ADVANCED MONITORING TECHNOLOGIES THE NEXT FRONTIER

LAKI TISOPULOS, PhD, PE

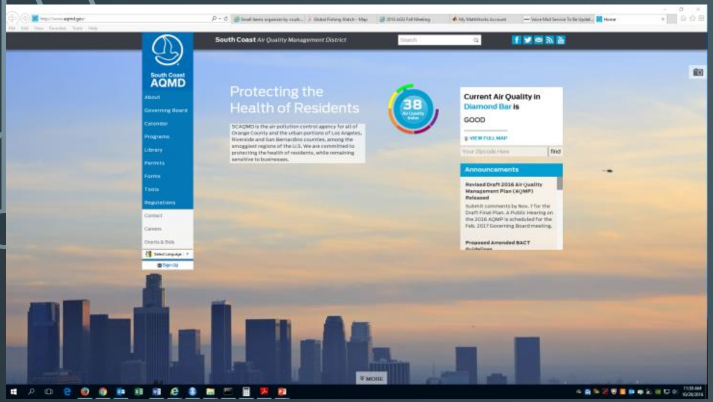
Deputy Executive Officer, Engineering and Permitting

SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT, DIAMOND BAR, CALIFORNIA

OUTLINE

- South Coast Air Quality Management District – who we are and what we do
- Optical Remote Sensing
  - SCAQMD Fenceline Monitoring and Optical Remote Sensing Program
  - Technology Demonstration Studies
  - Controlled-release Experiment
- Low-cost Air Quality Sensors
  - Air Quality Sensor Performance Evaluation Center (AQ-SPEC)
  - Sensor Network Pilot Studies
- Future work

SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT



http://www.aqmd.gov/

SCAQMD Headquarters
Diamond Bar, California

- 4-county region
- 10,000 sq. miles
- Over 17 million residents
- Over 11 million gasoline vehicles
- Over 261,000 diesel vehicles
- Combined Ports of Long Beach and Los Angeles - nation's largest cargo gateway
- Regulate over 27,000 stationary sources
- Refineries, power plants, landfills, fueling stations

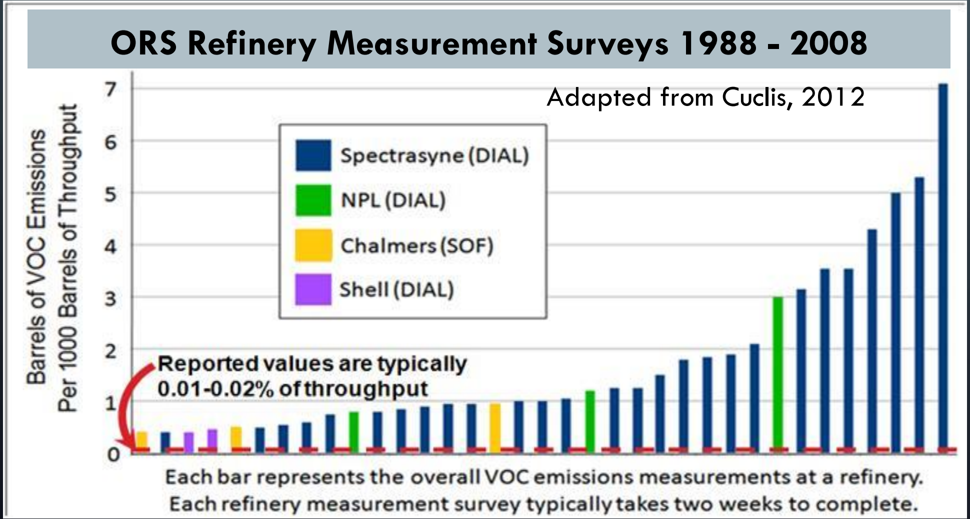
SCAQMD Air Monitoring Station
(N Main Street, Los Angeles)

SCAQMD Laboratory in Diamond Bar

OPTICAL REMOTE SENSING

MOTIVATION

- Optical Remote Sensing (ORS) technologies evolved significantly in the past decade
- Fully automated / continuous / no calibration required
- Ideally suited for long-term fenceline monitoring. Can characterize and quantify emissions
- Can be deployed from various mobile platforms for rapid leak detection, concentrations mapping and emission flux measurements
- Measured VOC emissions can be higher (up to an order of magnitude) than those from emission inventories



Technical Memorandum

TO: EPA Docket No. EPA-HQ-OAR-2003-0146

FROM: Brenda Shine, EPA/SPPD

DATE: July 27, 2007

SUBJECT: Potential Low Bias of Reported VOC Emissions from the Petroleum Refining Industry

SCAQMD OPTICAL REMOTE SENSING MONITORING PROGRAM

- Demonstrate feasibility and effectiveness of fenceline monitoring using optical remote sensing
- Improve LDAR program and reduce emissions
- Provide real-time alerts to downwind communities
- Measure actual facility-wide emissions
- Improve existing emission inventory estimates

South Coast AQMD

2016-2018
Combined ORS and low-cost sensors deployments to study impacts of HAPs on communities

2015
ORS measurements campaign to study emissions from refineries, small stationary sources and ships

AOS UCLA Atmospheric & Oceanic Sciences

FluxSense

2012 – 2014
Two successful technology demonstration projects for refineries

2008
LP-DOAS for fenceline monitoring. Contractor failed to fulfill obligations

2015 SCAQMD OPTICAL REMOTE SENSING STUDY

- Project 1: Quantify fugitive emissions from large refineries

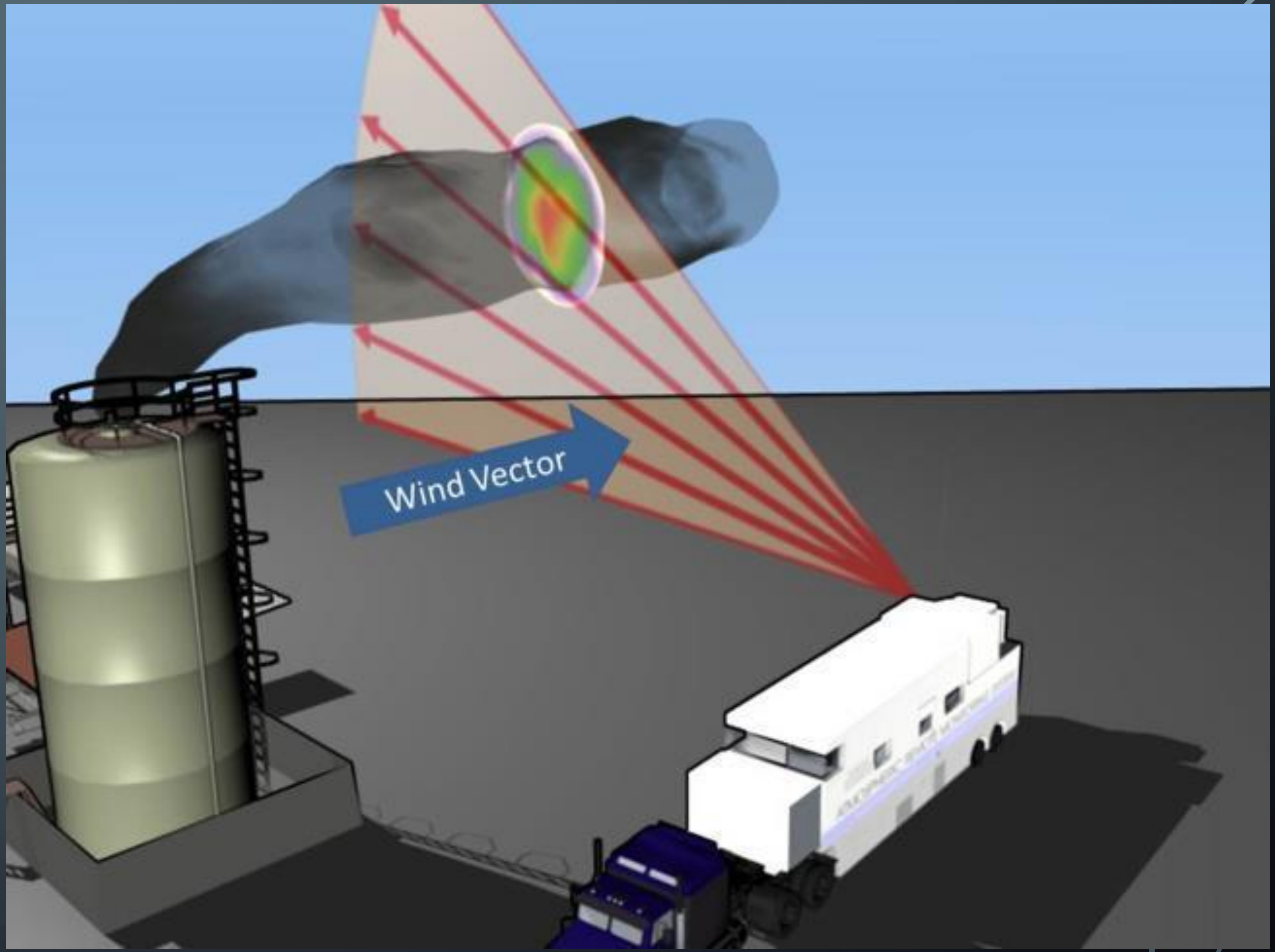
- Project 2: Quantify gaseous emissions from small point sources

- Project 3: Quantify stack emissions from marine vessels/ports

METHODS: SOLAR OCCULTATION FLUX (SOF)

- Mobile measurements to record total mass of molecules along path traveled
- Total mass and wind data used to calculate flux emissions (kg/s)
- Also can be used identify "hot-spot" areas inside the facility
- Light source – direct sunlight
- Daylight measurements only
- Accurate wind data obtained using SCAQMD's LIDAR

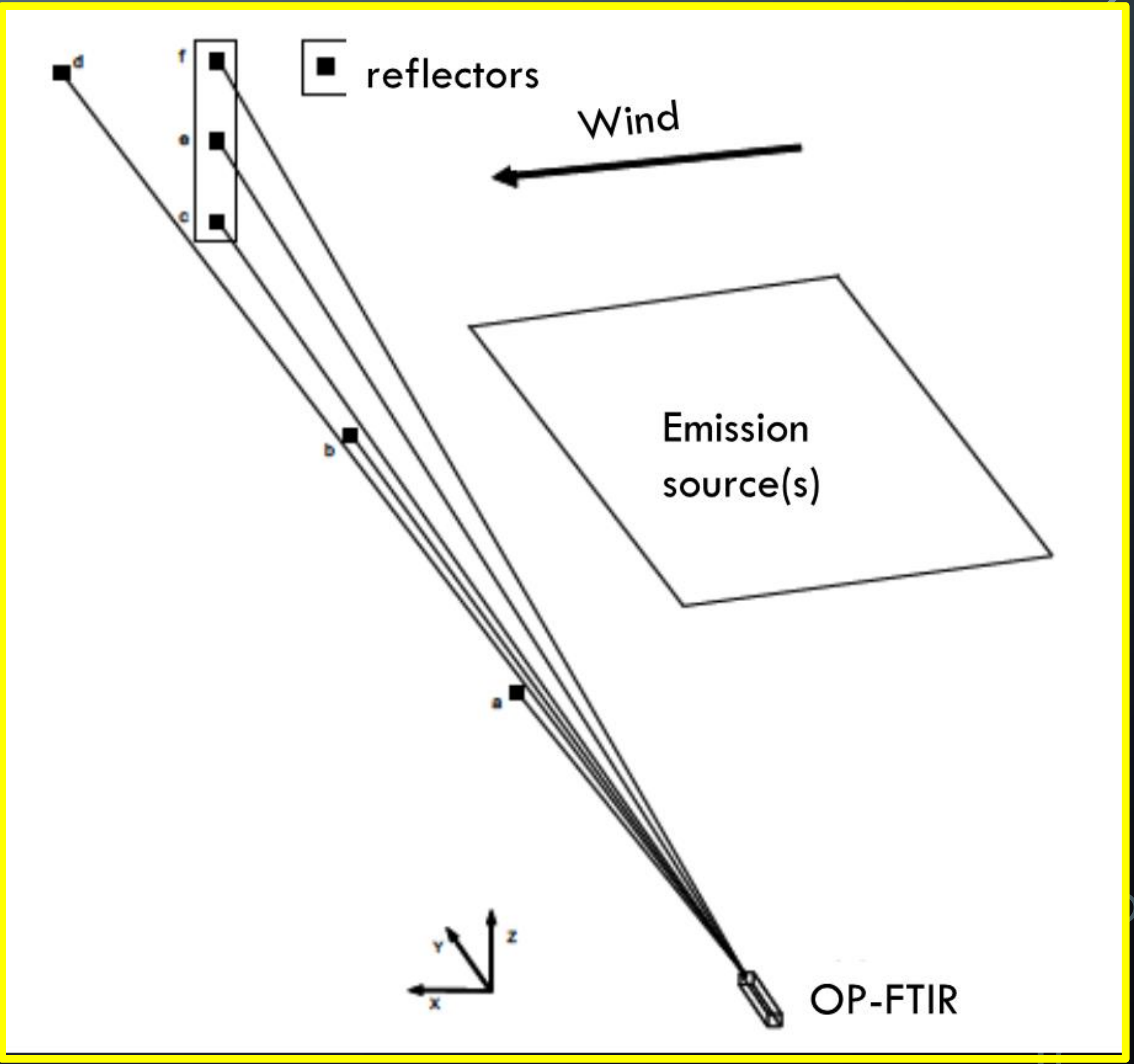
METHODS: DIFFERENTIAL ABSORPTION LIDAR (DIAL)



- Vertical scans enable plume mapping and flux calculation
- Combine integrated concentration with simple wind field to obtain flux
- Can measure away from source
- Light source – IR or UV laser
- Daytime and nighttime measurements

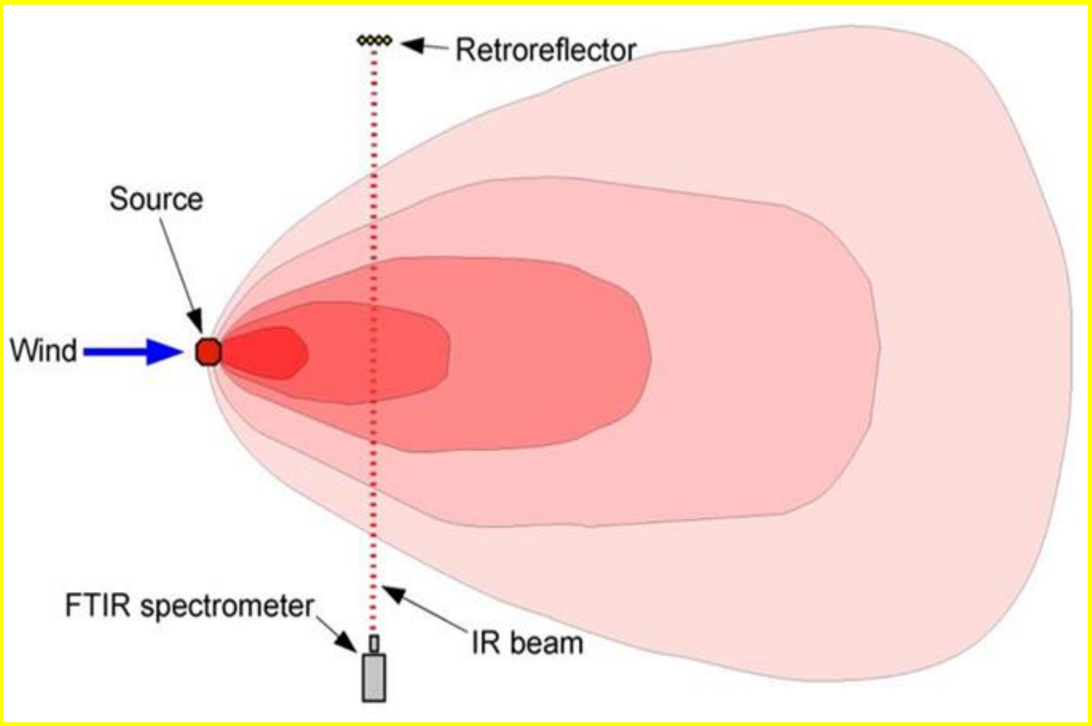
METHODS: VERTICAL RADIAL PLUME MAPPING (VRPM)

- OP-FITR system is positioned downwind from the source
- Multiple retroreflectors strategically placed to cover outflow from the source
- VRPM combines path-averaged concentrations from OP-FITR measurements with wind speed and direction to calculate emission fluxes
- Permanent installation



METHODS: AREA SOURCE TECHNIQUE

- Single light path OP-FITR system is positioned downwind from the source
- Retroreflector is placed so emission plume crosses the light path
- Path-averaged concentrations from OP-FITR measurements, wind speed and direction used to model emission fluxes
- Quick installation for short-term deployments



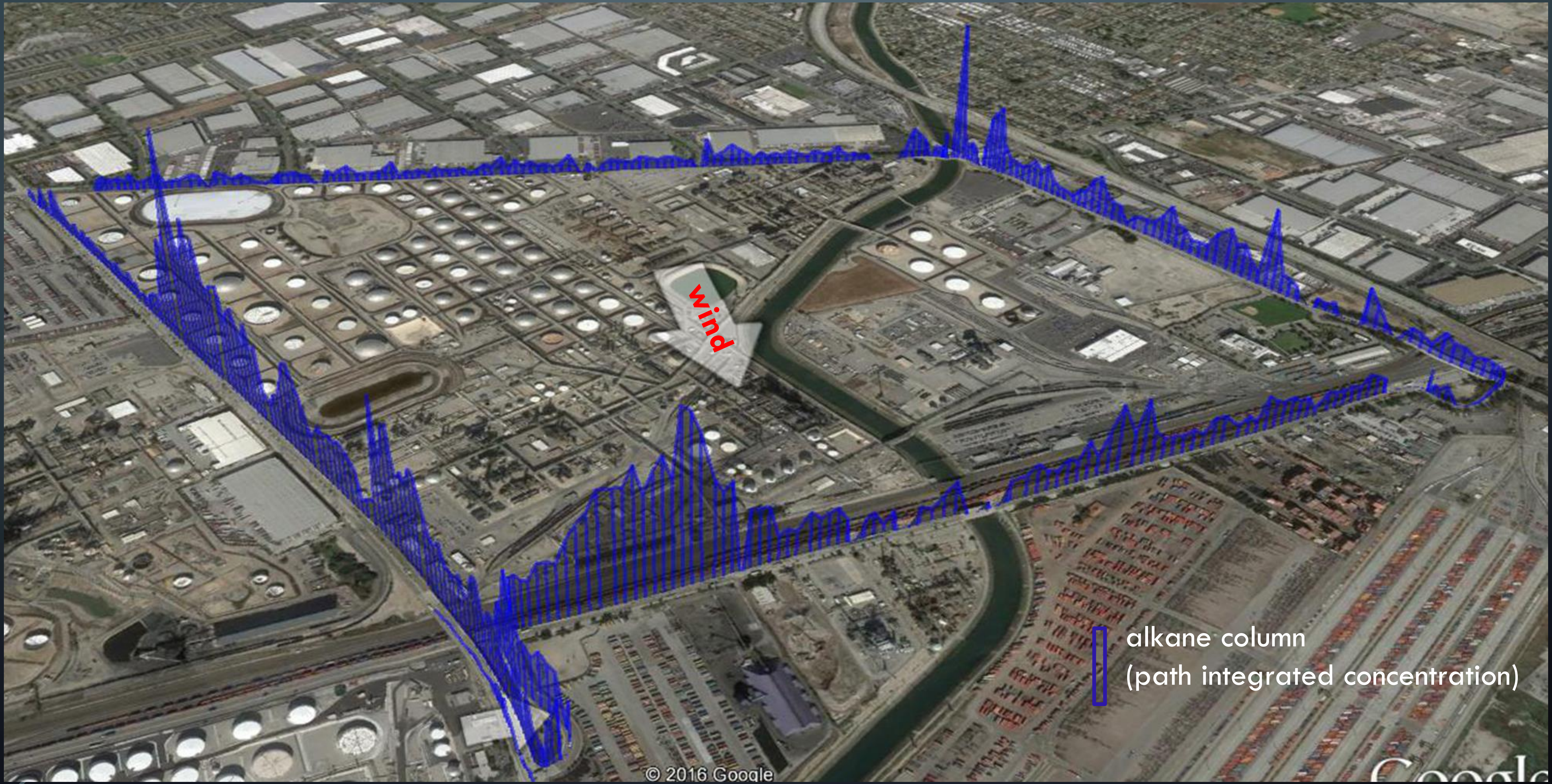
PROJECT 1: QUANTIFY FUGITIVE EMISSIONS FROM LARGE REFINERIES

- *FluxSense*
  - **SOF + FTIR + DOAS**
  - Mobile measurements (daytime only)
  - 5 week study at 6 refineries in the SCAB
  - Facility-wide emissions of methane, non-methane VOCs, NO_2, SO_2, BTEX

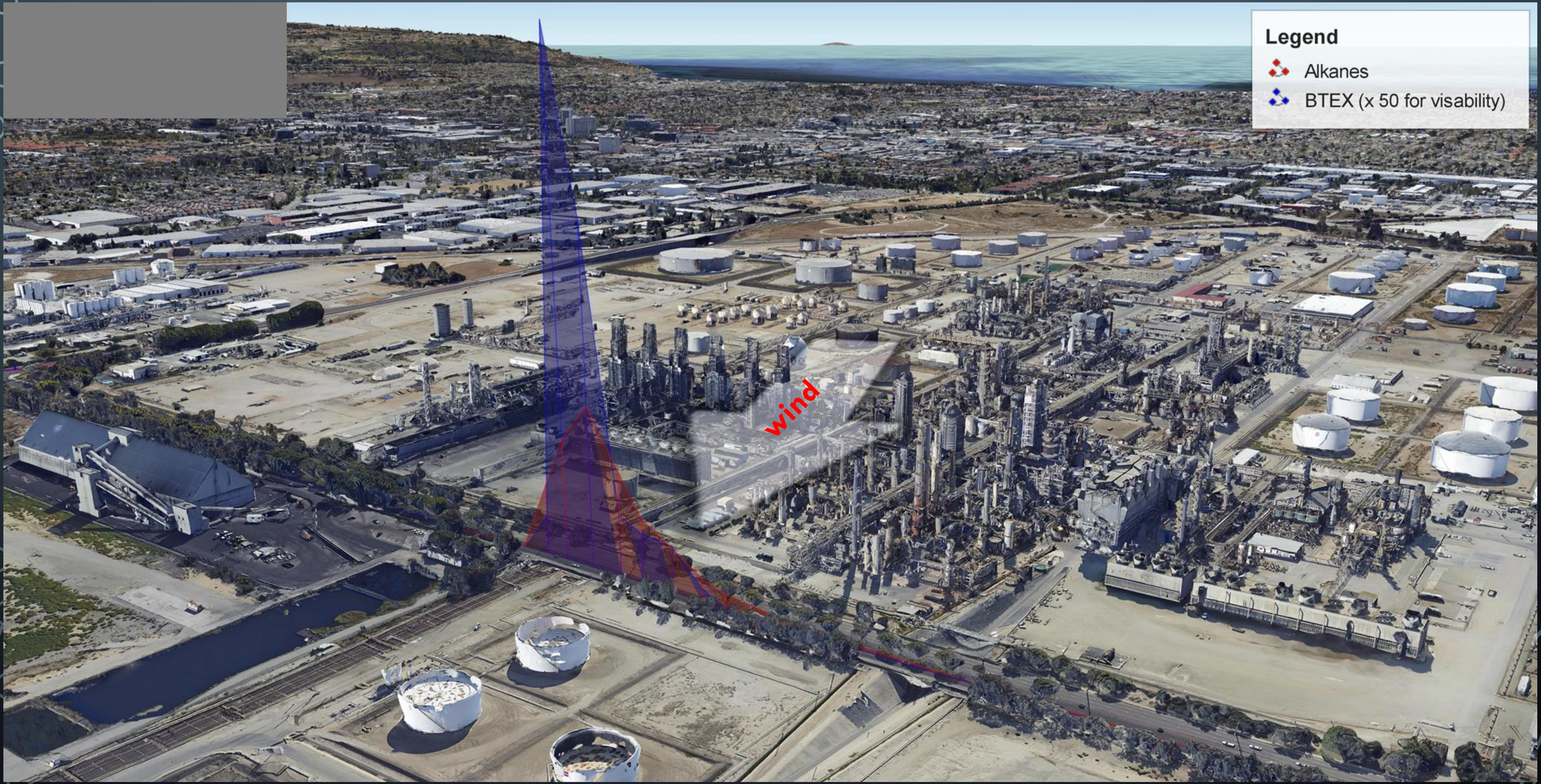
- *National Physical Laboratory (NPL)*
  - **DIAL**
  - Stationary daytime and nighttime measurements
  - 1-week study at 1 refinery
  - Facility-wide emissions of non-methane VOCs, BTEX
  - **Ideal for field validation**

- *Atmosfir Optics*
  - **VRPM Using Open-path FTIR**
  - Large installation, continuous (24/7) measurements
  - 5-week study at 1 refinery
  - Emissions of methane, non-methane VOCs
  - EPA OTM-10 method
  - **Complements mobile and other short-term observations**

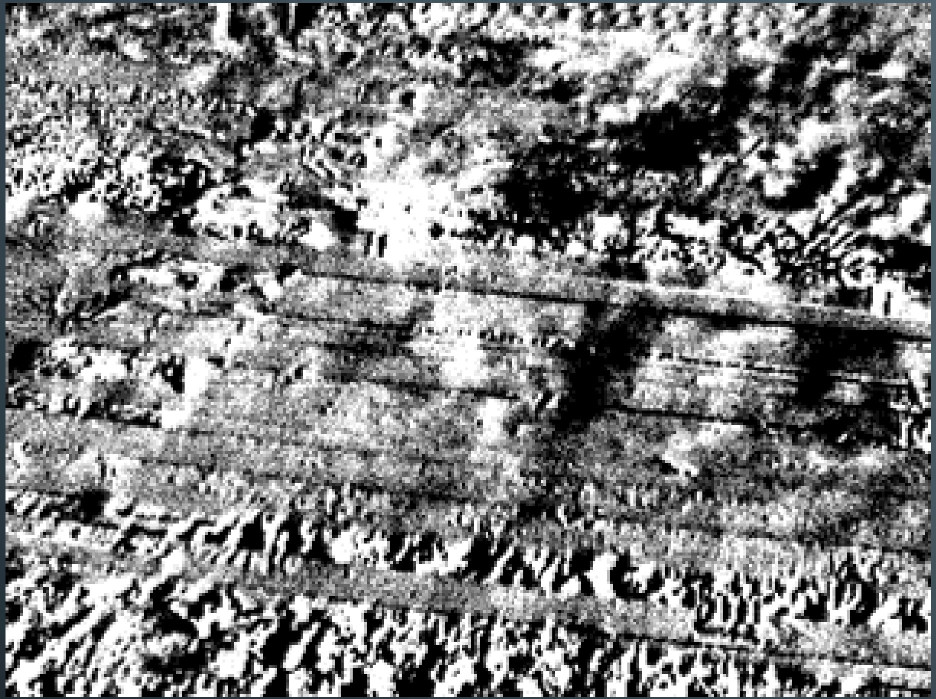
SOF MEASUREMENTS ALONG REFINERY FENCELINE

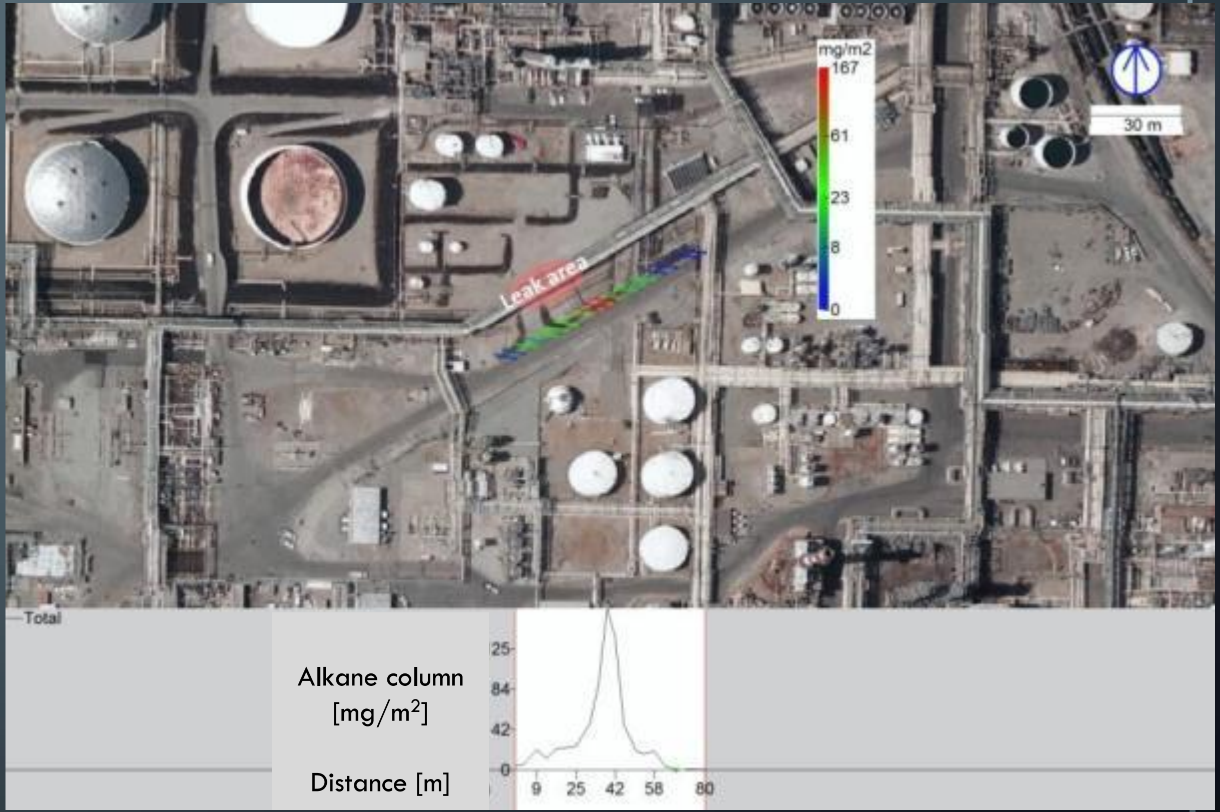


ALKANES AND BTEX DOWNWIND OF A REFINERY



DISCOVERY OF UNDERGROUND LEAK FROM A CORRODED PIPE

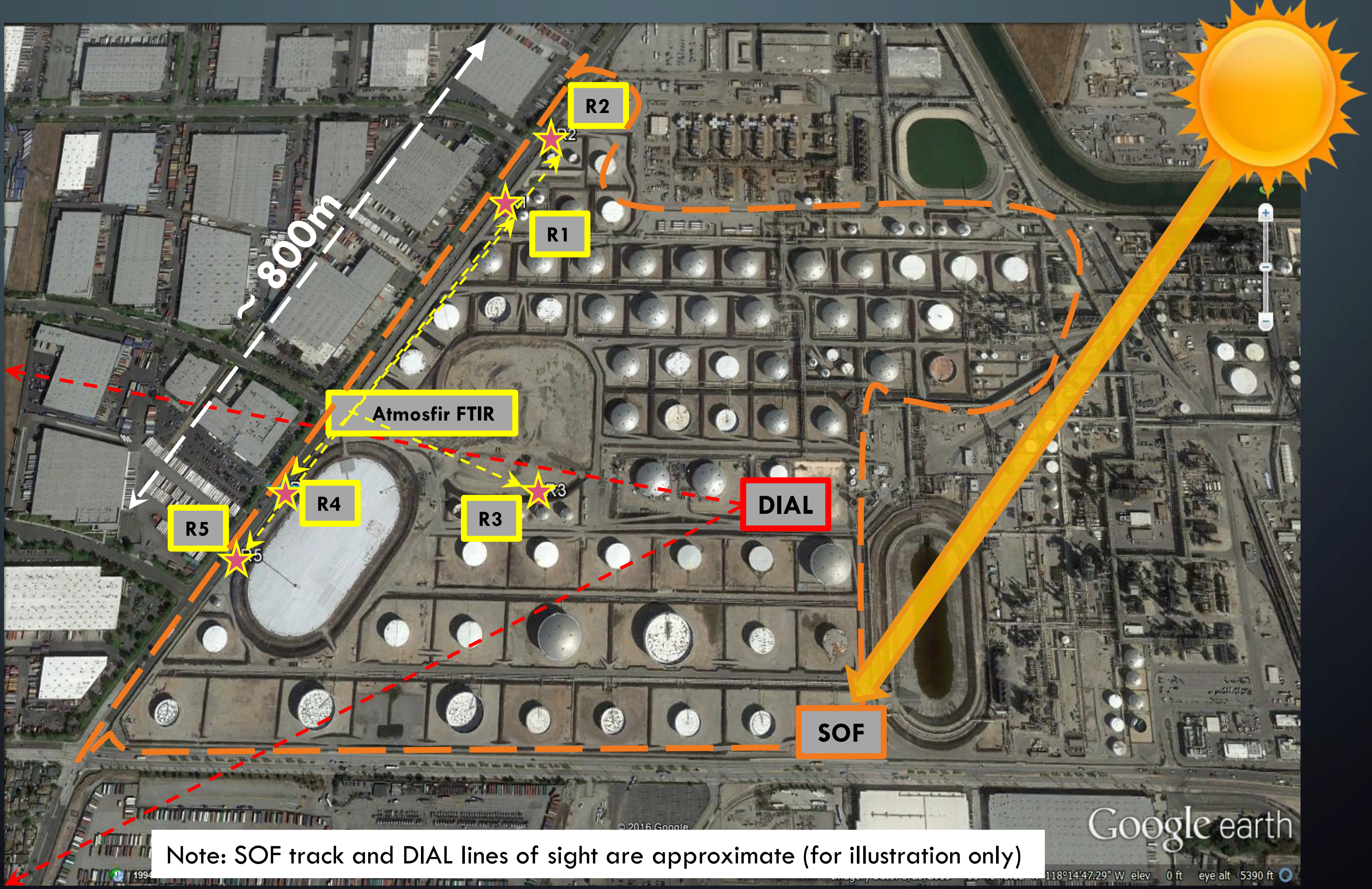




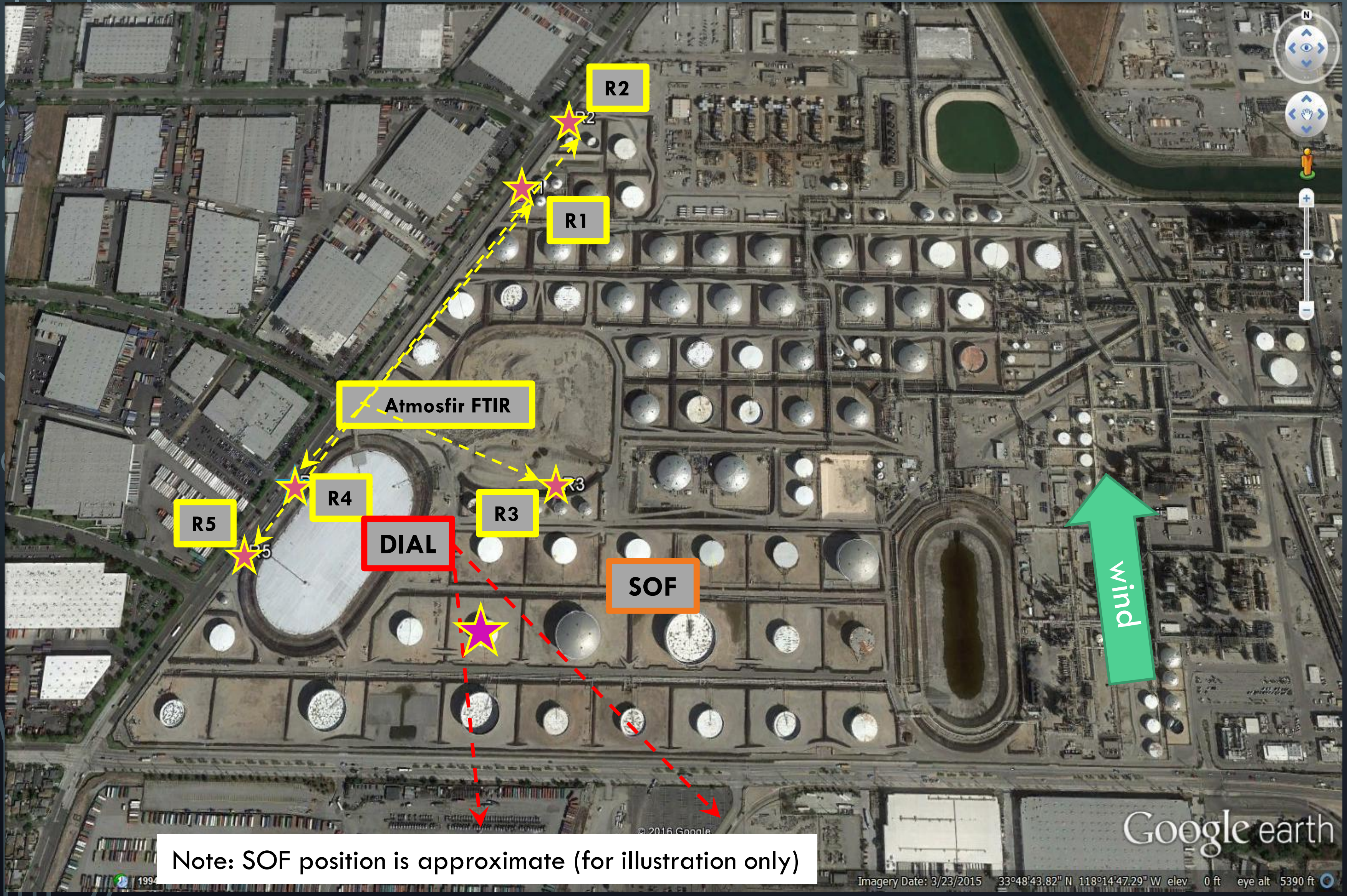
- September 30, 2015, at ~4:00pm
- Fluxsense discovered a leak from a corroded underground pipe
- Discovery was made while driving inside the facility
- FLIR images/videos confirmed emissions from the ground

- Measured alkanes concentrations: ~70,000 ppb
- Average VOC emissions: 31 kg/h

CO-LOCATED MEASUREMENTS AT REFINERY TANK FARM

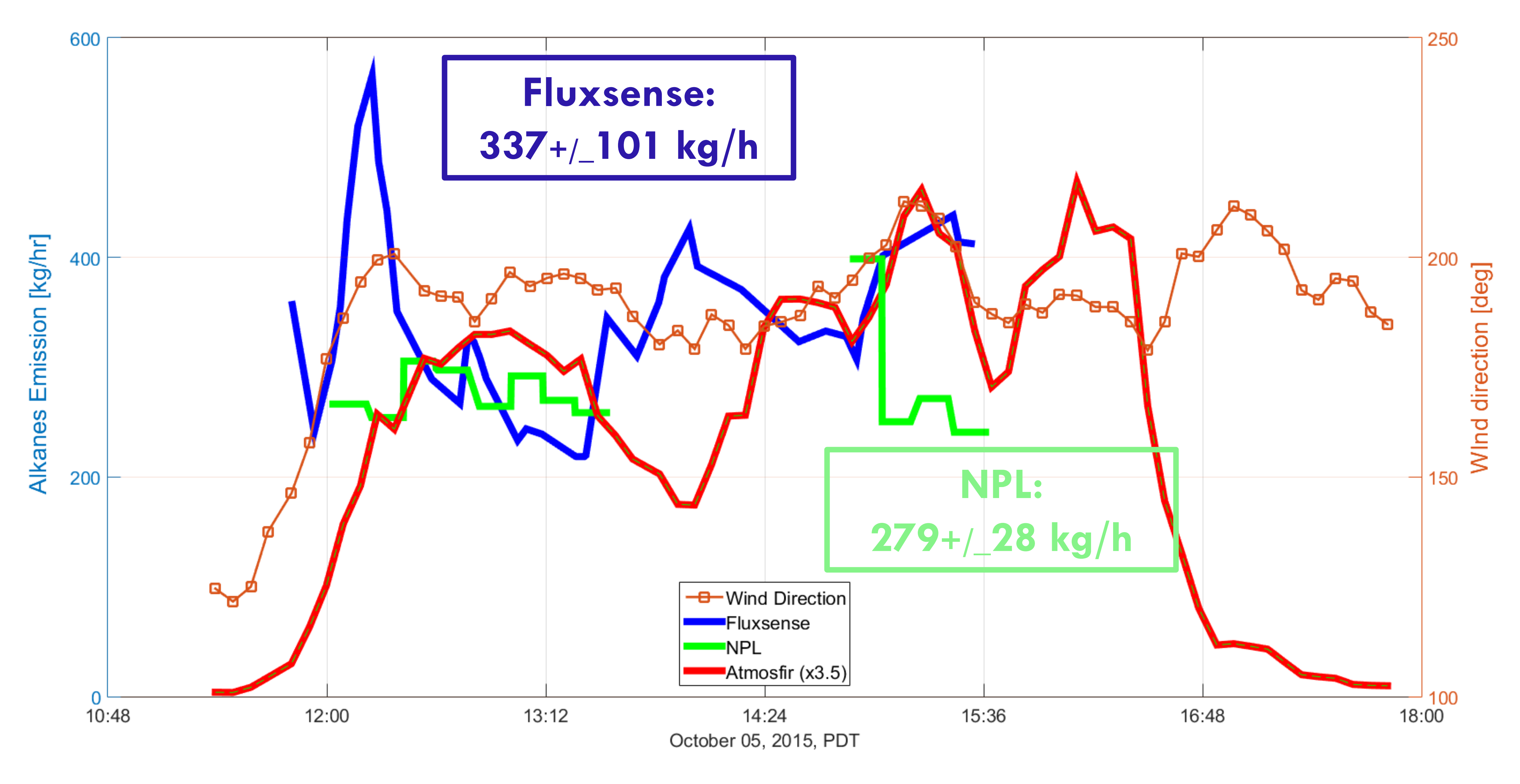


MONITORING OF A TANK LEAK EVENT

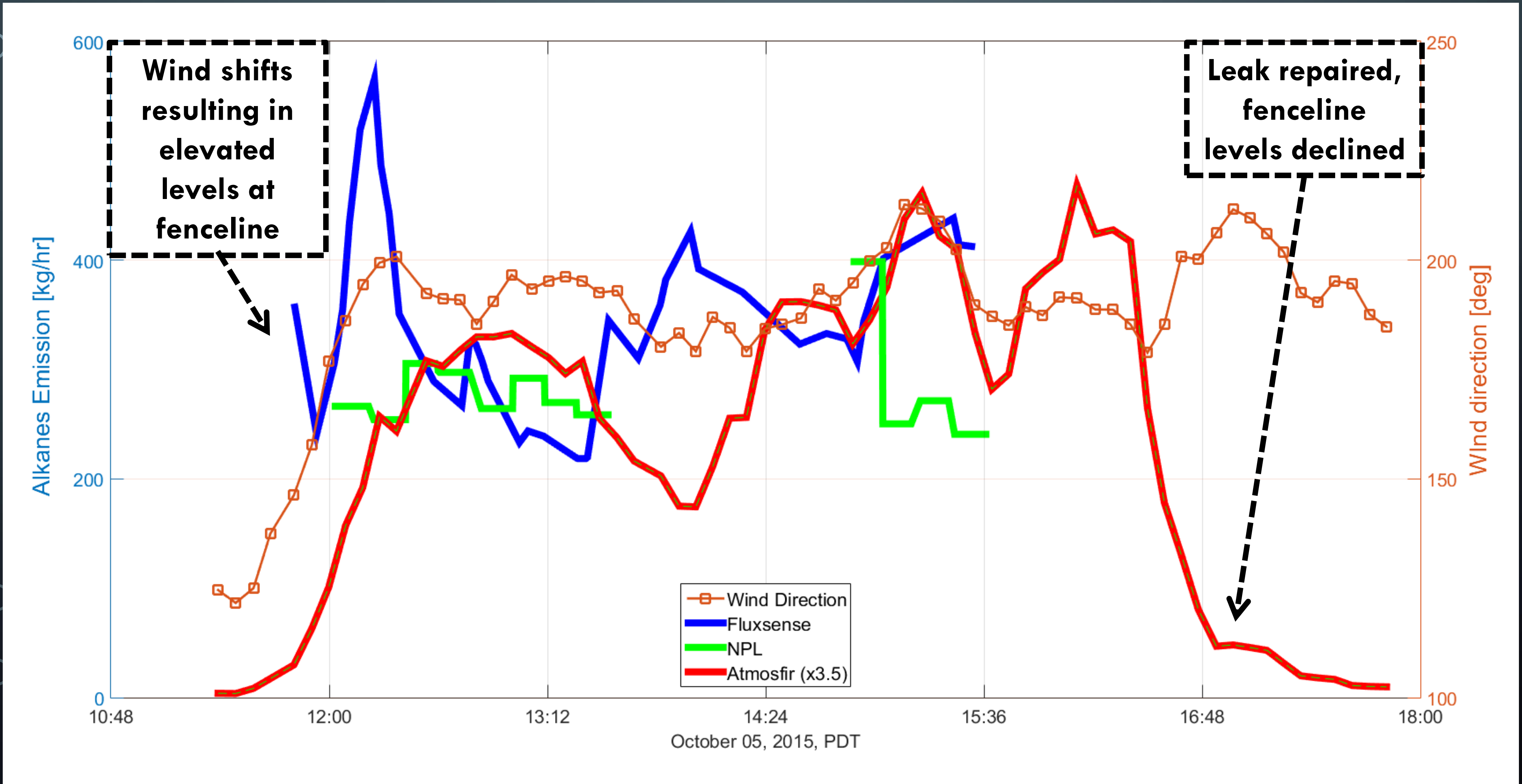


- October 5, 2015 11:30am-4:30pm
- Emissions from a tank were observed by all three ORS technologies
- Fenceline concentrations of alkanes decreased dramatically after emissions stopped

EMISSIONS OF ALKANES FROM A LEAKING TANK



DETECTION OF ELEVATED ALKANES AT REFINERY FENCELINE



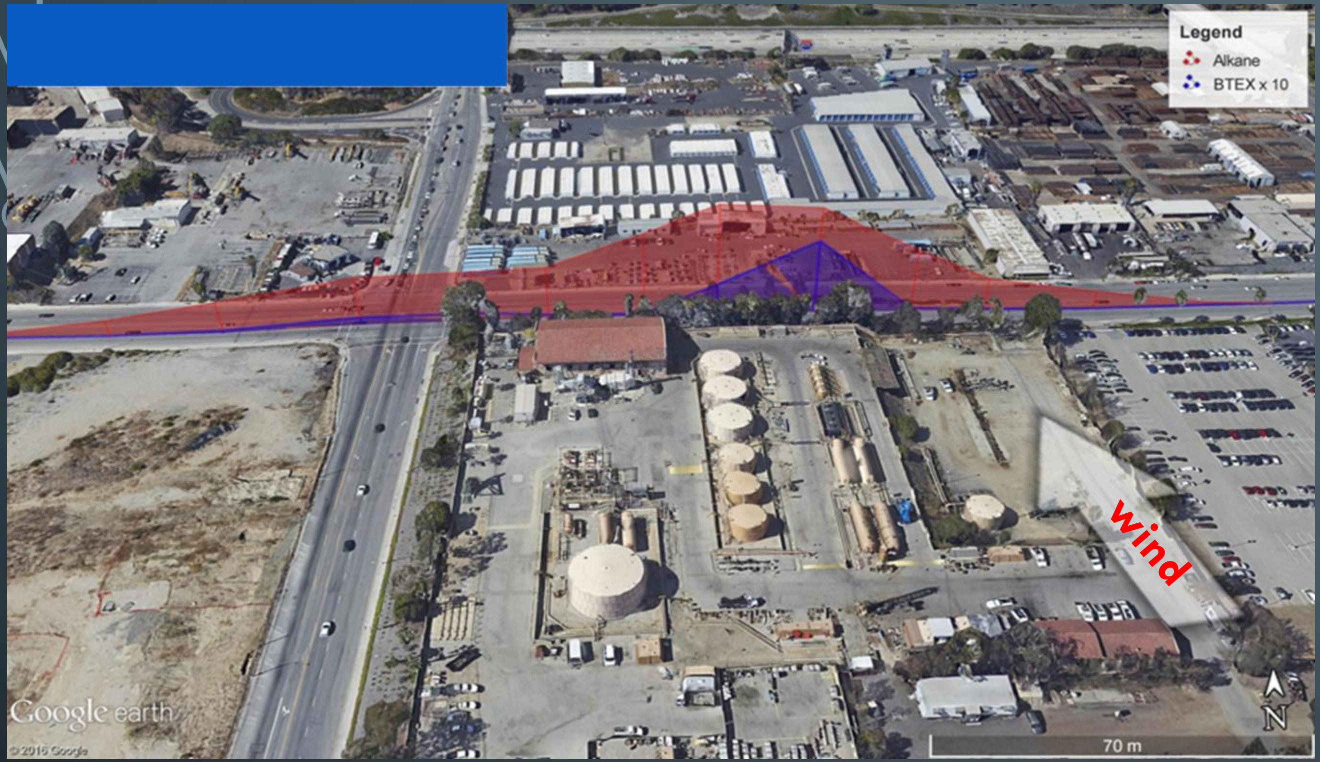
PROJECT 2:
QUANTIFY GASEOUS EMISSIONS FROM SMALL POINT SOURCES

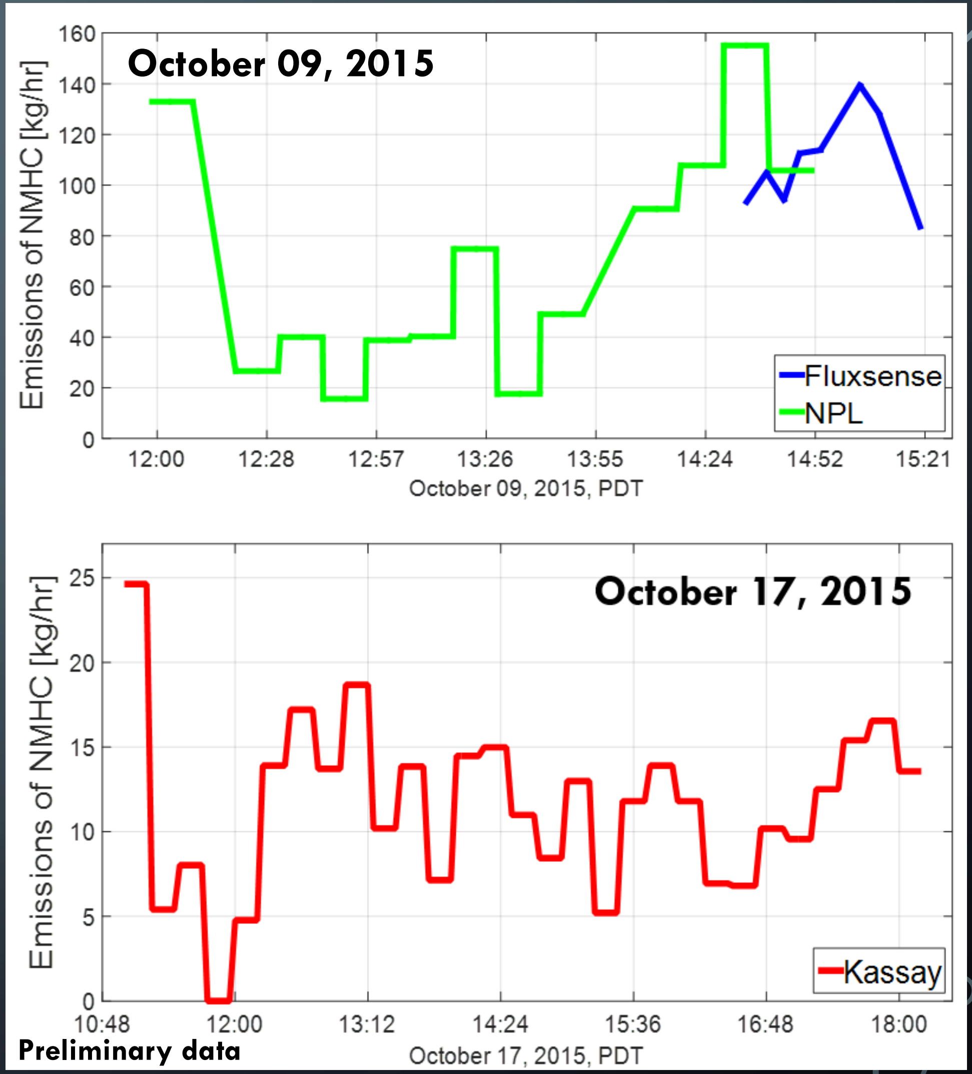
- *FluxSense*
  - **SOF + Extractive FTIR + DOAS**
  - Mobile measurements (daytime only)
  - 5 week study of ~100 small sources:
    - Oil wells
    - Intermediate oil treatment facilities
    - Gas stations
    - Other small sources
  - Methane and non-methane VOCs, BTEX

- *National Physical Laboratory (NPL)*
  - **Differential Absorption Lidar (DIAL)**
  - Stationary daytime and nighttime measurements
  - 1 week study at selected sources
  - Methane and non-methane VOCs
  - **Ideal for field validation**

- *Kassay Field Services*
  - **Open-path FTIR + reverse plume modeling**
  - Stationary daytime and nighttime measurements
  - 5 week study at ~50 small sources
  - Methane and non-methane VOCs, BTEX
  - OP-FTIR using EPA TO-16 method

EMISSIONS FROM A SMALL OIL TREATMENT FACILITY

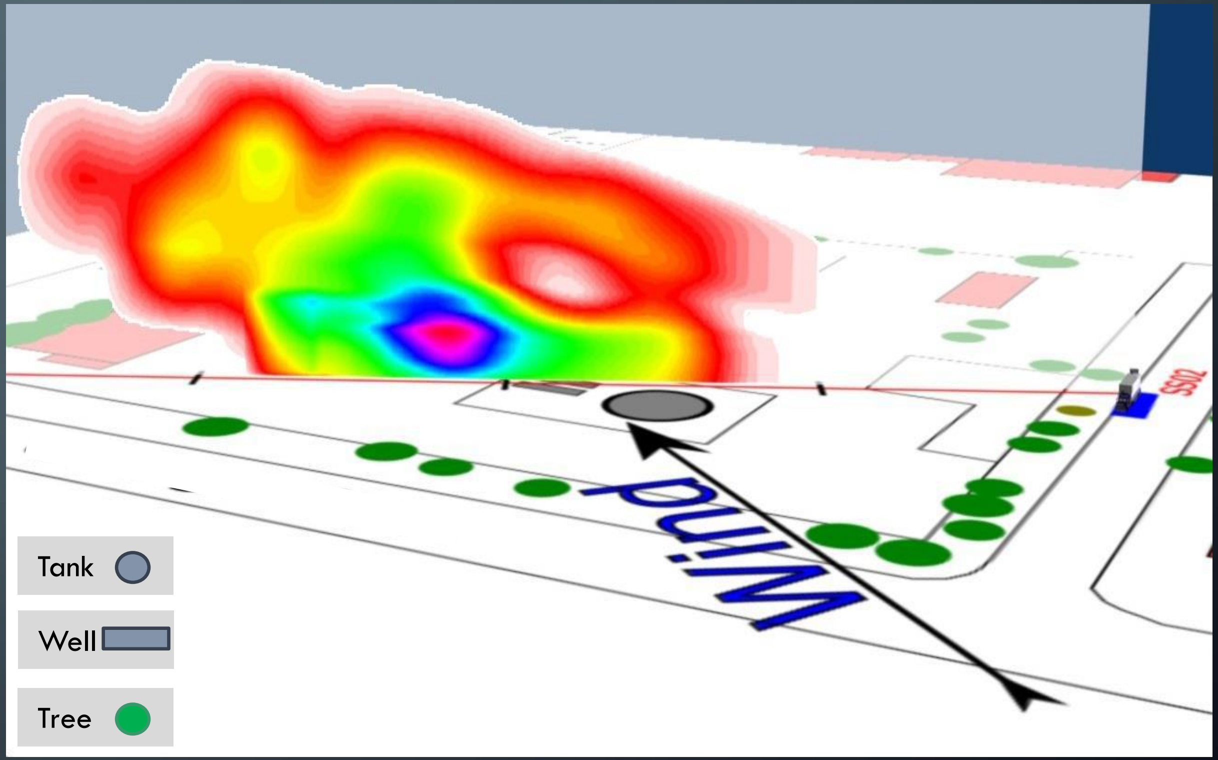




- 24 mobile SOF surveys over 5 weeks
- Elevated NMHC emissions detected during all monitoring days
- Good agreement between SOF and DIAL during co-located measurements
- FTIR not able to capture the entire plume, but useful for long-term trends

VISUALIZATION OF EMISSIONS FROM A SMALL OIL TREATMENT FACILITY

FLIR video

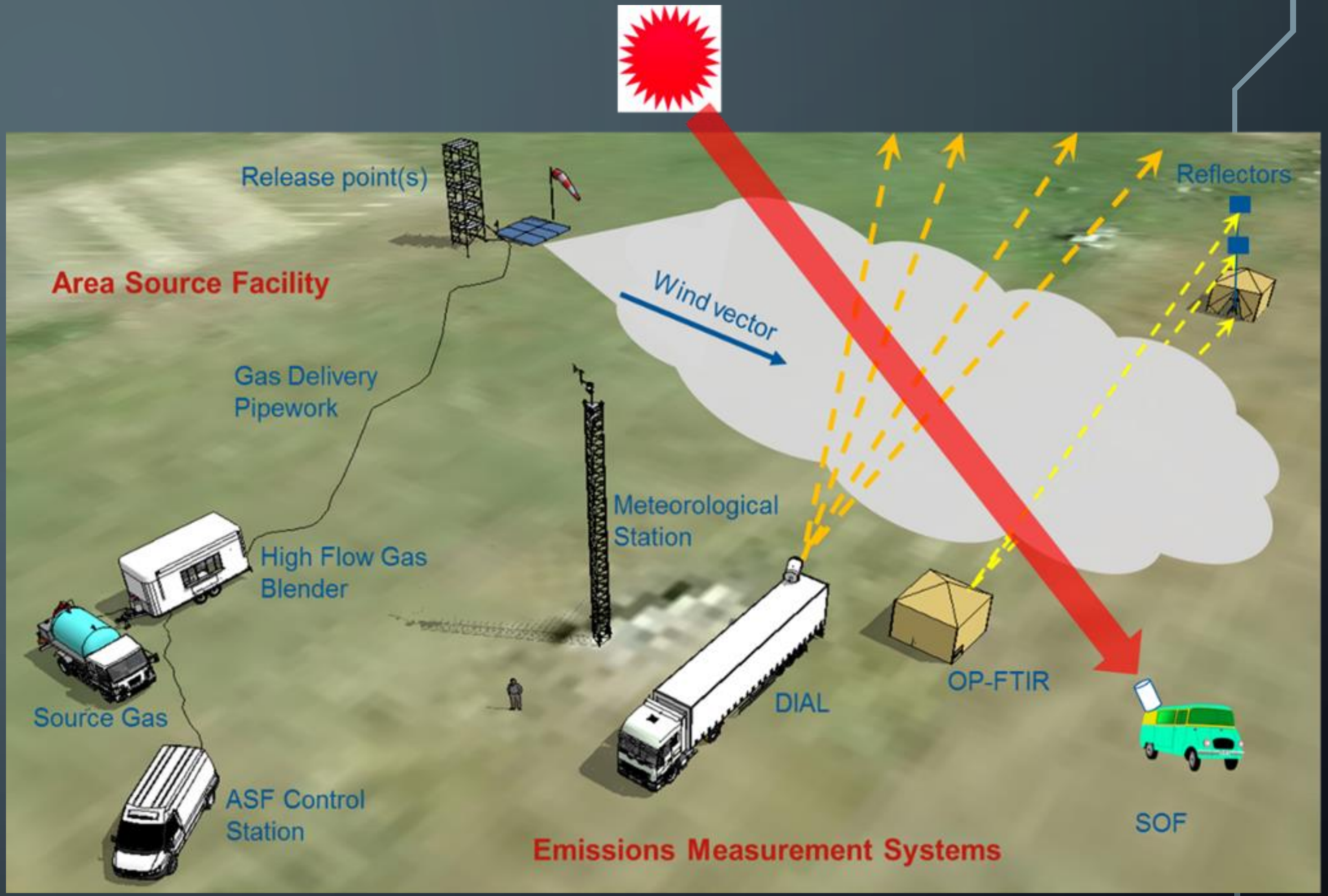


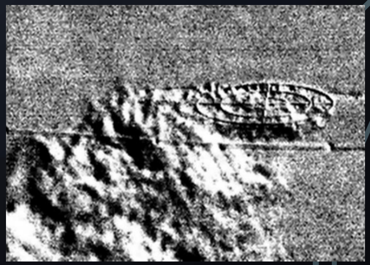
DIAL visualization of VOC emissions

Storage tank is most likely the main source of emissions from the facility

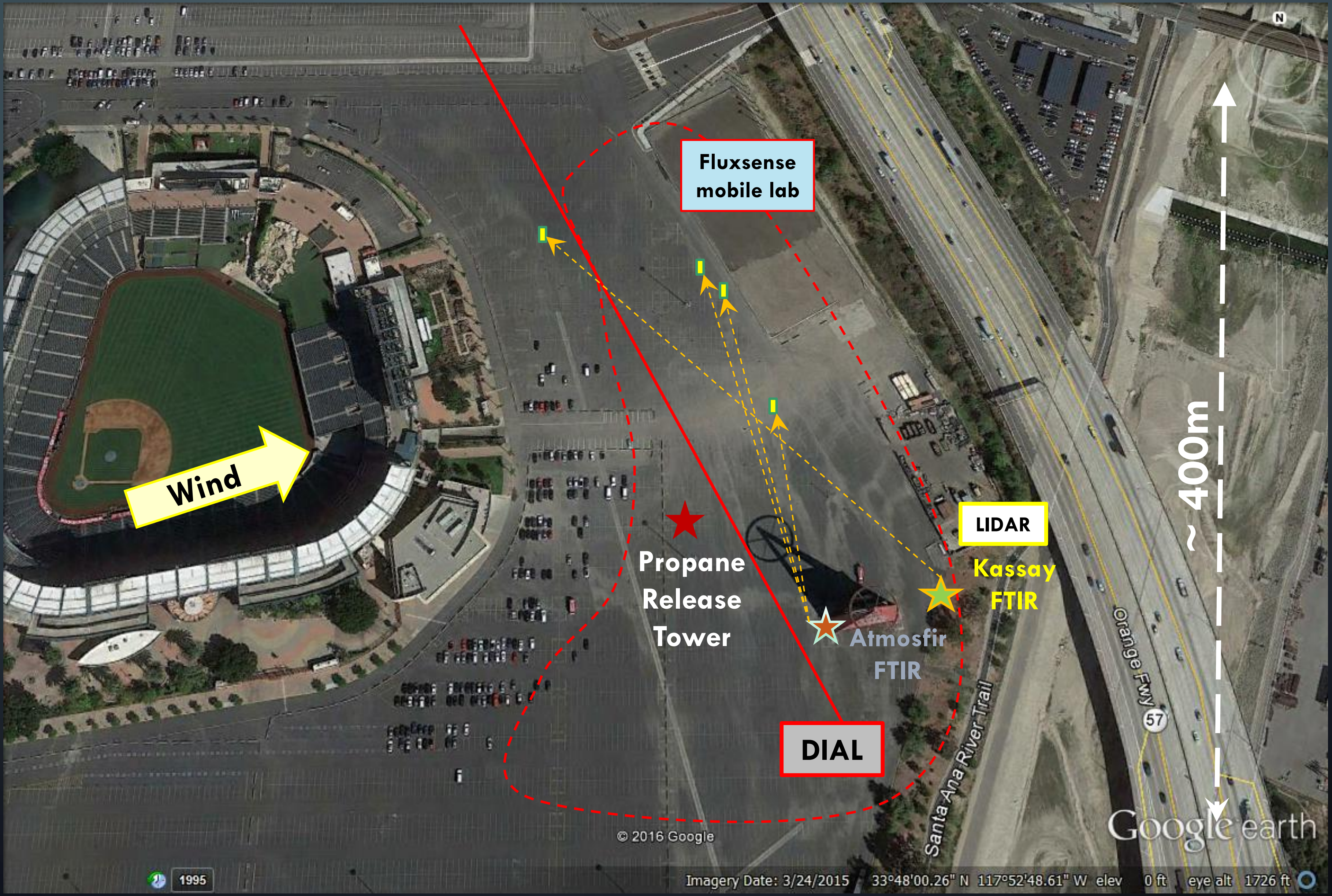
CONTROLLED-RELEASE METHOD INTERCOMPARISON STUDY

- Conducted on October 12–13, 2015 inside the Angels' Stadium in Anaheim, CA
  - Complex urban environment
  - Near a major freeway
- NPL Area Source Facility (ASF) operated by SCAQMD staff
- Non-odorized propane released at various emission rates; each release lasted ~1 hour
- Release point heights: 3m, 6.4m, 7.9m
- Blind measurements performed by all ORS contractors
- Meteorological data collected by and shared with all vendors
  - SCAQMD operated LIDAR to provide accurate wind profile data





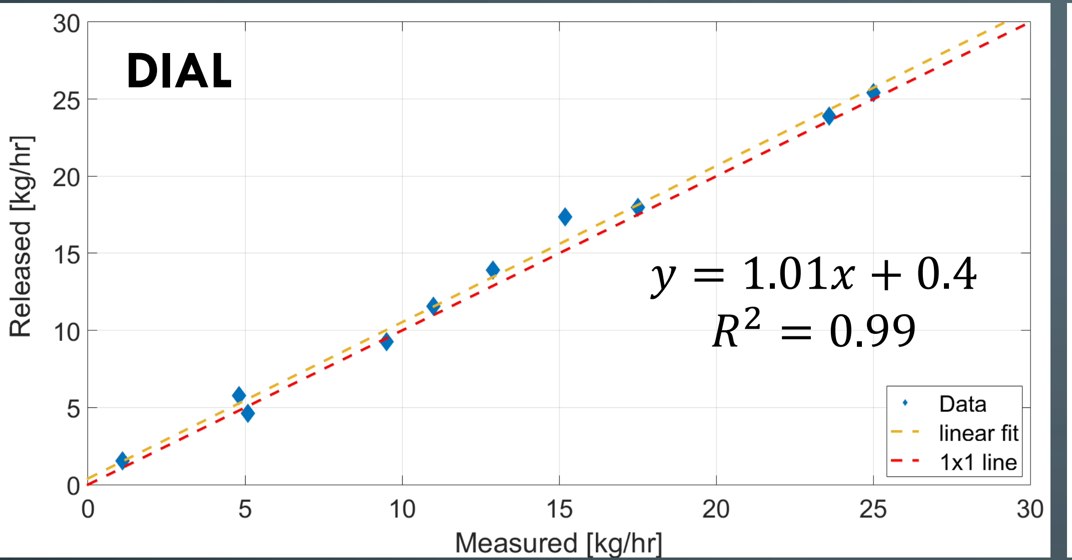
EXPERIMENTAL SETUP

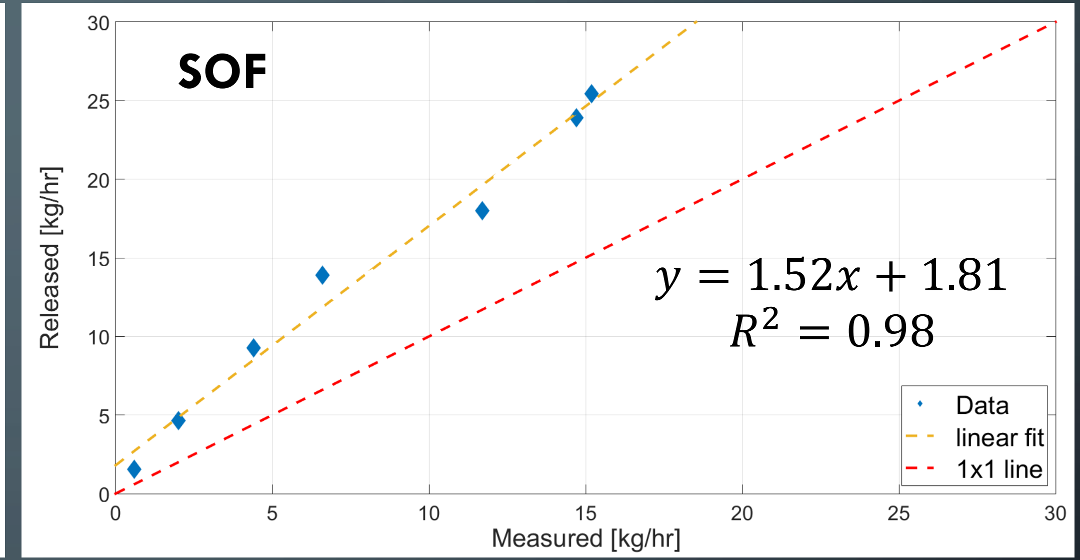


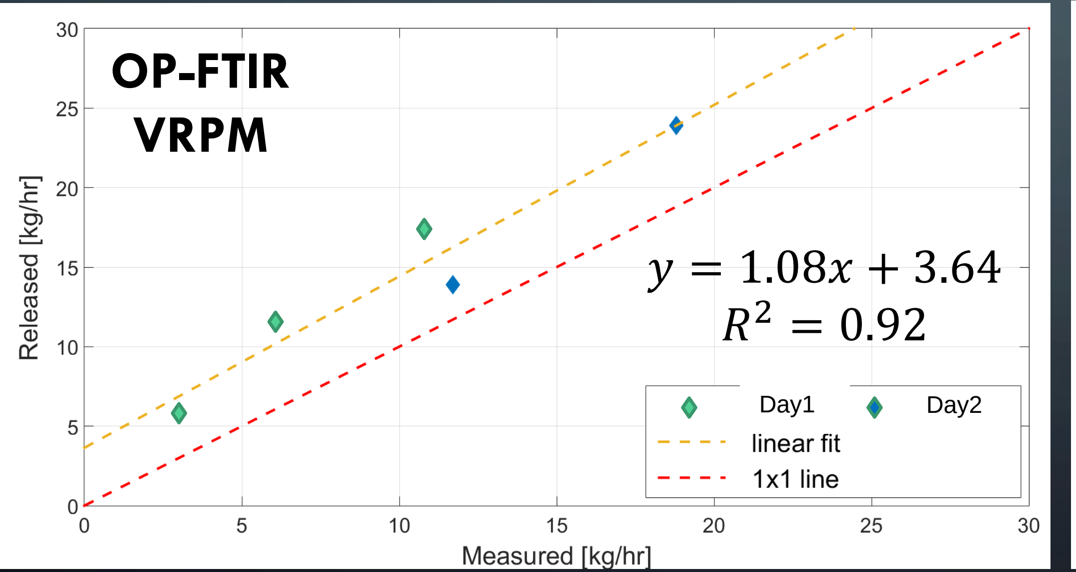
PROPANE PLUME VISUALIZATION

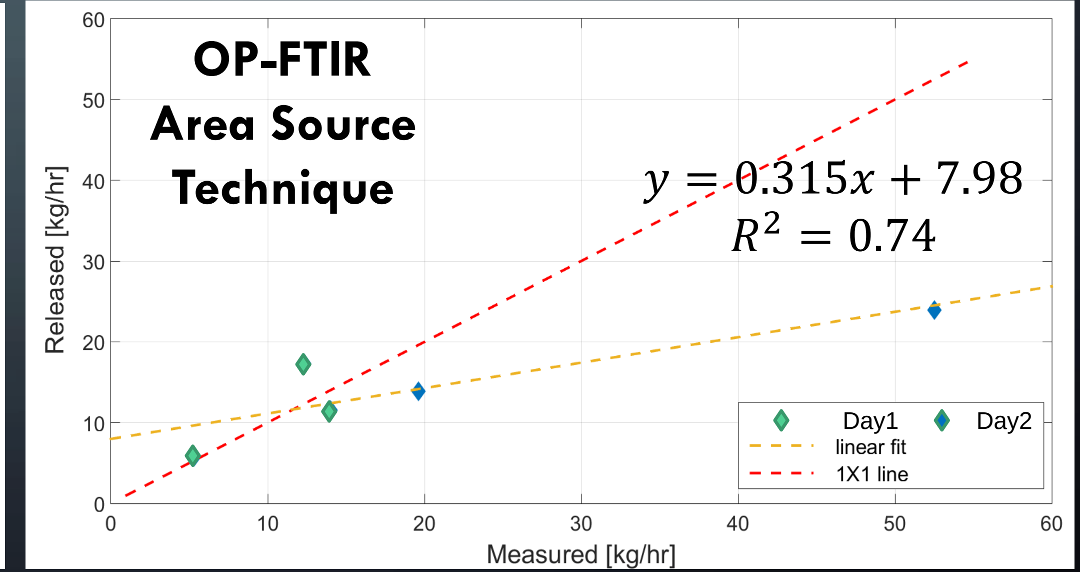
- FLIR video (October 13, 2015 3:41pm)

CONTROLLED-RELEASE STUDY: RESULTS



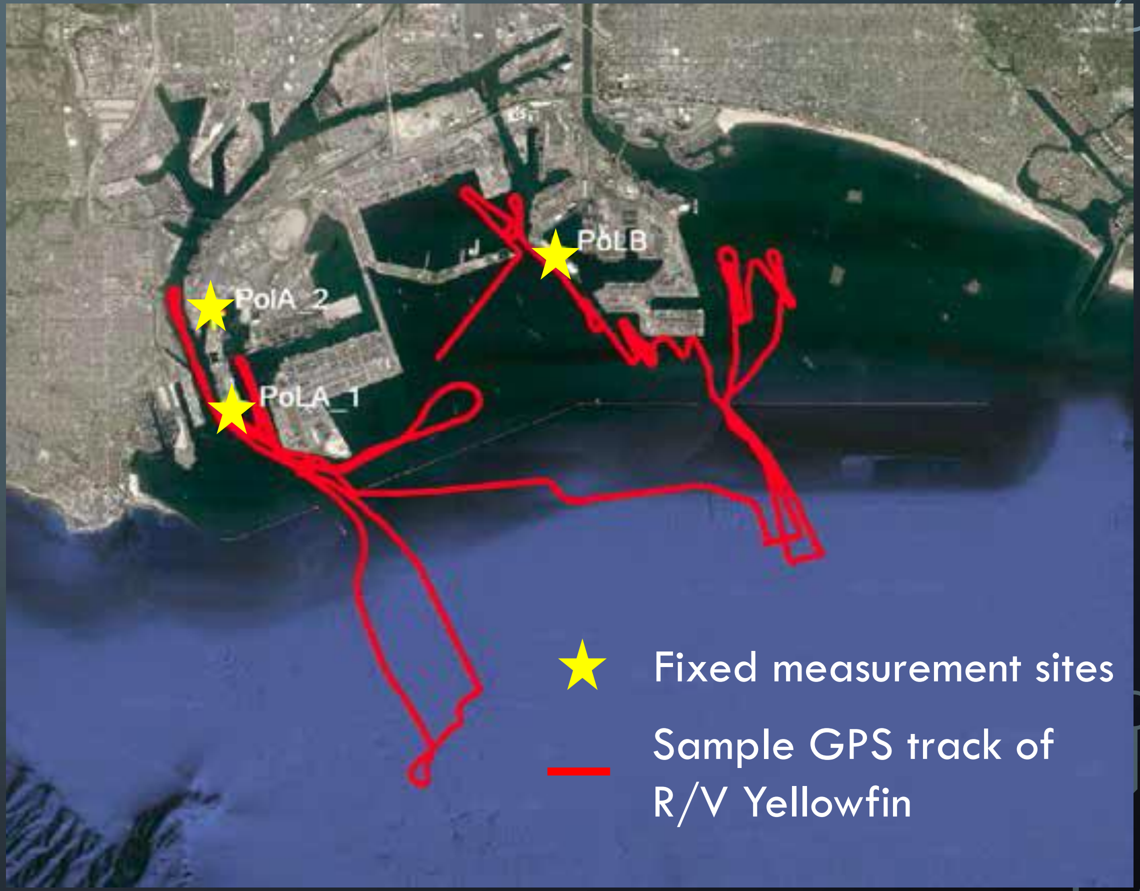




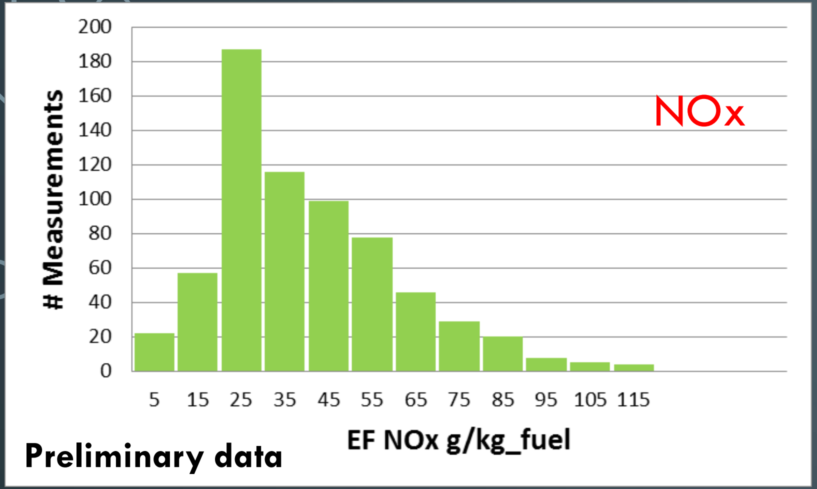


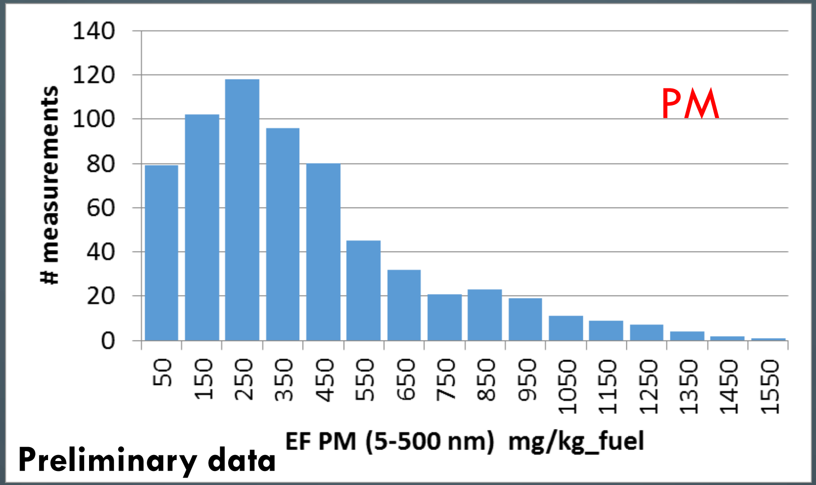
PROJECT 3:
QUANTIFY STACK EMISSIONS FROM MARINE VESSELS

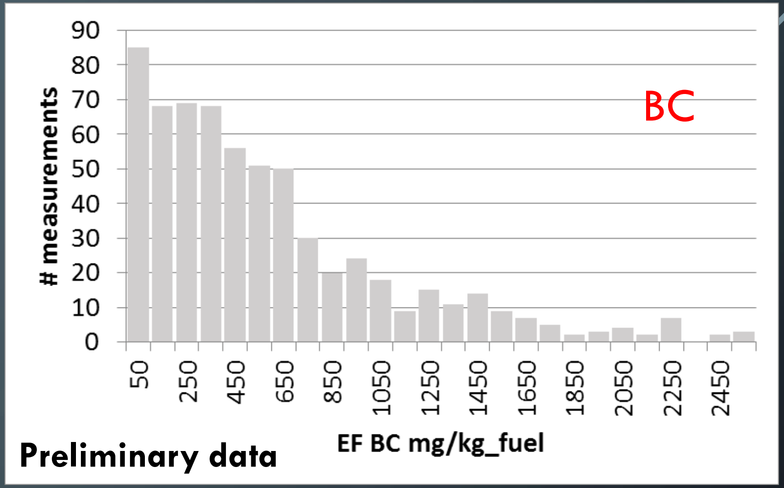
- *FluxSense*
  - **Mini-SOF, DOAS and "traditional" methods**
  - Measurements of individual ships
  - 4 week study at Port of Los Angeles and Port of Long Beach
  - Measurements performed
    - on-shore at fixed locations within POLA and POLB
    - off-shore from R/V Yellowtail provided by Southern California Marine Institute
  - "Real world" emissions (g/s) of SO2 and NO2 and "actual" emission factors (g/Kg fuel burnt) of SO2, NOx and particulates from individual ships
  - 692 ships sampled during the study

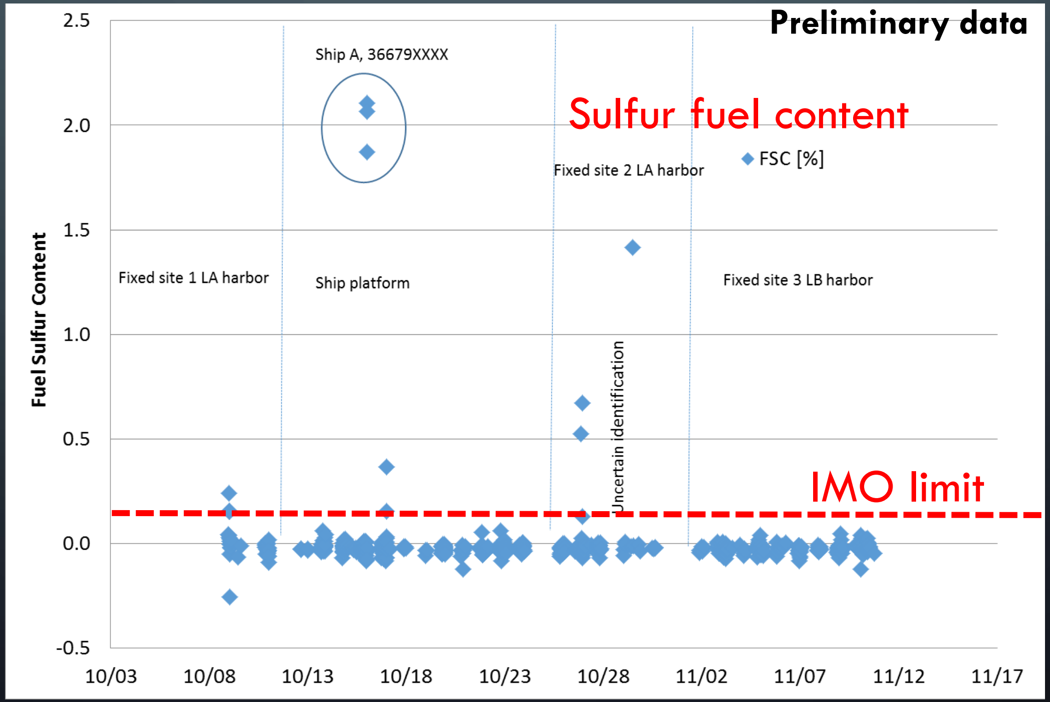


EMISSIONS FROM 692 SHIPS SAMPLED IN POLA AND POLB





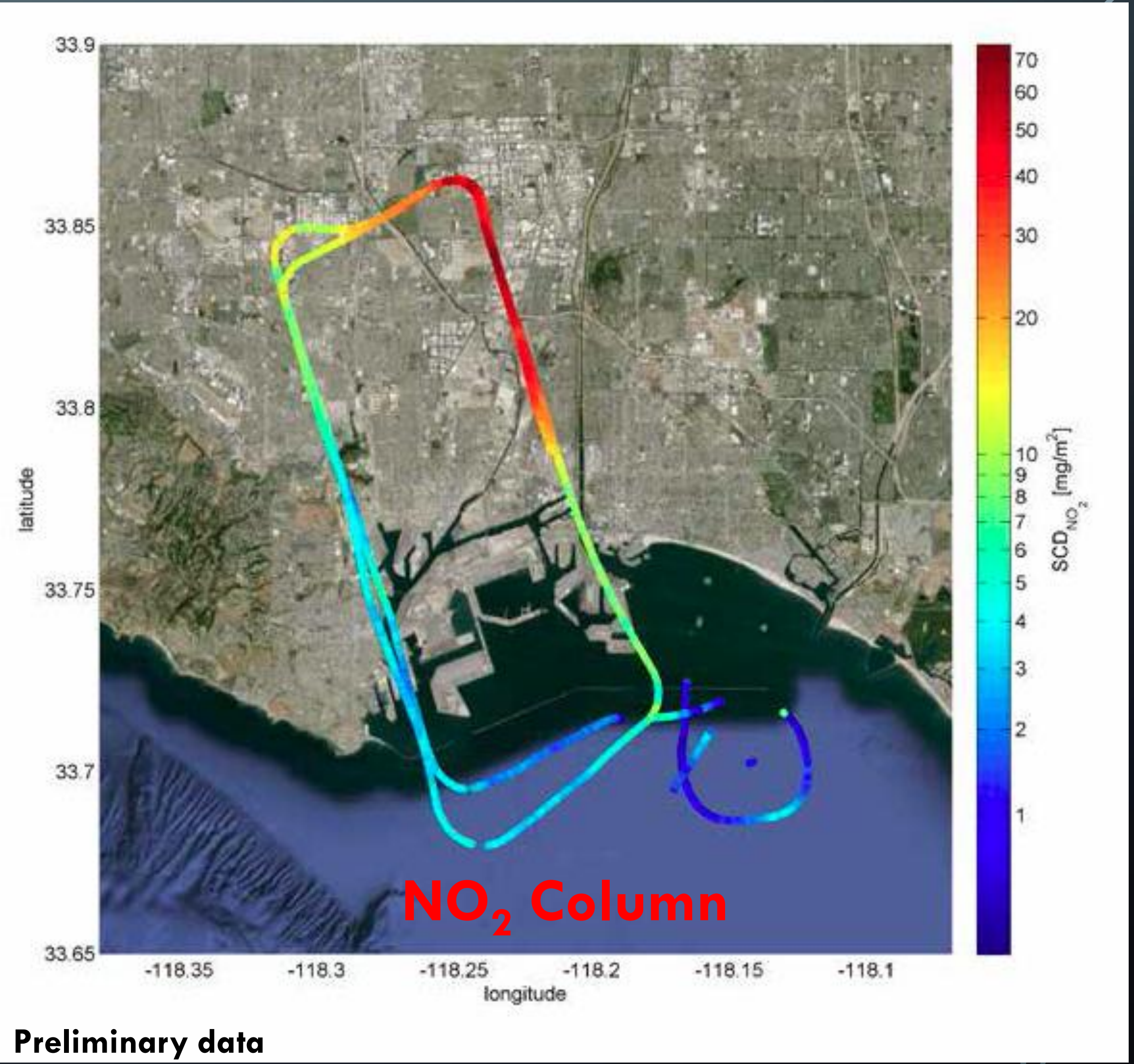




AIRBORNE OPTICAL REMOTE SENSING MEASUREMENTS

MAX-DOAS Telescope looking out of pilot's window

MAX-DOAS Spectrometer on the back seat

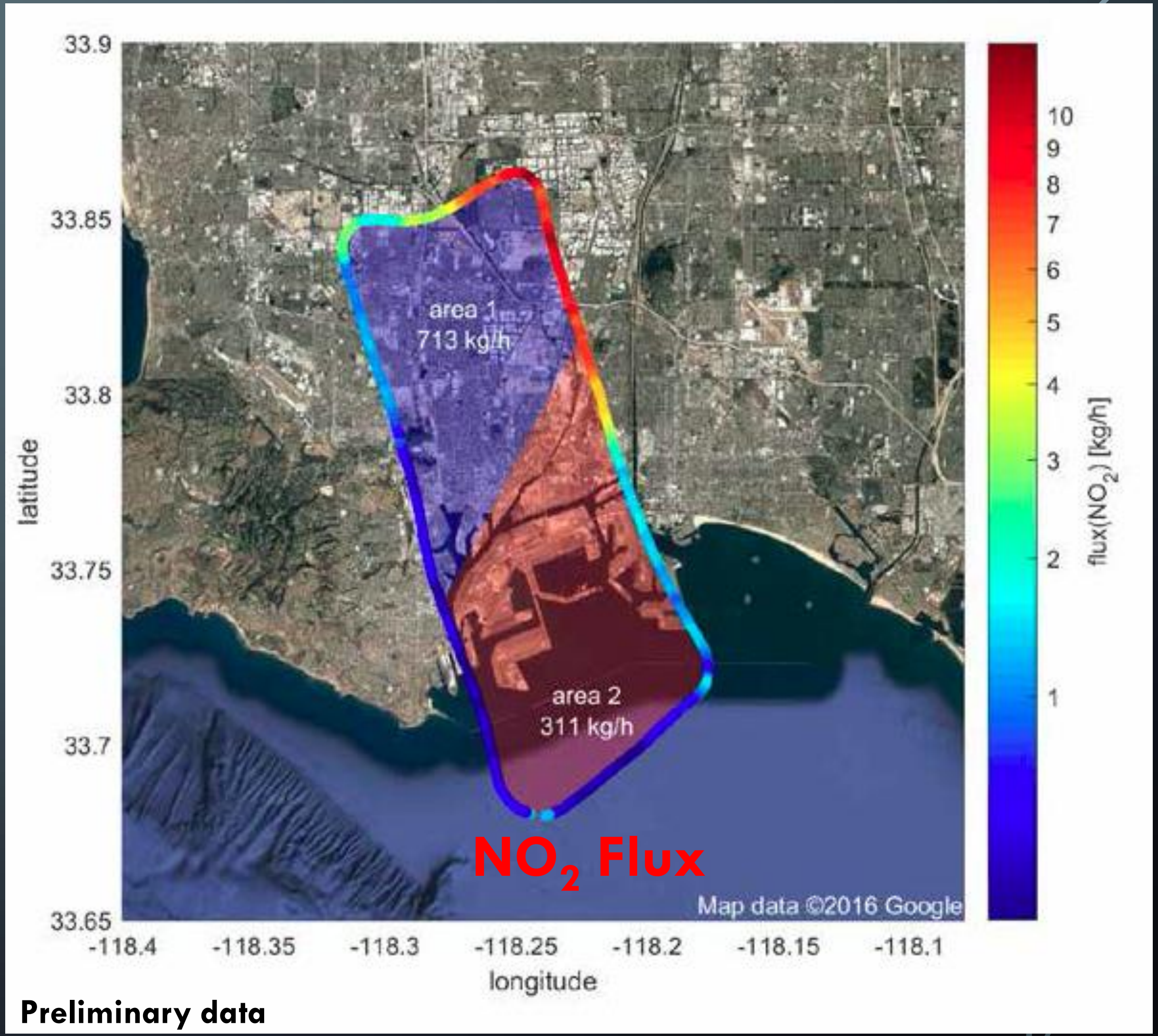


Sunday, November 08, 2015

AIRBORNE OPTICAL REMOTE SENSING MEASUREMENTS

MAX-DOAS Telescope looking out of pilot's window

MAX-DOAS Spectrometer on the back seat



Sunday, November 08, 2015

SUMMARY – OPTICAL REMOTE SENSING

- ORS techniques can provide:
  - Quick identification of potential leaks, offering substantial improvement of LDAR program or ISD systems
  - Detailed characterization of areas that contribute the most to measured emissions
  - Real or near-real time emission measurements
  - Improved emission inventories
- ORS methods are suitable for monitoring of emissions from large facilities as well as small sources
- Mobile ORS methods are effective way to screen large number of small sources quickly
- Good agreement between different ORS techniques during co-located measurements of “real-life” sources
- Strong correlations (R^2) between released and measured emissions for all methods during controlled-release study
- Strengths and weaknesses of each technology:
  - SOF: mobile measurements are ideal for routine surveys inside and outside facilities
  - DIAL: very precise and accurate, but not suited for long-term monitoring
  - OP-FTIR: can provide useful information on long-term variability of emissions and record fenceline concentrations of pollutants

LOW-COST AIR QUALITY SENSORS

South Coast AQMD

AQ-SPEC

Air Quality Sensor Performance Evaluation Center

BACKGROUND

- AQ-SPEC was established in July 2014
- Over $500,000 investment
- Main Goals & Objectives
  - *Provide guidance & clarity for ever-evolving sensor technology*
  - *Catalyze successful evolution/use of "low-cost" sensors*
  - *Minimize confusion*
- Sensor Selection Criteria
  - *Commercially available (American, European and Asian markets)*
  - *Real- or near-real time*
  - *Criteria pollutants & air toxics*

FIELD DEPLOYMENT

- September 2014: First sensor was deployed in the field
- October 2016: Nearly 30 sensors have been field-tested

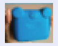
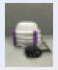
- Rubidoux station (main)
  - Inland site
  - Fully instrumented

- I-710 station
  - Near-roadway site
  - Fully instrumented

www.aqmd.gov/aq-spec

FIELD TESTING RESULTS

PM Sensors

Sensor Image	Manufacturer (Model)	Type	Pollutant(s)	Approximate Cost (USD)	Time Resolution	Sensor vs FEM/FRM Method[1]
	**AethLabs** (microAeth)	Optical	BC (Black Carbon)	~$6,500	1 - 300 sec	R^2 ~ 0.79 to 0.94
	**Air Quality Egg** (Version 1)	Optical	PM	~$200	1 min	R^2 ~ 0.0
	**Air Quality Egg** (Version 2)	Optical	PM	~$240	1 min	$PM_{2.5}$: R^2 ~ 0.79 to 0.85 PM_{10}: R^2 ~ 0.31 to 0.40
	**Alphasense** (OPC-N2)	Optical	$PM_{1.0}$, $PM_{2.5}$ & PM_{10}	~$450	15 sec	$PM_{1.0}$: R^2 ~ 0.63 to 0.82 $PM_{2.5}$: R^2 ~ 0.38 to 0.80 PM_{10}: R^2 ~ 0.41 to 0.60
	**Dylos** (DC1100)	Optical	$PM_{(0.5\text{-}2.5)}$	~$300	1 min	R^2 ~ 0.65 to 0.85
	**HabitatMap** (AirBeam)	Optical	$PM_{2.5}$	~$200	1 min	R^2 ~ 0.65 to 0.70
	**MetOne** (Neighborhood Monitor)	Optical	$PM_{2.5}$	~$1,900	15 min	R^2 ~ 0.53 to 0.67
	**Naneos** (Partector)	Electrical	PM (LDSA: Lung-Deposited Surface Area)	~$7,000	1 min	$PM_{1.0}$: R^2 ~ 0.1 $PM_{2.5}$: R^2 ~ 0.2
	**Perkin Elmer** (ELM)	Optical	PM	~$5,200	1 min	R^2 ~ 0.0
	**PurpleAir**	Optical	$PM_{1.0}$, $PM_{2.5}$ & PM_{10}	~$150	20 sec	$PM_{1.0}$: R^2 ~ 0.93 to 0.95 $PM_{2.5}$: R^2 ~ 0.77 to 0.92 PM_{10}: R^2 ~ 0.32 to 0.44
	**RTI** (MicroPEM)	Optical	$PM_{2.5}$	~$2,000	10 sec	R^2 ~ 0.65 to 0.90
	**Shinyei** (PM Evaluation Kit)	Optical	$PM_{2.5}$	~$1,000	1 min	R^2 ~ 0.80 to 0.90
	**Speck**	Optical	$PM_{2.5}$	~$150	1 min	R^2 ~ 0.32
	**TSI** (AirAssure)	Optical	$PM_{2.5}$	~$1,500	5 min	R^2 ~ 0.82

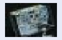
More results available on AQ-SPEC website

- Overall, PM sensors showed:
  - *Minimal down time*
  - *Moderate intra-model variability*
  - *Good correlation (R^2) with "EPA approved" instruments*
- However…
  - *Sensor "calibration" is needed in most cases*
  - *Very small particles are not detected*
  - *Bias in algorithms used calculate particle mass*

South Coast AQMD
AQ-SPEC
Air Quality Sensor Performance Evaluation Center

FIELD TESTING RESULTS

Gaseous Sensors

Sensor Image	Manufacturer (Model)	Type	Pollutant(s)	Approximate Cost (USD)	Time Resolution	Sensor vs FEM/FRM Method[1]
	**2B Technologies** (PO_3M)	UV absorption (FEM Method)	O_3	~$4,500	10 sec	R^2 ~ 1.00
	**Aeroqual** (S-500)	Metal Oxide	O_3	~$500	1 min	R^2 ~ 0.85
	**Air Quality Egg** (Version 1)	Metal Oxide	CO, NO_2 & O_3	~$200	1 min	CO: R^2 ~ 0.0 NO_2: R^2 ~ 0.40 O_3: R^2 ~ 0.85
	**Air Quality Egg** (Version 2)	Electrochem	CO & NO_2	~$240	1 min	CO: R^2 ~ 0.0 NO_2: R^2 ~ 0.0
	**Air Quality Egg** (Version 2)	Electrochem	O_3 & SO_2	~$240	1 min	O_3: R^2 ~ 0.0 to 0.20 SO_2: R^2 n/a
	**AQMesh** (v.3.0)	Electrochem	CO, NO, NO_2, SO_2 & O_3	~$10,000	1 - 15 min	CO: R^2 ~ 0.75 to 0.90 NO: R^2 ~ 0.75 to 0.90 NO_2: R^2 ~ 0.0 SO_2: R^2 ~ 0.0 O_3: R^2 ~ 0.25 to 0.55
	**AQMesh** (v.4.0)	Electrochem	CO, NO, NO_2 & O_3	~$10,000	1 - 15 min	CO: R^2 ~ 0.42 to 0.80 NO: R^2 ~ 0.0 to 0.44 NO_2: R^2 ~ 0.0 to 0.46 O_3: R^2 ~ 0.46 to 0.83
	**Perkin Elmer** (ELM)	Metal Oxide	NO, NO_2 & O_3	~$5,200	1 min	NO: R^2 n/a NO_2: R^2 ~ 0.0 O_3: R^2 ~ 0.89 to 0.96
	**Smart Citizen Kit**	Metal Oxide	CO, NO_2	~$200	1 min	CO: R^2 ~ 0.50 to 0.85 NO_2: R^2 ~0.0
	**Spec Sensors**	Electrochem	CO, NO_2 & O_3	~$500	1 min	CO: R^2 ~ 0.84 to 0.90 NO_2: R^2 ~ 0.0 to 0.16 O_3: R^2 ~ 0.0 to 0.24
	**UNITEC** (SENS-IT)	Metal Oxide	CO, NO_2 & O_3	~$2,200	1 min	CO: R^2 ~ 0.33 to 0.43 NO_2: R^2 ~ 0.60 to 0.65 O_3: R^2 ~ 0.72 to 0.83

More results available on AQ-SPEC website

- Overall, gaseous sensors showed:
  - *Acceptable data recovery*
  - *Wide intra-model variability*
  - *CO; NO; O_3 (when measured individually): good correlation with "EPA approved" instruments*
  - *O_3 + NO_2: low correlation with "EPA approved" methods (potential O_3/NO_2 and RH interferences)*
  - *SO_2; H_2S: difficult to measure with available sensors*
  - *VOCs: qualitative readings (not quantitative)*

South Coast AQMD
AQ-SPEC
Air Quality Sensor Performance Evaluation Center

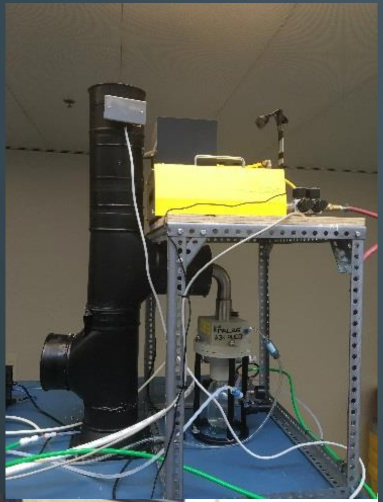
LABORATORY CHAMBER SYSTEM

Main components:

- Professional-grade environmental test chamber
- Dry, gas- and particle-free air generation system
- Small PM generator & Large PM dispenser
- U.S. EPA approved FRM/FEM and BAT instruments
- Custom computer software (remote control, sequences, 24/7 operation)

LABORATORY TESTING

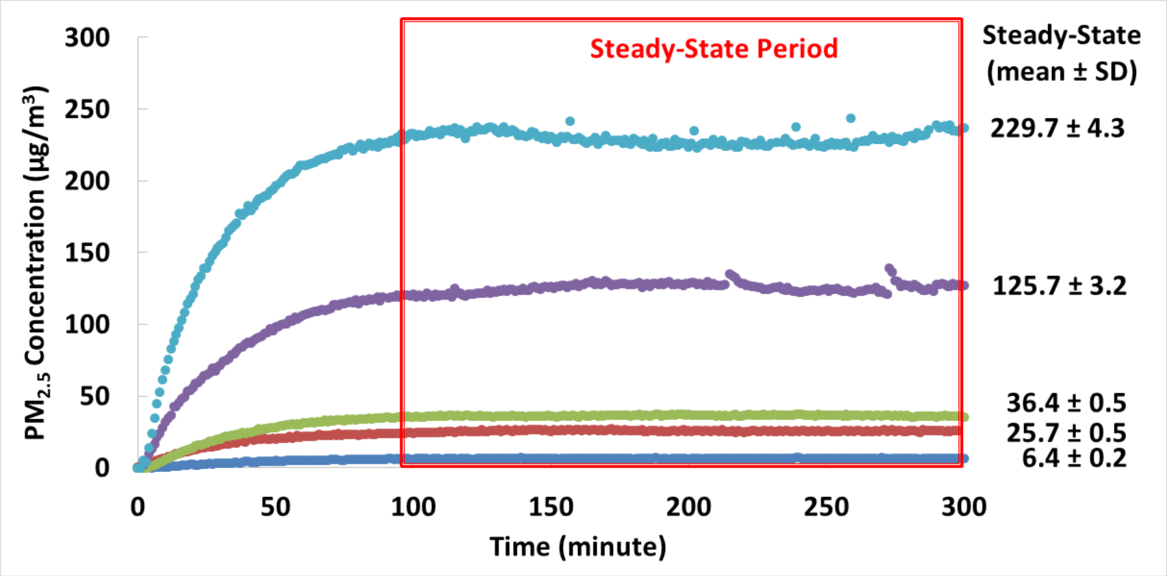
Aerosol Test



Gas Test

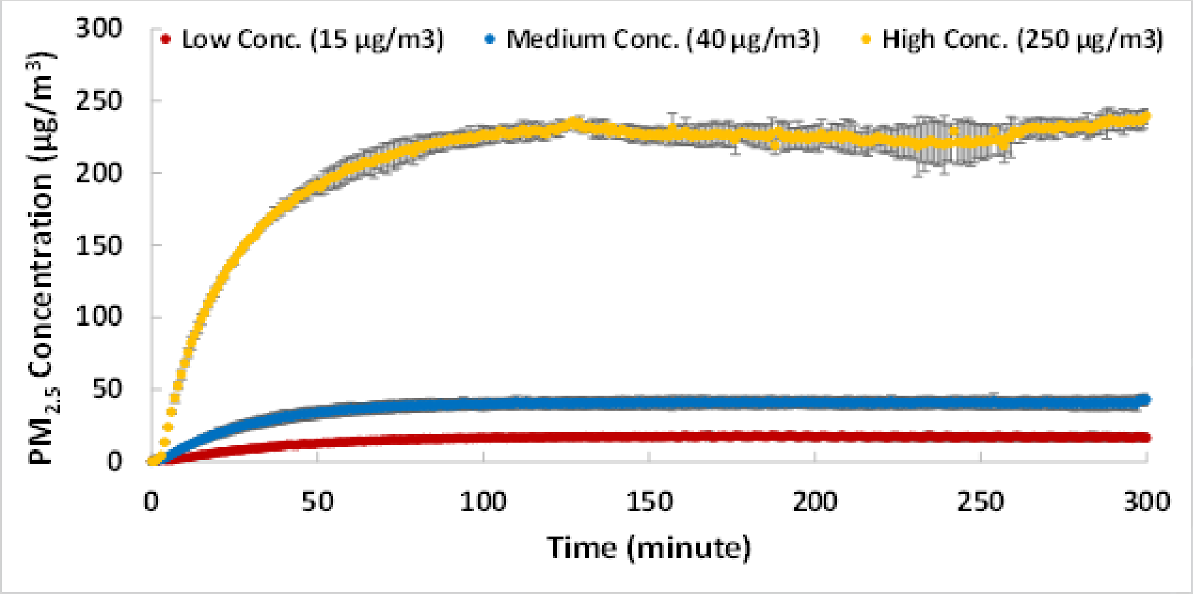
T and RH controlled: T (0-50 ^{0}C); RH (5-95%)

PM/GAS SENSOR TESTING



Stability

Reproducibility

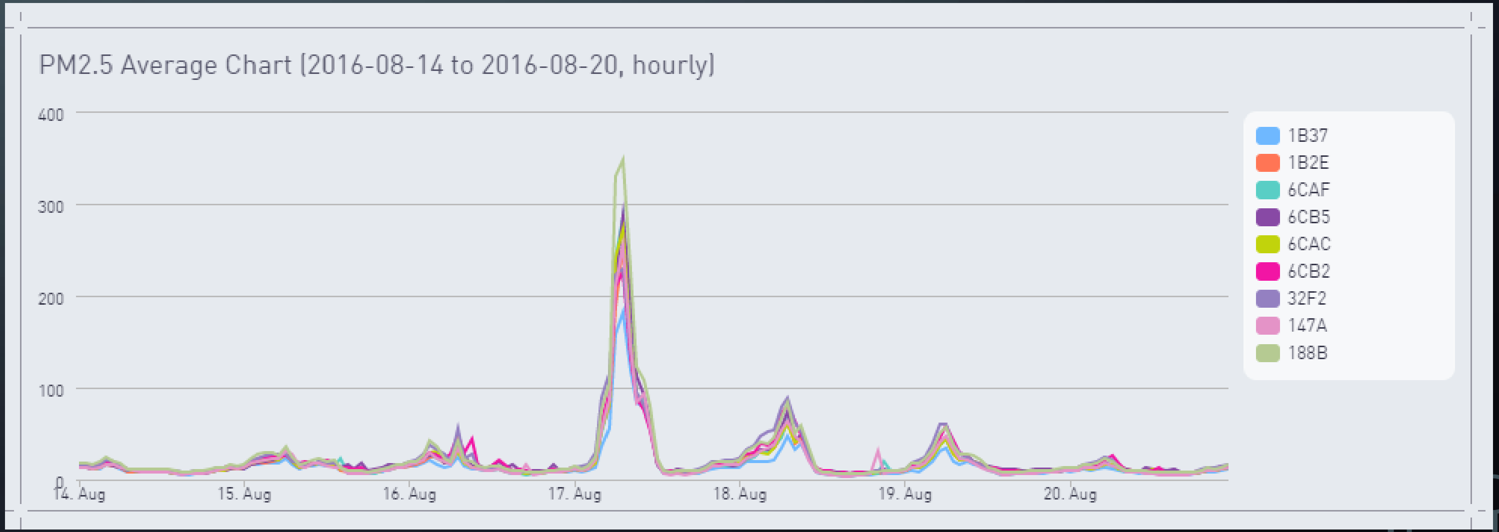


SENSOR NETWORK: PILOT STUDY #1

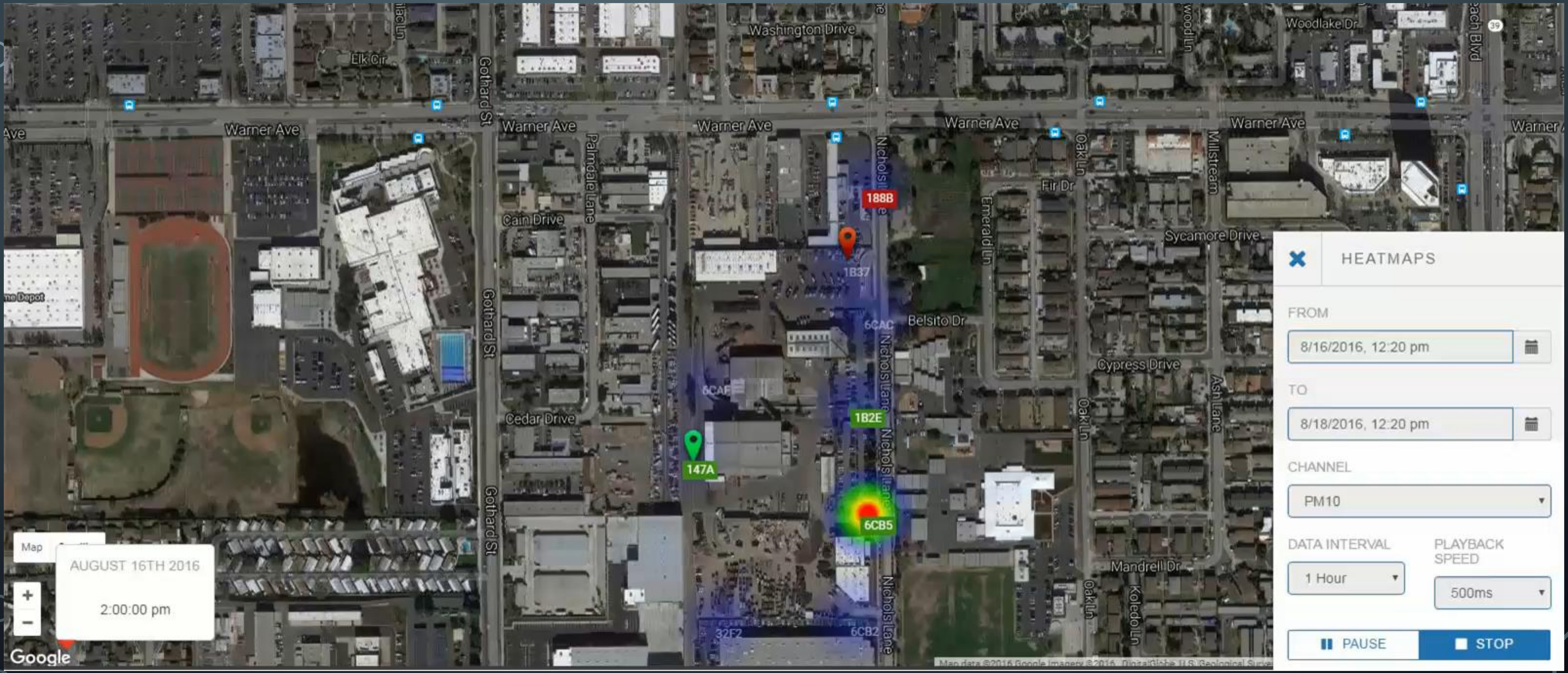
- Monitor fugitive emissions from a Waste Disposal facility in Southern California
- 9 sensor nodes deployed at facility fenceline
- Wireless network / remote server
- Real-time PM_1, $PM_{2.5}$ and PM_{10} monitoring

SENSOR NETWORK: PILOT STUDY #1

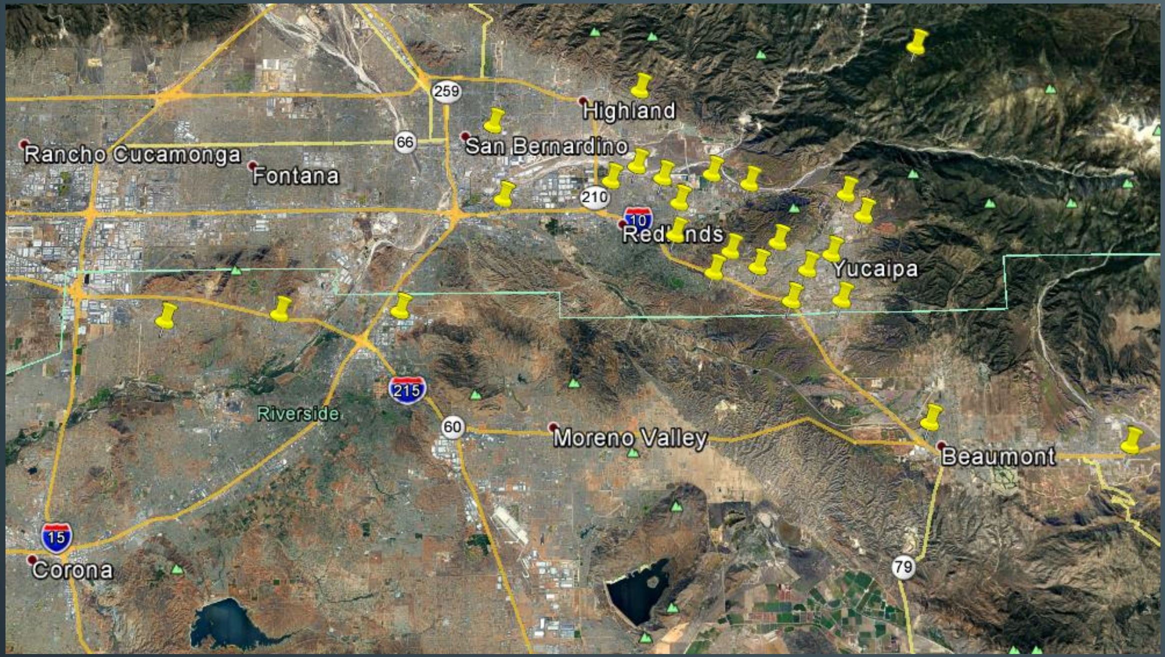
- Dedicated website
  - *www.aqmd.meshify.com*
  - *Real-time data logging, display, and mapping*
  - *Data analytics*
  - *Email and/or text alerts*
- Project benefits
  - *Correlate PM measurements w/ on-site activities*
  - *Measure PM levels before and after facility upgrades*

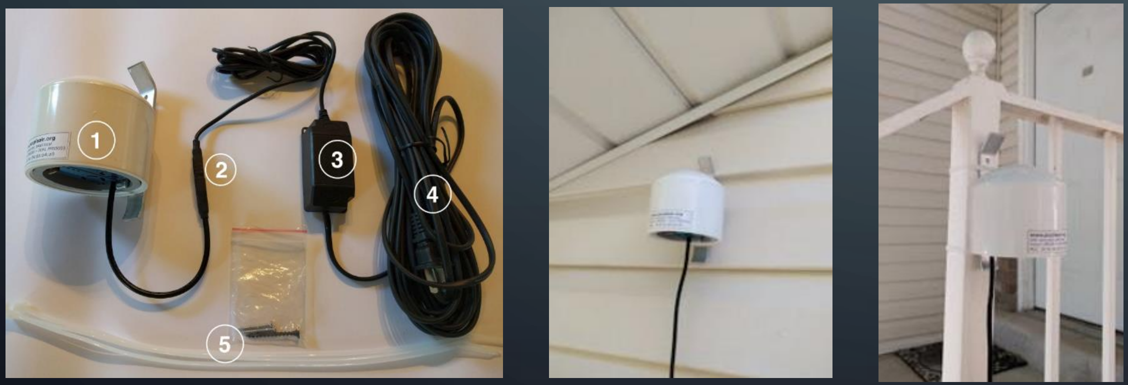


SENSOR NETWORK: PILOT STUDY #1



SENSOR NETWORK: PILOT STUDY #2





Purple Air Sensors ($180 / unit)

- 25 "low-cost" PM sensors deployed in the Redlands, CA area
- Real-time PM_1, $PM_{2.5}$ and PM_{10} monitoring
- Wireless network / remote server
  - *Microsoft + Element Blue/Sensor Insight*
- Project goals
  - *Test sensor durability*
  - *Show ability to scale up in near future*

UPCOMING PROJECT:
EPA SCIENCE TO ACHIEVE RESULTS (STAR) GRANT

- Provide California communities with the knowledge necessary to select, use and maintain low-cost sensors and to correctly interpret the collected data

- Four specific aims:
  - *#1: Develop educational material for communities*
  - *#2: Evaluate / identify candidate sensors for deployment*
  - *#3: Deploy selected sensors in California communities*
  - *#4: Communicate the lessons learned to the public*

- Three year study in collaboration with:
  - University of California Los Angeles (UCLA; Co-PI)
  - Sonoma Technology Inc. (STI; Co-PI)

South Coast AQMD

UCLA

STi Sonoma Technology, Inc.

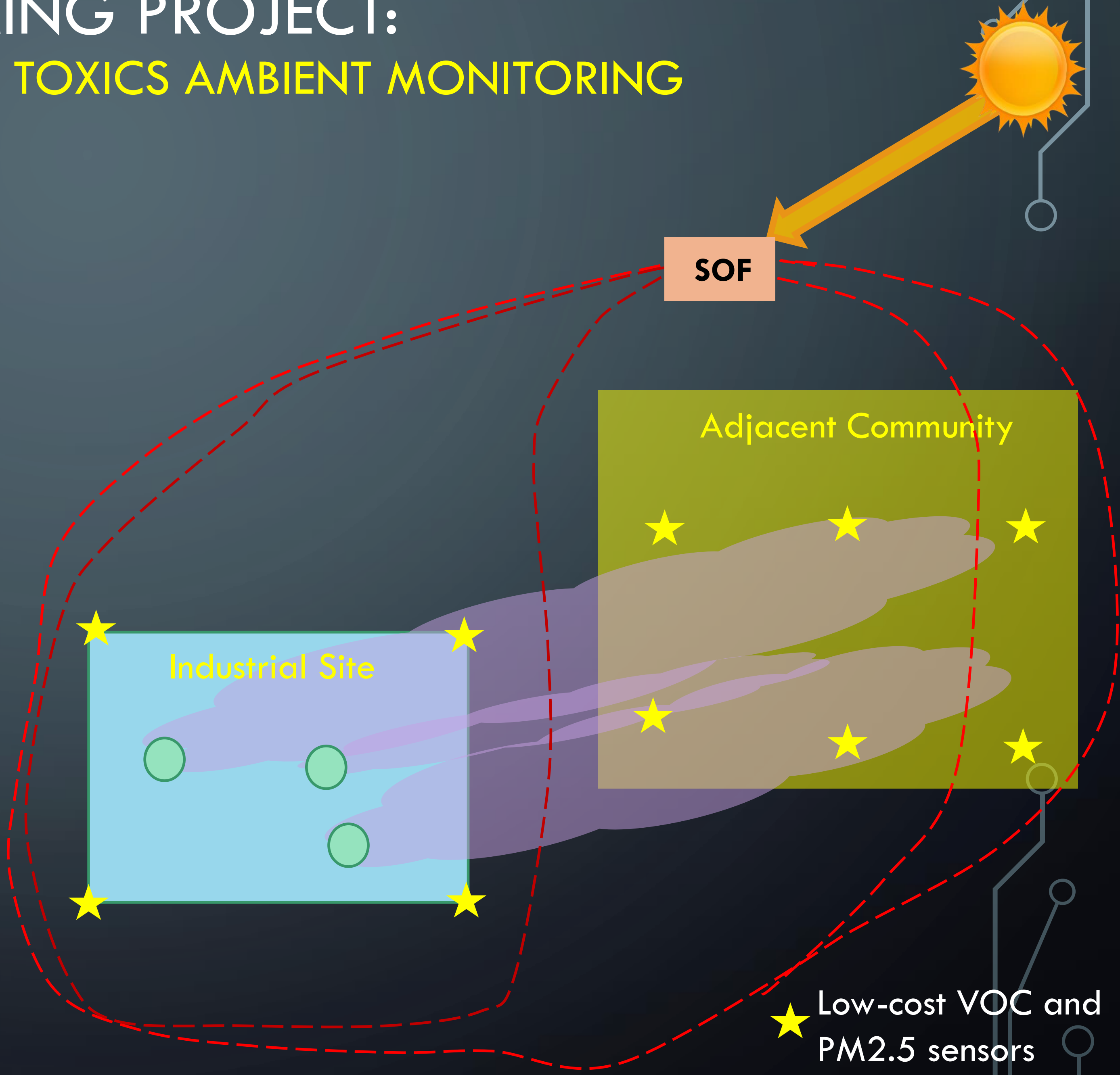
- 6 selected CA communities
- EJ areas
- 200+ subjects
- > 150 sensors

UPCOMING PROJECT:
COMMUNITY-SCALE AIR TOXICS AMBIENT MONITORING

- Comprehensive 3-year study aiming to:

1. use of ORS methods to monitor HAP emissions from refineries and to estimate their annual VOC emissions
2. use of ORS methods and “low-cost” sensors for assessing the impact of industrial HAP emissions on surrounding communities.

- Mobile ORS – detailed understanding of emissions and concentrations mapping (quarterly surveys)
- “Low-cost” sensors network – long-term monitoring of VOC and PM2.5 around fenceline and inside the community



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  - ORS Program: Andrea Polidori, Olga Pikelnaya
  - AQ-SPEC Center: Andrea Polidori, Vasilios Papapostolou, Brandon Feenstra, Hang Zhang

- ORS contractors
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    FluxSense Inc., San Diego, CA
  - Rod Robinson, Fabrizio Innocenti, Andrew Finlayson

    National Physical Laboratory, Hampton Rd, Eddington, United Kingdom
  - Steve Perry

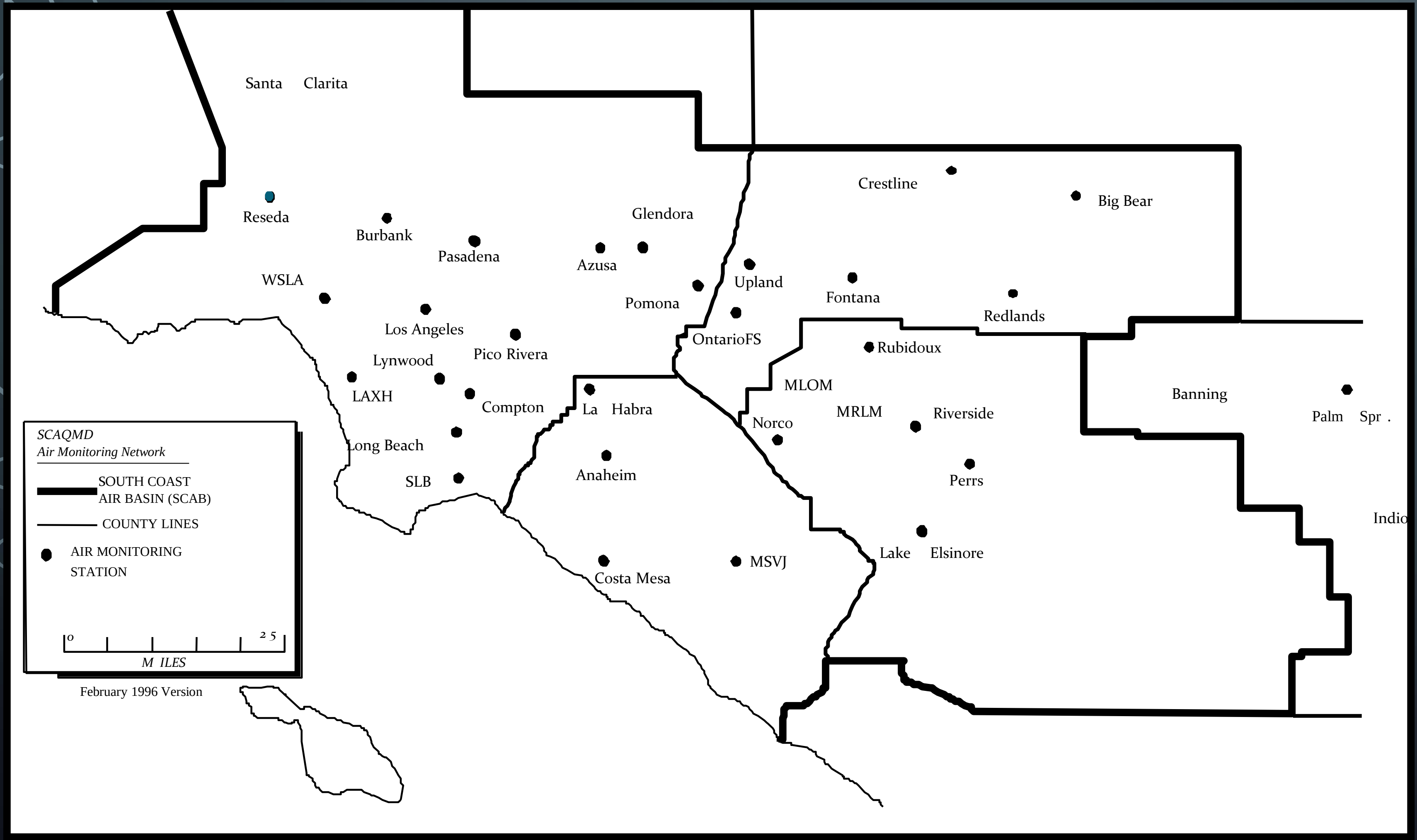
    Kassay Field Services, Mohrsville, PA
  - Ram Hashmonay

    Atmosfir Optics Ltd., Ein Iron, Israel

- Tesoro Carson refinery environmental staff for assisting with measurements inside the refinery tank farm

EXTRA SLIDES

SCAQMD AIR MONITORING NETWORK



- 38 permanent air monitoring stations
- 4 single-pollutant source impact Pb air monitoring sites
- Temporary sites for special monitoring purposes (e.g. incident response)

Ozone

Nitrogen Dioxides

PM10, PM2.5

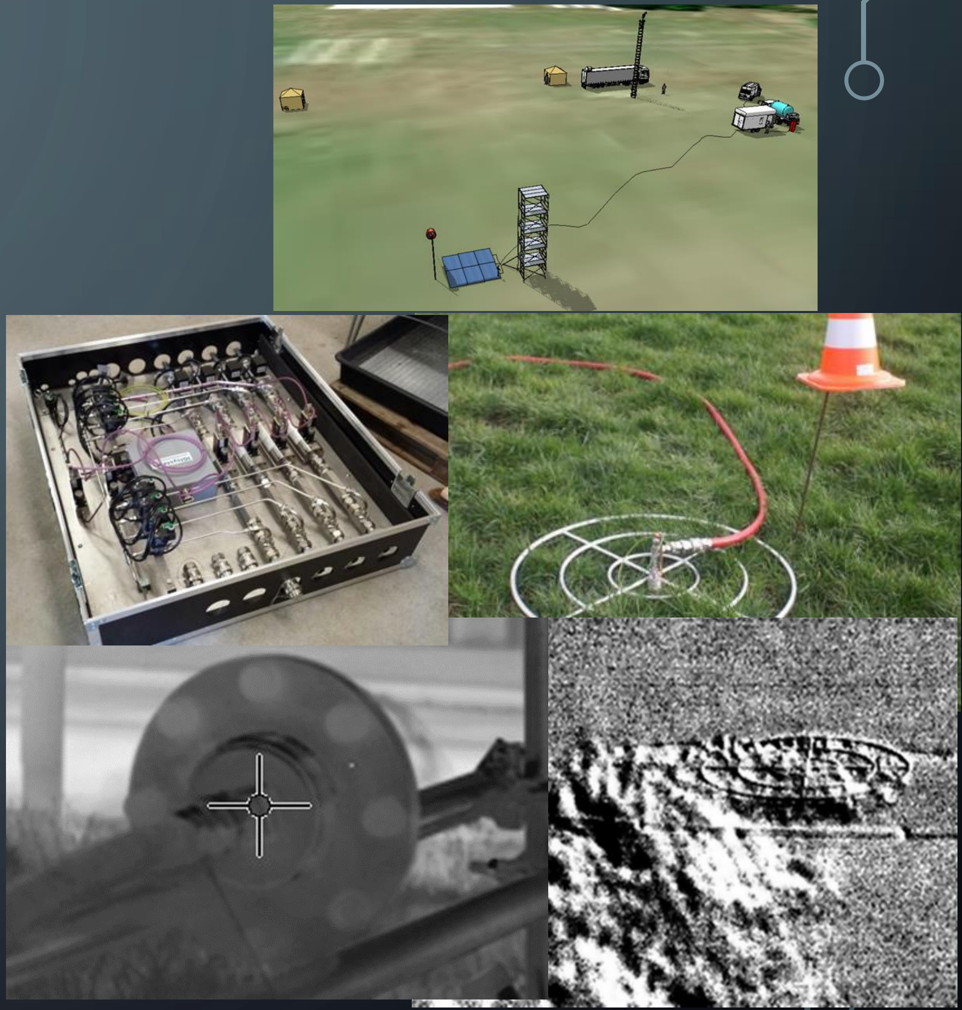
Carbon Monoxide

Sulfur Dioxide

Particulate Lead

AREA SOURCE EMISSIONS FACILITY (ASF)

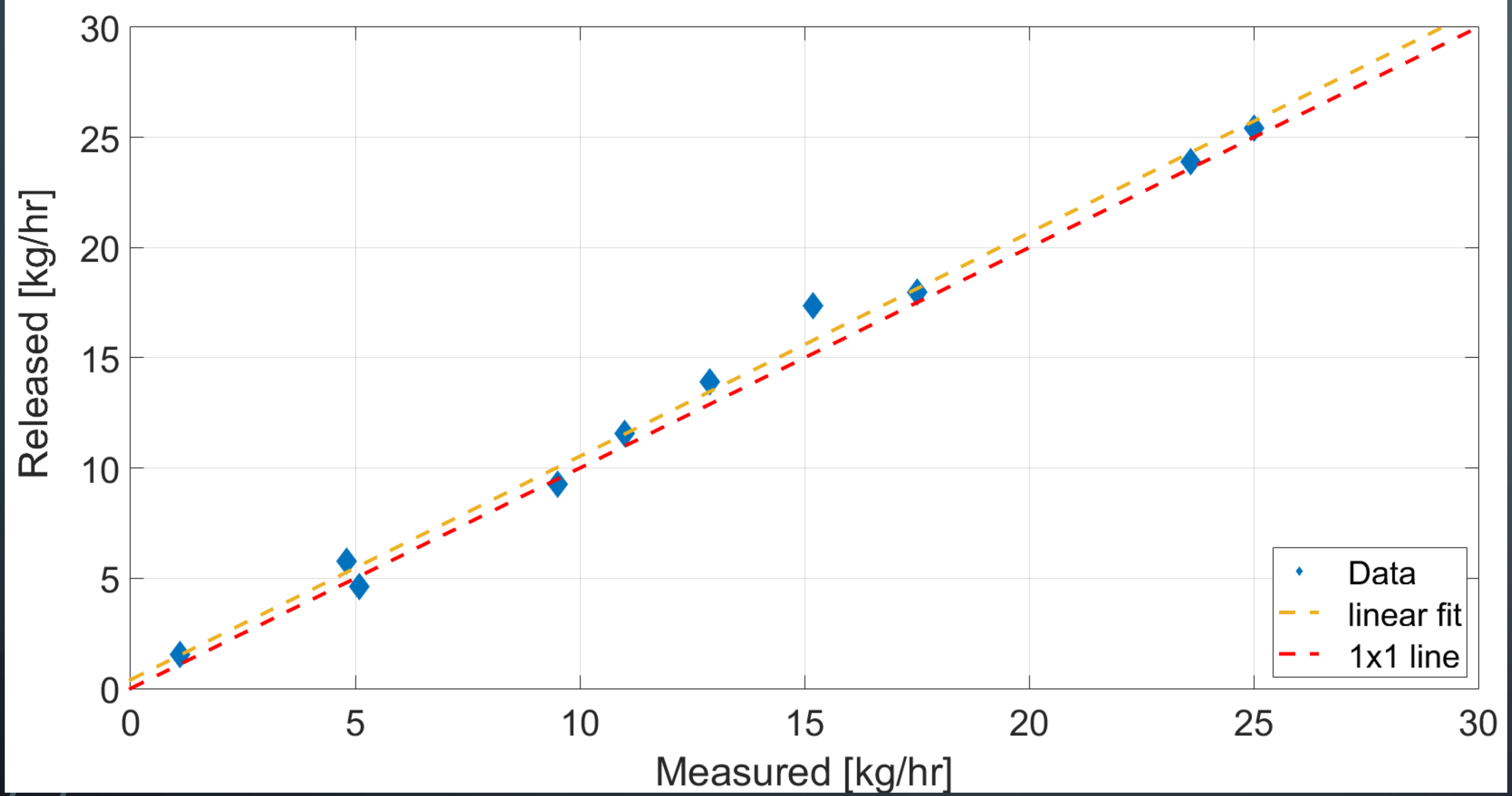
- A high flow gas blending system was constructed that allows gas species to be released at controlled traceable rates comparable to small-medium industrial emissions: (1.1 –55 kg/h for C3H8; 0.7 –36 kg/h for CH4; and 2 –99 kg/h for CO2).
- The system is configurable–four release nodes to replicate spatial and temporal characteristics of different emission scenarios.
- The system is housed within a trailer for easy transport.
- Gas dispersion from nodes has been validated using several techniques including DIAL and Optical Gas Imaging (OGI) technology.
- The system has been successfully utilized in a number of campaigns to date, including replicating emission sources from shale gas processing equipment.
- Work is continuing to develop
  - larger diffusive emission nodes
  - nodes to simulate component emissions.



CONTROLLED-RELEASE STUDY: DATA OVERVIEW

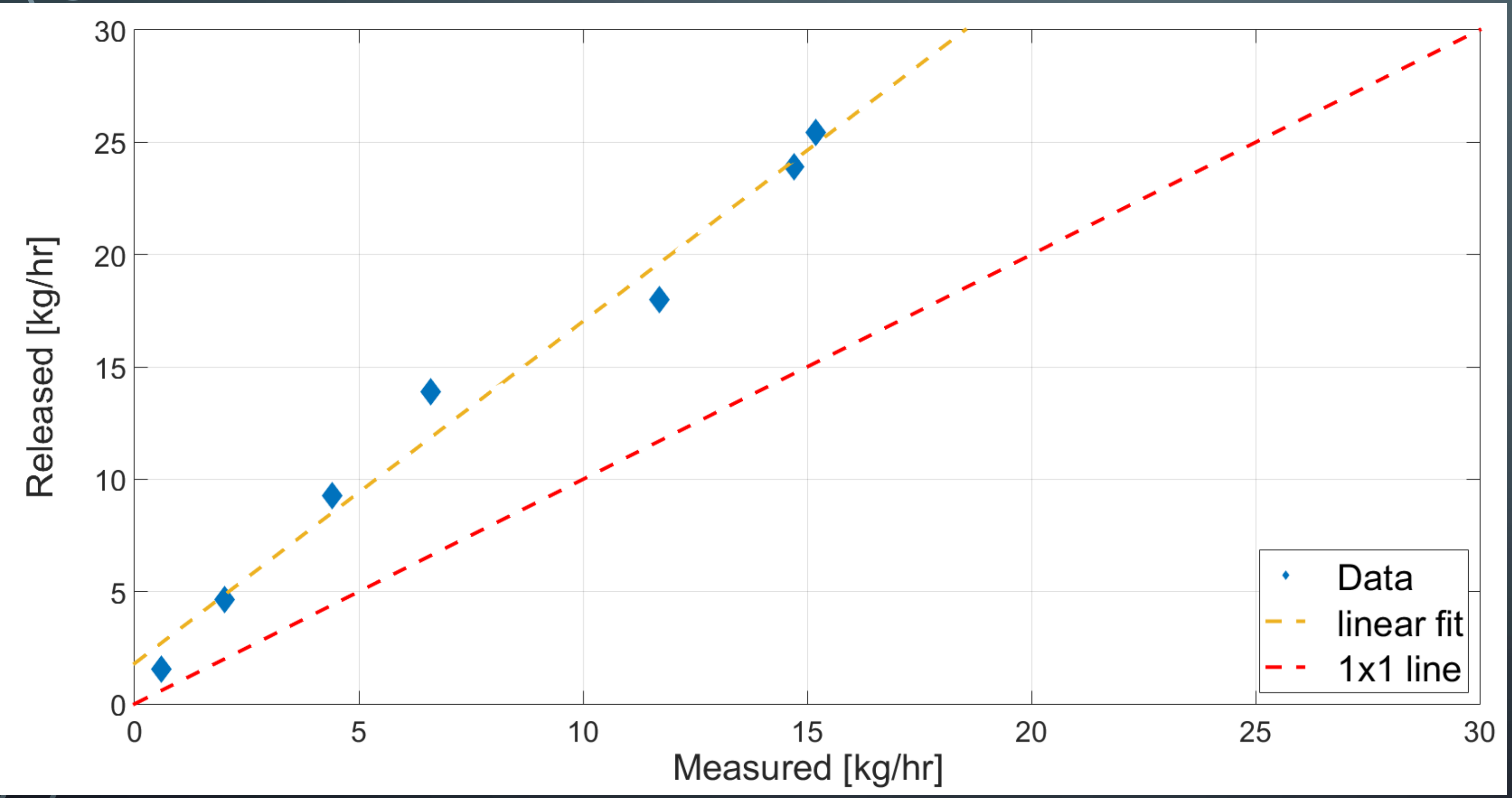
Date	Alt. (m)	Release rate [kg/hr]	Fluxsense	NPL	Atmosfir	Kassay	Weather Conditions
10/12/15	3	5.8	No data due to unfavorable weather	4.8	3	5.3	Cloudy, variable winds (1.5 - 3.5 m/s)
10/12/15	3	11.6	Same as above	11	6.1	14	
10/12/15	3	17.4	Same as above	15.2	10.8	12.3	
10/13/15	3	13.9	6.6	12.9	11.7	19.6	
10/13/15	6.4	4.6	2.0	5.1	No data - VRPM not applicable	No data - method not applicable	Clear sky, steady wind (2.5 - 7 m/s)
10/13/15	6.4	18.0	11.7	17.5	Same as above	Same as above	
10/13/15	6.4	1.6	0.6	1.1	Same as above	Same as above	
10/13/15	6.4	9.3	4.4	9.5	Same as above	Same as above	
10/13/15	7.9	25.4	15.2	25	Same as above	Same as above	
10/13/15	3	23.9	14.7	23.6	18.8	52.5	

CONTROLLED-RELEASE STUDY: RESULTS OF DIAL MEASUREMENTS



- DIAL method accurately quantified and visualized propane emission plume
- DIAL measurements not affected by meteorological conditions
- $y = 1.01x + 0.4$
  $R^2 = 0.99$

CONTROLLED-RELEASE STUDY: RESULTS OF SOF MEASUREMENTS



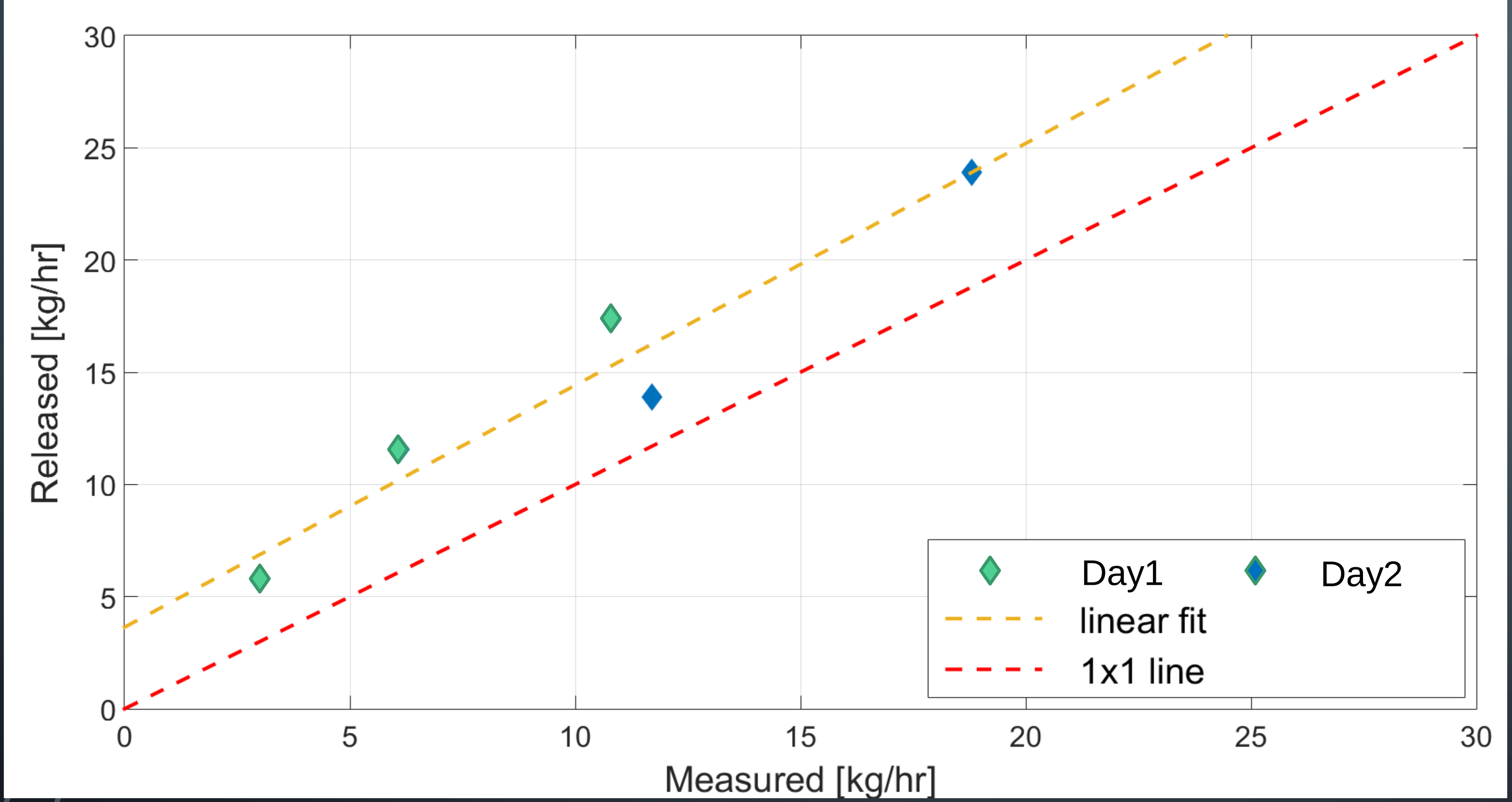
- Excellent linearity and correlation coefficient

$$y = 1.52x + 1.81$$

$$R^2 = 0.98$$

- SOF method consistently underestimated emissions by ~40%
- Close proximity to release source caused underestimation

CONTROLLED-RELEASE STUDY: RESULTS OF VRPM MEASUREMENTS

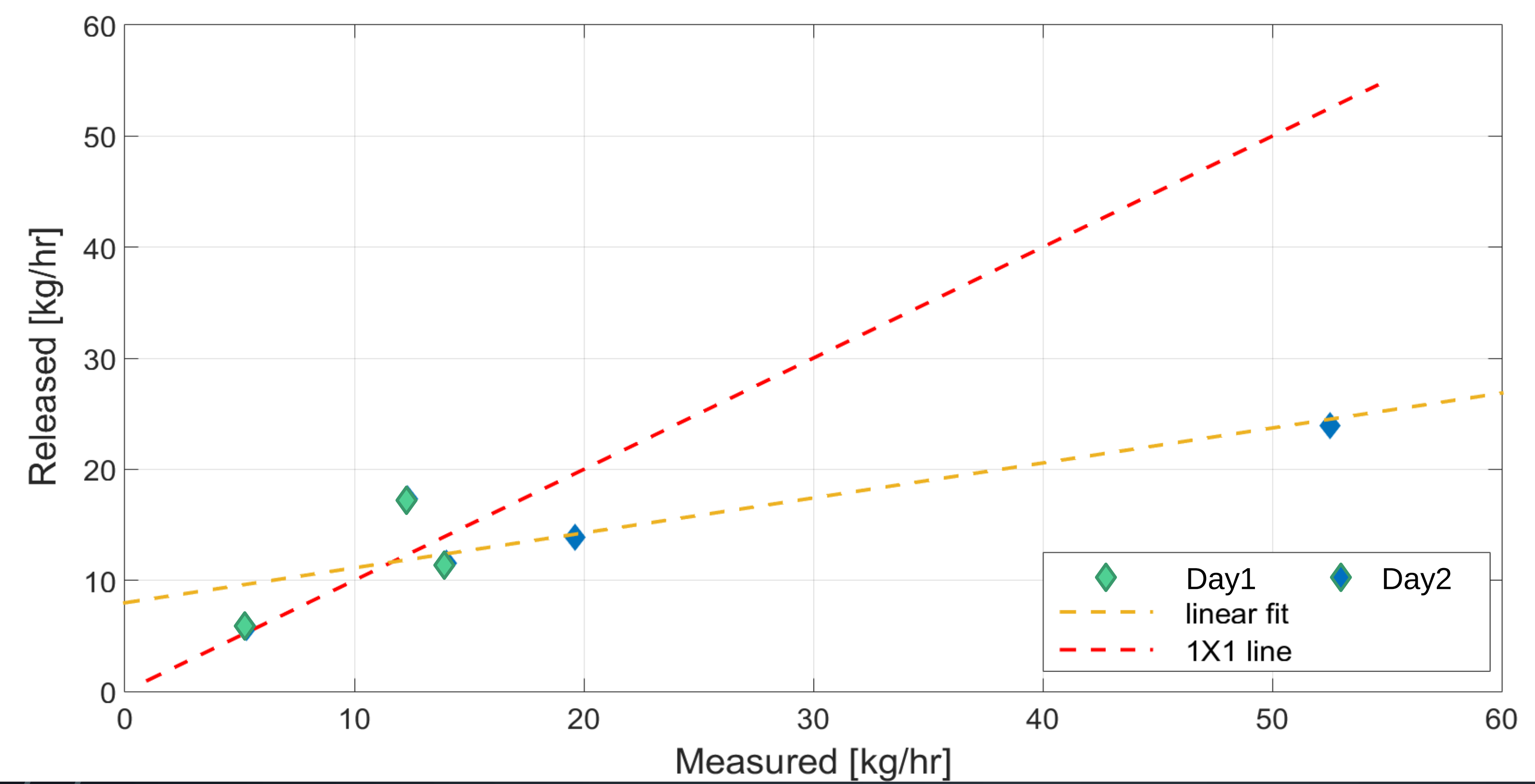


- Quantified releases from 3m altitude only
- Good linearity and correlation coefficient

$$y = 1.08x + 3.64$$
$$R^2 = 0.92$$

- Measured fluxes were slightly underestimated
- Better performance during day 2 due to more favorable meteorological conditions

CONTROLLED-RELEASE STUDY: INITIAL RESULTS FOR AREA SOURCE TECHNIQUE



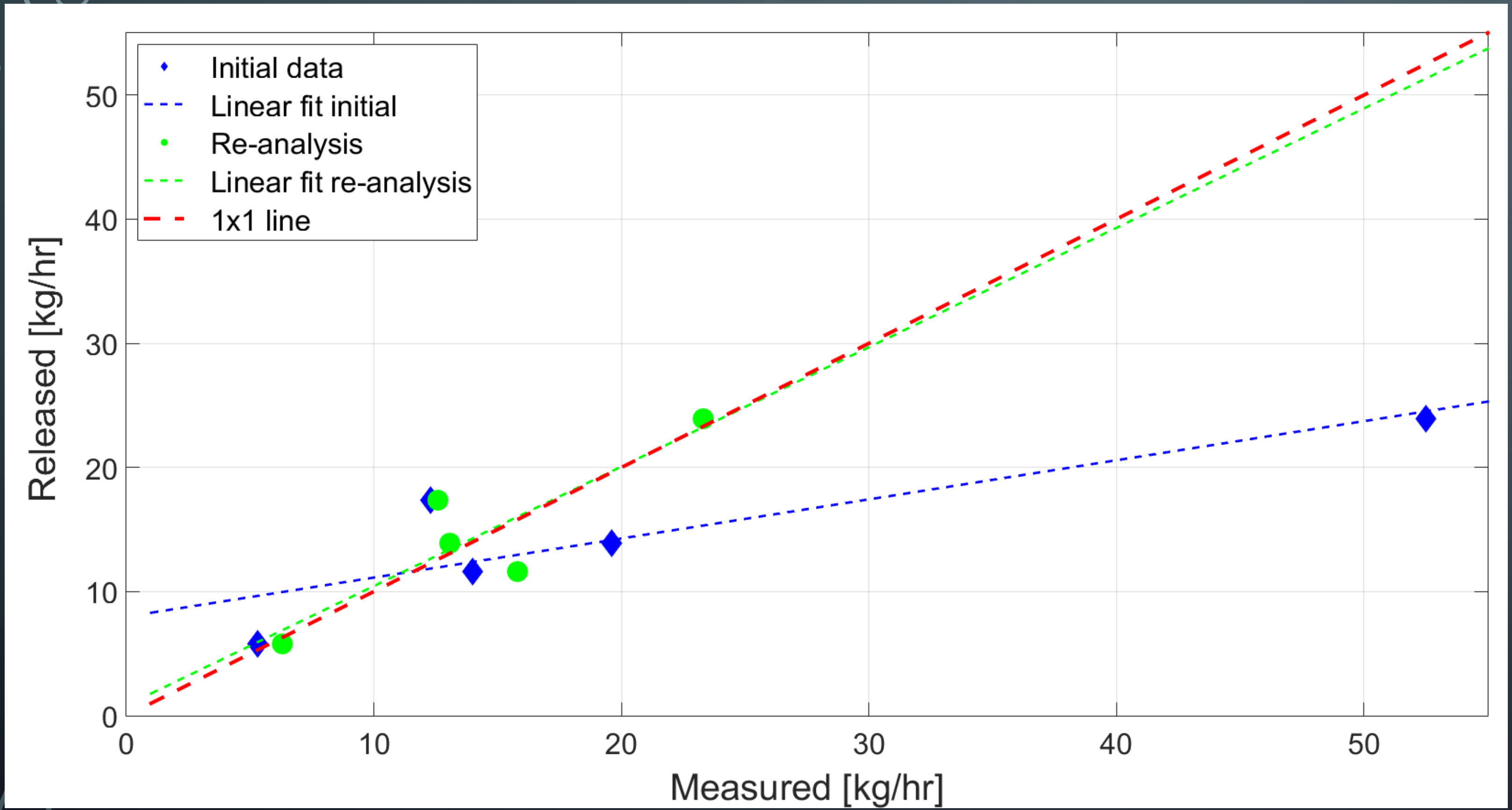
- Quantified releases from 3m altitude only

$$y = 0.315x + 7.98$$

$$R^2 = 0.74$$

- First day fluxes ranged between -29.2% and 20.9% of actual release rates
- Day two fluxes were overestimated by factor of two

CONTROLLED-RELEASE STUDY: REANALYSIS FOR AREA SOURCE TECHNIQUE



- Reanalysis of the data by
  - adjusting surface roughness parameter
  - Accounting for stable atmospheric conditions on day two
- Significant improvements in calculated fluxes

$$y = 0.962x + 0.824$$

$$R^2 = 0.77$$

- Care should be taken in selecting model input parameters