Progress towards Non-Intrusive Optical Measurement of Gas Turbine Exhaust Species Distributions

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Abstract—We report on the development of three systems intended to provide fast, non-intrusive measurement of cross-sectional distributions of pollutant species within gas turbine exhaust flows, during ground-based testing. This research is motivated by the need for measurement systems to support the introduction of technologies for reducing the environmental impact of civil aviation. Tomographic techniques will allow estimation of the distributions of CO_2, unburnt hydrocarbons (UHC), and soot, without obstruction of the exhaust, bypass or entrained flows, from measurements made in a plane immediately aft of the engine.

We describe a CO_2 imaging system that performs wavelength modulation spectroscopy (WMS) simultaneously on 126 beam paths. Its novel architecture uses a Tm-doped fiber amplifier to generate sufficient optical power for the entire beam array (> 3 W) from a single 1997.2 nm diode-laser seed, reducing cost and enabling fully parallel detection and signal recovery. Various optical propagation issues are considered, including those arising from the varying degrees of interaction with the exhaust flow that exist within the beam array, as well as pointing errors arising from the limited rigidity of the measurement system's structure.

We also report first steps towards a similar UHC measurement system, operating in the mid-infrared (MIR) region and targeting partially decomposed or oxidized fuel constituents, including formaldehyde and propene. Progress towards the chalcogenide glasses and fibers, needed for light delivery and/or amplification at these wavelengths is described.

Finally, we report on the development status of a tomographic soot imaging system, based on laser induced incandescence (LII). We have demonstrated both long (192 ns) and short (17 ns) pulse variants of LII using fiber laser sources. Single path tests on a laboratory soot generator and, in the long pulse case, on a jet engine have confirmed that the energy and beam quality available from the fiber lasers is sufficient to enable an autoprojection approach, using just two intensified CCD cameras having 'near-orthogonal' views, with respect to the excitation laser.

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1. INTRODUCTION

The past two decades have seen public concern over the environmental impact of civil aviation increase markedly, to the point where it has the potential to significantly inhibit the sector's growth. In 2010, the UK airport operator BAA was forced to drop plans for expansion at Heathrow and Stansted, in the face of strong local opposition and a consequent loss of government backing for the proposal [1]. Regulatory pressure on in-flight emissions is also on the increase; the EU Emissions Trading Scheme, applicable to flights within the EEA, commenced in 2010 and imposes a tradable *diminishing* cap on CO_2 emissions. Technological solutions are only one aspect of achieving more sustainable aviation [2] but are able to play an important role in both addressing public concerns and meeting regulatory targets. Many alternative sustainability measures involve constrained or reduced air travel, which is unattractive from an industry perspective and divides public opinion regarding the appropriate balance between environmental and economic priorities. In contrast to this, the ability of technological solutions – whether to do with the engines, airframe or use of alternative fuels – to reduce per km emissions makes them almost universally popular; it is hard to argue against improved efficiency.

The introduction of new technologies against a regulatory backdrop can, however, be problematic. In some cases, established measurement methods are unable to keep pace with technological development. Within the aviation sector, smoke number [3] remains the industry basis of regulatory standards relating to smoke emissions from gas turbine engines, even though modern engines are rapidly approaching the limits of its sensitivity [4]. Other industries subject to strong environmental emissions regulation have experienced similar situations. The automotive sector has sometimes found itself poorly equipped to undertake the measurements necessary to meet evolving standards. Euro 6 (September 2014) [5] imposes particulate matter limits that are just 3.6% of those imposed at the Euro standard series' inception in 1992. The same period has seen similar reductions in permissible levels of other species and the regulation of NO_X and hydrocarbon emissions. A particularly undesirable situation can occur when regulation itself moves ahead of the means to verify compliance, a situation that some would argue exists in the waste incineration industry in regard to combustion chamber gas temperature. The rationale here was that the introduction of regulation would provide the demand necessary to drive commercial instrument development. In reality, no wholly satisfactory solution has been realized and compliance is often less-than-convincingly demonstrated using the defense of 'best available technology' and considerable reliance on computational fluid dynamics modelling [6]. Returning to the aviation sector, it is clearly desirable that appropriate measurement tools are developed to support the introduction of those innovations in engine and fuel technology that must ultimately reduce the environmental impact of civil aviation.

Extractive techniques presently remain the mainstay of emissions measurement within the sector, despite their significant limitations. They offer very limited temporal resolution, restricting their application to quasi-static situations, and their high extraction to measurement latency effectively precludes measurements involving transient species. Where spatial resolution is available, for example by mechanical scanning of the sampling point, the information is typically not simultaneous across the flow field. Such arrangements can also affect other measurements, e.g. acoustics, precluding their simultaneous use. Line-of-sight optical techniques are latency free and have obvious potential for improved temporal resolution but they have enjoyed limited take up, perhaps on account of the need to interpret path integrated absorption measurements.

In this paper, we will provide an overview of a series of instruments currently being developed to enhance existing measurement capability in respect of aero engine emissions. The work is being undertaken by the FLITES consortium, which comprises four leading UK universities (Strathclyde, Southampton, Edinburgh, and Manchester) working in conjunction with industrial partners Shell, Rolls-Royce, OptoSci, Fianium and Covesion. The instruments bring together the consortium's expertise in fiber laser systems, tunable diode laser absorption spectroscopy (TDLAS), laser induced incandescence (LII) and optical tomography to address the measurement of cross-sectional distributions of CO_2, soot and UHCs in jet exhaust plumes. By overcoming the path-integration limitation associated with conventional line-of-sight optical diagnostics, this combination of technologies has the potential to deliver non-intrusive emissions measurement with hitherto unavailable spatiotemporal resolution. The program also includes preliminary work on adding NO_X measurement capability, in anticipation of further technological progress in the mid-IR region.

The systems will initially be used in a development test bed context, although their design means that on-wing ground-based tests will ultimately be practicable, suggesting potential application to in-service diagnostics. In contrast to many instrument development studies, the FLITES systems will be applied to current generation engines, with already low emissions. Following validation on conventional jet fuels, the systems will be used in tests of a number of biofuels to illustrate their utility in supporting technology adoption. As Bainbridge [7] notes, "… sustainable alternative fuels will play a central role in the future of aviation … there is greater work involved in the assessment of data gained from these sources as opposed to those with standard emission factors."

In this paper, we first provide an overview of the manner in which the systems will be deployed, followed by consideration of the difficulties associated with cross-plume optical measurements. We will then describe the proposed design and current implementation status of each system.

programme is being carried out by the FLITES consortium (see www.flites.eu).

2. SYSTEM OVERVIEW

Within the test bed, the systems are intended to be operated immediately aft of the engine, before the exhaust flow enters the detuner. In order that the systems do not affect any concurrent measurements, their components are all positioned outside of the exhaust, bypass and entrained flows, necessitating optical path lengths of at least 7 m. The CO_2 and UHC systems are based on infrared absorption tomography techniques [8, 9] and will be mounted on a dodecagonal gantry, implementing six tomographic projection angles (Figure 1).[1] Optical field-of-view considerations mean that some elements of the LII-based soot measurement system are mounted somewhat further from the plume axis. Although the systems are not fully coplanar, at typical flow velocities their axial displacement corresponds to a temporal offset in the millisecond regime, slightly less than the time typically required for each spectral scan.
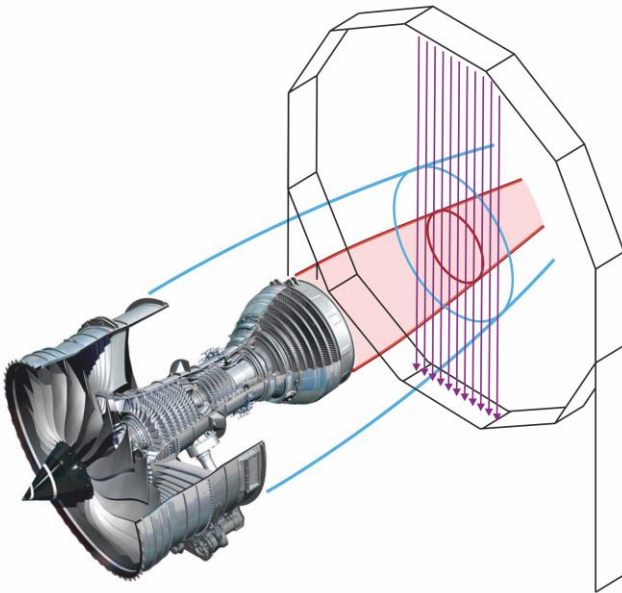
Figure 1 – Dodecagonal mounting frame for tomographic systems showing approximate extent of exhaust and bypass flows and their intersection with one projection (Trent engine cutaway © Rolls-Royce plc)

3. OPTICAL CONSIDERATIONS

Optical measurements within jet exhaust flows must consider the effects of the flow itself upon beam propagation. Indeed, one of the earliest applications of laser diagnostics was in the characterization of turbulence within jet exhaust [11]. The exhaust flow's high velocity and temperature combine to generate turbulence over a wide range of scales with strong refractive index gradients. Light propagation through turbulent atmospheres has been studied extensively in several fields, including astronomy and free space optical communications, but the resulting literature provides little quantitative insight into the expected propagation behavior in jet plumes. Of greater utility is work considering the propagation of laser-based IR countermeasures through the protected aircraft's own exhaust, e.g. [12, 13].

The effect of the plume on the propagating beam can be described in terms of the induced beam wander (steering) and scatter (divergence). Sirazetdinov [14] provides a detailed theoretical and experimental treatment, addressing the effects of wavelength, beam diameter and intersection angle, and has proved particularly useful. Even this has significant shortcomings for our purposes as the models developed for wander and divergence are strictly valid only for diametric intersection with the plume. As can be seen from Figure 1, a tomographic measurement grid will include beams having variable proportions of bulk and surface scales, as well as beams that remain entirely outside of the hot exhaust region. For diametric beams, the literature consensus is that plume-induced divergence is unlikely to exceed 250 µrad rms but will give rise to a fine grained speckle pattern and considerable scintillation. Beam wander is expected to be less significant, contributing up to 150 µrad rms. The overall spreading effect of the plume is therefore expected to be around 300 µrad rms, which in the proposed frame geometry would lead to 7 mm (pk-pk) of beam expansion. This is insufficient to pose a crosstalk problem in the proposed system geometries but does have other implications for the design of the detection system, as discussed below. Importantly, from a tomographic image reconstruction perspective, the absence of crosstalk enables the use of so-called 'hard-field' methods, in which straight line beam propagation from source to receive may be assumed.

Pointing errors, arising from the finite rigidity of the mounting structure, must also be considered. The stability of the frame has been modelled, using forcing vibrations measured in the proposed test venue, and modified to enhance its performance in this respect. Construction of the frame is due to commence in early 2015.

The combined effects of plume-induced divergence and wander, scintillation and pointing error bring surprising subtlety to the optical design of the beam path and detector. Our overall aim is optimization of the properties of the signal collected from each detector. The combination of high plume velocity and short turbulence scales largely rule out methods reliant on 'freezing' the wavefront disturbance. Even if the disturbance bandwidth were manageable, wavelength chirp is inherent in TDLAS so the effects of

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[1] This six-projection design was arrived at following detailed simulation of the measurement grid's performance, including consideration of annular burner configurations; see [10]   D. McCormick, M. G. Twynstra, K. J. Daun, and H. McCann, "Optimising laser absorption tomography beam arrays for imaging chemical species in gas turbine engine exhaust plumes," in *WCIPT7: 7th World Congress on Industrial Process Tomography*, Krakow, Poland, 2013, pp. 505-514.

dynamic speckle are inescapable. In the absence of the plume, it would be reasonable to overfill the receiver to mitigate the effects of pointing error but this is likely to degrade signals collected in the plume's presence as increased scintillation will arise from partial sampling of the speckle pattern. Aperture averaging, in which the full beam is integrated at the detector, is highly desirable in this regard but the use of large area detectors incurs noise, bandwidth and cost penalties.
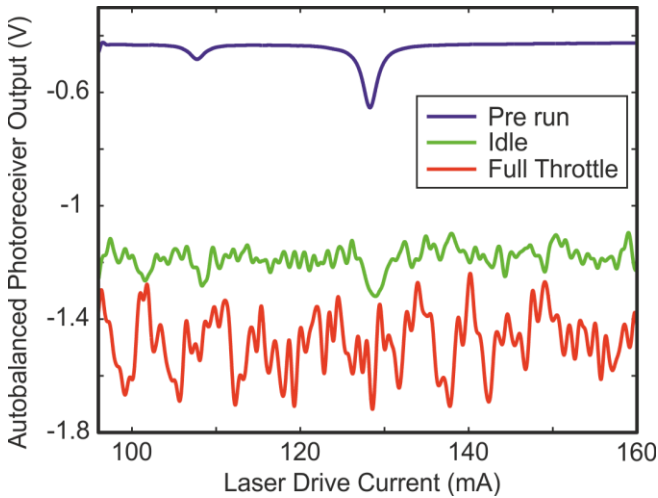
Figure 2 – Effect of jet plume on direct TDLAS measurement over a near-diametric 2.5 m path.

The seriousness of these issues is underlined by Figure 2, which shows three water vapor line spectra acquired using a direct TDLAS system under engine off, idle and full thrust conditions. Particularly worrying is the increase in these effects that may be seen at the required 7 m path length. Although the marked degradation in signal quality associated with engine operation can be mitigated by various means, for example the use of temporal averaging or wavelength modulation spectroscopy (WMS), it is evident that improving the properties of the underlying optical signals may bring about substantial overall performance gains. Our optical design goal is therefore the minimization of the detector area required to implement full aperture averaging in the face of representative levels of both pointing error and plume-induced scattering. Three basic design templates (collimated, moderately divergent, mid-plume focus) have been evaluated in preliminary laboratory trials, as described in [15], but the artificial thermal disturbance used is unable to replicate fully the properties of the turbulent aerojet plume. The mid-plume focus is an attempt to exploit the relatively local nature of the scattering source within the beam path. Scattering occurring close to the focal region then acts primarily to change the numerical aperture seen by the receiver, with little effect on the apparent origin of the rays. This approach does however reduce the effective beam diameter within the plume region, which will alter the balance between beam wander and scatter. As the relevant balance of pointing error and scattering is as yet unknown, the final decision will be made following initial on-frame testing, making focus adjustment an essential component of the optical design.
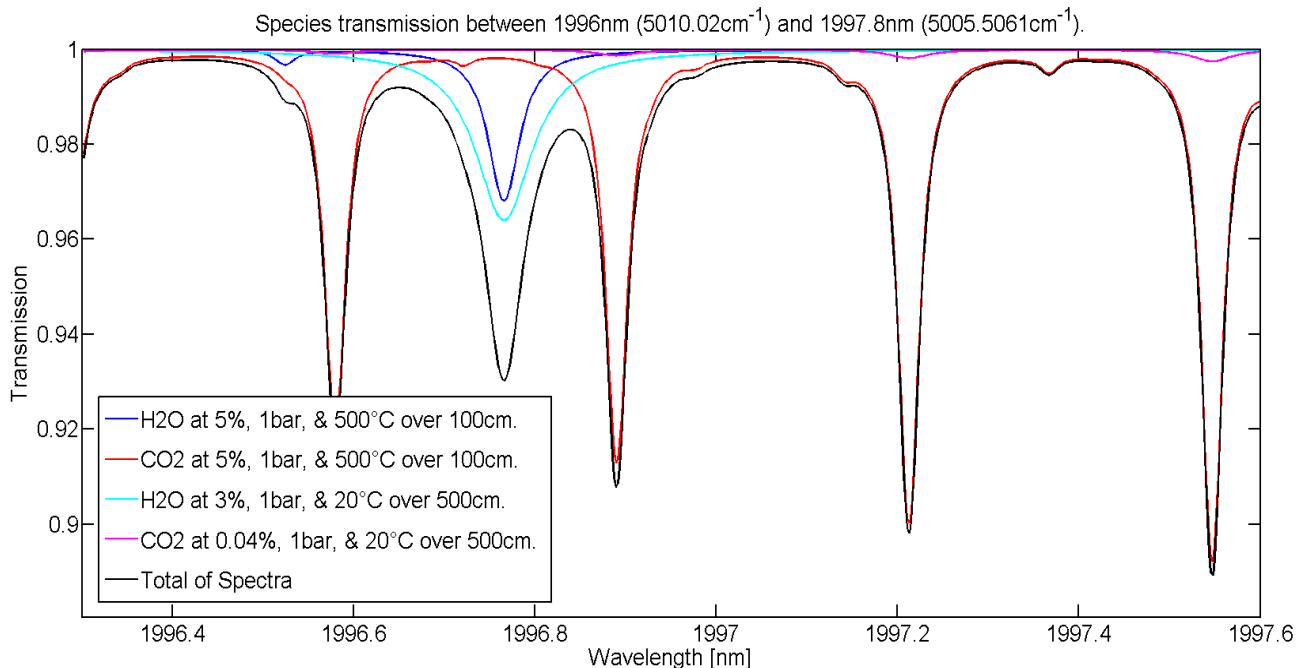
Figure 3 – CO$_2$ and H$_2$O spectra at 20°C and 500°C in the vicinity of the R(48) ν1+2ν2+ν3 feature

4. CO₂ Measurement

Spectroscopy

The near-IR region has abundant opportunities for monitoring major constituent species within gas mixtures, where its typically lower linestrengths can actually be an advantage. Technology for this region is mature, having benefitted from developments in the telecommunications sector, and far cheaper than that needed at mid-IR wavelengths. In the case of combustion exhaust measurement, both CO_2 and H_2O are accessible in the near-IR region but our focus here is on CO_2 quantification, with a view to supporting implementation of the industry's strategy for carbon neutral growth from 2020 (CNG2020) [16]. The initial determination of an appropriate absorption feature was done by simulation, using the HITRAN database [17], and led to the selection of the R(48) $\nu1 + 2\nu2 + \nu3$ line, located at 1997.2 nm. This absorption feature is well isolated from cross-interference due to other species that absorb in the same region, considering both ambient and elevated temperatures (Figure 3). Other considerations were the availability of suitable lasers and the relative strength of the absorption bands. Of the three bands of CO_2 in the 2µm region, $4\nu2+\nu3$, $2\nu1+\nu3$ and $\nu1+2\nu2+\nu3$, the $\nu1+2\nu2+\nu3$ band has the greatest absorption cross-section.

System Architecture

The CO_2 measurement system will use 126 path-integrated laser absorption measurements, arranged into 6 regularly-spaced projections of 21 beams at 75 mm pitch. Alternating the propagation direction between adjacent beams provides additional, but probably unnecessary, protection against crosstalk. The measurement region, defined by the intersection of these projections, extends beyond the hot exhaust zone sufficiently that the peripheral sections of each beam are inactive with regard to the spectroscopy of the chosen absorption line, rendering the system insensitive to ambient CO_2.

The system is functionally equivalent to 126 single-path TDLAS systems but the cost of 126 diode lasers and their associated temperature and current controllers is obviously prohibitive. Instead a Master Oscillator Power Amplifier (MOPA) approach has been implemented, in which a single DFB diode laser seed is amplified by a Thulium-Doped Fiber Amplifier (TDFA). The TDFA output retains the amplitude and wavelength modulation properties of the seed but at optical power levels up to 2.5 W. Passive splitters are then used to output the required 126 optical channels over single mode (SM) fiber at power levels consistent with shot noise limited detection performance. This Tunable Fiber
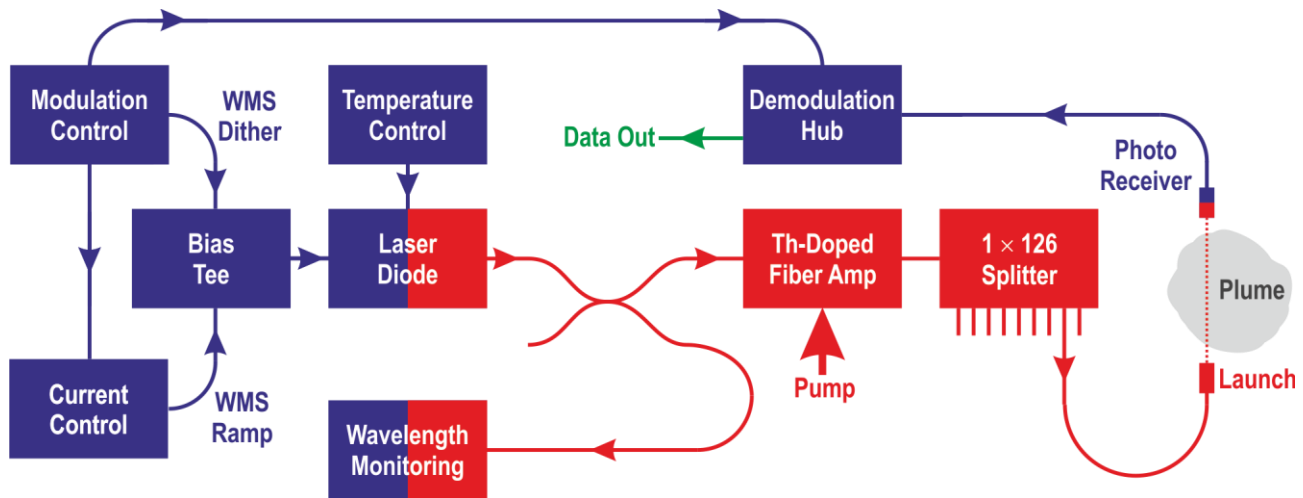

Figure 4 – TFLAS architecture. Colors denote electronic (blue), optical (red), and data (green) connections.

A soon-to-be-published experimental characterization of the selected absorption line was then undertaken, considering temperature, pressure and broadening effects. Using the resulting parameters, laboratory TDLAS tests, using a 5.5 cm pathlength of 100% CO_2 at 300 mbar and 600°C to provide a realistic path-integrated transmittance, could be fitted with rms residual errors of less than 0.1%, in comparison to a 3.5% transmittance change.

Laser Absorption Spectroscopy (TFLAS) arrangement, illustrated in Figure 4, constitutes a significant technological advance; the need to share a small number of diode laser sources across many beam paths has been performance limiting in previous optical absorption tomography systems, e.g. that used in [18], necessitating considerable effort in receiver amplifier design [19]. The system will implement a WMS detection scheme, acquiring one hundred spectral scans per second per beam path, using an adjustable dither frequency in the range 50 to 500 kHz.
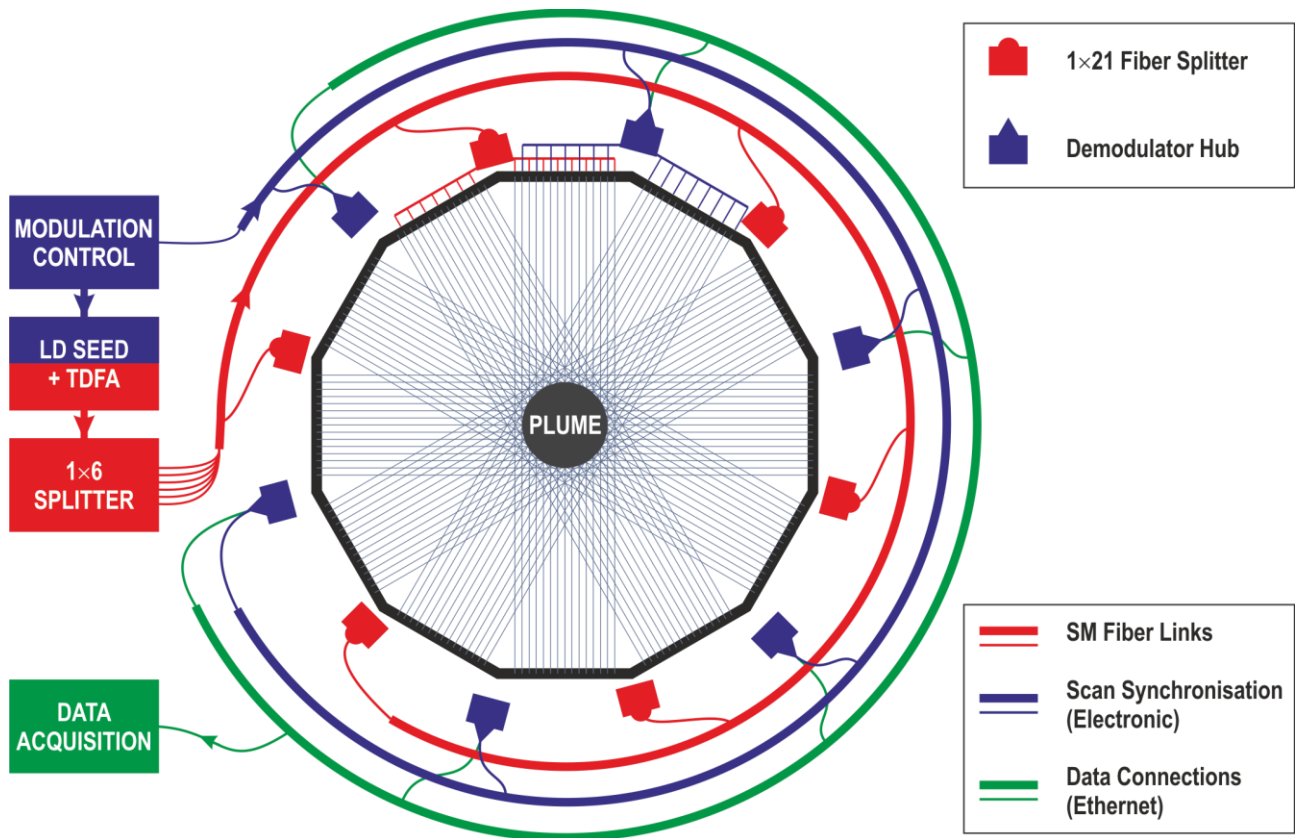
Figure 5 – Concept drawing of the dodecagonal mounting frame showing fiber-based light delivery (red), electronic signal connections (blue) and Ethernet data transfer (green). For clarity, the interleaved projection level connections are shown for only one fiber splitter and an adjacent demodulator hub.

The outputs from the 126 individual photoreceivers, each consisting of an extended InGaAs photodiode, transimpedance amplifier and line driver, will be grouped together in 21-channel blocks to enable efficient implementation of the sampling and digital demodulation electronics. Each of these six hubs receives timing signals to enable synchronization with the scanning cycle of the seed laser. Two Ethernet interfaces per hub are used for data output to remote PCs. Figure 5 shows the proposed system architecture.

Hub Design

Each hub serves 21 photoreceivers, drawn from the two projections adjacent to the vertex where it is mounted. Each photoreceiver output will be sampled at 40 MSPS, with up to 14 bit resolution, leading to a total data rate exceeding 10 Gb s^{-1} per hub, making local digital demodulation and subsequent decimation essential. This demodulation process is the principal function of the field programmable gate arrays (FPGAs) within each hub. I/Q demodulation will be performed at 1f and 2f, where f is the WMS dither frequency, generating four 32-bit values for each point of the wavelength scan. Each 10 ms scan comprises 500 such points, resulting in a post-demodulation hub aggregate data rate of around 128 Mb s^{-1}. The use of two ports per hub avoids reliance on gigabit Ethernet, even once protocol overheads are accounted for. The use of digital modulation control and demodulation permits frequency agility, potentially allowing the WMS measurement to be made in a favorable spectral region for the prevailing engine operating conditions. The inherent parallelism of FPGAs has led to their use in numerous multichannel digital demodulation systems, e.g. [20]. 32 measurement channels are implemented per hub, providing 11 additional channels for either simultaneous operation of the UHC system, or future expansion of the CO_2 system.

The optical power available from the TDFA is sufficient to provide SNR in excess of 80 dB at each photoreceiver output. Realizing the full potential of these signals makes the hub a challenging mixed signal design, requiring coexistence of these high SNR analogue signals and a relatively low jitter (<10 ps) sampling clock with no less than 40 high speed digital serial lines, each operating at 560 Mbps.

Single Channel Engine Tests

Single channel 2f/1f TDLAS measurements, carried out in an aero-engine exhaust plume, have confirmed the viability of the proposed measurement approach (Figure 6).
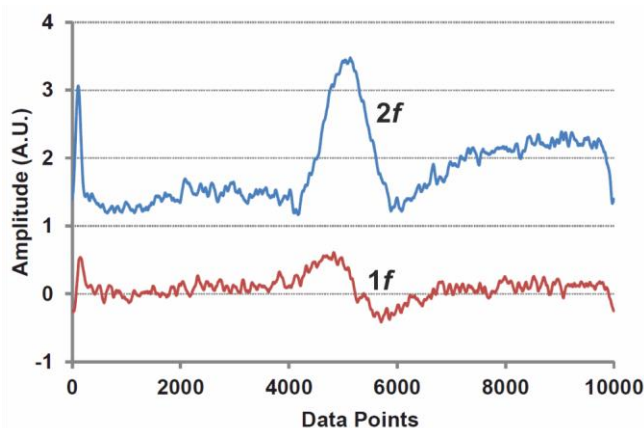
Figure 6 – Second harmonic signal (blue), X-channel, with the residual Y-channel signal (red). At 50 kHz modulation frequency the signal requires significant averaging to remove excess noise (64 averages).

Demonstration of TFLAS

In what we believe is the first demonstration of its kind, a TDFA amplified seed has been used to make direct and $2f$-WMS measurements of CO_2 under laboratory conditions (Figure 7). A full characterization of the TDFA's response under a range of seed modulation conditions is now underway.
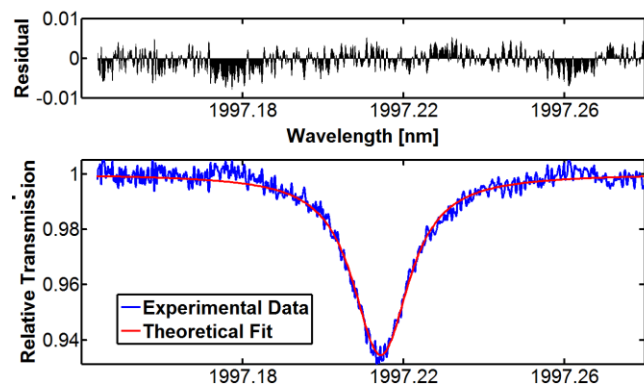
Figure 7 – Direct measurement of CO_2 line using a TDFA operating just above threshold. Phantom is 100% CO_2 at 300 mbar and 373 K.

5. UHC MEASUREMENT

The mid-IR region offers tremendous opportunities for the observation of many chemical species. The higher linestrengths typical of this spectral region are undeniably advantageous at the low concentrations relevant to emissions monitoring but the region is technologically less accessible than the near-IR. The proposed UHC measurement system is intended to target several unburnt or partially decomposed hydrocarbon species, using wavelengths in the vicinity of 3.3 μm.

The proposed architecture is similar to that of the CO_2 system, but using 6 projections of 8 beams each. The

mounting frame and demodulation hubs are also shared but dedicated light generation, distribution and detection systems are required.

Spectroscopy

The transient spectroscopy techniques required for some of the target species of interest lie outside of the FLITES consortium's expertise. The spectroscopic parameters of these species will be characterized in the group of Professor Ron Hanson at Stanford University.

Glass and Fiber Development

The lack of suitable mid-IR glasses for use in fiber amplification or distribution is indicative of the less developed nature of mid-IR technologies and is a major barrier to the use of high channel count mid-IR systems. To date, a variety of IR materials have been drawn into optical fiber. These include the heavy metal fluoride glasses (HMFG), chalcogenide and polycrystalline fibers as well as hollow rectangular waveguides [21]. While none of these fibers had physical properties even approaching those of conventional silica fibers, they are, nevertheless, useful in lengths less than 2 to 3 m for a variety of IR sensor and power delivery applications.
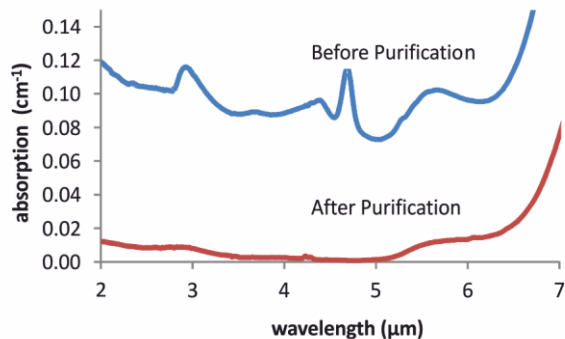
Figure 8 – Purification processes introduced during chalcogenide glass melting have led to significant improvements in glass transmission, with absorption peaks significantly reduced and an overall reduction in background scattering (this work).

For the purposes of this project we have identified chalcogenide glasses as the most promising material, offering higher temperature stability than other mid-IR materials and the potential for longer, lower loss fibers providing suitable glasses can be obtained. Our work therefore includes development of high purity chalcogenide glasses, suitable for drawing into optical fiber, for applications in the 2 to 5 μm region. We have focused on the chalcogenide glass family based on gallium lanthanum sulfide (Ga:La:S) which offers several advantages over other commercially available chalcogenides. Commercial chalcogenide glasses are typically based on toxic arsenic, selenium and/or tellurium and melt at temperatures below $500^{\circ}C$. The Ga:La:S glasses however contain no toxic elements and have the highest temperature stability of any

chalcogenide making them better suited for harsh environments [22]. To date, substantial progress has been made through the implementation of a gas delivery system which provides a dry, high purity atmosphere under which glasses are melted. Background scattering loss has been lowered by a factor of 100 and, crucially for UHC applications, moisture impurities have also been substantially reduced, improving transparency around 3 μm. In addition, the infrared absorption edge has been pushed beyond 5 μm by reducing oxide impurities, opening up much of the mid-IR window, including that needed for NO_X measurement (Figure 8). Fiber drawing trials of these glasses are now underway.

Light Sourcing and Distribution

In recent years, mid-IR sources have seen considerable development with improvements in output power and increasing accessibility of longer wavelengths. Quantum cascade lasers have become preeminent, despite being comparatively inefficient and expensive. Direct bandgap III-V semiconductor diode lasers can operate in the range of 2–3 μm at room temperature but are limited at longer wavelengths, due to Auger recombination. Ceramic lasers based on for example, Cr^{2+}:ZnSe are commercially available but thermal lensing limits the output power. In addition to providing an excellent solution for near–IR sensing of CO_2, fiber lasers are strong candidates for mid-IR applications, offering significant advantages over alternative sources [23].

lasing has been proven at 2.7 and 3.6 μm and research continues in parallel with our activities on up-doped fiber for mid-IR transmission (Figure 9).

Of greater concern are the difficulties apparent in distributing the light to the required beam launch locations. The scale of the mounting frame is such that fiber lengths of at least 10 m must be expected. Even our lowest bulk glass losses to date correspond to less than 1% transmittance over such a fiber at 3.3 μm, suggesting that fiber-based distribution may be unrealistic at this wavelength with present technologies, despite the substantial progress that has been made in suppressing the 3 μm water peak.

6. SOOT MEASUREMENT

LII has been applied to soot measurement for more than three decades [25]. In-situ LII studies of aero-engine exhaust plumes have been undertaken, including some incorporating scanning arrangements to provide rudimentary spatial insight, e.g. [26, 27]. These scanned studies relied on detection of the backward scattered component of the incandescence so their outputs show the angular variation of path-integrated incandescent emission, rather than its 2-D distribution. FLITES aims to combine fiber laser technology with tomographic techniques, first demonstrated in fluorescence tomography [28, 29], to achieve true cross-sectional imaging of the soot distribution in the plume. The proposed method involves the use of a scanned excitation
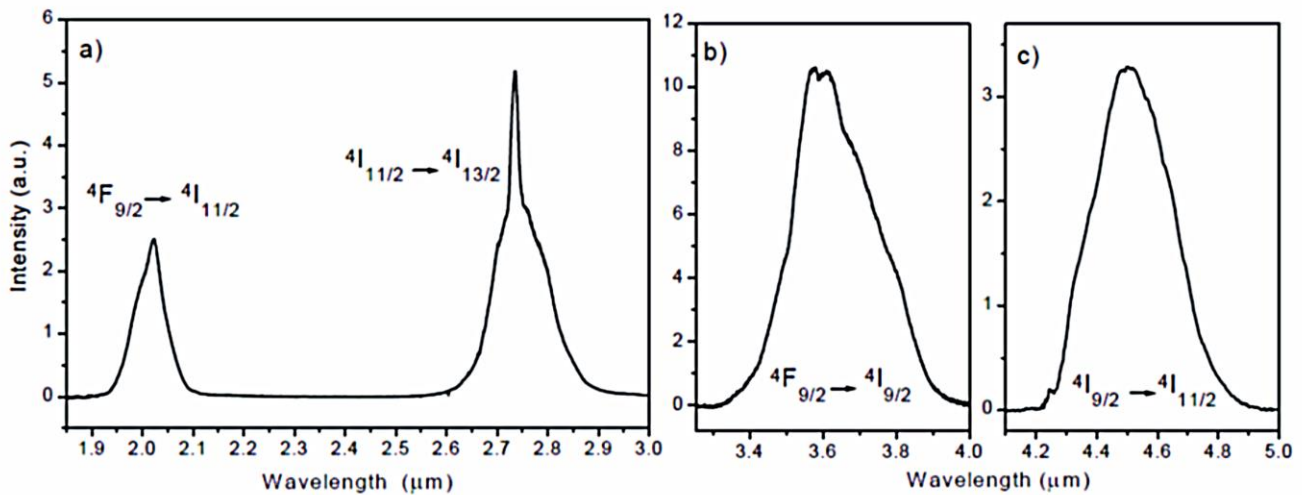
Figure 9 - Fluorescence spectra of Er3+ doped chalcogenide glass showing (a) 2.0 μm and 2.75 μm emission and (b) 3.6 μm emission when pumped with 60 mW at 660 nm and (c) 4.5 μm emission when pumped with 570 mW at 810 nm [24].

Ga:La:S glasses offer an ideal host for rare earth doping. Unlike other chalcogenides, the lanthanum in these glasses can be easily substituted by any of the rare earth ions including erbium, thulium, holmium and dysprosium, all of which offer mid-IR transmission [24]. Although at an early stage, this project is currently evaluating erbium in particular, as a possible fiber laser dopant. The potential for

laser with 'near-orthogonal' detection using one or more gated intensified CCD cameras (Figure 10). The use of cameras avoids the need to align many individual point detectors with the scan plane of the excitation source. In this 'autoprojection' approach to tomographic imaging the spatial origin of an LII signal is determined by considering the intersection of the laser path responsible for its

generation with the relevant pixel's field-of-view.
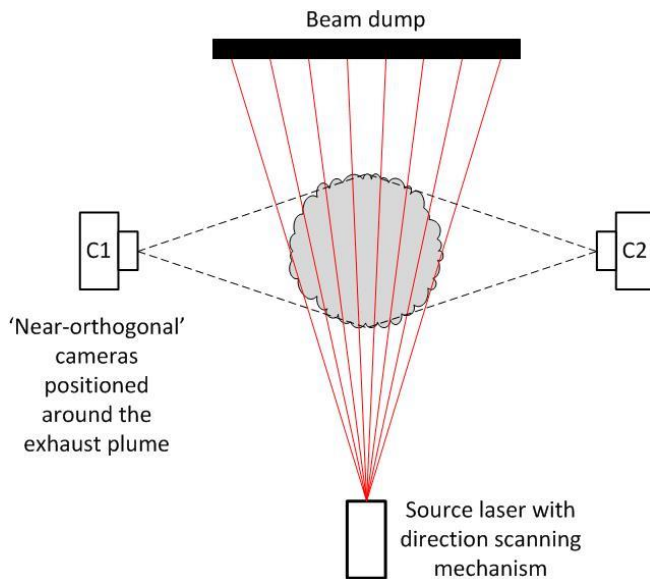
Figure 10 – Proposed LII imaging geometry

The Q-switched Nd:YAG lasers typically used to excite soot particles in LII studies provide short (~10 ns) pulse durations at modest (~10 Hz) repetition rates. We have investigated the use of fiber lasers, which are able to offer much higher repetition rates and are therefore better suited to imaging applications. We have been able to demonstrate both long and short pulse LII using fiber laser sources.

Long Pulse—Although the physics of long pulse LII is less well developed, the technique promises a significant sensitivity advantage over the conventional short pulse variant [30]. We have observed LII in both a jet exhaust plume and ambient air using a gated intensified CCD camera (Andor DH734) in conjunction with a fiber laser of 192 ns pulse width. These demonstrations used average powers of either 2.2 W or 11 W, well below the laser's 30 W capability, and a repetition rate of 30 kHz. The camera's field-of-view was arranged orthogonal to the excitation beam, in anticipation of the proposed tomographic arrangement.

Short Pulse— The physics of LII generated from short laser pulses, of the order of 10 ns, is well understood from the literature. Fiber lasers have several potential advantages for short pulse LII studies, including high power and repetition rate, as well as the potential for temporal pulse shaping. We have recently demonstrated short pulse LII, at a 10 kHz pulse repetition rate, using a fiber laser of 17 ns pulse width. To date, this system has only been deployed in laboratory studies.

7. SUMMARY

Measurement technology has an important role to play in supporting the transition to more sustainable civil aviation. To this end, the FLITES project is attempting to develop tools for imaging the cross-sectional distributions of both major constituent (CO_2) and minor pollutant (UHC, soot) species within jet exhaust plumes. The program has already demonstrated the viability of key elements of these three measurement systems, including TDFA-based TFLAS for CO_2 quantification and both short and long pulse fiber LII.

Two of the three systems (CO_2, soot) are now moving into their implementation phases. At the time of writing, construction of the dodecagonal mounting frame is imminent and contracts for the manufacture of the associated passive fiber optic splitting/distribution system and electrical wiring harnesses are being negotiated.

The spectroscopic aspects of the CO_2 measurement system are established and TFLAS has been demonstrated. The system's electronic design is in the layout phase and most elements of its firmware are at an advanced stage of development. The finished system will implement the core functionality of 126 conventional TDLAS systems, including the high-bandwidth lock-in amplifiers needed for $2f/1f$ WMS. The synchronization and data communication mechanisms required by the distributed nature of the system, and its high aggregate output data rate (around 1 Gb s^{-1}), are yet to be tested.

It appears unlikely that we will deliver a full UHC imaging system within the present project, as sufficiently low-loss and low-cost fiber remains elusive, although very significant progress towards realizable mid-IR systems has been made. It is nonetheless expected that the program will deliver proof-of-principle, in the form of i) relevant spectroscopy, ii) a single UHC measurement channel and iii) an evaluation of the feasibility of fiber delivery, at both 3.3 μm and elsewhere in the mid-IR region.

Progress towards LII system implementation has focused on source development, supported by fixed path tests on both laboratory phantoms and jet plumes. The demonstration of long pulse LII in a jet plume is a significant first. Extension of these single path measurements to a full LII imaging capability requires comparatively little additional hardware development, primarily the introduction of suitable optical scanning and timing synchronization arrangements, but some further work is needed in regard of system modelling and calibration. Overall, however, there appears to be no fundamental barrier to successful implementation of LII-based soot imaging.

In conclusion, the project is on track to deliver cross-sectional imaging of both CO_2 and soot in jet exhaust plumes, as well as substantial advancement of mid-IR technologies that will eventually permit tomographic imaging of pollutant species such as UHCs or NO_X.

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BIOGRAPHY

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Daniel W Hewak was born in Canada where he received the B.Sc. Degree in Physics from McMaster University, Hamilton, Ontario in 1982 and Ph.D. from the University of Waterloo, Waterloo, Ontario in 1988. In 1988 he joined the National Optics Institute in Ste. Foy, Quebec research scientist in particular working on industrial sponsored projects from IBM and Digital Equipment of Canada. In 1991 he left Canada to take a research position at the Optoelectronics Research Centre, University of Southampton in the United Kingdom. He now specializes in the production and application of chalcogenide glass and is recognized internationally as a leader in the production and use of chalcogenides and a pioneer in their fabrication and application. His research has led to IR fibers for sensing, medical and aerospace, fiber amplifiers for telecom, the first chalcogenide-glass lasers and also solar-cell, thermoelectric and memory devices. This diversity is a testament to the truly advanced functionality of chalcogenides. Over the past five years, Dan has contributed to the management of several large projects, notably the EPSRC Centre for Innovative Manufacturing in Photonics (CIMP). His research is well funded by industry, including Merck, Pirelli and DSTL and currently via Samsung's Global Research Outreach Program, and he works closely with Ilika Technologies Ltd on material development and characterization. He has authored over 270 papers and conference publications (h-index 34), holds 9 patents, with 3 licensed

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Khouler Khan was born in Trinidad where he received a B.Sc. Degree in Electrical and Computer Engineering from the University of the West Indies, Trinidad in 2003. He obtained and M.Sc. in Nano-electronics and mechanics from the University of Sheffield, United Kingdom in 2009 and is currently studying for his Ph.D. at the University of Southampton, United Kingdom. In 2004 he joined the Petroleum Company of Trinidad and Tobago in Trinidad as an Engineer and has worked on many large and small scale industrial projects in the Oil and Gas field. He now specializes in using his engineering and instrument talents to build innovative automated system solutions to improve the manufacturing of high purity infrared transmitting materials. Over the past four years, Khouler has made significant progress on improving the quality and production methods of infrared materials at the Optoelectronics Research Centre under the EPSRC Centre for Innovative Manufacturing in Photonics.

Paul Bastock graduated from the University of Glasgow with a Bachelor's in Mechanical Engineering with Aeronautics accompanied with the Highest Overall Engineering Degree Prize, 2011. In 2011, he joined the Optoelectronics Research Centre, University of Southampton working on novel fiber manufacture and funded through the EPSRC Centre for Innovative Manufacturing in Photonics. Research has focused in particular on specialty fiber manufacture and low loss mid-IR transmitting fiber for gas sensing and non-linear active fiber devices. Paul has worked as part of numerous industrial partnered projects and international collaborative research projects, most recently with Nanyang Technical University, Singapore. His research has been presented at five conferences so far throughout his PhD in the Optoelectronics Research Centre.

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