Scalable Modular Tomography Sensor for High-Speed Gas-Turbine Exhaust Imaging

ABSTRACT

Understanding the complex dynamics of gas-turbine exhaust is a cornerstone of modern aerospace and energy research, yet capturing real-time data in these volatile environments typically requires cumbersome, tailor-made hardware. Researchers from the UK have developed a novel design in Chemical Species Tomography (CST): a scalable, modularized sensor array capable of high-speed, 2D mapping of exhaust plumes. By deploying a 128-beam system managed by independent emitter-receiver units, researchers achieved spatial resolution of 8.1mm and instantaneous imaging with 250 frames per second. This modular approach, stabilized by precision control electronics, allows for the precise tracking of water vapor (H_2O) concentration and temperature distributions across various engine scales, providing a versatile tool for optimizing combustion efficiency, diagnosing gas-turbine exhaust, and reducing environmental impact.

GAS TURBINES

In the global effort to decarbonize the aviation, marine, and power generation sectors, the accurate diagnostics of combustion processes have become a critical priority. Modern gas turbines are under constant pressure to meet more stringent emission standards while simultaneously pushing the limits of thermal efficiency. To achieve this, engineers must understand the complex, three-dimensional spatiotemporal characteristics of exhaust gases, specifically temperature and concentration profiles.[1] These parameters serve as the fingerprint of the combustion process, providing direct evidence of fuel-air mixing efficiency, flame stability, and the overall health of the engine's internal components. Whether the turbine is used for propulsion in aviation and aerospace applications or power generation critical to energy grids (**Figure 1**), there is a need to provide insight into the combustion, exhaust, and general turbine performance.
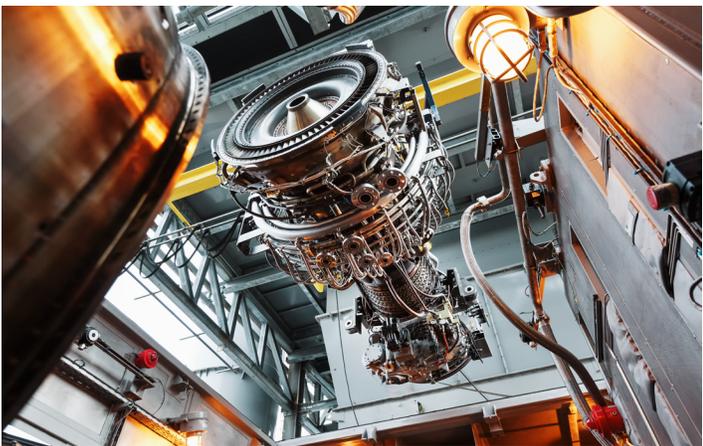

Figure 1.   Gas turbine for generating electricity.

PROBLEMS AND GOALS

Traditionally, turbine exhaust diagnostics have relied on extractive sampling probes. However, these physical probes are invasive and can significantly disturb the flow field they are intended to measure. Furthermore, extractive methods are inherently slow and provide only point-source data, which fails to capture the spatial inhomogeneities and rapid transient phenomena that define turbulent combustion.[1] This lack of real-time spatial data makes it difficult to validate numerical combustion models or to detect localized problems that can lead to premature turbine blade failure. Non-intrusive techniques like Chemical Species Tomography (CST) offer a transformative solution, providing high-speed, two-dimensional cross-sectional images of the exhaust plume. By visualizing these dynamic gas-state distributions through laser absorption spectroscopy, researchers can optimize combustion designs for lean-burn technology, reduce unnecessary emissions, and significantly extend the operational lifespan of critical engine hardware.

Developing a CST system capable of surviving and performing in a gas-turbine test cell presents a formidable set of engineering challenges. The exhaust environment is notoriously hostile: temperatures can reach 800ºC, gas velocities often reach 150 m/s, and acoustic noise levels can climb as high as 135 dB. This intense vibrational and thermal stress can easily misalign optical components or introduce significant electronic noise into the detection circuitry. Furthermore, the physical scale of gas turbines varies wildly across the industry. An Auxiliary Power Unit (APU) might have an exhaust diameter of just 0.2 m, while a large-scale civil aero-engine can exceed 2.0 m. An ideal CTS sensor should be modular and scalable for all exhaust applications.[1]

Historically, this meant that a CST system designed for one engine was entirely incompatible with another, requiring a complete and expensive mechanical redesign for every new test campaign. Existing systems are also plagued by a trade-off between spatial and temporal resolution; systems with enough laser beams for clear imaging are often too slow to capture dynamic pulsations (limited to 1–2 fps), while faster systems lack the beam density to resolve small-scale flow features.

METHOD

Researchers from the Universities of Edinburgh, Sheffield, and Strathclyde, UK, have developed a 128-beam CST sensor arranged into four equi-angular projections (0°, 45°, 90°, and 135°), with 32 parallel beams per projection. Every individual laser beam is managed by a self-contained, compact emitter-receiver module shown in **Figure 2**. By standardizing these units, the sensor can be scaled to any engine size simply by rearranging the modules on a different octagonal frame. Each emitter unit consists of a miniaturized fiber-coupled C-lens collimator, a right-angle prism, and a spring-loaded mirror mount allowing for precision alignment. The receiver units utilize a convex lens to focus transmitted light onto a PIN photodiode connected to a custom Trans-Impedance Amplifier (TIA) circuit with a -3 dB bandwidth of 3.16 MHz.[1]
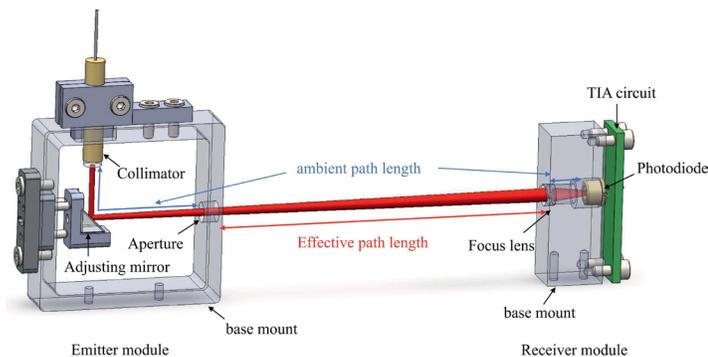

Figure 2. Design of a laser emitter-receiver unit for the modularized CST sensor.[1]

To validate the modularized CST sensor, researchers set out to reconstruct water vapor concentration and temperature fields in an exhaust plume of a commercial gas turbine Auxiliary Power Unit (APU). Due to the modular and scalable nature of the design, researchers could assemble the 128-beam CST sensor for a specific APU for testing and validation (**Figure 3**). Before field-deploying their system, experiments in the lab could confirm performance on a smaller scale in post-combustion flow fields with varying profiles and dynamics.
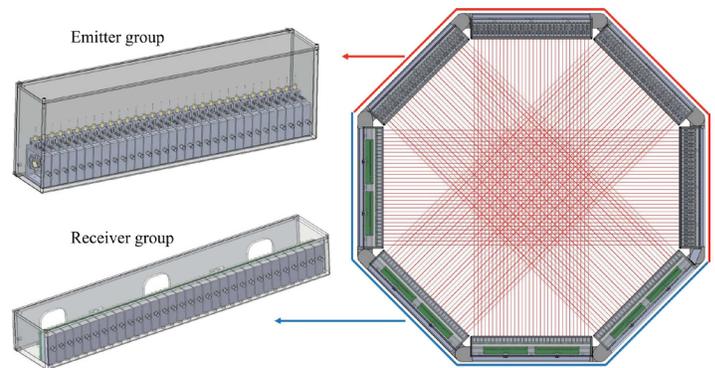

Figure 3. Assembly of the 128-beam modularized CST sensor for APU exhaust imaging.[1]

The setup for the lab-scale validation is shown in **Figure 4** with the 128-beam design separated into four emitter and receiver modules, two lasers with splitters and laser drivers and temperature controllers, a signal generator for frequency scanning and modulation, a data acquisition (DAQ) system, and a workstation for data analysis.
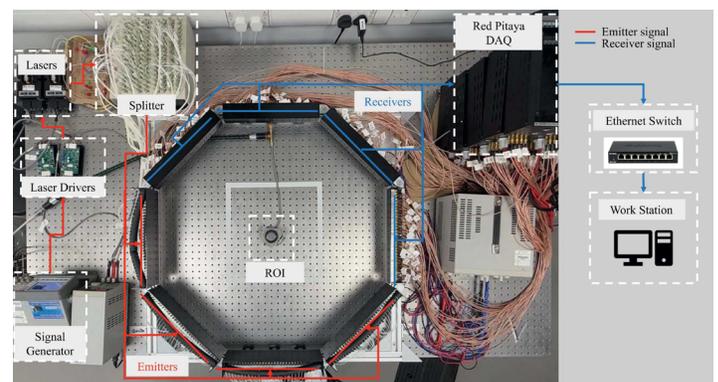

Figure 4. CST system setup for lab-scale validation.[1]

The system targets two water vapor absorption transitions at 1391 nm (7185.6 cm^{-1}) and 1343 nm (7444.4 cm^{-1}) to perform ratio thermometry, which provides sensitivity across a wide range of 300 to 1800 K, capturing the temperature range of the exhaust plume.[1] Based on the Beer-Lambert Law, researchers can use laser absorption spectroscopy to determine the water concentration. To ensure stable laser operation, Wavelength Electronics LDTC2/2E controllers were integrated to manage the current and temperature of the Distributed Feedback (DFB) laser diodes. This setup enabled Wavelength Modulation Spectroscopy (WMS), with injection currents scanned at 1 kHz and modulated at 188 kHz and 250 kHz for high signal-to-noise ratio detection. A high-speed 16-hub data acquisition (DAQ) system digitized the signals, facilitating the 250 fps imaging rate.

For on-site testing on the APU exhaust plume (**Figure 5**), the region of interest (ROI) was one of the main parameters that changed with the scalable and modular CST design. The ROI was set with a side length of 310 mm to cover the full extent of the plume. With the ROI meshed into 50 x 50 grid cells, the spatial resolution in this ROI is 8.1 mm.[1]
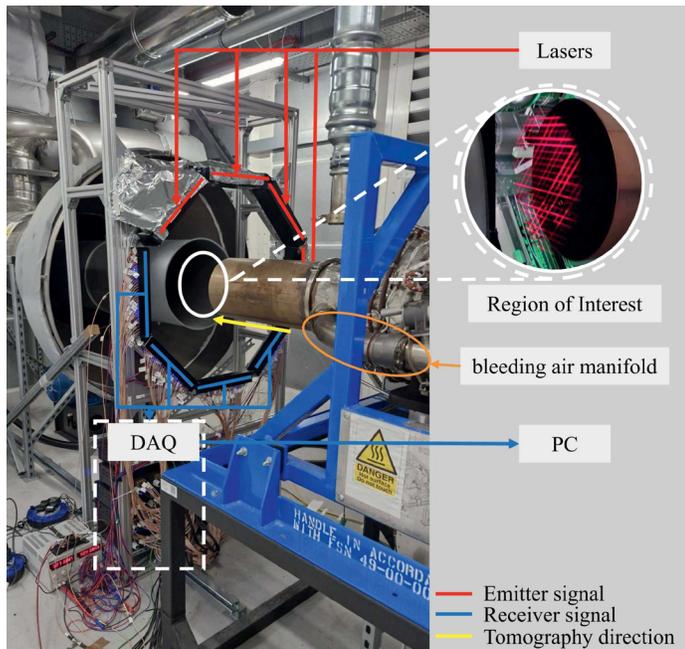

Figure 5. On-site CST system setup on imaging the APU exhaust plume with beams from two projection angles (out of the four angles, due to the limited intensity of the red laser) is shown in ROI visualization.[1]

RESULTS

The system's efficacy was first validated through lab-scale experiments on propane/air flames and subsequently deployed on a commercial Honeywell 131-9 A APU. The results demonstrated significant advancements in diagnostic precision.

Researchers first reconstructed water vapor concentration and temperature distributions in post-combustion fields with lab-scale burners (annular and triple flame). With the central ROI reduced to 160 x 160 mm², imaging of the temperature and concentration of water vapor is determined. **Figure 6** shows the reconstructions of both the annular and triple flame setups. For a reconstructed annular flame, the system measured a peak temperature of 1127.4 K and a peak concentration of 0.059. In triple-flame tests, the sensor accurately localized three distinct hot spots with peak temperatures and concentrations of 1264 K and 0.041, 1141 K and 0.036, and 1279 K and 0.038.[1]
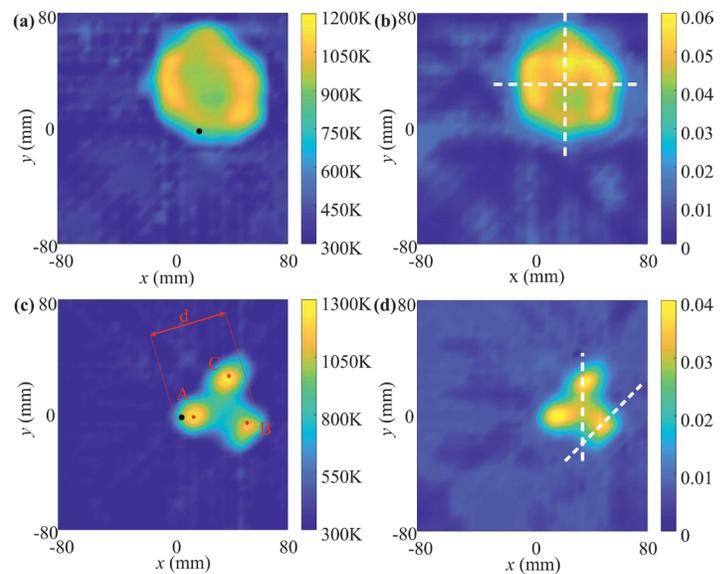

Figure 6. One-second averaged reconstructions of (a) temperature and (b) H_2O concentration of the annular flame, and (c) temperature and (d) H_2O concentration of the triple flame.[1]

The reconstructed flames show strong agreement with the expected flame features, specifically the flame positions, geometric dimensions, and non-uniformity. The measured distance between the triple-flame sub-centers was 54.9 mm, deviating by only 1.5 mm from the actual 56.4 mm layout, confirming the sensor's spatial accuracy. The spatial distribution also gives insight into the internal structure and symmetry of the flames.[1]

At 250 fps, the sensor captured a dominant fluctuation frequency of 9 Hz in the annular flame, likely caused by periodic vortex shedding,[1] a feature that slower systems would miss entirely. With the reconstructions successfully performed, the CST sensor was further validated through the on-site APU experiment.

As thermal expansion can lead to 20-30 mm extension of the experiment exhaust tube, the CST imaging plane was chosen 45 mm downstream from the exit. With only three minutes of test runtime, the sensor successfully reconstructed 2D fields across a 310 mm ROI. There was minimal noise added to the system due to mechanical vibrations because of the well-aligned laser beams. The wavelength modulation spectroscopy (WMS) based CST system provided raw laser transmission of one representation beam across four consecutive scans in 4 ms (**Figure 7**a) as well as demodulated $2f/1f$ signals at the corresponding water vapor absorption feature transitions (**Figure 7**b & c). **Figure 8** shows the reconstruction of the distributions of temperature and water vapor concentrations of the gas turbine. The reconstructions clearly revealed non-uniform gas-state distributions in the APU's exhaust plume, proving the system's readiness for industrial environments.
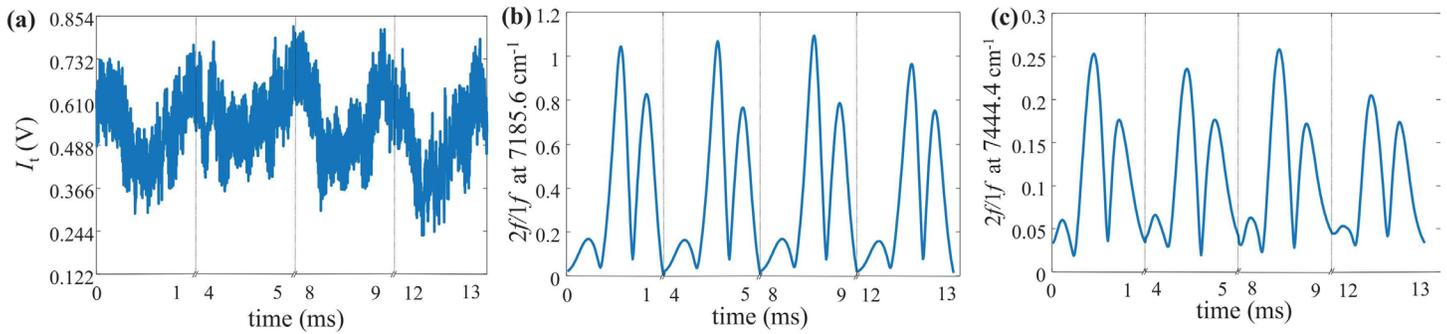
Figure 7. Four-consecutive-scan laser transmission of a laser beam penetrating the APU exhaust. (a) shows the TDM raw laser transmissions. (b) and (c) show the demodulated 2f/1f signals centered at 7185.6 cm^{-1} and 7444.4 cm^{-1}, respectively.[1]
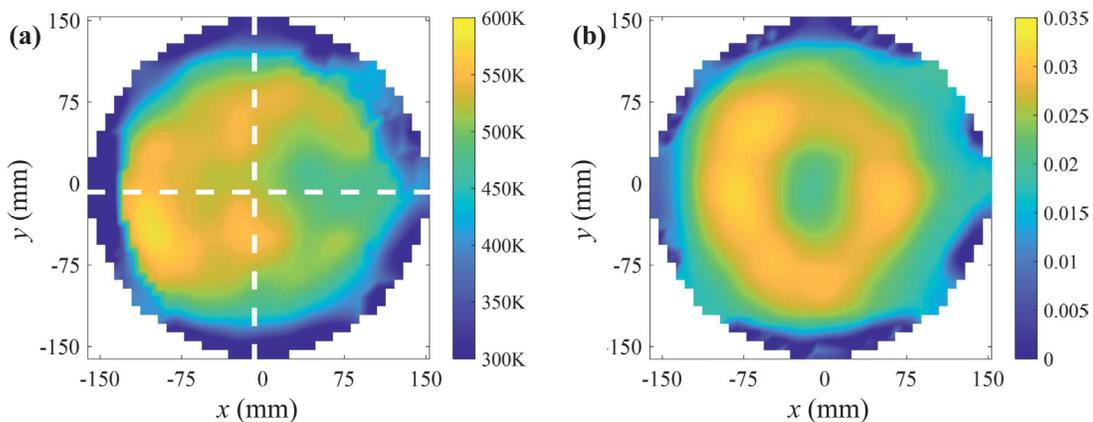

Figure 8. Distributions of (a) temperature and (b) H$_2$O concentration reconstructed using one-second-averaged measurement data under no-load conditions.[1]

WMS served as one of the primary mechanisms of noise rejection, minimizing the turbulence-induced beam steering, thermal background radiation, and mechanical vibration noises seen in the raw laser transmission. In the temperature and water concentration distributions, higher standard deviations were observed near the flow boundaries, showing enhanced turbulence and mixing in the plume region downstream of the APU exhaust plume. The central region exhibited lower variability. Mixing and swirling of the combustion products in the exhaust created the ring-shaped profile in the water concentration.[1]

This modularized approach paves the way for future research into large-scale gas turbine testing. Because individual modules contain both emitter and receiver units, the modular design allows for ease of maintenance and replacement of individual modules in case of potential misalignment or damage when deployed. The successful deployment of this 128-beam modular sensor on a gas turbine APU validates a new paradigm in industrial diagnostics. By simply rearranging the 128 modules on larger octagonal frames and adjusting the ROI to the appropriate size, researchers can adapt the high-speed sensor for turbines with diameters exceeding 1.5 m. These results prove that modular architecture is a versatile, cost-effective, and scalable solution for real-world turbine assessment, replacing rigid hardware with a plug-and-play blueprint for future low-emission engine designs, facilitating standardized, commercial-grade CST instruments for global aviation and power industries.

WAVELENGTH'S ROLE

Researchers utilized Wavelength Electronics' LDTC2/2E Laser Diode and Temperature Controller, which played an essential role in the success of this modularized CST architecture. In high-speed tomography, any instability in the laser source can introduce errors that are amplified during the image reconstruction process. Stable laser output during modulation and frequency scanning is crucial to accurate laser transmission data. The LDTC2/2E combines the drive power of the WLD33ND laser diode driver and the WTC32ND temperature controller onto one high-precision board.

The laser drivers provided up to 2.2A of drive current to the laser and stable output for WMS operation. The lasers were scanned at 1 kHz and modulated at 188 kHz and 250 kHz. Although most of the noise in the experiment was mechanical or thermal, electrical noise was minimized through the LDTC2/2E to the laser diode.

The temperature controllers also provided up to 2.2A of drive current to the TECs, driving the laser diodes' temperature. With a temperature stability as low as 0.0009ºC, the LDTC2/2E enabled the lasers to consistently output the desired wavelength at the high sensitivities that laser absorption spectroscopy requires.

The LDTC2/2E enabled consistent and high-speed dynamic imaging for the gas turbine exhaust, maintaining constant current and stable temperature for highly sensitive water vapor concentration and temperature reconstruction. The combination of fully featured controllers, engineering support, and responsive technical assistance illustrates how Wavelength Electronics collaborates with high-tech researchers and manufacturers to successfully execute complex, strategic projects while ensuring reliable performance in challenging environments.

REFERENCES

1. Zhou, M., Zhang, R., Xia, Y., Chen, Y., Ahmed, I., Pourkashanian, M., Armstrong, I., Lengden, M., Johnstone, W., McCann, H., & Liu, C. A modularized chemical species tomography sensor for dynamic imaging of gas-turbine exhaust. *Sensors and Actuators B: Chemical*, 444, 138459 (**2025**). https://doi.org/10.1016/j.snb.2025.138459

USEFUL LINKS

- LDTC2/2E Product Page

PERMISSIONS

Figures 2 - 8 in this case study were obtained from Reference 1. The article (Ref. 1) is distributed under terms of Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided that you give appropriate credit to the original authors and the source, provide a link to the Creative Commons license, and indicate if changes were made.

No changes were made to the captions or images. They are presented here in their original form.

PRODUCTS USED
LDTC2/2 E

KEYWORDS
Chemical species tomography, CST, laser absorption spectroscopy, gas turbine, exhaust gas temperature, water vapor concentration, laser diode driver, temperature controller, LDTC2/2E, dynamic imaging, modularized

REVISION HISTORY

Document Number: CS-LDTC17

REVISION	DATE	NOTES
A	January 2026	Initial Release