UNIVERSITY OF NOTRE DAME

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Harmonisation within Atmospheric
Dispersion Modelling
for Regulatory Purposes

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Dry Deposition onto Vertical Surfaces in the Urban Environment

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Particle Deposition

- Important consideration for dispersion modelling
  - Key sink within aerosol budget
- Vertical surfaces dominate urban environment
  - Some models only account for deposition onto horizontal surface, e.g. Bruse (2007)
- Impacts on human health – exposure pathway
- Deterioration and dirtying of built environment – cultural heritage

Outline

1. Background: Review of past experiments
2. Experimental set-up
3. Experimental results
    a) Micrometeorology
    b) Deposition velocity
4. Analysis: Governing parameters
5. Conclusions

BACKGROUND: REVIEW OF PAST EXPERIMENTS

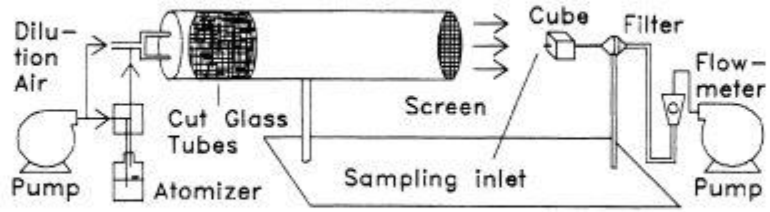
Long-term measurements

- Roed (1990) performed series of analyses on urban surfaces
- Following nuclear tests and Chernobyl disaster in 1980s
- Deposition velocities on vertical surfaces an order of magnitude (or more) less than on horizontal surfaces

- Also long-term component to Salissure de Façade (SaliFa) project (France)

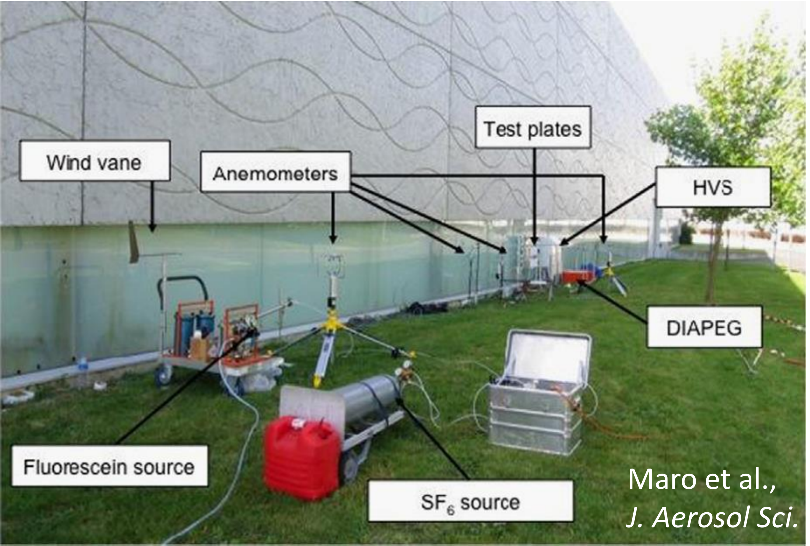
Short-term measurements

- Pesava et al. (1999) measured deposition velocity onto surfaces of a cube place outdoors
  - Not a real urban surface



Peseva et al., *Sci. Tot. Environ.*

- SaliFa short-term experiments
  - Maro et al. (2014) conducted 2 sets of experiments in 2005 and 2006
  - Constructed panels of glass and plaster glazing
  - Deposition of fluorescein on timescale ~1 hour



Maro et al., *J. Aerosol Sci.*

  - Detailed observations of flow, turbulence, and aerosol concentrations

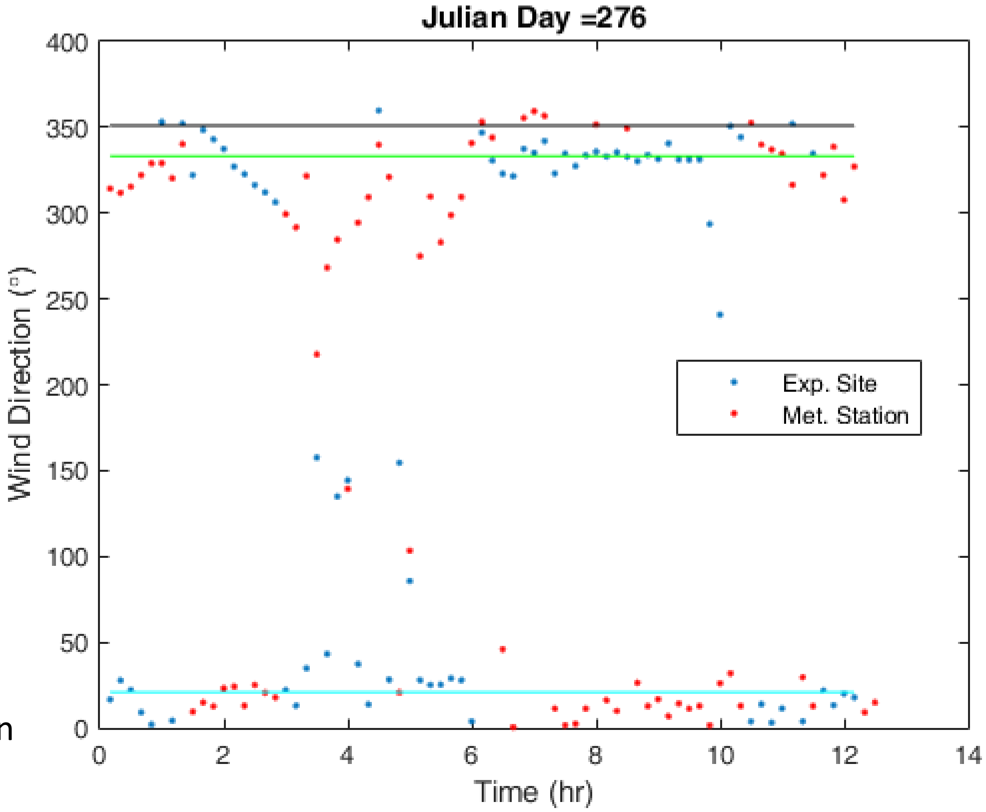
Submicronic aerosols

- The 0.1-1 µm range has been focus of past studies;
- Peak range in urban areas (Horvath et al. 1996), including soot, radionuclides, etc.

EXPERIMENTAL SET-UP

Preliminary analyses

- Set up in-situ meteorological station to guide experimental design
- Input in CFD model FLUENT

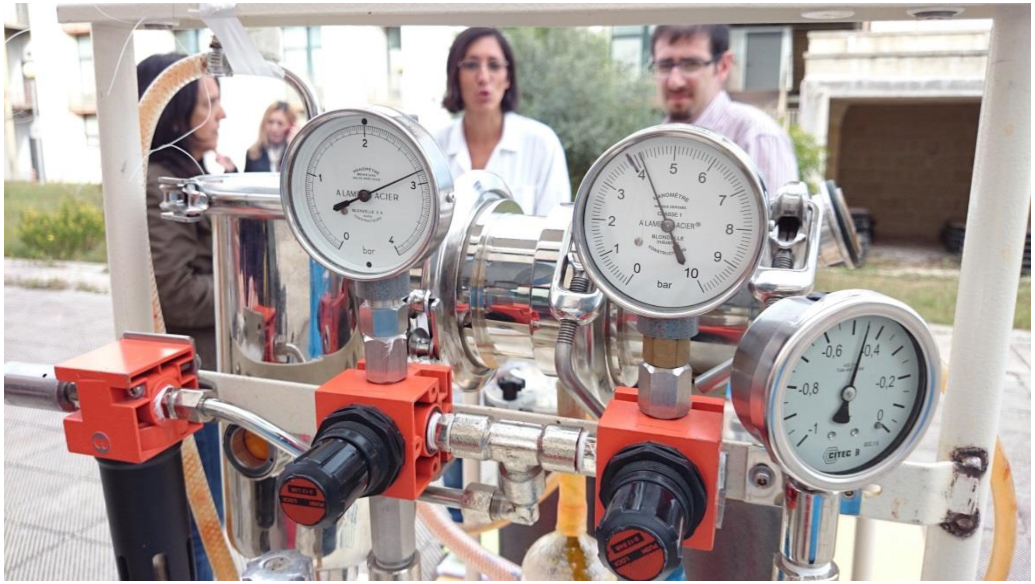


● Synoptic wind direction

● Test site wind direction

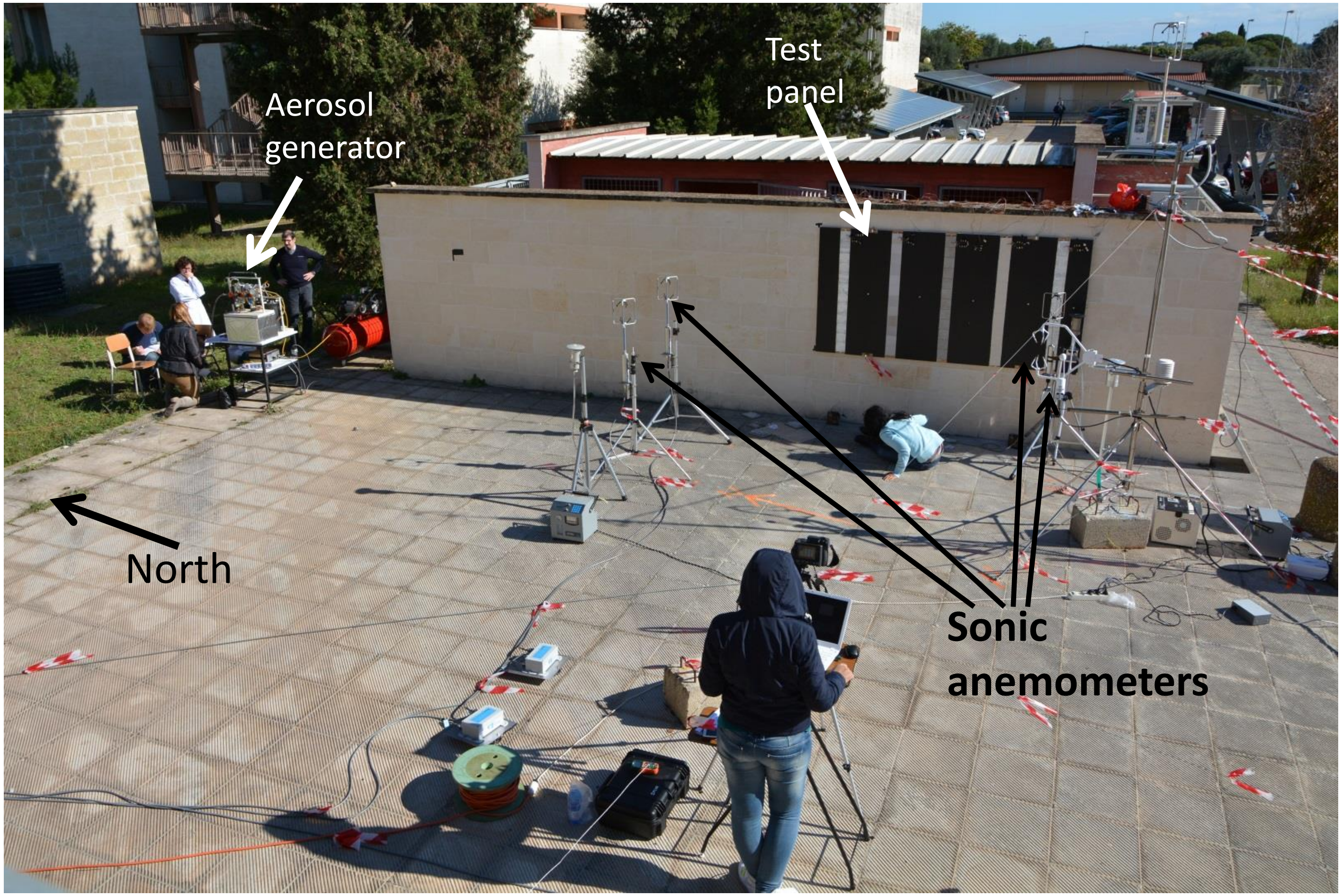
Aerosols emitted

- Pneumatic generator of Fluorescein rented from TechSystemes
- Diameter: 0.138 μm
- Mass flow rate: 33.9 $\frac{mg}{hr}$
- Density: 1.5 $\frac{g}{cm^3}$



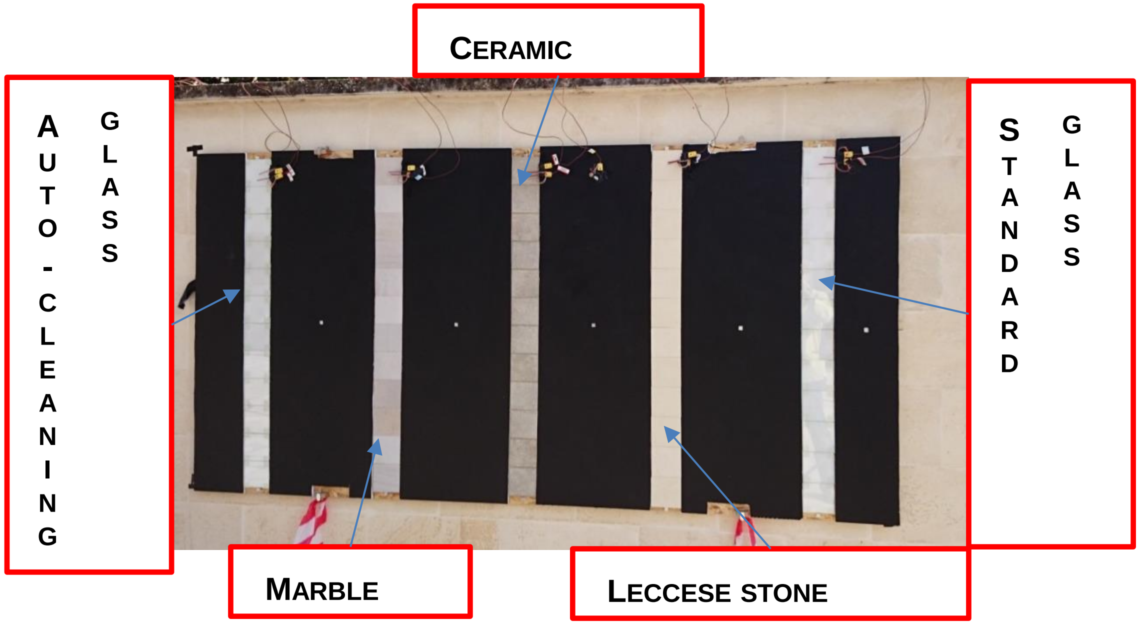
Experimental set-up

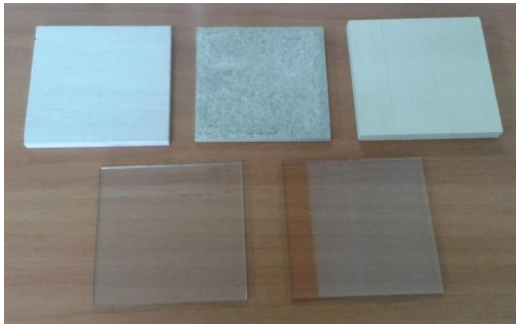
Experimental set-up



Panel and materials

- Selected 2 glass types (same as SaliFa) and 3 additional common building materials – marble, ceramic, Leccese stone
- Constructed panel with wood and foam so no significant surface elevation changes at boundaries (± 2 mm)





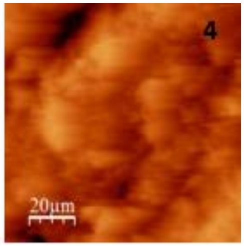
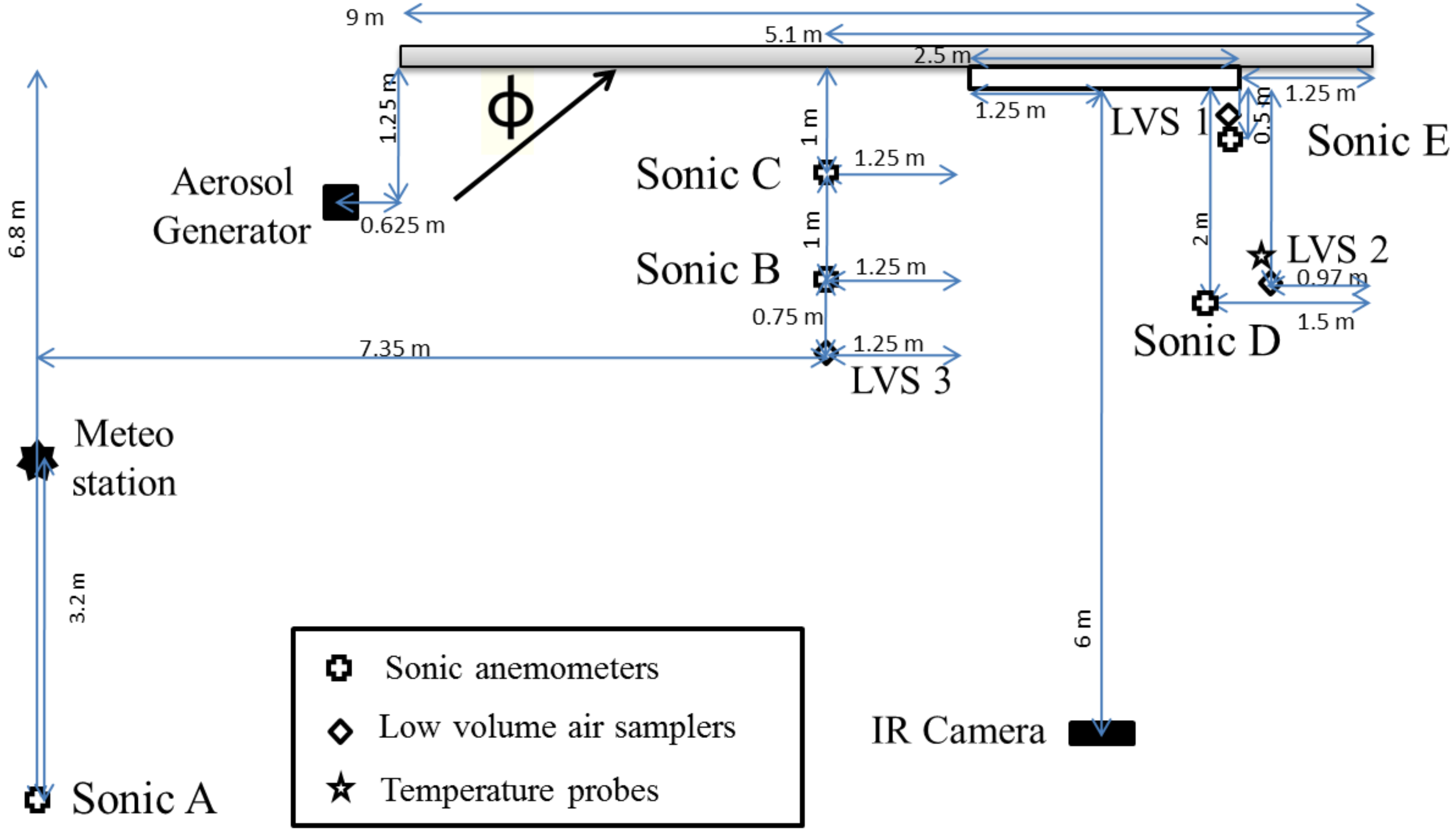


Image from AFM

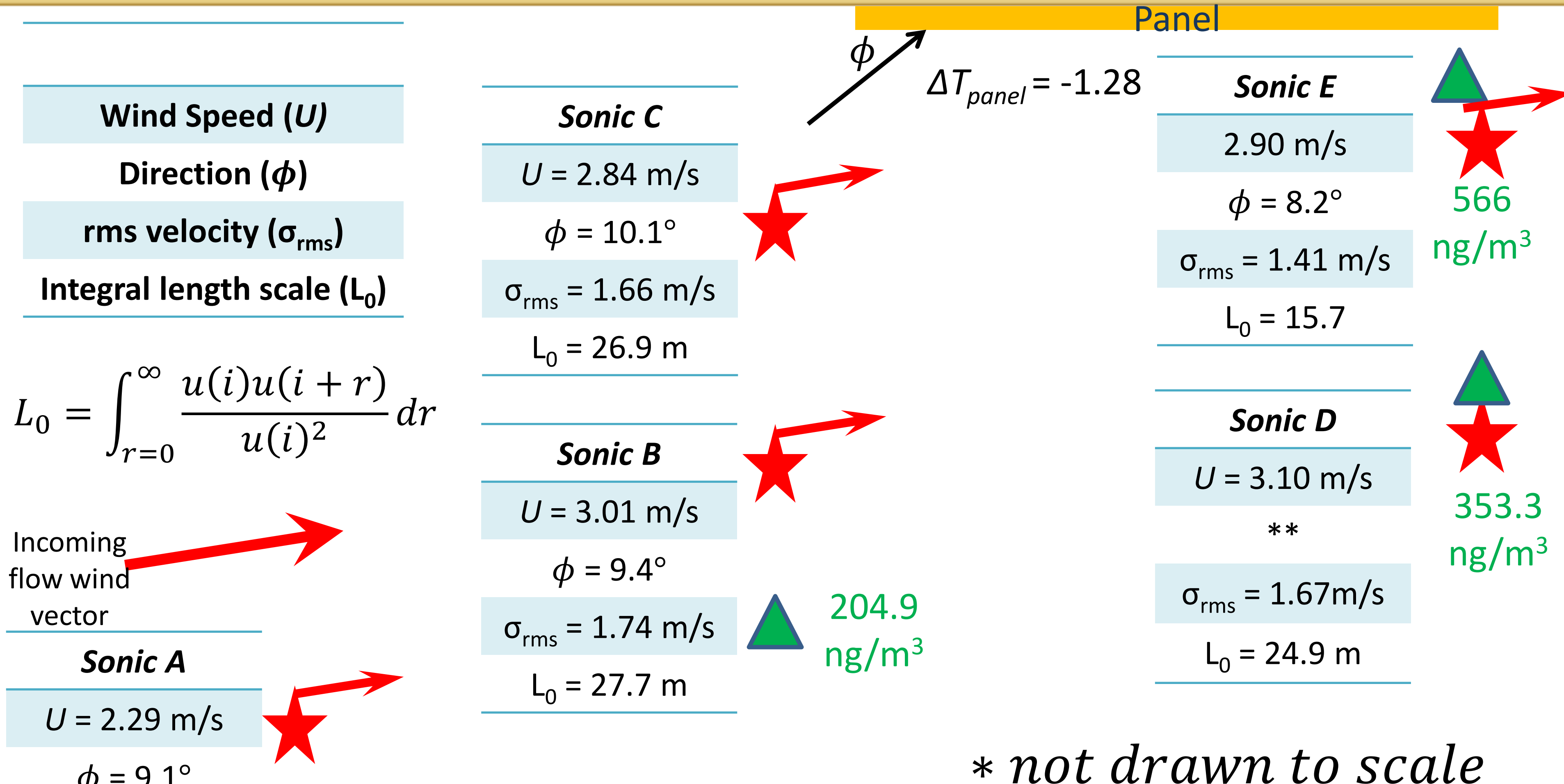
- Roughness height measurements for ceramic and marble via atomic force microscope reveals consistently ~0.8 µm

Plan view


9 m
5.1 m
2.5 m
1.25 m
ϕ
1.25 m
1.25 m
0.5 m
LVS 1
Sonic E
Aerosol Generator
0.625 m
1 m
Sonic C
1.25 m
1 m
Sonic B
1.25 m
0.75 m
2 m
LVS 2
0.97 m
Sonic D
1.5 m
6.8 m
7.35 m
1.25 m
LVS 3
Meteo station
3.2 m
6 m
IR Camera
Sonic A
Sonic anemometers
Low volume air samplers
Temperature probes

EXPERIMENTAL RESULTS: MICROMETEOROLOGY

Test 1



Wind Speed (U)

Direction (ϕ)

rms velocity (σ_{rms})

Integral length scale (L_0)

$$L_0 = \int_{r=0}^{\infty} \frac{u(i)u(i+r)}{u(i)^2} dr$$

Incoming flow wind vector

Sonic A

U = 2.29 m/s

ϕ = 9.1°

σ_{rms} = 1.91 m/s

L_0 = 20.7 m

Sonic B

U = 3.01 m/s

ϕ = 9.4°

σ_{rms} = 1.74 m/s

L_0 = 27.7 m

204.9 ng/m³

Sonic C

U = 2.84 m/s

ϕ = 10.1°

σ_{rms} = 1.66 m/s

L_0 = 26.9 m

ΔT_{panel} = -1.28

Sonic E

2.90 m/s

ϕ = 8.2°

σ_{rms} = 1.41 m/s

L_0 = 15.7

566 ng/m³

Sonic D

U = 3.10 m/s

**

σ_{rms} = 1.67m/s

L_0 = 24.9 m

353.3 ng/m³

$$\Delta T_{panel} = T_{IR,panel} - T_{\infty}$$

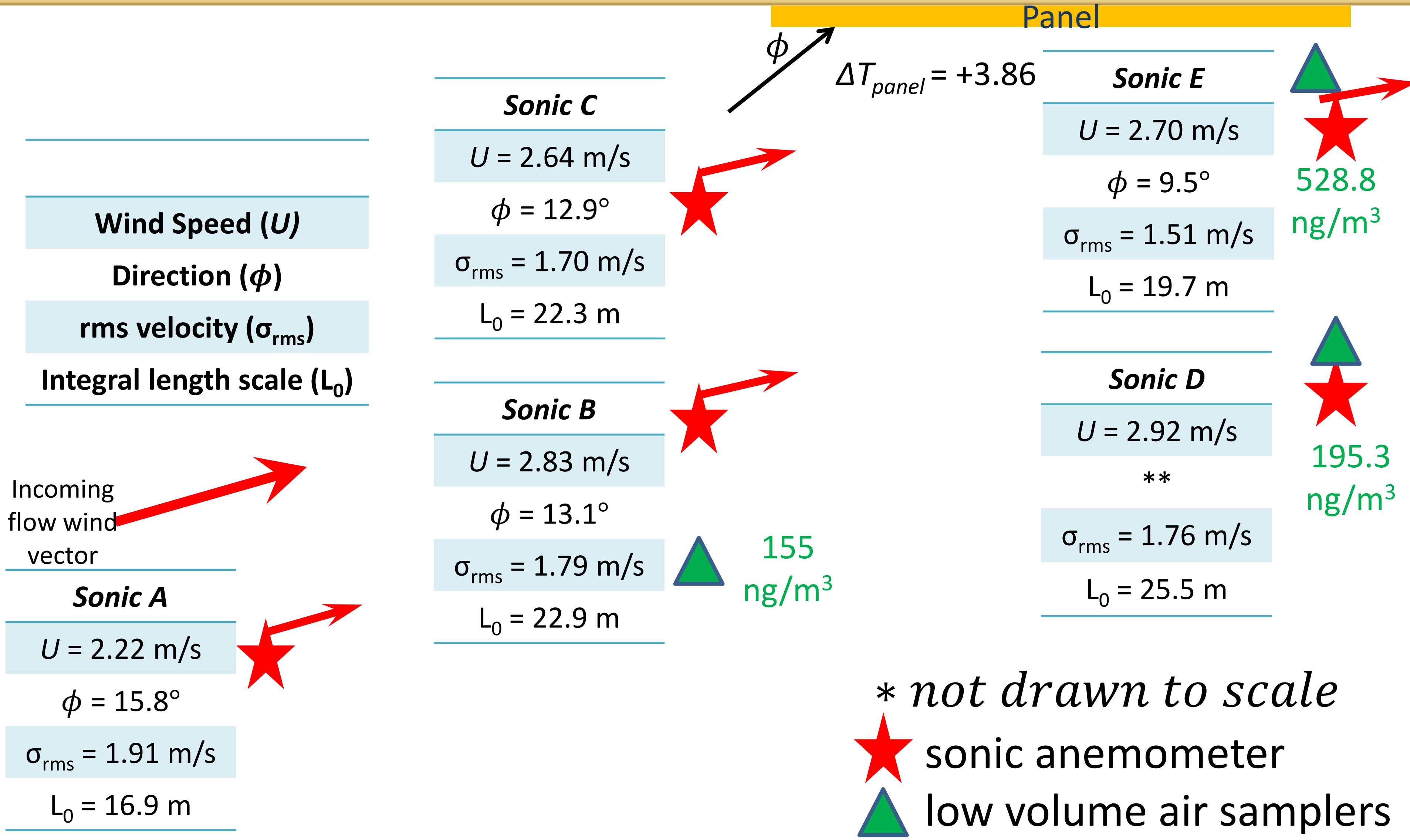
buoyancy effects near panel

$*$ *not drawn to scale*

★ sonic anemometer

▲ low volume air samplers

Test 2



Panel

ϕ

ΔT_{panel} = +3.86

Wind Speed (*U*)
Direction (ϕ)
rms velocity (σ_{rms})
Integral length scale (L_0)

Incoming flow wind vector

Sonic A
U = 2.22 m/s
ϕ = 15.8°
σ_{rms} = 1.91 m/s
L_0 = 16.9 m

Sonic C
U = 2.64 m/s
ϕ = 12.9°
σ_{rms} = 1.70 m/s
L_0 = 22.3 m

Sonic B
U = 2.83 m/s
ϕ = 13.1°
σ_{rms} = 1.79 m/s
L_0 = 22.9 m

155 ng/m^3

Sonic E
U = 2.70 m/s
ϕ = 9.5°
σ_{rms} = 1.51 m/s
L_0 = 19.7 m

528.8 ng/m^3

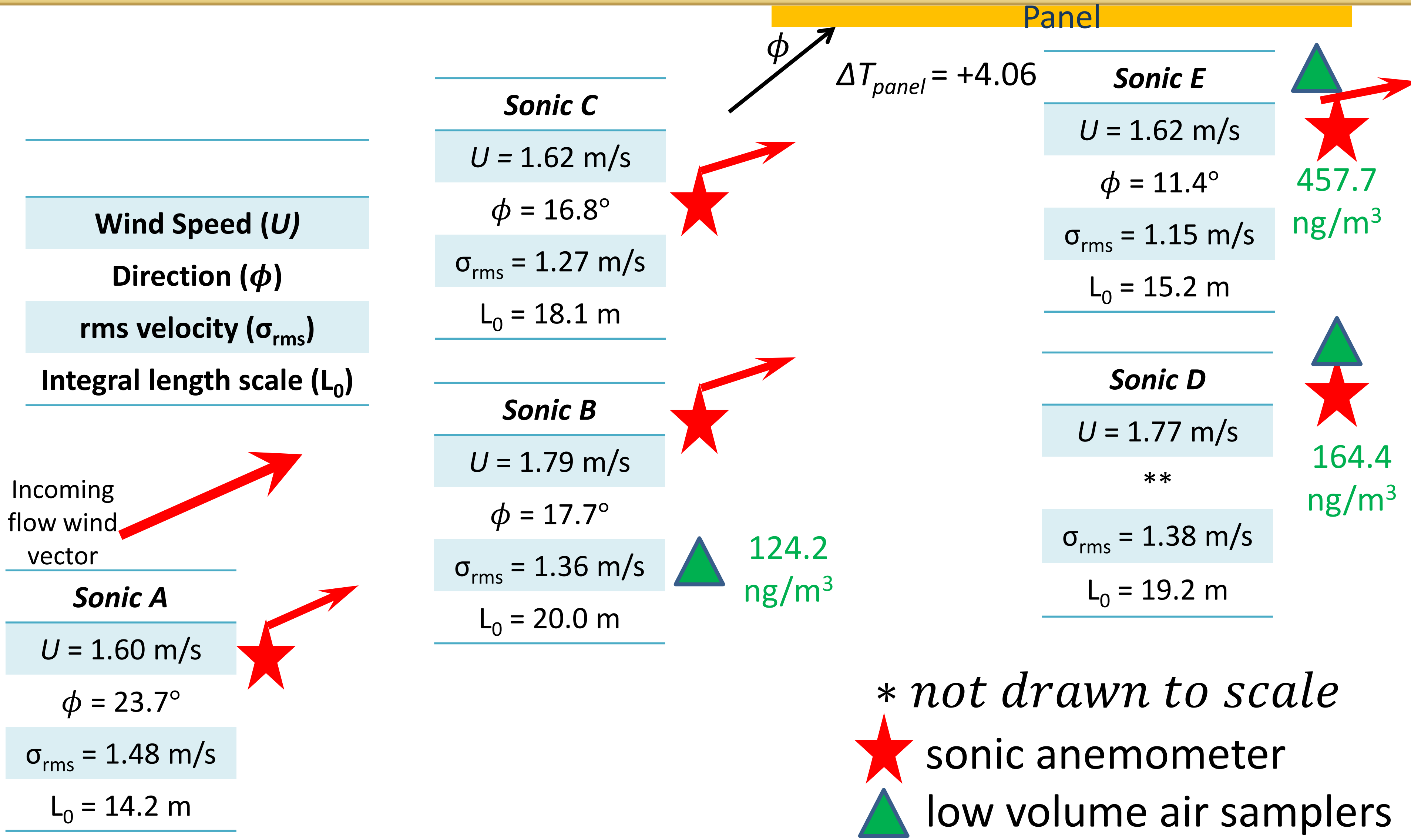
Sonic D
U = 2.92 m/s
**
σ_{rms} = 1.76 m/s
L_0 = 25.5 m

195.3 ng/m^3

** not drawn to scale*

★ sonic anemometer
▲ low volume air samplers

Test 4



Wind Speed (U)
Direction (ϕ)
rms velocity (σ_{rms})
Integral length scale (L_0)

Incoming flow wind vector

Sonic A
U = 1.60 m/s
ϕ = 23.7°
σ_{rms} = 1.48 m/s
L_0 = 14.2 m

Sonic B
U = 1.79 m/s
ϕ = 17.7°
σ_{rms} = 1.36 m/s
L_0 = 20.0 m

124.2 ng/m^3

Sonic C
U = 1.62 m/s
ϕ = 16.8°
σ_{rms} = 1.27 m/s
L_0 = 18.1 m

Panel

ϕ

ΔT_{panel} = +4.06

Sonic E
U = 1.62 m/s
ϕ = 11.4°
σ_{rms} = 1.15 m/s
L_0 = 15.2 m

457.7 ng/m^3

Sonic D
U = 1.77 m/s
**
σ_{rms} = 1.38 m/s
L_0 = 19.2 m

164.4 ng/m^3

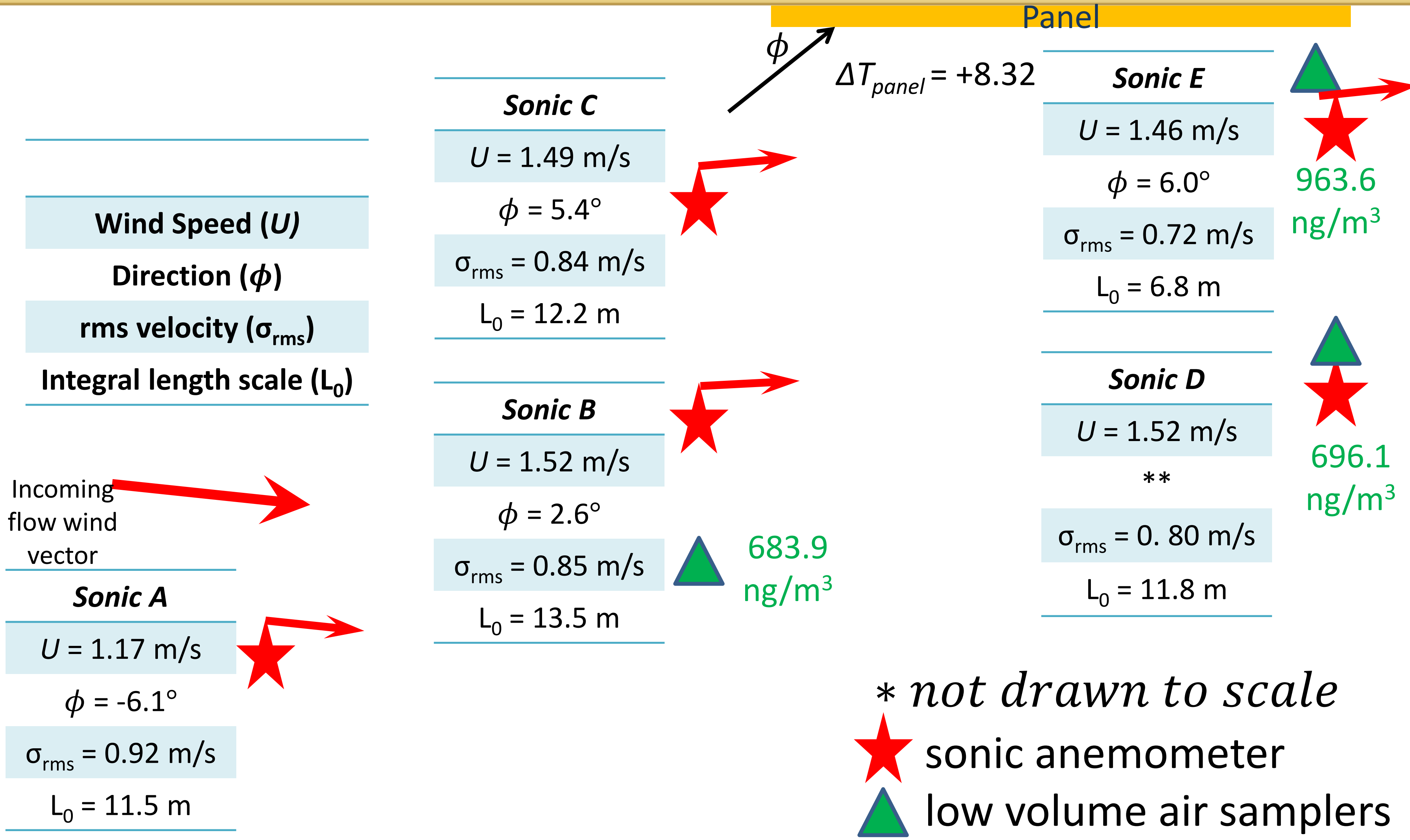
$*$ *not drawn to scale*

★ sonic anemometer
▲ low volume air samplers

Flow characteristics

- Tests 1, 2, and 4 similar
- Flow channelization along wall
- Wall acts as local sink of turbulent kinetic energy (TKE)
- Elongation of eddies parallel to wall
- Negative buoyancy in Test 1; positive buoyancy in Tests 2 & 4

Test 3



Wind Speed (U)

Direction (ϕ)

rms velocity (σ_{rms})

Integral length scale (L_0)

Incoming flow wind vector

Sonic A

U = 1.17 m/s

ϕ = -6.1°

σ_{rms} = 0.92 m/s

L_0 = 11.5 m

Sonic C

U = 1.49 m/s

ϕ = 5.4°

σ_{rms} = 0.84 m/s

L_0 = 12.2 m

Sonic B

U = 1.52 m/s

ϕ = 2.6°

σ_{rms} = 0.85 m/s

L_0 = 13.5 m

683.9 ng/m^3

Panel

ϕ

ΔT_{panel} = +8.32

Sonic E

U = 1.46 m/s

ϕ = 6.0°

σ_{rms} = 0.72 m/s

L_0 = 6.8 m

963.6 ng/m^3

Sonic D

U = 1.52 m/s

**

σ_{rms} = 0. 80 m/s

L_0 = 11.8 m

696.1 ng/m^3

* *not drawn to scale*

★ sonic anemometer

▲ low volume air samplers

EXPERIMENTAL RESULTS: DEPOSITION VELOCITY

Deposition velocity

- Material samples and LVS filters analyzed using spectrofluorometric technique
- $V_d = -\frac{J}{C_\infty}$
  - *J* is mass flux onto surface (kg m^{-2} s^{-1}), get from materials post-analysis
  - C_∞ is concentration (kg m^{-3}), take from LVS 1 assuming uniform near panel

Deposition Velocity (m s^{-1})	**Auto-cleaning glass**	**Standard glass**	**Marble**	**Ceramic**
Test 1	8.17×10^{-3}	7.53×10^{-3}	1.05×10^{-3}	1.03×10^{-3}
Test 2	5.27×10^{-4}	6.71×10^{-4}	6.56×10^{-4}	2.94×10^{-4}
Test 3	1.75×10^{-4}	2.18×10^{-4}	2.07×10^{-4}	7.1×10^{-5}
Test 4	4.16×10^{-4}	5.11×10^{-4}	2.44×10^{-4}	2.49×10^{-4}
SaliFa2: Test 3	$\sim1.65\times10^{-5}$	$\sim2.05\times10^{-5}$	■	■

- Spans three orders of magnitude!

*** These are preliminary results – chemical analysis is ongoing for Leccese stone results and quality control of other materials*

ANALYSIS: GOVERNING PARAMETERS

Dimensional analysis

$$V_d = \mathrm{F}\{U, \phi, \sigma_{rms}, L_0, g\beta\Delta T_{panel}, \upsilon, \alpha, \xi_{mat}\}$$

$$\frac{V_d}{\sigma_{rms}} = F\left\{\phi, \xi_{mat}, \frac{UL_0}{\upsilon}, \frac{{L_0}^3 g\beta\Delta T_{panel}}{\upsilon^2}, \cancel{\frac{\upsilon}{\alpha}}\right\}$$

Reynolds, Grashof, and Prandtl numbers

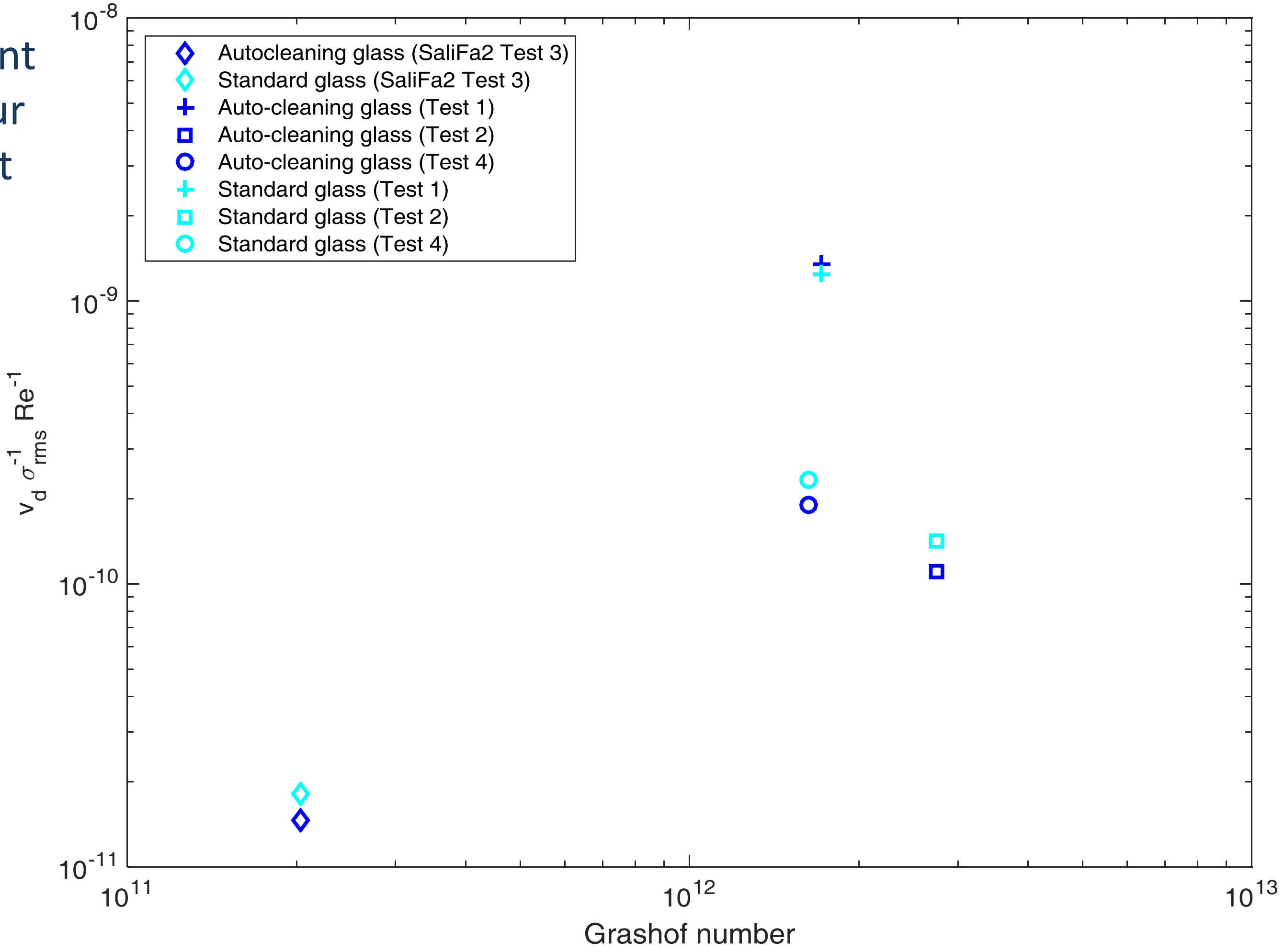
Applying to our case

- $V_d = \mathrm{F}\{U, \phi, \sigma_{rms}, L_0, g\beta\Delta T_{panel}, \upsilon, \alpha, \xi_{mat}\}$
- $\frac{V_d}{\sigma_{rms}} = F\left\{\phi, \xi_{mat}, \frac{UL_0}{\upsilon}, \frac{{L_0}^3 g\beta\Delta T_{panel}}{\upsilon^2}, \cancel{\frac{\upsilon}{\alpha}}\right\}$
- For Tests 1, 2, and 4, ϕ was approximately constant (~15°)
- Can extract all needed parameters for single test from Maro et al. (2014) except L_0 for which assumed constant energy dissipation $({\sigma_{rms}}^3/L_0)$ between our Test 4 and SaliFa2 Test 3

Test #	Reynolds Number (Re)	Grashof Number (Gr)	Wind Angle (ϕ)
1	3.2×10^6	(-) 1.7×10^{12}	9.1
2	2.5×10^6	2.7×10^{12}	15.8
3	9.8×10^5	2.4×10^{12}	-6.1
4	1.5×10^6	1.6×10^{12}	23.7
SaliFa2_3	8.9×10^5	2.0×10^{11}	? ~≥0

Relating dimensionless parameters

ξ_{mat} constant between our experiment and SaliFa

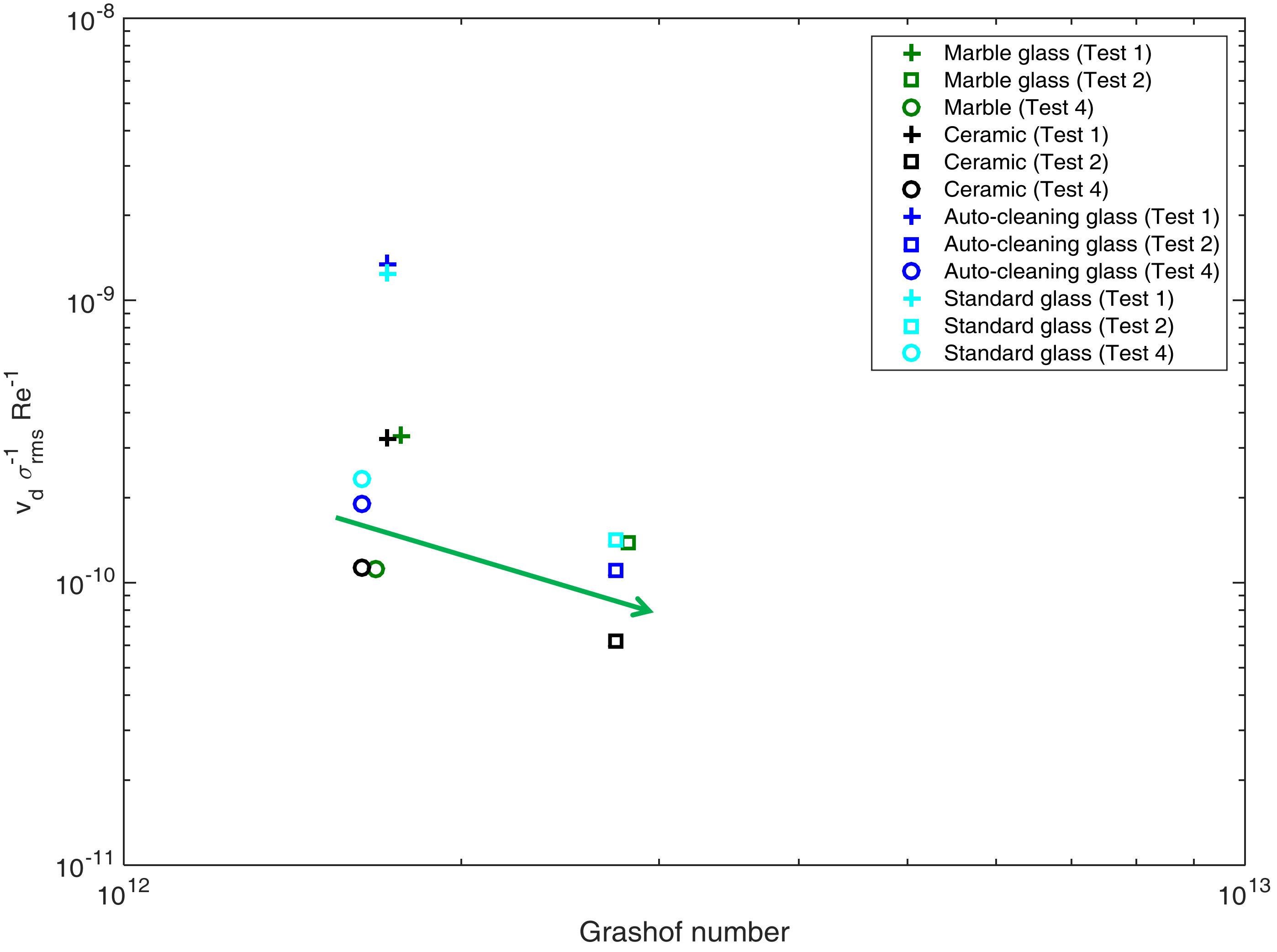


$$\frac{V_d}{\sigma_{rms}} \propto Re^m Gr^{\ n}$$

Relating dimensionless parameters

- Test 1 stands out because only case where ΔT_{panel} is negative so divergence is attributable to thermophoresis (Di Nicola et al. 2016)
- Consistent trend between standard and auto-cleaning glass (except Test 1) – self-cleaning properties rely on sunlight (Parkin and Palgrave 2005)
- SaliFa order of magnitude difference with our experiments on x-axis and y-axis

Relating dimensionless parameters



CONCLUSIONS

Conclusions

- At large Grashof numbers (>10^{12}), the deposition velocity depends principally on sign (+/-) of buoyancy due to thermophoretic effects
- When surface heated, at high Gr and Re, deposition velocity may be approximately constant, independent on Gr and even the material properties
- More experiments are needed at intermediate Gr to address discrepancies between results
- Just addressed principally one micrometeorological scenario – there are many more to solve with further experiments, but challenges still exist in conducting these experiments
- Introduction of an approach which helps to quantify near-wall deposition processes based on local-scale urban flow regime for dispersion modelling

Acknowledgements

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Thank you

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