Aircraft emissions and airport air quality monitoring

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Motivation, background and problems

Methodology of measurements and inverse dispersion modelling

Measurement results

Conclusions

**International Colloquium “Safeguarding Airport Air Quality: Angles of Approach”,
Manchester, April 12th, 2007**

Motivation

For the execution of the European Air Quality Framework Directive 96/62/EC and its daughter directives it is required from the EU member states to submit 12-monthly air pollution maps that show the spatial distribution of air pollutants

- for the member state in total,

- for conurbations with more than 250.000 inhabitants and

- for micro environments as, e.g., city districts subject to high pollutant concentrations: spatial resolution of 200 m^2

Motivation

- Airport air quality is not well known because emission inventories are estimated only

- On airports, aircraft engines are one of the major sources for air pollutants

- Emission indices for NO_x and CO (UHC, smoke number) of ICAO* are used to calculate aircraft main engines emissions: 4 different thrust levels – Idle, approach, climb out, take off (LTO cycle)

=> Applicability of ICAO data from certification measurements must be shown with measured data at airports

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***ICAO: International Civil Aviation Organization**

Motivation

- APU are running during all services

- Emission indices of APU are not listed by ICAO

- Initiatives within the EU-Network of Excellence ECATS (Environmentally Compatible Air Transport System)

- Road traffic and ground support equipment have a significant influence on airport air quality also

Motivation

Due to ongoing improvement of air quality regulations and steadily growing air traffic it is possible that also airport authorities must decide about emission reduction measures

Long-term strategic framework to reduce specific emissions from air traffic in the context of airport expansion plans required to meet future demands of air traffic: Operation ability of air pollution modelling necessary - data requirements, forecasting

As many metropolitan areas include airports this would be a contribution to enhance urban air quality

Background and problems

Determination of strengths of all emission sources at airports is required:

- emission indices of aircraft exhaust emissions and
- diffuse or heterogeneous emissions

Interaction between exhaust plume and ambient air is not well understood but important for small-scale chemistry-transport models

Where are the “hot spots” of airport air quality?

Which interactions between airport air pollution and air pollutions in the surroundings e.g. urban areas exist?

Methods

- Passive remote sensing using FTIR-spectroscopy (K300, SIGIS) for determination of exhaust composition at aircraft engine nozzle exit

- Concentration measurement across the plume with FTIR & DOAS

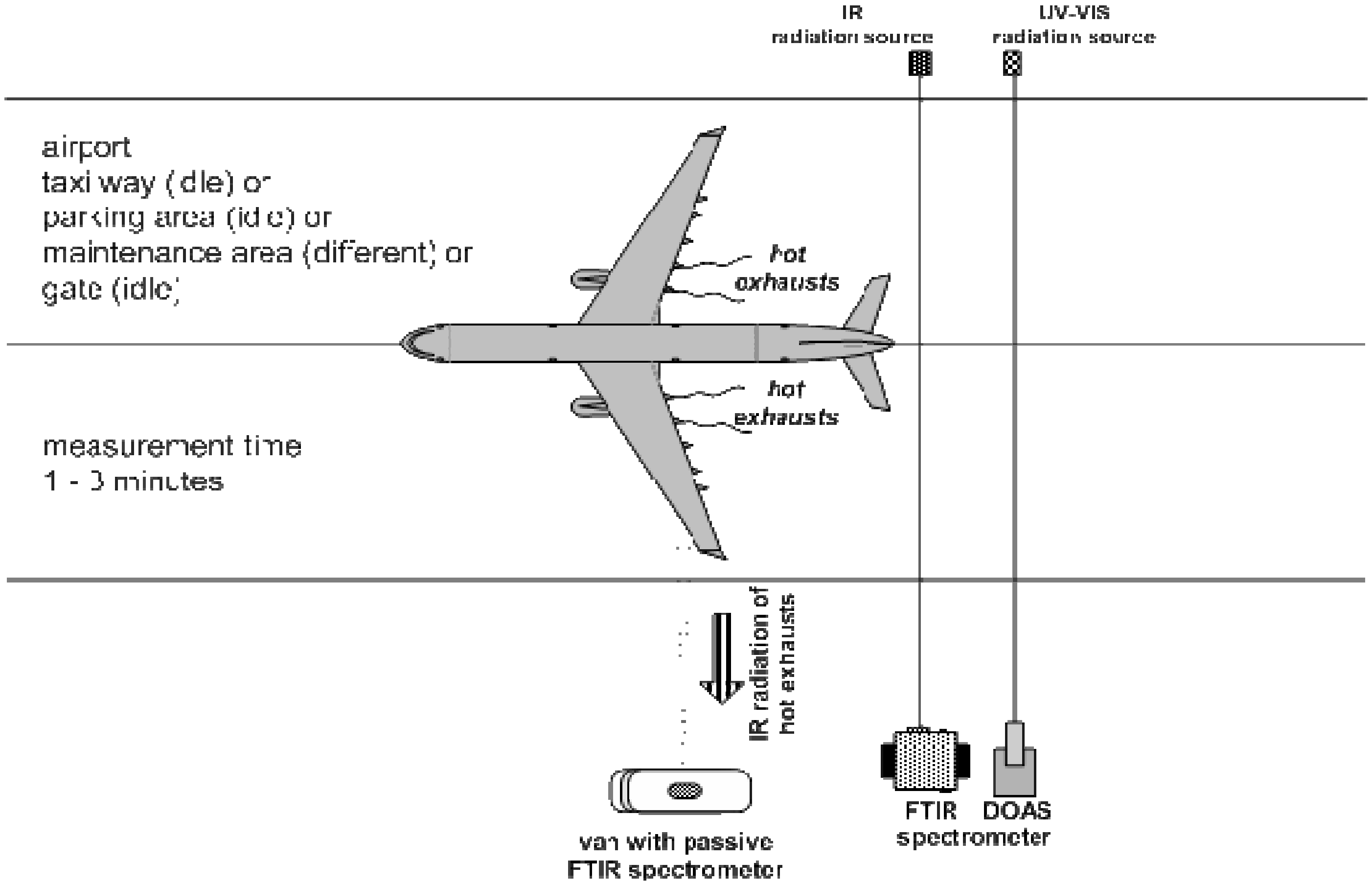
- Determination of emission indices

- Inverse modelling to estimate multiple sources from heterogeneous emissions

Measurement – Set up

- Detailed observations of aircraft movements

- Application of other measurement devices for Inverse Dispersion Modelling



Average emission index *EI* of a molecule *X* in g/kg kerosene:

$$EI(X) = EI(CO_2) \times \frac{M(X)}{M(CO_2)} \times \frac{Q(X)}{Q(CO_2)}$$

M: molecular weight

Q: concentrations (mixing ratios, column densities etc.), difference to background

Theoretical emission index of CO_2: calculated from stoichiometric combustion of kerosene to be 3,159 g/kg

EI (NO_x) = EI (NO* and NO_2) is related to the mass of NO_2:

EI (NO*) = EI (NO) x 46/30

Measurement – Instrumentation

FTIR spectrometry with a spectrometer from Kayser Threde or Bruker and the use of glowbars as IR-source

DOAS from Opsis in monostatic configuration with retroreflectors

Measurement Locations

Airport Zurich (ZRH)

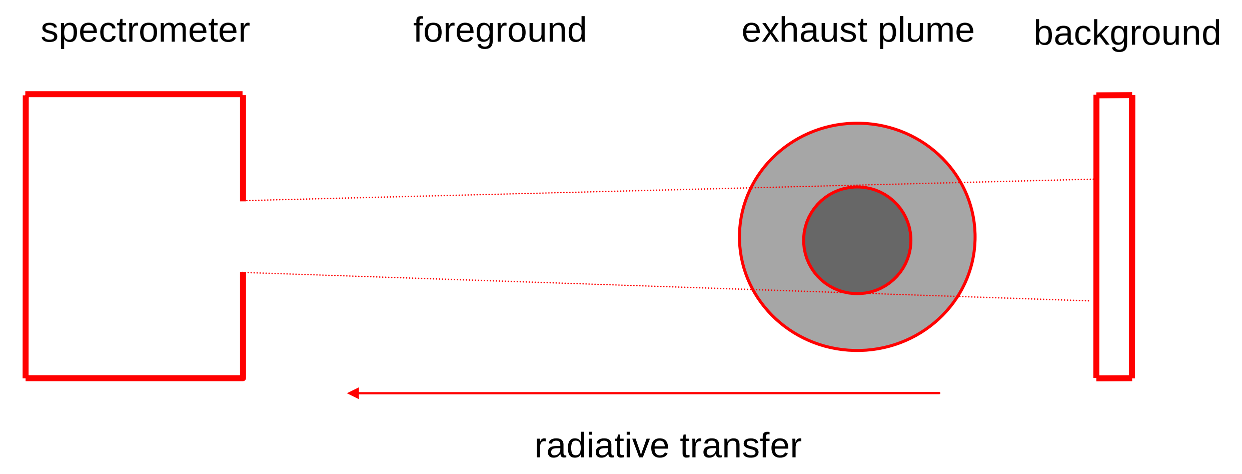
Vienna

Airport Paris Charles de Gaulle (CDG)

London-Heathrow

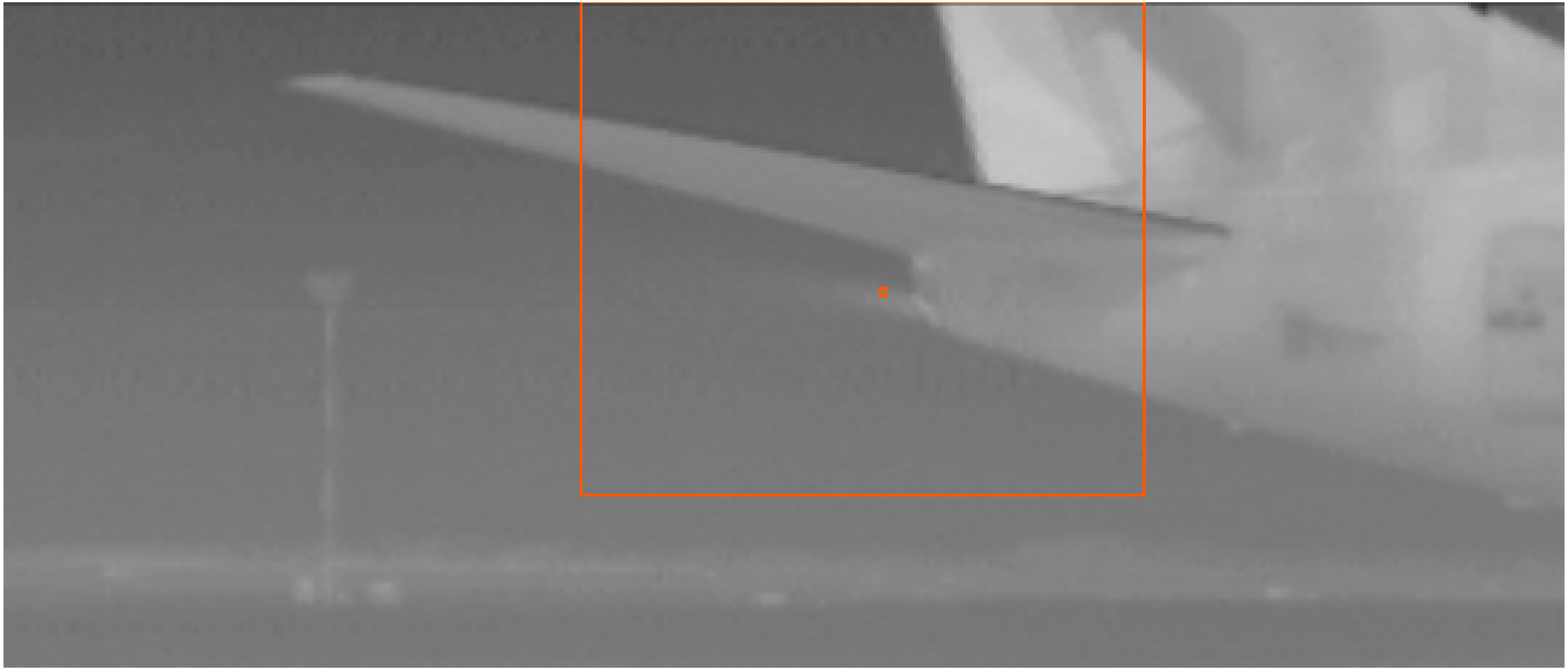
Airport Mexico City

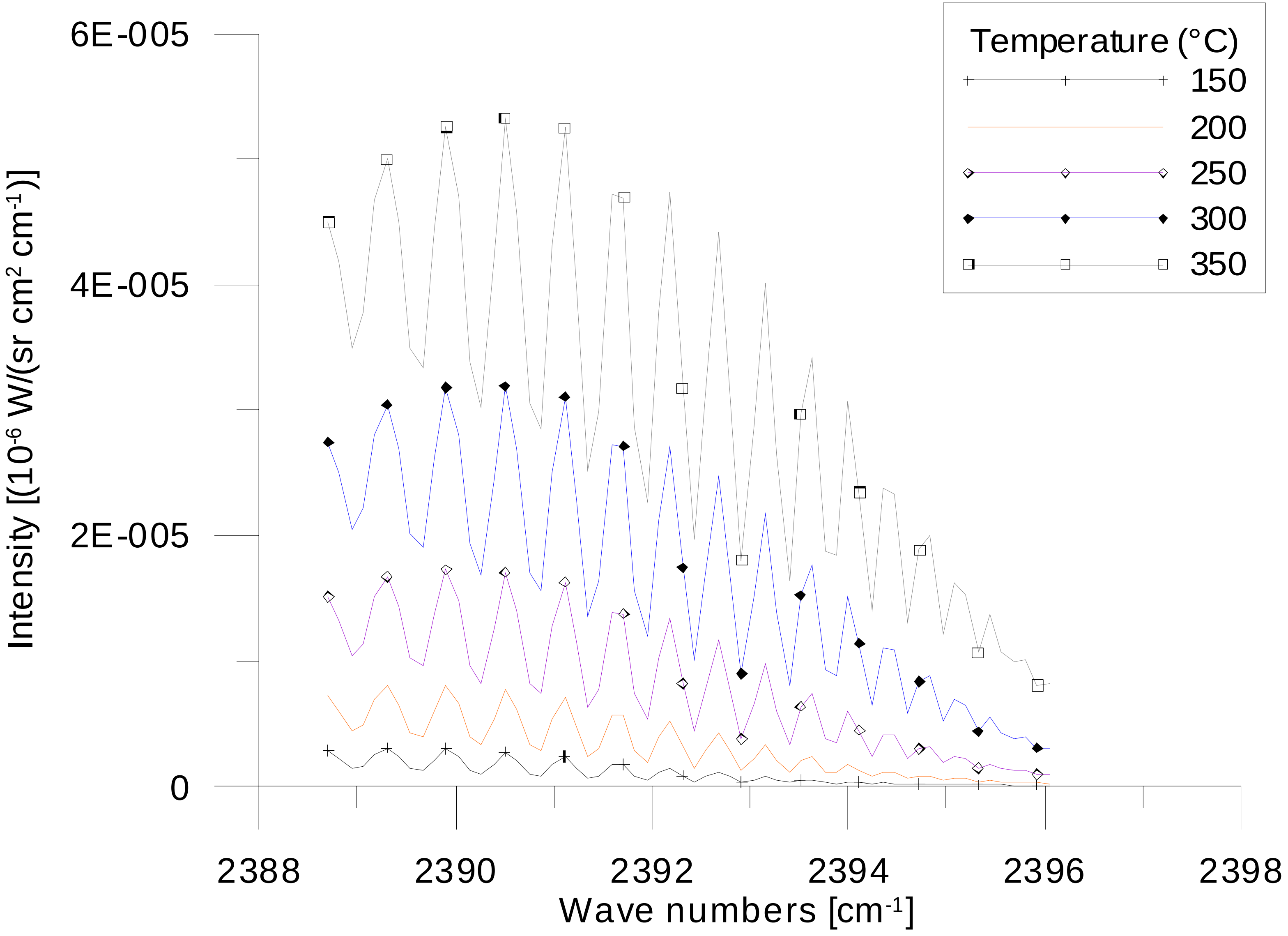
Measurement principle

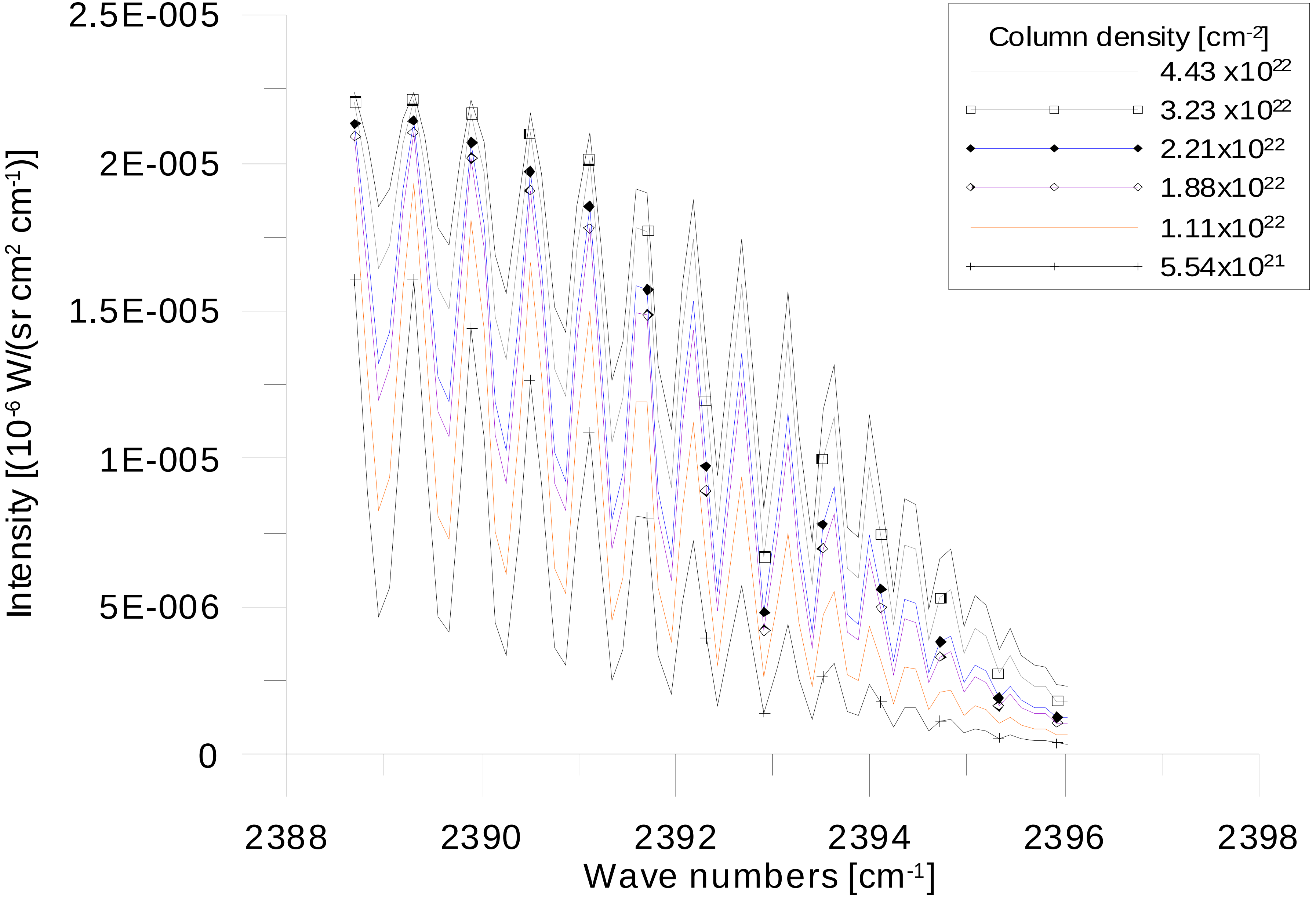


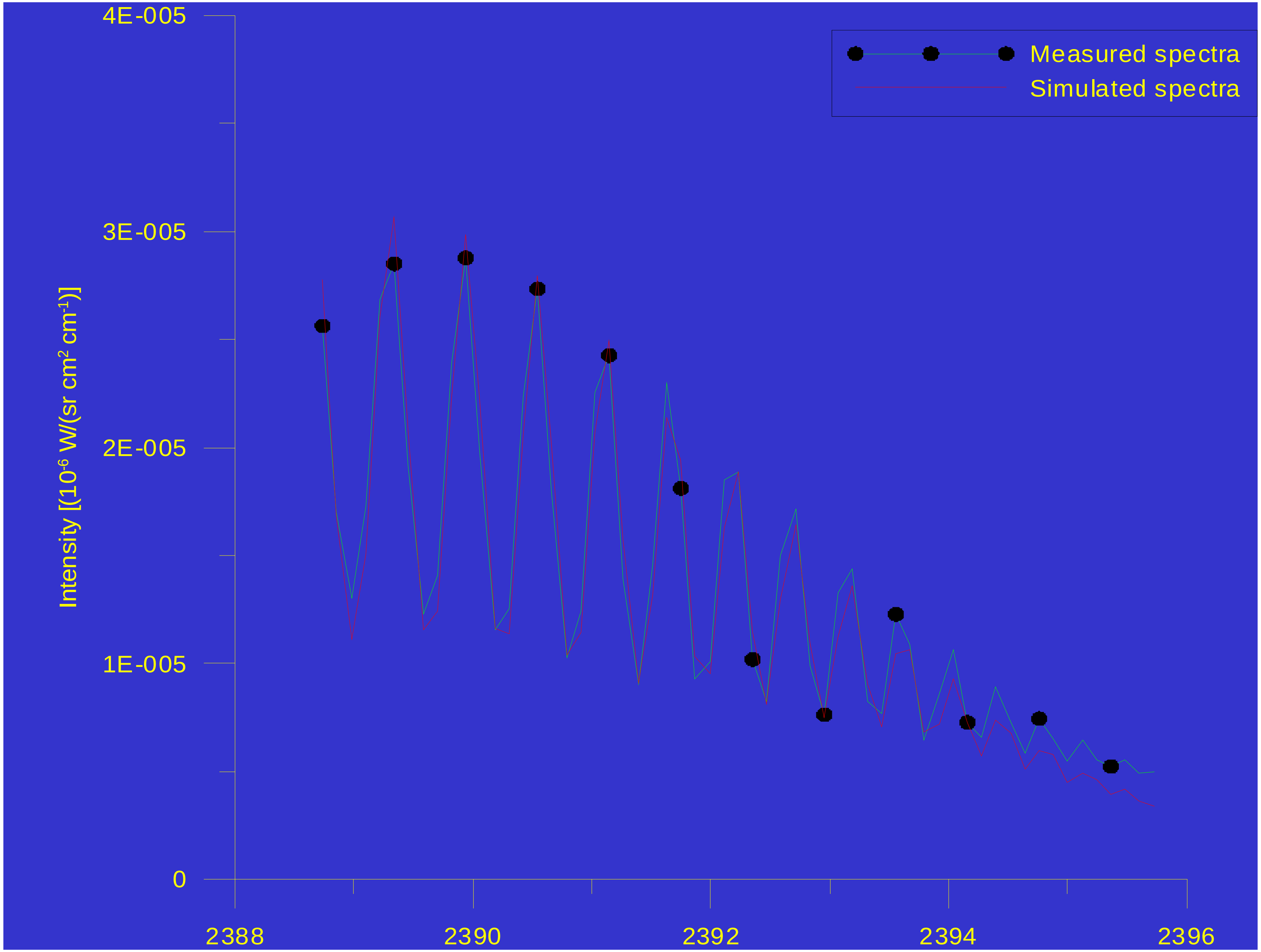
$$I = I_b \tau_p \tau_f + I_p \tau_f + I_f$$

$$\tau_{\Delta\nu}(L) = \left\{ \int_{\Delta\nu} \prod_{i=1}^{N} \exp[-k_i(\nu) n_i L] d\nu \right\} \exp[-k_a(\Delta\nu) n_a L]$$

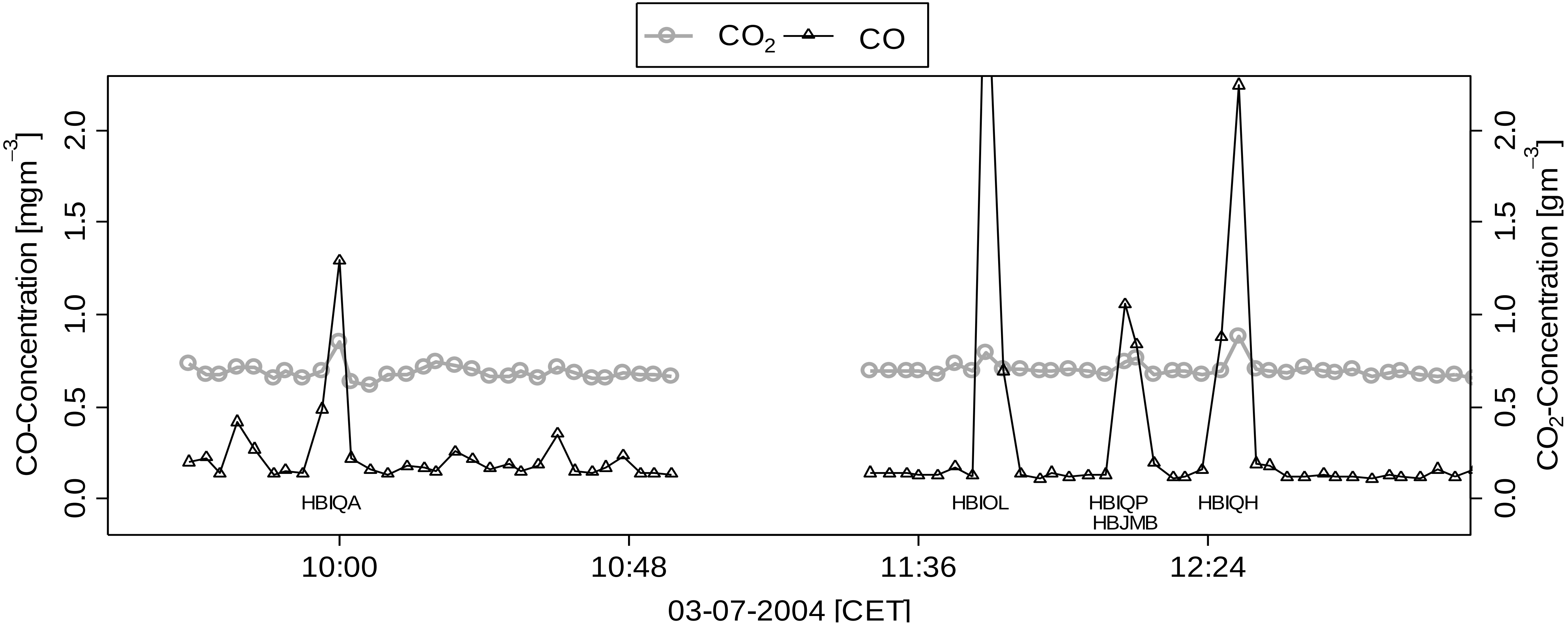



Temperature (°C)
150
200
250
300
350
6E-005
4E-005
2E-005
0
Intensity [(10⁻⁶ W/(sr cm² cm⁻¹)]
2388
2390
2392
2394
2396
2398
Wave numbers [cm⁻¹]

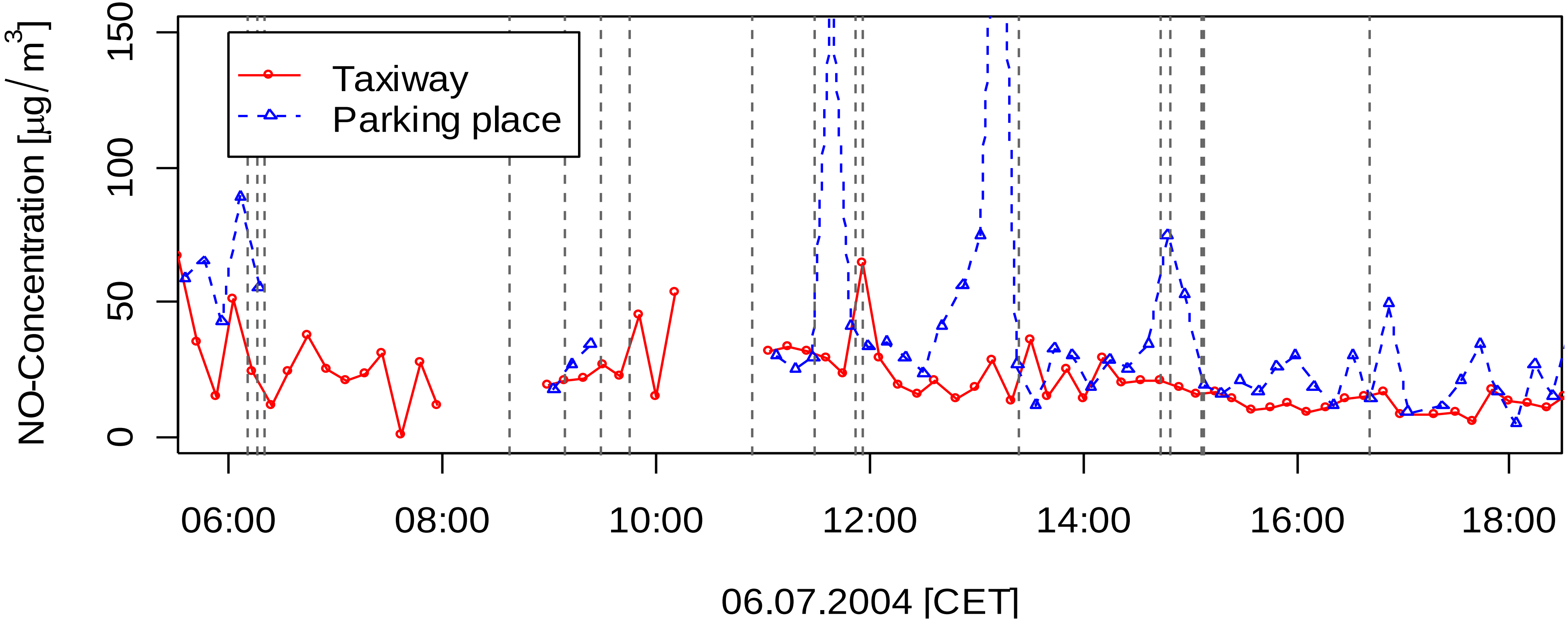

Intensity [(10⁻⁶ W/(sr cm² cm⁻¹)]
2.5E-005
2E-005
1.5E-005
1E-005
5E-006
0
2388
2390
2392
2394
2396
2398
Wave numbers [cm⁻¹]
Column density [cm⁻²]
4.43 x10²²
3.23 x10²²
2.21x10²²
1.88x10²²
1.11x10²²
5.54x10²¹


4E-005
3E-005
2E-005
1E-005
0
Intensity [(10^-6 W/(sr cm^2 cm^-1)]
2388
2390
2392
2394
2396
Measured spectra
Simulated spectra

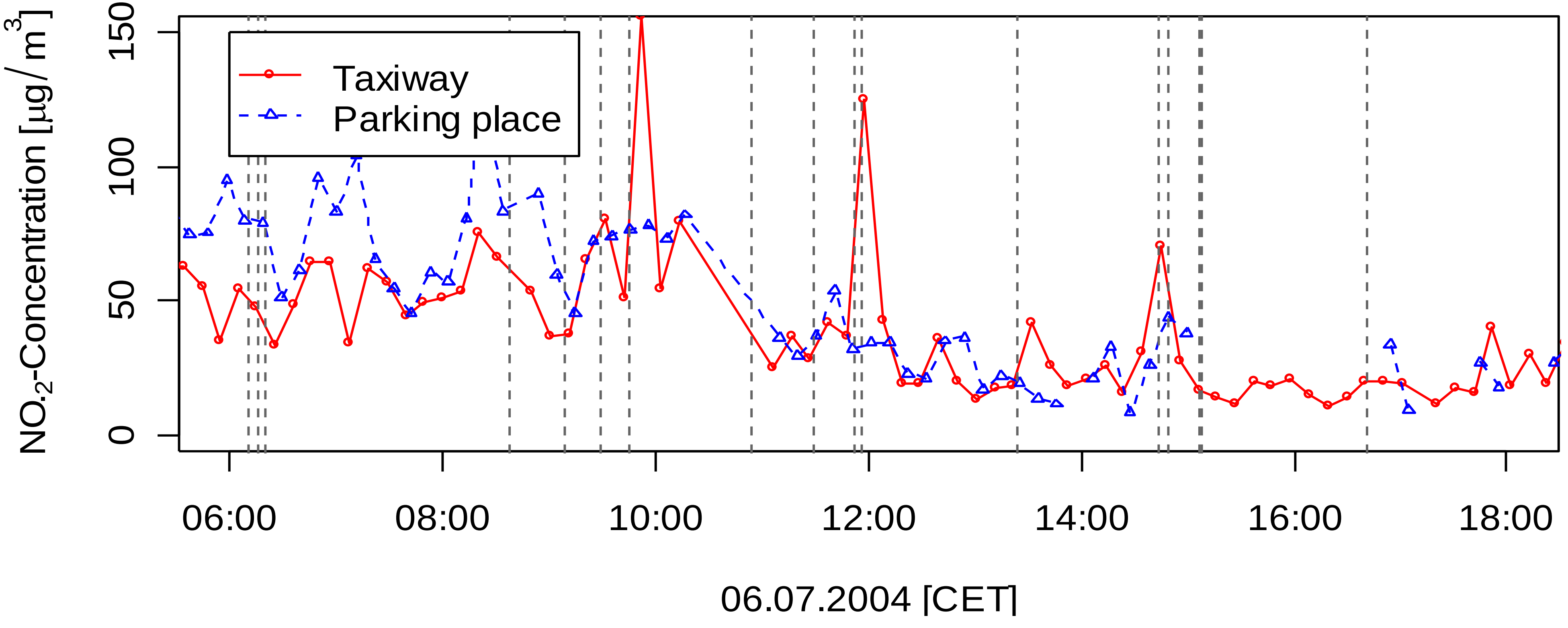
Measurement results



Measurement results



Measurement results



Measured Pollutants by FTIR and DOAS

Name		**Comment**
CO	**Carbon monoxide**	**very good, passive and active**
CO_2	**Carbon dioxide**	**very good, passive and active**
H_2O	**Water**	**high background, passive/active**
HCOH	**Formaldehyde**	**good**
C_2H_4	**Ethene**	**very good**
C_2H_2	**Ethine**	**good, interferences to CO_2 & H_2O**
CH_4	**Methane**	**difficult, passive and active**
C_3H_6	**Propene**	**good, low concentrations**
C_4H_6	**Butadiene**	**good, low concentrations**
N_2O	**Nitrous oxide**	**difficult, passive and active**
NO	**Nitrogen oxide**	**very good, passive and active**
NO_2	**Nitrogen dioxide**	**very good**

Measured emission indices

CO2

NO2

Measured compounds:

- FTIR passive: CO, NO, CO_2 – simultaneous
- FTIR active: CO, CO_2 – simultaneous
- DOAS: NO, NO_2 – one after another

Averaging temporal interval: ~ 1 - 3 minutes

CO

NO

Measured engines up to now

Engine Type	Nozzle diameter	Usage
CFM56-3B1	115 cm	Civil, med. range
CFM56-3B2	115 cm	Civil, med. range
CFM56-5A1	65 cm	Civil, med. range
CFM56-5B1P	66 cm	Civil, med. range
CFM56-5B1/2	66 cm	Civil, med. range
CFM56-5B1/2P	66 cm	Civil, med. range
CFM56-5B2	66 cm	Civil, med. range
CFM56-5B3P	66 cm	Civil, med. range
CFM56-5B4/2	66 cm	Civil, med. range
CFM56-5B4/2P	66 cm	Civil, med. range
CFM56-5C2	140 cm	Civil, long range
CFM56-7B22/2	68 cm	Civil, med. range
CFM56-7B27	68 cm	Civil, med. range
GE CF 34-3A	43 cm	Civil, short range
GE CF 34-3A1	43 cm	Civil, short range
GE CF 34-3B	43 cm	Civil, short range
GE CF 700-2D2	44 cm	Civil bus. jets
GE90-85B	150 cm	Civil, long range
JT8D-15	108 cm	Civil, med. range
JT8D-217C	95 cm	Civil, med. range
PW123B	43 cm	Civil, short range
PW150A	45 cm	Civil, short range
RB211-524D4	90 cm	Civil, long range
RB211-524D4X	90 cm	Civil, long range
RB211-524H2	170 cm	Civil, long range
RB211-535C	84 cm	Civil, med. range
RB211-535C-37	84 cm	Civil, med. range
RB211-535E4	145 cm	Civil, med. range
RB211-535E4-37	145 cm	Civil, med. range
RR M45H	50 cm	Civil bus. jets
RR-TAY MK 620	90 cm	Civil, short range
PW4168A	99 cm	Civil, med. range
V2500-A1	124 cm	Civil, med. range
APS2000	35 cm	APU
APS3200	35 cm	APU
GT CP85-98DHF	35 cm	APU
GT CP331-200/250	55 cm	APU
GT CP331-500	55 cm	APU
GT CP660-4	55 cm	APU
PW901A	55 cm	APU

Mean values of emission indices of APU

bdl: below detection limit i.e. a signature in the measured spectra cannot be inverted

Extrema as minimum and maximum value of all measured data are given in brackets

Aircraft	Number of aircraft	APU type	EI CO [g/kg]	EI NO [g/kg]	EI NO_x [g/kg]
A320-200	1	APS3200	2.9 ± 0.30 (2.5 -3.1)	0.3 (bdl - 0.8)	0.4 (bdl - 1.3)
B737-406	1	APS2000	2.7 ± 0.29 (2.5 - 3.1)	1.7 ± 0.34 (1.4 - 2.2)	2.5 ± 0.53 (2.3 - 3.3)
B737-800	1	GTCP85-98DHF	13.9 ± 1.07 (12.4 - 15.1)	0.8 ± 0.07 (0.7 - 0.8)	1.2 ± 0.11 (1.0 - 1.3)
B747-236	1	GTCP660-4	2.2 ± 0.32 (1.9 - 2.4)	0.1 (bdl - 0.3)	0.2 (bdl - 0.4)
B747-400	3	PW901A	11.6 ± 3.98 (5.5 - 18.0)	1.1 ± 0.37 (0.6 - 1.8)	1.7 ± 0.56 (0.8 - 2.7)
B747-436	8	PW901A	12.4 ± 5.26 (0.5 - 31.3)	0.6± 0.75 (bdl - 2.7)	1.0 ± 1.14 (bdl - 4.2)
B757-236	3	GTCP331-200/250	1.1 ± 0.41 (0.2 - 1.7)	2.6 ± 0.79 (0.4 - 3.6)	3.9 ± 1.21 (0.6 - 5.5)
B777-236	3	GTCP331-500	1.3 ± 0.63 (0.5 - 2.2)	3.0 ± 0.87 (bdl - 4.5)	4.6 ± 1.33 (bdl - 6.9)

Comparison of measurement results in different parts of the exhaust plume and with ICAO databank

Aircraft	No for CO	EI CO [g/kg]				No for NO_x	EI NO_x [g/kg]			
		FTIR Em. spectr.	FTIR Abs. spectr.		ICAO		FTIR Em. spectr.	DOAS		ICAO
DHC 8Q	29	8.9	17.27		None	11	1.25	3.41		None
Fokker 70	20	23.1	32.33		24.10	24	0.3	2.08		2.50
RJ	15	38.27	23.16		42.60	15	1.0	2.64		3.82
MD80	5	10.3	28.32		17.84	5	Bdl	2.84		4.18
A320	50	41.7	40.72		30.07	40	0.95	2.76		4.35
A340	3	6.0	17.79		32.98	2	Bdl	1.83		4.23
B737	14	31.46	36.16		26.95	13	1.25	2.91		4.48
B747	9	23.6	25.45		15.03	7	0.3	2.93		4.56
B757	15	8.8	15.47		17.90	13	0.65	3.43		3.67
B767	3	7.3	25.09		11.75	3	-	3.18		4.09
B777	6	24.6	43.34		13.67	5	0.4	3.44		6.01

Conclusions

The presented methods are a tool to determine EI:

Schäfer, K., Jahn, C., Sturm, P., Lechner, B., Bacher, M.: Aircraft emission measurements by remote sensing methodologies at airports. Atmospheric Environment 37, 37 (2003), 5261-5271

EI for idle conditions under in-use conditions in comparison to ICAO data base: EI(CO) higher, EI(NO_x) slightly smaller

Idle during operational conditions unequal to ICAO definition

APU emissions cannot be neglected at airports

For better conclusions, more measurements are necessary for a statistical treatment of the data

Improvement of measurement technique

Passive FTIR emission spectrometry has also the capability to determine the composition of hot exhausts but also the plume behaviour non-intrusively

Are there inhomogeneous distributions along the plume i.e. temporal variations in the measurement volumes?

SIGIS: Instrumentation improved to detect exhausts composition of aircraft on the ground nearly automatically

Spectrometer OPAG coupled with an IR camera: rapid selection of the hottest exhaust area is possible

Imaging of the scenery behind the turbine with the scanning mirror:

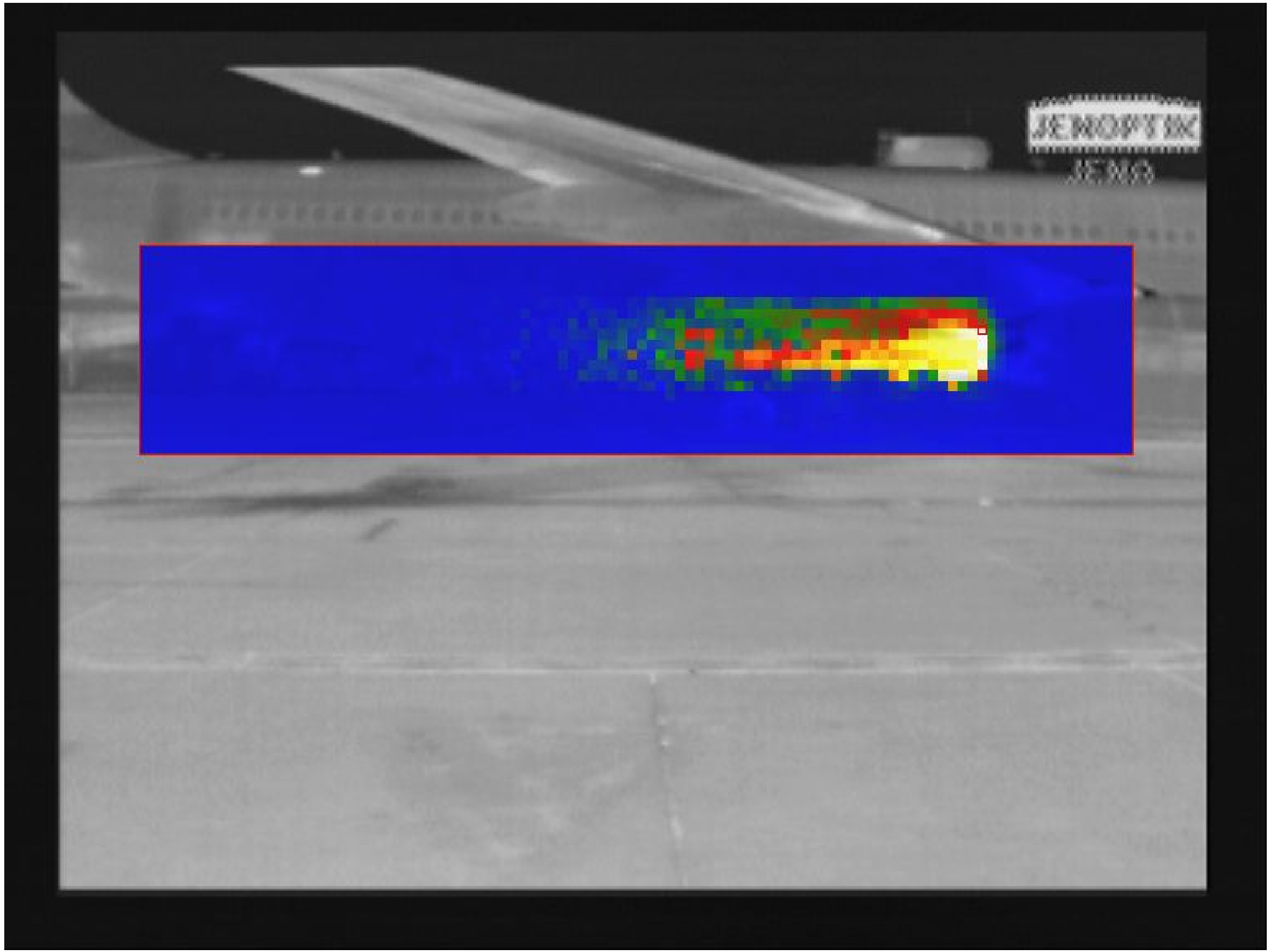
- low-resolution spectra are measured and analysed in a spectral range which is sensitive for plume temperature

- software for real-time visualisation of the plume shape in this spectral range

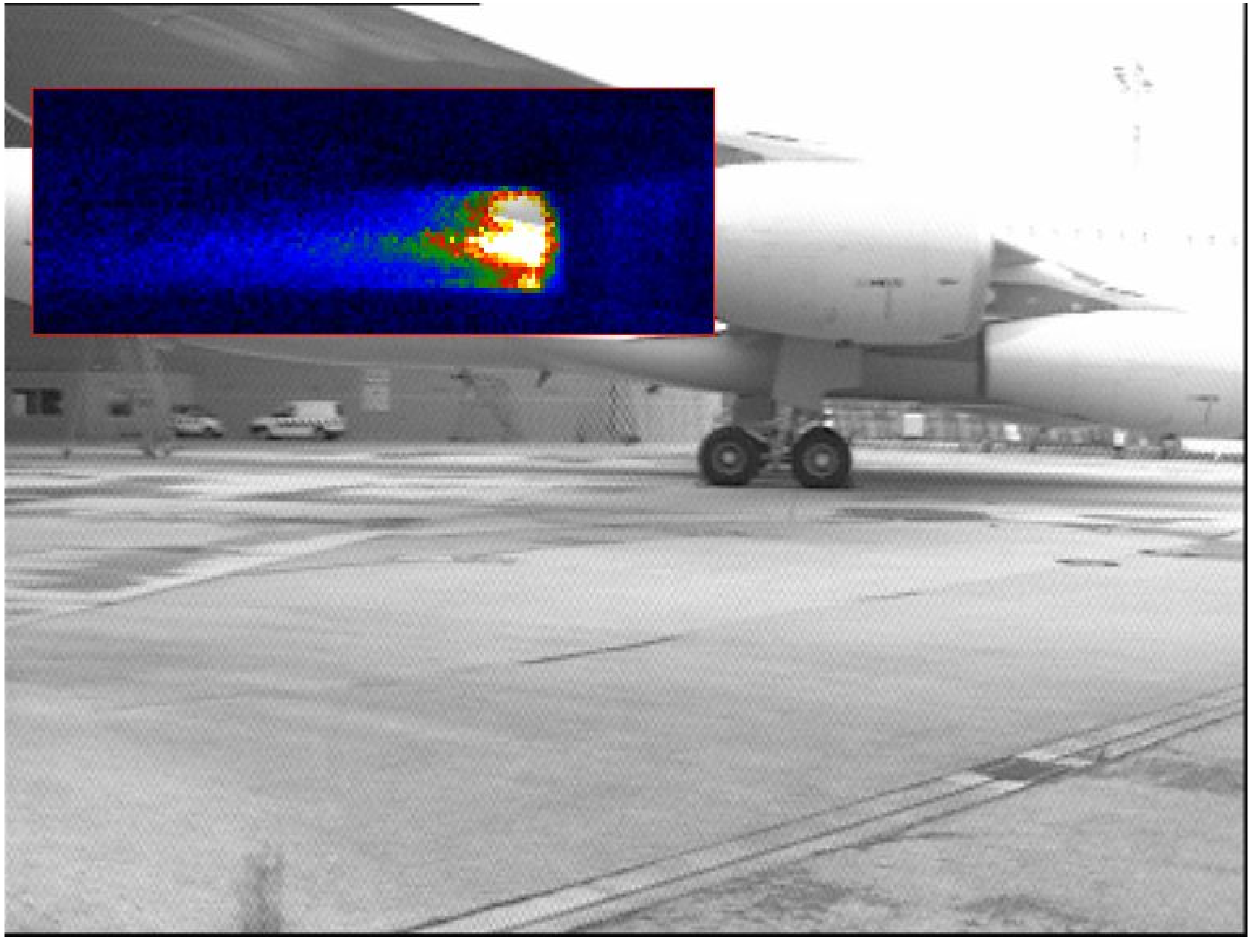
Aircraft, main engine PW4168A: IR camera picture

Main engine: gas temperature mode

approximated length 11 m, diameter 2.4 m

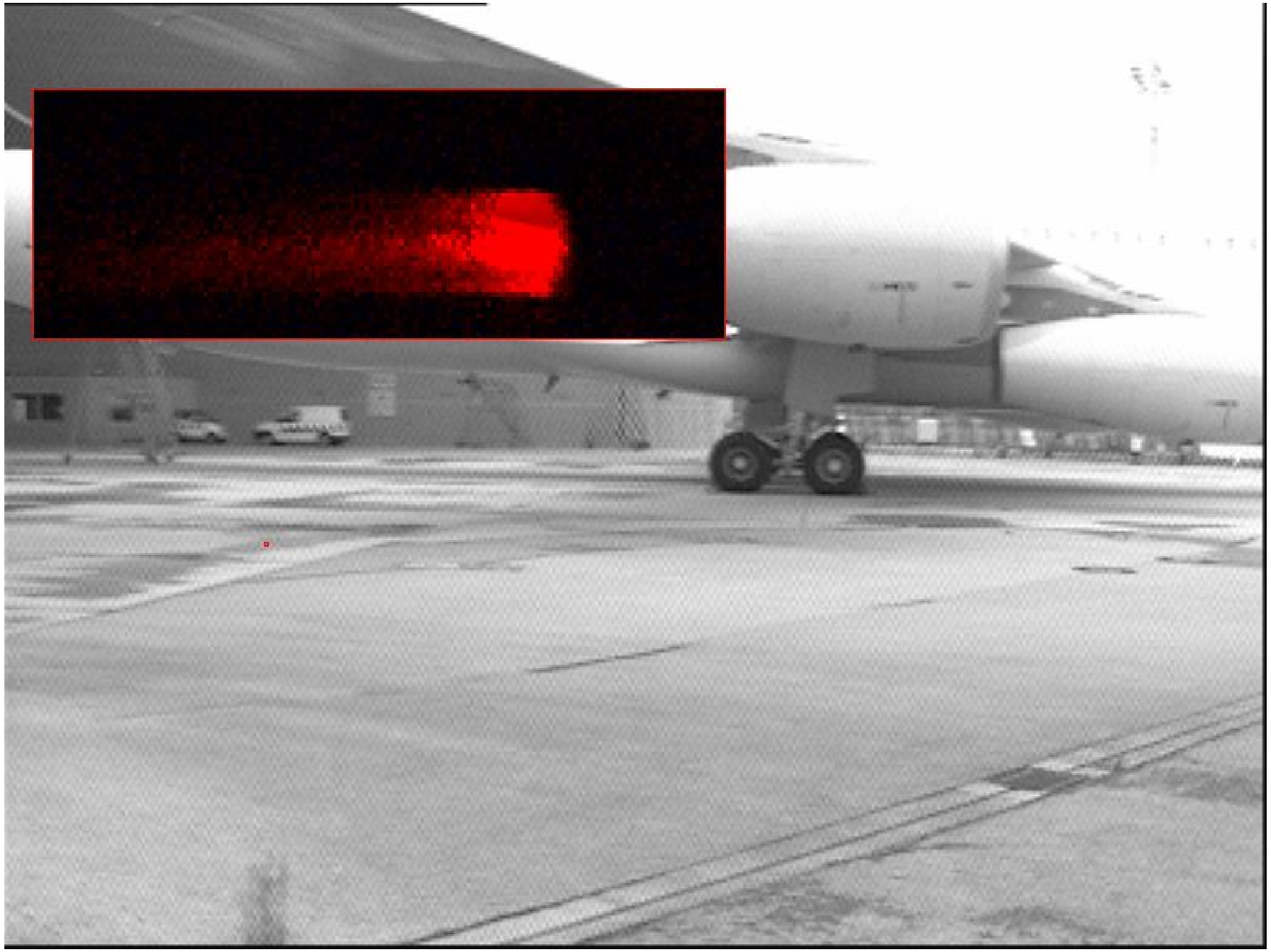


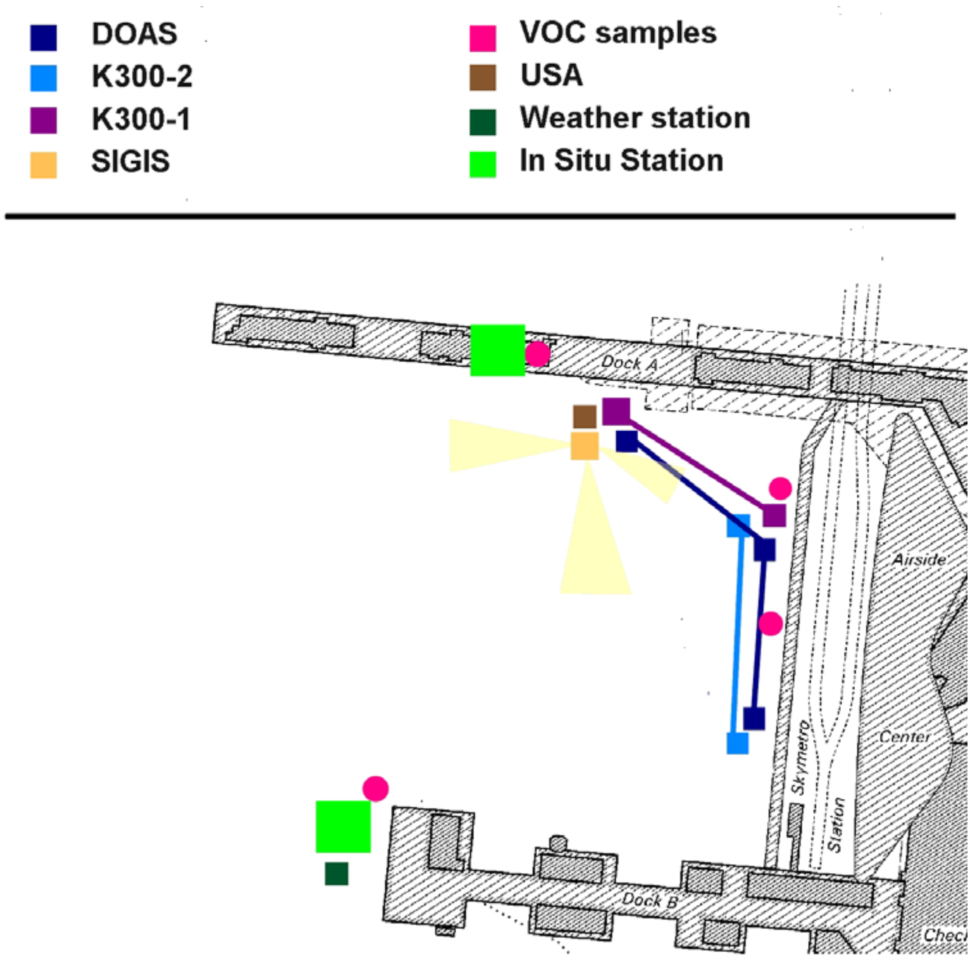
Aircraft, main engine CFM56-5C2F: gas temperature mode asymmetry, approximated plume length 8.4 m



Main engine: gas radiation mode (absorption / emission)

approximated length of hottest part 3.8 m, diameter 1.4 m





Schürmann, G., Schäfer, K., Jahn, C., Hoffmann, H., Bauerfeind, M., Fleuti, E., Rappenglück, B.: The impact of NO_x, CO and VOC emissions on the air quality of the airport Zurich. Atmospheric Environment 41 (2007), 103-118, doi:10.1016/j.atmosenv.2006.07.030.

Airport air pollution

Zuerich July 2004

Following the definitions the air quality is good

But during periods of high air traffic at the apron area the air quality is moderate only

Results

- Reactive C_2–C_3 alkenes in significant amounts in the exhaust of an engine compared to ambient levels

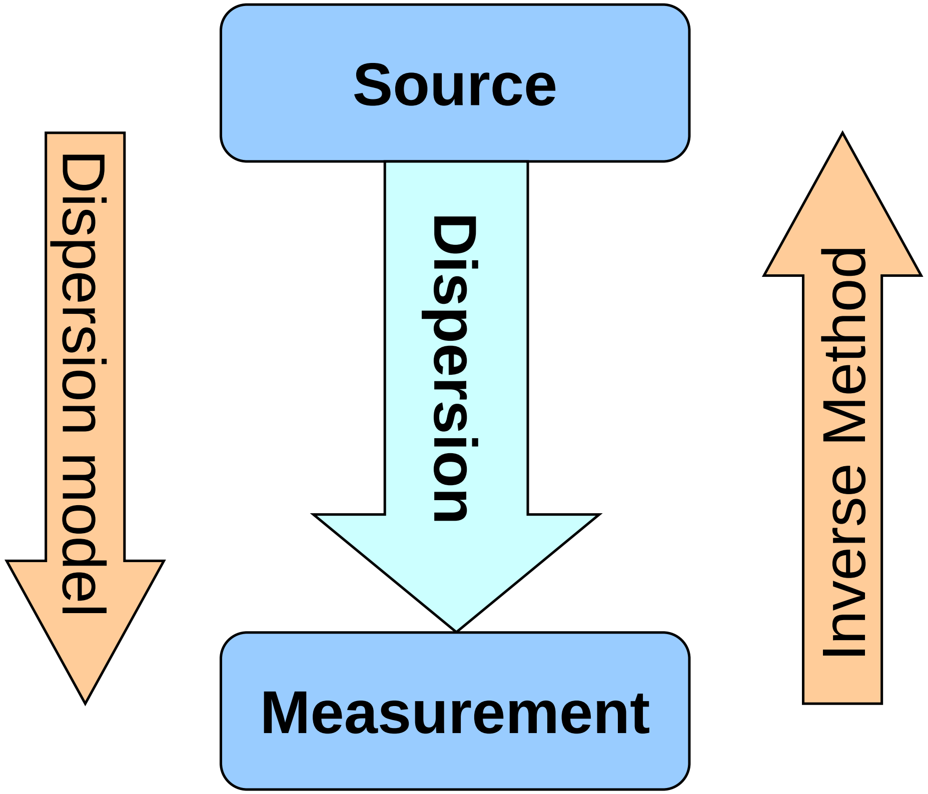
- Also, isoprene, a VOC commonly associated with biogenic emissions, in the exhausts

- Benzene to toluene ratio used to discriminate exhaust from refuelling emission:

  In refuelling emissions the ratio was well below 1

  For exhaust this ratio was usually about 1.7

Inverse dispersion modelling



Source

Dispersion

Measurement

Dispersion model

Inverse Method

Dispersion matrix by modelling with the Lagrangian model Austal2000 from Janicke

Emission rates for NO on the taxiway 4.4 up to 146 mg/s, parking places 1.6 up to 357 mg/s

CO emission rates for taxiing aircrafts 0.4 up to 7.5 g/s,

parking places 0.01 up to 0.35 g/s

NO_2 on the taxiway 13 mg/s up to 90 mg/s, parking places

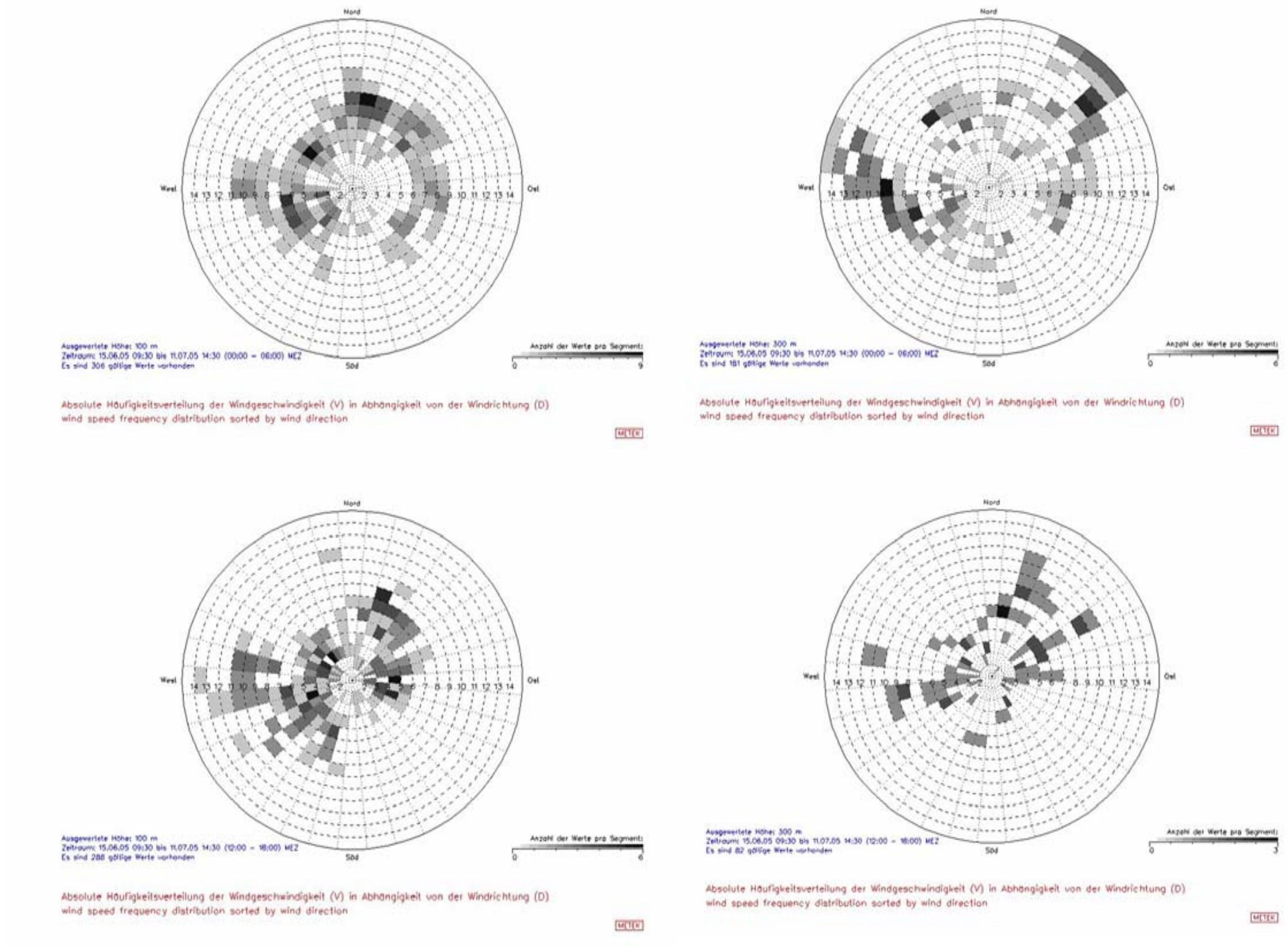
0.25 mg/s up to 113 mg/s

Meteorological measurement tasks at Paris CDG

Altitude profiles of turbulence and wind were measure by the METEK DSD3x7 mono-static Doppler SODAR: three antennas, each including seven sound transducers

Averaged every 30 minutes, vertical resolution 20 m, minimum height 40 m and maximum height is 800 m above ground

Wind speed resolving wind roses for 100 m (left) and 300 m (right) above ground for night-time (0 to 6 hours GMT+1, top) and daytime (12 to 18 hours) bottom



Ausgewertete Höhe: 100 m
Zeitraum: 15.06.05 09:30 bis 11.07.05 14:30 (00:00 – 06:00) MEZ
Es sind 306 gültige Werte vorhanden

Absolute Häufigkeitsverteilung der Windgeschwindigkeit (V) in Abhängigkeit von der Windrichtung (D)
wind speed frequency distribution sorted by wind direction

Ausgewertete Höhe: 300 m
Zeitraum: 15.06.05 09:30 bis 11.07.05 14:30 (00:00 – 06:00) MEZ
Es sind 181 gültige Werte vorhanden

Absolute Häufigkeitsverteilung der Windgeschwindigkeit (V) in Abhängigkeit von der Windrichtung (D)
wind speed frequency distribution sorted by wind direction

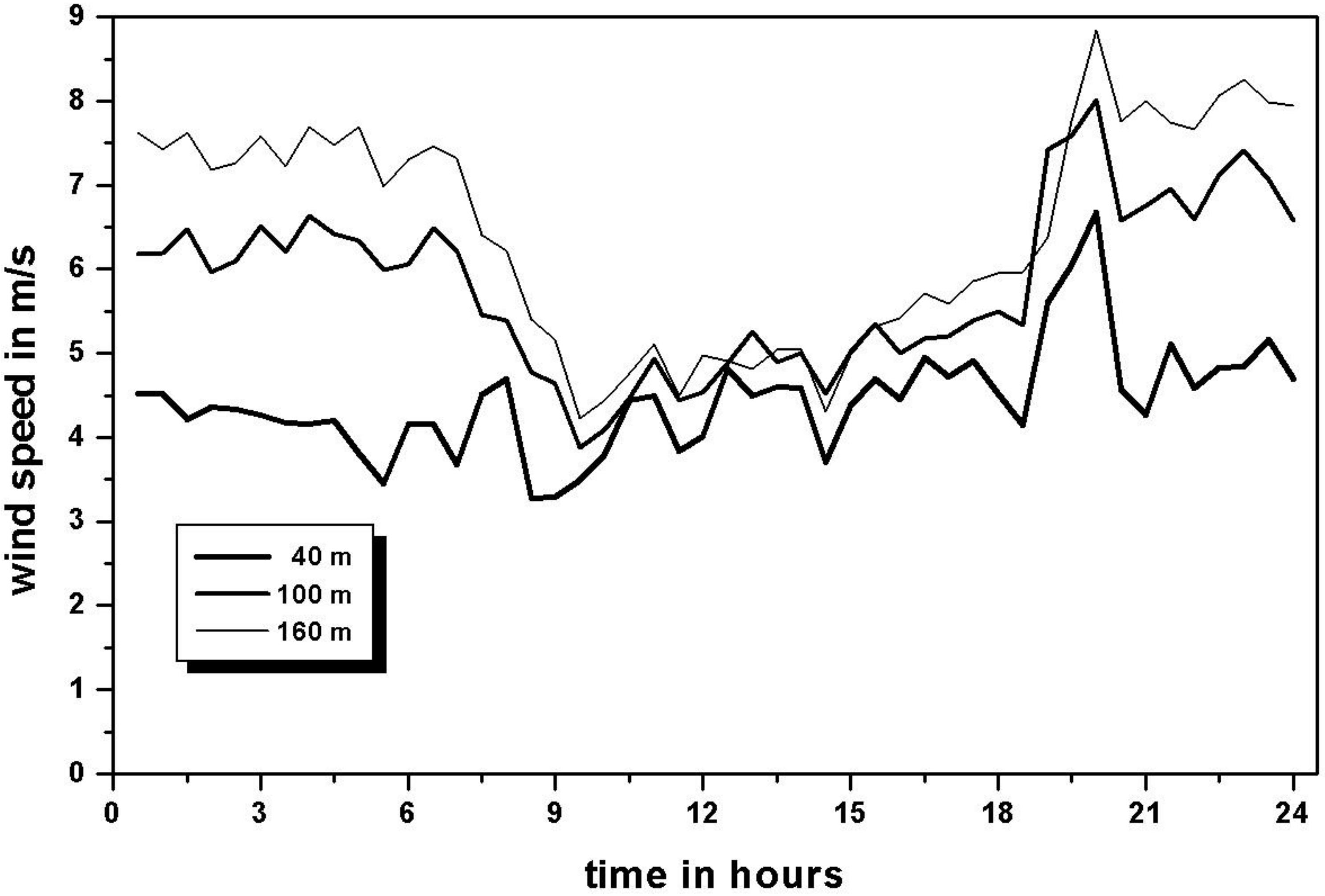
Ausgewertete Höhe: 100 m
Zeitraum: 15.06.05 09:30 bis 11.07.05 14:30 (12:00 – 18:00) MEZ
Es sind 288 gültige Werte vorhanden

Absolute Häufigkeitsverteilung der Windgeschwindigkeit (V) in Abhängigkeit von der Windrichtung (D)
wind speed frequency distribution sorted by wind direction

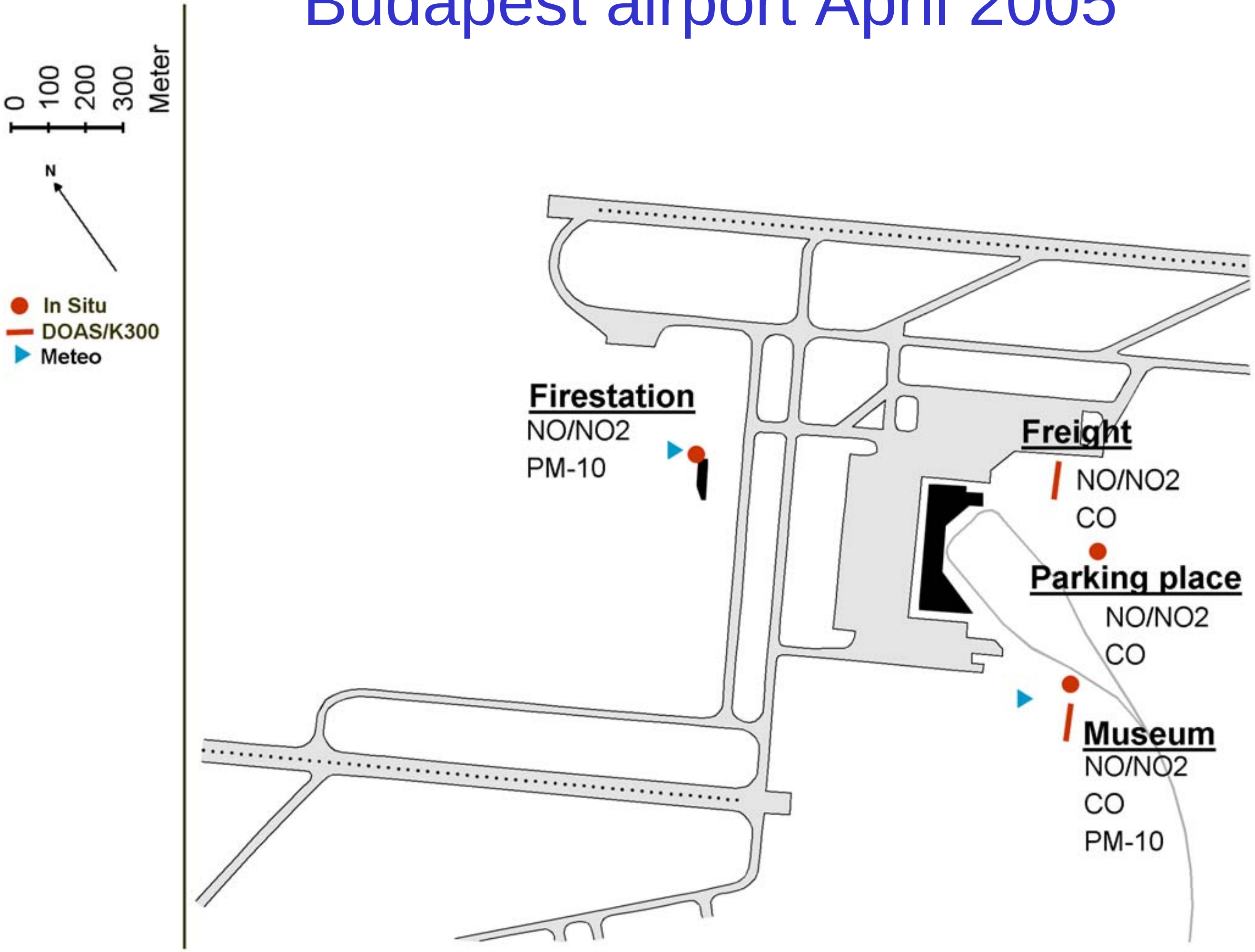
Ausgewertete Höhe: 300 m
Zeitraum: 15.06.05 09:30 bis 11.07.05 14:30 (12:00 – 18:00) MEZ
Es sind 82 gültige Werte vorhanden

Absolute Häufigkeitsverteilung der Windgeschwindigkeit (V) in Abhängigkeit von der Windrichtung (D)
wind speed frequency distribution sorted by wind direction

Mean daily courses



Budapest airport April 2005



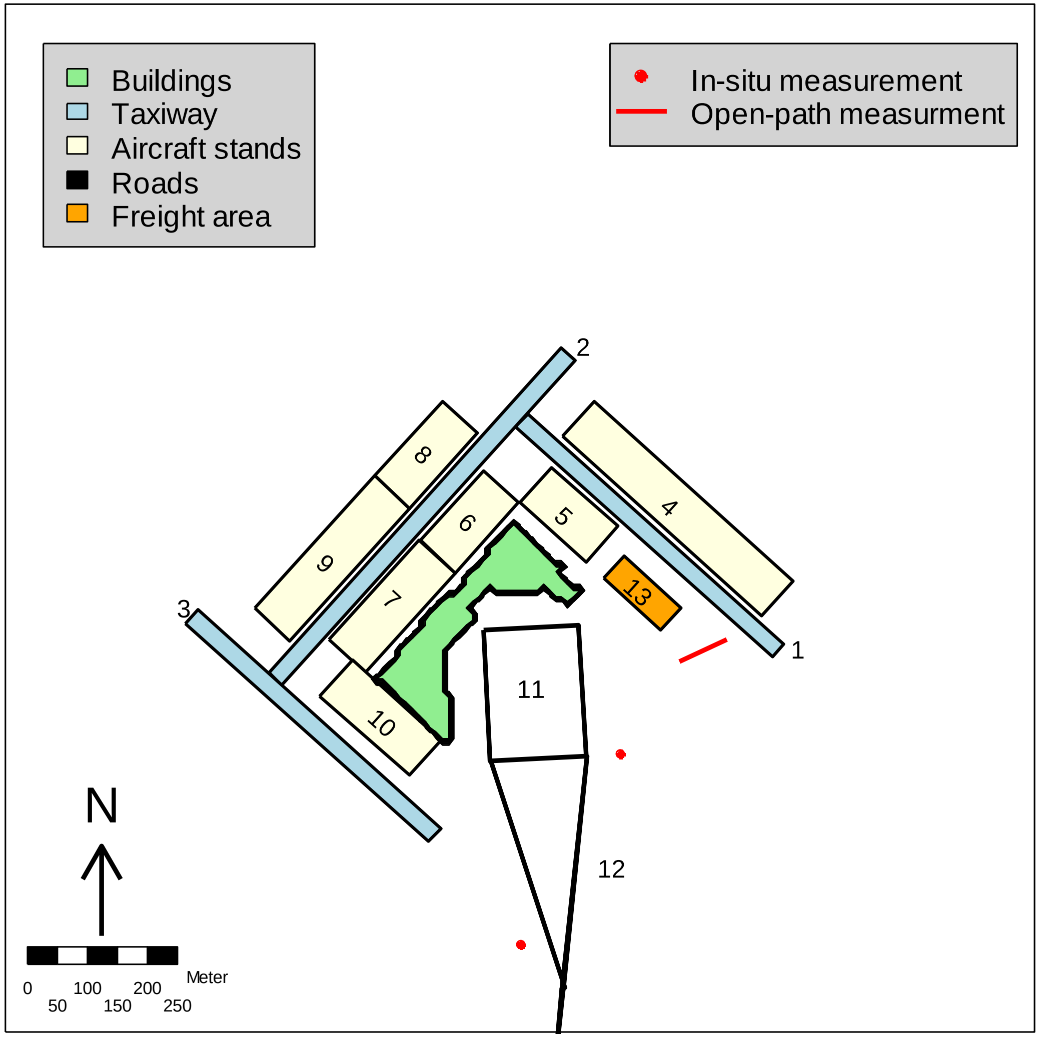
More sources than measurements
=>
Use of a-priori knowledge within the inverse procedure

Firestation as background measurement

<u>NO/NO$_2$</u>
DOAS, TE42-95, TE42-96, AC-31M
<u>CO</u>
K300-1, K300-2, AL5001
<u>PM10</u>
FH62 I-R, FH62 I-N

Meteorological measurements
Detailed observations of aircraft movements and handling activities

Inverse dispersion modelling

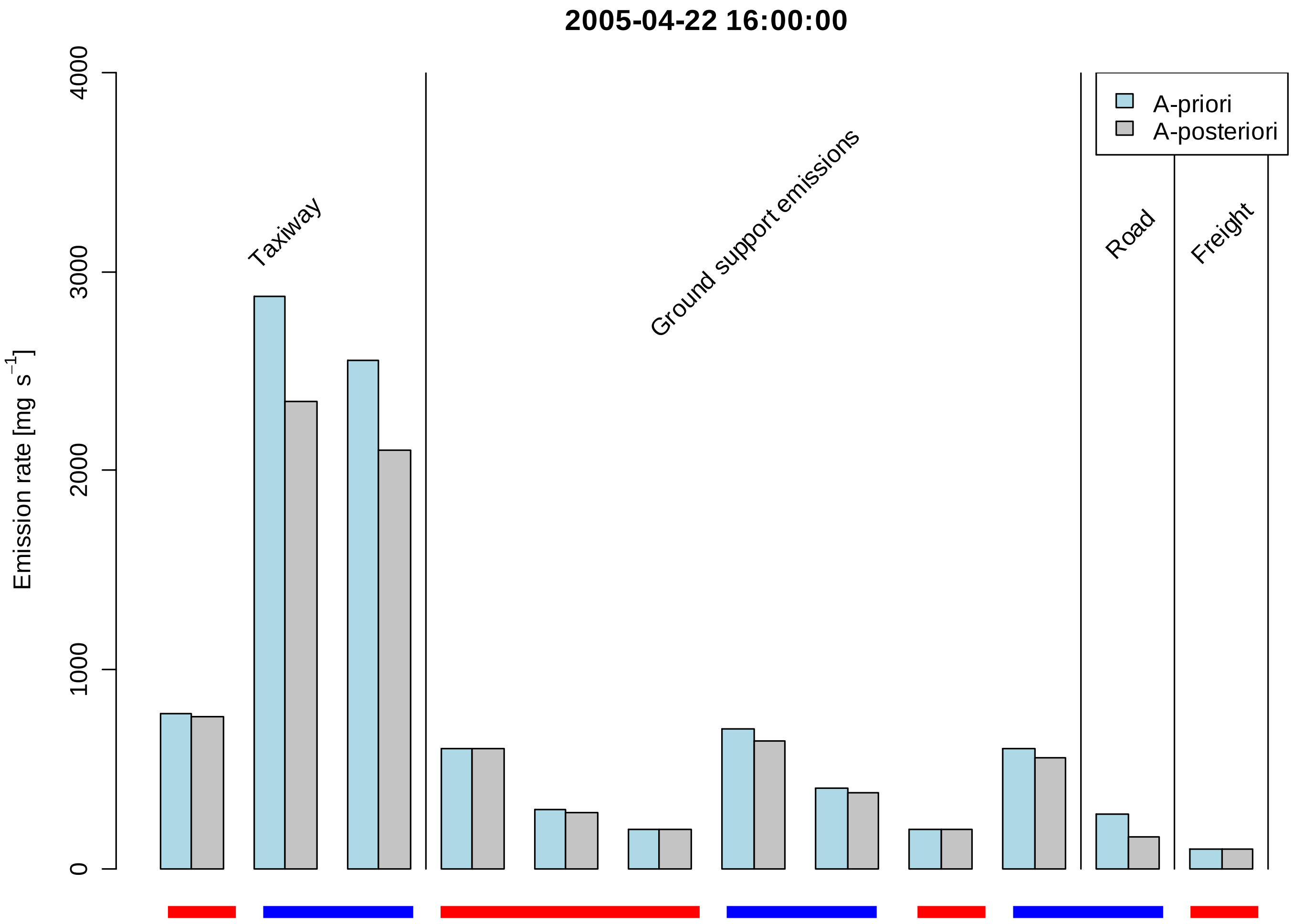


Bayesian statistics is used to solve the inverse problem: on the basis of hourly averaged concentration measurements

All kind of emissions on the airport Budapest show very high temporal variability

The traffic itself on the airport is highly variable

Results



Highest concentrations during low wind speed conditions downwind of the airport

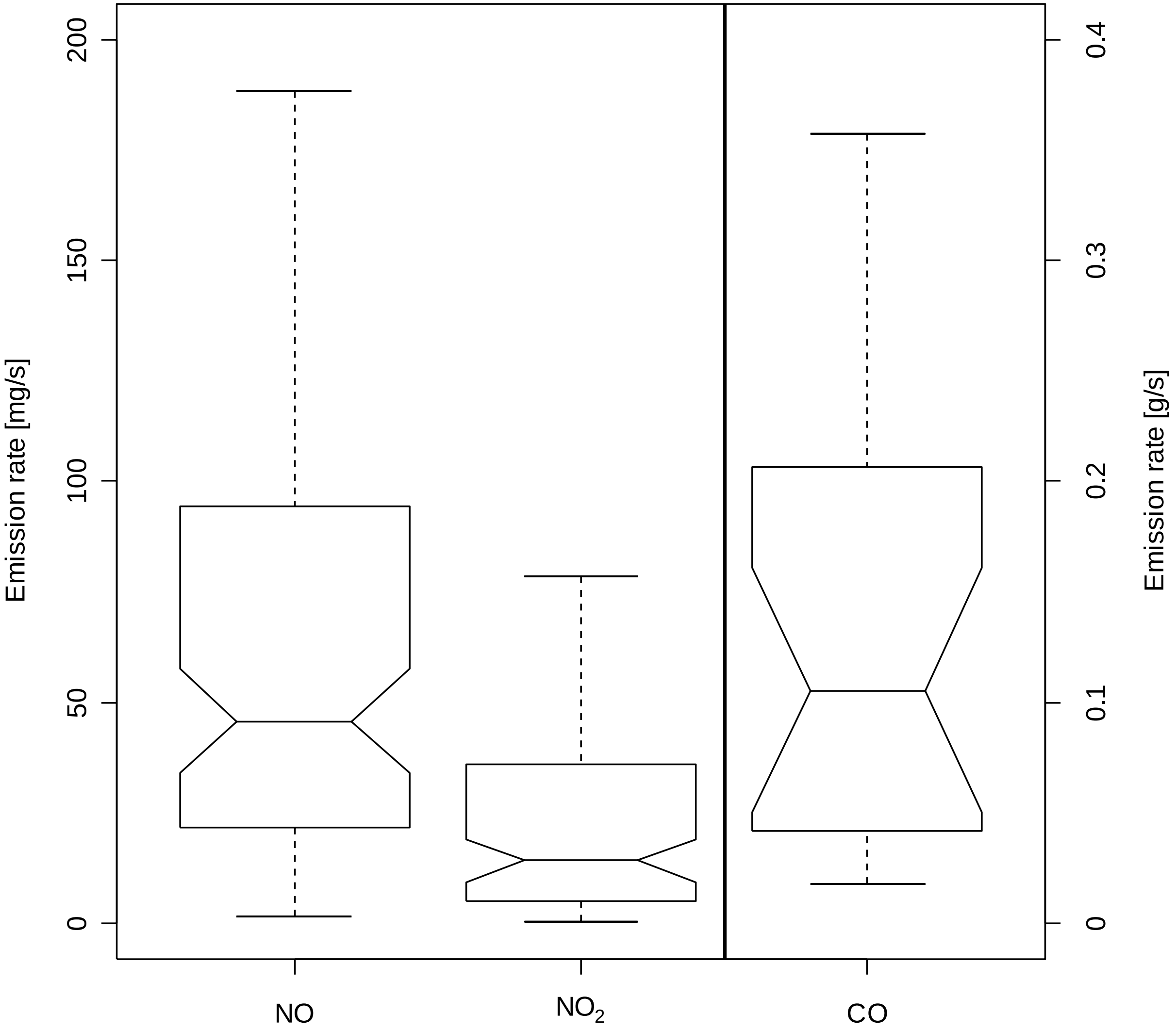
Reliable background measurements are required

3 taxiways, 7 aircraft stands, 1 road, 1 freight area

A-priori dominates results, if no measurement are available

Adjustment of a-priori, if measurements are available

Ground support emissions



Comparison with aircraft emissions:

CO is a factor of 10 lower

NO and NO_2 with comparable emission levels

=>

CO originates mainly from aircrafts while NO_x is caused by aircrafts and all other sources

Conclusions

Overall, emissions of taxiing aircrafts were the most important sources for NO_x around Terminal 2 during the measurement campaign

Freight and car park emissions reach similar emission levels

But emissions on runways were not considered because they were not located in the measurement area

It is well known, that NO_x emissions of an aircraft are highest during take-off

Future activities

- EU-network of excellence ECATS (Environmentally Compatible Air Transport System):
  - Capability gap analyses
  - Capability enhancement
  - Research initiatives
  - Education
- Research projects: 7th Framework Program of the EC

Acknowledgements

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During these investigations we worked successfully together with Roland Harig and Peter Rusch (Arbeitsbereich Messtechnik, Technische Universität Hamburg-Harburg, Hamburg), Peter Sturm, Bernhard Lechner and Michael Bacher (Institut für Verbrennungskraftmaschinen und Thermodynamik, Technische Universität Graz, Graz), Szabina Török and Veronika Groma (Health and Environmental Physics, KFKI Atomic Energy Research Institute, Budapest, Hungary) as well as Richard Ramaroson (ONERA)

Acknowledgements

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Without this co-operation no reliable investigations would have been possible