Online Determination of “Aircraft Engine Nanoparticle Emission Indices” at Zurich Airport, Switzerland

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In a cooperation of German Aerospace Center (DLR - Stuttgart), Federal Office for Civil Aviation (FOCA – Bern, Switzerland) and Unique Flughafen Zürich AG, we did nanoparticle measurements at Zurich airport. The test equipment was positioned close to the taxiway of runway 16. If winds are from west (which is often the case), the exhaust gases of passing aircrafts are transported by wind drift to our equipment. Because of high dilution of the exhaust gases with ambient air and the transient events we used fast and sensitive devices like Engine Exhaust Particle Sizer (EEPS) and a NDIR CO_2 photometer. The size range of the EEPS is 5.6 nm to 560 nm and time resolution is 10 Hz. Time resolution of the NDIR CO_2 photometer is 1 Hz.

The so called particle Emission Index (EI_{PM}) gives the mass of nanoparticles formed during combustion of 1 kg fuel. $EI_{PM\ mass} = mg_{particles} / kg_{fuel}$. The Emission Index is a clear indicator for the quality of a combustion process! To determine an Emission Index by CO_2 concentration measurement, it is necessary to know the carbon mass content of the fuel. The fuel normally used in civil passenger aircrafts is kerosene called JET-A1. Due to the strict specifications, the mass ratio of carbon to hydrogen is nearly constant. Therefore, burning of 1 kg of Jet-A1 forms always 3.16 kg of CO_2 (+- 3%). To determine an $EI_{PM,}$ it is necessary to measure the CO_2 concentration and particle concentration in parallel. Under stationary conditions this is normally no problem. In our case of highly transient events, both instruments must be fast enough to detect the maximum of the peaks. The Emission Indices can be calculated independent from exhaust gas dilution. It is assumed that CO_2 and particles are diluted always by the same factor.

The aerosol background at Zurich airport is very low. Therefore for nearly all passing aircrafts the corresponding particle cloud could be identified. (The nose is also a good detector. Whenever we smelled exhaust gas, we also had clear signals in CO_2 and particles.)
We calculated Emission Indices for particle mass as well as for particle number. The measured range of values is

$EI_{particle\ mass} = 53 - 214\ mg_{PM} / kg_{fuel}$ $EI_{particle\ \#} = 1.5 - 4.7\ E16\ \# / kg_{fuel}$

The geometric mean diameter measured is in the range of 9.4 to 13.5 nm, which is less than normally found at engine test rig measurements. The reason here may be the direct exhaust dilution with bypass- and fan air at engine exit.
(At rig tests, dilution is normally done at the end of the sampling line. Agglomeration takes place in the sampling line, due to high particle concentration.)

Within the “International Civil Aviation Organization (ICAO)” there is a working group called “Committee on Aviation Environmental Protection (CAEP)”. This CAEP committee developed a “First Order Approximation (FOA3)” for particle mass estimation (volatile + nonvolatile). For this PM Estimation method, values from the ICAO engine database are used (Smoke Number, UHC, Sulfur Conversion Factor, AFR, ….). Using the FOA3 method, the calculated range of values is

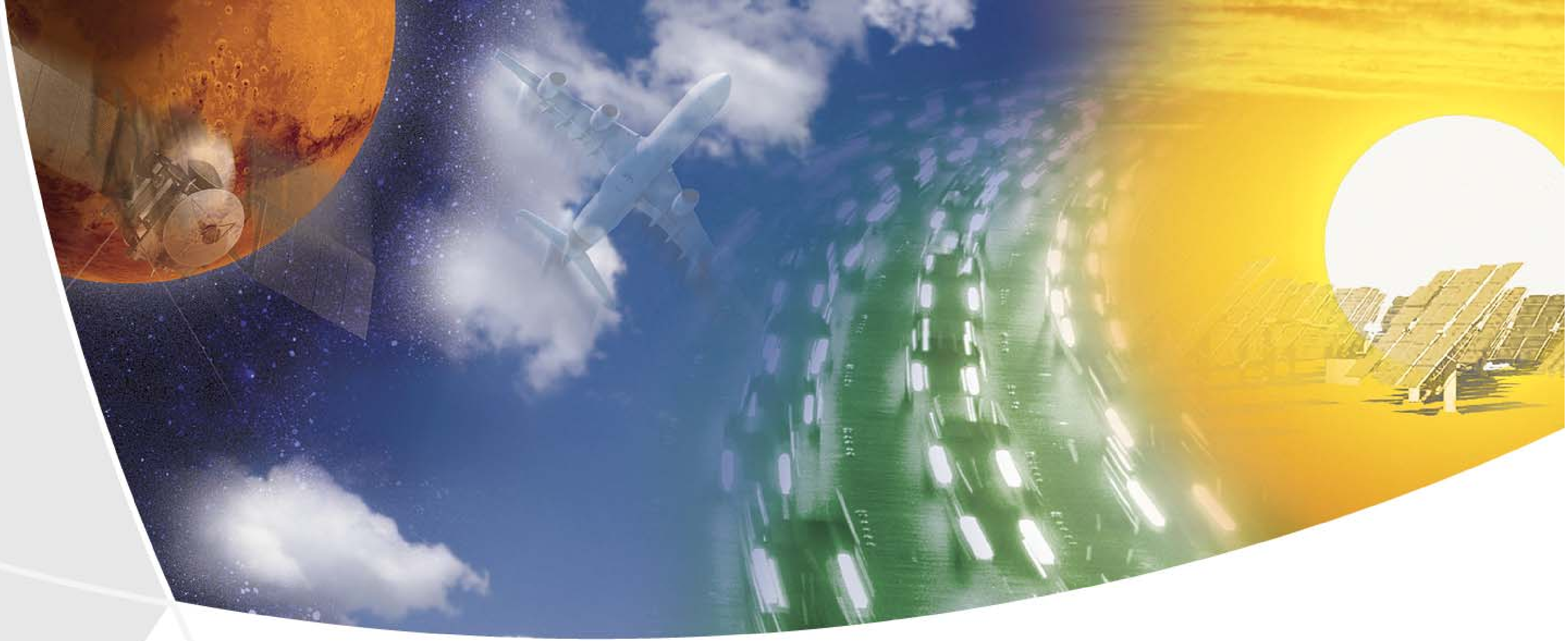
$EI_{PM\ FOA3}$ = 54 to 248 mg $_{PM}$ / kg $_{fuel}$

It should be mentioned that the engine power setting at “ICAO Taxi” is 7% of the maximum engine thrust. The real “Taxi” power setting in our measurements at Zurich is about 4% of maximum thrust.

Assignment of engine types to measured aircraft can be done on the basis of publicly available data. Our method is a simple technique to determine EI’s for the actual aircraft engine fleet.
The method should also work on streets with low “car frequency” to get EI’s for the actual car fleet.

The authors want to thank Peter Frei and Emanuel Fleuti of UNIQUE Flughafen Zürich AG for making this measurements possible.

Please do not use this results out of the context of this presentation, due to the big error bars in CO_2 measurements (+- 20%) and the mentioned limitations.



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13th ETH Conference on Combustion Generated Nanoparticles

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#Bundesamt für Zivilluftfahrt BAZL
Abteilung Luftfahrtentwickung


SWISS

Why Emission Index? EI = mg pollutant / kg burned fuel

- clear indicator for combustion quality
- to compare combustion concepts
- to calculate total emissions into the atmosphere

Particle Measurement in Aircraft Engine Exhaust Plumes close to the Taxiway

- wind drift from engine exit to detector

- exhaust gas plumes of aircrafts are clearly identified (not too many aircrafts)

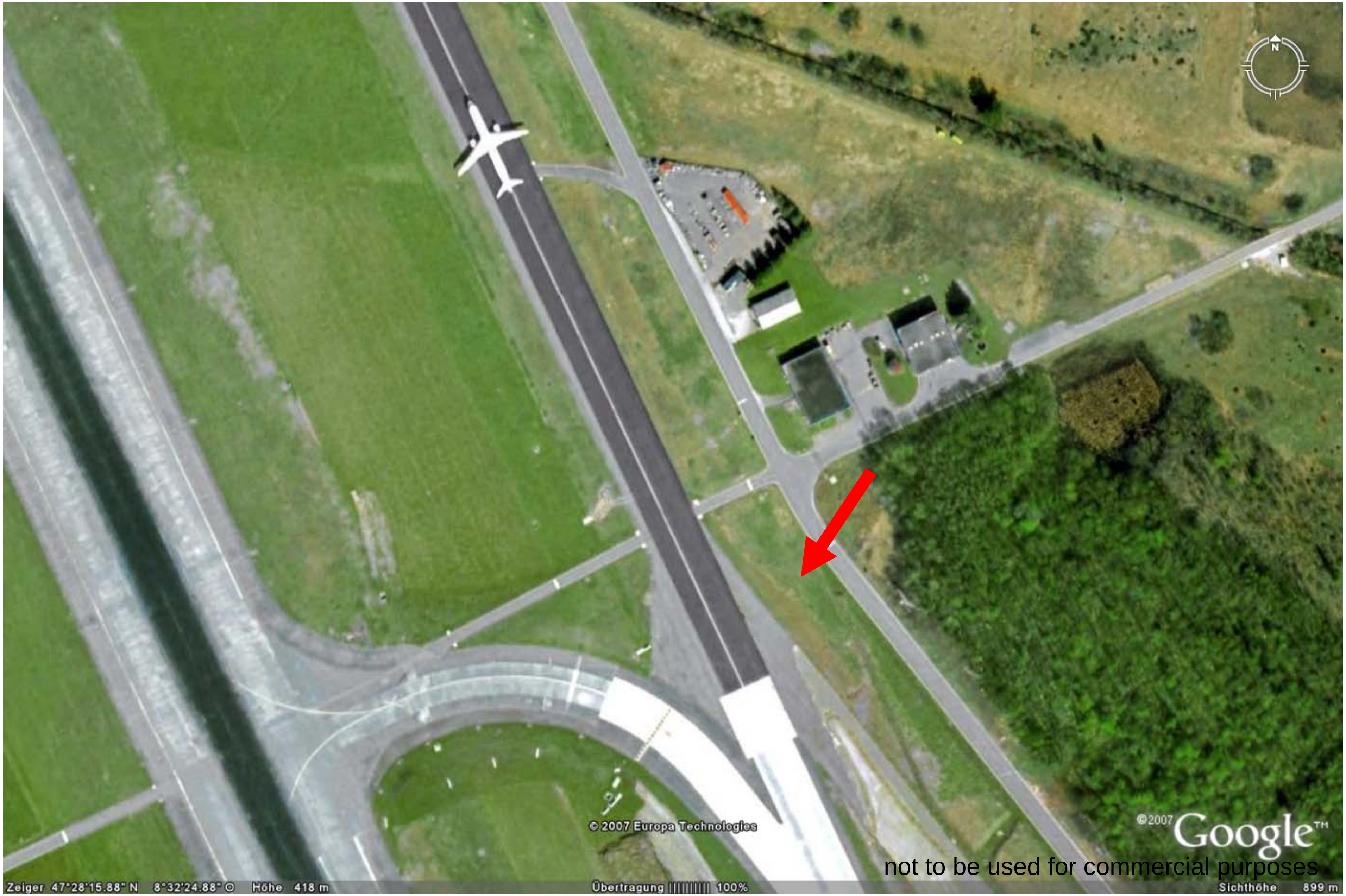
- engine type is known

- low background concentration!

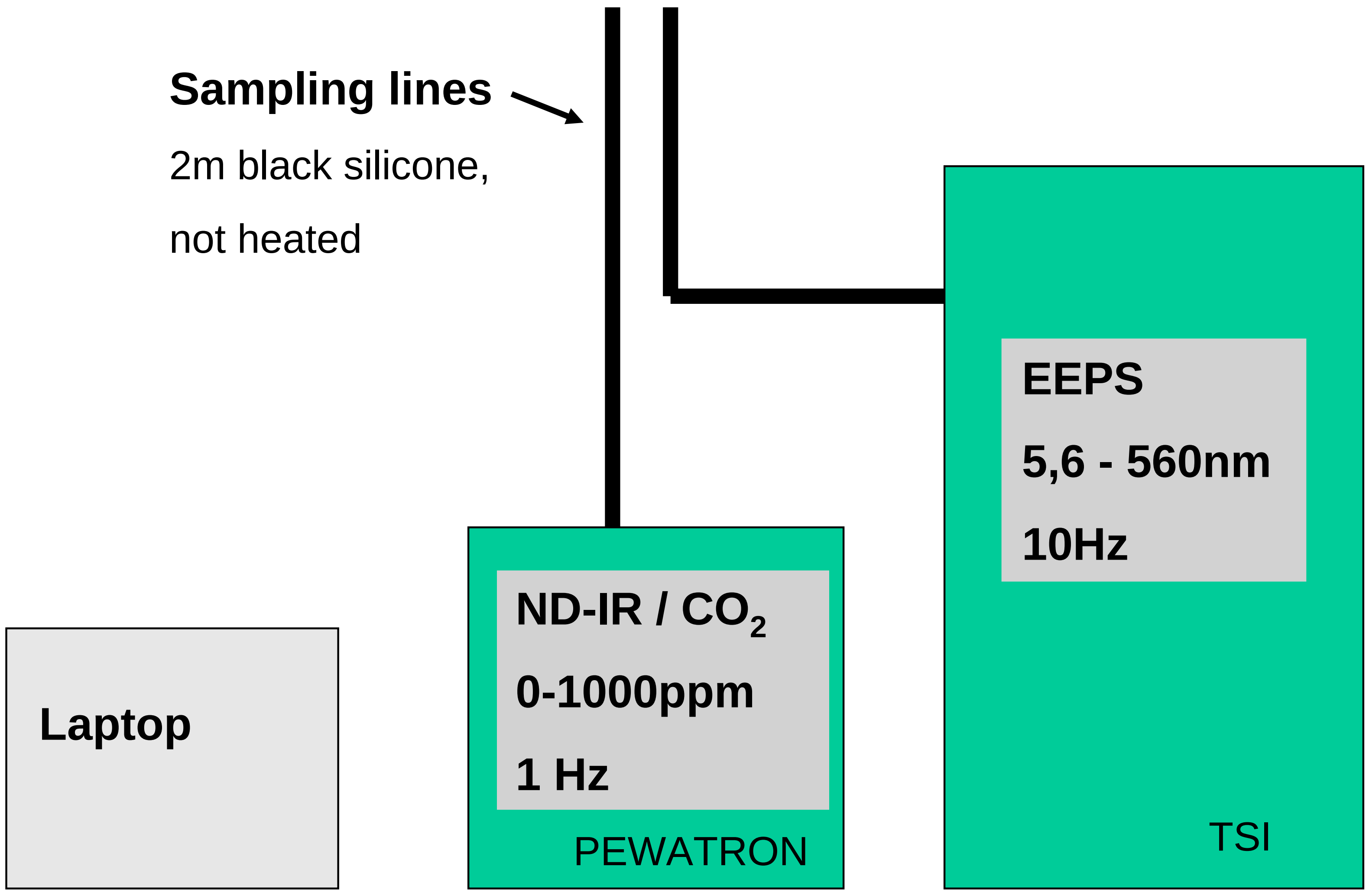
west


Oberglatt
Rümlang
Kloten
Kloten
at Zürich Airport landing fees are emission depending
not to be used for commercial purposes

east


© 2007 Europa Technologies
©2007 Google™
not to be used for commercial purposes
Zeiger 47°28'15.88" N 8°32'24.88" O Höhe 418 m
Übertragung 100%
Sichthöhe 899 m


SWISS
INSPECTOR
FOCA
16 1:07PM


Sampling lines
2m black silicone,
not heated
EEPS
5,6 - 560nm
10Hz
ND-IR / CO_2
0-1000ppm
1 Hz
PEWATRON
TSI
Laptop

Emission Index $EI = mg_{particles} / kg_{burned\ fuel}$

1 kg Kerosene JET-A1 → 862,2 g Carbon → 3,16 kg CO_2 +- 3%

1 kg JET-A1 → 1609440 m^3 exhaust gas with 1 ppm CO_2

Example:

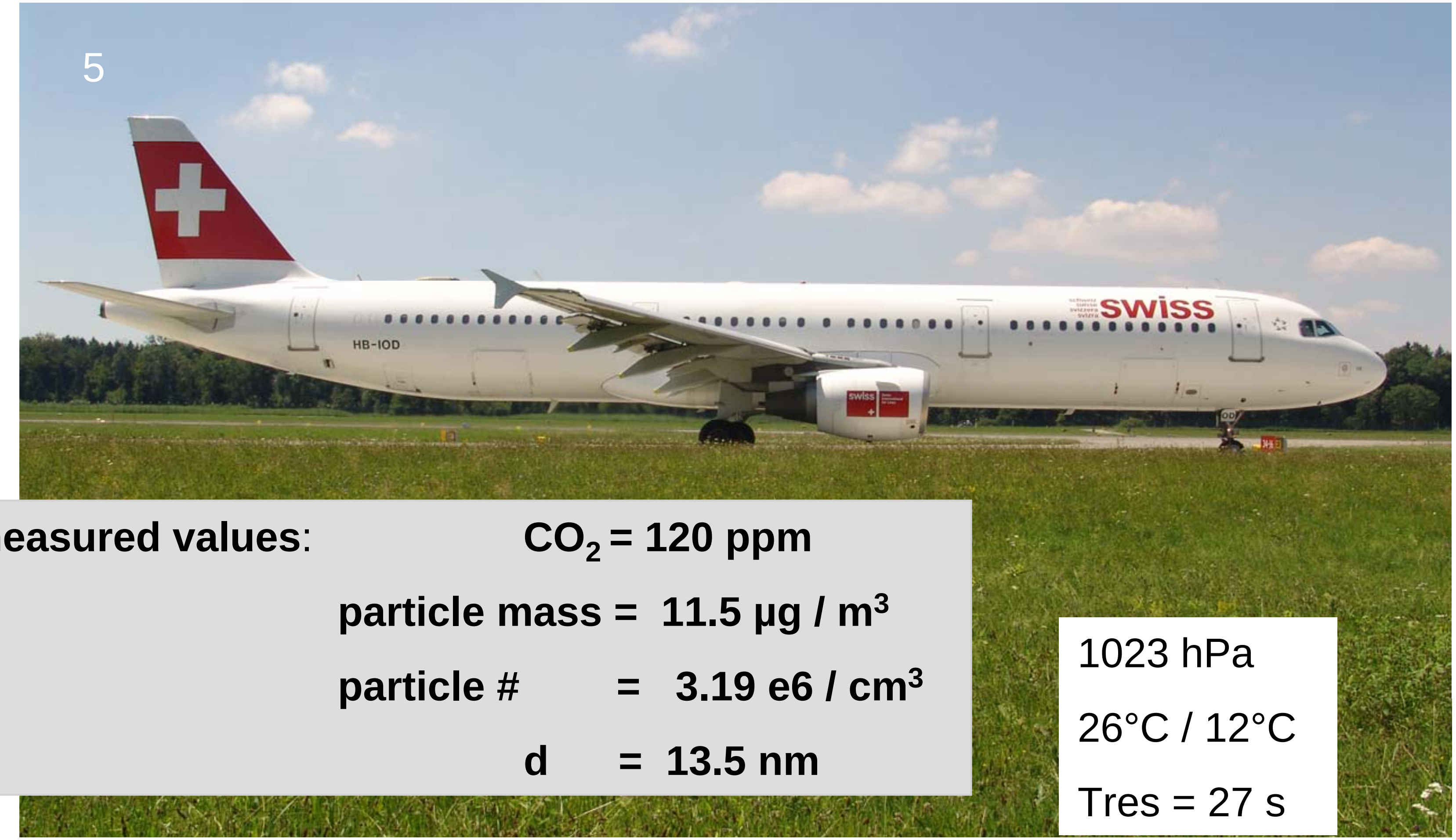
Exhaust gas volume of 1kg burned Jet-A1 containing **120 ppm CO_2** :

$V_{EX\ 120ppm}$ = 1609440 / 120 = **13412 m^3**

→ EI can be calculated by measuring pollutant and CO2 in parallel

C12 H23 “substitute formula” → 86,22 % carbon mass

Swiss Airbus - A321 fitted with CFM56-5B1/2P engines DAC



measured values: **CO_2 = 120 ppm**

particle mass = 11.5 µg / m^3

particle # = 3.19 e6 / cm^3

d = 13.5 nm

1023 hPa

26°C / 12°C

Tres = 27 s

Example: Swiss Airbus - A321 fitted with CFM56-5B1/2P engines

measured values: CO_2 = 120 ppm

particle mass = 11,5 µg / m^3

particle # = 3,18 e6 / cm^3

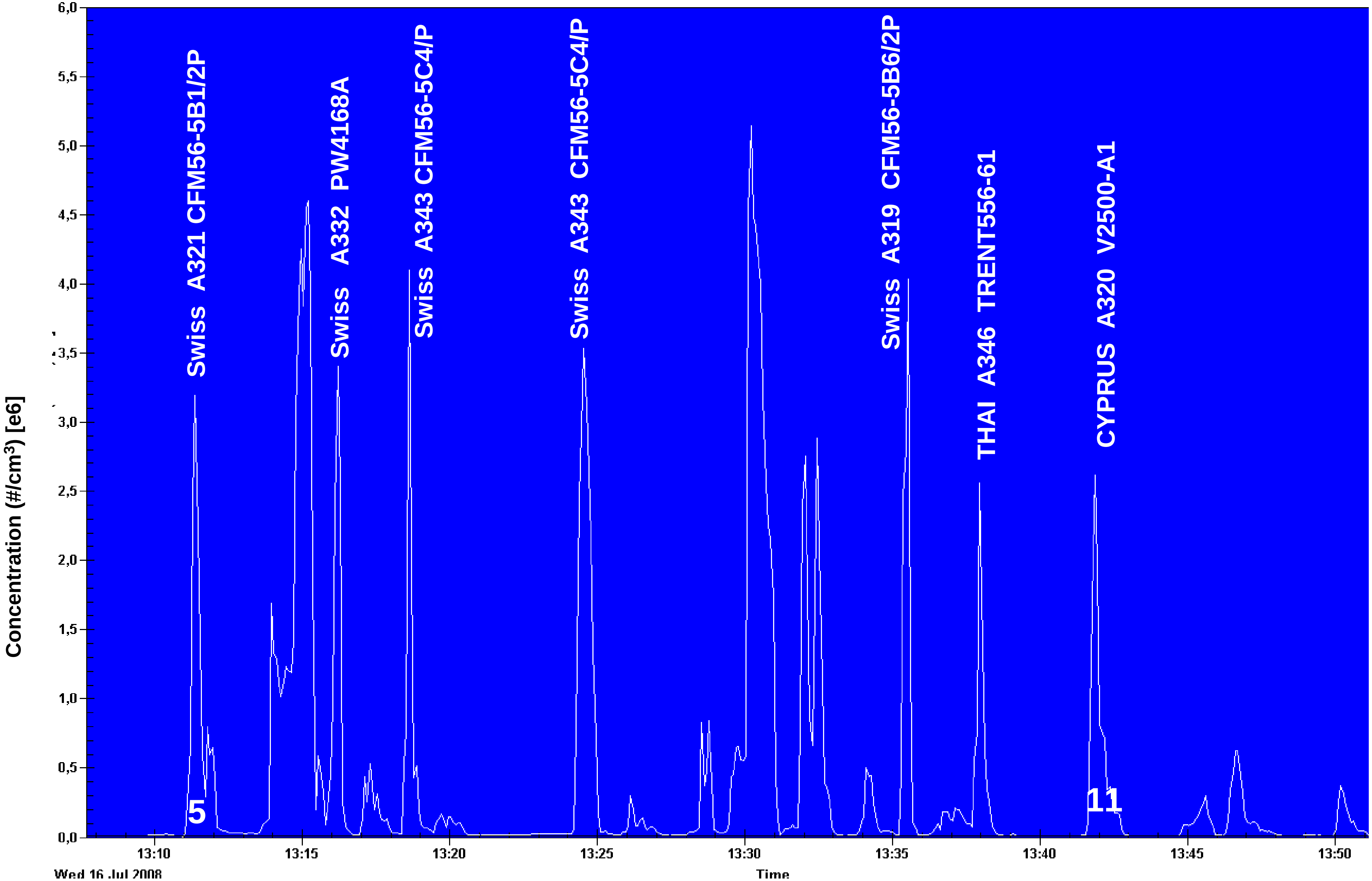
Exhaust gas volume of 1kg burned Jet-A1 containing **120 ppm CO_2** :

$V_{EX\ 120ppm}$ = 1609440 / 120 = **13412 m^3**

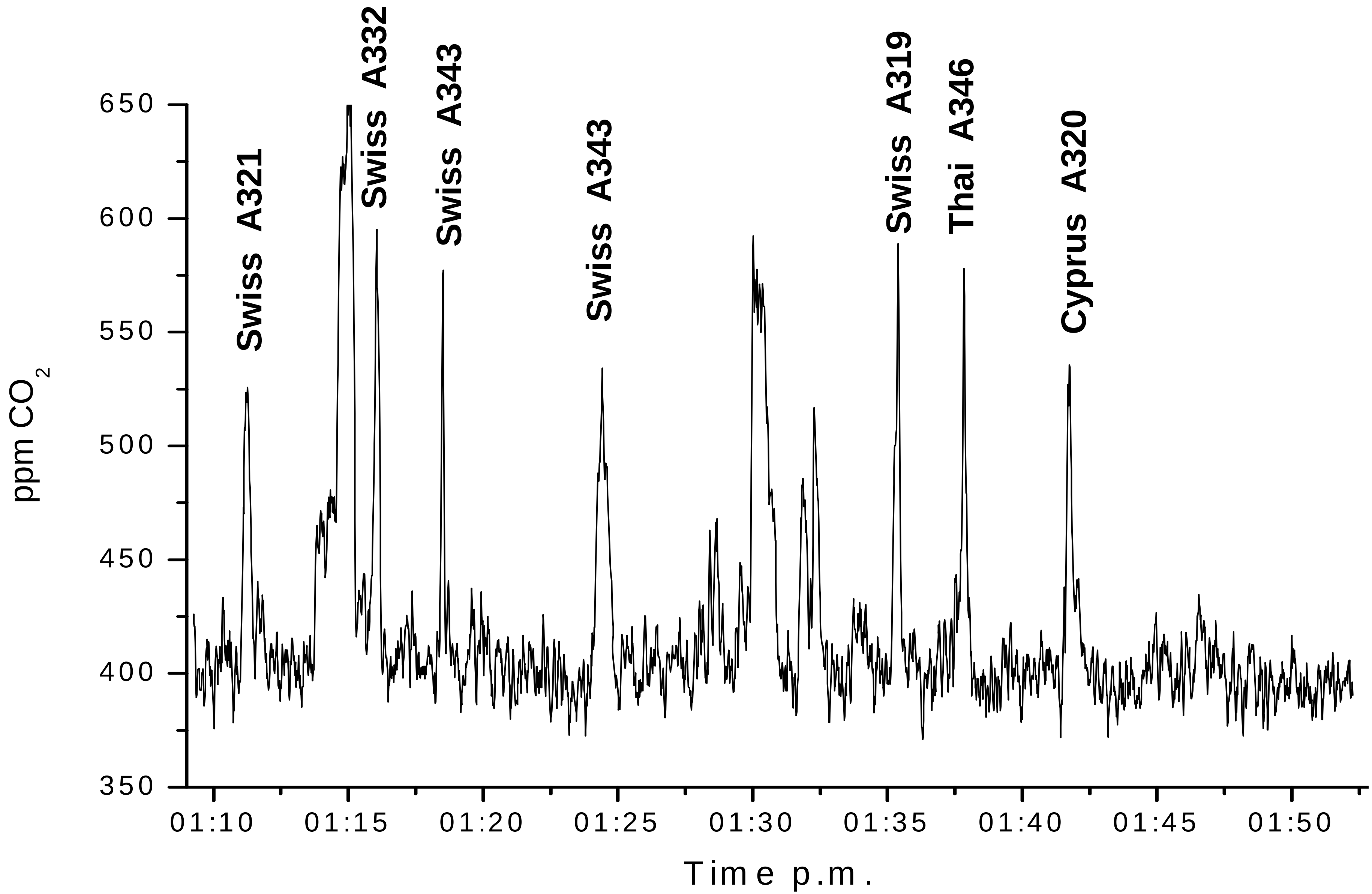
$EI_{particle\ mass}$ = 11,5 µg / m^3 * 13412 m^3 = **152 mg / kg $_{burned\ Jet\text{-}A1}$**

$EI_{particle\ \#}$ = 3,19e6 / cm3 * 13412 m^3 = **4,3 e16 / kg $_{burned\ Jet\text{-}A1}$**

method is independent from plume dilution !!

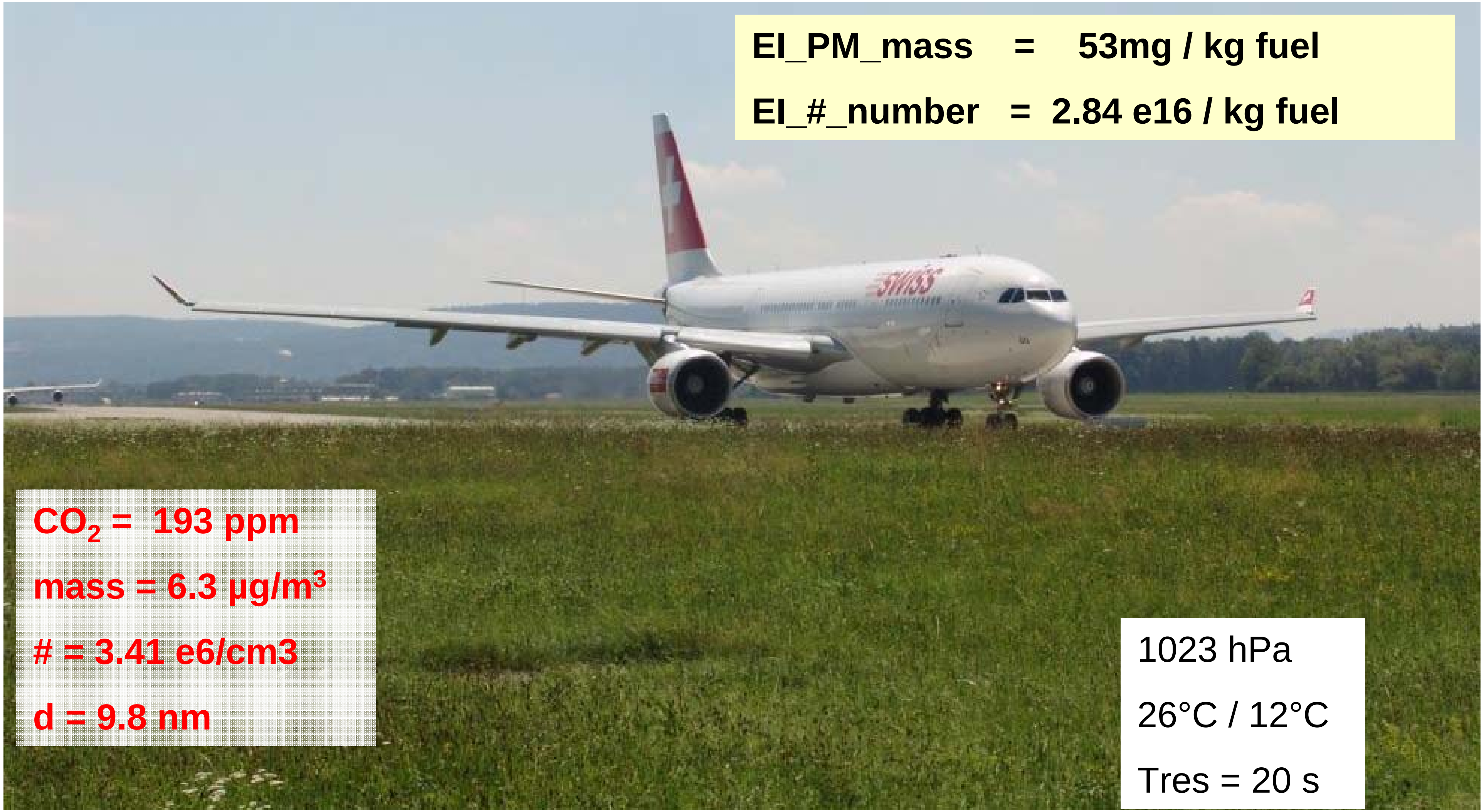


Concentration (#/cm³) [e6]
6,0
5,5
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
13:10
13:15
13:20
13:25
13:30
13:35
13:40
13:45
13:50
Wed 16 Jul 2008
Time
Swiss A321 CFM56-5B1/2P
Swiss A332 PW4168A
Swiss A343 CFM56-5C4/P
Swiss A343 CFM56-5C4/P
Swiss A319 CFM56-5B6/2P
THAI A346 TRENT556-61
CYPRUS A320 V2500-A1
5
11



Swiss A321
Swiss A332
Swiss A343
Swiss A343
Swiss A319
Thai A346
Cyprus A320
ppm CO_2
350
400
450
500
550
600
650
01:10
01:15
01:20
01:25
01:30
01:35
01:40
01:45
01:50
Time p.m.

Swiss Airbus A332 fitted with PW4168A



EI_PM_mass = 53mg / kg fuel

EI_#_number = 2.84 e16 / kg fuel

CO_2 = 193 ppm

mass = 6.3 µg/m^3

= 3.41 e6/cm3

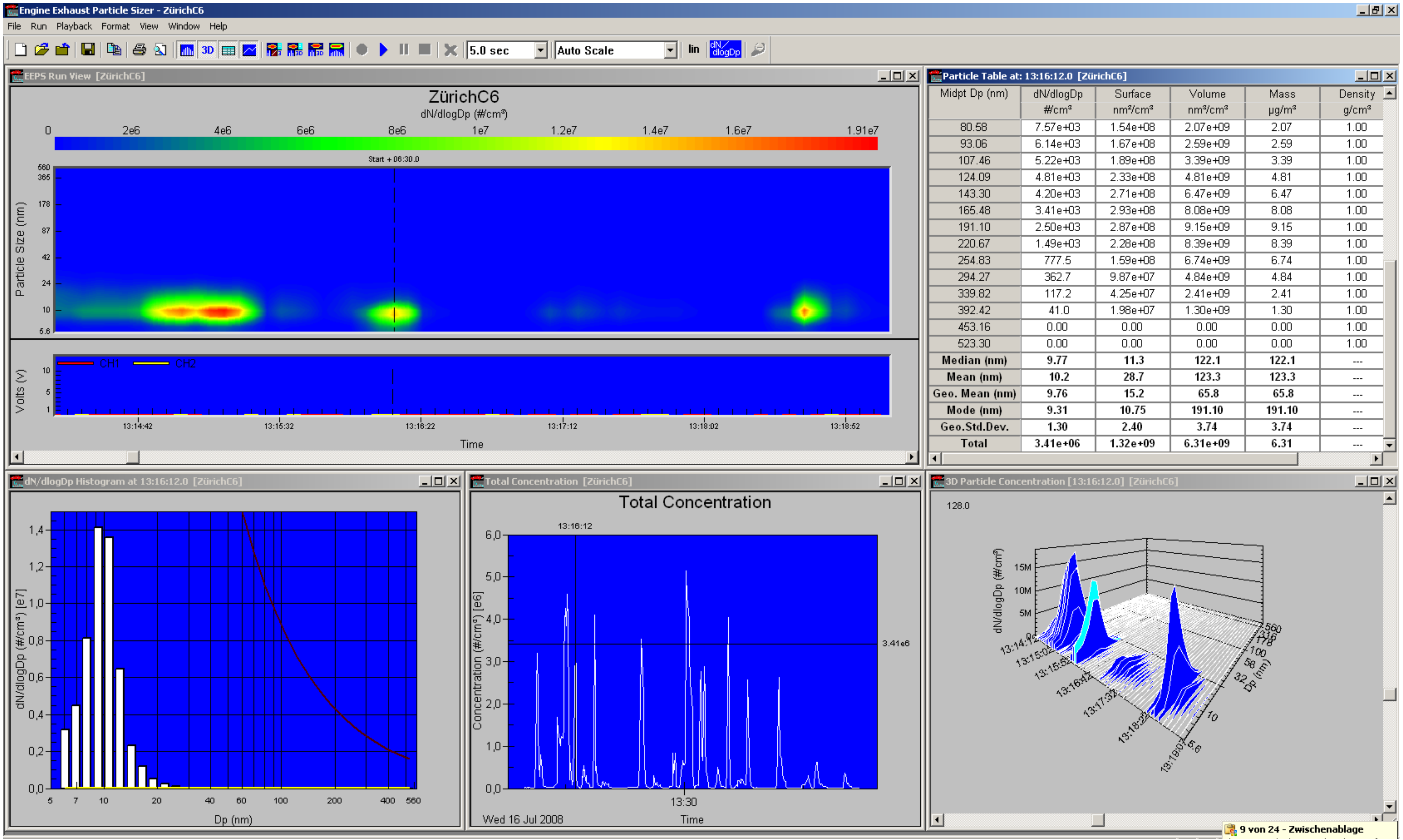
d = 9.8 nm

1023 hPa

26°C / 12°C

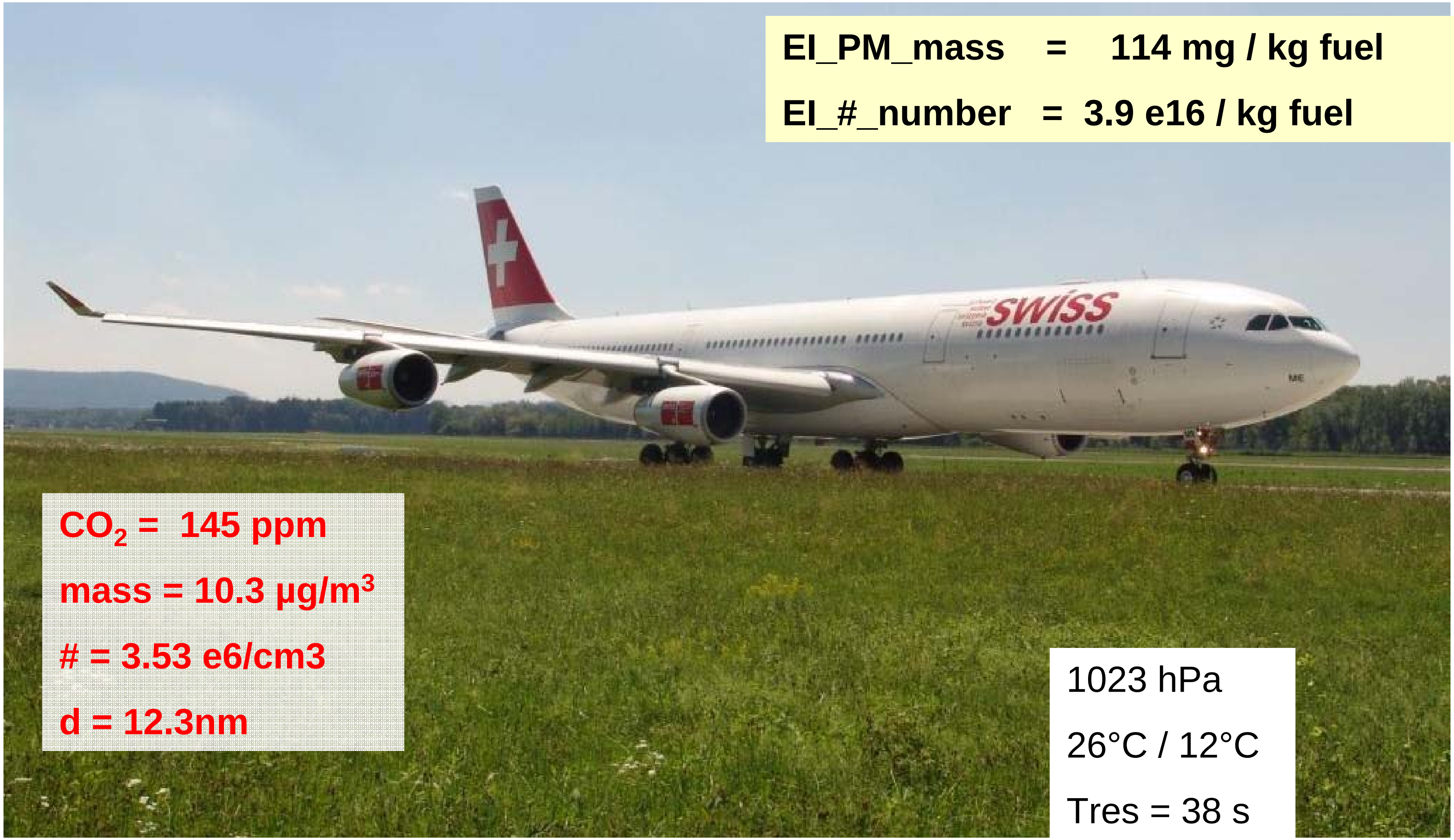
Tres = 20 s

Swiss Airbus A332 fitted with PW4168A



Midpt Dp (nm)	dN/dlogDp #/cm³	Surface nm²/cm³	Volume nm³/cm³	Mass µg/m³	Density g/cm³
80.58	7.57e+03	1.54e+08	2.07e+09	2.07	1.00
93.06	6.14e+03	1.67e+08	2.59e+09	2.59	1.00
107.46	5.22e+03	1.89e+08	3.39e+09	3.39	1.00
124.09	4.81e+03	2.33e+08	4.81e+09	4.81	1.00
143.30	4.20e+03	2.71e+08	6.47e+09	6.47	1.00
165.48	3.41e+03	2.93e+08	8.08e+09	8.08	1.00
191.10	2.50e+03	2.87e+08	9.15e+09	9.15	1.00
220.67	1.49e+03	2.28e+08	8.39e+09	8.39	1.00
254.83	777.5	1.59e+08	6.74e+09	6.74	1.00
294.27	362.7	9.87e+07	4.84e+09	4.84	1.00
339.82	117.2	4.25e+07	2.41e+09	2.41	1.00
392.42	41.0	1.98e+07	1.30e+09	1.30	1.00
453.16	0.00	0.00	0.00	0.00	1.00
523.30	0.00	0.00	0.00	0.00	1.00
Median (nm)	**9.77**	**11.3**	**122.1**	**122.1**	---
Mean (nm)	**10.2**	**28.7**	**123.3**	**123.3**	---
Geo. Mean (nm)	**9.76**	**15.2**	**65.8**	**65.8**	---
Mode (nm)	**9.31**	**10.75**	**191.10**	**191.10**	---
Geo.Std.Dev.	**1.30**	**2.40**	**3.74**	**3.74**	---
Total	**3.41e+06**	**1.32e+09**	**6.31e+09**	**6.31**	---

Swiss Airbus A343 fitted with CFM56-5C4/P



EI_PM_mass = 114 mg / kg fuel

EI_#_number = 3.9 e16 / kg fuel

CO_2 = 145 ppm

mass = 10.3 μg/m^3

 # = 3.53 e6/cm3

d = 12.3nm

1023 hPa

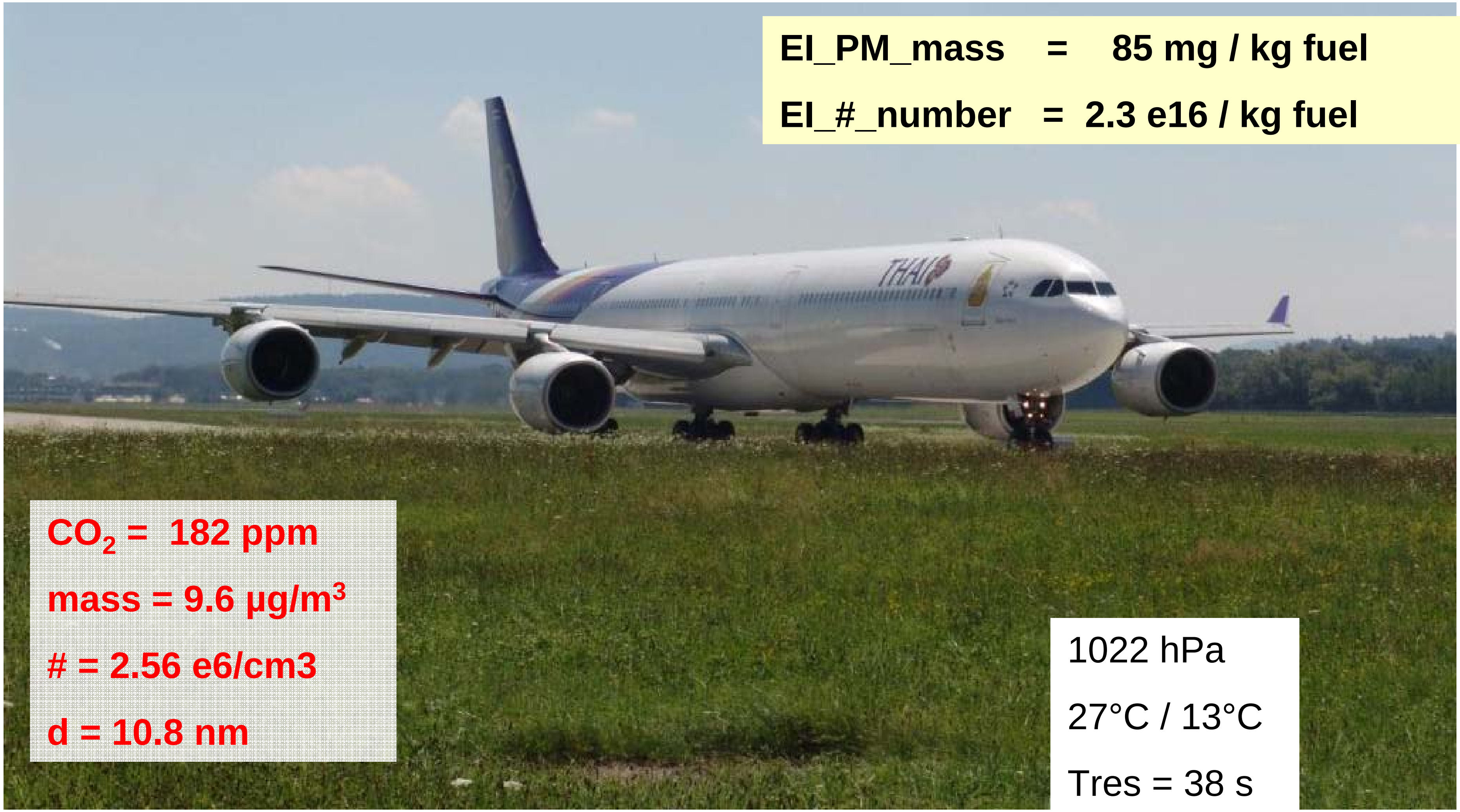
26°C / 12°C

Tres = 38 s

THAI Airbus A346 fitted with TRENT 556-61

EI_PM_mass = 85 mg / kg fuel

EI_#_number = 2.3 e16 / kg fuel



CO_2 = 182 ppm

mass = 9.6 µg/m^3

= 2.56 e6/cm3

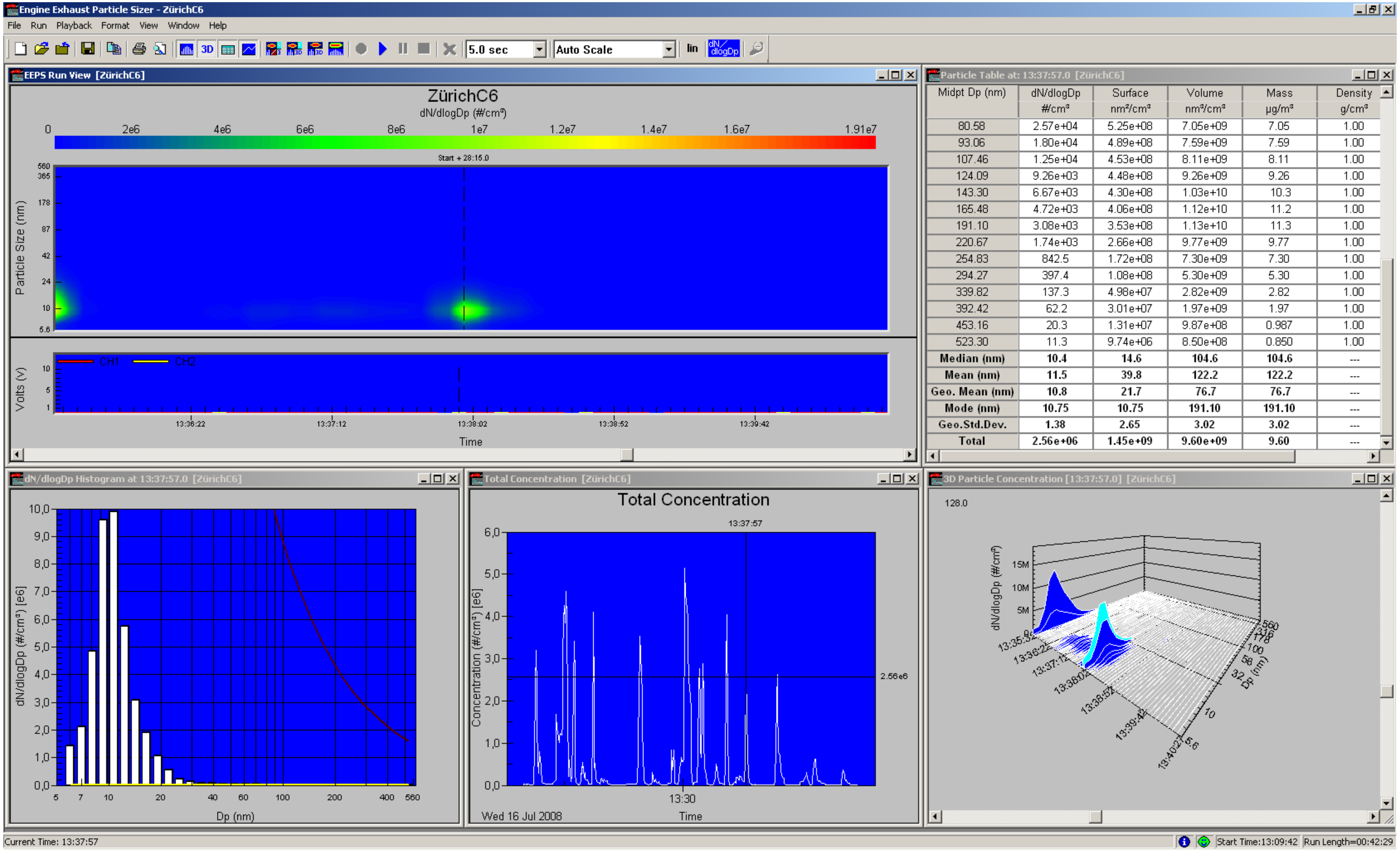
d = 10.8 nm

1022 hPa

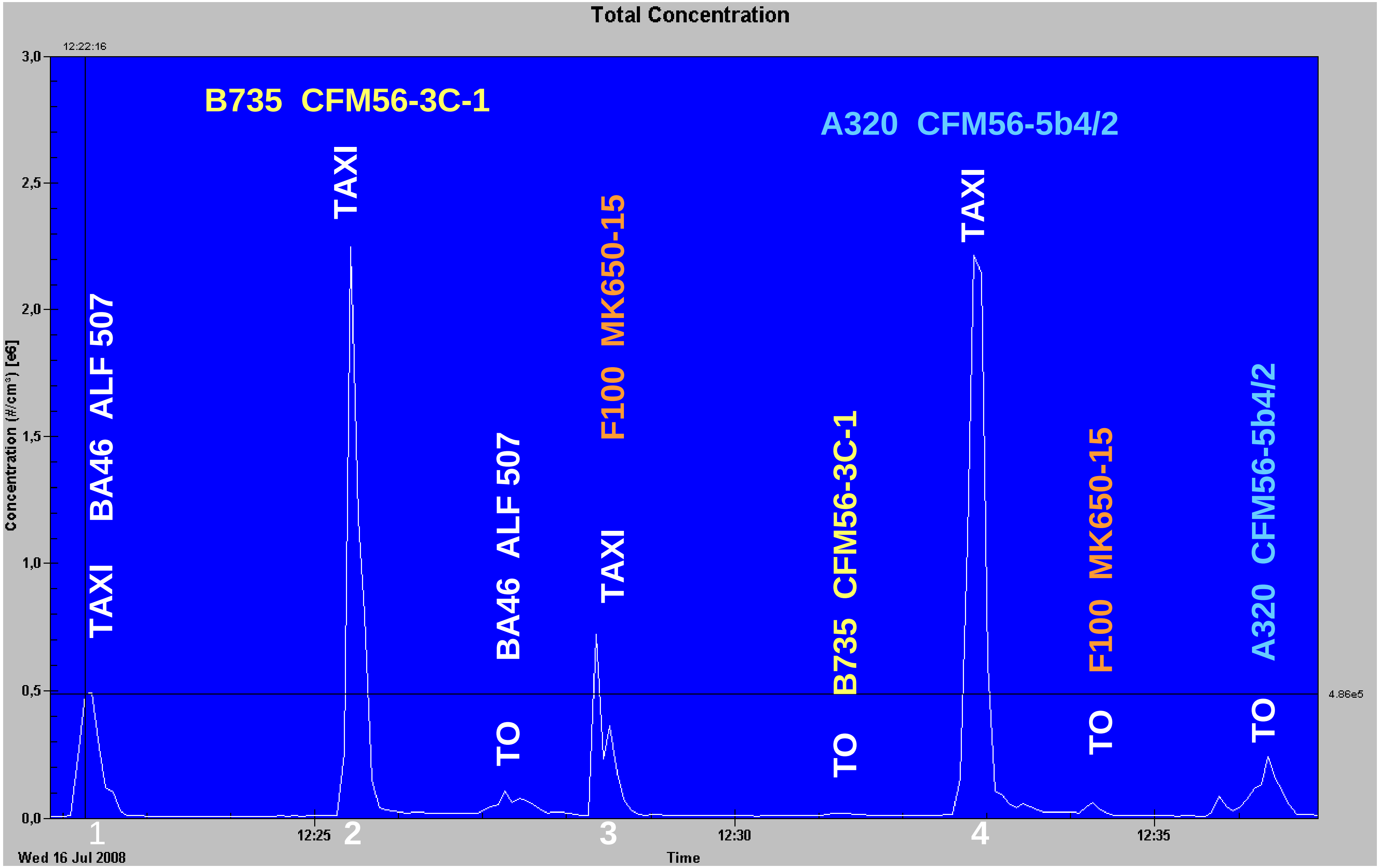
27°C / 13°C

Tres = 38 s

THAI Airbus A346 fitted with TRENT 556-61

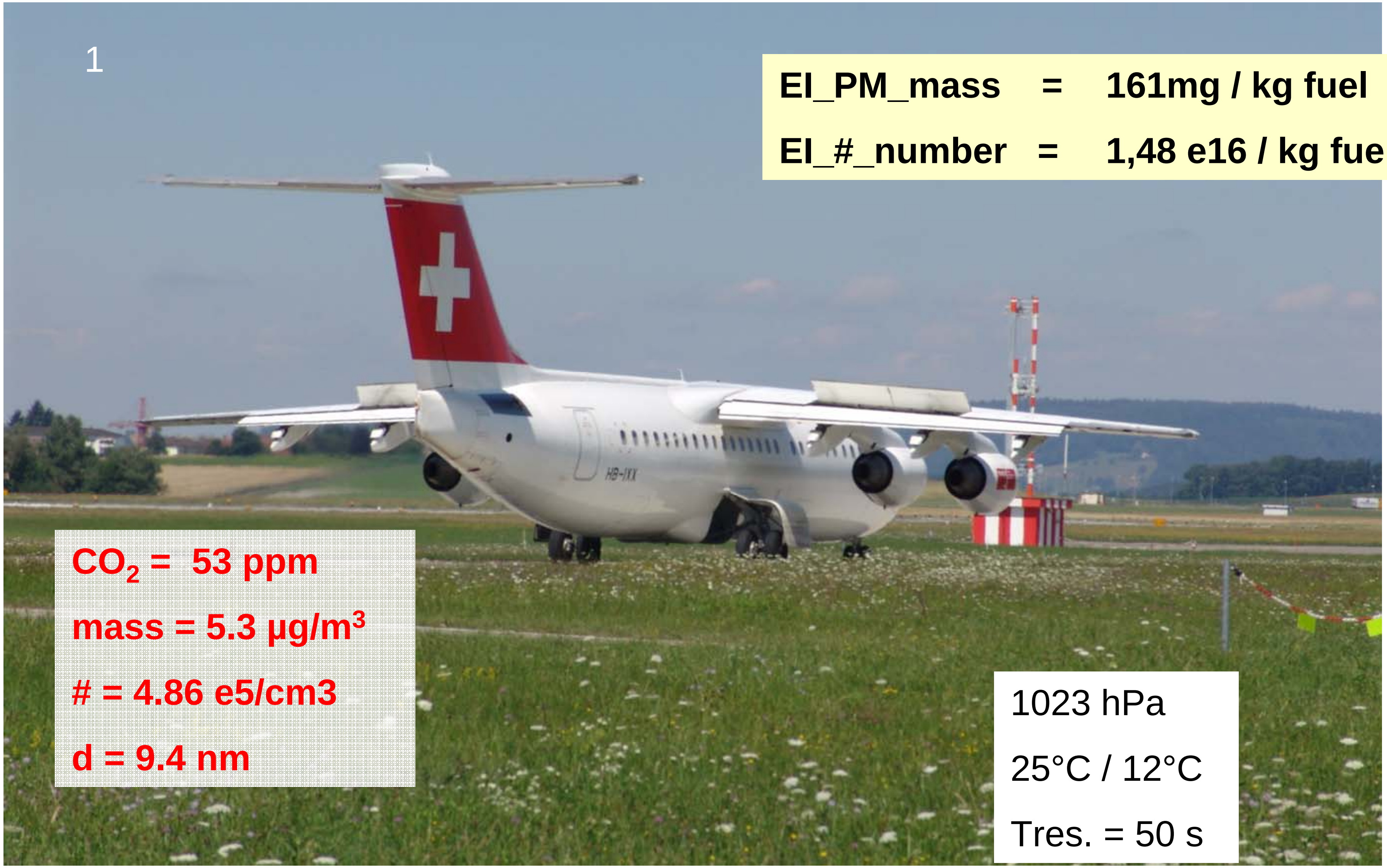


Midpt Dp (nm)	dN/dlogDp #/cm³	Surface nm²/cm³	Volume nm³/cm³	Mass µg/m³	Density g/cm³
80.58	2.57e+04	5.25e+08	7.05e+09	7.05	1.00
93.06	1.80e+04	4.89e+08	7.59e+09	7.59	1.00
107.46	1.25e+04	4.53e+08	8.11e+09	8.11	1.00
124.09	9.26e+03	4.48e+08	9.26e+09	9.26	1.00
143.30	6.67e+03	4.30e+08	1.03e+10	10.3	1.00
165.48	4.72e+03	4.06e+08	1.12e+10	11.2	1.00
191.10	3.08e+03	3.53e+08	1.13e+10	11.3	1.00
220.67	1.74e+03	2.66e+08	9.77e+09	9.77	1.00
254.83	842.5	1.72e+08	7.30e+09	7.30	1.00
294.27	397.4	1.08e+08	5.30e+09	5.30	1.00
339.82	137.3	4.98e+07	2.82e+09	2.82	1.00
392.42	62.2	3.01e+07	1.97e+09	1.97	1.00
453.16	20.3	1.31e+07	9.87e+08	0.987	1.00
523.30	11.3	9.74e+06	8.50e+08	0.850	1.00
Median (nm)	**10.4**	**14.6**	**104.6**	**104.6**	---
Mean (nm)	**11.5**	**39.8**	**122.2**	**122.2**	---
Geo. Mean (nm)	**10.8**	**21.7**	**76.7**	**76.7**	---
Mode (nm)	**10.75**	**10.75**	**191.10**	**191.10**	---
Geo.Std.Dev.	**1.38**	**2.65**	**3.02**	**3.02**	---
Total	**2.56e+06**	**1.45e+09**	**9.60e+09**	**9.60**	---



Total Concentration
12:22:16
3,0
2,5
2,0
1,5
1,0
0,5
0,0
Concentration (#/cm³) [e6]
B735 CFM56-3C-1
A320 CFM56-5b4/2
TAXI BA46 ALF 507
TAXI
BA46 ALF 507
TO
F100 MK650-15
TAXI
B735 CFM56-3C-1
TO
TAXI
F100 MK650-15
TO
A320 CFM56-5b4/2
TO
4.86e5
1
12:25
2
3
12:30
4
12:35
Wed 16 Jul 2008
Time

BA46 SWISS   Honeywell ALF507



EI_PM_mass = 161mg / kg fuel

EI_#_number = 1,48 e16 / kg fuel

CO_2 = 53 ppm

mass = 5.3 µg/m³

 # = 4.86 e5/cm3

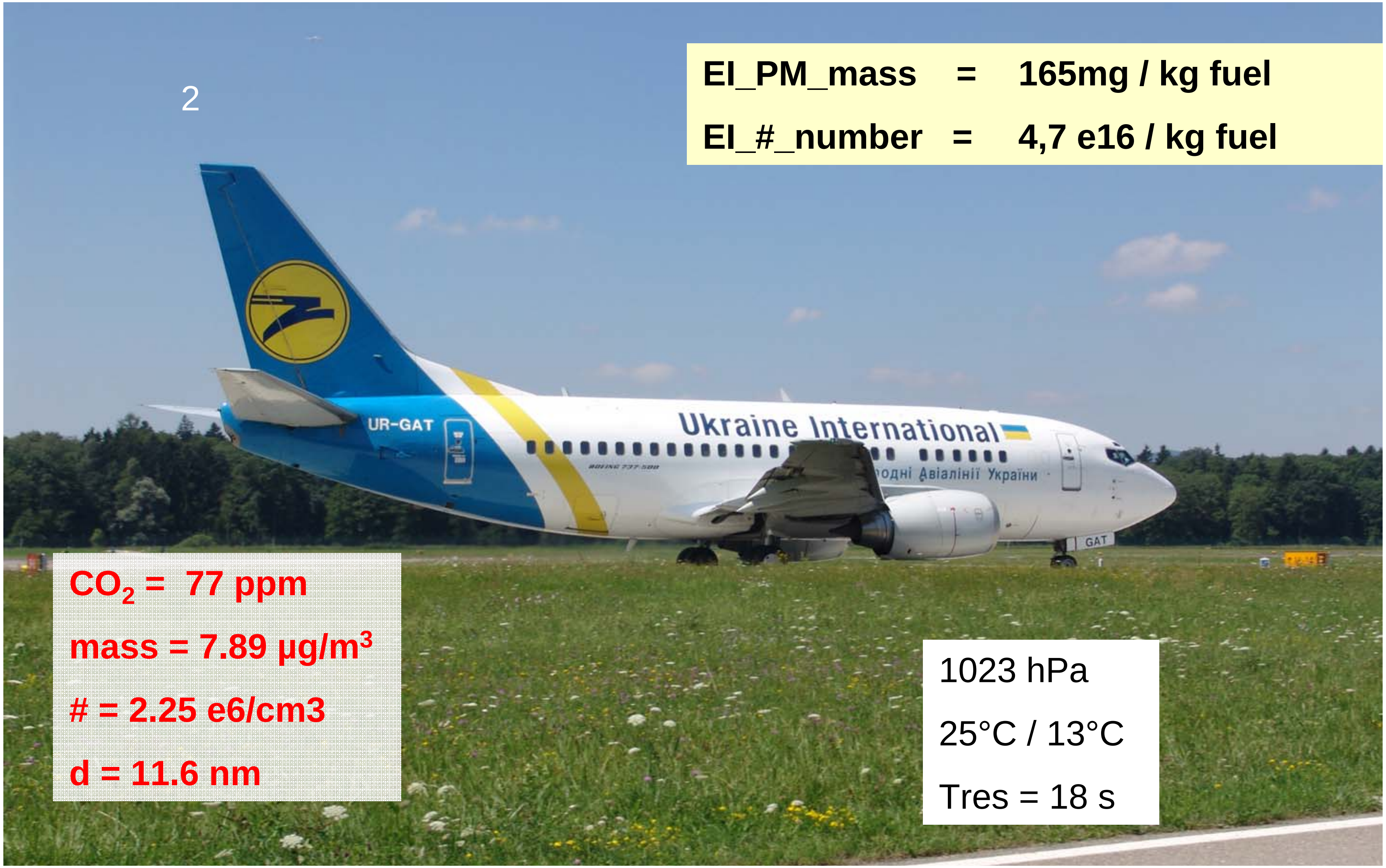
d = 9.4 nm

1023 hPa

25°C / 12°C

Tres. = 50 s

B737 – 500 Ukraine International CFM56-3C-1



EI_PM_mass = 165mg / kg fuel

EI_#_number = 4,7 e16 / kg fuel

CO_2 = 77 ppm

mass = 7.89 µg/m^3

 # = 2.25 e6/cm3

d = 11.6 nm

1023 hPa

25°C / 13°C

Tres = 18 s

Fokker 100 STAR ALLIANCE TAY MK650-15

EI_PM_mass = 214mg / kg fuel

EI_#_number = 3,06 e16 / kg fuel

CO_2 = 38 ppm

mass = 5.05 µg/m^3

 # = 7.23 e5/cm3

d = 11.5 nm

1023 hPa

25°C / 13°C

Tres = 24 s

Results for particle mass and particle number EI's determined from exhaust plume during aircraft taxi (~ 4% power setting)

Number	Reg	Type	Engine	Measured Taxi EI_PM_mass (mg/kg)	Measured Taxi EI_PM_number (#/kg)	Geometric mean diameter (nm)
1	-	BA46	ALF 507	161	$1.48 * 10^{16}$	9.4
2	-	B735	CFM56-3C-1	165	$4.70 * 10^{16}$	11.6
3	-	F100	MK650-15	214	$3.06 * 10^{16}$	11.5
4	-	A320	CFM56-5B4/2	146	$3.11 * 10^{16}$	13
5	-	A321	CFM56-5B1/2P	154	$4.30 * 10^{16}$	13.5
6	-	A332	PW4168A	53	$2.84 * 10^{16}$	9.8
7	-	A343	CFM56-5C4/P	79	$3.70 * 10^{16}$	11
8	-	A343	CFM56-5C4/P	114	$3.90 * 10^{16}$	12.3
9	-	A319	CFM56-5B6/2P	105	$3.40 * 10^{16}$	12.4
10	-	A346	TRENT 556-61	85	$2.30 * 10^{16}$	10.8
11	-	A320	V2500-A1	115	$3.00 * 10^{16}$	11

ICAO = International Civil Aviation Organization

CAEP = Committee on Aviation Environmental Protection

FOA3 = Fist Order Approximation for total particle mass (volatile + nonvolatile)

PM Estimation: Smoke Number + UHC + Sulfur Conversion Factor + AFR + ……

Comparison of measured and calculated EI's

				ICAO CAEP* Approximation	~ 4% TAXI Zürich /online
Number	Rated Max. Thrust (kN)	Type	Engine	7% Taxi FOA3 EI_PM_total (mg/kg)	Measured Taxi EI_PM_total (mg/kg)
6	302,5	A332	PW4168A	69	53
10	261,5	A346	TRENT 556-61	54	85
7	149,9	A343	CFM56-5C4/P	108	79
8	149,9	A343	CFM56-5C4/P	108	114
5	133,5	A321	CFM56-5B1/2P	81	154
4	117,9	A320	CFM56-5B4/2	103	146
11	111,2	A320	V2500-A1	89	115
9	104,5	A319	CFM56-5B6/2P	89	105
2	104,6	B735	CFM56-3C-1	74	165
3	67,2	F100	MK650-15	248	214
1	31,0	BA46	ALF 507	140	161

*CAEP = Committee on Aviation Environmental Protection

Results

- Emission indices can be calculated independent from plume dilution
- EI_PM_mass = 53 to 214 mg/ kg fuel (including volatiles)
- EI_PM_# = 1,48*10^{16} to 4.7 *10^{16} #/kg fuel (including volatiles)
- geo.mean d = 9.4 to 13.5 nm (smaller than measured at engine test beds)
- statistical errors are estimated +-20%, mainly due to limitations of the CO_2 measurement.

Limitations

-fuel composition not exactly known,   (+- 3% carbon content)

-accuracy of CO_2 measurement !!   (10 cm ND-IR)

-accuracy of EEPS measurement

-assumption that CO_2 and particles are diluted by the same factor with ambient air

-assumed particle density of 1 g/cm^3

-volatile and non-volatile particles are not separated   (fuel sulfur, UHC)

-measured EI's are the mean of all engines of the aircraft

- different transfer time from engine exit to measuring point because of wind speed and direction

- ambient temperature

Conclusion

- the “online method” is working, independent from the plume dilution
- **it is possible to screen the current aircraft fleet in a few days**
- Results for EI_total_particle mass correlate well with ICAO CAEP First Order Approximation FOA3
- **Please do not use this results out of the context of this presentation (only a few first measurements with big error bars)**

Outlook

- **next campaign at Zürich airport is already planned**
- **CO_2 measurement will be improved** (5,11m FT-IR instead of 10 cm ND-IR)
- **EI's for NO, NOx, CO, HC and formaldehyde should be possible (FT-IR)**
- **it is planned to measure TAKE OFF EI's**
- **identification of volatile and non-volatile particles** (two EEPS, thermodenuder or hot dilution….)
- **use the method for trucks and passenger cars…….**

Acknowledgment:

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of **UNIQUE Flughafen Zürich AG**

for making this measurements possible

Thank you for your attention