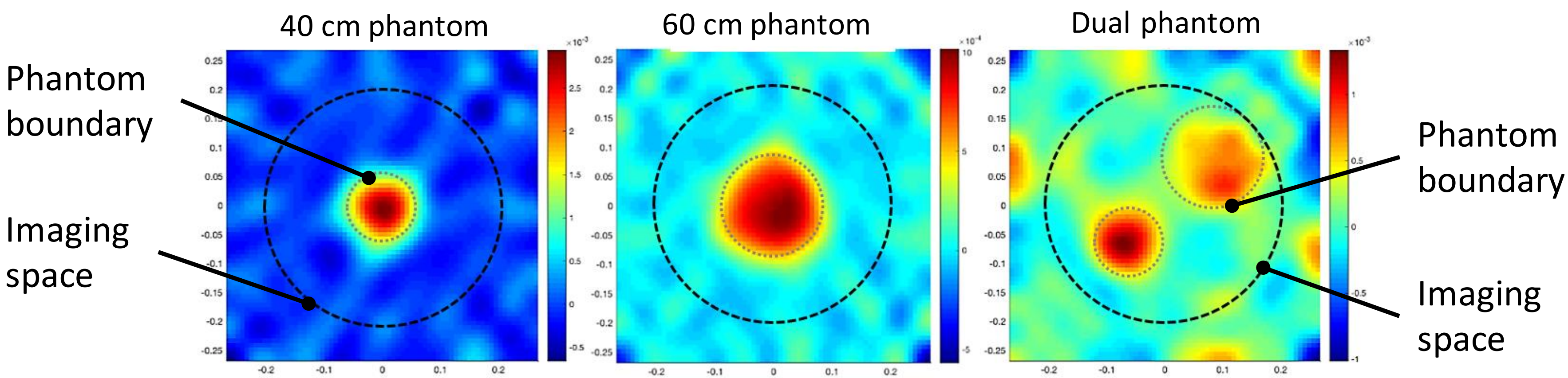
$$y = Ac \xrightarrow{z=\log(c)} y = Ae^z$$

standard linear forward model — reformulated non-linear forward model

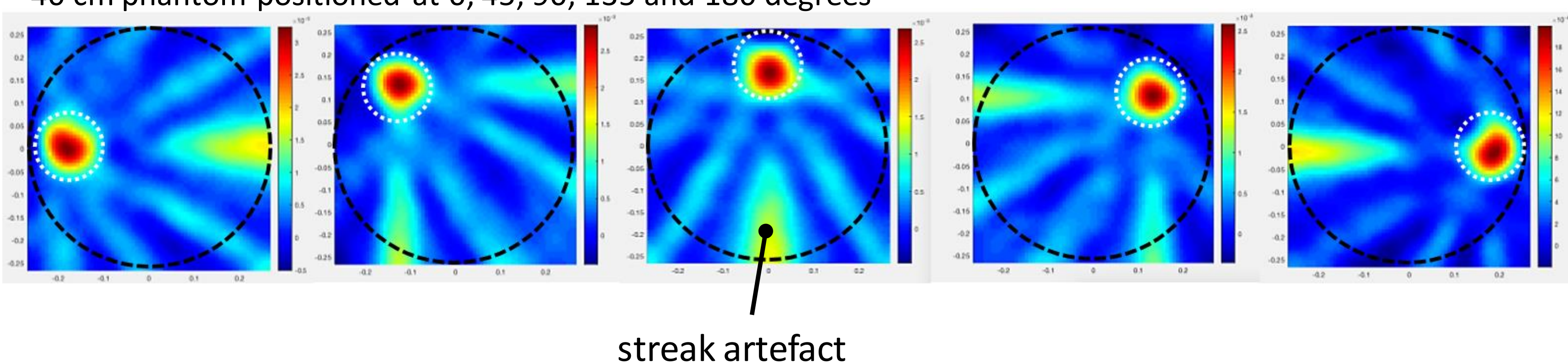
- ✓ Ideal for sparse concentration distributions
- ✓ Computationally efficient, 8 iterations typically needed

Preliminary results

- Smoothness-imposing algorithm



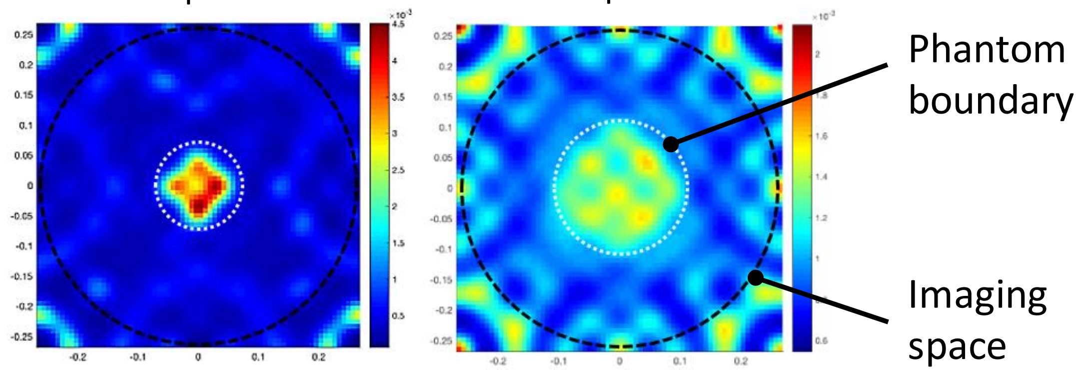
40 cm phantom positioned at 0, 45, 90, 135 and 180 degrees



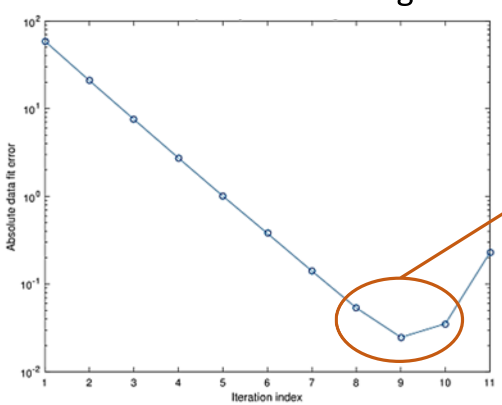
Preliminary results

- Positivity-imposing algorithm

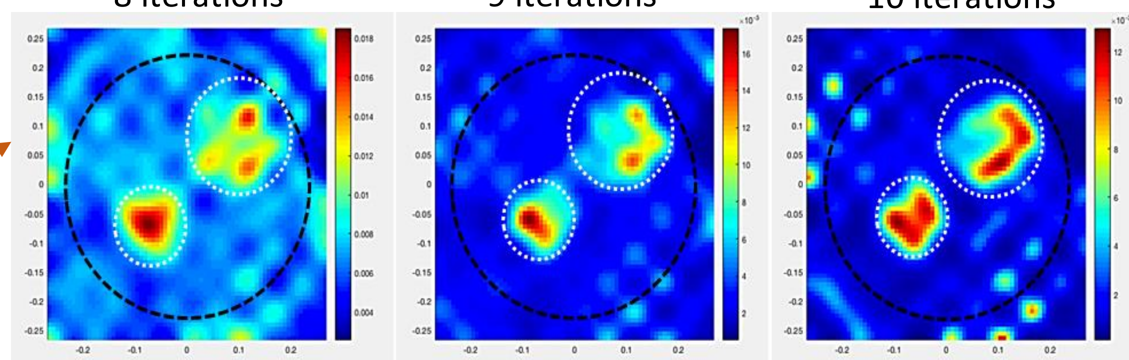
40 cm phantom 60 cm phantom



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