Minority effluent measurements of aircraft Engine emissions by infrared Laser Spectroscopy (MENELAS) project - Final Technical Report

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This final report compiles the results obtained during the MENELAS project executed in the EC 5th FrameWork (2002-2006). The objectives were to develop new spectroscopic instruments to characterise minority species in aircraft engine emissions or in research combustors. The project focused on the development of two novel apparatus, namely a doubly resonant optical parametric oscillator (DROPO) and a picosecond lidar, both working in the mid infrared spectral domain to probe species like CO, NO, CO2, CH4,… on their fundamental levels. There were also some field experiments to demonstrate the capability of spectroscopic measurements for such applications: infrared absorption spectrometers using diode lasers have been successfully used to probe an APZ combustor at DLR Koln and the exhaust gases of NLR’s Cessna Citation II research aircraft at a test site at Amsterdam Airport Schiphol.

Key words:
AIRCRAFT ENGINE EXHAUST GAS ; AIRCRAFT GROUND TEST ; SPECTROSCOPIC MEASUREMENTS ON AIRPORT ; COMBUSTOR ; COMBUSTION CHAMBER ; SPECTROSCOPIC MEASUREMENT ; CO CONCENTRATION ; CO2 ; NO ; H2O ; DIODE LASER ABSORPTION SPECTROSCOPY ; MID INFRARED LASER SOURCE
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FINAL TECHNICAL REPORT

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Glossary

CARS  Coherent anti-Stokes Raman Scattering
CLEO  Conference on Laser and Electro Optics
CIR  Chalcogenide Infra Red
DLAS  Diode Laser Absorption Spectroscopy (same as SDLA)
DFG  Difference frequency Generation
DFWM  Degenerate four Wave Mixing
DGV  Doppler Global Velocimetry
ECOPO  Entangled cavity optical parametric oscillator
FTIR  Fourier Transform Infra Red
HITRAN  High-resolution TRANsmission molecular absorption database
ICAO  International Civil Aviation Organisation
IR  Infra Red
LDA  Laser Doppler Anemometry
MENELAS  Minority effluent measurements of aircraft ENgine Emissions by infrared LAser Spectroscopy
MIDROPO  Mid-Infrared Doubly Resonant Optical Parametric Oscillator
MIR  Mid Infra Red
MIRPL  Mid Infra Red Picosecond Lidar
MIR DFG  Mid Infra Red Difference Frequency Generation
NIR  Near Infra Red
OPO  Optical Parametric Oscillator
PIR  Polycrystalline Infra Red
PIV  Particle Image Velocimetry
PIVNET  Particle Image Velocimetry NETwork
PPLN  Periodically Poled Lithium Niobate
SDLA  Spectroscopy by tuneable Diode Laser Absorption (same as DLAS)
QCL  Quantum Cascade Laser
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1. EXECUTIVE PUBLISHABLE SUMMARY

1.1. General objective

The goal of MENELAS was to develop innovative measurements and related apparatus that are capable of reducing time and costs for aeroplane engine development. These apparatus, with new technologies in accordance to present ICAO regulations, should bring to the aeronautics community original developments in infrared coherent sources specially designed for effluent trace detection in engine research and atmospheric impact studies.

1.2. Scheduled Work

The work performed in this project consists in the development and the validation of two new types of optical sources usable for high resolution spectroscopy in the mid infrared domain. Specifically, a mid infrared optical parametric oscillator (MIDROPO) and a mid infrared picosecond lidar (MIRPL) had to be designed for high repetition rate optical diagnostic of gas emission. These designs require beforehand a careful evaluation of compatible species and absorption lines as well as experimental conditions to perform appropriate demonstrations. The performances of these two instruments were then to be further characterised through laboratory cross calibration experiments and by comparison with concentration and temperature measurements performed by use of the SDLA/DLAS approach (spectroscopy by tuneable diode laser absorption). In addition, outside campaigns of measurements were to be conducted on a combustor facility and a jet aircraft. In combination with the development of high-resolution laser systems, the potential use of infrared fibres had also to be investigated for propagating the input beam or collecting the signal beam. In parallel, a study had to be performed on the potentialities of various techniques to get velocity and density measurements of the jet engine exhaust gas.

1.3. Work performed

At end of the project, most of the scheduled work have been performed as summarized in the following list:

- **Definition and requirements**:
  - a selection of relevant species has been established taking into account ICAO recommendations and cross correlation possibilities
  - a test plan for aircraft ground tests has been established;
  - velocity and density measurements potentialities have been determined for implementation at the exhaust plume of an aircraft;

- **MidInfrared DROPO (MIDROPO) instrument development**
  - a laboratory MIDROPO apparatus has been built and tested over the 3.5 to 4 µm spectral range;
  - absorption spectra of N₂O have been recorded with the MIDROPO apparatus;
- an industrial MIDROPO spectrometer prototype has been built

- MidInfrared Picosecond LIDAR (MIRPL) instrument development
  - the MIRPL has been mounted and tested over the 3.85 to 4.65 µm spectral range;

- Calibration and other support actions
  - line broadening coefficients have been measured for CO and CH₄ with air and pure nitrogen;
  - degenerate four wave mixing spectra have been calculated for CO₂ at different temperatures;
  - calibration measurements for the MIR-DFG system with methane at about 3.47 µm have been performed in the hot gas cell
  - the SDLA spectrometer has been upgraded for cross correlation validations;
  - two mid-infrared optical fibres have been procured and partly characterised;
  - the Risoe hot gas cell facility used in the AEROPROFILE project has been upgraded and adapted for calibration purposes of the present project.

- Field experiment campaigns
  - An atmospheric primary zone combustor has been thoroughly characterised by the DLR for the field experiments aiming at validating the spectroscopic instruments;
  - Field experiments on an DLR combustor with SDLA/DLAS from ONERA on CO, CO₂, H₂O and NO and with MIRPL from TUC on CH₄;
  - Aircraft ground tests experiments at NLR facility on Schiphol airport with SDLA/DLAS from ONERA on CO, CO₂, H₂O and NO and from TUC on NO and H₂O.

1.4. Main results

There has been much progress in the laboratory development of the two novel optical apparatus (the MidDropo and the Pico-second Lidar) as well as in the building of prototypes for industrial use. Unfortunately, it appears at the end of the project that these two sophisticated instruments are not yet mature to perform measurements at exit of a combustor or of an aircraft engine on an airfield as planned in the project.

Nevertheless, some field experiments to demonstrate the capability of spectroscopic measurements at such locations have been performed with classical infrared absorption spectrometers using diode lasers initially envisioned in the project for benchmarking the novel instruments. These demonstrations have been successfully performed using the ONERA SDLA/DLAS instrument to probe an APZ combustor at DLR Koln and the exhaust gases of NLR’s Cessna Citation II research aircraft at a test site at Amsterdam Airport Schiphol. For the latter, there were also successful measurements by TUC who developed for the occasion an absorption spectrometer using a Quantum Cascade Laser.

The calibration hot cell at RISOE has been successfully upgraded for high temperature purposes but only few calibration experiments by TUC have been performed as the developed instruments were not yet operational.

There have been also preliminary study of the use of infrared fiber optics to ease propagation of infrared laser beams to measurement locations as well as a survey of other techniques presenting velocity and density measurements potentialities for implementation at the exhaust plume of an aircraft.
2. **OBJECTIVES OF THE PROJECT**

The technical and scientific objectives of this program are the development of new optical instruments that can be implemented in combustion test rigs for selective measurement of minor pollutant species, which are produced at the exhaust plume of an aircraft jet-engine. The instrumentation are based on two optical systems delivering a coherent mid-infrared beam according to the following specifications:

- the spectral line width must be less than a few GHz to ensure a high selectivity on detected species;
- the spectral frequency must be tuneable over a wide range for multi-species detection;
- pulsed operation have to be considered in order to fulfil spatial resolution requirements;
- pulses have be emitted at a multi-kHz repetition rate to reduce the measurement time;
- the devices must be rugged and compact for implementation in industrial environment.

By providing such innovative optical instruments for gas analysis, the study has the objective to support the development of environmentally friendly aircraft propulsion systems. These new tools are considered to be specially useful for the characterisation of the effluent emissions regarding the ICAO recommendations. On the other hand, the short measurement time of these instruments is thought to contribute to a full characterisation of combustion mechanisms as well as the reduction of the testing costs of industrial facilities.

Beyond the field of application in aeronautics, the development of new optical gas analysis instruments are considered to be particularly useful for monitoring industrial sites, air quality and atmosphere composition. In conclusion, the technological developments undertaken in MENELAS are expected to contribute to improve our knowledge of the impact of the human activities on the environment.

2.1. **Details on the work program**

The administrative and management work is performed in work package WP1000. The scientific work is divided into the following five work packages:

- **WP2000**: Requirements and definitions for the development and validation of the instruments
- **WP3000**: Laboratory development or adaptation
- **WP4000**: Laboratory calibration
- **WP5000**: Field experiments on two test cases (combustor under development and exhaust gases of an aircraft running at full power on an airfield)
- **WP6000**: Synthetis and recommendations as well as dissemination of results.

The technical work starts with **WP2000** (Requirements and Definitions) dedicated to a thorough study of infrared spectral characteristics of the gases to be investigated in the engine and combustor exhaust. This is based on experience from previous projects on hot gas spectroscopy. Single lines and small groups of lines within the tuning range of the prospective laser systems are to be considered applying existing data bases (like HITRAN). Goals are the identification and selection of spectral lines (microwindows) with respect to the dependence of their strength and width on temperature and pressure, as well as their detectability (superposition of neighbouring lines of other species) and required accuracy of the measured
spectra. In parallel investigations are to be performed and decisions made with regard to the question which gases are to be detected by which of the participating laser systems. This is useful, because at this basic research status it is not necessary that all laser systems cover the whole spectral range required for all gases. Finally, in WP2000 a potentiality study is to be performed about which detection techniques can be the most promising in order to perform exhaust gas velocimetry and to provide high spatial resolution gas concentration measurement. This study is to be a first step towards non-intrusive measurement of the exhaust gas emission index, i.e. grams of COX and NOX per kg burned fuel.

WP3000 deals with instrumentation development or adaptation based on the requirements established in WP2000. The laser systems are to be designed with respect to their spectral and tuning range, their power, their sensitivity in order to assess the gas spectra with the required accuracy (in the ppb to ppm range depending on the absorption length, species,…). The subsequent construction, assembly and, as far as the MIDROPO is concerned, prototyping of the instrumentation is to be specifically guided by provisions to ruggedize the subsystems for operation in aircraft engine test-bed environment as well as by fitting them to a unified setup with optical integration elements to allow a reproducible, combined, and common observation geometry.

After completion of hard- and software tools, WP4000 will deal with the calibration and validation of the subsystems in laboratories with cross-verifications with other mid-infrared absorption techniques (SDLA/DLAS, FTIR).

The project then continues with WP5000 which deals with ground test rig trials at a combustor as well as at an aircraft engine. These are to be performed at different power settings and accompanied by spatially resolved intrusive measurements. Data collected are to be intensively analysed, cross checked and verified for consistency.

During the whole project duration, various efforts like contributions to conferences and in refereed journals are to continuously promote dissemination and utilisation of results in WP6000. Patents opportunities are also to be investigated.

The subtasks and their corresponding work packages are presented in the tree diagram of Figure 1. More details of the corresponding objectives and work to be performed will be recalled before presenting the results of each task in chapter four.
2.2. Planning

The project duration was initially planned for 36 months. It has been prolonged twice (8 months and then 2 months) for a total duration of 46 months (start date: 1st May 2002; end date: 28th February 2006). Figure 2 presents the updated planning.
### Updated Planning

**WP 1000 Coordination**
- Task 2100 Species
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 2000 Requests & Defs**
- Task 2200 Spectral lines
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 3000 Instrumentation**
- Task 3100 Lab MIDROPO prototype
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 4000 Calibration**
- Task 4100 Lab Calibration
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 5000 On site experiments**
- Task 5100 Combustors
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 6000 Exploitation**
- Task 6100 Industrial exploit.
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 7000 Coordination**
- Task 7100 Systems validated
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 8000 Requests & Defs**
- Task 8100 MIDROPO prototype
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 9000 Instrumentation**
- Task 9100 Lab MIDROPO prototype
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 10000 Calibration**
- Task 10100 Lab Calibration
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 11000 On site experiments**
- Task 11100 Combustors
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

**WP 12000 Exploitation**
- Task 12100 Industrial exploit.
  - 1st year
  - 2nd year
  - 3rd year
  - Meeting 6 month
  - Meeting 12 month
  - Meeting mid-term
  - Meeting 24 month
  - Meeting 30 month
  - Meeting 36 month
  - Meeting 44 month

### Milestones

<table>
<thead>
<tr>
<th>Milestone No.</th>
<th>Due date (month)</th>
<th>Brief description of Milestone objective</th>
<th>Decision criteria for assessment</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td></td>
<td>Start of project</td>
<td>Contracts signed</td>
<td>OK</td>
</tr>
<tr>
<td>M2</td>
<td></td>
<td>Requirements defined</td>
<td>All parameters covered (D1,D2)</td>
<td>OK</td>
</tr>
<tr>
<td>M3</td>
<td>20</td>
<td>Labs instruments operational</td>
<td>Technical Specifications fulfilled as described in WP2000 (D4,D5,D6)</td>
<td>OK for D5&amp;D6, partial fulfilment for D4</td>
</tr>
<tr>
<td>M4</td>
<td>24</td>
<td>MIDROPO Prototype and Software operational</td>
<td>Tech. Specifications fulfilled (D8)</td>
<td>Partial fulfilment</td>
</tr>
<tr>
<td>M5</td>
<td>28</td>
<td>Systems validated</td>
<td>Lab. Cal./Val. Successful (D9)</td>
<td>Partial fulfilment</td>
</tr>
<tr>
<td>NM1</td>
<td>37</td>
<td>Instruments ready for field tests</td>
<td>Laboratory tests results</td>
<td>Not ready</td>
</tr>
<tr>
<td>NM2</td>
<td>41</td>
<td>Instruments are optimized for further field tests</td>
<td>First field tests &amp; laboratory tests results SDLA/DLAS only + eventual QCL</td>
<td></td>
</tr>
<tr>
<td>M6</td>
<td>36 -&gt; 44</td>
<td>Experiments and analysis verified</td>
<td>Intrusive and non-intrusive results matching (D11-D12)</td>
<td>OK</td>
</tr>
<tr>
<td>M7</td>
<td>36 -&gt; 44</td>
<td>End of Project</td>
<td>Final reports accepted (D13)</td>
<td>OK</td>
</tr>
</tbody>
</table>

**Figure 2** - Planning for MENELAS


**Figure 3** - List of milestones for the MENELAS project
3. SCIENTIFIC AND TECHNICAL DESCRIPTION OF THE RESULTS

The technical achievements are given below on a task per task basis, following the objectives recalled in section 3.1.

3.1. WP2000 -Requirements and definitions

As an end user motorist, SNECMA emitted the following needs and recommendations for the instruments and measurements studied in the present project:

- SNECMA needs pollution measurements, in accordance to present and future ICAO recommendations, in order to:
  - certificate the civil engines
  - characterize combustors and after-burners
  - obtain the pollution of the air breathed by the pilots and the passengers, air taken in the compressor.
- To meet these needs SNECMA requires:
  - to make measurements at the exit of engines, of combustors, in the bleed of the compressors (T max < 2200 °K, P max < 45 bar)
  - to analyse the gas during the engine test
  - to measure all species in five minutes at most
  - that pollution covers the whole aircraft operation
  - to make non intrusive measurements to avoid perturbations of the jet
  - to have local measurements
  - to obtain radial or circumferential (one point by one point) measurements with a good spatial resolution (1 mm), all the measurements made in the same plane
  - representative samples and analysis
  - to get the concentrations of NO, NO2, CO, CO2, H2O, N2O, SOx unburnt species with ± 2% accuracy for each pollutant, with one system
  - an instrument easy to use (one day at most for preparation, calibration in the bench) and a system relatively light (50 kg at most)
  - a system insensible to the tested engine vibrations
  - that the system be in accordance to CEM (electromagnetic compatibility) rules.

3.1.1. WP 2100, 2200 & 2310 -Selection of species and spectral lines (NEO, All)

3.1.1.1. Objectives

- Selection of relevant species and identification of spectral lines that have to be probed in this project, taking into account ICAO recommendations, cross-correlation possibilities and potentialities of the optical techniques
3.1.1.2. Main results

Based on the practical wavelength range for the OPOs that are developed in the project, a list of relevant species that can be detected within the spectral range of the OPO and the MIRPL has been discussed and agreed among the partners. Figure 4 presents spectral region chosen on a chart of absorption lines simulated from the Hitran database. Most of the species of interest for aeronautics (except NO) are within this range. The available SDLA/DLAS instrument for benchmarking in this project will work in the region 4.1 to 5.3 µm depending on available diodes. For demonstration purposes, the practical experiments are to be limited to a maximum of 3 species.

A cross-interference analysis based on the HITRAN database has been made by NEO to ensure that the lines are interference free, i.e. there are no interfering spectral lines from the other gases in the actual gas matrix. The table of potential candidates is shown in Table 1. Among the interesting gases that are not within the spectral range of the OPO is NO, which absorbs from 5 to 6 µm.

The selected species, CH₄, CO, CO₂ and NO (Table 1), have been chosen for four reasons:
i) they are concerned with the ICAO recommendations,

ii) during test periods, their concentrations can be sampled and recorded with classical probes,

iii) most of these species can be probed with the different optical techniques, which are involved in Menelas,

iv) the selected species must be produced over a large scale of concentration so as to allow to test the capability of the different techniques having each a specific sensibility. A special attention will be devoted to CO$_2$ since the large concentration of this molecule leads to a large absorption in the mid-infrared.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Wavelength (cm$^{-1}$)</th>
<th>Wavelength (nm)</th>
<th>DL ppm (10$^{-4}$*1 m)</th>
<th>Interference</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>2950</td>
<td>3390</td>
<td>0.05</td>
<td>H$_2$O</td>
</tr>
<tr>
<td>NO$_2$</td>
<td>2890</td>
<td>3460</td>
<td>0.3</td>
<td>CH$_4$, H$_2$O</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>2331</td>
<td>4290</td>
<td>0.005</td>
<td>H$_2$O</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>2338</td>
<td>4277</td>
<td>0.004</td>
<td>H$_2$O</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>2237</td>
<td>4470</td>
<td>0.015</td>
<td>H$_2$O, CO$_2$</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>2202</td>
<td>4541</td>
<td>0.015</td>
<td>CO, H$_2$O</td>
</tr>
<tr>
<td>CO</td>
<td>2203</td>
<td>4539</td>
<td>0.06</td>
<td>N$_2$O, H$_2$O</td>
</tr>
<tr>
<td>CO</td>
<td>2198</td>
<td>4550</td>
<td>0.03</td>
<td>H$_2$O, N$_2$O, CO$_2$</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>1967</td>
<td>5084</td>
<td>1.19</td>
<td>CO, CO$_2$, NO, N$_2$O</td>
</tr>
<tr>
<td>NO</td>
<td>1964</td>
<td>5092</td>
<td>131.74</td>
<td>CO, H$_2$O, N$_2$O</td>
</tr>
<tr>
<td>NO</td>
<td>1754</td>
<td>5700</td>
<td>Not known</td>
<td></td>
</tr>
</tbody>
</table>

*Table 1 - List of selected species and absorption lines*

Table 2 gives the expected ranges for concentration and temperature of some of the different species that have to be probed during the calibration procedure (WP 4000) and during on-site experiments (WP 5000).

<table>
<thead>
<tr>
<th>Measurement Range (ppm)</th>
<th>Temperature range (K)</th>
<th>Measurement Range (ppm)</th>
<th>Temperature Range (K)</th>
<th>Measurement Range (ppm)</th>
<th>Temperature Range (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DLR</td>
<td>DLR</td>
<td>NLR</td>
<td>NLR</td>
<td>RISØ</td>
<td>RISØ</td>
</tr>
<tr>
<td>CO</td>
<td>10-10000</td>
<td>700-2300</td>
<td>1-80</td>
<td>280-500</td>
<td>&lt; 500 *</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>0.25 - 10%</td>
<td>700-2300</td>
<td>500-2%vol</td>
<td>280-500</td>
<td>&lt; 5% vol*</td>
</tr>
<tr>
<td>NO</td>
<td>1-100</td>
<td>700-2300</td>
<td>1-50</td>
<td>280-500</td>
<td>&lt; 100 *</td>
</tr>
</tbody>
</table>

*Table 2 - Concentration and temperature ranges in Menelas*

3.1.2. **WP2320 Conditions for the aircraft ground runs**

Aircraft tests require a rigorous test plan, in conformance to NLR’s quality procedures, so as to guarantee safe, efficient and orderly performance of aircraft ground runs and flight trials. In the first one-year period, NLR issued the deliverable D2, i.e. MENELAS Technical Note D2 ‘Test Plan for MENELAS
aircraft ground tests’ describing the test plan for the operation of NLR’s Cessna Citation II research aircraft in MENELAS aircraft ground tests.

3.1.3. **WP 2400 – Velocimetry & Densitometry potentialities (NLR)**

3.1.3.1. **Objectives**
- Study on the potentialities of various techniques for providing velocimetry and high spatial resolution of concentration measurements of the jet engine exhaust gas. These velocimetry and tomographic concentration measurements will provide a first step to extension of the spectroscopic techniques from concentration measurements towards non-intrusive exhaust gas emission index measurements, i.e. COX and NOX grams per kg burned fuel.
- Issue of Deliverable D3

3.1.3.2. **Main results**
A literature study was made on both non-intrusive velocity measurement techniques and density measurement techniques. The obtained ideas on the outlook of the various non-intrusive measurement techniques for this specific application were reported in deliverable MENELAS Report D3: ‘Velocimetry and density measurement potentialities on the exhaust plume of an aircraft jet engine’. Concerning the velocimetry techniques, techniques based on both the time-of-flight concept and Doppler-shift concept were investigated on their applicability for this specific application. Since for civil aviation aircraft jet engines it is highly uncertain whether seeding may be applied at the engine inlet, an important parameter in investigated techniques is the requirement to seed the flow with particles. Therefore the optimal techniques were investigated both with and without the seeding option available.

It turned out that although seeding-based techniques, e.g. PIV, LDA and DGV provide the best prospects; also seedless techniques are promising for high accuracy non-intrusive velocimetry. Of those seedless techniques the Spark Tracing Velocimetry, Thermal Grating Velocimetry and H₂O-based Molecule Tagging Velocimetry techniques provide good prospects, although for the full-scale jet-engine application, no ‘Commercial-Off-The-Shelf’ systems are available yet.

Concerning optical density measurement techniques, again techniques based on two physical concepts are available: density measurements based on (particle or photon) absorption or scattering and density measurements based on variations in the refractive index. For density measurements at the exhaust plume of a jet-engine the ‘Background Oriented Schlieren’ technique seems to have the best prospects for a quantitative, high accuracy tomographic measurement.

Tables showing a comparison for various velocimetry and densitometry techniques at the aircraft jet-engine exhaust plume are given in deliverable D3.
3.2. Instrumentation (WP3000)

WP3000 (Instrumentation) is focused on the development and set up of optical instrumentation.

3.2.1. WP 3100 – laboratory mid-DROPO

3.2.1.1. Objectives

- Realisation of a mid infrared entangled cavity doubly resonant optical parametric oscillator (MIDROPO). Two identical units are to be manufactured: one for ONERA for calibration, test cell measurements, ... and one for the prototype fabrication by NEO.

3.2.1.2. Main results

The scheme of the doubly-resonant optical parametric oscillator (DROPO) [1] using an entangled cavity resonator is presented in Figure 5 and a picture of the laboratory device is given in figure 6.

Figure 5- Schematic of the entangled cavity DROPO
The resonator is composed of two stable cavities: M₁-M₃ and M₂-M₄ which are resonant at the signal ($\omega_s$) and idler ($\omega_i$) radiation, respectively. The mirrors M₂ and M₃ are deposited on the end faces of the 5-mm-long PPLN crystal which is heated around 100 °C to avoid photorefractive damage. This crystal comprises 8 grating sections with a spatial period varying from 25.5 to 28.7 µm allowing a coarse frequency tuning. The optical parametric conversion takes place in this PPLN non-linear crystal. The two external mirrors (M₁ and M₄) are mounted on two PZT actuators for fine frequency tuning. This MIDROPO cavity is pumped with a small Nd:YAG laser (from Innolight) which delivers 20 µJ, 13 ns long pulses at a 12 kHz repetition rate at 1.06 µm. The combination of the latter wavelength and the PPLN properties result in output wavelengths between 3.5 and 4 µm in the mid-infrared region for the present DROPO.

The configuration provides a unique device for spectroscopic applications because it can provide single-frequency operation with narrow linewidth (~100 MHz; Fourier limited) at a low threshold of oscillation, owing to the doubly resonant feature. Under single frequency operation, we have recorded the evolution of the output energy delivered by the OPO versus the pump energy. As seen in Figure 7, the threshold of oscillation is less than 4 µJ. Four times above the threshold, the available energy at 3.8 µm is close to 1 µJ i.e. 330 W for 3-ns long pulses (full width at half maximum).
The main performances that have been obtained with the laboratory MIDROPO are summarized in Table 3.

<table>
<thead>
<tr>
<th>Spectral range</th>
<th>3.5 to 4 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral linewidth</td>
<td>100 MHz, from 3.8 to 4 µm</td>
</tr>
<tr>
<td>Continuous fine tuning</td>
<td>150 GHz</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>12 kHz</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>3 ns</td>
</tr>
<tr>
<td>Maximum pulse energy</td>
<td>1 µJ</td>
</tr>
<tr>
<td>Beam quality</td>
<td>M2~1.8</td>
</tr>
</tbody>
</table>

Table 3: Performances of the laboratory MIDROPO prototype

The potentialities of the MIDROPO spectrometer have been tested by recording absorption spectra of N$_2$O around 3.9 µm. From Figure 8 (left side), it is seen that several absorption lines can be scanned thanks to the wide mode-hop-free tuning range of the MIDROPO. Furthermore, at low pressure (right side), closed spectra lines are well resolved thanks to the narrow linewidth (Fourier limited) of the MIDROPO.
The two prototypes built have a smaller continuous tuning capability than expected due to problems encountered with the mirrors delivered to build these new OPOs: they do not meet the specifications ordered and reflects too much the pump laser beam. Investigations of the effects of pump reflection have been carried out. Pump reflection at certain mastered levels can be advantageous, but in the present case, the level is too high and limits the fine tuning. Actions have been taken to get reimbursed from the mirror coating manufacturer and to obtain new coatings from a new supplier. The delays in obtaining the mirrors and their testing (there were 3 cycles of procurement-testing for the mirrors) did not allow to obtain an operational OPO at the end of the project which discarded participation in all field experiments.

3.2.2. **WP 3200 – MIDROPO prototyping and signal processing (NEO)**

3.2.2.1. **Objectives**

This task has comprised design and implementation of the complete electronic control system for the prototype spectrometer comprising a flexible drive and control system for the MIDROPO source as well as a detection system for measurement of gas concentration based on single line direct absorption spectroscopy, adapted to the operational characteristics of the MIDROPO.

3.2.2.2. **Main results**

Figure 9 shows the basic outline of the MIDROPO spectrometer system which has been realised. A more detailed description of the system is given in Chapter 13 -Annex 3.
The performance of the MIDROPO prototype and its various subsystems have been studied carefully during the course of the project. The most critical component of the prototype is the MIDROPO source itself which exhibits unstable operation. The difficulties in the development of the source in Task 3100 have had significant impact on the development of the prototype in this task. The performance of the source has not been satisfactory for proper operation of the prototype, and problems with manufacturing and extended delays in the delivery of custom optics for the MIDROPO has made significant impact on the progression of the work in this task.

The electronics developed for the MIDROPO has proved well suited to the operation of the prototype except for the choice of MIR detectors which present non-linearities at high laser energies.

The unstabilities of the source limited the automated tuning range to 0.1 cm\(^{-1}\). Nevertheless, this allowed the demonstration of an automated measurement of an absorption line (partial scan) of N\(_2\)O (Figure 10).

**Figure 9**  
(a) Schematic of MIDROPO spectrometer system. The MIDROPO spectrometer comprises an optical bench with the MIDROPO source and detectors on top, mounted above the control electronics. (b) Block diagram of the MIDROPO electronics.

**Figure 10**  
(a) Measurement of part of absorption line near 3.85 \(\mu\)m in 100 % N\(_2\)O at atmospheric pressure, 25 °C, path length 50 mm. Part of the idler beam has been used for the reference pulse energy measurement. High energy pulses in the non-linear range of the detectors have been filtered out. (b) Same as a) only with the pulse energy normalization carried out.
This proves (and the laboratory development result depicted in Figure 8) that it is feasible to use an OPO for single line spectroscopy in the mid-infrared, although significant improvement is needed before the OPO can be considered for use in an application outside the laboratory. Capability of measurement of one single line would be a significant step, but arriving at a widely tunable source with capability of measuring several species with the same OPO source does not seem likely at the present time.

3.2.3. **WP 3300 – PS-MIR-DIA-LIDAR (TUC)**

3.2.3.1. **Objectives**

Development of a picosecond mid infrared lidar by frequency difference generation for differential absorption detection. This instrument aims at determining exhaust gases of aircraft jet engines with a high spatial resolution.

3.2.3.2. **Main results**

A laboratory scale prototype of a ps-MIR LIDAR spectrometer based on difference-frequency generation, which can be used in field experiments to measure emission gases from jet engines, has been developed (see Figure 11). The principles of the technique as well as detailed descriptions on major components are given in Chapter 10 -Annex 1.

![Figure 11-Set-up of the ps-MIR DFG LIDAR system.](image-url)
We summarise below in Table 4, the obtained performances of the MIRPL developed during this study.

<table>
<thead>
<tr>
<th></th>
<th>Objectives</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>2.8 – 4 µm</td>
<td>3.32 – 3.46 µm</td>
</tr>
<tr>
<td>Spectral resolution</td>
<td>&lt; 10-2 cm⁻¹</td>
<td>5.4 · 10⁻² cm⁻¹</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>&gt; 1 kHz</td>
<td>≈ 4 kHz</td>
</tr>
<tr>
<td>MIR pulse duration</td>
<td>100 ps</td>
<td>≈ 550 ps</td>
</tr>
<tr>
<td>MIR pulse energy</td>
<td>&gt; 1 nJ</td>
<td>≈ 0.5 nJ</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>1.5 cm</td>
<td>≈ 8 cm</td>
</tr>
<tr>
<td>Species</td>
<td>NO, CO₂ and H₂O</td>
<td>Methane, Ethylene</td>
</tr>
</tbody>
</table>

Table 4 - MIRPL laser source performance

The MIRPL laser source performance depicted in table 3 is not so far from required performance. Even with such spatial resolution, acceptable concentration profiles are expected in an exhaust plume of an aircraft jet engine. There has been much work also on the detection component of the LIDAR system which is not so readily available in the picosecond time regime for the mid infrared domain. New strategy based on sum-frequency generation is being envisioned and laboratory tests are quite promising.

The difficulties encountered in the laser emission and optical detection parts of the LIDAR and the search for alternative solutions did not allow to obtain an operational instrument for the field experiments. Only laboratory demonstration on CH₄ in a cell at TUC and in RISOE’s hot cell have been possible.

3.2.4. **WP 3400 – SDLA/DLAS adaptation (ONERA)**

3.2.4.1. **Objectives**

- Adaptation of an existing mid-infrared tunable laser diode apparatus for COx and NOx spectroscopy in order to:
  - validate infrared absorption technique by itself as a precious optical diagnostic tool for the determination temperature and trace gas measurements of a selection between CO, CO₂, NO, NO₂ … gases (defined in WP 2000) in test cells.
  - help to define the MIDROPO and the picosecond lidar acquisition procedures (spectral scanning range for temperature determination, detection as a function of power and RIN,…)
  - participate in the field experiments to cross-check results from the two instruments developed in the project
  - Issue of Deliverable D6 (SDLA/DLAS spectrometer)
3.2.4.2. SDLA/DLAS description

Salt Lead Lasers are used in the 3 to 10 µm band, and are tuneable over approximately 100 cm\(^{-1}\). The emission line-width of these infrared lasers is less than 10\(^{-3}\) cm\(^{-1}\). By adjustment of the diode current the emission is tuned over a small spectral range (1 cm\(^{-1}\)) which contains the absorption line of the molecule. The comparison between emission and reception spectrum after going through gas supply the exactly profile line studied at a resolution of 10\(^{-3}\) cm\(^{-1}\). The method enables the detection of numerous molecules like NO, NO\(_2\), N\(_2\)O, H\(_2\)O, CO, CO\(_2\), CH\(_4\), O\(_3\), HCl, OCS... A detection threshold of about 5.10\(^{-5}\) is possible with this technique. Using an absorption length of few meters and the most intense spectral line, a sensitivity in the few 10 ppb is expected for NO, CO\(_2\), CO and CO\(_2\) measurements.

The SDLA/DLAS spectrometer (Figure 12 & Figure 13) from ONERA is quite an operational instrument routinely used to characterize NO, CO, CO\(_2\) and H\(_2\)O in chemically reacting flows of high enthalpy wind tunnels [2]. The instrument is composed of a laser emission head, photodetectors and fast digitizers to convert and record the signals from the photodetectors. The laser emission head is in the form of a liquid nitrogen cooled cryostat containing a lead-salt diode operating near 100 K (Laser Components PbEuSe diode laser). Stabilized current generators are used to control more finely the diode temperature and current for the required laser emission. A 500-mm focal length monochromator and several other optical components are used to filter a single mode out of the emission spectrum of the diode and collimate the output laser light into a 14-mm diameter beam. About 30% of this beam is deviated for wavenumber and intensity calibrations using a 0.00975 cm\(^{-1}\) free spectral range confocal spherical Fabry-Perot etalon and a reference cell filled with NO at 100 Pa. All these elements are grouped on an optical bench 1.5m long and 0.8m wide. The rest of the laser beam exiting this bench is then made to cross the gas medium to be studied with the help of mirrors before measuring its intensity on a third photo-detector. Figure 14 presents a set of three absorption spectra (two for calibration and one for the medium being probed) which is typical when performing measurements with this instrument.

![Figure 12 - SDLA/DLAS spectrometer setup](image)
3.2.4.3. Main results

For the MENELAS project, the SDLA/DLAS spectrometer has been upgraded through the following actions:

- the data acquisition VXI controller has been upgraded to increase the sensitivity of the SDLA/DLAS bench;
- the working operation ranges of the CO and CO\textsubscript{2} diodes have been checked to cover CO, CO\textsubscript{2} and NO lines compatible to the present project (Figure 15);
- data reduction has been adapted to deal with high temperature and pressure absorption spectra (see section 3.3.1.1).

The SDLA/DLAS setup can detect absorption down to $10^{-3}$ (through direct absorption, i.e. no heterodyne method). The study carried out through averaging over a large number of acquired spectra did not improve the sensitivity to the targeted value of $10^{-5}$. The main reason is an electronic jitter problem during acquisition which forbids averaging. Recommended solutions are to use a better acquisition system or more sophisticated post-acquisition processing which could not be implemented during this project.
Nevertheless, the $10^{-3}$ absorption sensitivity has been sufficient for laboratory tests as well as for the field experiments (WP5000) for the CO, CO$_2$, and H$_2$O molecules. However, a higher sensitivity is required for the NO molecule in the conditions of the field experiments.

![Available SDLA diodes](image)

**Figure 15 - SDLA/DLAS : available diode lasers for MENELAS**

### 3.2.4.4. Summary of SDLA/DLAS performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
</table>
| Spectral range                 | Diode 1 : 4.7 to 5.2 $\mu$m (CO, NO)  
                              | Diode 2 : 4.2 to 4.4 $\mu$m (CO$_2$) |                                                                         |
| Spectral resolution            | ~ $10^{-4}$ cm$^{-1}$        | Laser diode has CW single mode emission; Spectral tuning : a window of at least 1 cm$^{-1}$ can be swept with a repetition rate up to 20 kHz |
| Measurements repetition rate   | up to 10 kHz                 |                                                                         |
| Sensitivity                    | Absolute absorption of $10^{-3}$ | ~$10^{-4}$ expected shortly                                             |
| Spatial resolution             | None (line of sight technique); | Measurements given are averaged over the absorption length of the beam in the probed medium. Abel inversion procedures are yet to be implemented in the data reduction code. |
| Species targeted for MENELAS   | NO, CO, CO$_2$               | From the possibilities of the laser diodes, measurements will have to be performed on other (but equivalent) lines than those chosen for the two new instruments developed in MENELAS. |
3.2.5. **Optical fibers for the mid infrared**

3.2.5.1. **Objectives**

- Study of mid-infrared fiber optics to ease laser light transportation to the combustor sites from laser setups kept at distance.
- Issue of Deliverable D7 (Fiber optics test report)

3.2.5.2. **Main results**

An evaluation of infrared fibers on the market and their properties with regards to applications in the MENELAS project has been carried out for this task. Based on the findings in this study, a raw C2 chalcogenide IR fibre (1 - 7 µm), and PIR (3 - 17 µm) / CIR (2 - 6 µm) fibers from ART-Photonics have been procured and tested by RISOE with the help of a Bomem MB100 FT-IR spectrometer. The transmission curves matched to the MENELAS spectral region are presented in Figure 16. These two fibers seem suitable to be employed with the laser systems developed in the project. Further tests with pulsed laser operation which exhibits high peak powers are required. These tests were not possible because of the difficulties met by the pulsed laser sources developed in the project. But from the properties stated for these fibers, one can be confident that they will withstand the peak powers envisioned for the lasers of the project.

![Figure 2: PIR optical fiber](image2.png)

![Figure 3: CIR optical fiber](image3.png)

**Figure 16**: Transmission of the 2 fiber optics tested with FTIR by RISOE
3.3. Calibration and validation (WP4000)

3.3.1. WP4100 Laboratory tests

3.3.1.1. WP4110 SDLA calibrations (ONERA)

A series of tests have been performed on CO lines (P28 and P30 lines). Absorption lines have been recorded at room temperature, for different pressures in order to determine the line broadening coefficient of CO with air or N₂. It was seen that there is some atmospheric H₂O interference with the P28 line which makes it more difficult to obtain an accurate baseline for data reduction. The P30 line (2018 cm⁻¹) was preferred to perform the line broadening verification (Figure 17). It was found that the line broadening coefficient obtained for air or N₂ pressure broadening corresponds within 10 % accuracy to the value given in the HITRAN database.

![Test of pressure broadening of CO line](image)

In a 10 cm long cell at 300 K, initially filled with 100 mbar of CO

Figure 17 -SDLA/DLAS : pressure tests

3.3.1.2. WP4120 MIRPL calibrations (TUC)

3.3.1.3. Objectives

- Laboratory test measurements with the ps-MIR-laser system (MIRPL) in a McKenna atmospheric flat burner.

3.3.1.4. Main results

Tomographical scans of the concentration of CO in the flame of a McKenna burner have been performed with an absorption set up using the laser source of the ps-MIR-laser system. Some results are depicted in Figure 18. More details of the experiment can be found in [3].
3.3.2. WP 4200 Cross Validation and calibration

3.3.2.1. WP4210 High temperature reference gas cell (RISOE)

The performances of the developed laser instruments in the project should be characterized through laboratory test and cross calibration experiments prior to campaign measurements. The Risoe hot gas cell facility used in the AEROPROFILE project for verification of methods based on FTIR spectroscopy has been upgraded to cover the needs in the MENELAS project.

The stainless steel surfaces of the inner hot cell parts has been coated with a ceramic coating to cope with reactive gases like CO and NO at high temperatures in the MENELAS project in order to avoid problems with gas reaction due to catalytic effects. Similar, the gas cell windows have been replaced with wedged CaF₂ windows to reduce etalon effects. All temperature sensors have been calibrated. The gas cell can now be operated at low pressures far from ambient due to the replacement of the graphite seals by a ceramic inner cell with wedged sapphire windows.

Different water generators available on the commercial market were considered, e.g. NEOs Hovacal water generator and dew-point generators from Michell, but the water generators would be difficult to apply in the needed concentration range and with calibration gases. Therefore, a system for addition of water vapor has been designed, built and adapted. A given amount of pure water from a syringe pump is injected directly into the preheated gas flow from the gas mixing system before it enters the gas cell (Figure 19).
Gas from the Environics 4000 gas mixture system or from bottle is preheated and water vapor is added to the gas flow before it enters the gas cell via a heated gas line. The syringe pump controls the water flow rate. The evaporation of the water leaving the narrow bore tube is smooth and effective through the large surface area of the quartz wool.

The upgraded hot gas cell facility at Risoe was finally tested in August 2003 prior to experiments with the laser systems using an FTIR spectrometer with fiber optics sensitive in the spectral range 1800 – 6500 cm\(^{-1}\) (Figure 20). The test was performed with 1% CO, 1%CO\(_2\) and 1% CH\(_4\) in nitrogen at 800°C in order to provoke gas reactions. It is concluded that gas reactions are very small with the ceramic coating and operating the gas cell with at a flow rate of 2 l/min. Similar, test measurements with the water generator was carried out at different water vapor levels. Experiments with approx. 1% CO\(_2\), 1% CH\(_4\) and nitrogen with and without high levels of water has been carried out at 1073 K, and it was shown that water could be removed by subtraction of the measured water spectrum in nitrogen (Figure 21 and Figure 22).

It is concluded that the water vapor concentration is very stable, short term as long term, and it can be varied over a wide range.
Figure 20- Experimental setup in tests of upgraded hot gas cell.

MIR (C2 chalcogenide) fibers were used in measurements with extended spectral range to cover fundamental bands of CO, CH4 and CO2. The temperature range is from ambient to 1073 K with gas cell windows of CaF2.

Figure 21 - Measured CO spectrum compared with calculated spectrum from HITRAN96

For 1% CO at 1 atm, 1073 K and 50 cm pathlength. The spectral resolution in the calculated spectrum is 2.3 cm⁻¹. The deviation in area between the two curves is 1.3%. The gas flow rate through the gas cell was 2 l/min.
3.3.2.2. **WP4220 MIDROPO and SDLA (ONERA)**

The technical difficulties met on the MIDROPO instrument discarded any calibration tests on the RISOE hot cell. There were no tests either with the SDLA instrument due to its frequent unavailability for intensive use in wind-tunnels and it was estimated that high temperature effects on the absorption lines to be probed was, in this phase, less than of a concern with respect to flow fluctuations and background illumination where the efforts have been placed.

3.3.2.3. **WP4230 PS-MIR-DIA-LIDAR calibration (TUC)**

#### 3.3.2.3.1. Objectives:
- Hot cell calibration of the PS-MIR-DIA-LIDAR for concentration measurements at different temperatures in the spectral range around 3 µm.
- 3D concentration profile measurements for different temperatures

#### 3.3.2.3.2. Main results:

There was an experiment with TUC PS-MIR-DIA-LIDAR to perform test and line-broadening measurements at Risoe’s hot gas cell. Measurements were carried out for CH₄ in air, nitrogen and with addition of water vapor at temperatures from ambient and upwards in steps of 50 K.

TUC performed first measurements in the hot gas cell with the ps-MIR DFG laser system (see also deliverable D5). Measurements were carried out for pure methane (CH₄), methane with synthetic air (79%)
nitrogen, 21% oxygen), methane with pure nitrogen and with addition of 2% of water vapor at temperatures from ambient (T=23 °C) up to 180 °C.

In this first campaign (Figure 23), TUC investigated a single rotational line of methane at 2883.45 cm\(^{-1}\). TUC measured with its laser system line profiles of the single rotational line for different combinations of the above-mentioned foreign gases at different temperatures as follows:

- Constant pressure: 1 atm;
- Temperatures: 23°C, 70°C, 120°C, 180°C;
- Concentrations of methane: 0%, 3%, 5%, 7%, 9%, 11%, 13%, 15%, 17%, 19%;
- Synthetic air: 21% oxygen and 79% nitrogen;
- Water vapor: const. 2%.

The analysis of every measured absorption profile has been done by fitting a Voigt profile to the measured data. On the basis of the Lorentian and Gaussian proportion of the width or the area of the Voigt profile it is possible to determine temperature dependent self- and foreign broadening coefficients which are necessary for calibration the laser system and measurement of absolute values in the planned field campaigns at DLR and NLR.

This measurement campaign showed that the broadening effect of synthetic air and pure nitrogen are the same (see Figure 24 and Figure 25). The influence of 2% water vapor can be neglected.
Figure 24 - Measured slopes for different mixtures at T=120 °C. Results based on experiments on hot gas cell during TUC visit to RISOE.

Figure 25 - Dependence of the slope on the temperature. Results based on experiments on hot gas cell during TUC visit to RISOE.
3.3.3. 4300 Degenerate four wave mixing experiments (ONERA)

In conventional absorption spectroscopy, the signal is integrated along the line of sight of the measurements. Obviously, such an approach is not sufficient for the analysis of reactive flows encountered in jet exhaust which requires spatially-resolved measurements. To fulfil this requirement, two different methods have been proposed in the frame of MENELAS. One is based on a picosecond lidar (WP 3300), the second takes advantage of the third order optical non-linearities in gases which can allow unambiguous spatial concentration through four wave mixing methods (present WP 4300).

3.3.3.1. Objectives:
- Feasibility of DFWM experiments on a test cell in order to investigate the detectivity and spatial resolution of this method.
- Issue of Deliverable D10 (Performances of the DFWM for spatial resolution)

3.3.3.2. Main results
A general diagram of the envisioned DFWM experimental apparatus is shown in Figure 26. It is composed of two main parts: a 10 kHz Nd:YAG laser followed by a Nd:YVO4 amplifier that produces the pump radiation at 1.06 µm and a second stage which consists of an OPO (optical parametric oscillator) and an OPA (optical parametric amplifier) that delivers tunable radiation from 3.8 to 4.4 µm. The OPO is pumped by half of the laser energy whereas the full power coming from the Nd:YVO4 amplifier is used to pump the OPA.

![Figure 26: General diagram of the optical bench.](image-url)
3.3.3.2.1. Pump stage characteristics

The pump laser is a commercial passively $Q$-switched Nd:YAG laser based on a non planar ring oscillator (Mephisto Q, Innolight GmbH). This laser delivers 9 ns-long pulses at a 12 kHz repetition rate, the average power is ~ 400 mW. At the exit of the isolator, 50 % of the laser energy goes through a 3D multipass amplifier whose architecture, depicted in Figure 27, is based on the one described in [4].

![Nd:YVO₄ multipass amplifier](Image)

To characterize the performances of the amplifier, we have recorded the evolution of the output power ($P_{\text{out}}$) versus the input power ($P_{\text{in}}$) when pumping at a 20 W level. This $P_{\text{in}}$-$P_{\text{out}}$ dependence and the related efficiency coefficient ($P_{\text{out}}/P_{\text{in}}$) are shown in Figure 28. Although a strong saturation is clearly observed (for $P_{\text{in}} > 40$ mW), we demonstrated that it is possible to extract more than 1.5 W of the amplifier, i.e. 150 µJ energy per pulse. Note that the efficiency could still be improved by use of a longer focal length doublet in order to increase the beam overlap inside the crystal.
3.3.3.2.2. Mid-infrared stage characteristics

The tunable narrow-linewidth ($\Delta \nu < 100$ MHz) mid-IR radiation is produced by an entangled cavity optical parametric oscillator (ECOPO), see description in WP3100. The available energy at 3.8 $\mu$m is close to 1 $\mu$J i.e. 330 W for 3-ns long pulses (full width at half maximum).

To increase the output power while preserving the spatial and spectral qualities of the emitted beam, the OPO is followed by an OPA stage. The idler beam produced by the OPO is mixed with the amplified pump beam in a 20-mm-long PPLN crystal. The two beams are focused at the center of the crystal with the same diameter (120 $\mu$m spot size radius). At the maximum pump energy (150 $\mu$J), it has been possible to increase the mid-IR energy by more than a factor 10 yielding to 3.2-kW peak-power mid-IR pulses—see Figure 29.
All the above optical components stand on a compact optical bench (60cm X 60 cm) as shown in Figure 30.

![Figure 30: Picture of the DFWM optical bench](image)

The performances of this optical bench are reported in Table 5.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range (µm)</td>
<td>3.8 - 4.3</td>
</tr>
<tr>
<td>Typical pulse duration (ns)</td>
<td>9</td>
</tr>
<tr>
<td>Repetition rate (kHz)</td>
<td>12.5</td>
</tr>
<tr>
<td>Maximum pulse energy (µJ)</td>
<td>10</td>
</tr>
<tr>
<td>Maximum peak power (kW)</td>
<td>3.2</td>
</tr>
</tbody>
</table>

*Table 5 – DFWM performance*

The amplification stages seem satisfactory but have not yet been tested for DFWM because of the spectral tuning problems of the OPO.

Work nevertheless continues after MENELAS on this subject at ONERA through a PHD thesis with scheduled experiments on CO₂.

### 3.4. WP5000 Field Experiments and Analysis

The objectives of the tasks in this work package were to test the non-intrusive systems of the project on a combustion chamber (WP5100) and on an aircraft engine during ground tests (WP5200).
3.4.1. **WP5100 Combustor operation and non-intrusive measurements**

This task aimed at validating the newly developed optical measurement techniques on a combustor rig with generic aeroengine burners for methane and kerosene at atmospheric pressure. All results are compiled in Deliverable D11 "Results from measurements on the DLR APZ combustor(WP5100)".

3.4.1.1. **WP5110 Characterisation of combustor**

3.4.1.1.1. **Objectives**

The target of this subtask was to provide a validation test case for the newly developed optical measurement techniques for exhaust gas species. An optical accessible combustor operated at atmospheric pressure (APZ combustor) was chosen for this reference experiment. The idea was to provide a well described flow of exhaust gas with a temperature, gas velocity and gas composition typical for the combustor exit plane of modern and future gas turbine combustors.

3.4.1.1.2. **Test rig description**

The combustor was designed to provide a reacting flow field which is typical for burners in aero engine gas turbine combustors. In order to reduce the complexity and the operating costs the combustor was limited to atmospheric pressure. Other relevant characteristics like velocity, temperature and species distribution were realistic for gas turbine combustors. The atmospheric combustor had a hexagonal cross section and a cross sectional area equivalent to an inner diameter of \( d = 100 \text{ mm} \). The combustor walls consisted of modules either with or without optical windows. These modules could be placed arbitrarily and permitted flexible optical access to the first \( x = 58 \text{ mm} \) downstream the burner exit plane. The windows were made of quartz for the velocity measurements and of sapphire for the infrared measurement techniques. A photograph of the combustor in operation is given in Figure 31.

A sketch of the different supply lines of the natural gas operated combustor is given in Figure 32. The main or burner air mass flow could be preheated to temperatures up to \( T_3 = 870 \text{ K} \). The air mass flow was measured by a critical nozzle. Natural gas and kerosene could be used as fuel. The natural gas composition is given in Table 6.

<table>
<thead>
<tr>
<th>Concentration [Vol.-%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane CH(_4)</td>
</tr>
<tr>
<td>Nitrogen N(_2)</td>
</tr>
<tr>
<td>Ethane C(_2)H(_6)</td>
</tr>
<tr>
<td>Carbon dioxide CO(_2)</td>
</tr>
<tr>
<td>Propane C(_3)H(_8)</td>
</tr>
<tr>
<td>Other hydrocarbons</td>
</tr>
</tbody>
</table>

*Table 6: Natural gas composition*
Figure 31 - Combustor in operation

Figure 32 - Supply lines of natural gas operated combustor
The combustor walls were cooled with cold air. All cooling air mass flows were measured by critical nozzles, see Figure 32. Wall modules without a window were convectively cooled on the back side and the cooling air was flowing into the combustor close to the combustor exit plane. The windows were cooled by a film of cold air on the hot gas side starting in the burner exit plane. The walls downstream of the windows were also cooled convectively. The details of the different cooling arrangements are given in Figure 33. The cooling air mass flows for convection and film cooling could be set independently.

![Figure 33: Cross section through combustor and cooling air flow](image)

Measuring equipment like thermocouple or suction probes and optical measurement equipment could be mounted on a three axis traversing unit. The resolution of the traversing system was $\Delta s=0.1$ mm. The position of the traversing unit and the operating conditions were logged on a computer.

The burner was a premix burner operated with natural gas. The gas was injected through a ring into a non-swirling air flow (Figure 34). In the mixer the air fuel mixture was interacting with two additional swirling air flows (inner and outer swirler). The mixture was homogenized by the turbulence in the shear layers between swirling and non-swirling air. The residence time of the fuel air mixture inside the burner was $\tau = 0.66$ ms. The residence time is limited by the auto-ignition time of the fuel air mixture at real engine take-off conditions.
3.4.1.1.3. Operating conditions

The minor species in the emissions of a flame, especially carbon monoxide CO and nitric oxides NOx, mainly depend on the flame temperature. The reaction rate coefficient $k$ generally shows a strong dependency on the temperature $T$ which can be described by the Arrhenius approach:

$$ k = A \cdot \exp \left( - \frac{E_a}{RT} \right) $$

The reaction path of the NOx formation governed by the flame temperature is called the Zeldovich mechanism, see[5]. This is the relevant path of the NOx formation under gas turbine combustor conditions. The decomposition of CO, oxidation of CO to CO2, is also strongly affected by the flame temperature. At temperatures of $T>2000$ K the reaction rate of the CO/CO2 conversion becomes so fast that even under atmospheric pressure the chemical equilibrium is reached within typical gas turbine combustor residence times. With increasing temperature the chemical equilibrium is shifted in favour of the CO concentration.
The second important quantity is the air preheat temperature which is together with the flame temperature characteristic for different engine power settings. So each operating point is defined by these two quantities:

1. Air preheat temperature \( T_3 \)
2. Flame temperature \( T_F \)

The burner air mass flow was calculated from a constant reduced air mass flow \( m_{\text{red}} = \frac{0.81 \text{ kg} \cdot \sqrt{K}}{s \cdot \text{bar}} \) and the preheat temperature \( T_3 \). The combustor pressure was ambient pressure. In a second step the fuel mass flow was calculated from the flame temperature, the preheat temperature and the air mass flow. Natural gas with a known composition was used in this investigation, see Table 6. The fuel mass flow was calculated with the chemical equilibrium software GASEQ was used, see [6]. The calculated air and fuel mass flows are listed in

<table>
<thead>
<tr>
<th>Air preheat temperature ( T_3 ) [K]</th>
<th>Air mass flow [g/s]</th>
<th>Flame temperature ( T_F ) [K]</th>
<th>Fuel mass flow [g/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>708</td>
<td>27.8</td>
<td>1950 … 2100</td>
<td>1.08 … 1.27</td>
</tr>
<tr>
<td>759</td>
<td>29.4</td>
<td>1950 … 2150</td>
<td>1.17 … 1.44</td>
</tr>
<tr>
<td>850</td>
<td>30.4</td>
<td>1950 … 2150</td>
<td>1.26 … 1.47</td>
</tr>
</tbody>
</table>

*Table 7: DLR APZ combustor operating conditions*

### 3.4.1.1.4. Main results on combustor characterisation with convention means

For the characterization of the combustor’s flow field and exhaust gas composition, measurements were done spatially resolved inside the combustor and in the combustor exit plane (Figure 35).

The following measurements were conducted:

1. The temperature distribution was measured with a type B thermocouple (Figure 36).
2. Conventional exhaust gas measurements with a suction probe were performed. The measured species were CO, CO\(_2\), O\(_2\), NO, NO\(_x\) and unburned hydrocarbons (UHC). Some results are presented in Figure 36 at exit plane of the combustor and in Figure 37 and Figure 38 for measurements inside the combustor.
3. The gas velocity distribution was measured by Laser Doppler Anemometry (LDA) and presented in Figure 39.

An detailed description of all these measurements are given in Deliverable D11 "Results from measurements on the DLR APZ combustor(WP5100)".
Figure 35 - Measurement positions on the DLR APZ combustor

Figure 36 - Combustor exit plane: Spatially resolved gas temperature and NO, CO and CO₂ concentrations for the operating point $T_j = 850$ K and $T_F = 2000$ K
Figure 37- CO (left) and UHC (right) concentrations inside the combustor at $T_3=850$ K and $T_F=2000$ K
Figure 38: NO concentrations inside the combustor at $T_3 = 850$ K and $T_F = 2000$ K.

Figure 39: Gas velocity distribution inside the combustor at $T_3 = 850$ K and $T_F = 2000$ K.
3.4.1.2. Measurement campaign with MIRPL (TUC)

A first campaign applying only a direct absorption method with the laser source developed for the MIRPL has been tried by TUC to check the feasibility of detecting methane at the DLR combustor test rig.

3.4.1.2.1. MIRPL laser source setup for absorption measurements on methane (TUC)

The ps-MIR DFG laser-source (a detailed description and characterization is given in the Deliverable D5 for WP 3300) setup for direct absorption measurement in the DLR combustion chamber running on natural gas is presented in Figure 40. The laser source was set to probe the two absorption lines of methane at 2937.49 cm\(^{-1}\) and 2937.76 cm\(^{-1}\).

![Figure 40 - Experimental set-up for the optical measurements on methane by TUC MIRPL apparatus](image)

3.4.1.2.2. MIRPL absorption measurements on methane results (TUC)

The laser beam was traversed to regions in the flame known to have high concentrations of unburned hydrocarbons, see Figure 37 right. But methane was not detectable at any measuring position or operating condition in this combustor.

In order to check the sensitivity of the system, the detection limits of the optical system applied to this combustor have been recalculated. The detection limit is defined as the concentration calculated from a
minimum absorption. Using molecular constants from known databases, the detection limit (for an optical path length of L=10cm) for different absorptions is plotted versus the temperature in Figure 41a. The corresponding integral UHC concentrations and temperatures measured with conventional techniques are shown in Figure 41b. The measurements were done at different horizontal positions in the horizontal plane $x=10\text{ mm}$ behind the burner exit.

![Figure 41 - Detection limit for absorption and conventionally measured integral UHC concentration and temperature](image)

The methane absorption measurement results (an example is given in Figure 42) revealed a noise level of about 10% in the relevant spectral range around 2937.49 cm$^{-1}$. Thus an absorption of significantly more than 10% from the probed methane is necessary for a sufficient signal-to-noise ratio. The comparison in Figure 42 of the detection limits for 10% absorption with the concentrations of unburned hydrocarbons and the corresponding temperatures in the combustor gives an explanation for the failure of the optical methane measurement campaign. Assuming the actual methane concentration being equivalent to the measured UHC concentration is a very optimistic approach in this case. The decomposition of methane is one of the initial steps in the reaction so that the actual methane concentration is significantly lower than the measured UHC concentration and is below the detection limit.
3.4.1.3. Measurement campaign with SDLA/DLAS (ONERA)

Due to the technical difficulties encountered by the MIDDROPO instrument, only the DLAS technique was used for the measurement campaign on the DLR combustor.

3.4.1.3.1. SDLA/DLAS setup at DLR combustor test rig

A photo of the DLAS optical setup together with the DLR combustor is given in Figure 43.
3.4.1.3.2. Data acquisition with DLAS

The used wavelength for detecting different species in the exhaust gas are listed in Table 8. Measurements were performed in a wavelength band about 1 cm\(^{-1}\) wide around the listed center wavenumbers.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Species</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2064 cm(^{-1})</td>
<td>CO and H(_2)O</td>
<td>Data for CO and H(_2)O acquired</td>
</tr>
<tr>
<td>1934 cm(^{-1})</td>
<td>NO and H(_2)O</td>
<td>Data for H(_2)O acquired, no NO lines were found</td>
</tr>
<tr>
<td>1926 cm(^{-1})</td>
<td>NO</td>
<td>no NO lines were found</td>
</tr>
<tr>
<td>2306 cm(^{-1}) and 2347 cm(^{-1})</td>
<td>CO(_2)</td>
<td>Data not processable; inadequate optical filtering and failure of the Fabry-Perot calibration channel.</td>
</tr>
</tbody>
</table>

Table 8 - Selected wavenumbers for SDLA/DLAS experiments on DLR combustor

Fast fluctuations in the flow with a time scale of less than 1 ms were observed (see Figure 44) for CO measurements. In order to diminish the effects on the spectra acquisition, the spectrometer was set to conduct measurements at a \(f=10\) kHz repetition rate:

- The diode was monitored, through current tuning, to emit a cw tunable wavelength in a spectral window of about 1 cm\(^{-1}\) swept in 0.1 ms and repeated at \(f=10\) kHz.
- Each spectrum was digitized at \(f=20\) MHz and therefore was sampled with 2000 points.
3.4.1.3.3. SDLA/DLAS measurements on CO

Due to memory limitations only a set of 25 successive spectra of 2000 points could be acquired continuously and saved to a file. But this operation could be repeated every 20 seconds. Due to a triggering problem on the electronic acquisition card, some of the spectra out of each series of 25 were disturbed but fortunately series of 12 successive spectra could be processed (Figure 45).
Using the reference spectra (described in WP3400), each absorption spectrum is then calibrated in wavelength and intensity (lowest spectrum in Figure 45) before spectrum inversion (described in Deliverables D11 & D12). The results of temperature, pressure, and CO concentrations for 3 series (acquired...
at 20 seconds interval) of successive spectra at kHz pace are given in Figure 46 (only measurements points for spectra which could be inverted are presented).

**Figure 46 - SDLA/DLAS measurements on CO Scan x= 10 mm; y=15 mm**

### 3.4.1.4. Interpretation of SDLA/DLAS measurements on CO

The optical measuring techniques from TUC and ONERA were integrating along the line of sight of the laser beam. Therefore integral values had to be calculated from the spatially resolved measurements with the conventional techniques to allow a comparison with the optically measured data. The method used to calculate these integral values is described in Deliverable 11.

#### 3.4.1.4.1. CO Measurements inside the combustor

The horizontal profile of the integral CO concentrations at $x=10$ mm downstream the burner exit is shown in Figure 47. There is a good agreement with a deviation of about 10 % in the range $z \leq 10$ mm. For $z>10$ mm the deviation of the optically measured CO concentrations to the reference data increased up to 300% at $z=23$ mm. This large deviation resulted from a qualitative difference in the CO distributions.
In the integral temperature distributions this effect is even more pronounced, see Figure 48. In the range \( z = 0 \ldots 10 \text{ mm} \) there is a very good agreement between the optically and conventionally measured temperatures. The deviation is in the order of magnitude of \( \Delta T \approx 3 \% \). For \( z > 10 \text{ mm} \) there is a sudden change in the qualitative distribution of the optically measured temperatures. Based on the local temperature distribution in the combustor (Figure 36 top left) and the local distribution of the gas composition (Figure 37) the distribution of the optically measured temperatures can not be given. The different conventional measurements are consistent with each other and they confirm an internally stabilized reacting flow field with rather cold areas close to the wall due to the window cooling air entering the combustor at \( x = 0 \text{ mm} \).
A comparison of the integral CO concentrations for different axial positions through the centre of the combustor is given in Figure 49. The agreement between the optical and the conventional measurements is similar to the central positions in the horizontal profile in Figure 47. The general streamwise development of the CO concentration was underestimated by the optical measurement. In the investigated area of the combustor CO was produced by the oxidation of the unburned hydrocarbons, see Figure 37. But the qualitative distribution of the optically measured CO concentrations was consistent with the combustion process.

The comparison of the vertical profiles of the integral temperatures in Figure 50 did not allow an clear analysis. In the horizontal profiles the agreement between optical and conventional measurements was qualitatively the same for the CO concentrations and the temperatures. In areas with a good or a poor agreement in the CO measurements there was also a good or poor agreement in the temperature measurements respectively. For the vertical temperature profiles the situation was different. Especially the data reduction of the optically measured temperature from $x=10$ mm to $x=20$ mm in Figure 50 could not be explained by the combustion process. At $x=30$ mm a temperature increase is measured by the DLAS but with a considerably large deviation ($\Delta T \approx 10\%$) from the temperature measured by thermocouple.
3.4.1.4.2. CO Measurements at the combustor exit

The measurements at the combustor exit, see Figure 51, were suffering from the fact, that averaging had to be performed based on only very few individual measurements. The low CO concentration at the combustor exit resulted in a low absorption of the infrared laser beam. Consequently the signal to noise ratio was poor and only a few of the collected samples could be processed. This lead to a poor statistical reliability of the CO concentrations and temperatures measured at the combustor exit. Nevertheless a comparison with the conventionally measured reference values allows an evaluation whether the orders of magnitude were met in this region of the flow with low CO concentrations.
In Figure 51 a comparison of the measured CO concentrations in a horizontal profile at the combustor exit is given. The overall order of magnitude was met well by the DLAS measurements but due to the poor statistical basis, the measurements at different positions reveal a strong oscillation around the conventionally measured distribution.

![Figure 51 - Horizontal profile of integral CO concentrations at the combustor exit at $T_f = 850$ K and $T_f = 2000$ K](image)

The corresponding comparison of the integral temperatures is shown in Figure 52. Here the overall trend in the temperature distribution was measured correctly by the DLAS but especially at $z = 10$ mm there is a large deviation of $\Delta T \approx 340$ K between the DLAS temperature and the reference data which may be attributed to the poor statistical basis.
3.4.1.4.3. SDLA/DLAS measurements on other species - NO, H₂O and CO₂

Several spectral windows (around 1924 cm⁻¹, 1935 cm⁻¹ and 1944 cm⁻¹) where NO lines are known to be present have been tried but with no success in detecting NO. It seems that these lines were not sensitive enough to be used for such low NO concentrations produced by the combustion (Figure 36 and Figure 38). In the future lines with higher absorption coefficients around 1900 cm⁻¹ or 1876 cm⁻¹ should be tried. For the DLAS equipment used within this project these lines were beyond the spectral range of the laser diode used.

H₂O absorption lines were acquired in the CO spectra (see Figure 45 centre) but unfortunately, none was exploitable. The absorptions have a major contribution from ambient atmospheric H₂O encountered by the laser beam along the beam path from the diode laser source and to the detector. In order to remove this contribution, this background absorption should have been acquired while the combustor was not running. Unfortunately, this procedure had not been carried out during the DLR experiments as priority was given to CO measurements. For detecting CO such a procedure was not required as the ambient CO concentration is negligible.

In future measurements on H₂O this background subtraction procedure should be performed. A second approach would be to use ‘hot’ H₂O lines which are present only at temperatures higher than 300K.

The diode dedicated to CO₂ has been set to the spectral region between 2300 cm⁻¹ and 2400 cm⁻¹ for CO₂ characterization. Figure 53 presents some acquired spectra where CO₂ absorption lines are clearly present. The spectra presented in Figure 53 also show intense CO₂ absorption lines due to atmospheric CO₂. From the ‘hot’ CO₂ it was expected that a data processing would be possible. The major problem while probing for CO₂ was an oscillating background in the absorption spectra, see Figure 53 left. The measurements were performed after procurement of an optical filter to band pass only CO₂ lines around 2300 cm⁻¹ and therefore diminish the high oscillating background line. Although not well optimized the filter helped to reduce oscillations in the offset of detection. But the oscillating background and line mixing
features finally did not allow acceptable intensity calibrations and no measurement has been derived from the spectra up to now.

![Plot](image)

*Figure 53 - CO₂ absorption spectra from measurements in the combustor at Tₐ=850 K and Tᵥ=2000 K*

### 3.4.2. W5200 Aircraft test and non intrusive measurements

The objectives of this task was to perform final testing of the spectroscopic instrumentation under on-site conditions on an NLR research aircraft running its engines on the ground.

#### 3.4.2.1. WP 5210 Organisation of ground tests

The procedures to perform these ground tests have been defined in Deliverable D2 (see §4.1.3 also). There have also been establishment of short documents describing the instruments (performance, requirements and agreed setups) in the last months prior to the experiments.

The NLR research aircraft Cessna Citation II is equipped with two Pratt & Whitney type JT15D-4 turbofan engines. The engine ran at power settings (Table 9) defined in the ICAO LTO cycle (Take-off, Climb, Approach and Taxi / Ground Idle) plus thrust settings representing to a certain degree other phases of a “typical” flight.
Operating mode | Thrust setting  
--- | ---  
Take-off | 100 % $F_{\infty}$  
Climb | 85 % $F_{\infty}$  
Cruise | 50 % $F_{\infty}$ and 70 % $F_{\infty}$  
Approach | 30 % $F_{\infty}$  
Flight Idle | 15 % $F_{\infty}$  
Taxi / ground idle | 7 % $F_{\infty}$

Table 9- NLR aircraft power settings

The ground tests were performed at an engine test run area at Schiphol. The test site was hired for one day (15th December 2005). In the NLR hangar at Schiphol the spectrometers had been prepared and tested in the days before the ground test. The spectrometers were transported with a van to the test site on the day of the ground tests. After arriving at the test site the spectrometers from ONERA and TUC were installed in and near the van and light beams were projected through the exhaust plume.

3.4.2.2. WP 5220 Intrusive measurements

Because of uncertainties in holding these tests with the spectroscopic instruments up to the end of the project, it was not possible to plan well in advance the scheduled intrusive measurements and data from past calibration have been used as reference for the non-intrusive spectroscopic measurement techniques (see Deliverable D12).

3.4.2.3. WP 5230 SDLA/DLAS measurements

Initially, integrated absorption spectroscopy on a specified line for concentration determination of some specified species was to be performed using the MIDROPO prototype of partner NEO. Due to the technical difficulties on that last instrument, the SDLA/DLAS has been used to at least demonstrate the feasibility of such spectroscopic measurements.

3.4.2.3.1. SDLA/DLAS experimental setup at the Schiphol airport

The SDLA/DLAS setup (cf§4.24) was the one already used for measurements at the DLR combustor (WP5100). The overall geometrical configuration, prepared in the hangar near the plane and afterwards brought on the airfield, is illustrated in Figure 54. Mirrors are mounted on X95 poles and the laser beam (of 14 mm diameter) crosses vertically the flow at a distance of 80 cm downstream the engine exit. The SDLA spectrometer was in a van at a distance of approximately 4 meters from the probed zone (Figure 55).
In a van at a few meters

Emission bench

Acq. control

Detection box

Engine

Jet

Mirror (1 inch diameter)

Laser beam

M1

M2

X95 pole

Fixed on ground but movable to probe at different distances from engine exit

Figure 54 - Setup at NLR

Figure 55 - Setup on the airfield with views of the SDLA instrument in the van
Concerning wavelength settings, the NO-CO diode has been operated to emit in the following spectral windows (each of about 1 cm\(^{-1}\) wide) centered around:

- 2068 cm\(^{-1}\): for CO and CO\(_2\): no data due to unstable laser emission
- 2064 cm\(^{-1}\): for CO and H\(_2\)O probing: data on CO and H\(_2\)O acquired
- 1934 cm\(^{-1}\): for NO and H\(_2\)O: no NO lines were found, only H\(_2\)O ones
- 1926 cm\(^{-1}\): for NO: no NO lines were found

- The CO\(_2\) diode has not been used due to lack of time during the one day test period.

Data acquisition scheme was the same as the one used for the DLR combustor tests (§3.4.1.3.2). Figure 56 illustrates a typical serie of data acquisition for the CO case and an example of calibrated spectrum in wavelength and intensity to be fed to spectrum inversion routines.
3.4.2.3.2. SDLA/DLAS results from aircraft tests

Only measurements on CO and H₂O were possible. The sensitivity of setup for the chosen NO absorption lines was insufficient to measure the NO specie. The CO₂ diode has not been used due to lack of time.

The spectral inversion of an absorption line provides values for the pressure and the temperature of the gas probed as well as the density of the probed specie (CO or H₂O in our case). Such values, traced...
against time for 15 successive spectra, are presented for the CO specie in Figure 57. The mean values averaged over the successive spectra are also given in the same figure. It is these mean values that are compared to classical gas analyser results in the next paragraphs.

<table>
<thead>
<tr>
<th>DLAS measurements on</th>
<th>15/12/2005 13:38</th>
<th>Req. Thrust</th>
<th>Req. N1</th>
<th>Actual N1</th>
<th>Actual N2</th>
<th>Fuel Flow (lbs/hr)</th>
<th>ITT °C</th>
<th>Oiltemp</th>
<th>OilPress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average values over an absorption path length of</td>
<td>40 cm</td>
<td>G/l</td>
<td>G/l</td>
<td>30.6</td>
<td>49.1</td>
<td>190</td>
<td>300</td>
<td>102</td>
<td>65</td>
</tr>
</tbody>
</table>

![Graph showing CO density over time](image1)

**Mean value for CO density = 7.6E+15 cm-3**

![Graph showing CO concentration over time](image2)

**Mean value for CO concentration = 542 ppm**

![Graph showing temperature evolution](image3)

**Mean value Temperature = 535 K**

![Graph showing pressure evolution](image4)

**Mean value for pressure = 1033 hPa**

*Figure 57 CO Measurements – Thrust Idle N1=30% – Without CO filter*

Figure 58 presents how the different averaged parameters evolve with N1 engine parameter for the CO case. Data acquisition was quite noisy for high thrust and showed very weak absorption lines for N1 at 100%.
Figure 58 - NLR aircraft experiments - SDLA/ DLAS mean values from measurements on CO
3.4.2.3.3. Interpretation of SDLA/DLAS results from aircraft tests

The data from SDLA measurements and gas sample measurements can be compared for CO. For H₂O the comparison can be made between SDLA measurements and the water concentrations calculated from the CO₂ measurements. The measured gas temperatures can be compared with the ITT. Figure 59 to Figure 61 show the result of the comparison.

Figure 59 - Measurement of water concentration in the exhaust gas of the JT 15D engine at different thrust settings. The purple line represents data obtained with the SDLA spectrometer, the dark blue line represents data calculated from CO₂ sample measurements.

Figure 60 - CO concentration measurements in the exhaust gas of the JT 15D engine at different thrust settings. The purple line represents data obtained with the SDLA spectrometer, the dark blue line represents data calculated from CO sample measurements.
The CO values measured with SDLA do not correlate with the values measured with the gas sampling technique. Uncertainty margins estimated for the SDLA and the uncertainty margins for the sample measurements do not bridge the gap between the values. The gas sample values are remarkably low at low thrust settings. It is not in line with expectations for CO emission of an engine increasing for low thrust setting. Furthermore this is not consistent with the ICAO data base values for this engine. However, the values were measured several times on different days and in different runs.

The H$_2$O values measured with SDLA and the values calculated from CO$_2$ gas sample measurements do not agree within the uncertainty margins for measurements, but do have the same order of magnitude. The trend in the SDLA data that values decrease for increasing thrust settings is not in line with what is expected for an engine.

The temperature measurements of gases are in the same order of magnitude. The data derived from the spectra indicate that the gases do not cool much between the ITT temperature sensor and the point in the plume where spectroscopic measurements were made (one meter from exit).

3.4.2.4. **WP 5240 Non intrusive QCL absorption measurements by TUC**

Due to difficulties in the development of the PS-MIR-DIA-Lidar, TUC brought a quantum cascade laser (QCL) based absorption spectrometer setup to perform measurements on NO and H$_2$O for the NLR’s aircraft ground tests.
The set-up of this experiment is shown in Figure 62. The collimated beam of the quantum cascade laser (Alpes Laser #sb193 UP, P~1.5 mW; depicted in red in Figure 62) is guided to a rugged frame where mirrors are mounted that allows a double pass of the laser through the plume. From the frame the beam is guided back to an InSb detector with integrated Germanium- and bandpass-filter (Northumbria Optical Coatings, transmission range 5.3µm ±0.265 µm). The alignment procedure was supported by a green HeNe-laser which has been overlapped with the 5.3µm beam of the quantum cascade laser.

![Figure 62: Set-up of the experiment.](image)

The wavelength of the QCL is tunable by a voltage ramp (U=0...2V is equivalent to a wavelength tuning of 0.43 cm⁻¹) to scan over absorption lines of NO and H₂O, respectively. For different thrust settings according to ICAO standard measurements have been performed. An example of a measurement of four absorption lines of water (1894.518 cm⁻¹, 1894.528 cm⁻¹, 1894.654 cm⁻¹, and 1894.684 cm⁻¹) for different settings is given in Figure 63.
Figure 63- Absorption measurement of water for different thrust settings according to ICAO standard.

For the evaluation of the raw data a calibration had to be performed. Thus a reference measurement (black line in Figure 63) was measured through the same geometry but with aircraft engine not running. After standard data reduction (see Deliverable D12), the results for H$_2$O concentrations for different thrust settings are shown in Figure 64.
During a 100% thrust engine setting also nitrogen oxide (NO) has been probed but no absorption has been observed. The signal-to-noise ratio was too low for NO concentrations of a maximum of 50 ppm.

3.4.2.4.1. Interpretation of TUC QCL results from aircraft tests

In the same manner as for the SDLA spectrometer the H\textsubscript{2}O measurements with the QCL spectrometer can be compared with the water concentrations calculated from the CO\textsubscript{2} measurements (Figure 65).
Figure 65 - Measurement of water concentration in the exhaust gas of the JT 15D engine at different thrust settings. The purple line represents data obtained with the QCL spectrometer, the dark blue line represents data calculated from CO₂ sample measurements.

The QCL measurements do not correlate with sample measurements within uncertainty levels. The correlation with the SDLA measurements is neither apparent.

3.4.3. WP5300 Data Analysis (NLR)

This work package has been removed but the included tasks - laboratory tests analysis, Combustor tests analysis, aircraft tests analysis- are merged to the respective topics already discussed above and in the respective deliverables D9, D11 and D12.
3.5. WP6000 Assessment and Exploitation

3.5.1. WP 6100 Industrial Exploitation

3.5.2. WP 6200 Patents and Licenses

Prior to the starting date of this project, the entangled-cavity doubly resonant optical parametric oscillator was protected by the following patents:

- B. Scherrer, M. Lefebvre
  ‘Oscillateur paramétrique optique impulsionnel monomode’
  FR 97 00774, 24 January 1997

- B. Scherrer, M. Lefebvre
  ‘Pulsed optical parametric oscillator’
  US 00 5995 522, November 30, 1999
  EP 0855 616, April 02, 2003

During the course of the project, a new patent on the MIDROPO has been deposited:


3.5.3. WP 6300 Publications

3.5.3.1. Conférences

2. Desormeaux A., Drag C., Lefebvre M., Rosencher E. - CLEO Europe, Munich 2003
4. Desormeaux A., Lefebvre M. - European CARS workshop, Besançon 2003
5. Desormeaux A., Lefebvre M., Rosencher E. - "High resolution molecular spectroscopy in the mid-infrared by a free running pulsed doubly resonant optical parametric oscillator", CLEO US 2004

3.5.3.2. Publications


3.5.3.3. Thesis

A. Desormeaux
Développement d’un oscillateur paramétrique optique monofréquence et réalisation d’un montage pour la spectroscopie infrarouge non linéaire.
4. **LIST OF DELIVERABLES**

Table 2 gives the list of the deliverables that have been issued from the start date of the project.

<table>
<thead>
<tr>
<th>Deliverable No.</th>
<th>Delivery date (month)</th>
<th>Output from WP Nr.</th>
<th>Nature of deliverable and brief description</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0</td>
<td>6, 12, 18, 24, 30, 36 -&gt; 38, 44</td>
<td>All</td>
<td>Progress, midterm, final, milestone reports</td>
<td>6,12,18, 30,38 delivered</td>
</tr>
<tr>
<td>D1</td>
<td>6 2100–2300</td>
<td>Technical Note: List of species, spectral lines, accuracies</td>
<td>Delivered</td>
<td></td>
</tr>
<tr>
<td>D2</td>
<td>6 2300</td>
<td>Technical Note: Def. of engine and ground-run parameters</td>
<td>Delivered</td>
<td></td>
</tr>
<tr>
<td>D3</td>
<td>9 2400</td>
<td>Report: Study on exhaust gas velocimetry and spatial</td>
<td>Delivered</td>
<td></td>
</tr>
<tr>
<td>D4</td>
<td>20 3100</td>
<td>Demonstrator: MIDROPO laboratory spectrometer</td>
<td>Delivered</td>
<td></td>
</tr>
<tr>
<td>D5</td>
<td>20 3300</td>
<td>Demonstrator: ps-MIR-DIA Lidar system</td>
<td>Delivered</td>
<td></td>
</tr>
<tr>
<td>D6</td>
<td>20 3400</td>
<td>Demonstrator: SDLA spectrometer</td>
<td>Delivered</td>
<td></td>
</tr>
<tr>
<td>D7</td>
<td>24 3500</td>
<td>Report: Fiber optics for mid-infrared remote experiments</td>
<td>Delivered</td>
<td></td>
</tr>
<tr>
<td>D8</td>
<td>24 3200</td>
<td>Demonstrator: MIDROPO prototype</td>
<td>Delivered</td>
<td></td>
</tr>
<tr>
<td>D9</td>
<td>26 -&gt; 38 4100</td>
<td>RISOE</td>
<td>Report: Results of instrument cal. and lab. testing</td>
<td>Delivered</td>
</tr>
<tr>
<td>D10</td>
<td>26 -&gt; 38 4200</td>
<td>ONERA</td>
<td>Report: Performances of the DFWM for spatial resolution</td>
<td>Delivered</td>
</tr>
<tr>
<td>D11</td>
<td>26-&gt; 44 5100, 5300</td>
<td>DLR</td>
<td>Report: Results from comb. chamber investigations</td>
<td>Delivered</td>
</tr>
<tr>
<td>D12</td>
<td>26-&gt; 44 5200, 5300</td>
<td>NLR</td>
<td>Report: Results from aircraft measurements</td>
<td>Delivered</td>
</tr>
<tr>
<td>D13</td>
<td>26 -&gt; 44 6000</td>
<td>ONERA, ALL</td>
<td>Technology Insertion Plan, Technology route map</td>
<td>Delivered with final report</td>
</tr>
</tbody>
</table>

*Table 10 - List of deliverables*
5. **COMPARISON OF INITIALLY PLANNED ACTIVITIES AND WORK ACTUALLY ACCOMPLISHED.**

The following Table 11 gives the comparison of initially planned activities and the work actually accomplished.

<table>
<thead>
<tr>
<th>Task</th>
<th>Initially planned</th>
<th>Status</th>
<th>Reference § in present report and deliverable n°</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100</td>
<td>Task 2100 Species (All partners)</td>
<td>100% Accomplished</td>
<td>3.1.1 Deliverable D1</td>
</tr>
</tbody>
</table>
| 2200 | Task 2200 Spectral lines and degenerate four wave mixing calculations (ONERA,TUC,NEO) | 100% Accomplished:  
• Species and absorption lines have been chosen  
• Degenerate four wave mixing calculations moved to WP4300. | 3.1.1 Deliverable D1 |
| 2310 | Accuracies of spectra and spatial resolution(ONERA,TUC,NEO): | 100% Accomplished (Performed in 2200) | 3.1.1 Deliverable D1 |
| 2320 | Specification of ground run measurement conditions (NLR) | 100% Accomplished | 3.1.2 Deliverable D2 |
| 2400 | Velocimetry and spatial resolution potentialities (NLR) | 100% Accomplished | 3.1.3 Deliverable D3 |
| 3100 | MIDROPO development (ONERA) | 70% accomplished through building of a laboratory prototype and laser emission for N₂O spectroscopy. Mirror coatings problems forbid laser emission for CO₂, CO and NO lines | 3.2.1 Deliverable D4 |
| 3200 | MIDROPO prototyping and signal processing (NEO) | 70% Accomplished through building of a complete spectrometer. Laser emission stability and Mirror coatings problems forbid did not allow an operational instrument for CO₂, CO and NO probing. | 3.2.2 Deliverable D4 |
| 3300 | PS-MIR-DIA-LIDAR (TUC) | 70% accomplished:  
• Wavelength coverage limited to CH₄ but other wavelength attainable with change of some optics;  
• Pulse duration higher (500 ps) which limits spatial resolution to about 7cm instead of 1 cm;  
• Energy lower than expected which limits sensitivity to 10%  
These problems did not allow an operational instrument to probe NO₂, CO₂ and H₂O in combustion facilities. Nevertheless CH₄ detection feasibility was demonstrated in laboratory. | 4.2.3. Deliverable D5 |
<table>
<thead>
<tr>
<th>ID</th>
<th>Task Description</th>
<th>Status</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3400</td>
<td>SDLA/DLAS set-up adaptation (ONERA)</td>
<td>70% accomplished</td>
<td>- Absorption detection threshold of $10^{-2}$ instead of expected $5 \times 10^{-5}$. The averaging doesn’t work due to triggering problems: too much investment on electronics needed to achieve initial objective. But the obtained sensitivity allow measurements of CO, CO$_2$, and H$_2$O during the field experiments of WP5000.</td>
</tr>
<tr>
<td>3500</td>
<td>Mid infrared fiber optics (RISOE)</td>
<td>70% accomplished</td>
<td>- Bibliographic study leads to procurement and transmission characterisation of two types of MIR optical fibers. Only high power tests could not be performed due to unavailability of lasers sources (consequent to problems in WP3100-3300).</td>
</tr>
<tr>
<td>4110</td>
<td>MIDDROPO and SDLA/DLAS calibrations at ONERA</td>
<td>100% accomplished</td>
<td>- MIDROPO calibration on N$_2$O</td>
</tr>
<tr>
<td>4120</td>
<td>MIRPL calibrations (TUC)</td>
<td>100% accomplished</td>
<td>3.3.1.2</td>
</tr>
<tr>
<td>4210</td>
<td>High temperature reference gas cell (RISOE)</td>
<td>100% accomplished</td>
<td>3.3.2.1 Deliverable D9</td>
</tr>
<tr>
<td>4220</td>
<td>MIDDROPO and SDLA at RISOE’s hot cell</td>
<td>0% accomplished due to technical difficulties in MIDDROPO development and unavailability of SDLA spectrometer</td>
<td>3.3.2.2</td>
</tr>
<tr>
<td>4230</td>
<td>PS-MIR-DIA-LIDAR calibration (TUC)</td>
<td>70% accomplished</td>
<td>- Measurements on CH$_4$ only.</td>
</tr>
<tr>
<td>4300</td>
<td>Degenerate four wave mixing experiments (ONERA)</td>
<td>70% accomplished</td>
<td>- The amplification stages seem satisfactory but have not yet been tested for DFWM because of the tuning problems of the OPO.</td>
</tr>
<tr>
<td>5110</td>
<td>Characterisation of combustors</td>
<td>100% accomplished.</td>
<td>3.4.1 Deliverable D11</td>
</tr>
<tr>
<td>5120</td>
<td>Measurement campaigns for partners ONERA and NEO</td>
<td>0% accomplished for MidDROPO due to problems in WP3200. 80% accomplished for SDLA/DLAS: CO and H$_2$O integral concentrations as well as temperature measured in and outside combustor. CO$_2$ spectra acquired but cannot be processed due to calibration problems. NO not detectable from the absorption lines probed. Abel inversion could not be tried due to insufficient quantity of acquisitions.</td>
<td>3.4.1.3 Deliverable D11</td>
</tr>
<tr>
<td>5130</td>
<td>Measurement campaigns for partner TUC</td>
<td>70% accomplished with set up to measure CH$_4$. But sensitivity was not enough to detect CH$_4$.</td>
<td>3.4.1.2 Deliverable D11</td>
</tr>
<tr>
<td>5210</td>
<td>Organisation of ground tests</td>
<td>100% accomplished</td>
<td>3.4.2.1 Deliverable D2</td>
</tr>
<tr>
<td>5220</td>
<td>Intrusive measurements (NLR)</td>
<td>0% accomplished. Partly replaced by search for data from old measurements. Uncertainties in holding the spectroscopic tests up to the end of the project and cost considerations discarded to have these intrusive measurements simultaneously with the spectroscopic ones.</td>
<td>3.4.2.2</td>
</tr>
</tbody>
</table>
However, comparison with old non intrusive data appeared as sufficient to verify data from the first feasibility experiments with the spectroscopic devices.

| 5230 | MIDROPO (NEO) and SDLA/DLAS (ONERA) experiments on NLR aircraft | 0% accomplished for MidDROPO due to problems in WP3200. 70% accomplished for SDLA/DLAS: CO and H₂O concentrations as well as temperature measured at engine exit. CO₂ not tried due to lack of time. NO not detectable with the absorption lines probed and the sensitivity of the instrument. | 3.4.2.3 Deliverable D12 |

| 5240 | PS-MIR-DIA-Lidar (TUC) on NLR aircraft | 0% accomplished. However TUC participated with success in the aircraft ground tests with an absorption spectrometer based on QCL set to probe NO and H₂O. Only measurements on H₂O were obtained. | 3.4.2.4 Deliverable D12 |

| 5300 | Data Analysis (NLR) | 100% accomplished (included in the different WP5100 and WP5200) | WP5100 and WP5200 |

| 6100 | Industrial Exploitation | 70% accomplished. Dissemination of results and products from MENELAS throughout their various departments and business units of motorists are yet to take place (after the contract). | 3.5.1 Deliverable D13 |

| 6200 | Patents and Licenses | 100% accomplished | 3.5.2 |

| 6300 | Publications | 100% accomplished  
• Ten presentations at international conferences  
• Four publications in refereed journals  
Some more are expected based on the field experiments results. | 3.5.3 |

Table 11 - Comparison of initially planned activities and work actually accomplished.

6. MANAGEMENT AND CO-ORDINATION ASPECTS

6.1. Performance of the consortium and communications

6.1.1. Contractual and financial

There was no problem between partners to sign the Consortium Agreement. Identically, there were no major problems in cost statements and payments for all partners during the course of this project.
6.1.2. Periodic meetings

<table>
<thead>
<tr>
<th>Meetings</th>
<th>Date</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kick-off</td>
<td>12th June 2002</td>
<td>Palaiseau (ONERA)</td>
</tr>
<tr>
<td>6 months</td>
<td>7-8th January 2003</td>
<td>Amsterdam (NLR)</td>
</tr>
<tr>
<td>12 months</td>
<td>12-13th June 2003</td>
<td>Lillestrom (NEO)</td>
</tr>
<tr>
<td>Mid term</td>
<td>29-30th January 2004</td>
<td>Palaiseau (ONERA)</td>
</tr>
<tr>
<td>24 months</td>
<td>3-4th June 2004</td>
<td>Cologne (DLR)</td>
</tr>
<tr>
<td>30 months</td>
<td>13-14th December 2004</td>
<td>Clausthal (TUC)</td>
</tr>
<tr>
<td>Final - 38 months</td>
<td>27-28th June 2005</td>
<td>Roskilde (RISOE)</td>
</tr>
<tr>
<td>Final</td>
<td>12-13th December 2005</td>
<td>Amsterdam (NLR)</td>
</tr>
</tbody>
</table>

After each meeting, ONERA has sent to all the partners and EC the agenda, the minutes and CDROM or PDF copy of all the presentations.

6.1.3. Interactions between partners

6.1.3.1. Instrument development

The design a spectrometer based on the MIDROPO lead to a continuous exchange of technical information between the researchers at ONERA and researchers at NEO and the two groups have also worked together at their respective labs. NEO researchers visited ONERA in 2003 and afterwards an OPO prototype was delivered from ONERA to NEO for further tests. ONERA visited NEO’s lab in 2003 and 2005.

6.1.3.2. Calibration

The calibration work implied mainly RISOE and TUC. The latter made two measurement campaigns Risoe National Laboratory (in 2003 and 2004).

6.1.3.3. Field experiments

The experiments at DLR were accompanied by much exchange of technical information between DLR, ONERA, TUC and RISOE. Identically, the aircraft ground tests implied the partners NLR, ONERA and TUC.

6.1.3.4. Field experiment preparation documents

In the last six months of the project, there have also been establishment of several documents circulated between partners to share information on the instruments, the envisioned setups and expected conditions at the test sites.

6.1.3.5. Monthly progress letters

As from the 38th months meeting and in order to prepare the field measurements campaign monthly progress letters were written and distributed to all partners.
6.1.4. Interactions with other EC networks:

- NLR has participated to a PIVNET thematic network meeting in Lisbon (July 2002). New ideas related to non-intrusive measurements techniques were debated.
- NLR has contributed to a workshop on Emissions measurements techniques (September 16th-17th 2002, Berlin). This workshop was organised by DLR in the course of AERONET II. The objectives of MENELAS were presented.
- ONERA made a presentation of the project at the ‘Low Emission’ Cluster meeting the 9th of June 2004 in London.
- DLR made a presentation of the project at the Low emission Cluster meeting in Dahlewitz, 26/27 Jan.2005.

7. RESULTS AND CONCLUSIONS

Two novel optical instruments, namely the MidDropo and the Pico-second Lidar as originally planned, have been developed for probing in the infrared spectrum some minority species like CO, NO and CO₂ in the effluents of combustors for aeronautics. Unfortunately and although that there has been much progress in the laboratory developments, it appears that these two sophisticated instruments are not yet mature to perform measurements at exit of a combustor or of an aircraft engine on an airfield as planned in the project.

Nevertheless, some field experiments to demonstrate the capability of spectroscopic measurements at such locations have been performed with classical infrared absorption spectrometers using diode lasers initially envisioned in the project for benchmarking the novel instruments. These experiments were done using the ONERA SDLA/DLAS instrument to probe an APZ combustor at DLR Koln and the exhaust gases of NLR’s Cessna Citation II research aircraft at a test site at Amsterdam Airport Schiphol. For the latter, there were also measurements by TUC who developed an absorption spectrometer using a Quantum Cascade Laser.

The calibration hot cell at RISOE has been successfully upgraded for high temperature purposes but all the potential of this facility has not been exploited: there were only a few calibration experiments by TUC. When the spectroscopic instruments will be mature, calibration in such a calibration facility will be essential before any field experiments.

There have been also preliminary study of the use of infrared fiber optics to ease propagation of infrared laser beams to measurement locations as well as a survey of other techniques presenting velocity and density measurements potentialities for implementation at the exhaust plume of an aircraft.
8. ACKNOWLEDGEMENTS

The authors thank Professor E. Rosencher of ONERA for having initiated this project and the EC Scientific Officers, R. Dunker and D. Knoerzer, who were always of kind help and good advice. The authors are also indebted to all the engineers and technicians working in background and without whom the experimental campaigns at the airport and the combustor rig would not have been successful.

Figure 66 – Picture of the main participants of the MENELAS project. At the NLR hangar on Schiphol airport during the final meeting and the day before the aircraft tests.
9. REFERENCES


10. ANNEX 1 - TUC CONTRIBUTION - PS-MIR DFG LIDAR DETAILED DESCRIPTION

10.1. Introduction

The objective of this work package WP3300 is to determine exhaust gases of aircraft jet engines with a high spatial resolution with ps-LIDAR in the mid-infrared spectral range.

Thus a laboratory scale prototype of a ps-MIR LIDAR spectrometer based on difference-frequency generation, which can be used in field experiments to measure emission gases from jet engines, is set up (see Figure 1).

The acronym LIDAR stands for Light Detection And Ranging, an optical analog of RADAR (Radio Detection And Ranging). The conventional version of LIDAR requires a laser transmitter to launch short pulses of coherent light. As the transmitted laser energy passes through the atmosphere, the gas molecules and particles or droplets encountered cause scattering. A small fraction of this energy is backscattered in the direction of the LIDAR system and is therefore available for detection. The scattering out of the forward direction or propagation, or absorption by the gases and particles, reduces the intensity of the beam. Such attenuation applies to both the path to and from a distant backscattering region [1,2].

At the LIDAR, backscattered energy is collected with suitable receive optics and transferred to a photo-detector. This produces an electrical signal, the intensity of which at any instant is proportional to the optical power received. Since light travels at known velocity, the range of the scattering volume producing the signal received at any instant can be uniquely determined from the time interval since transmission of the pulse. The magnitude of the received signal is determined by the backscattering properties of the atmospheric target at successive ranges, and also by the two-way atmospheric attenuation. Atmospheric backscattering in turn depends upon the wavelength of the laser energy used, and the number, size, shape and refractive properties of the particles or droplets (or molecules) intercepted by the incident energy [1].

The basic LIDAR principles outlined above may be expressed formally in the single-scattering LIDAR equation.

\[
Pr(R) = P_0 \left(\frac{c t}{2}\right) \beta(R) A_R R^{-2} \cdot \exp\left[-2\int_0^R \alpha(r) dr\right]
\] (1)

where \(P_r\) is the instantaneous received power at time \(t\), \(P_0\) is the transmitted power at time \(t_0\), \(c\) is the velocity of light, \(\tau\) is the pulse duration, \(\beta(R)\) is the volume backscattering coefficient of the atmospheric target, \(R\) is range, \(A_R\) is the effective receiver area, and \(\alpha(r)\) is the volume extinction coefficient of the atmosphere, which is defined as \(\alpha = \sigma N + \xi\), where \(\sigma N\) is the contribution from the absorbing gas under investigation (\(\sigma\) is the absorption cross section and \(N\) is the gas density) and \(\xi\) is the coefficient associated with any other extinction process (mostly absorption from other interfering molecules) [1].

Consider two adjacent range cells, denoted as 1 and 2, and two wavelengths that correspond to the peak of an absorption line (\(\lambda_{on}\)) and to a minimum of absorption (\(\lambda_{off}\)), respectively. By writing equation (1) for the two cells and the two wavelengths, one obtains a four-equation system. Solving the system with the assumption of constant \(N\) and \(\Delta\sigma\) in the range cell \((R_1, R_2)\), a molecular density in the cell can be derived [3]:

\[
N(R_1, R_2) = \frac{1}{2}\frac{\Delta\sigma}{\Delta R} \left[ \ln \left( \frac{P_{off,2}}{P_{off,1}} \frac{P_{on,1}}{P_{on,2}} \right) + \ln \left( \frac{\beta_{on,2} \beta_{off,1}}{\beta_{on,1} \beta_{off,2}} \right) + \int_{R_1}^{R_2} (\xi_{on} - \xi_{off}) dr \right]
\] (2)

where \(\Delta\sigma = \sigma_{on} - \sigma_{off}\) is the differential absorption cross section, \(\Delta R = R_2 - R_1\) is the linear dimension of the cell, \(P_{on,j}\) and \(P_{off,j}\) (\(j = 1, 2\)) are the on-line and off-line returns from the scattering cell \(j\), and...
\( \beta_{\text{on},j}, \beta_{\text{off},j}, \xi_{\text{on}}, \xi_{\text{off}} \) are the backscattering coefficients and the extinction coefficients at \( \lambda_{\text{on}} \) and \( \lambda_{\text{off}} \), respectively.

If \( \lambda_{\text{on}} \) and \( \lambda_{\text{off}} \) are close enough to each other the backscattering and extinction terms on the right hand side of equation (2) can be neglected. Under these assumptions, equation (2) reads as

\[
N(R_1, R_2) = \frac{1}{2 \Delta \sigma(R_2 - R_1)} \ln \left( \frac{P_{\text{off},2} P_{\text{on},1}}{P_{\text{off},1} P_{\text{on},2}} \right). \tag{3}
\]

In particular, the simplifying assumptions that lead to equation (3) are met in the infrared spectral region, where major atmospheric species and pollutants display narrow absorption lines.

Since the size of gas molecules is very small compared to all laser wavelengths, elastic backscattering by atmospheric gases, except at the wavelengths of absorption lines, is described by the Rayleigh scattering approximation [1]:

\[
\beta = N \frac{d\sigma_R(\pi)}{d\Omega} \tag{4}
\]

where \( N \) is the number of gas molecules per unit volume and \( \frac{d\sigma_R}{d\Omega} \) is the differential Rayleigh cross section at scattering angle \( \theta = \pi \).

This cross section can be calculated:

\[
\frac{d\sigma_R(\pi)}{d\Omega} = 5.45 \left[ \frac{\lambda_{[\mu m]}}{0.55} \right]^{-4} \cdot 10^{-28} \text{ cm}^2 \text{ sr}^{-1} \tag{5}
\]

With a molecular number density of \( N_g = 2.55 \cdot 10^{19} \text{ cm}^{-3} \), equations (4) and (5) yield to

\[
\beta = 1.39 \left[ \frac{\lambda_{[\mu m]}}{0.55} \right]^{-4} \cdot 10^{-8} \text{ cm}^{-1} \text{ sr}^{-1}. \tag{6}
\]

From equations (1), (3), and (6) the following criteria for a pulsed laser-source for a mid-infrared LIDAR system can be derived:

1. powerful pulses for a short range set-up (\( R=2..4\text{m} \)),
2. short pulses for a spatial resolution in the centimeter regime,
3. narrow bandwidth to resolve two adjacent absorption lines,
4. wavelength tunable between on- and off-resonance position.

Due to the high selectivity and sensitivity in the mid-infrared spectral region the importance and usefulness of a short range MIR LIDAR system with a spatial resolution in the centimeter regime is obvious.

Existing MIR LIDAR systems are using e.g. CO_2-lasers [4] or OPOs [5] as laser-source with pulse duration of at least several tens of nanoseconds and have therefore a not suitable spatial resolution for the applications mentioned in the MENELAS project.

Difference-frequency generation (DFG) in periodically poled LiNbO_3 (PPLN) makes widely tunable and narrow bandwidth mid-infrared laser radiation available [6,7,20,21].
10.2. Difference-frequency generation

In order to describe the different possible frequency conversion processes, the dielectric polarization $\vec{P}$ of the material in which the frequency conversion is to take place needs to be considered [7]. This material polarization is induced by the electric field of the incident light which distorts the wave functions of the outer electrons. This in turn results in a separation of charges which gives rise to a dipole moment. The dipole moment per unit volume is called the polarization of the material. It can be separated into two different parts: a linear part $\vec{P}_{lin}$ and a nonlinear part $\vec{P}_{nl}$:

$$\vec{P} = \vec{P}_{lin} + \vec{P}_{nl}.$$  

The linear polarization $\vec{P}_{lin}$ of the material can be written in the form:

$$\vec{P}_{lin} = \varepsilon_0 \chi^{(1)} \vec{E},$$

where $\varepsilon_0$ is the permittivity of free space and $\chi^{(1)}$ is the linear susceptibility.

The nonlinear polarization $\vec{P}_{nl}$ can be expanded as a power series of the electric field $\vec{E}$ and the nonlinear susceptibilities $\chi^{(m)}$ of order $m$:

$$\vec{P}_{nl} = \varepsilon_0 \sum_{m=2}^{\infty} \chi^{(m)} \vec{E}^m.$$
For the power series to converge, the following must hold:

\[ \chi^{(1)} \hat{E} \gg \chi^{(2)} \hat{E}^2 \gg \chi^{(3)} \hat{E}^3 \gg \ldots \]

\( \chi^{(m)} \) is a tensor quantity and thus depends on the direction of the electric field involved. For example, the \( \chi^{(2)} \) tensor is represented by its 3x3x3 tensor element. In tensor notation, the second-order nonlinear polarization is:

\[ P_i^{(2)} = \epsilon_0 \chi^{(2)}_{ijk} E_j E_k, \]

where the first index \( i \) corresponds to the index of the induced polarization while the second index \( j \) and the third index \( k \) are related to the indices of the incident electric field. All these indices represent the three axes of space \((1, 2, \text{ and } 3)\). The lowest-order nonlinear susceptibility \( \chi^{(2)} \) describes second-order nonlinear processes [7].

The difference-frequency \( \omega_i = \omega_p - \omega_s \) (or energy conservation, see Figure 2.a) results from nonlinear mixing of two incoming photons at frequencies \( \omega_p \) and \( \omega_s \). By convention, the laser beam with the highest frequency \( \omega_p \) is called the pump laser beam, the one with the lowest frequency \( \omega_s \) is the idler beam, and the remaining one is the signal laser beam at a frequency \( \omega_s \).

\[ \Delta \mathbf{k} = \mathbf{k}_p - \mathbf{k}_s - \mathbf{k}_i = 0, \]

where \( \Delta \mathbf{k} \) is the so-called phase mismatch, and \( \mathbf{k}_p \), \( \mathbf{k}_s \), and \( \mathbf{k}_i \) denote the wave vectors of the pump, signal, and idler beam, respectively [7].

Owing to the shape of dispersion relation within a material, it is often difficult or even impossible to fulfill both energy and momentum conservation simultaneously for most materials. Although there are many materials for which the phase-matching condition and energy conservation can simultaneously be fulfilled, the largest nonlinear coefficient can quite often not be used for the frequency conversion process. An example is the negative birefringent nonlinear material LiNbO_3. Its largest nonlinear coefficient is \( d_{33} \) which implies that the polarizations of all three beams involved are the same. In birefringent phase matching, this...
coefficient unfortunately cannot be used. One way to avoid this conflict is to use periodically poled nonlinear materials and take advantage of quasi-phase matching (QPM) [7].

Figure 3: Quasi phase matching in a periodically poled nonlinear optical material. a) Idler intensity for a DFG process in a single crystal if the phase-mismatch $\Delta k$ is equal to zero. b) Idler intensity for quasi phase matching. c) Idler intensity in a single crystal if the phase-matching condition is not met.

If the phase matching condition is not met ($\Delta k \neq 0$), after each coherence length $l_c$ given by $l_c = \pi / \Delta k$, the newly generated light will destructively interfere with the light generated in the previous coherence length (see Figure 3.c). Thus, after twice the coherence length all generated light will be destroyed. On the other hand, if the polarization of the material is changed by 180° after each coherence length and a build-up of the generated light is observed (see Figure 3.b). This implies that the length of a domain $\Lambda_{QPM}$ with constant polarization must be an even multiple of the coherence length $l_c$, i.e., $\Lambda_{QPM} = 2 \cdot l_c$.

The optical output power for difference-frequency generation can be calculated by [8]

$$P_{DFG} = \frac{4 \cdot \omega_{DFG}^2 \cdot k_s \cdot d_{eff} \cdot l \cdot h(\mu, \xi)}{\varepsilon_0 \pi e^3 \cdot n(\lambda_p) \cdot n(\lambda_s) \cdot n(\lambda_{DFG}) \cdot (1 + \mu)} \cdot P_p \cdot P_s$$

with

- $\mu = \frac{k_s}{k_p}$
- $\xi = \frac{l}{k_p \cdot w_{p}^2} = \frac{l}{k_s \cdot w_{s}^2}$
- $w_{p,s}$: diameter of pump and signal beam
- $l$: effective length of crystal
- $d_{eff}$: effective nonlinear coefficient
- $h(\mu, \xi)$: focus function for Gaussian beams
- $n$: refractive index of crystal
- $P_p, P_s$: optical power of pump and signal laser

As easily can be seen from this equation the optical output power in the mid-infrared ($P_{DFG}$) is proportional to the power of the pump and signal laser. Thus it is necessary to use powerful pump and signal lasers to generate powerful pulses as needed for a LIDAR experiment.

In the following amplification schemes for the signal laser (Fiber amplified passively Q-switched microchip laser) and pump laser (Single-mode laser diode with tapered amplifier) are discussed. Since PPLN
possesses one of the highest effective nonlinear coefficient and due to observed depletion of the pump beam using other or longer crystals is not reasonable [6].

10.3. Fiber amplified passively Q-switched microchiplaser

In the present investigation a passively Q-switched Cr\(^{4+}\):Nd\(^{3+}\):YAG microchiplaser (see Figure 4) is used as a seed laser for an ytterbium-fiber amplifier [9,10].

![Figure 4: Schematic diagram of a microchiplaser.](image)

The Cr\(^{4+}\)-ions in the laser crystal act as a passive Q-switch [9]. Therefore, when the Cr\(^{4+}\):Nd\(^{3+}\):YAG laser crystal is pumped with a continuous wave (cw) diode laser (\(\lambda = 808\) nm, \(P = 2\) W) the microchiplaser emits pulses with a duration of \((713\pm2)\) ps (see Figure 5), a repetition rate of up to 4 kHz and a pulse energy of typically 10 µJ [10].

![Figure 5: The shape of the microchiplaser has been measured with an Alphalas UPD-70-UVIR Photodiode (rise time < 70 ps). The average pump pulse duration is \(\Delta t=(713\pm2)\)ps.](image)
For high power amplification an ytterbium-fiber amplifier (see Figure 6 and Figure 8) is used [11 to 15]. A large mode area (LMA) double clad (DC) ytterbium doped optical fiber (diameter core $d = 30 \, \mu m$, cladding $d = 250 \, \mu m$) is pumped by a high power cw diode laser ($P = 30 \, W$, $\lambda = 976 \, nm$). The output of the microchip laser and the pump light are combined by a dichroitic mirror and then coupled into the Yb-LMA-DC fiber. In order to avoid the destruction of the Yb-fiber due to the high power density at the end where the pump light is focussed on the fiber surface a cap (length $l = 1 \, mm$) with a larger diameter ($d = 400 \, \mu m$) compared to the amplifier fiber is spliced as a conical horn waveguide (see Figure7). The spectral characteristic of the amplified microchip laser pulses is shown in Figure9. The spectral single mode character of the seed laser is maintained during the amplification process.

Figure 6: Schematic set-up of a fiber amplified microchip laser.

Figure 7: Inclined polished end face.
Figure 8: Photography of a fiber amplified microchip laser.

Figure 9: Spectral characteristic of the fiber amplifier.
When using the microchip laser as seed laser pulse amplification by a factor of up to 14 is obtained (see Figure 10 and thus pulse energies of up to 144 µJ are achieved at a repetition rate of 4 kHz.

Figure 10: Pulse energy of the fiber amplifier for seed pulse energy of $E=10\mu J$ of the microchip laser.

Figure 11 shows the dependence of the amplification on the repetition rate of the seed laser. A lower repetition rate allows a higher amplification factor. At repetition rates $< 2kHz$ destruction of the end facets of the amplification fiber has been observed (see Figure 12).

Figure 13 shows the crucial dependence of the amplification on the coupling lens (lens 2 in Figure 6). Measurements for two different lenses ($f=30mm$ and $f=25mm$) have been performed. The amplification efficiency differs by a factor of 4.

Figure 11: Dependence of the pulse energy on the repetition rate.
Figure 12: Destruction of the seed-side of the amplification fiber after too strong amplification.

Figure 13: Dependence of the output-power on the coupling lens.

The temporal characteristic of the amplified microchip laser pulses has been measured with an Alphalas UPD-70-UVIR Photodiode (rise time < 70ps). The average pump pulse duration is $\Delta \tau = (606 \pm 8)\, ps$. This shows that the amplification process shortens the pulse duration from about 700 ps (Figure 5) to about 600 ps (Figure 14).
Figure 14: The shape of the amplified microchip laser has been measured with an Alphalas UPD-70-UVIR Photodiode (rise time < 70 ps). The average pump pulse duration is $\Delta \tau = (606 \pm 8) \text{ps}$.

Figure 15 shows the polarization of (a) the seed laser and (b) the amplified laser pulses. The polarization degree $P$ is defined as:

$$P = \frac{\phi_{e,p} - \phi_{e,s}}{\phi_{e,p} + \phi_{e,s}}$$

with

$\phi_{e,p}$ : laser power measured in polarization plane,

$\phi_{e,s}$ : laser power measured perpendicular to polarization plane.

This leads to a polarization degree $P = 62\%$ of the seed laser and $P = 46\%$ of the amplified laser beam.

Figure 15: Polarization of (a) the seed laser and (b) the amplified laser pulses.
10.4. Single-mode laser diode with tapered amplifier:

A tapered amplifier system shown in Figure 18 consists of a cw seed laser diode, the output beam of which is amplified in a single pass by the tapered gain element (see Figure 16) [16,17].

![Diagram of a tapered amplifier](image)

Figure 16: Diagram of a tapered amplifier.

From the laser diode up to 100mW of power are available to seed the tapered amplifier, but only about 15mW are used due to destruction of the anti-reflection coated input facet of the amplifier element.

![Emission wavelength of the cw seed laser diode for different temperatures](image)

Figure 17: Emission wavelength of the cw seed laser diode for different temperatures.

Coupling of the seed beam to the amplifier is done by mode-matching the seed laser with the backwards traveling beam emitted by the tapered amplifier. The divergence angles from seed laser emission and backward directed tapered amplifier emission are similar. Hence, sufficient mode-matching is obtained using identical collimation lenses for both \( f=4.5\, \text{mm}, \, NA=0.55 \). An optical isolator with 60 dB isolation protects the stabilized seed laser from feedback by the mode-matched beam of the amplifier. Additional
mode shaping is done by using anamorphic optics and a telescope set-up \((f=20\, \text{mm} \text{ and } f=60\, \text{mm})\). The seed beam is coupled into the tapered element with a focusing lens \((f=8.2\, \text{mm})\).

![Figure 18: Set-up tapered amplifier.](image)

The plane of the tapered gain element is vertically orientated, so that diffraction yields a large horizontal divergence. This is collimated similar to the seed input, but yields a focus in the vertical plane. With a cylindrical lens \((f=90\, \text{mm})\) the astigmatism of the beam is compensated.

![Figure 19: Photography of the tapered amplifier.](image)
Figure 20: Gain profile of the tapered amplifier diode. The amplification maximum is at 810 nm.

Figure 21: Optical output power of the tapered amplifier for three different seed powers. Amplification by a factor of approximately 30 has been achieved.
A λ/2-plate is used in the set-up (Figure 23) in order to adjust the polarization of the seed laser beam to the input facet of the tapered amplifier. In this case measurements (a) and (b) leads to a polarization degree P>99%.

Figure 23: Polarization of the cw laser diode (a) before and (b) after passing the λ/2-plate.

10.5. Set-up of the ps-MIR DFG laser system:

In the present set-up for difference-frequency generation in periodically poled LiNbO₃ (A=21.0µm-22.4µm, 0.2µm steps, 19mm long) a single mode cw laser diode (Sharp LT017MDO, P=40 mW, λ = 810nm) and a passively Q-switched Cr³⁺:Nd³⁺:YAG microchip laser (E_p=10µJ, ∆τ = 710 ps, λ = 1064 nm) are used as pump and signal sources.
A schematic diagram of the laser system is shown in Figure 24.a. Since one of the fundamental beams is pulsed, the generated idler radiation is expected to be pulsed in the subnanosecond time-regime, too. Because of the narrow bandwidth and tunability a cw laser diode is chosen as pump source rather than a second pulsed laser.

Rayleigh-scattering is strongly dependent on the wavelength ($S_R \sim \lambda^{-4}$). This requests powerful pulses of the laser system to be able to detect any backscattered light in the mid-infrared spectral region.

Since the generated difference-frequency output power is proportional to the product of pump and signal power [8], it is necessary to enlarge the power of both laser-sources to maximize the power of the generated mid-infrared pulses.

To increase the output power of the microchip laser a fiber amplifier is used. A large mode area non-polarization maintaining double clad fiber with Ytterbium doping is chosen (Liekki Yb1200-30/250DC, 1.2m long). The fiber is pumped by a 30 W fiber coupled diode laser operating at 976 nm. An amplification by a factor of 14 and hence output energies of up to 144 µJ have been achieved at a repetition rate of 4 kHz (see Figure 10).

An average pulse duration of the amplified microchip laser pulses of $\Delta \tau = (606\pm8)$ ps has been measured with an Alphalas UPD-70-UVIR Photodiode (rise time < 70 ps) on a Tektronix CSA 8200 Communications Signal Analyzer with Sampling Module 80E01. A typical temporal pulse shape is shown in Figure 14.

A tapered amplifier (Eagleyard Photonics) is used to enhance the output power of the pump laser diode (SDL 5411-G1, $P=100mW$, $\lambda=808nm$) by a factor of approximately 30. In Figure 21 the optical output power of the tapered amplifier is shown for different seed powers of the laser diode and different pump currents.
10.6. Characterization

Without any amplification of the pump and signal sources maximum mid-infrared pulse energy of 
$E_p = 0.3 \mu J$ at a repetition rate of 3.5 kHz has been measured. The generated mid-infrared radiation is 
tunable between 3.40 µm and 3.47 µm. The combination of a fiber amplified microchiplaser and an 
amplified laser diode results in a maximum increase of the mid-infrared laser power and leads to pulse 
energy of $E_p = 0.5 nJ$.

In contrast to the visible spectral range, there are no detectors available in the mid-infrared spectral 
region with a time resolution of picoseconds and sufficient sensitivity for detection of weak signals 
(typically $\leq 10^{-15}$ J). However, an upconversion of the mid-infrared radiation to the visible spectral range 
allows the use of very sensitive photomultipliers and the application of photon counting technique in 
combination with a cross correlation set-up [18,19].

Since sum-frequency generation is a non-linear process it is suitable for a cross correlation 
measurement using pulses from the fiber amplified microchiplaser as reference.

The set-up of a cross correlation experiment is shown in Figure 24 b. The intensity of the amplified 
signal pulse is divided into two beams by a 15:85 beam splitter. The more intense beam is used for the 
difference-frequency generation, the weaker one as pump pulse for the sum-frequency generation. Applying 
a delay-line with a length of 1.5m a temporal width of 9ns is covered to characterize the temporal profile of 
the MIR pulses.

For sum-frequency generation an AgGaS$_2$ crystal (type I, $\theta=72^\circ$, 10mm long) is used. The two input 
beams show extraordinary polarization and generate an ordinary polarized wave. The difference in 
polarization is used to block any radiation but the generated sum-frequency off the detection unit. This is 
assisted by an edge pass filter (FES1000) in front of the polarizer.

A photomultiplier (Hamamatsu R928) and a photon counter (Ortec 9315) are used as detection unit. 
The photon counter is gated (gate-width $\approx 5$ns) with pulses from the microchiplaser as trigger. Figure 25 
shows the measured convoluted signal.

In general the convolution of two (pulse) functions $f(t)$ and $g(t)$ is defined as:

\[
(f \ast g)(t) = \int_{-\infty}^{\infty} f(\tau)g(t - \tau) d\tau.
\]

For Gaussian pulses the pulse width of the convoluted functions is:

\[
\Gamma_{f \ast g}^2 = \Gamma_f^2 + \Gamma_g^2.
\]
Figure 25: Cross correlation measurement of a mid-infrared pulse (signal) and a 1064 nm reference pulse (pump) ($\Delta \tau = (606 \pm 8)$ ps, see Figure 14) in an AgGaS$_2$ crystal. A deconvolution with the reference pulse leads to a mid-infrared pulse duration of $\Delta \tau = (538 \pm 22)$ ps.

A width of $(811 \pm 9)$ ps is derived by fitting the measured convoluted signal with a Gaussian profile. Deconvolving with the reference pulse ($\Delta \tau = (606 \pm 8)$ ps, see Figure 14) leads to a pulse duration of $(538 \pm 22)$ ps in the mid-infrared. This pulse duration leads to a mid-infrared output power of $P=67$ mW and corresponds to a spatial resolution of $(8.07 \pm 0.33)$ cm in a LIDAR experiment.

A narrow spectral line width is necessary to resolve single rotational absorption lines of gaseous species in a complex gas mixture. An absorption cell (path length 45cm) is filled with methane at pressures between 10 mbar and 205 mbar. Spectral line shapes for an absorption line at $2936.24 \text{ cm}^{-1}$ are measured and plotted versus the pressure. From the y-axis intercept a line width of the mid-infrared laser system $\Delta \bar{\nu} \approx 5.4 \cdot 10^{-2} \text{ cm}^{-1}$ is estimated.
Figure 26: The spectral line shapes for an absorption line of methane at 2936.24 cm\(^{-1}\) is measured and plotted versus the partial pressure (absorption path length 45cm). From the y-axis intercept a line width of the mid-infrared laser system of \(\Delta \nu \approx 5.4 \times 10^{-2} \text{ cm}^{-1}\) is estimated.

The line width is narrow enough for performing on- and off-resonance measurements, especially taking into account that the absorption lines are strongly broadened at elevated temperatures.

With the measured pulse duration \(\Delta \tau\) and the spectral line width \(\Delta \nu\) a time-bandwidth product of 0.87 is calculated. Assuming a Gaussian profile the theoretical Fourier-limited time-bandwidth product is 0.441. This shows that the generated mid-infrared pulse is not Fourier-limited. A possible explanation is given in [20]. They observed a dependence of the DFG line width on the pump power. In order to characterize the temporal behaviour of the pulse it is not sufficient to measure its spectral properties, but a cross correlation measurement as discussed before is necessary.

Measurements on- and off-resonance of an absorption line are required for differential absorption LIDAR. Due to the wavelength-tunability of the laser-diode in the difference-frequency generation set-up such measurements are possible. In Figure 27 an absorption line of methane has been measured by scanning continuously over \(\Delta \nu = 0.25 \text{ cm}^{-1}\).
In Figure 28 a rectangular wave voltage has been applied to the laser diode switching with a repetition rate of 0.3 Hz between two voltages and wavelengths, respectively. The on- and off-resonance positions are indicated in Figure 27.

Figure 28: Detection of methane at $\tilde{\nu} = 2936.24 \text{cm}^{-1}$ ($p=25.0 \text{ mbar}, L=45\text{cm}$) with on- and off-resonance measurements of this absorption line.
Due to degradation of the laser diode and not-stable wavelength positions a faster switching is not reasonable. But averaging at one wavelength over many pulses is possible because of the high repetition rate.

10.7. Detection unit

Typical detectors in the mid-infrared spectral region have a time resolution of about 10ns (e.g. LN$_2$ cooled InSb detector, Polytec R-1703-IS). Using these detectors with a preamplifier changes this for the worse. This combination has a typical time resolution of about 10µs and thus is not suitable for the detection of mid-infrared pulses in the picosecond time regime as necessary for the mentioned ps-MIR DFG LIDAR set-up.

However, upconversion in silverthiogallate has been proved for the characterization of picosecond pulses as demonstrated in the last section.

Because of the high sensitivity of the sum-frequency generation set-up [18, 19] it can also be used as detection unit for the LIDAR system.

10.8. Summary and outlook

The performance of the actual ps-MIR DFG laser-source is close to the planned characteristic. According to the four criteria for a mid-infrared LIDAR system the present set-up fulfils all of them. Powerful pulses ($E \approx 0.5nJ$) have been generated for a short range set-up (R=2..4m), with a pulse duration of $\Delta \tau = 538\,\text{ps}$ which corresponds to a spatial resolution of about 8cm. The spectral line width ($\Delta \nu = 5.4 \cdot 10^{13}\,\text{cm}^{-1}$) is narrow enough for performing on- and off-resonance measurements, especially taking into account that the absorption lines are strongly broadened at elevated temperatures.

The present mid-infrared laser-source is a good trade-off between a sufficient spatial and spectral resolution for measuring three-dimensional concentration profiles of an exhaust plume of an aircraft jet engine.
For further enhancement of the output power another more efficient mixing scheme (e.g. \( \lambda_p = 1064\,nm \) (pulsed) and \( \lambda_s = 1548\,nm \) (cw)) can be used [21]. Recent developments in passively Q-switched microchiplasers demonstrate pulse energies of up to 150 µJ. Using this laser in an Yb-fiber amplifier gives pulse energies of more than 1mJ [22]. Applying these more powerful pulses with the 1548nm signal laser will provide mid-infrared laser pulses with a power of nJ.

Since the generated output power of difference-frequency signal is crucial dependent on the polarization of the input lasers, it is necessary to optimize the polarization degree of the microchiplaser and the fiber amplifier, respectively.

Recent investigations on polarization of microchiplaser emissions and polarization maintaining amplification fibers show a high potential for generating high power pulses with a polarization degree \( P > 70\% \).

An improvement of the spatial resolution from actual \( \Delta s = 8cm \) to the planned resolution of \( \Delta s = 1.5cm \) makes another concept with pulse durations of about 100ps for the microchiplaser necessary. Recent developments in Saturable Absorber Mirror (SAM) technique (Figure 29) allows the generation of such short pulses.

![Diagram of a Saturable Absorber Mirror (SAM)](image1)

Figure 29: Diagram of a Saturable Absorber Mirror (SAM).

Theoretical pulse duration of \( \Delta \tau \approx 120\,ps \) with energy of about 10µJ can be achieved with this configuration. A first laboratory set-up (Figure 30) delivers pulses with duration of \( \Delta \tau \approx 400\,ps \) (Figure 31) and pulse energy of 1-2 µJ.

![Schematic set-up of a SAM microchiplaser](image2)

Figure 30: Schematic set-up of a SAM microchiplaser.
Figure 31: First laboratory measurement of the pulse duration of a SAM microchiplaser.
10.9. References for MIRPL study

11. ANNEX 2 – ONERA CONTRIBUTION – DUAL-CAVITY DOUBLY-RESONANT OPTICAL PARAMETRIC OSCILLATOR

11.1. Introduction

Optical parametric oscillators (OPOs) [1] are very attractive sources for the quantitative analysis of gas composition in reactive flows. Indeed, OPOs have a wide spectral tuning range that makes possible the detection of many trace gas. Furthermore, OPOs can deliver high peak power nanosecond pulses at a multi-kHz repetition rate that is well suited for investigation of industrial burners for which local measurements have to be performed in a short acquisition time.

However, in their basic configuration (singly resonant optical cavity), nanosecond OPOs show a multi-frequency behavior which is detrimental for gas monitoring. Therefore alternatives have been proposed for achieving single-frequency radiation from pulsed OPOs:

- Insertion of Fabry Perot étalons inside the optical cavity [2]. Oscillation can be maintained on only one longitudinal mode but the insertion losses appear as a main limitation regarding the low gain value that is obtained in parametric processes. Therefore, OPOs with intra cavity étalon show a high threshold of oscillation which is detrimental for high repetition rate operation;
- Dispersive gratings have been implemented in OPO cavities [3] mainly in the Littman configuration. Although this arrangement was fully validated with dye lasers, previous configurations cannot be simply duplicate to OPOs. More precisely, the relatively low reflectivity of diffraction gratings is a serious limitation for OPOs due to the low amplification coefficients sustained in parametric processes, in comparison with dye lasers;
- Frequency locking of the OPO emission by injection of a cw radiation [4]. Basically, the OPO oscillation is forced on only one axial mode by introduction of a pure radiation into this mode during its build-up time. For that purpose, the injected frequency matches only one axial mode and the seeded power is sufficiently large compared to the noise level so that the injected mode starts to deplete the pump before any adjacent mode can oscillate. Compared to spectrally selective cavities, the injection technique is very attractive since the OPO does not suffer from additional optical losses. However, the dynamic of a seeded OPO is not trivial and several mechanisms can lead to a frequency shift between the injected frequency and the OPO output. The main imitation of the seeded approach is its high complexity which is detrimental for industrial applications;
- Doubly resonant OPOs (DROPOs) where two optical cavities are used to force the oscillation on only one frequency [5]. This approach takes advantage of the specific property of the parametric conversion which is the production of two different wavelengths, namely signal and idler, from one pump wavelength. This technique shows two advantages: i) a low threshold of oscillation, ii) a very compact design that is advantageous for industrial applications.

The last solution has been developed in the Menelas study. Main features are given below.
11.2. Mode selection in doubly resonant optical parametric oscillators – the Vernier effect

The principle of mode selection in dual cavity DROPOs is depicted in Figure 1. According to Giordmaine and Miller [6], the axial mode distributions of the signal and idler fields are plotted on two opposite axes versus their respective frequencies, $\omega_s$ and $\omega_i$. In such a diagram, only the resonances that are in coincidence satisfy to the energy conservation condition ($\omega_s + \omega_i = \omega_p$ where $\omega_p$ is the pump frequency). Hence, only those pairs of modes in coincidence are emitted. Figure 1 illustrates a simple case for which only one exact coincidence stands within the parametric gain curve. Practically, the finite finesse of each cavity leads to a Lorentzian line shape of the signal and idler modes yielding a partial mode overlap that can be characterised using the mode-overlap integral ($\Delta S$), see the shaded areas in Figure 1.

Using dual-cavity DROPOs allows one to adjust separately the optical paths at the signal and idler frequencies. Thus, the two cavity lengths can be chosen to i) obtain a single-exact coincidence and ii) decrease neighbouring mode overlapping below threshold within the parametric gain bandwidth. Obviously, the difference between the two optical paths cannot be increased too much without disturbance of the spectral output by another exact mode coincidence coming into the parametric gain bandwidth (Vernier effect). Therefore, single-longitudinal-mode operation results from a trade-off between the imperfect mode overlap of neighbouring modes and the influence of well spectrally-separated exact coincidences.

![Figure 1: Principle of mode selection in dual cavity doubly resonant OPOs. The oscillation takes place at the central coincidence where the mode overlapping between the signal and idler combs is maximum.](image)

11.3. Entangled-cavity architecture

A detailed study of the conditions for single mode operation has been conducted in [5]. From this analysis, one deduces that the optimal geometry is obtained for the shortest signal and idler cavity lengths whereas the crystal length has to be as long as possible. In order to fulfil these contradictory conditions, we have developed a compact entangled-cavity arrangement (ONERA patent). As shown in Figure 2, the entangled cavity is composed of four mirrors symmetrically placed on each side of the crystal [7]. The signal and idler waves oscillate between the pairs of mirrors M1-M3 and M2-M4, respectively. The inner mirrors (M2, M3) are deposited onto the crystal faces whereas the external mirrors (M1, M4) are mounted on two PZT actuators for fine frequency tuning. The radius-of-curvature of external mirrors are determined to ensure an optimum overlap between the modes of the two cavities and the pump beam waist.

Single-mode operation is achieved by adjusting carefully the lengths $L_s$ and $L_i$ of the signal and idler cavities. The two external mirrors are mounted on PZT elements for fine tuning of the output frequency.
Figure 3 shows the general diagram of the optical source that has been developed for the Menelas study. The 14 ns-long pump pulses are delivered at a 12 kHz repetition rate by a compact passively Q-switched Nd:YAG laser (Innolight, model Mephisto Q). The 20 µJ pump beam passes through a Faraday isolator. Next, the beam is focused to a 75µm spot (radius at 1/e² of the peak intensity) within a PPLN crystal from Crystal Technology Inc comprising eight grating sections with a spatial period varying from 28.5 to 29.9 µm. The 6 mm-long, 11.5 mm-wide and 0.5 mm-thick PPLN crystal is heated around 100 °C to prevent any photo-refractive damage. The input power applied to the OPO is adjusted by means of a half-wave plate in combination with a polarizer. The mirrors M2 and M3 are deposited on the end faces of the PPLN crystal while two PZT actuators hold M1 (RoC = 50 mm) and M4 (RoC= 20 mm) symmetrically on either side of the crystal. The output coupling of the idler field is obtained through M4, which has a partial reflectivity (70 %) around 4 µm.

Basically, we obtain stable single longitudinal mode operation only with the three shortest period gratings of the PPLN crystal that display the smallest parametric gain bandwidth (10 cm⁻¹, typically). Furthermore, changing Ls or Li by more than one millimetre apart from the optimal SLM position (Ls = 14.7 mm, Li = 14.28 mm) leads to a multi-mode behaviour.

First characterisations have been carried out by recording the dependence of the idler output power versus the input pump power. From the experimental values reported in Figure 4, it is seen that the threshold of oscillation stands at a low pumping level (6 µJ) as a consequence of the doubly resonant arrangement. Above threshold, the idler energy increases linearly with the pump energy with a slope efficiency close to 10 % leading to a quantum efficiency of 40 %. At the maximum pump energy (14 µJ), the idler energy reaches 0.7 µJ meaning that the peak power is close to 70 W.
Next, the beam quality has been characterised. For that purpose, we monitor the spot size evolution of the idler radiation after focusing the beam with a 200 mm focal length lens. Assuming a Gaussian beam propagation, we find that the spot size evolution in the vertical and horizontal directions is well fitted if the first order parameters $M_x$ and $M_y$ are adjusted to 1.26 and 1.46, the difference is due to a slight asymmetry of the beam, (see Figure 5). Thus, one finds a $M^2$-square value of 1.8, which attests of the good quality of the output beam as a consequence of the implementation of two stable cavities in the entangled-cavity configuration.

![Figure 5](image)

Figure 5: spatial evolution of the radius of the idler beam (measured at 1/e$^2$ of the maximum intensity) : experimental values (filled squares), calculated Gaussian beam propagation (solid curve). Inset, idler beam at the entrance of the focal lens.

By adjusting simultaneously the applied voltages to the two PZT actuators in such a manner that $L_s$ and $L_i$ are changed in opposite directions, it is possible to tune continuously the idler frequency in a mode hop free way. Basically, a ramp voltage is applied to the signal PZT while the idler one is adjusted manually to maintain SLM output. A Fizeau wavemeter (LM17 from ATOS GmbH) monitors the visible radiation which is produced from the OPO due to a pump and signal sum-frequency process. Measuring both the wavelengths of the red and pump beams gives the idler wavelength. Given the 10 µm maximum displacement of the idler PZT, the idler frequency can be continuously tuned over 1.8 cm$^{-1}$. However, by
changing the idler PZT voltage only, one can select another pair of modes that are in coincidence and so extend the fine tuning range of the output frequency. Following this procedure, the frequency can be tuned over 5 cm\(^{-1}\) i.e. half of the parametric gain curve. For fixed PZT voltages, SLM operation is maintained over a few minutes without any cavity control system.

### 11.4. Doubly resonant optical parametric oscillator with back conversion minimisation

Although the entangled cavity doubly resonant OPOs provides stable single-longitudinal mode output with a fine tuning range of several wavenumbers, two main limitations are encountered with this architecture:

- Obtaining the parametric oscillation seems to be very difficult to achieve at particular wavelengths. This limitation was attributed to residual reflections at the pump wavelength on mirrors M3 and M4 yielding unwanted Fabry Perot resonances that lead to deep modulations in the parametric gain curve, see Figure 6. Calculations demonstrate that the optical transmission of M3 and M4 at the pump wavelength has to be higher than 99.5 % to avoid these parasitic effects. Such a technical specification is difficult to satisfy, especially because the high transmission at the pump wavelength has to be achieved in combination with a broadband reflection (or transmission) at the signal (or idler) wavelength. Thus, the coating specification is clearly a critical issue regarding the entangled-cavity configuration.

- Compared to singly resonant OPOs, the doubly resonant operation leads to a lower conversion efficiency as a result of the back conversion process in which the signal and idler fields recombine together to a pump radiation. More precisely, after reflection onto mirrors M3 and M4, the signal and idler fields propagate through the non linear crystal and recombine together producing a radiation at the pump wavelength through a sum frequency process (signal + idler \(\rightarrow\) pump). Basically the two processes (pump \(\rightarrow\) signal and idler) and (signal + idler \(\rightarrow\) pump) can take place given that both are governed by the same phase matching condition. In fact, the parametric conversion (first process) is mainly efficient if the pump beam is intense (in the forwards direction) whereas the back conversion process builds up as soon as the pump is absent (backwards direction). Hence, doubly resonant OPOs can be considered as a non linear mirror that reflects the pump radiation towards the laser, see Figure 7.

![Figure 6: Modulations of the parametric gain curve due to unwanted reflections at the pump wavelength.](image-url)
As explained hereafter, these two limitations can be circumvented by using a partial reflection of the pump beam after passing through the OPO, see Figure 8. If the relative phase of the three interacting fields $\phi_p - (\phi_s + \phi_i)$ is properly adjusted [8], one can demonstrate that the parametric conversion can be achieved efficiently in both directions through the non linear crystal. Hence, one avoids the detrimental effect of the signal and idler recombination. Yet, the main drawback of this new configuration is that the axial position of mirror M5 has to be finely and continuously adjusted with a PZT element to achieve the proper phase value whatever the output wavelength. Consequently, the optical arrangement and the frequency tuning procedure are more complicated, compared to previous one.

During this study a detailed analysis of the back conversion process has been conducted both theoretically and experimentally [9]. As shown below in Figure 9, the pump intensity reflected in the backwards direction ($I_{pr}$) depends on the reflection coefficient ($R_p$) of M5 at the pump wavelength. For $R_p = 0$, it is seen that 20% of the incident pump beam intensity ($I_p$) is reflected towards the laser due to the back conversion process (signal + idler $\rightarrow$ pump). If the reflectivity of M5 is chosen to reflect the pump intensity at a level which corresponds to the back conversion process (around 20%), the total reflected pump intensity is slightly reduced to 17%. In such conditions, the pump reflection on M5 minimises the effect of back conversion. For higher values, the total pump which is reflected towards the laser increases up to 35%. Hence, a 20% reflection coefficient for M5 is sufficient for reducing the detrimental effect of the back conversion mechanism and limiting the pump power which is reflected towards the laser.
In Figure 10, we have reported the evolution of the oscillation threshold for different coefficients of the pump reflection. Clearly, a 20% reflection is sufficient to reduce the threshold of oscillation by a factor 2. Note also the good agreement between the experiment and the calculated values. Figure 11 shows a comparison of the output energy versus the pump intensity for two different conditions: Rp = 0 and Rp = 20%. It is clear that a 20% pump reflection leads to a lower threshold of oscillation and a higher conversion efficiency. Experimental values plotted in both figures have been obtained after adjusting the position of mirror M5 to the optimal value.

As concerns the spectral behaviour of the OPO, it was clear that the partial pump reflection improves significantly the mode selection of the entangled-cavity (a side mode suppression ratio > 40 dB is reached) as well as the short-time frequency stability. In addition, even if it was not possible to suppress totally the influence of unwanted pump reflections onto M3 and M4, the regions where parametric oscillation was not obtained have been strongly reduced.

In conclusion, this work demonstrates that the performances of doubly resonant OPOs can be significantly improved by using an additional mirror with a 20% pump reflection coefficient. Following this work, a new architecture with only three mirrors will be developed and investigated by ONERA, reducing so the complexity of the five-mirror geometry currently used.
11.5. References for Laboratory MIDROPO study

Parametric oscillators and nonlinear materials
pp. 47-160.

Single-mode KTiPO₄ optical parametric oscillator

Narrow band β-BaB₂O₄ optical parametric oscillator in grazing-incidence configuration

Frequency control of a pulsed optical parametric oscillator by radiation injection

Dual-cavity doubly resonant optical parametric oscillator : demonstration of pulsed single-mode operation

[6] J. A. Giordmaine, R.C. Miller,
Optical parametric oscillation in LiNbO₃

Entangled-cavity optical parametric oscillator for mid-infrared pulsed single-longitudinal-mode operation

[8] J. E. Bjorkholm
Improvement of optical parametric oscillators by non resonant pump reflection
IEEE. J of Quant. Electr., QE-6, 797-799 (1970.)

Développement d’un oscillateur paramétrique optique monofréquence et réalisation d’un montage pour la spectroscopie infrarouge non linéaire.
12. ANNEX 3 - NEO CONTRIBUTION

12.1. Contribution to WP 2000 – Requirements and definitions

12.1.1. Contribution to Task 2100 – Species selection

An application questionnaire has been generated by NEO and distributed to all partners for comments and feedback with the objective to establish at an early stage a common understanding and agreement for which gases should be measured. A list of potential gases, which all absorb in the mid-IR, and their corresponding detection limits have been generated from existing spectroscopic data bases (HITRAN). The feedback from the partners have been accumulated in a table where the range of operation of the different optical sources (MIDROPO, MIRPL and SDLA) are indicated as well. The related comments are reported in Deliverable D1.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Wavelength (cm⁻¹)</th>
<th>Wavelength (nm)</th>
<th>DL ppm (10⁻⁴*1 m)</th>
<th>Interference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₂</td>
<td>2890</td>
<td>3460</td>
<td>0,3</td>
<td>CH₄, H₂O</td>
</tr>
<tr>
<td>CO₂</td>
<td>2331</td>
<td>4290</td>
<td>0,005</td>
<td>H₂O</td>
</tr>
<tr>
<td>CO₂</td>
<td>2338</td>
<td>4277</td>
<td>0,004</td>
<td>H₂O</td>
</tr>
<tr>
<td>N₂O</td>
<td>2237</td>
<td>4470</td>
<td>0,015</td>
<td>H₂O, CO₂</td>
</tr>
<tr>
<td>N₂O</td>
<td>2202</td>
<td>4541</td>
<td>0,015</td>
<td>CO, H₂O</td>
</tr>
<tr>
<td>CO</td>
<td>2203</td>
<td>4539</td>
<td>0,06</td>
<td>N₂O, H₂O</td>
</tr>
<tr>
<td>CO</td>
<td>2198</td>
<td>4550</td>
<td>0,03</td>
<td>H₂O, N₂O, CO₂</td>
</tr>
<tr>
<td>H₂O</td>
<td>1967</td>
<td>5084</td>
<td>1,19</td>
<td>CO, CO₂, NO, N₂O</td>
</tr>
<tr>
<td>NO</td>
<td>1964</td>
<td>5092</td>
<td>131,74</td>
<td>CO, H₂O, N₂O</td>
</tr>
<tr>
<td>NO</td>
<td>1754</td>
<td>5700</td>
<td>Not known</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 - List of selected species for MENELAS

12.1.2. Task 2200 – Spectral lines and degenerate four wave mixing calculations

For measurement of the selected species a study has been carried out in this task to find suitable absorption lines of the respective species. Two main factors have been taken into account; i) the technical capabilities of the instrument, and ii) the properties of the gas mixture to be probed in WP 5000, the exhaust of a jet engine/combustor. Using the HITRAN database the spectral range addressable by the MIDROPO instrument (3.8 – 4.4 µm) has been scanned for absorption lines free from interferences with other species present in the combustor exhaust and with sufficient strength to be detectable by the instrument. While the target sensitivity of the MIDROPO instrument has been specified to a minimum detectable absorbance of 10⁻⁴, the search for lines has been limited to those giving an absorbance in the order of 10 % in the measurement gas in order to have a strong absorption signal to work with in the measurement campaigns in WP 5000.

Contrary to atmospheric air the combustor exhaust contains large amounts of combustion products, primarily CO₂ and H₂O. CO₂ exhibits strong absorption in the wavelength range from about 4.17 µm up to and beyond 4.4 µm, especially at the high temperatures present in the combustor exhaust. While these CO₂ lines may allow sensitive measurements of CO₂ (detection limit 4 ppb at room temperature for a path length
of 1 m and $10^{-4}$ minimum detectable absorbance), the absorption in the combustor exhaust is too strong for measurement of other species in the same wavelength region. CO$_2$ itself can be measured using one of the weaker lines around 4.18 µm. For the WP 5000 measurement campaigns the 4.183 µm line has been selected.

None of the other selected species (CH$_4$, CO, NO) exhibit strong absorption features in the 3.8 – 4.4 µm range. CH$_4$ has only weak lines in the accessible range. For CO only the tail (4.35 – 4.4 µm) of the absorption band centered around 4.6 µm is accessible. The accessible lines are weak and measurement is not possible due to the CO$_2$ interference. NO has no absorption lines in the accessible range.

Other species have been considered and listed in Table 2. H$_2$O has a number of lines in the range 4.15 – 4.4 µm. The 4.156 µm line is outside the CO$_2$ absorption band, but is highly temperature dependent and only sufficiently strong for detection above around 800 K. N$_2$O has a strong absorption band around 3.9 µm. While this species is well suited for laboratory measurements, the concentration levels expected in the combustor exhaust are too low for detection.

<table>
<thead>
<tr>
<th>Species</th>
<th>Temperature</th>
<th>Wavelength</th>
<th>Det. lim. (ppm) $10^{-4} \times 1$ m</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_4$</td>
<td>296 K</td>
<td>3390 nm</td>
<td>2950 cm$^{-1}$</td>
<td>0.05</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>700 K</td>
<td>3860 nm</td>
<td>2591 cm$^{-1}$</td>
<td>23</td>
</tr>
<tr>
<td>CO</td>
<td>296 K</td>
<td>4550 nm</td>
<td>2198 cm$^{-1}$</td>
<td>0.03</td>
</tr>
<tr>
<td>CO</td>
<td>1100 K</td>
<td>4403 nm</td>
<td>2271 cm$^{-1}$</td>
<td>0.6</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1100 K</td>
<td>4075 nm</td>
<td>2454 cm$^{-1}$</td>
<td>380</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>296 K</td>
<td>4277 nm</td>
<td>2338 cm$^{-1}$</td>
<td>0.004</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>600 K</td>
<td>4184 nm</td>
<td>2389.9 cm$^{-1}$</td>
<td>0.2</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>600 K</td>
<td>4183 nm</td>
<td>2390.5 cm$^{-1}$</td>
<td>0.25</td>
</tr>
<tr>
<td>H$_2$O</td>
<td>1100 K</td>
<td>4156 nm</td>
<td>2406 cm$^{-1}$</td>
<td>7</td>
</tr>
<tr>
<td>NO</td>
<td>296 K</td>
<td>5092 nm</td>
<td>1964 cm$^{-1}$</td>
<td>130</td>
</tr>
<tr>
<td>NO</td>
<td>296 K</td>
<td>5700 nm</td>
<td>1754 cm$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>N$_2$O</td>
<td>1100 K</td>
<td>3942 nm</td>
<td>2537 cm$^{-1}$</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2 - Species and spectral lines studied in Task 2200 for MIDROPO. The CO$_2$ line at 4.183 µm has been selected for laboratory demonstration and calibration and the WP 5000 measurement campaigns.

12.2. Contribution to WP 3000 – Instrumentation

12.2.1. Task 3200 – MIDROPO prototyping

The objective for this task has been realizing a prototype spectrometer suitable for field experiments based on the MIDROPO developed in Task 3100. This task has comprised design and implementation of the complete electronic control system for the prototype spectrometer comprising a flexible drive and control system for the MIDROPO source as well as a detection system for measurement of gas concentration based on single line direct absorption spectroscopy, adapted to the operational characteristics of the MIDROPO. Figure 1 shows the basic outline of the MIDROPO spectrometer system.
12.2.1.1. Development philosophy

Development of the MIDROPO prototype has been made with potential commercial exploitation in mind. The various subsystems for operation of the MIDROPO have been developed in-house in order to reduce the effort needed in the transition from an operational prototype to a commercial product. Even though commercialization of the MIDROPO prototype may be uncertain, the developed concepts and techniques are likely to be of value in other applications.

The work in Task 3200 has to a large extent been done in parallel with Task 3100. As a result, the characteristics of the MIDROPO have not been available before later in the project. To account for this, the control electronics has been developed with a high degree of flexibility incorporated in its design in order to adapt the logic and operation of the subsystems as the details of the MIDROPO characteristics become apparent. The flexibility has been achieved by using programmable digital circuits and interfaces where appropriate. This has allowed the hardware to be manufactured once and later be configured via software when needed.

12.2.1.2. Application constraints

The application in WP 5000, gas concentration measurements in the exhaust of a jet engine/combustor, puts demanding requirements on the detection system. The prototype is to be operated outside the friendly conditions present in the laboratory, exposed to heat/cold, wind, and noise/vibrations. In the exhaust plume the gas flows at high speed (for the jet engine up to 300 m/s), and fluctuations in concentration and temperature (and consequently the refractive index) are expected on a timescale of 1 ms or less. In order to obtain local measurements in the exhaust plume, the sampling time for each measurement point must be made very short. A short sampling time is also needed to reduce the effects of transmission fluctuations resulting from the fluctuating refractive index. Thus one primary goal for the MIDROPO prototype development has been maximizing the measurement rate.

12.2.1.3. MIDROPO source constraints

The MIDROPO source developed in Task 3100 emits pulsed radiation in the range 3.8 – 4.4 μm. The pulse repetition frequency and the pulse duration is imposed by the pump laser. The pump laser selected for Task 3200 (Innolight Mephisto-Q HA) is a passively Q-switched Nd:YAG laser with a pulse repetition frequency of 18 kHz and a pulse duration of 12 ns. While the output power of the pump laser is very stable,
the MIR output power of the MIDROPO source is fluctuating considerably from pulse to pulse, typically by an order of magnitude. In order to enable the detection system to distinguish a pulse emitted with reduced energy from a pulse partially absorbed by the gas to be probed a normalization scheme must be deployed. This means measuring the energy of each and every pulse before and after passage through the gas. The classical method is using a beam splitter and split off part of the beam to a reference detector. For the MIDROPO an alternative exists: using the NIR signal beam as reference. In the parametric conversion in the MIDROPO NIR signal photons and MIR idler photons are produced in pairs with their respective energies related by the energy conservation equation $\hbar \omega_{\text{pump}} = \hbar \omega_{\text{signal}} + \hbar \omega_{\text{idler}}$. Hence the idler pulse energy can be derived from the signal pulse energy with knowledge of the wavelengths. Using the signal beam as reference has the advantage that only one MIR detector is needed and more MIR power is made available, but complications arise from the fact that the signal and idler pulses are subject to the optical transmission functions $H_1(\omega)$, $H_2(\omega)$ of their respective optical systems as they travel from the MIDROPO crystal to their respective detectors (Fabry-Pérot etalon effects). This is also true in the beam splitter scheme, but in the signal beam reference scheme the wavelength dependence is expected to have a more significant impact as the signal and idler wavelengths are far apart. The MIDROPO prototype has been designed to accommodate either scheme.

For measurement of the selected gas absorption line the MIDROPO MIR wavelength is adjusted to match the wavelength of the line. This is done by means of selecting the proper crystal grating (via lateral translation of the crystal within the MIDROPO cavity) and temperature, and finally the bias voltage on the piezoelectric actuators controlling the position of the MIDROPO cavity mirrors. In general measurement of different lines requires different gratings and temperatures – only if the lines are close is it possible to address multiple lines by adjustment of the PZTs only. Scanning of the absorption line, that is, recording of a series of transmission measurements made at different wavelengths across the absorption line, must be done by simultaneous adjustment of the PZTs. As the MIDROPO operates in the pulsed regime the absorption line is sampled at discrete wavelengths, one wavelength for each pulse. As the pump laser is passively Q-switched and exhibits a pulse repetition period jitter ($\pm 0.5 \mu s$) the arrival time of the pump pulse into the MIDROPO cavity cannot be precisely predicted – only to within a certain interval. To accurately produce the desired wavelength the proper position of the PZTs must be maintained during this interval until the pulse arrives. The MIDROPO prototype has been designed to execute the following simple procedure to generate the wavelength scanning:

1. Step the voltage on the PZTs up/down to the proper levels required to generate the next desired wavelength.
2. Wait for the next pulse.
3. Repeat from step 1.

This procedure ensures that the wavelength scanning is always in the right phase with the pump pulses. The individual voltage steps are configurable through software and can in general be programmed to generate an arbitrary waveform, but to reduce the risk of resonances in the MIDROPO mechanical structure a sinusoidal waveform has been selected.

For proper long time operation the MIDROPO wavelength must be maintained at the wavelength of the absorption line. This can be achieved by incorporating a reference cell containing the species to be measured. Such a cell will provide an absolute, stable wavelength reference. For some MIR wavelengths it may be possible to find species that absorb at the NIR signal wavelength, which would allow the signal beam to be used with the reference cell, but this is not possible in the general case. A reference cell adds quite a bit of complexity to the system as in addition to the cell itself a beam splitter and a third detector channel is required if a continuous monitoring of the wavelength is desired. The MIDROPO prototype has
been designed to use a simpler scheme, whereby the reference cell is briefly inserted into the beam path before measurements start as to allow tuning of the MIDROPO to output the proper wavelength, and then removed. This wavelength tuning procedure can be repeated at regular intervals to correct for drift. The MIDROPO wavelength is required to remain sufficiently stable between each readjustment.

12.2.1.4. MIDROPO prototype detection system

![Figure 2](image)

**Figure 2** - (a) MIDROPO prototype control electronics unit. (b) MIDROPO prototype optical bench.

![Figure 3](image)

**Figure 3** - MIDROPO prototype detection system concept schematic. In this version part of the idler beam provides the reference.

Figure 2 shows the MIDROPO prototype constructed in this task. Figure 3 shows a schematic of the selected MIDROPO prototype detection system concept. The electronics developed in this task comprises MIDROPO control electronics and detector electronics as follows:

- PPLN crystal temperature controller
- PZT driver (three identical units)
- Idler pulse receiver
- Reference pulse receiver (idler or signal pulse)
- Pump pulse trigger

These components are all connected via digital interfaces to a central Altera Stratix based CPU, logic, and I/O card (COTS device). The Altera FPGA is programmed with firmware that exports access to the hardware via a C library. This library is used by a C program running on the CPU.

![Figure 4- MIDROPO prototype PPLN crystal temperature controller.](image)

The PPLN crystal temperature controller card contains the current driver for the PPLN crystal heating elements and the PPLN crystal thermistor sampling circuit. The temperature regulation is implemented in software on the CPU card: the temperature controller card samples in the voltage over the PPLN crystal thermistor and delivers this value to the CPU card, which in turn computes the new heating current, via a software PID regulator algorithm, and sends this value back to the temperature controller card.

<table>
<thead>
<tr>
<th>Thermistor sampling</th>
<th>24 bit, 50 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peltier driver</td>
<td>Pulse width modulated, 50 kHz</td>
</tr>
</tbody>
</table>

*Table 3 - Key specifications of the MIDROPO prototype PPLN crystal temperature controller.*

![Figure 5 - MIDROPO prototype PZT driver.](image)

The PZT driver cards contain circuits for generation of the PZT bias and modulation (wavelength scanning) voltage. Each card controls one PZT. The bias and modulation components are generated by separate DA converters. The card is programmed via software to generate a stepwise approximation to a sinusoidal waveform:

\[ V(k) = V_{dc} + \frac{1}{2} V_{pp} \sin \left(2\pi \frac{k}{N} + \frac{1}{2} \pi m\right), \]

where \( k \) is the pulse number, \( N \) is the period in number of pulses, and \( m \) is 0, 1, 2, or 3. Upon request from the CPU card generation of one period of the modulation is initiated. On every following trigger the output voltage is stepped up or down according to a precalculated pattern. The PZT driver cards share the trigger signal, so the stepping occurs simultaneously on all three boards. Once the full period of the modulation has been generated the PZT driver card notifies the CPU card, which normally requests a new scan immediately.
Bias voltage: 18 – 85 V
Modulation voltage amplitude: -7.5 – +7.5 V
Modulation phase: 0°, 90°, 180°, or 270°
Modulation frequency: 10 – 1000 Hz

Table 4 - Key specifications of the MIDROPO prototype PZT driver.

<table>
<thead>
<tr>
<th>Idler detector/idler reference detector</th>
<th>Vigo PDI-2TE-5/PDI-2TE-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal reference detector</td>
<td>Fermionics FD2000W</td>
</tr>
<tr>
<td>Pump detector</td>
<td>Hamamatsu S3883</td>
</tr>
<tr>
<td>Idler/reference detector sampling</td>
<td>16 bit, 100 kHz</td>
</tr>
</tbody>
</table>

Table 5 - Key specifications of the MIDROPO prototype photodiode receiver.

12.2.1.5. MIDROPO prototype evaluation

The performance of the MIDROPO prototype and its various subsystems have been studied carefully during the course of the project. The MIDROPO source itself is the most critical component of the prototype. The difficulties in the development of the source in Task 3100 have had significant impact on the development of the prototype in this task. The performance of the source has not been satisfactory for proper operation of the prototype, and problems with manufacturing and extended delays in the delivery of custom optics for the MIDROPO has made significant impact on the progression of the work in this task.

The main problem experienced with the MIDROPO source is the difficulty of achieving stable operation. To operate properly the alignment of the pump laser beam and MIDROPO cavity mirrors and crystal must be made carefully. This procedure is elaborate and time consuming; often a few days work is needed. Once aligned, the bias and modulation voltages on the three PZTs must be adjusted to obtain...
scanning of the wavelength across the selected absorption line. For adjustment the following manual procedure has been devised:

1. Set the modulation on all PZTs to zero.
2. Adjust the idler PZT bias voltage until maximum output power is obtained.
3. Adjust the pump feedback PZT bias voltage until maximum output power is obtained.
4. Adjust the signal PZT bias voltage until maximum output power is obtained.
5. Repeat from step 2 until the output power can be increased no further.
6. Slightly increase the signal PZT modulation voltage amplitude.
7. Increase the idler PZT modulation voltage amplitude until maximum output power is obtained (over the whole cycle).
8. Increase the pump feedback PZT modulation voltage amplitude until maximum output power is obtained (over the whole cycle).
9. Repeat from step 6 until the desired modulation amplitude has been reached.
10. With a reference cell in the idler beam path, adjust the bias voltage of all three PZTs as to center the modulation on the absorption line.

A good starting point for the choice of modulation amplitudes is using the theoretical ratios

\[ \frac{V_{\text{signal}}}{V_{\text{idler}}} = -\frac{\beta_{\text{idler}}\sigma_{\text{idler}} F_{\text{idler}}}{\beta_{\text{signal}}\sigma_{\text{signal}} F_{\text{idlersignal}}} \]
\[ \frac{V_{\text{pump}}}{V_{\text{idler}}} = \frac{\beta_{\text{idler}}\sigma_{\text{idler}}}{\beta_{\text{pump}}\sigma_{\text{pump}}} \]

where \( \beta \) is the PZT expansion coefficient, \( \sigma \) is the wavenumber, and \( F \) is the cavity free spectral range. Poor output power stability and narrow continuous tuning range limits the application of the above procedure. Figure 7 illustrates the output power fluctuations and limited tuning range as measured by the MIDROPO prototype. Long term stability of the MIDROPO has also been a problem, realignment of the whole system has been necessary several times during the course of the project.

![Figure 7: Plot of measured signal pulse energy vs. modulation phase. The plot contains data points from several sequential scans with a cosine modulation, period of 400 pulses. The spread in the vertical direction at a given phase is due to output power fluctuations. The horizontal variation in the average level is due to the limited continuous tuning range.](image)

The continuous tuning range of the MIDROPO source that has been achieved with the automated wavelength scanning driven by the PZTs is only 0.1 cm\(^{-1}\). Considering that the width of the absorption lines to be probed is typically 0.15 cm\(^{-1}\), a continuous tuning range of 0.5 – 1 cm\(^{-1}\) would be required to properly
scan the line. Determination of the baseline of the absorption line becomes more accurate with a wider tuning range. Figure 8 shows the first (partial) scan of an absorption line in N₂O made with the MIDROPO prototype.

![Figure 8 - (a) Measurement of part of absorption line near 3.85 µm in 100% N₂O at atmospheric pressure, 25 °C, path length 50 mm. Part of the idler beam has been used for the reference pulse energy measurement. High energy pulses in the non-linear range of the detectors have been filtered out. (b) Same as a) only with the pulse energy normalization carried out.](image)

The electronics developed for the MIDROPO has proved well suited to the operation of the prototype. The only exception is the choice of MIR detectors from Vigo (PDI-2TE-5 for the idler, PDI-2TE-6 for the idler reference). While these detectors for many applications have excellent characteristics, their characteristics are not well suited to the high-energy MIDROPO prototype. This is the conclusion from the system tests performed with these detectors. Figure 9 shows the measured detector response, which is strongly non-linear. As a result of the non-linearity the signal from the detector in the high-energy region changes only slightly when the incident power changes. This has dramatic consequences for the sensitivity of the prototype, as it is the ability to detect small changes in the pulse energy due to absorption which defines the sensitivity. The non-linearity problem can be solved, either by reducing the incident pulse power to fall in the linear range (the downside of which is amplification of the effect of detector and electronics noise), or better, to replace the detector. There may be e.g. pyroelectric detectors that are better suited for the MIDROPO application.
Figure 9 - Measured and ideal response of Vigo PDI-2TE-5 (idler) and PDI-2TE-6 (reference). Unity on the incident energy axis represents the peak output power of the MIDROPO.

The performance of the PPLN crystal temperature controller has on the other hand been satisfactory. The temperature stability achieved is ±3 mK peak deviation from the set temperature at 100 ºC. Figure 10 shows a log of the temperature over a period of 5 minutes. The behaviour is the same over longer time scales. The residual temperature fluctuations appear to be due to thermal effects in the MIDROPO cavity, such as convection currents and circulation in the ambient air. Providing a sealed and evacuated housing for the MIDROPO cavity may improve the stability further, if needed.

Figure 10 - Stability of PPLN crystal temperature, measured by the MIDROPO prototype. The set temperature is 100 ºC.

The performance of the PZT driver boards has also been satisfactory. The only issue that has surfaced concerns degradation of the PZT actuators themselves. During installation of the final version of the MIDROPO source it was found that two of the three PZT actuators in the MIDROPO had abnormally high internal leakage currents. A PZT actuator can for most purposes be considered as a capacitive load only, with very high internal resistance. Data from the supplier suggests a normal leakage current in the sub-µA region. However for the pump feedback PZT a leakage current in excess of 850 µA was measured at 29 V bias voltage. This gives an internal resistance of only 34 kΩ (in contrast to 20 MΩ for the idler PZT). As the electronics has not been designed to handle this load the available bias voltage range is reduced from 18 – 85 V to 4 – 19 V. The effect on the mechanical performance of the PZT has not been assessed. The reason for the degradation is not known.
The pump laser from Innolight is the most expensive component of the MIDROPO prototype. While its performance for the most part has been excellent, a few issues have been noted during the course of the project, with application in a commercial product in mind. The sensitivity to ambient temperature has been the most problematic for the operation of the MIDROPO prototype. The manufacturer specifies that the maximum ambient temperature for operation of the pump laser is 25 ºC. Often the temperature in the laboratory has exceeded this limit by a few degrees, with the result that the pump laser fails to properly stabilize the temperature of the Nd:YAG crystal, which is critical for the wavelength and mode stability of the pump. In an industrial environment a wide ambient temperature range must be tolerated, which can only be provided by appropriate thermal protection of the pump laser. A related issue may be the occasional need for realignment of the internal optics of the pump laser. While this is a relatively simple procedure to carry out for an experienced operator, it does involve some risk as the pump laser must be opened. On a final note the pump laser is rather bulky, in particular the electronics unit. In many applications the size of the instrument has little importance, but the ability to provide a more compact device would be preferred.

12.2.1.6. Conclusion

A detection system adapted to the operation of the MIDROPO source has been designed and implemented. Due to significant delays in delivery of critical components to the MIDROPO source and poor performance of the MIDROPO source there has not been sufficient time available for completion of assembly of the prototype and software and final testing and calibration. Per the original planning this task, which heavily depends on the output of Task 3100, should have been completed in month 24. The delivery of the final version of the MIDROPO source did not take place before month 42. While several earlier versions of the MIDROPO source has been available during the development, the performance of these has not been sufficient for obtaining a functional prototype. Had the MIDROPO source been available as planned, with the required performance, this task and the ones depending on it would most likely have progressed as planned. However, the problem of obtaining optical components satisfying the harsh specifications required for proper operation of the complex entangled cavity MIDROPO seems to be a fundamental one. While it appears likely that the performance of the MIDROPO prototype can be improved given enough time to fine-tune the system, it does not seem realistic that the performance in the end will meet the required specifications. Better optical coatings will improve the situation, but cost and available technology will make this difficult to obtain.

Despite the fundamental stability problems automated measurement of an absorption line in N₂O has been demonstrated. This proves that it is feasible to use an OPO for single line spectroscopy in the mid-infrared, although significant improvement is needed before the OPO can be considered used in an application outside the laboratory. Capability of measurement of one single line would be a significant step, but arriving at a widely tunable source with capability of measuring several species with the same OPO source does not seem likely at the present time. Going to other spectral regions would also be interesting for application in a spectrometer. This may be feasible with other non-linear crystals, e.g. GaAs.

In any mid-infrared spectrometer both the source and the detector are critical components. In this task most of the effort has been concentrated on developing and operating the source. The selected detector has however not been well matched to the characteristics of the source. Further work will be required to find better suited detectors. Continued development of mid-infrared detectors is an important part of development of mid-infrared spectroscopy.
12.3. Contribution to WP 5000 – Experiments and analysis

12.3.1. Task 5100 – Combustor operation and non-intrusive measurements

The measurement campaign has been planned in some detail, but as the MIDROPO prototype is not operational no measurements has been performed.

12.3.2. Task 5200 – Aircraft test and non-intrusive measurements

Ditto.

12.4. Contribution to WP 6000 – Assessments and exploitation

12.4.1. Task 6100 – Industrial exploitation

From NEO's perspective there has been two original main research objectives in the MENELAS project:

- To identify possible emission gases from aircraft jet engines that can be measured in the MID IR with a spectrometer based on a tunable OPO.
- To realize a laboratory scale prototype of a MID IR spectrometer based on a tunable OPO, which can be used in field experiments to measure emission gases from jet engines.

These research activities were expected to yield the following deliverables:

- List of species that can be measured within the spectral tuning range of the OPO and which are relevant for jet emissions.
- Design of spectrometer based on the OPO constructed and made by ONERA (from WP 3100).
- Demonstration of measurements of more than one gas species in the exhaust from jet engines.

12.4.1.1. Project's actual outcome

The list of species to be measured have been circulated to all partners and an agreed preferred list to be measured have been made. It was concluded that some of the interesting gases could not be measured within the projected tuning range of the OPO (up to 4500 nm).

A complete MID IR spectrometer prototype has been designed and built using electronic solutions that make transfer of the design to an industrial product as efficient as possible, and through this we have demonstrated that a product meeting current industrial standards can be realized provided that the OPO, being the key component in the system, has the required performance with respect to operational stability and tuning range.

The performance of the final version of the MIDROPO prototype dedicated to the spectrometer has been thoroughly evaluated and even if this work has been hampered by problems with optical coatings not meeting the required specifications, the final conclusion is that the current MIDROPO system with two external cavity mirrors appears to be too complex for industrial applications. The system has too many interdependent variables and is therefore very time consuming to manufacture, assemble and adjust.
Additionally, from a gas analyzer point of view, the frequency tuning range that we can achieve in practice is not adequate for the multigas applications an OPO based gas analyzer is supposed to cover.

12.4.1.2. Broad dissemination and use intentions for the expected outputs

An OPO is for the first time to our knowledge used as a single frequency radiation source for a MID IR spectrometer for single line spectroscopy. Single line spectroscopy has the unique advantage that it can provide interference free measurements of many gases and this technique is today commercially exploited by using tunable diode lasers in the NIR. These lasers have a very narrow frequency tuning capability making it possible to measure only one gas with one instrument. The much larger tunability of the OPO and the fact that it operates in the MID IR where many gases have stronger absorption will allow single line spectroscopic measurements in a multigas configuration. This opens up a range of applications where the traditional spectroscopic instruments have limited sensitivities due to cross-interference. Additionally, a spectrometer based on an OPO will allow measurements of several gases directly in the process stream (in-situ) thus avoiding problems with extracting a sample from the main gas stream. The most interesting applications will be in the exhaust stream from combustion processes or melting processes.

Even if we were not able to achieve the overall goals for the project we have been able to demonstrate that a multi-component industrial gas analyzer can be realized by using a tunable OPO as the single mode radiation source. The performance of the OPO in its present form is, however, far from acceptable for an industrial instrument, but the experience gained during the project will be very valuable for the continuation of the OPO development. The potential tuning range for the current design is relatively wide but we have in the project identified several important gas components that can not be covered within the available tuning range. There is work in progress with new materials such as GaAs that will enable us to extend the tuning range significantly, thus making it possible to cover virtually all gases of interest. The long term potential for this technique is therefore very large.

12.4.1.3. Market study to identify the potentialities (real and potential market)

Products based on single line spectroscopy will play a dominating role among spectroscopic instruments for quantification of gas concentrations. The extension of the spectral range from NIR into the fundamental vibrational/rotational transitions in the MIR will represent a major expansion of the product range and market base, as the new instruments will meet the market demand for multi-gas measurements, and be competitive in the three most important market segments, e.g. environmental monitoring (open path or point measurements), emission as well as process monitoring in industrial processes, and emissions from motor vehicles and engines.

A recent market study made by Frost & Sullivan, covering the European market quantifies the total market for gas monitors for all three market segments to 240 million ECU in 1998. This is expected to increase to 275 million ECU per year by the year 2005. The total number of instruments sold per year is for all three market segments around 20,000 units, and a large proportion of these are instruments based on spectroscopic techniques.

The European market is estimated to approx. 25% of the world market for these types of instruments, bringing the potential total world market up to around 1000 mill ECU per year.

With the exception of stack monitors, where European companies dominate the European markets, the other market segments are dominated (> 50% market share) by US and Japanese companies. Single line spectroscopy is expected to play a major role in the next generation of instruments for all three market segments, and as Europe currently is ahead of both US and Japan in commercial...
exploitation of the related technology, it may be one of the most important technologies which will make it possible to increase the market share for European companies in the future.

12.4.2. Task 6200 – Patents and licenses

None foreseen yet.

12.4.3. Task 6300 – Publications

No publications have been made or are foreseen by NEO.