OpenSense: City-Scale Air Quality Monitoring with Wireless Sensor Nodes

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Urban Air Quality

- Major concern in many cities worldwide
- Responsible for respiratory and cardiovascular illnesses

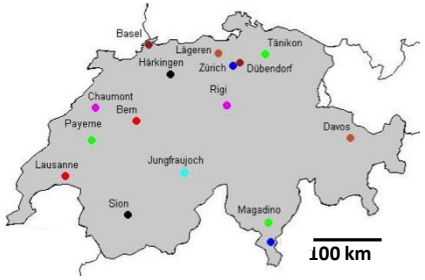
Air Pollution Monitoring

- Static measurement networks operated by national authorities
- Measurements are highly reliable and very accurate
- High acquisition and maintenance costs limit number of installations

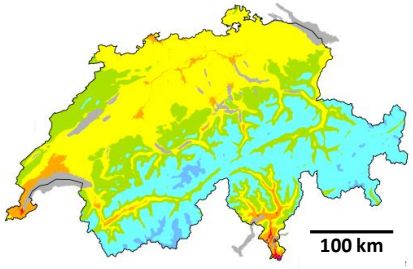
NABEL station in Zurich, Switzerland

Air Pollution Maps

- Today: Limited spatial or temporal resolution

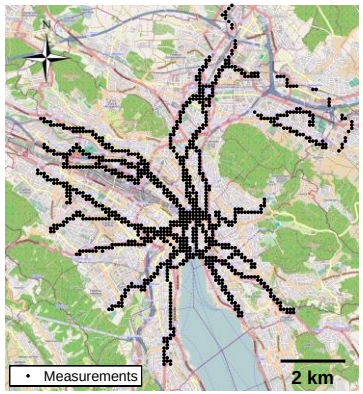


Static measurement network

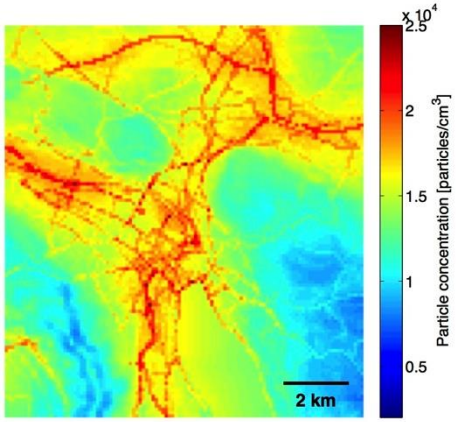


Fine particle pollution map

- Goal of OpenSense: Increase spatio-temporal resolution



City-wide coverage



Fine-grained pollution map

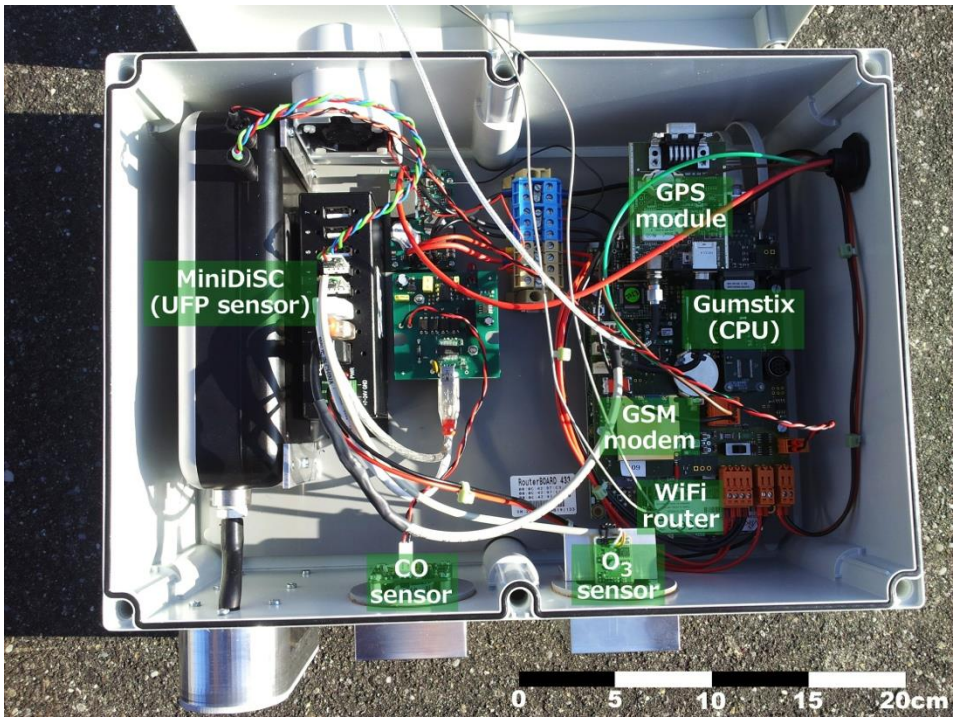
Mobile Sensor Nodes

- Sensors: ozone, carbon monoxide, ultrafine particles, temperature, humidity
- Location: GPS
- Communication:

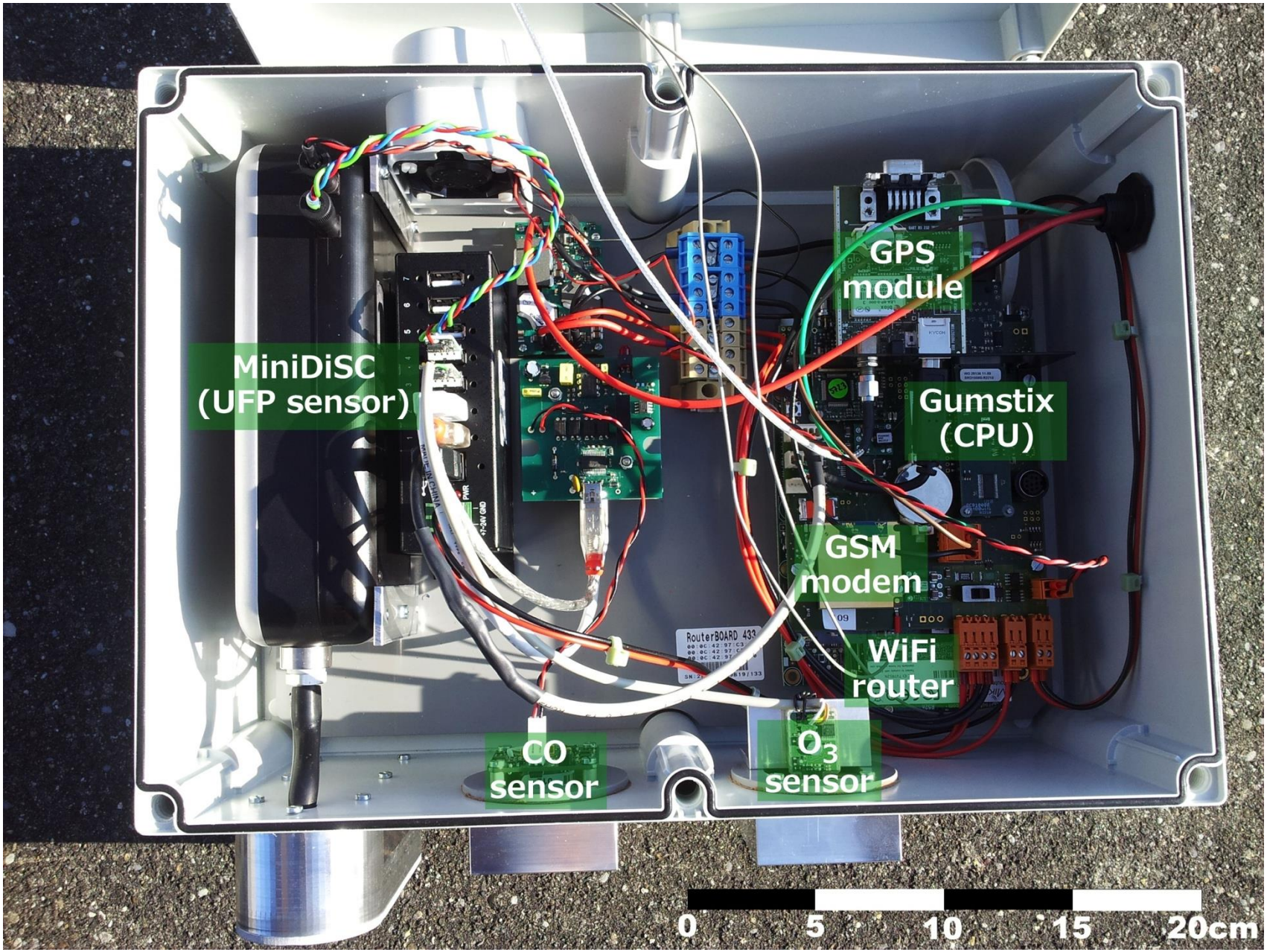
  GSM (cellular network)
- Interfaces:

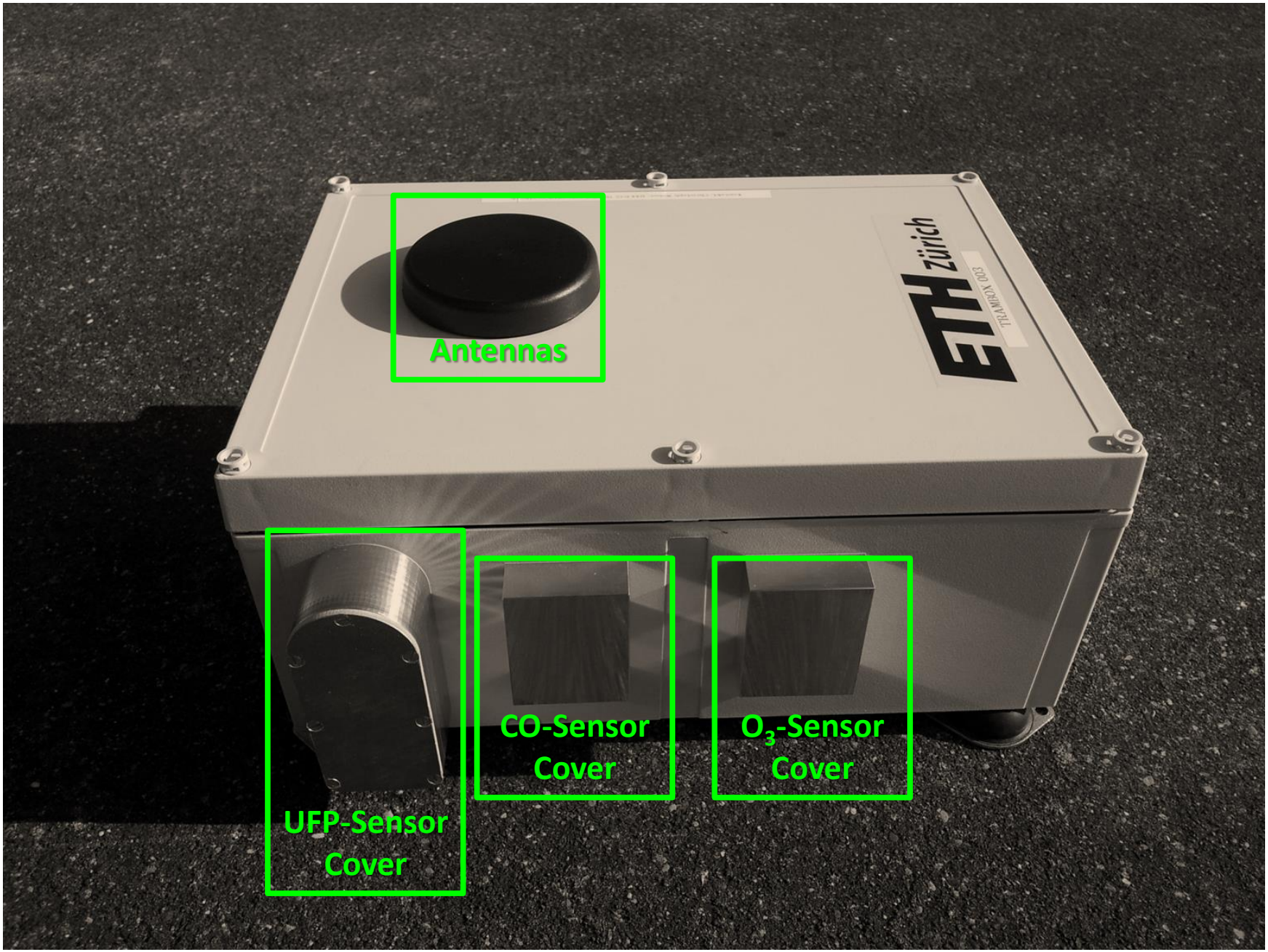
  USB, analog/digital
- Power supply:

  external (streetcar)



Air quality sensor node


GPS module
MiniDiSC (UFP sensor)
Gumstix (CPU)
GSM modem
WiFi router
CO sensor
O_3 sensor
0
5
10
15
20cm


Antennas
UFP-Sensor Cover
CO-Sensor Cover
O_3-Sensor Cover
ETH zürich

Deployments

- Static deployment

On top of a static measurement station

- Testing new sensors: stability, accuracy
- Long-term sensor tests

- Mobile deployment

On top of streetcars in the city of Zurich

- 10 nodes
- 20 hours per day in operation
- 2 years of measurements
- > 50 million data points

Deployments

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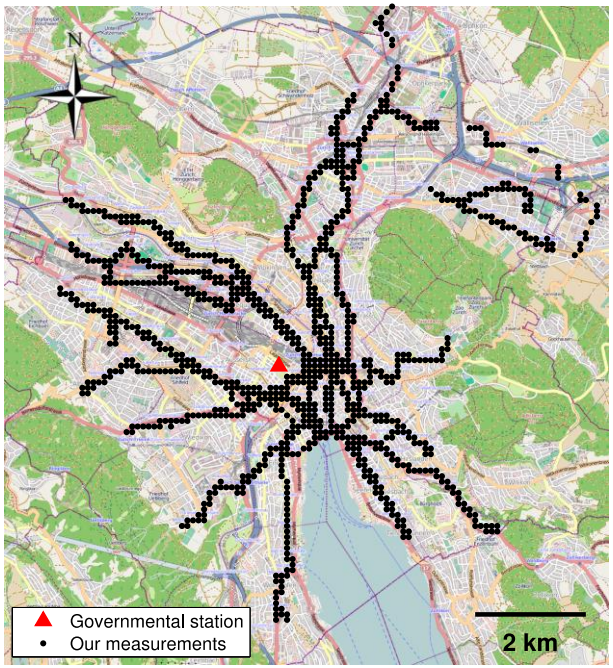
Mobile Sensor Network

- 10 sensor nodes on top of 10 streetcars
- Streetcars are not bounded to specific tracks

Sensor nodes are installed on top of streetcars



Measurement coverage

Monitoring Ultrafine Particles (UFPs)

- Particles with a diameter < 100nm
- Most countries have mass emission limits for particulate matter PM_{10} and $PM_{2.5}$, but no restrictions for UFP
- Adverse health effects of UFP most probably underestimated

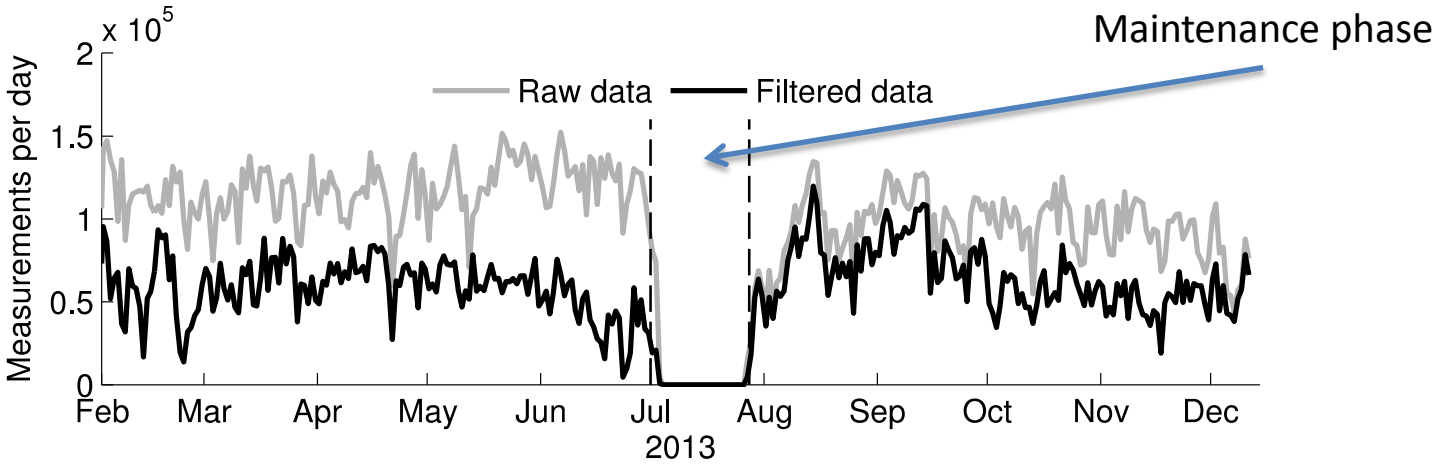
UFP sensor (MiniDisc)

Problem: Lack of spatially resolved exposure data, lack of epidemiological studies

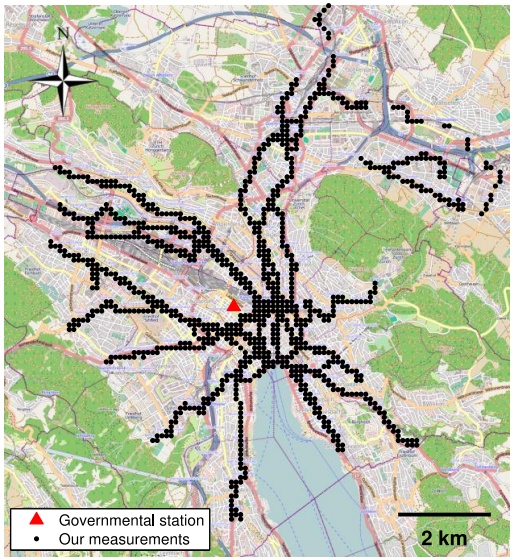
UFP Data Set

- 10 MiniDiscs are installed on top of 10 streetcars
  - Five installed in April 2012, five more in January 2013
  - Sampling rate of 20Hz, aggregated to one packet per 5s
  - Collected more than **40 million measurements**

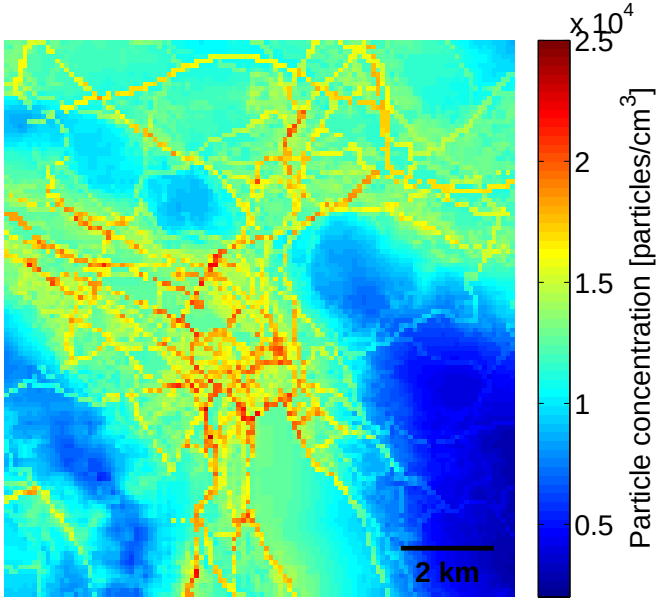
    (after filtering around 25 million remaining)



From Single Measurements to Fine-Grained Pollution Maps



Single measurements



Fine-grained pollution map

Processing steps:

Raw data → Data filtering & calibration → Data validation → **LUR model** → Pollution map → Map validation

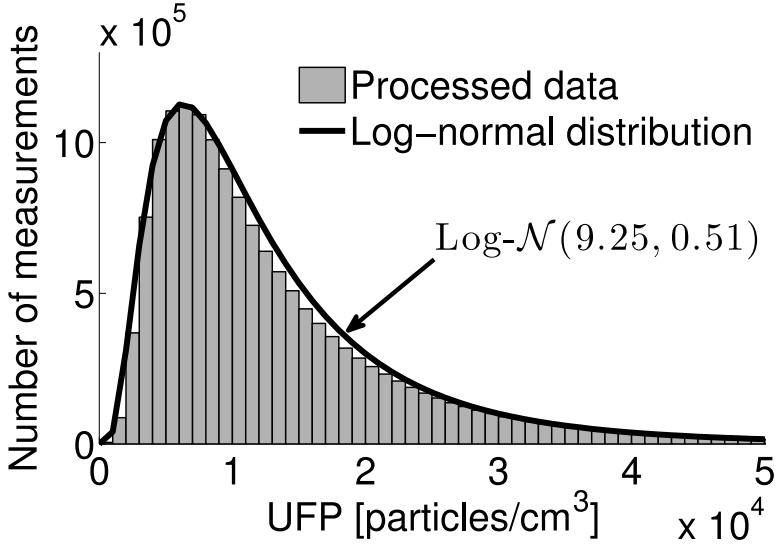
Data Validation

- Has the harsh deployment setting on top of streetcars an impact on data quality?
  - Long-term unattended operating times
  - Mobility and constant vibrations
  - High temperature and humidity variations

- Good data quality is a must for the development of reliable pollution maps
- **Challenge: only very sparse ground truth is available**

Statistical Distribution

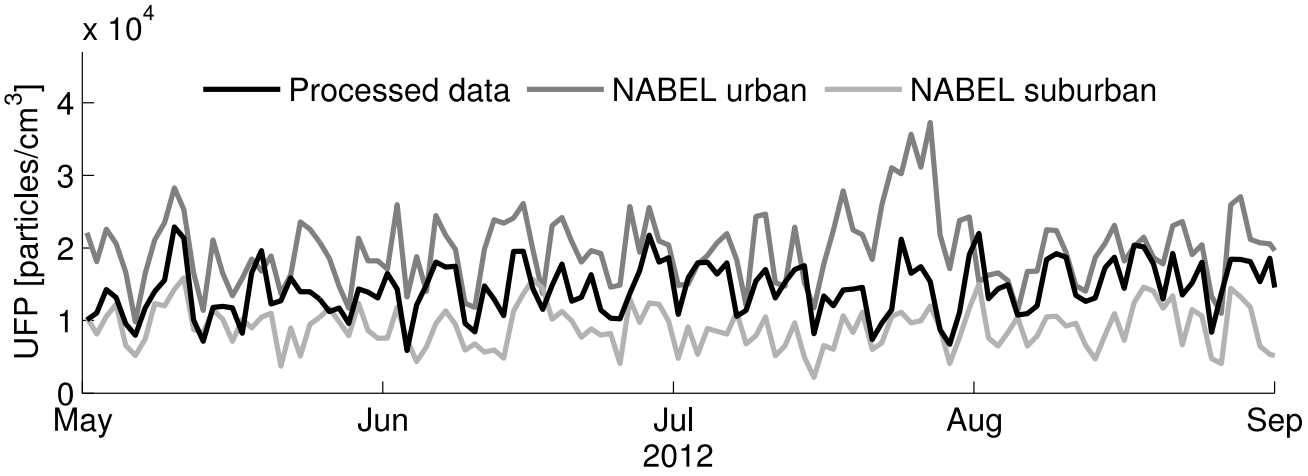
- UFPs are approximately **log-normally distributed**
- Log-normal distribution (black) with mean and standard deviation of the UFP data (gray)



- Distribution of the processed data closely follows a log-normal distribution

Comparison to High-Quality Data

- Comparison to UFPs measured by static stations of the Swiss National Air Pollution Monitoring Network (NABEL)
- Locations: **urban heavy traffic** and **suburban**



- Daily average measured UFP concentration corresponds well to the measurements of the two static stations

Developing Land-Use Regression Models to Create Pollution Maps

- Land-use regression (LUR) models widely used to assess spatial variation of air pollutants
- Use land-use and traffic characteristics (explanatory variables) to model pollution levels:
  1. Evaluate dependency between explanatory variables and monitored pollution levels
  2. Model pollution levels with the found relationships at locations without measurements but land-use data

Explanatory Variables

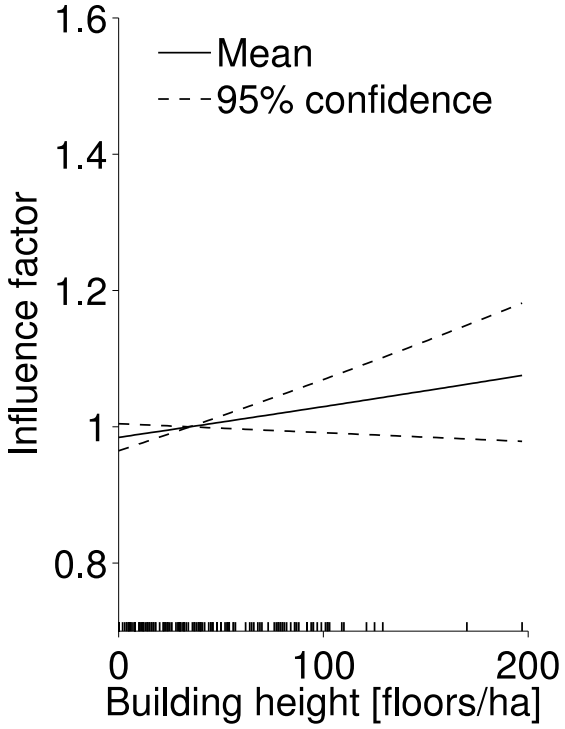
- Resolution: **100m x 100m (1 hectare)**
- **12 variables**:

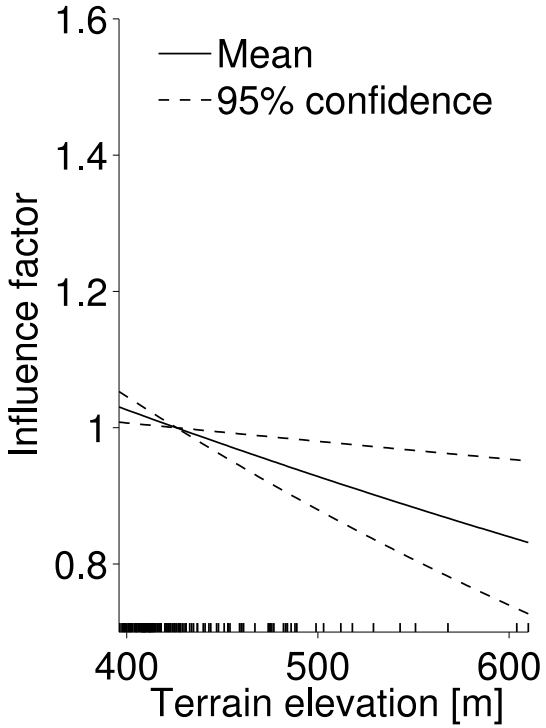
Variable [unit]	Variable [unit]
Population [inhabitants/ha]	Industry [industry buildings/ha]
Building height [floor levels/ha]	Heating [oil and gas heatings/ha]
Terrain elevation [average m (asl)/ha]	Road type [busiest road type/ha]*
Distance to next road [m]	Distance to next large road [m]†
Terrain slope [average degree/ha]	Terrain aspect [average degree/ha]
Traffic volume [vehicles per day/ha]	Distance to next traffic signal [m]

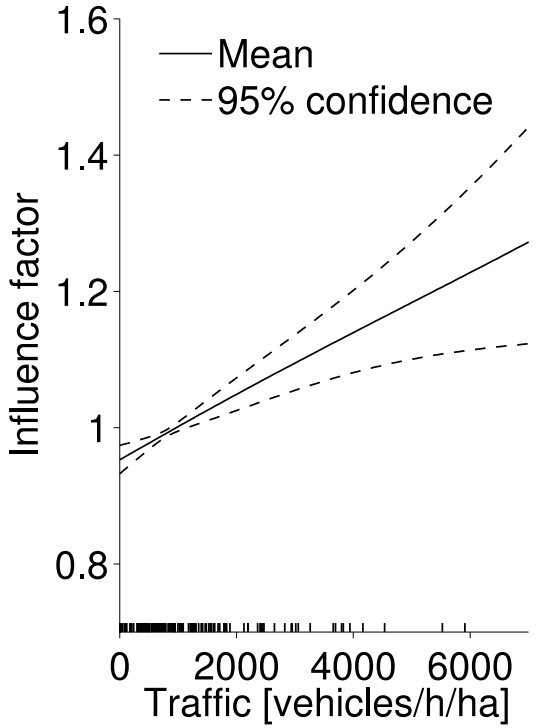
*Five road types: residential, tertiary, secondary, primary, and freeway.
†Road types classified as large: secondary, primary, and freeway.

Influence Factor

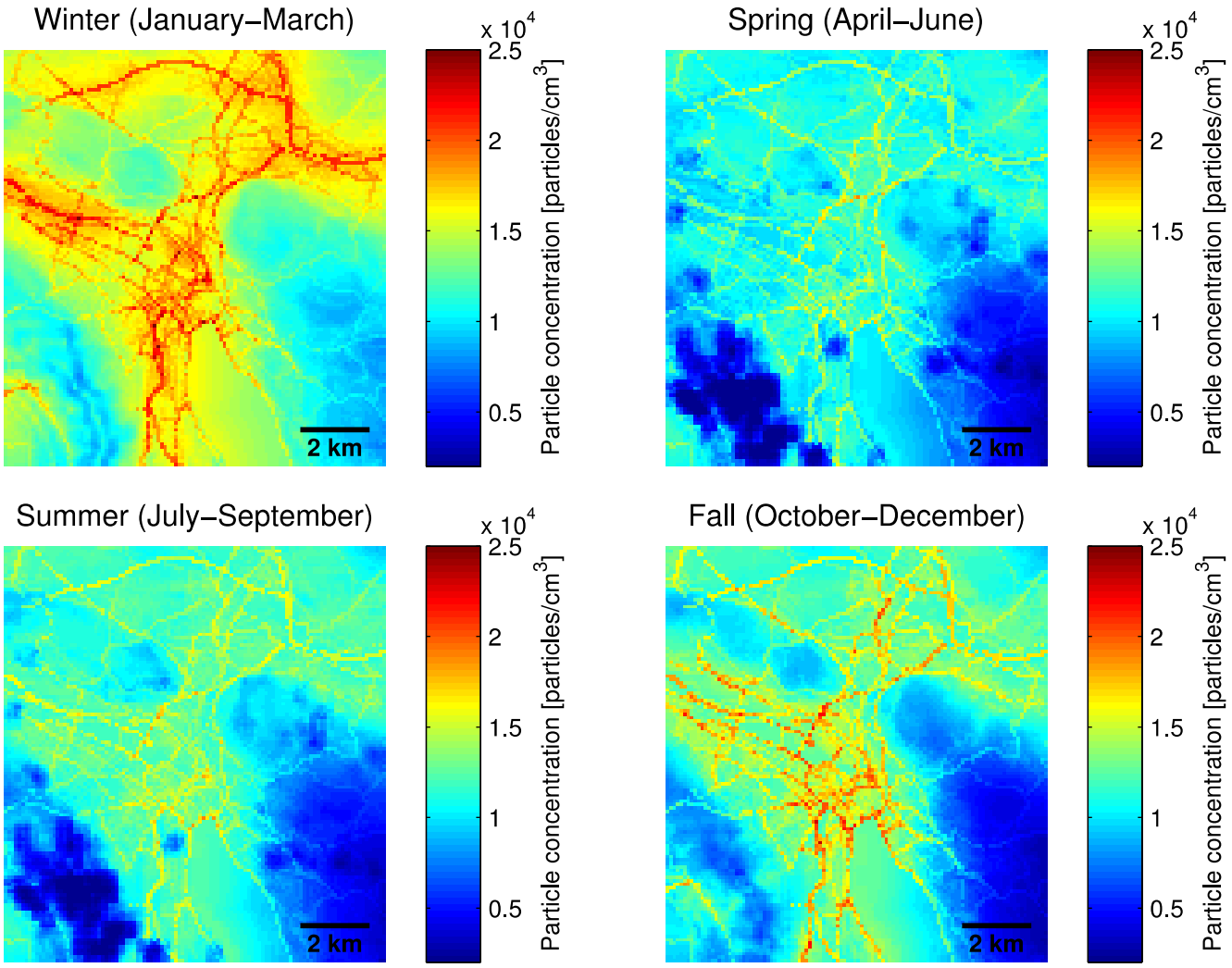
- Every variable has an **influence factor** on the modeled pollution level







Pollution Maps of Ultrafine Particles

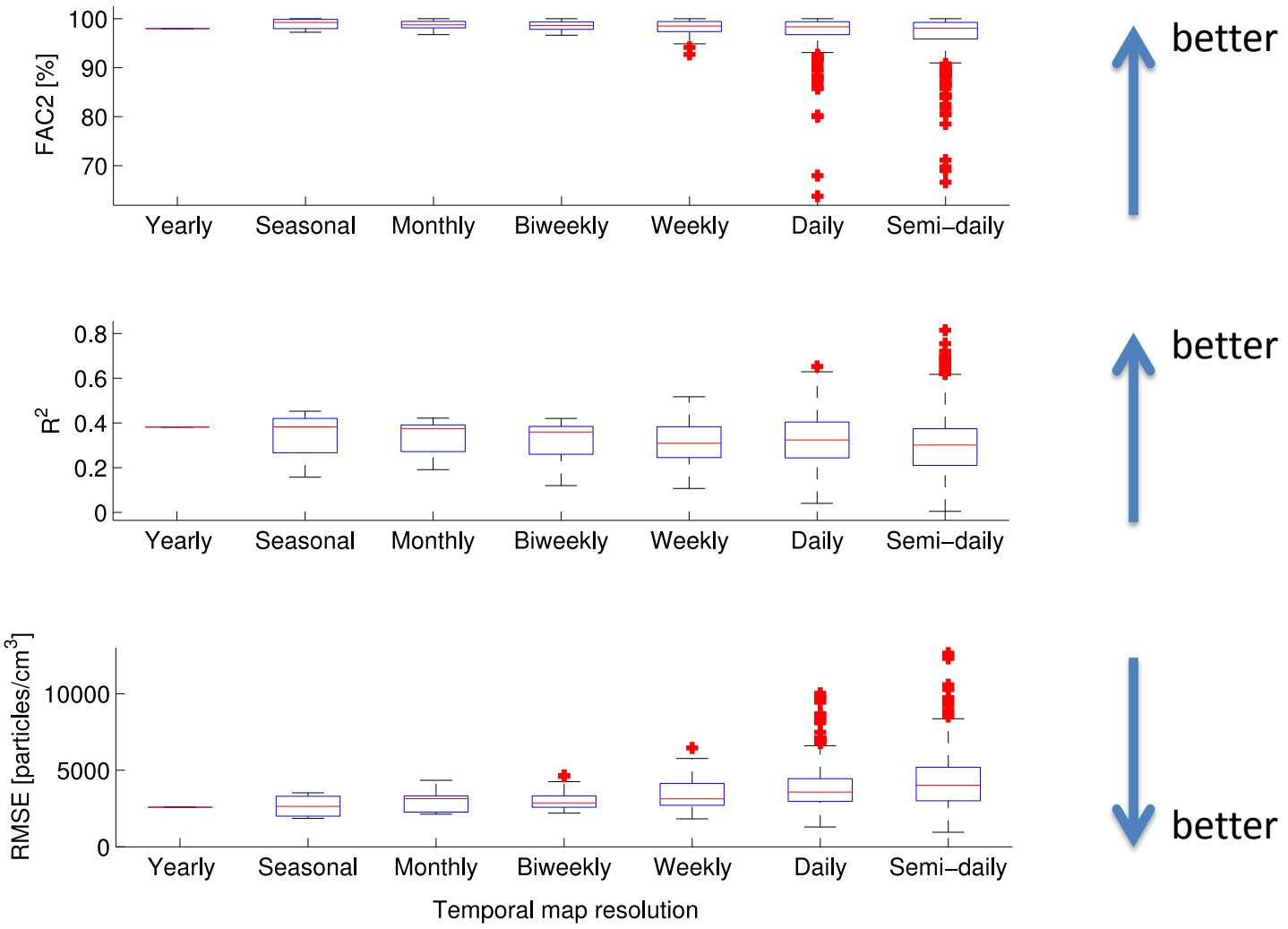


Model Performance (1/2)

- Generated **989 air quality models**:
  - 1 year of measurements: April 2012 to March 2013
  - Spatial resolution: 100m
  - Temporal resolution: **yearly to semi-daily**

- Metrics
  - Factor of 2 measure (**FAC2**): Fraction of predicted concentrations with an error less than a factor of two
  - Coefficient of determination (**R^2**): Indicates how well predicted concentration fits measurements
  - Root-mean-square error (**RMSE**): Quantifies difference between predicted and measured concentrations

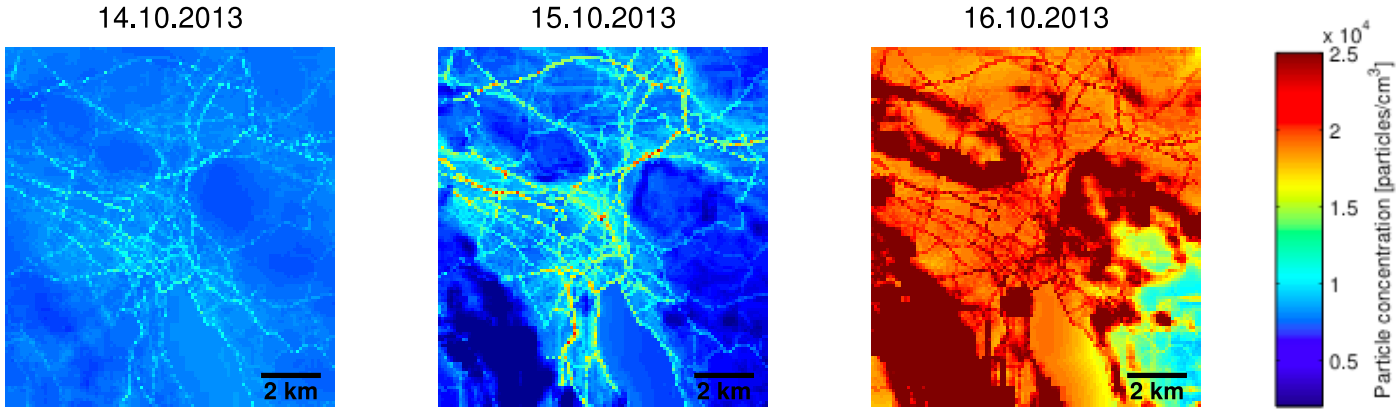
Model Performance (2/2)



Model Performance (2/2)

Challenges

- Lower number of measurements available to calculate the relationships to the explanatory variables
  - Limited temporal and spatial coverage of the measurements
  - Single erroneous and inaccurate measurements (e.g., outliers) have higher impact on the model



Outlook

- Increase spatial resolution (e.g., 10m resolution)
- Increase temporal resolution towards the goal of real-time pollution maps
- Analyze other pollutants, such as ozone (O_3), carbon monoxide (CO), and nitrogen dioxide (NO_2)
- Extend the mobile sensor network with measurements from locations not covered by the streetcar tracks

Website: www.opensense.ethz.ch

Backup Slides

Carbon Monoxdie (CO)

- Electrochemical gas sensor from Alphasense