Remote Sensing Technique for Aeroengine Emission Certification and Monitoring

AEROTEST

Final Publishable Executive Summary

Contract n°: AST3-CT-2004-502856

Partners	***(Short name)***
AUXITROL – Co-ordinator	*(AUXITROL)*
ROLLS-ROYCE	*(RR)*
SIEMENS	*(SIEMENS)*
KEMA	(KEMA)
OPTOELECTRONICA	*(OPTOEL)*
FZK/IMK-IFU	*(FZK)*
BU Wuppertal	*(BUW)*
RWTH Aachen	*(RWTH)*
Lund University	*(ULUND)*
PC2A-CNRS	*(CNRS/PC2A)*
University of Reading	*(READPH)*
NTUA	*(NTUA)*

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It has been demonstrated in previous European projects, AEROJET and AEROJET II, that non intrusive techniques like Fourier Transform Infrared spectroscopy (FTIR) and Laser Induced Incandescence (LII) are relevant to aero-engine exhaust gases measurement. These methods have been compared with intrusive methods within AEROJET II. This success has opened the path for their standardisation.
Simultaneously, aircraft engine industry stresses the need for a measurement method compatible with cost effectiveness, short-term implementation, fast availability of results and accuracy, meeting ICAO emission certification needs.

The aim of AEROTEST was to achieve a high level of confidence in aircraft engine emission measurements with a view of using the remote optical technique for engine certification.
Simultaneously, aircraft engine industry stressed the need for a measurement method compatible with cost effectiveness, short-term implementation, fast availability of results and accuracy, meeting ICAO emission certification needs, advantages that can be reached with optical methods.

Two main objectives were defined to meet the engine manufacturers' needs:

- first and major objective: address the standardisation issues, the ultimate aim being to promote non intrusive techniques to ICAO for engine emission certification, following a complete Quality Assurance and Quality Control approach, and developing procedures for calibration, set up and operation.
- second objective: to develop validated techniques for gas turbine monitoring, using emission data to be used routinely by engine manufacturers, both in development test programmes and for engine health monitoring (EHM).

The pollutants addressed in the project were CO_2, CO, NO, NO_2, UHC and soot particles. All gases have been measured with a single remote sensing system, composed of a FTIR spectrometer linked to a "White" mirror system, and soot particles have been detected with the Laser Induced Incandescence (LII) equipment.

FTIR & 'White' mirror system:
The FTIR measurement principle is based on a passive collect of a high resolution infrared spectrum; each line emitted by a species is function of the gas temperature as well as of the species concentration; an accurate analyse of the lines shape and intensity enables to retrieve the concentration of gases present in the exhausts;
During AEROTEST project, the FTIR equipment has been adapted, allowing to perform optical measurement of a good quality in a test bed environment.
The spectrometer can be used either in emission mode or in absorption mode:

- In emission mode, the radiation emitted by the exhausts is directly collected by the spectrometer; a motorised mirror allows the scan of the plume, and consequently the determination of the profile of temperature and of concentration at the engine exit; this mode is mainly used for the determination of plume temperature, and for high pollutants concentration;
- In absorption mode, the radiation of a calibrated hot source passes through the plume and is partly absorbed by the gases; this mode is linked to a White mirror system, also called 'White Cell', enabling several passes through the exhausts function on the sensitivity needed; this mode is used for the measurement of low pollutants concentration.

A selection of wavelengths appropriate to each molecule to detect can be made using an automatic rotating optical filter system installed in the FTIR equipment.
The collected spectrum is analysed using inversion software, in which the measured spectrum is compared to a simulated spectrum till a good fitting between the 2 spectra is obtained. The pollutant concentration is then quantified.

<u>LII system:</u>
One of the most promising techniques for in-situ measurements of soot volume fractions is laser-induced incandescence (LII). In this technique soot particles are exposed to a rapid nano-second laser pulse that heats the particles to their sublimation temperature (around 4000 K at atmospheric pressure). The increased thermal emission from the particles can readily be detected using photomultiplier tubes (time-resolved) or CCD cameras (imaging). The LII signal collected is proportional to the soot volume fraction.
Detection of the LII signal along the counter propagation of the incident laser beam (backward LII) has turned out to be a promising alternative in this respect, since it simplifies the experimental set-up considerably making it possible to mount both laser and detector system inside one shielded box. Improvements have been done on the equipment allowing to better quantify and to control the LII effect.

For both FTIR and LII systems, an important work has been done on calibration means. Based on existing standards, on our knowledge on optical systems, and on results from testing campaigns, procedures for calibration and measurement phases have been written by the consortium. These operational procedures are used as a basis for the VDI group in Germany for the development of guideline for passive FTIR spectroscopy.

Software has been developed for a global control of the equipment and an automation of the calibration/measurement phases.

Several tests have been done throughout the project on an ATAR 101 jet engine located in the RWTH test bed, allowing to validate the improvements applied to the equipment, and to characterise both LII and FTIR systems in term of accuracy and detection limit. Conventional intrusive measurements (gas analysers, SMPS) have been used for correlation with the optical measurements, see Figure 1.

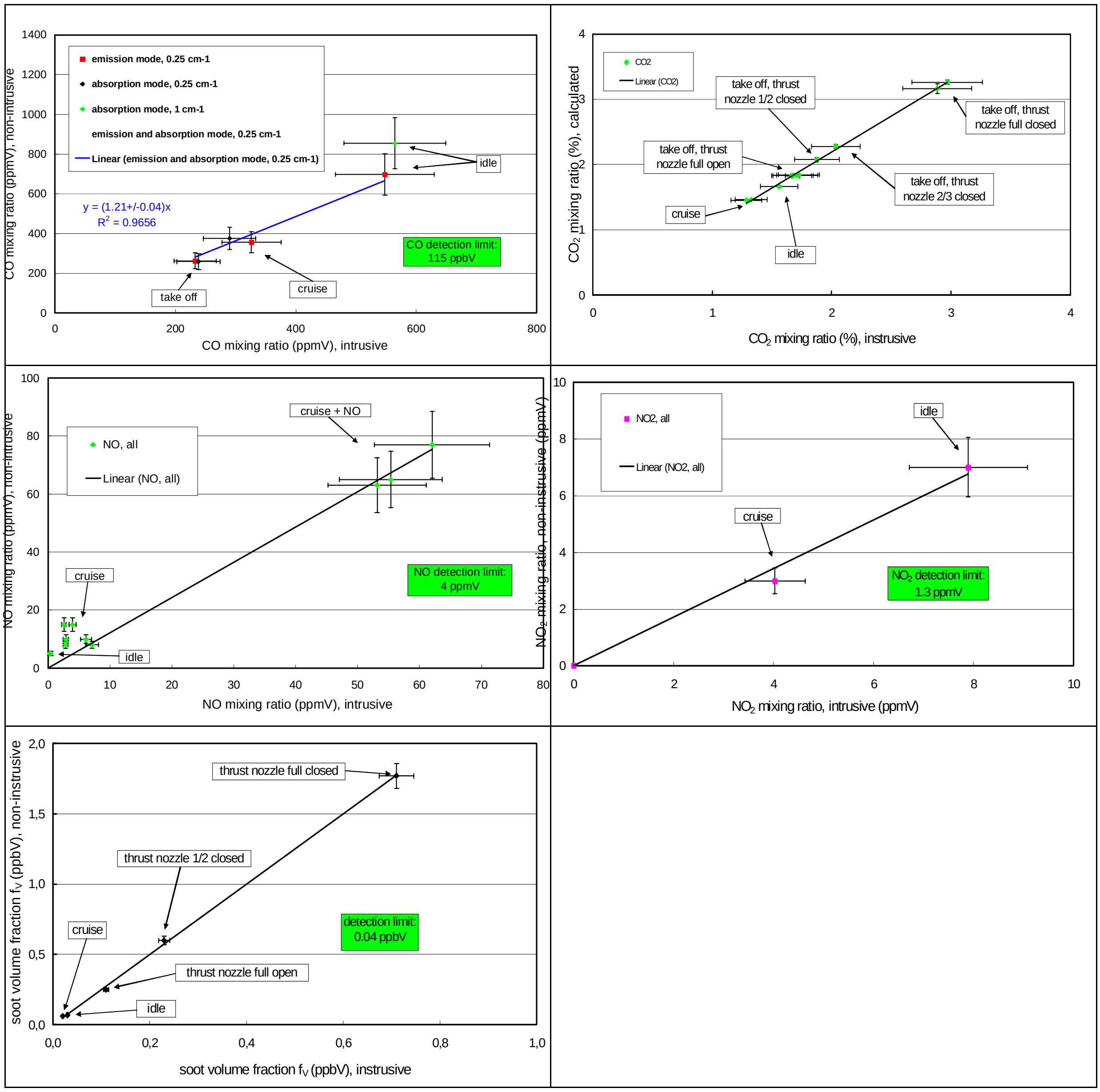


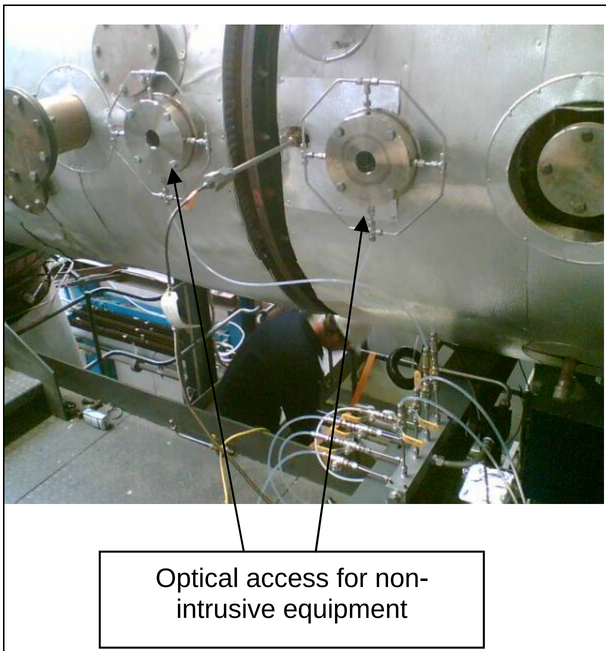
Figure 1: Correlation between intrusive and non-intrusive data, from measurements performed on an ATAR 101 jet engine

Characteristics obtained using remote optical systems are summarized in table 1 for each pollutant:

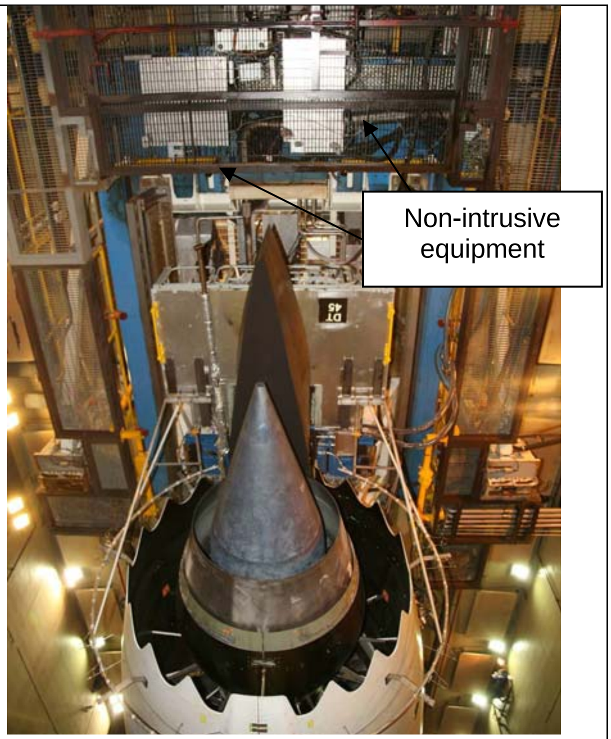
Pollutant	Optical system	Detection Limit	Accuracy
CO_2	FTIR	100 ppm	5%
CO	FTIR	0.115 ppm	5%
NO	FTIR	4 ppm	10%
NO_2	FTIR	1.3 ppm	30%
UHC	FTIR	0.5 ppmC	10%
Soot	LII	40 ppt	50%

Table 1: Detection limit and accuracy of AEROTEST optical systems, from measurements performed on an ATAR 101 jet engine

Testing campaigns have been done on a SGT300 industrial turbine from SIEMENS and in ROLLS-ROYCE facilities, on small engines (Gnome helicopter, Viper) and on large engines in the 57 test bed, showing the feasibility of using the equipment in different applications, see Figure 2.



SIEMENS – SGT300 turbine



ROLLS-ROYCE – 57 test bed

Figure 2: Testing campaigns in ROLLS-ROYCE and SIEMENS test beds

These campaigns gave the opportunity to acquire engine pollutants emissions data base. Based on this database, a status on how emissions measurement could give information on engine health monitoring was made;

Particularly, the capability to interrelate engine performance with semi-empirical correlations has been established. A large number of semi-empirical correlations have been identified in open literature and assessed through their application to existing data. It was found that these correlations can predict with a varying degree of accuracy the emitted pollutants when they are applied 'as published'. If however the physical mechanism for the various factors influence is taken into account, it is possible to derive values of the corresponding parameters, such that a specific engine is represented. Thus, a method that can be used to adjust a correlation and develop a set of parameters which gives the best fit to given experimental data has been established and verified – see Figure 3.

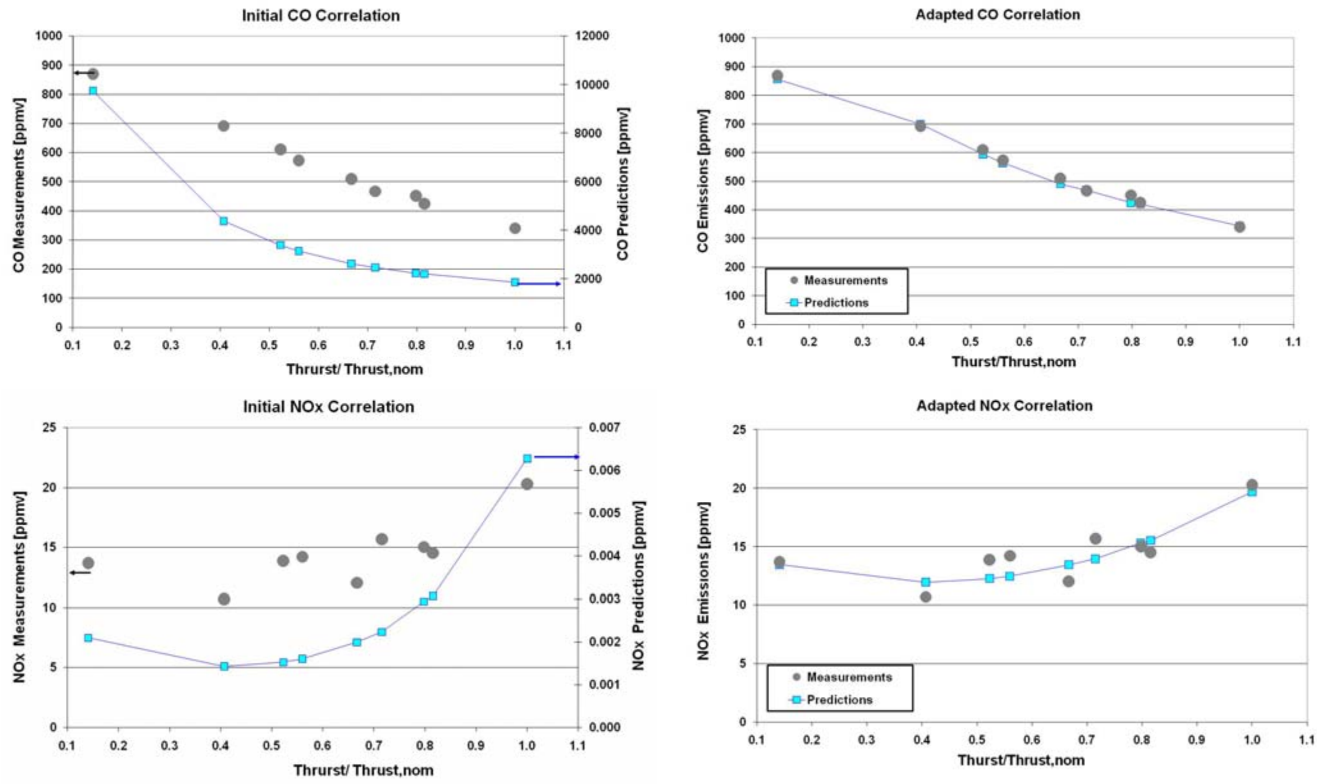


Figure 3: Measured and Predicted Emissions of a Turbojet Engine

The adapted emissions correlations were used in conjunction to engine performance models to investigate the effects of different engine malfunctions to produced pollutants. A sensitivity study and application of different deterioration scenarios of an industrial single shaft turbine has been carried out. It was found that the accuracy of the employed correlations is of high importance for diagnostic purposes, since it affects the predicted levels of emissions at certain engine operating conditions and health. Thus, criteria for the selection of the adapted emissions correlations to be used for health monitoring purposes were formulated.

A study for performance diagnostics enhancement has been also carried out. Extending aero thermodynamic data sets with emissions-derived quantities (e.g. fuel air ratio, air flow rate, turbine inlet temperature) was shown to improve diagnostic ability. Systematic study for the selection of measurements and diagnostic parameters was carried out and produced information on optimal diagnostic sets.
A method for exploiting additional information from emissions, independently from performance quantities was also developed. The method allows an automated recognition of the presence of deviations that could indicate malfunctions, from measurements of emissions distribution in the exhaust plume of an engine. The method is based on pattern recognition through the use of PNN (Probabilistic Neural Networks). A first application of the proposed method on data from a high by pass turbofan engine (Rolls Royce RB211) has shown that it can be an efficient tool for the diagnosis of engine faults – see Figure 4.

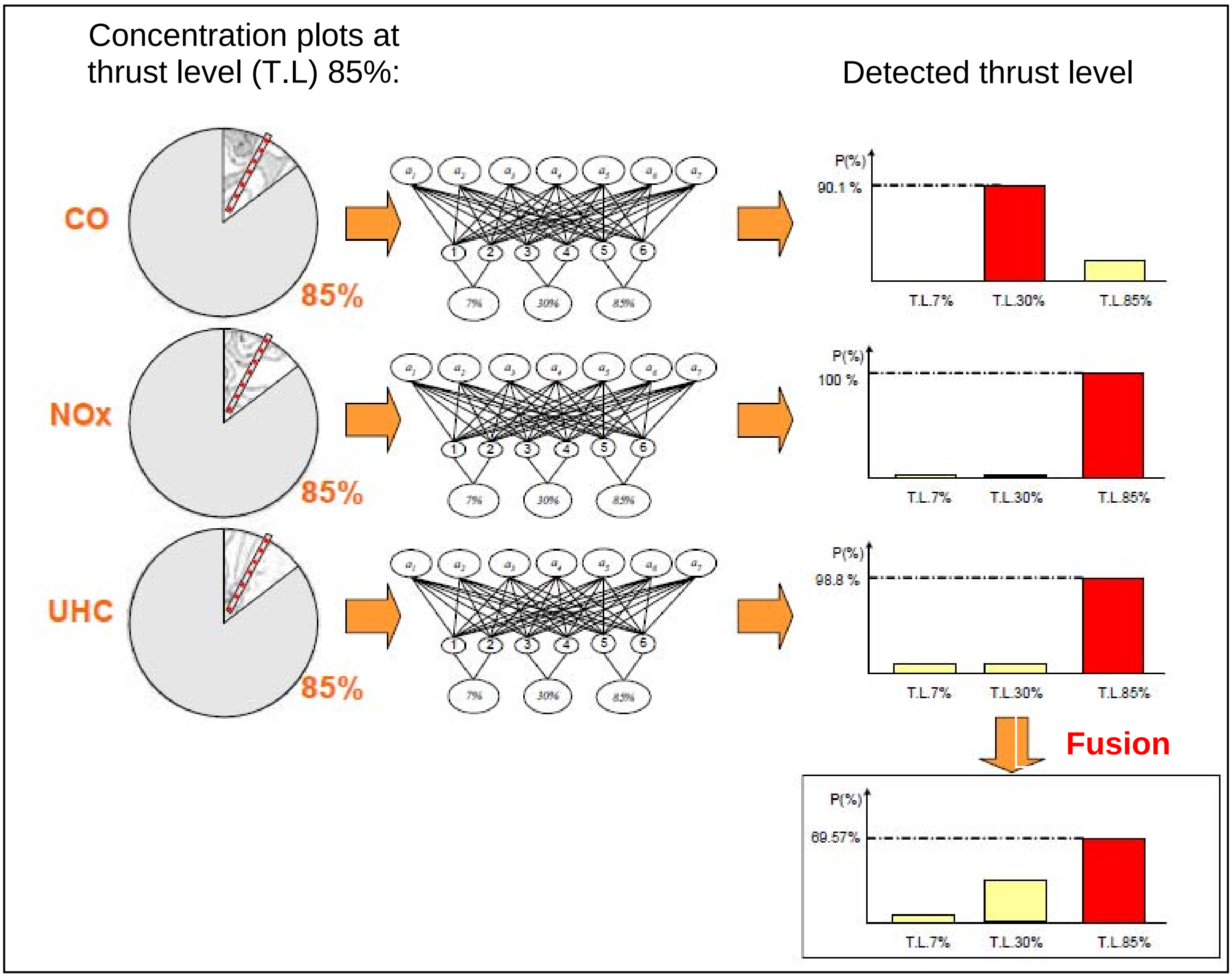


Figure 4: Diagnostic Exploitation of Spatial Emissions Distribution:
Example of operating condition detection at a specific peripheral position from three emission concentration plots

The final aim of AEROTEST project was the acceptance of non-intrusive methods for gas turbine monitoring. A first step has been reached at the end of the project by a presentation of AEROTEST work and results to the SAE E31committee (‘Aircraft Exhaust Emissions Measurement Committee’). An Aerospace Information Report (AIR) on non-intrusive emissions measurement has also been produced, outlining technology for discussion, with supporting data.

List of publications related AEROTEST activities and results:

- "Development of calibration methods for FTIR spectrometry to analyse hot exhausts" – FZK, OPTAM 2004
- "Imaging of laser wings effects and of soot sublimation in laser induced incandescence experiments" - CNRS and RR, Applied Physics B81, 181-186.2005;
- "Method for On-Site Determination of the Instrument Line Shape of Mobile Remote Sensing Fourier Transform Spectrometers" – FZK, SPIE 2005
- "Investigation of temperature and gas concentration distributions in hot exhausts (airplanes and burners) by scanning imaging FTIR spectrometry" – FZK, SPIE 2005
- "Development of a calibration method for FTIR spectrometry to determine emission indices of hot exhausts" – FZK, CEM 2006
- "Imaging scanning FTIR spectrometry to determine the composition of hot exhaust plumes" – FZK, OPTAM 2006
- H. Bladh, P.-E. Bengtsson, J. Delhay, Y. Bouvier, E. Therssen, P. Desgroux, Experimental and theoretical comparison of spatially resolved laser-induced incandescence (LII) signals in backward and right-angle configuration, Appl. Phys. B83, 423-433 (2006).
- 'Measuring trace hydrocarbons in gas turbine exhausts - a comparison of of optical spectroscopic and conventional sampling techniques', READPH, Photon06, 2006
- "Monitoring of Aircraft Exhaust Emissions by Scanning Imaging FTIR" – FZK, CEM 2007
- "Remote sensing of aircraft exhaust temperature and composition by passive Fourier Transform Infrared (FTIR)" – FZK, SPIE 2007
- "Detection of gas turbines malfunctions from emission concentration distribution" – NTUA, ASME conference publication: paper GT2007-27107;
- "Correlations adaptation for optimal emissions prediction" – NTUA, ASME conference publication: paper GT2007-27060;
- Schäfer, K., Flores, E., Harig, R., Jahn, C.: Remote sensing of aircraft exhausts composition at airports – basics of a new VDI guideline for passive FTIR. In: VDI-Berichte „Optische Analysenmesstechniken in Industrie und Umwelt", VDI-Verlag GmbH, Düsseldorf 2047, 121-129 (2008); ISBN 978-3-18-092047-4.
- "In-Situ Laser-Induced Incandescence of Soot in Large Civil Aero-engine Exhaust" - RR and CNRS, AIAA 2008;
- J. Delhay, P. Desgroux, E. Therssen, H. Bladh, P.-E. Bengtsson, H. Hönen, J.D. Black, I. Vallet, Soot volume fraction measurements in aero-engine exhausts using extinction-calibrated backward laser-induced incandescence, Appl. Phys. B 95, 825-838 (2009)
- Kurtenbach, R., Hönen, H., Schäfer, K., Wiesen, P.: Remote Sensing Technique for Aero Engine Emission Certification and Monitoring. The AEROTEST-Project. In: Proceedings of The Thirteenth International Symposium on Transport Phenomena and Dynamics of Rotating Machinery (ISROMAC-13), Proceedings CD, ISROMAC13-TS37 (2010)
- Schäfer, K., Harig, R., Blumenstock, T., Höfert, N., Weber, K.: Development of a VDI guideline for passive FTIR measurements in the atmosphere. Remote Sensing, SPIE Europe, Toulouse, France, 21 – 23 September 2010, accepted.

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