Wind Measurement Campaign on the Great Belt Bridge

Deutsches Zentrum für Luft- und Raumfahrt / German Aerospace Center (DLR)
Institute of Aerodynamics and Flow Technology
Department of Ground Vehicles

DLR

Contents

Objective

- DB Cargo has commissioned the German Aerospace Center (DLR) to carry out a detailed measurement campaign.

- The aim of the work is to measure the time-varying atmospheric wind - including gusts - that freight trains are exposed to in typical operation travelling over the West Bridge of the Great Belt Fixed Link between the Funen und Zealand islands in Denmark.

- This will be performed using the DLR FR8-LAB measurement container, a ‘swap-body’ fitted with a self-contained data acquisition, power supply and a communication system that can be transported on normal operating freight-trains.

- The FR8-LAB was developed in 2021 as a experimental platform for research into the safety, efficiency and performance of freight transport, as part of the EU Shift2Rail, FR8RAIL IV research project.

- A measurement set-up from DB Systemtechnik (DB ST), that can record the time-varying air velocity with ultrasonic anemometers (USA) is also installed, taking measurements in parallel.

Experimental Setup

DLR FR8-LAB

- The full-scale experiments will be performed using the DLR FR8-LAB measurement container.

- Time-varying surface-pressure measurements will be used to derive the transient wind that the container is exposed to.

- The surface-pressure measurements will also be integrated to provide an estimation of the global aerodynamic forces and moments acting on the container.

- A separate reduced-scale model wind-tunnel experiment will be performed to determine calibration data to associate the measured surface-pressure to wind speeds the container is exposed to during transport on the freight train across the bridge.

Experimental Setup

Wagon Setup: FR8-LAB

- The DLR FR8-LAB was positioned on a six-axle articulated - Sggmrs 714 wagon – coupled with an additional 4-axle Sgns 691 wagon.
- This configuration resulted in a minimum gap in front and behind of the measurement container of ~17m & ~29m respectively
- This ensured the FR8-LAB was ideally positioned in order to take robust cross-wind measurements.

Experimental Setup

Wagon Setup: FR8-LAB with DB ST ultrasonic anemometers from Feb 7th – March 4th

- From Feb 7th, 2022 the DB ST experimental setup was also installed & measurements made in parallel.
- Wagon configuration was changed:
  - The FR8-LAB was positioned on the same Six-axle articulated - Sggmrs 714 wagon
  - coupled with 3 additional 4-axle Sgns 691 wagons together.
  - Resulting in a minimum gap in front and behind of the FR8-LAB of ~10m & ~66m

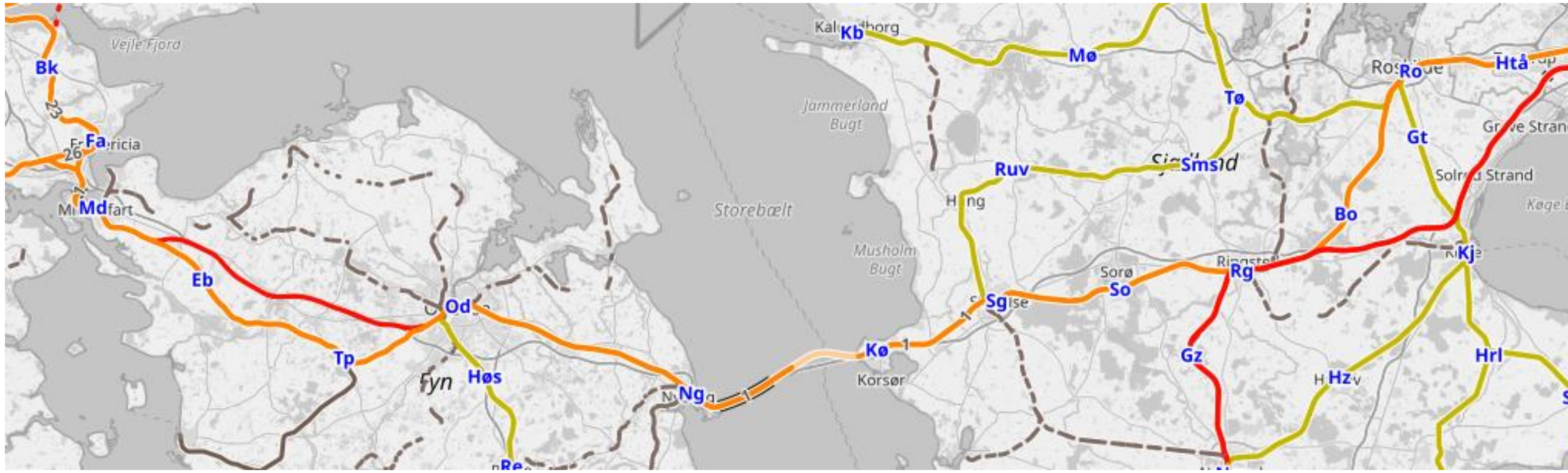
- The DB ST ultrasonic anemometers (USAs) were located centrally in the middle Sgns 691 with 9m spacing between them.
  - Resulting in distances of ~45m and 36m from the USAs respectively to the closest end of the FR8-LAB

Source: DB ST 220211 Belt-Bridge_info_prelim

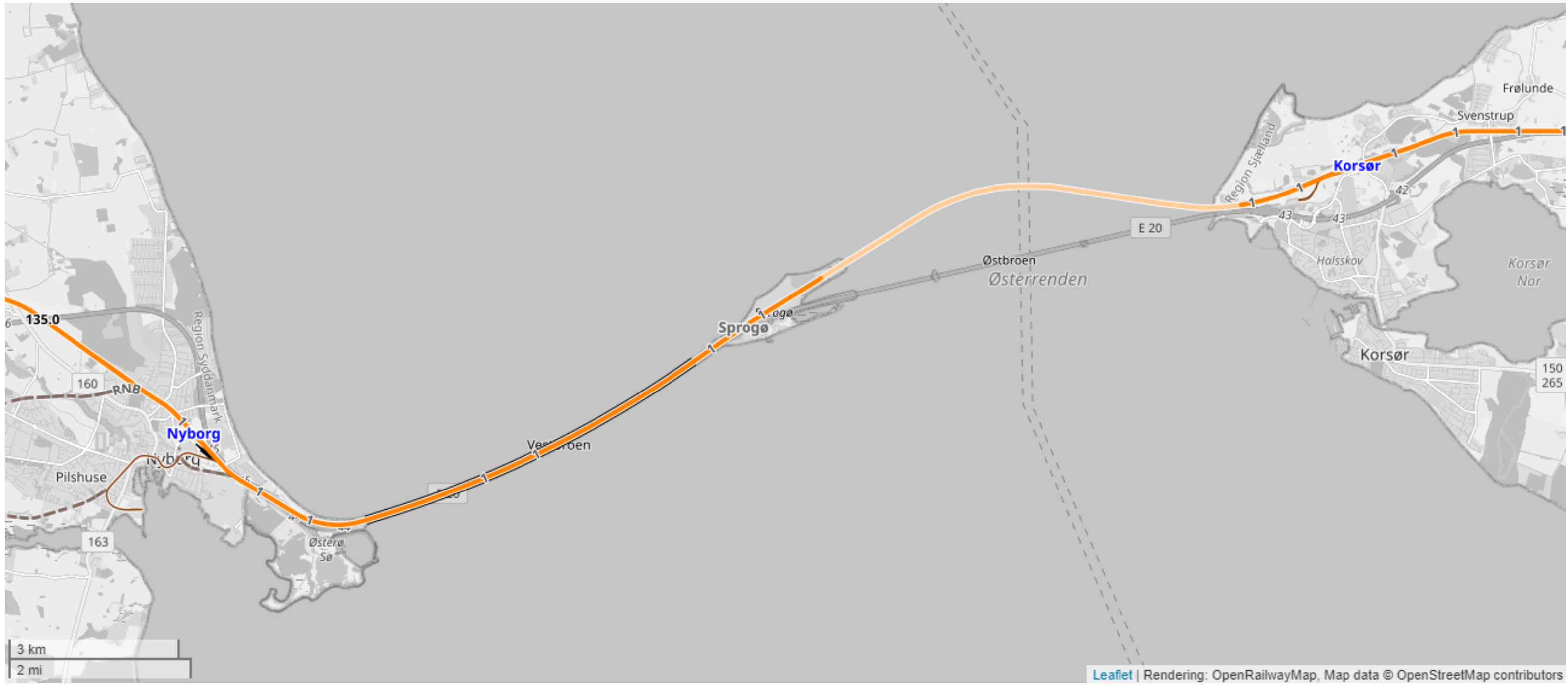
Experimental Setup

Test Plan

- Full Test-route:
  Taulov (**Tv**) - Fredericia (**Fa**) - Høje Taastrup (**Htå**)
- Primary Measurements focus:
  Nyborg (**Ng**) – Korsør (**Kø**)
- ~4 runs (2 round trips) per day
- Throughout the day (capturing different environmental conditions)
- Campaign duration: ~ 8 weeks



https://www.openrailwaymap.org/?style=standard&lat=55.66906586432122&lon=10.960235595703125&zoom=9



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Experimental Setup

DLR FR8-LAB Codification

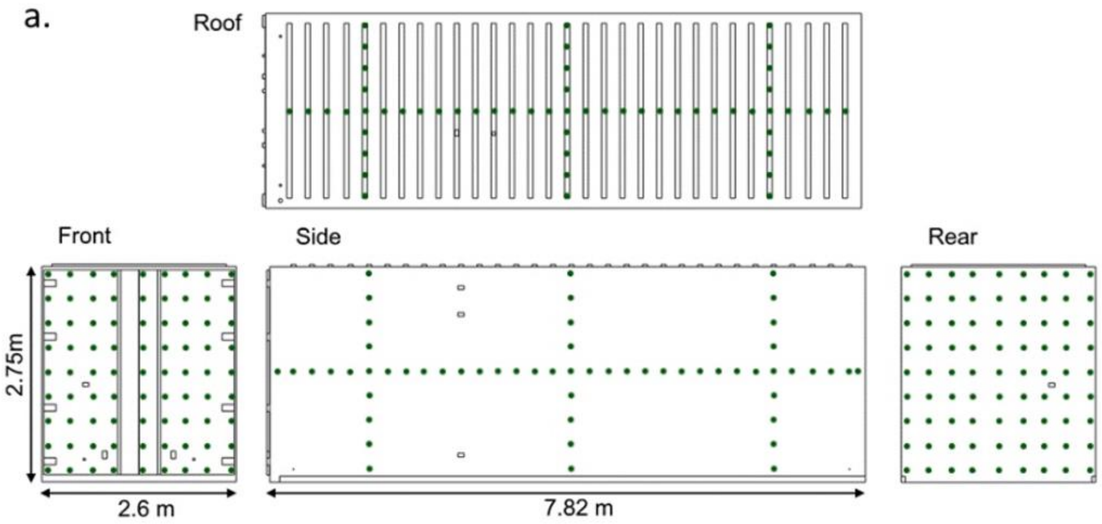
- The DLR FR8-LAB measurement container is a ‘swap-body’ that has been certified/codified, and can be transported on normal operating freight-trains.

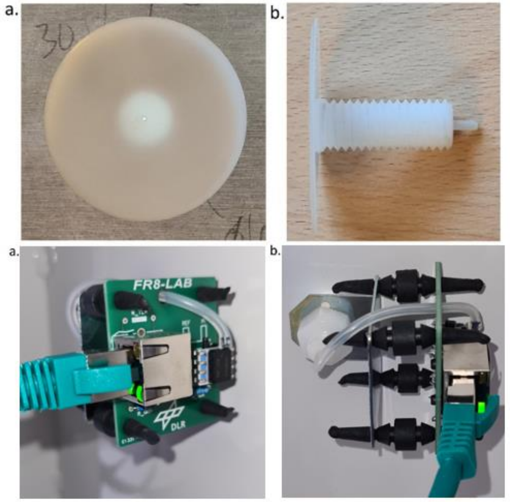
ILU-Code	DLRA 864512 2
WB-Typ	WK 7,7 STG
Länge	7820mm
Höhe	2750mm
Breite	2550mm
Gewicht (brutto)	3,9t
Kodifizierung	C48 S48 / 24 2550 XL / 006 • 001612 • 5W1229520

Measurement System

Surface Pressure

- up to 320 pressure measurement positions
- Honeywell HSC differential-pressure digital (I2C) sensors
  - ±4 kPa range
- Up to 1000 Hz sampling frequency
- >200,000 samples per sensor, per measurement run
- Distributed pressure transducers on inner surface of container

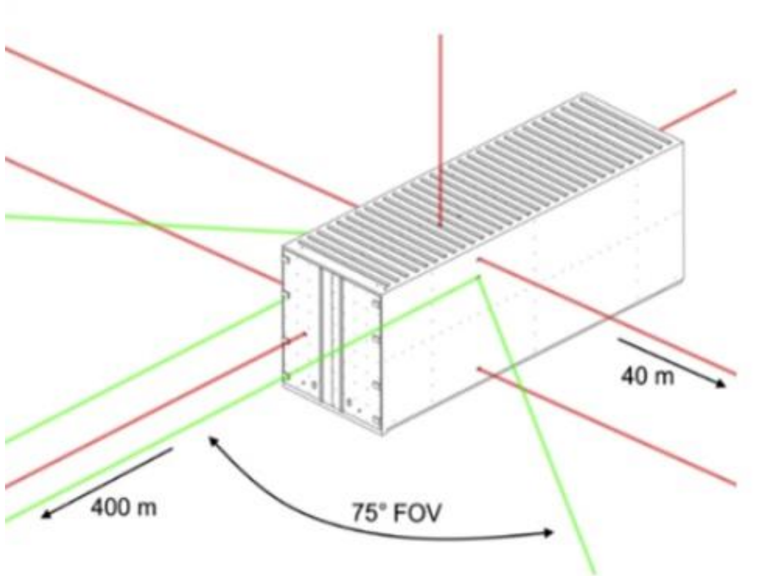


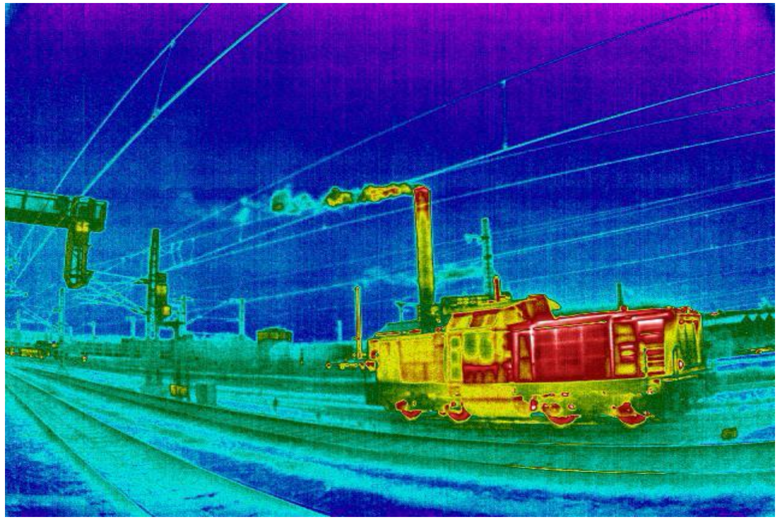


Measurement System

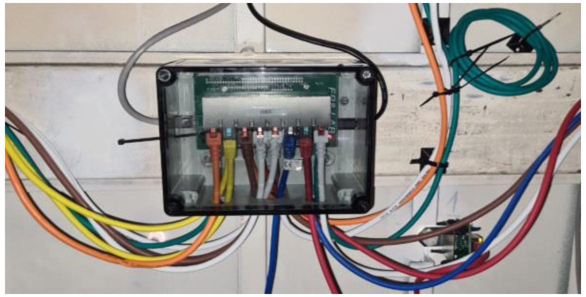
Environmental Monitoring

- Global navigational satellite system: vehicle velocity, position
- Up to 7 x LIDAR sensors: topography
  - single point @ roof, front, rear & sides
  - 40m range @~1000 Hz
- 2 x Thermal cameras: topography
  - FLIR ADK prototype @up to 60 Hz (2 image/m)
  - 75° field-of-view
- Accelerometers (vibrations)





Measurement System



Data Acquisition System

- IoT based: low power & robust
- *Nucleo* Microcontrollers DAQ Nodes
- *Raspberry Pi* Server (UDP & PTP)
  w/ Otto-von-Guericke-University of Magdeburg

- *InfluxDB:* database management
- *Grafana*: real-time monitoring

- 30 x 50W Solar Panels
- Remote-access with 4G comms
- Intelligent system (system idle, triggers: speed, geofencing)

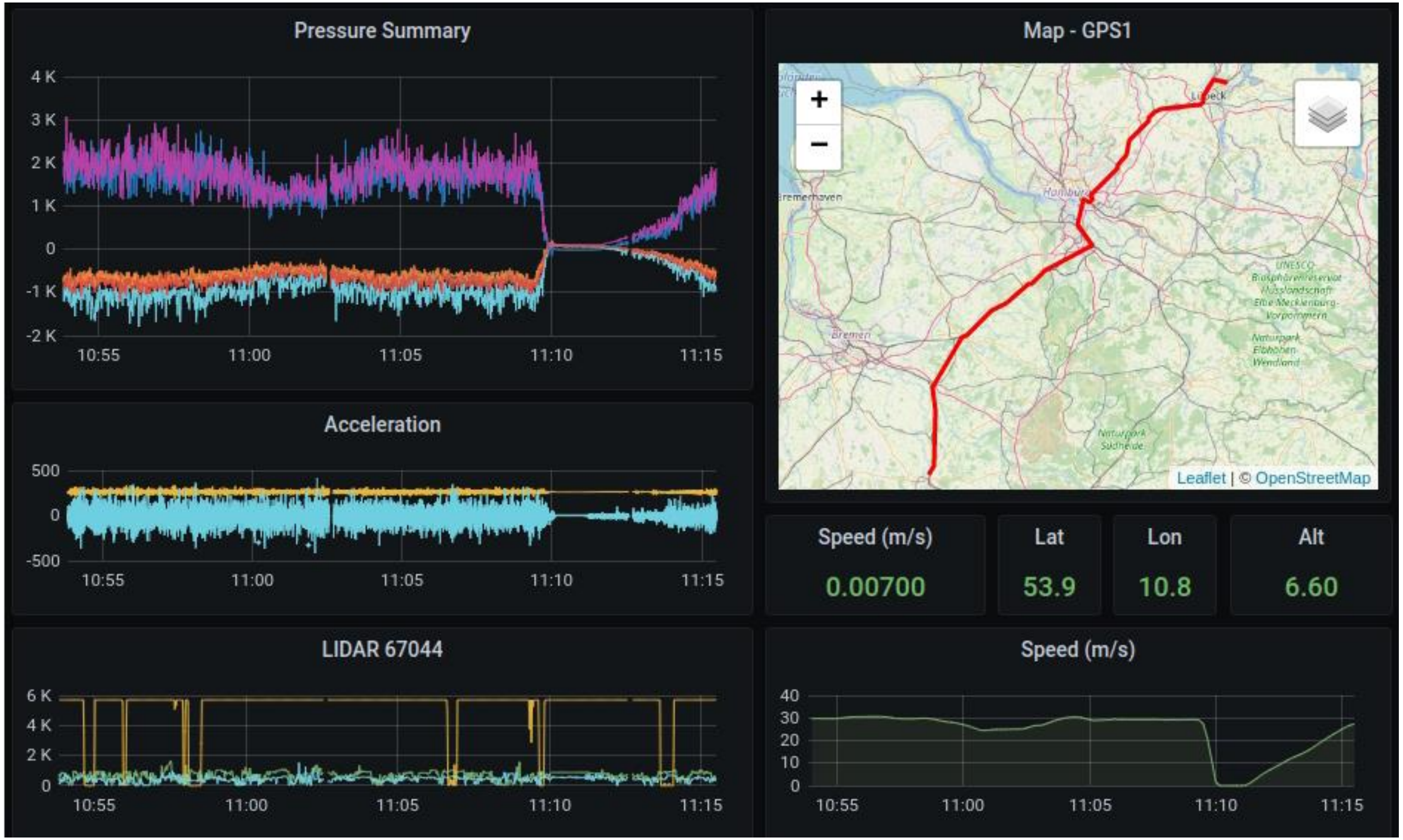
Measurement System

Real-time analysis

- Data sanity checking/troubleshooting/manual control

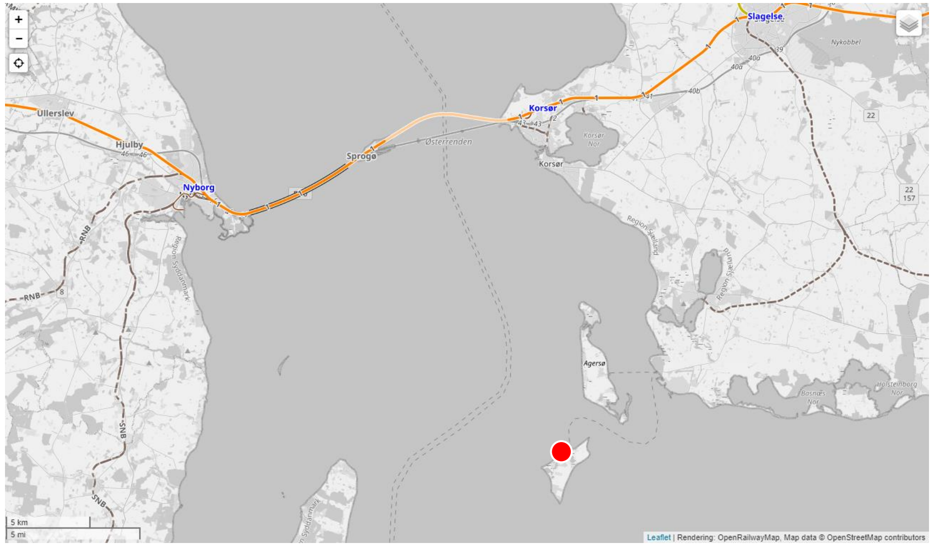
- Example of measured data: surface pressure, and environmental characteristics

- Raw data is presented, magnitude/units are not real



Measurement Campaign

- Measurements: Jan 10th - Mar 4th
- Wide range of weather conditions
- >70 bridge crossings measured
- >150GB data



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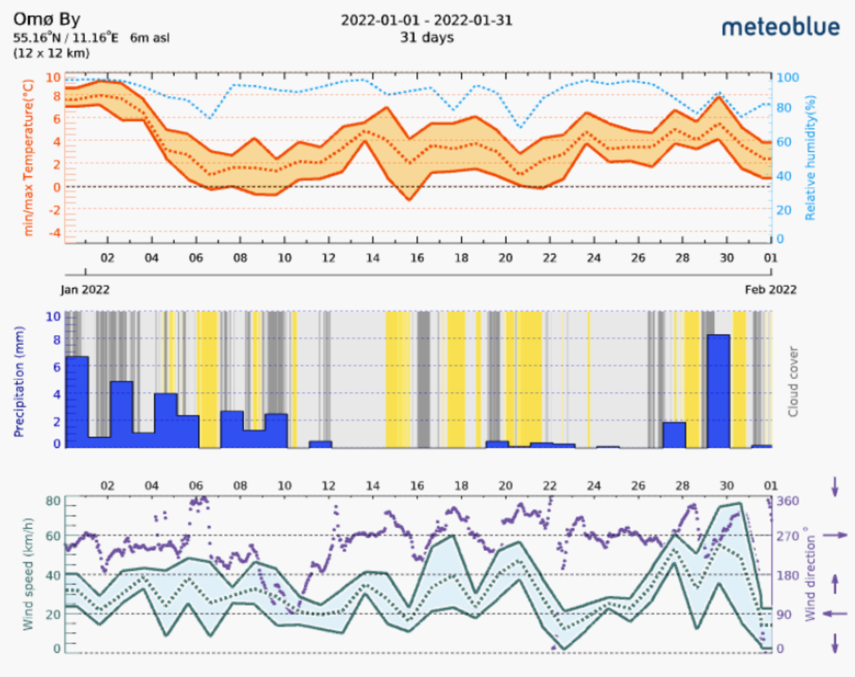
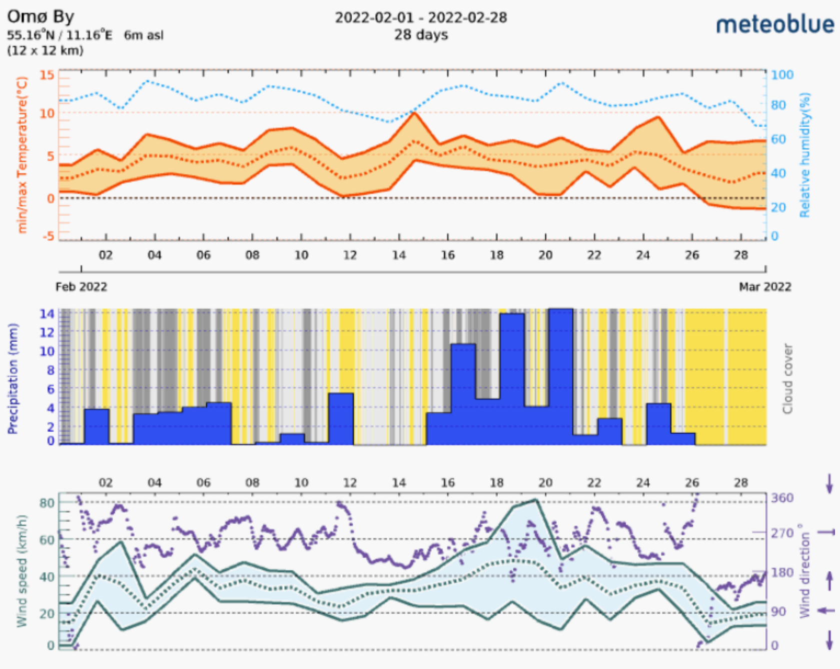
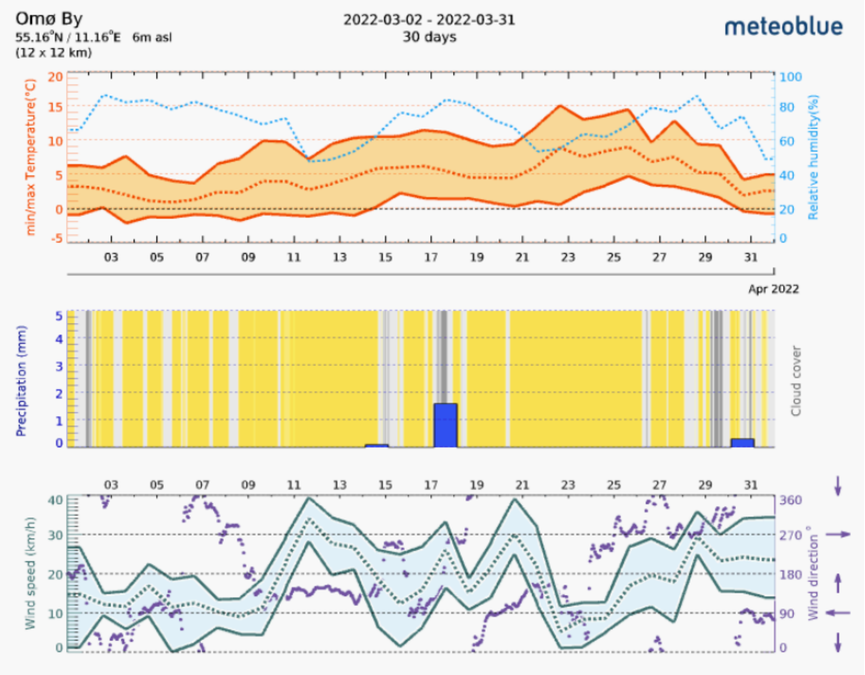


Jan 2022



Feb 2022



March 2022

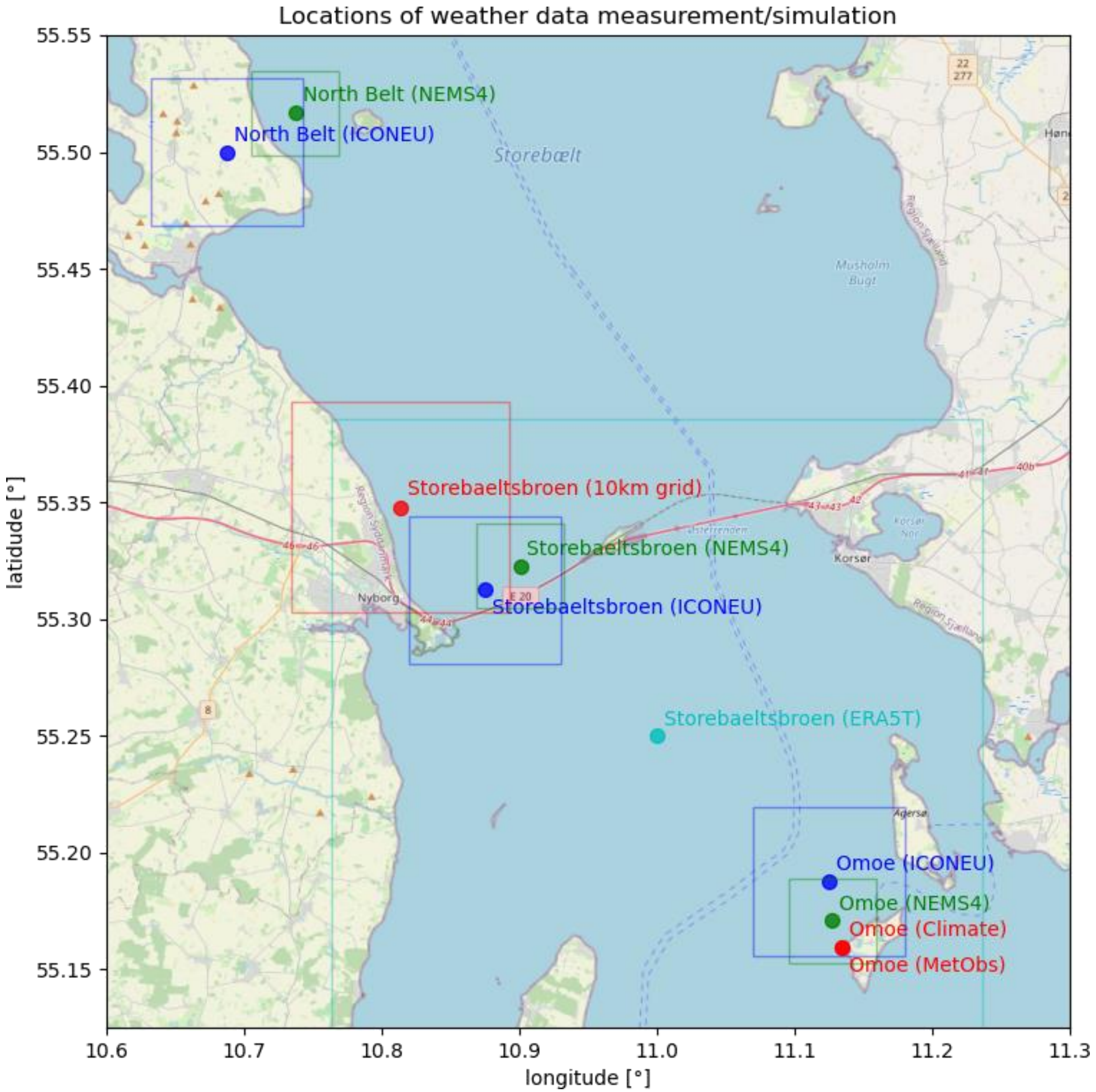
https://www.meteoblue.com/en/weather/historyclimate/weatherarchive/om%c3%b8-by_denmark_2615811?fcstlength=1m&year=2022&month=2

Weather Station Data

Validation
(in addition to DB ST Ultrasonuc Anemometers)

- Multiple data sources acquired
- Primary: Omoe weather station (MetObs)
  - best: \`real´ location & best available data
  - Danmarks Meteorologiske Institut (DMI) @ Omø Fyr, ID 06151
  - Height of velocity measurement: 10m
    https://confluence.govcloud.dk/pages/viewpage.action?pageId=26476616
  - Relative to bridge height > 18m
    https://storebaelt.dk/en/about-storebaelt/facts-history/

- Validated against: other stations, simulation data, & station data interpolated to bridge location



Weather Station Data

Validation (in addition to DB ST Anemometers)

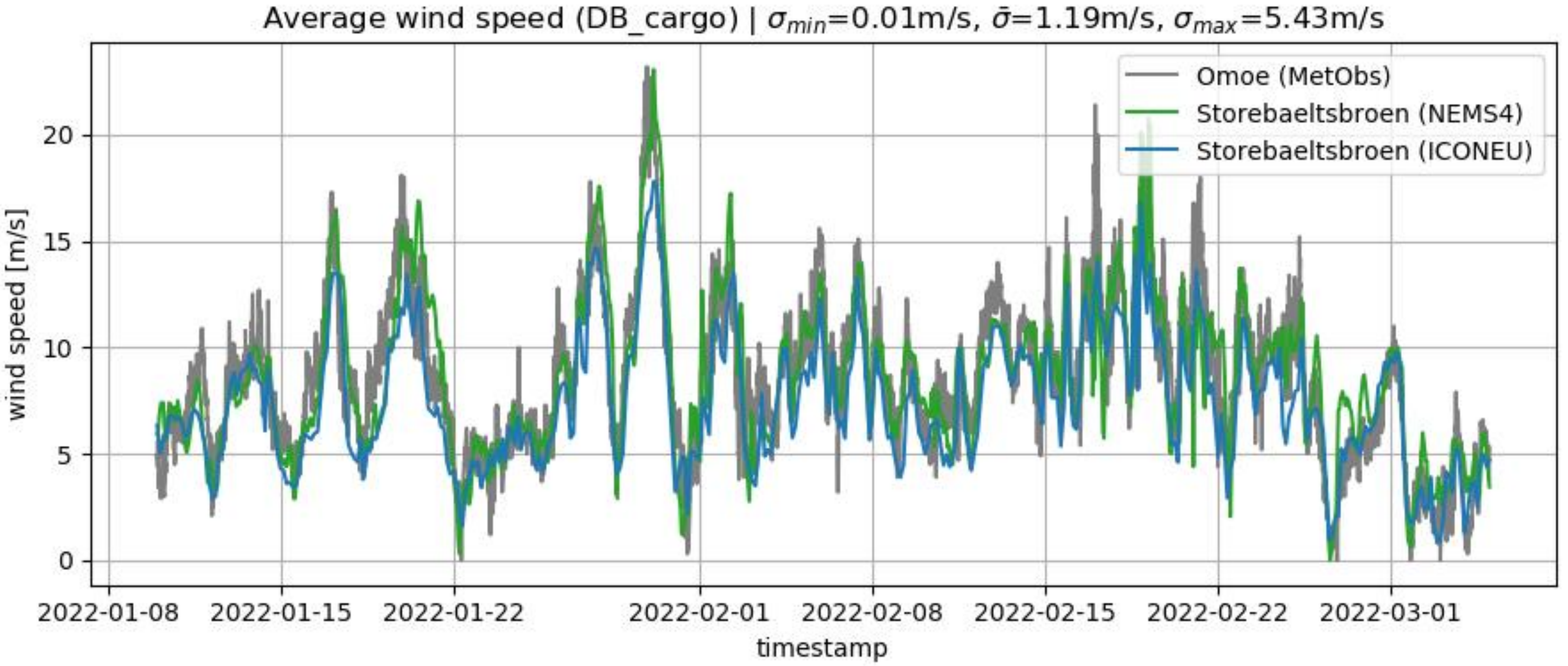
Mean wind speed: 10 minutes' mean measured 10 m over terrain
https://confluence.govcloud.dk/pages/viewpage.action?pageId=26476616

local 10min weather station:
Omoe (MetObs)

corresponds well to:

simulated @ bridge: (NEMS4)
measured/ interpolated
@ bridge: (ICONEU)

→ Omoe Weather station used as Primary Weather Data for validation



Weather Station Data

Validation (in addition to DB ST Anemometers)

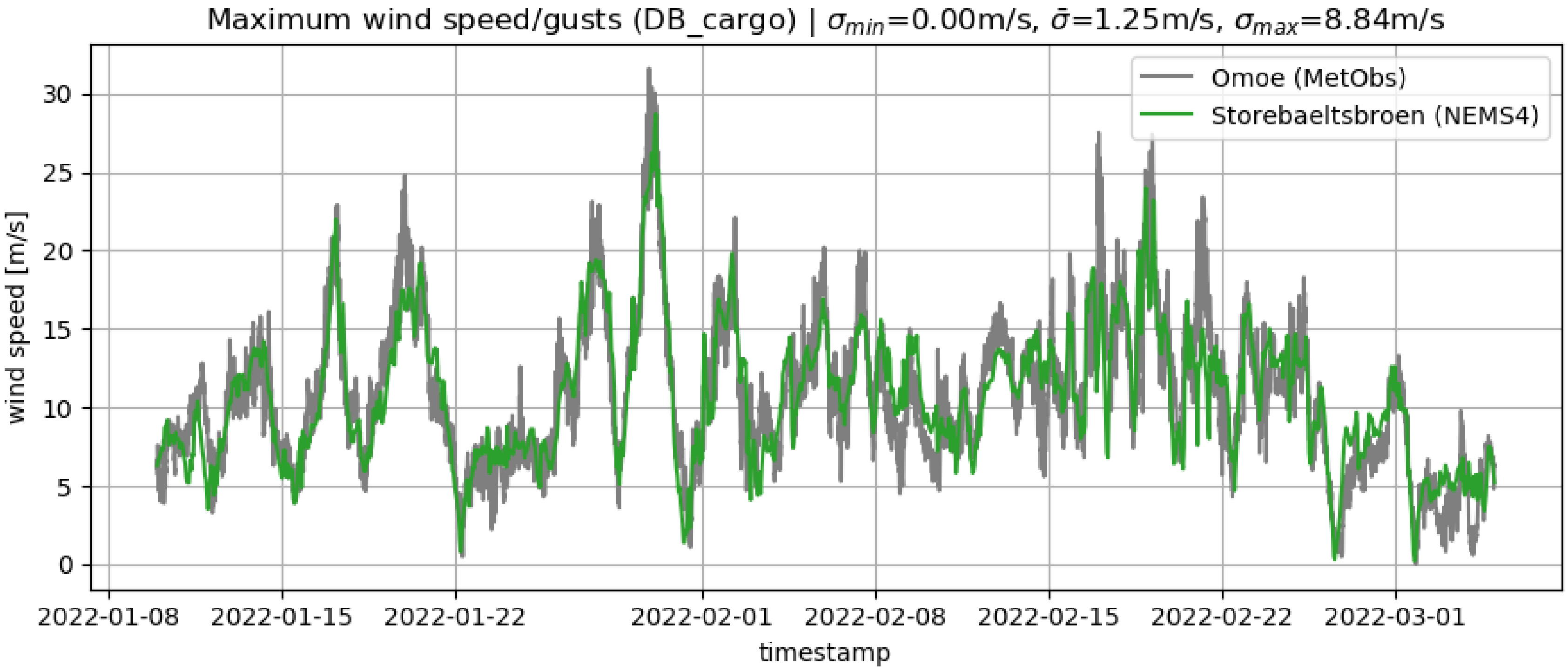
Gust (3s) wind speed: 10 minutes' highest 3 seconds mean wind speed measured 10 m over terrain
https://confluence.govcloud.dk/pages/viewpage.action?pageId=26476616

local 10min weather station:
Omoe (MetObs)

corresponds well to:

simulated @ bridge: (NEMS4)
measured/ interpolated
@ bridge: (ICONEU)

→ **Omoe Weather station used as Primary Weather Data for validation**



DLR

1:15 scale Wind-Tunnel Experiment: Calibration Methodology Container pressure taps as a Velocity (Magnitude and Direction) probe

Full-scale Experiment on Rail

measured:

- Pressures (Pa) at surface:
  front, rear, sides, roof
- Train speed: V_T
  from GNSS satellite system (m/s)

To derive:

- Wind: V_W
  atmospheric wind speed (m/s)

← Connected through →

Pressure at surface (Pa)
front, rear, sides, roof

- left-right pressure delta (normalized)
  → Yaw Angle, β
- combined pressure magnitudes
  → resultant velocity magnitude: V_R

Wind-Tunnel Experiment

We have:

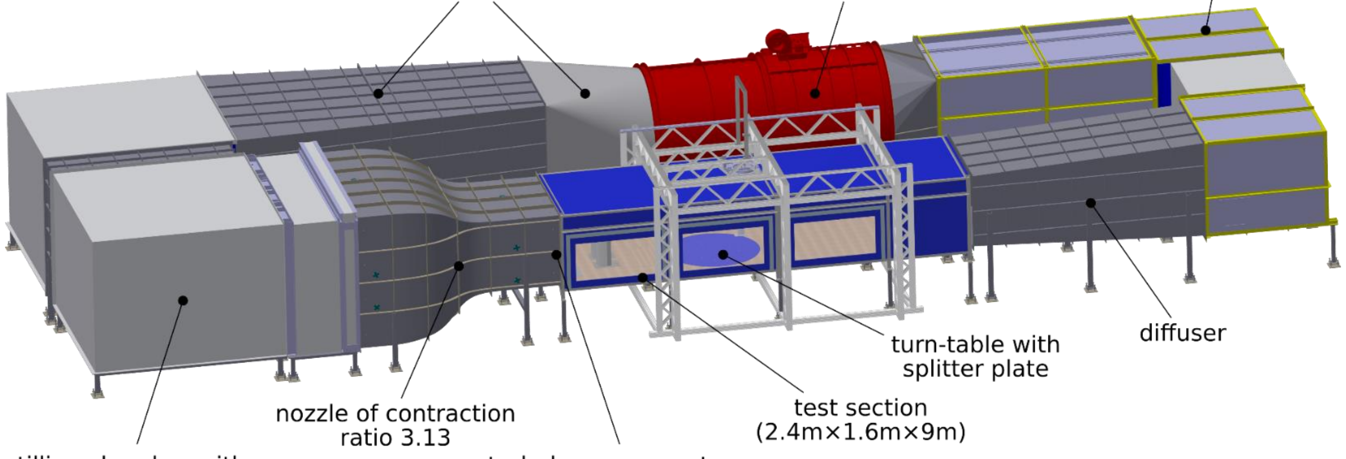
- Pressures at surface (Pa)
  front, rear, sides, roof
- Beta (yaw angle °)
  angle of model in wind-tunnel relative to oncoming flow
- Resultant wind speed: V_R (m/s)
  V_R =V_T+V_W
  *wind tunnel = freestream velocity corresponds to dynamic pressure, Q=0.5*density*V^2*

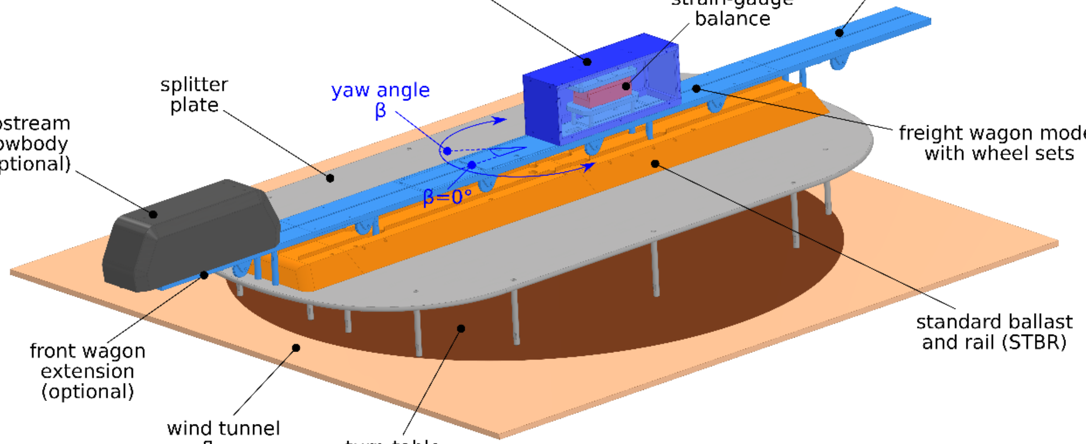
DLR

1:15 scale Wind-Tunnel Experimental Setup

Wind-Tunnel Calibration:
analogous surface pressure measurements were obtained in a 1:15 reduced-scale wind-tunnel experiment, with a FR8-LAB model statically exposed to different yawed oncoming flow (modelling crosswind exposure)

- @ discrete static yaw-angles, Beta: β = -90 : 90°
- @ a range of conditions:
  loading configurations (gaps: ∞, 9.3-17.8m), Reynolds no. (Re: 3-5x10^5), and turbulence intensities (~1,3,5%)

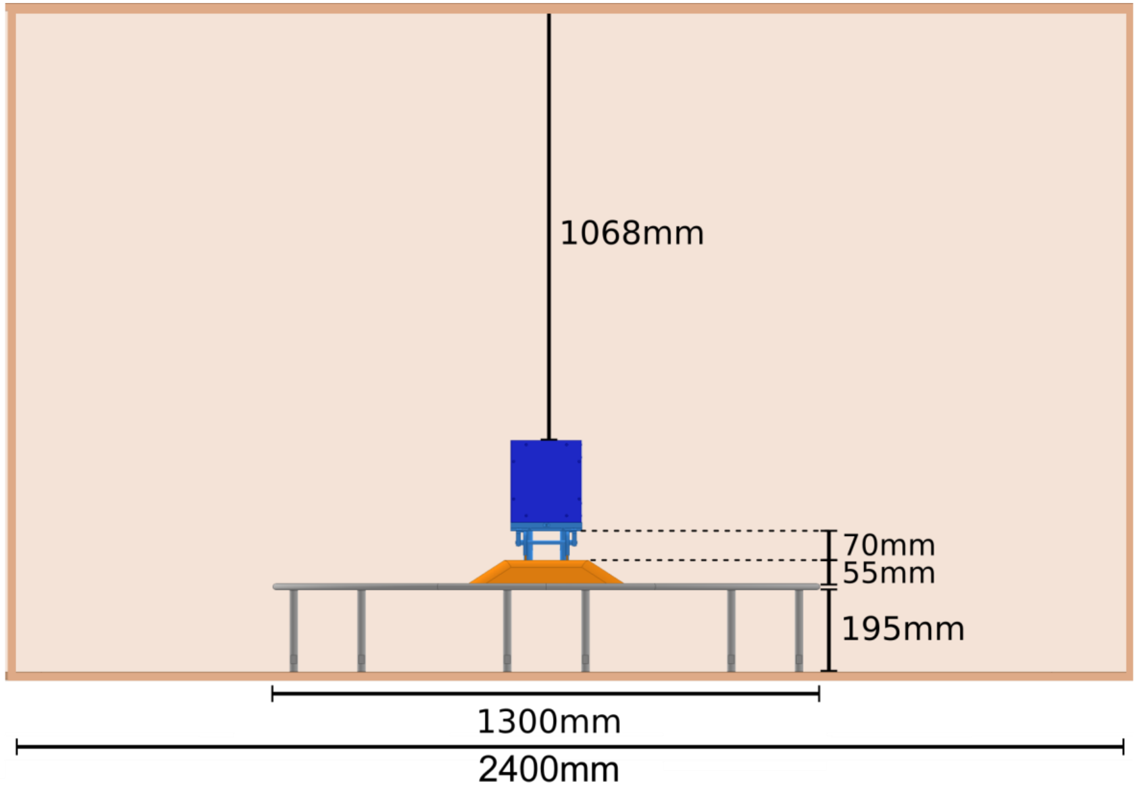




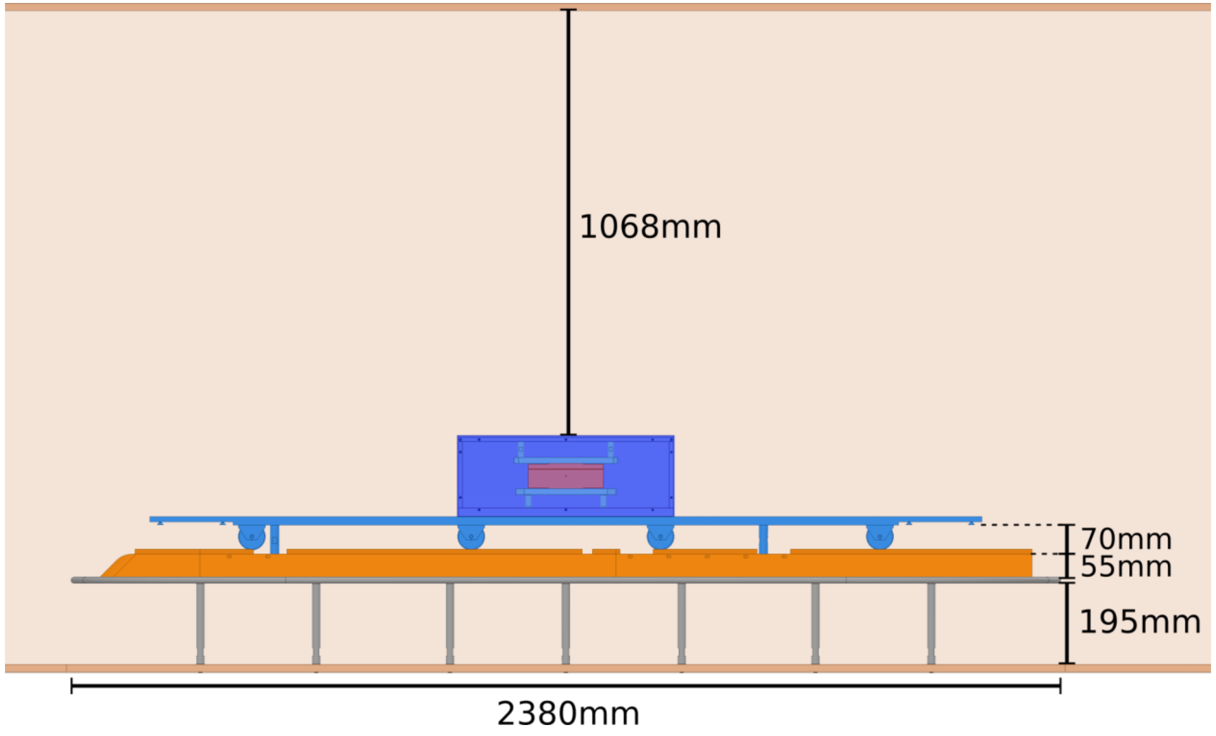
1:15 scale Wind-Tunnel Experimental Setup

1:15 scale Wind-Tunnel Experimental Setup

Front View

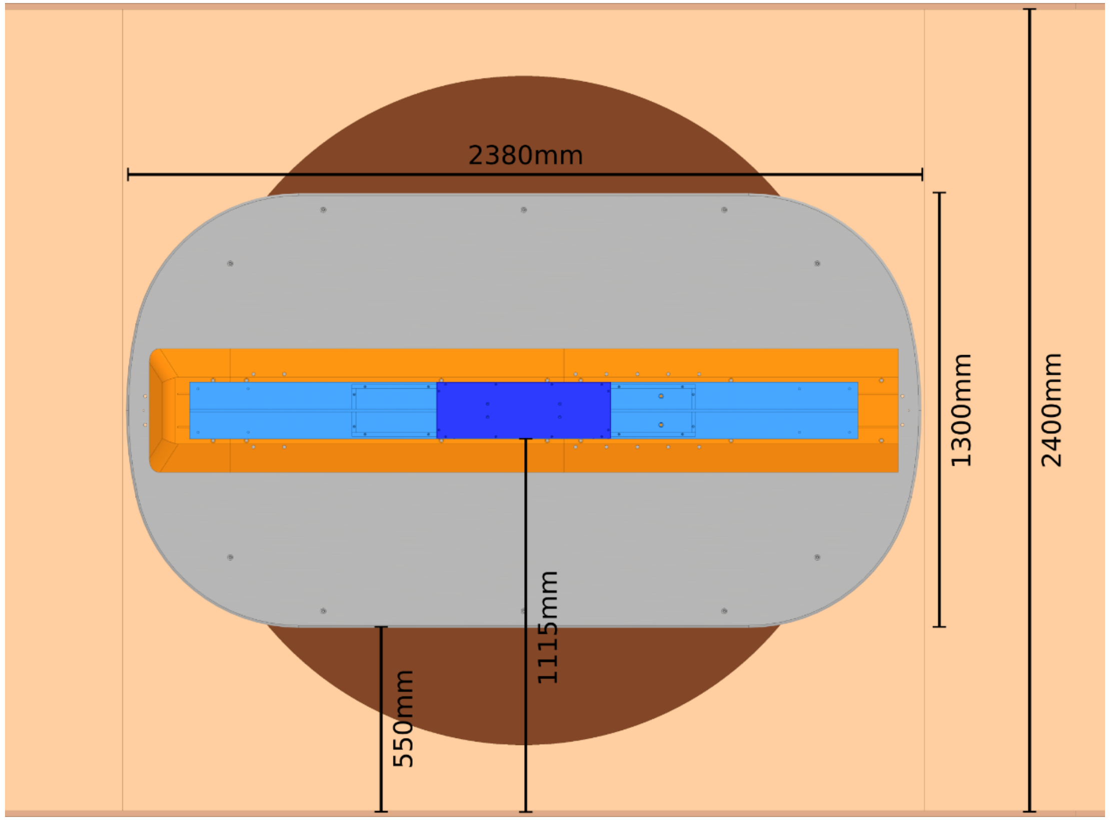


Side View

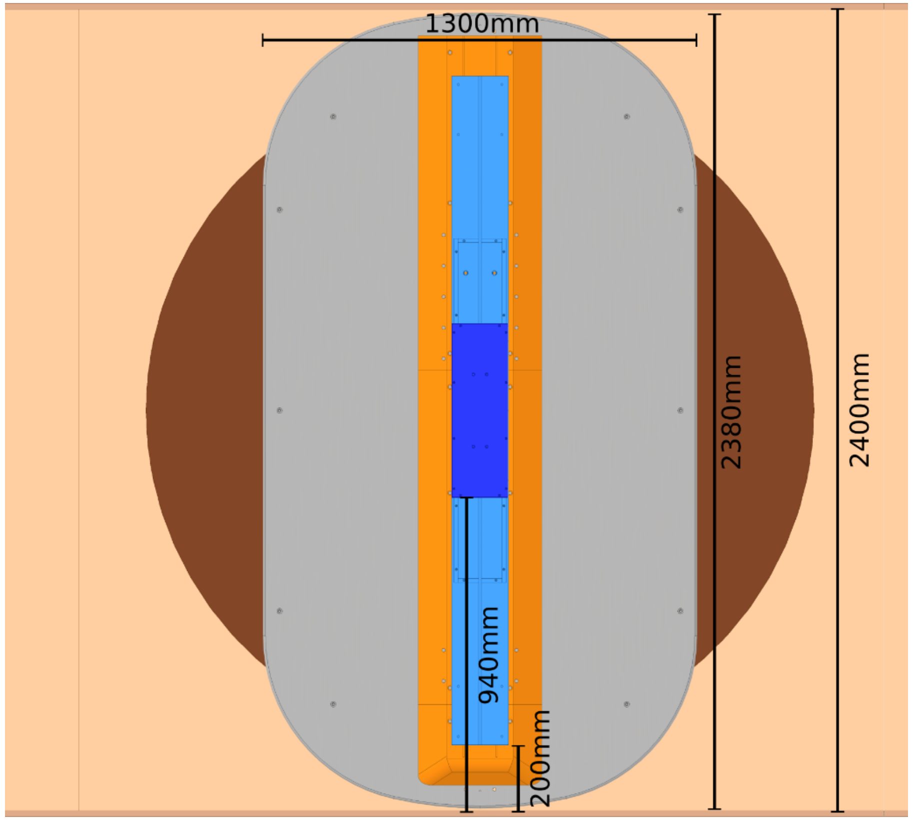


1:15 scale Wind-Tunnel Experimental Setup

Top View: 0° Yaw Configuration



Top View : 90° Yaw Configuration

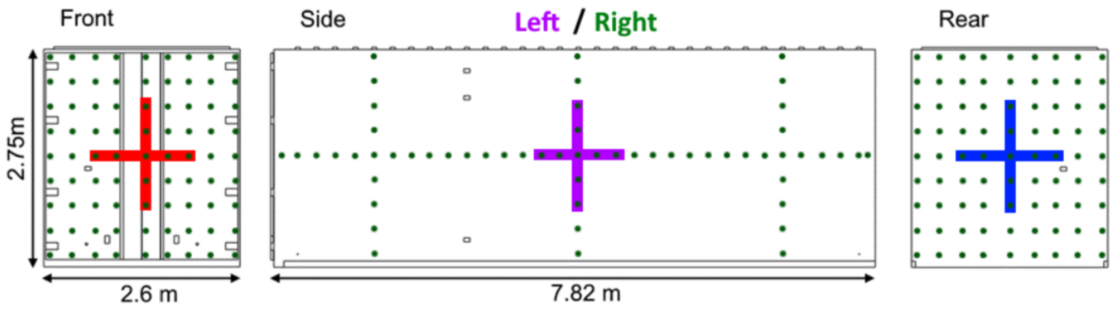


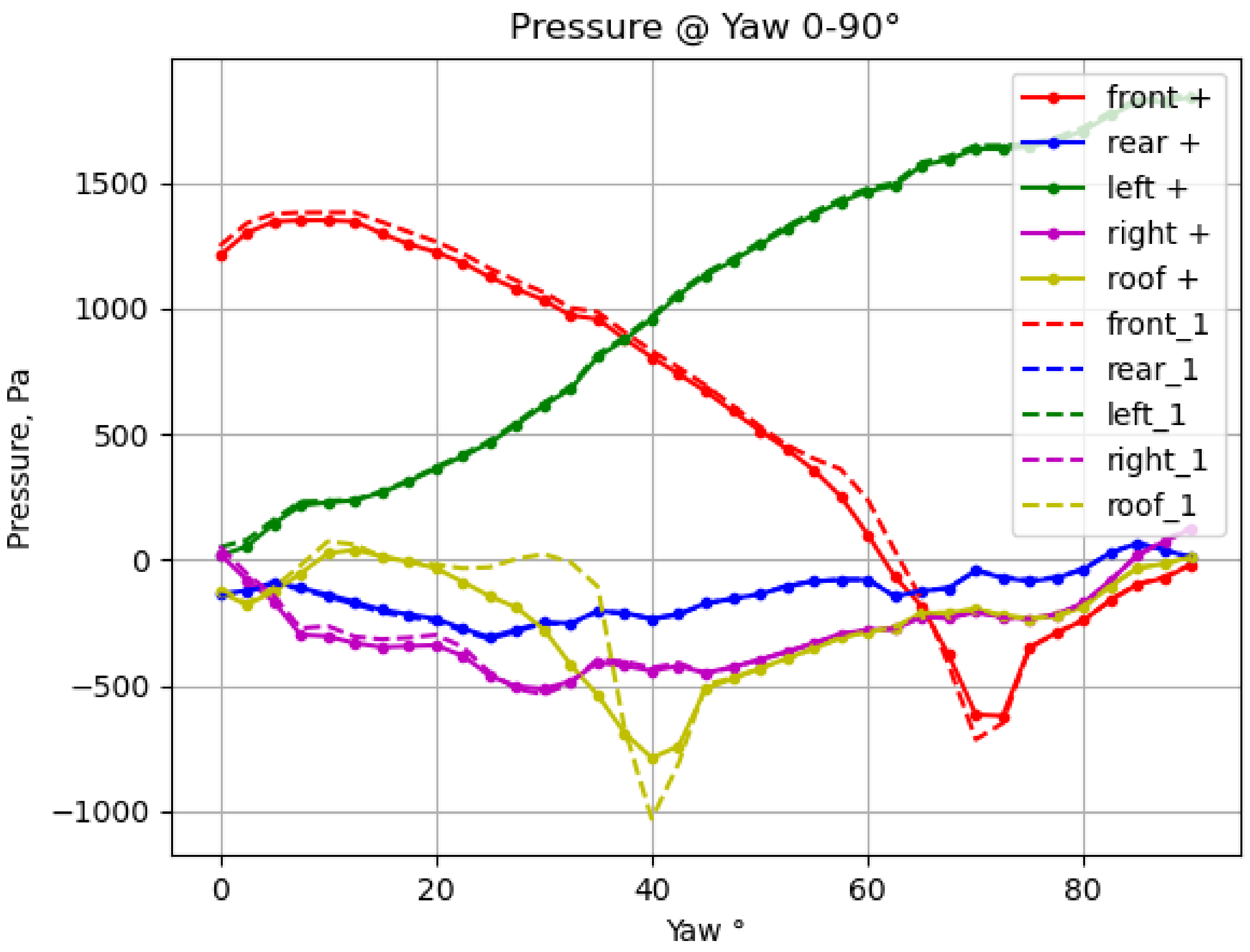
1:15 scale Wind-Tunnel Experiment: Calibration

Pressure @ different static yaw angles

- Front, rear, sides & roof show different pressure characteristics at different yaw angles:
  → effect of yawed flow

- 9-point +shaped average (solid lines) are equivalent to single centre-point characteristics (dotted lines)
  → enables more robust calibration and robust full-scale input data (multiple inputs)



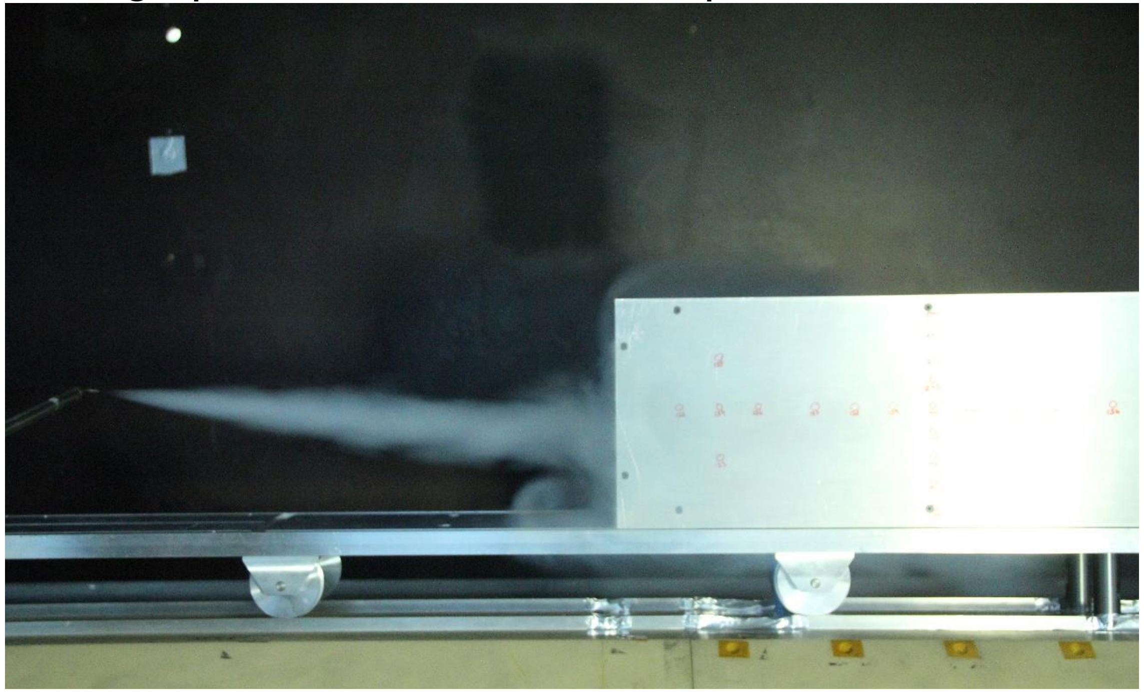


1:15 scale Wind-Tunnel Experiment: Flow Visualisation

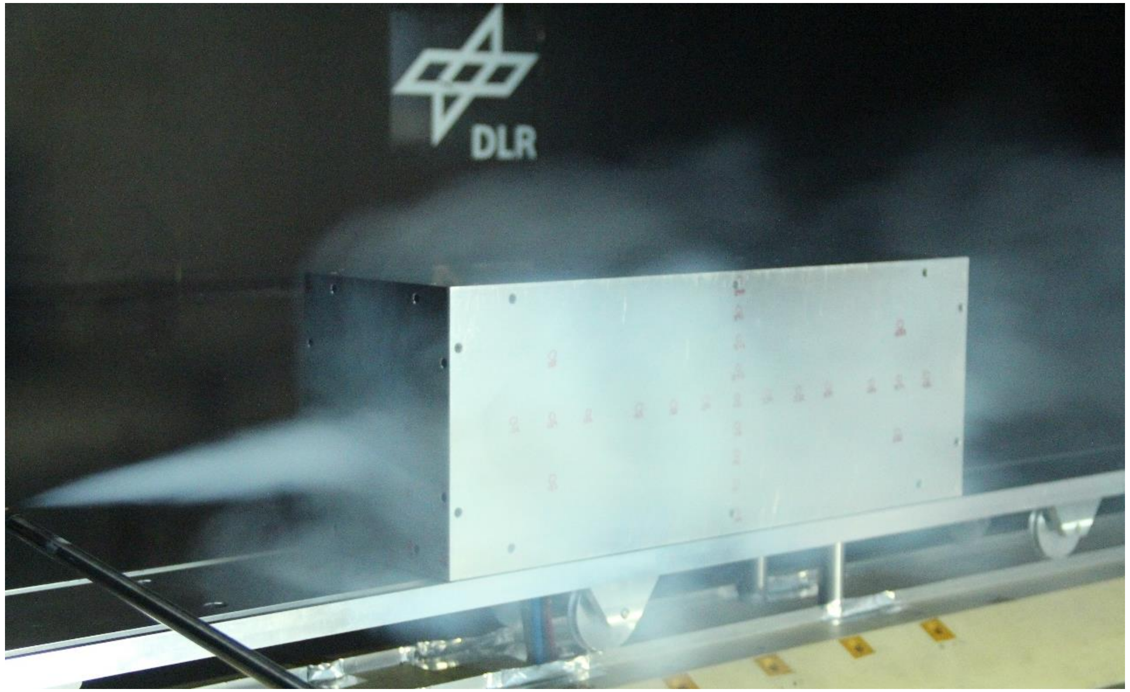
Flow Field @ 0° Yaw (no crosswind)

- Flow impinges/stagnates on front (windward facing) surface, recirculating underneath on front surface
- Flow moves outward, around the sides & over the roof, separating from at the leading edges (reattaching later)

→ High pressure @ front, lower pressure @ sides, roof



Front windward surface (facing toward wind)



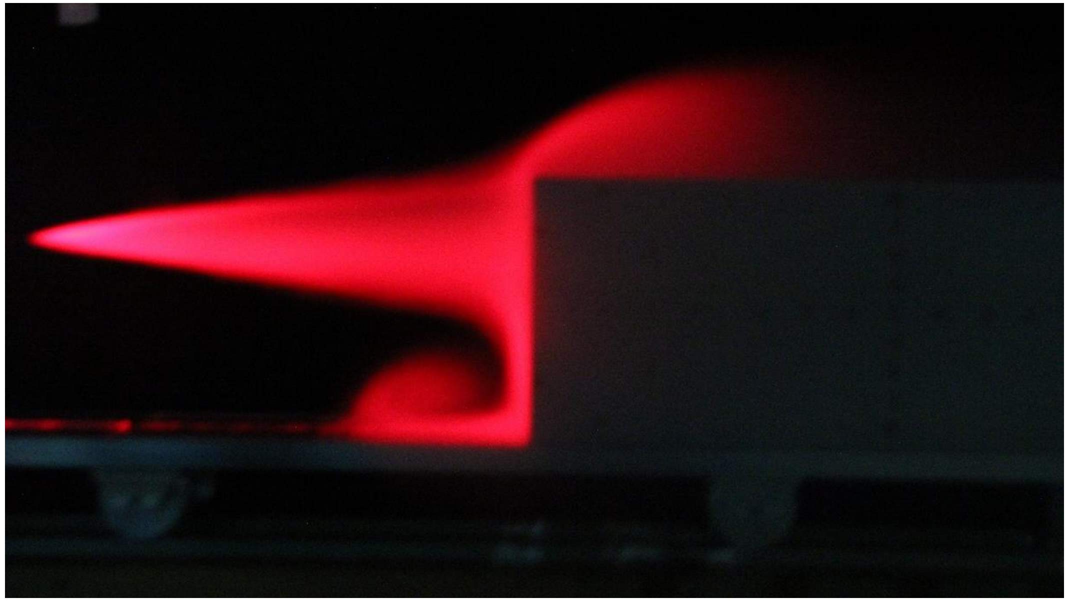
Front windward surface (facing toward wind)

1:15 scale Wind-Tunnel Experiment: Flow Visualisation

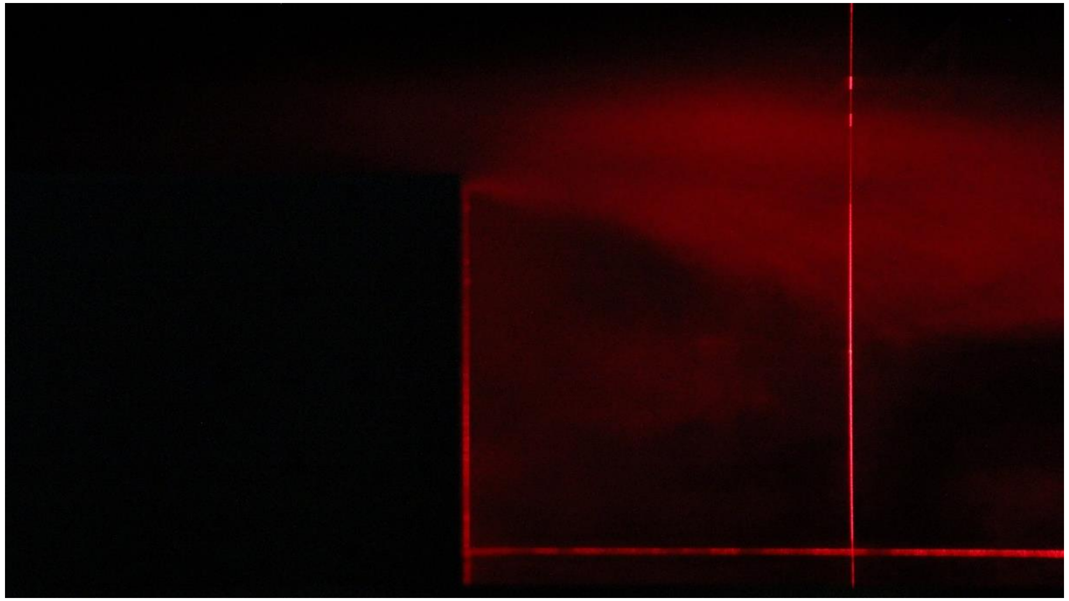
Flow Field @ 0° Yaw (no crosswind)

- Flow impinges/stagnates on front (windward) surface, recirculating underneath on front surface
- Flow moves outward, around the sides & over the roof, separating from at the leading edges (reattaching later)
- Flow separates at upper edge of rear (leeward) surface, recirculating behind container

→ High pressure @ front, lower pressure @ sides, roof, and rear



Front windward (facing toward wind) surface



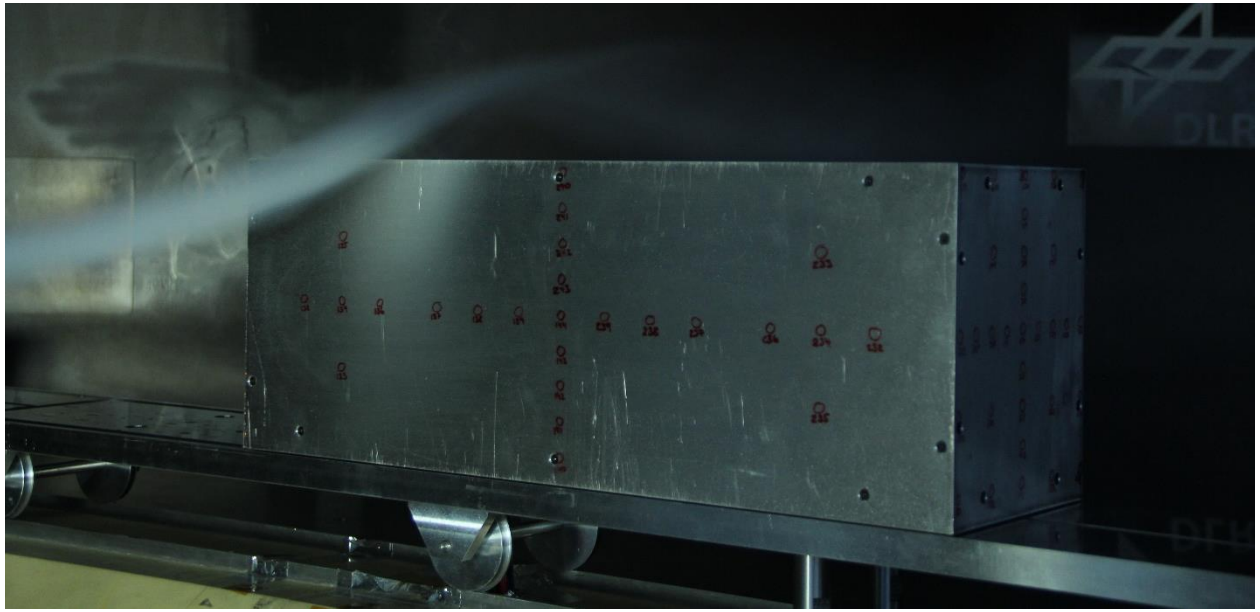
Rear surface

1:15 scale Wind-Tunnel Experiment: Flow Visualisation

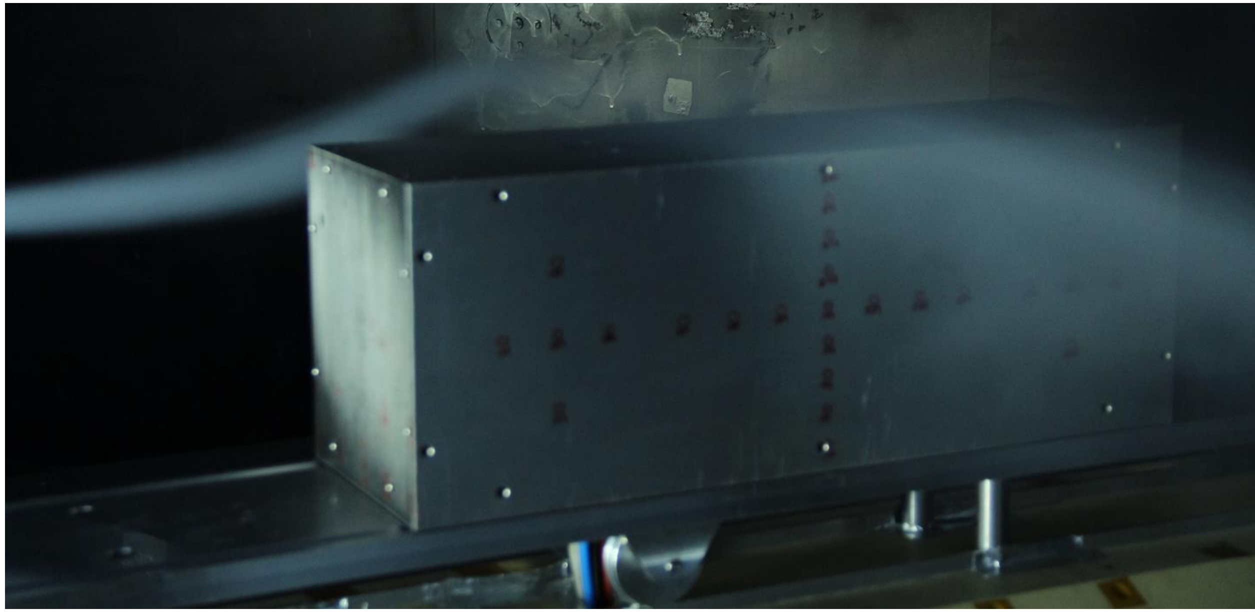
Flow Field @ 10-60° Yaw (crosswind)

- Flow impinges/stagnates on front (windward) surface and windward side surface
- Flow moves over container, separating from at the leading windward edge – forming a 3D longitudinal vortex
- Flow separates at upper edge of rear (leeward) surface, recirculating behind container

→ High pressure @ front & windward side, lower pressure @ leeward sides, roof, and rear



Windward side (facing toward wind)

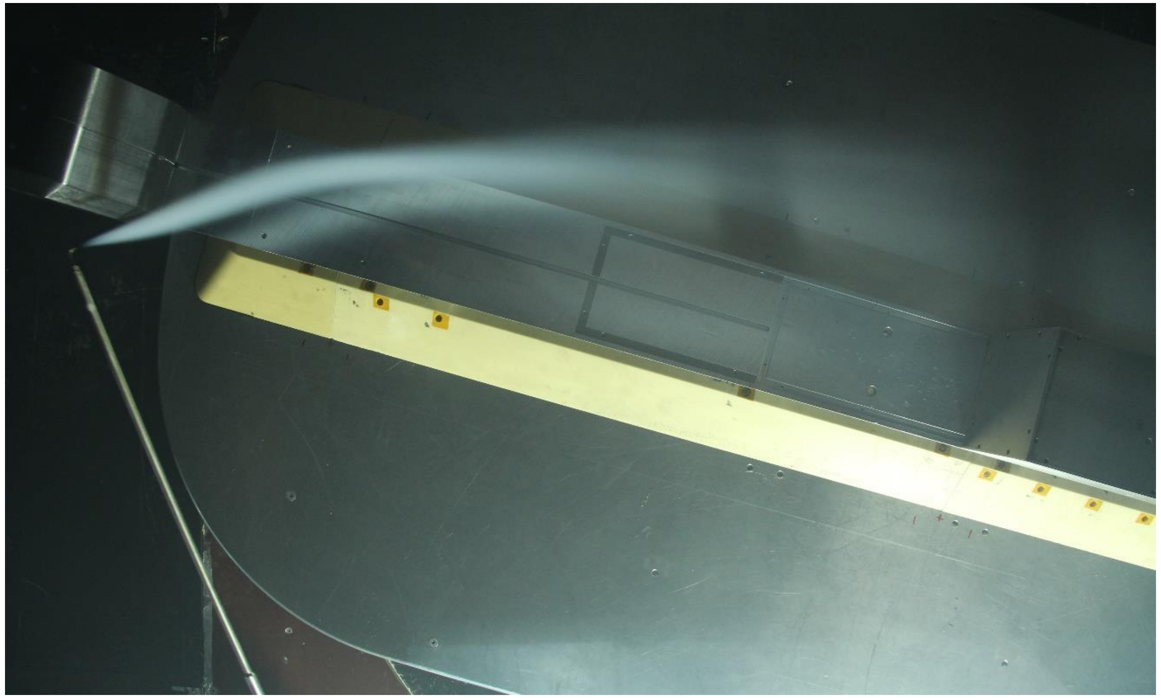


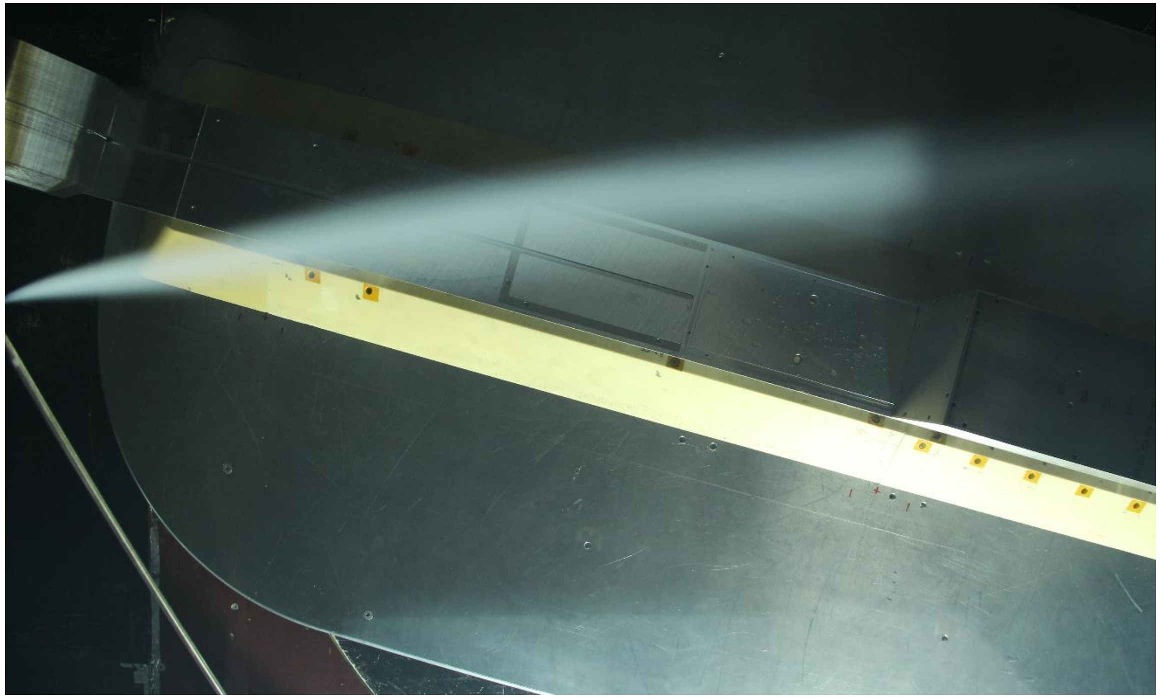
Leeward side (shielded from wind)

1:15 scale Wind-Tunnel Experiment: Flow Visualisation

Flow Field @ ~15° Yaw (crosswind)

- Flow that container experiences is ´clean´ not affected by upstream locomotive/container with: enough distance and enough crosswind (yaw angles > 15°)





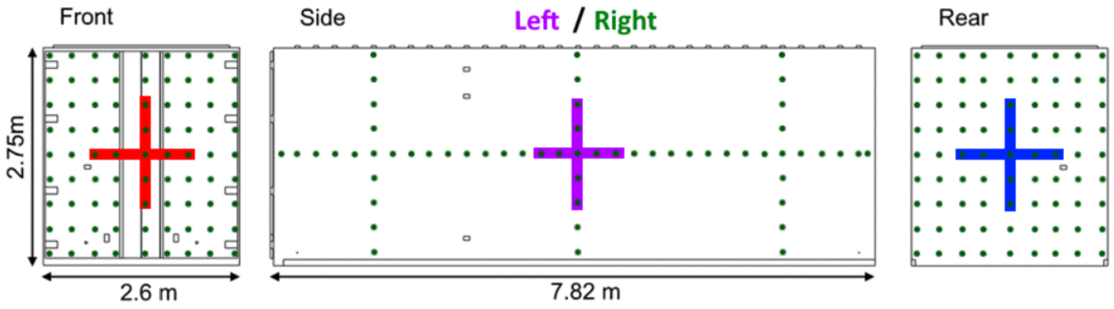
Top view: flow between upstream locomotive and downstream container

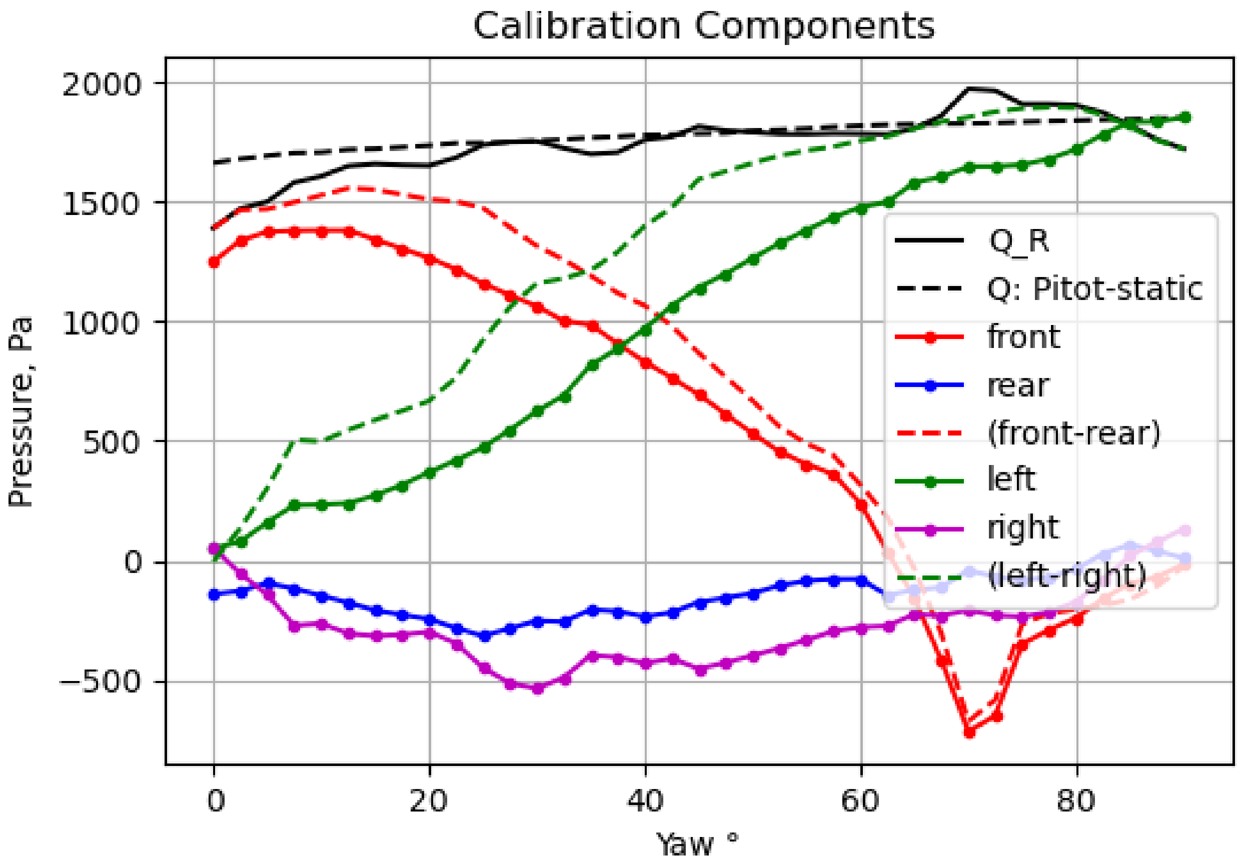
Calibration: Determining Magnitude (Dynamic pressure)

- **Q_R=sqrt((p_front-p_rear)^2+(p_left-p_right)^2)**
  - p_front,rear,left,right: pressure at each respective surface

- To determine Magnitude of flow in full-scale and normalize pressures in wind-tunnel &full-scale

- Q: Pitot-Static (dotted line) is dynamic-pressure measured from a pitot-static reference tube in the wind-tunnel test-section



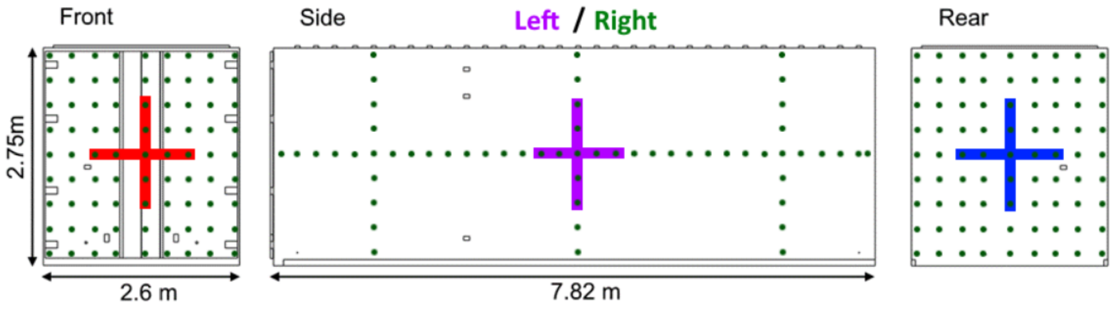


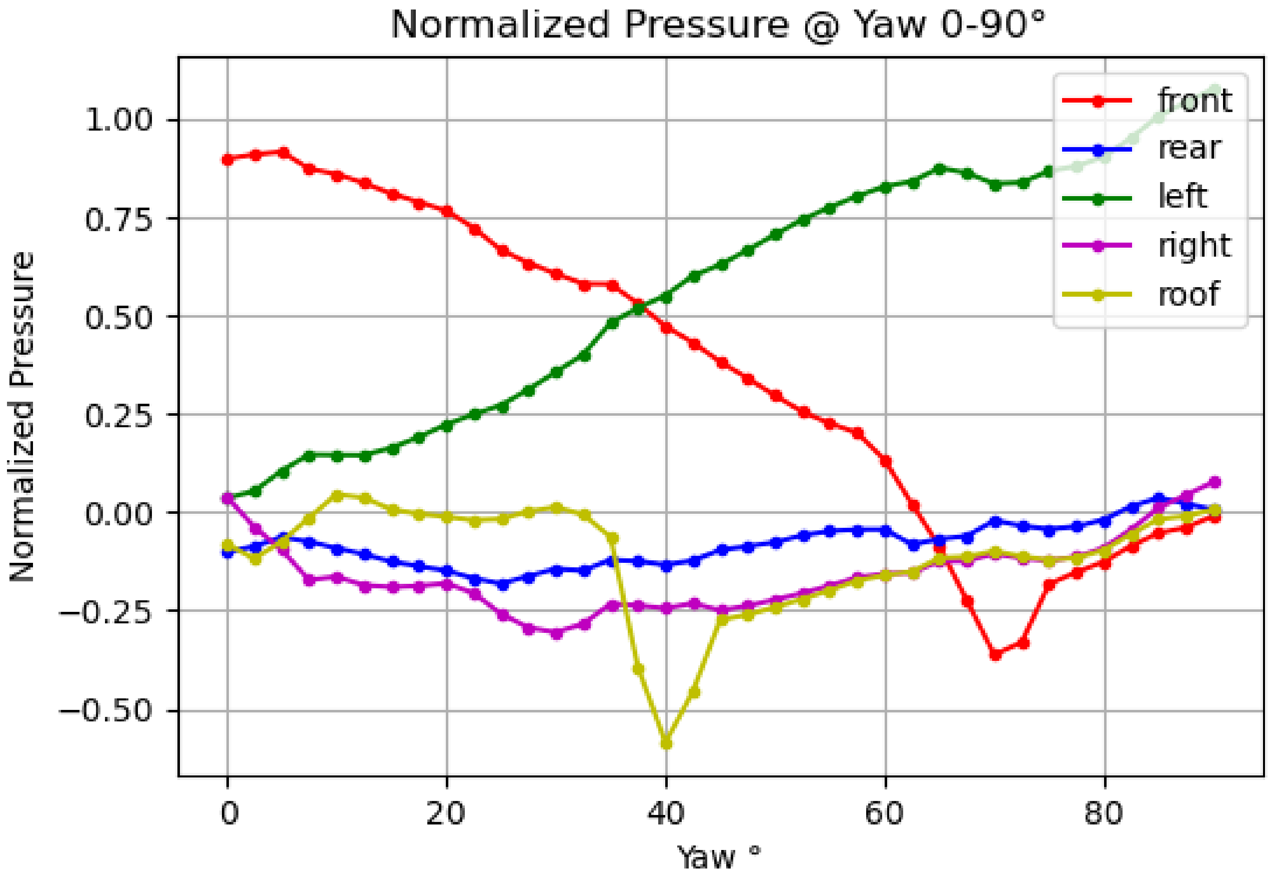
Calibration: Applying Magnitude (Dynamic pressure)

Normalized Pressure @ different static yaw angles: Using Q_R

- Normalized pressure = Pressure/Q_R

- Demonstrates suitability of Q_R (determined by combination of pressures on surface) as estimator of real Q :
  - P/Q_R of ~1 at front & range during yaw angle variation are consistent with yawed bluff-body pressure distribution

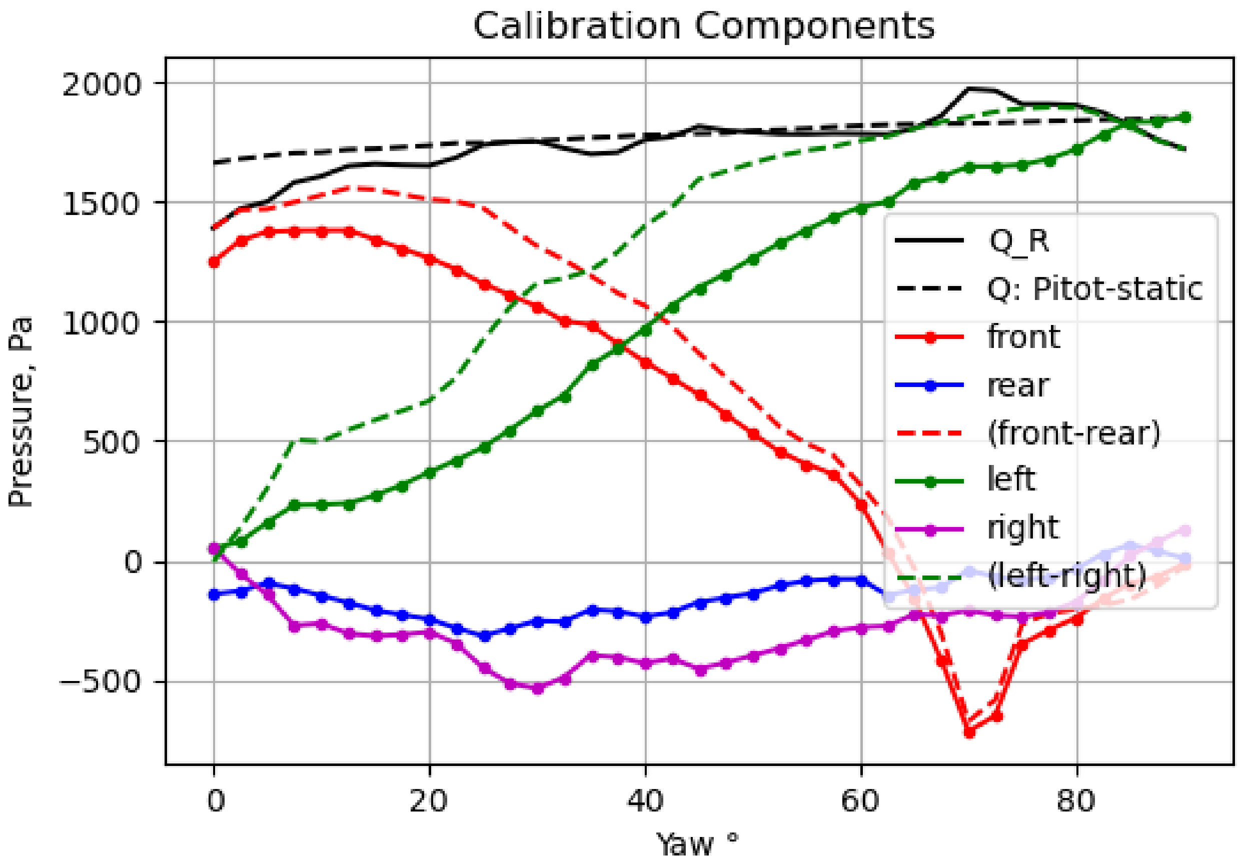




Calibration: Yaw Coefficient

Calibration Profile Components:
relates combination of surface pressures to yaw angle Beta, β

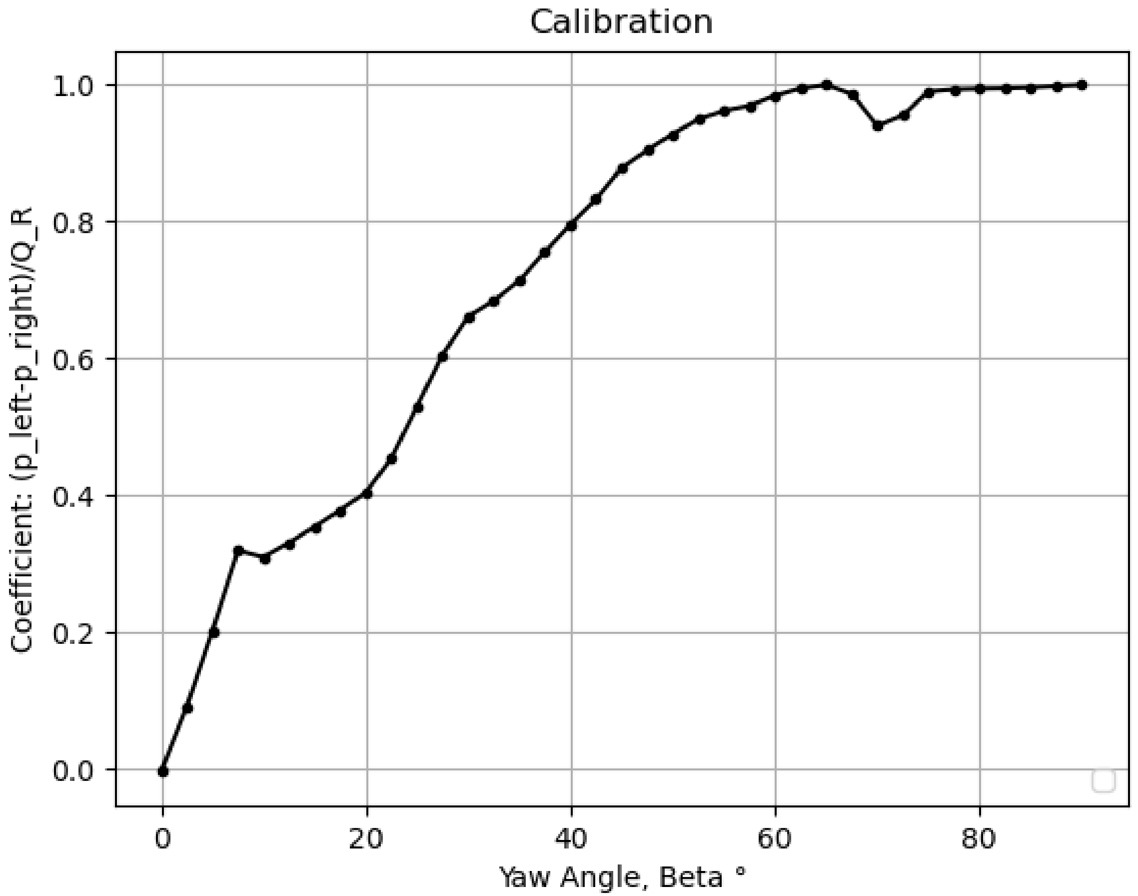
- **Calibration coefficient =(p_left – p_right) / Q_R**
- **Q_R=sqrt((p_front-p_rear)^2+(p_left-p_right)^2)**
- Similar concept as ‘car-as-probe’ & dynamic-pressure multi-hole probes (wind-tunnel measurement devices) utilized previously



1:15 scale wind-tunnel experiment: Calibration Function

Calibration Profile:
relates combination of surface pressures to
yaw angle Beta, β

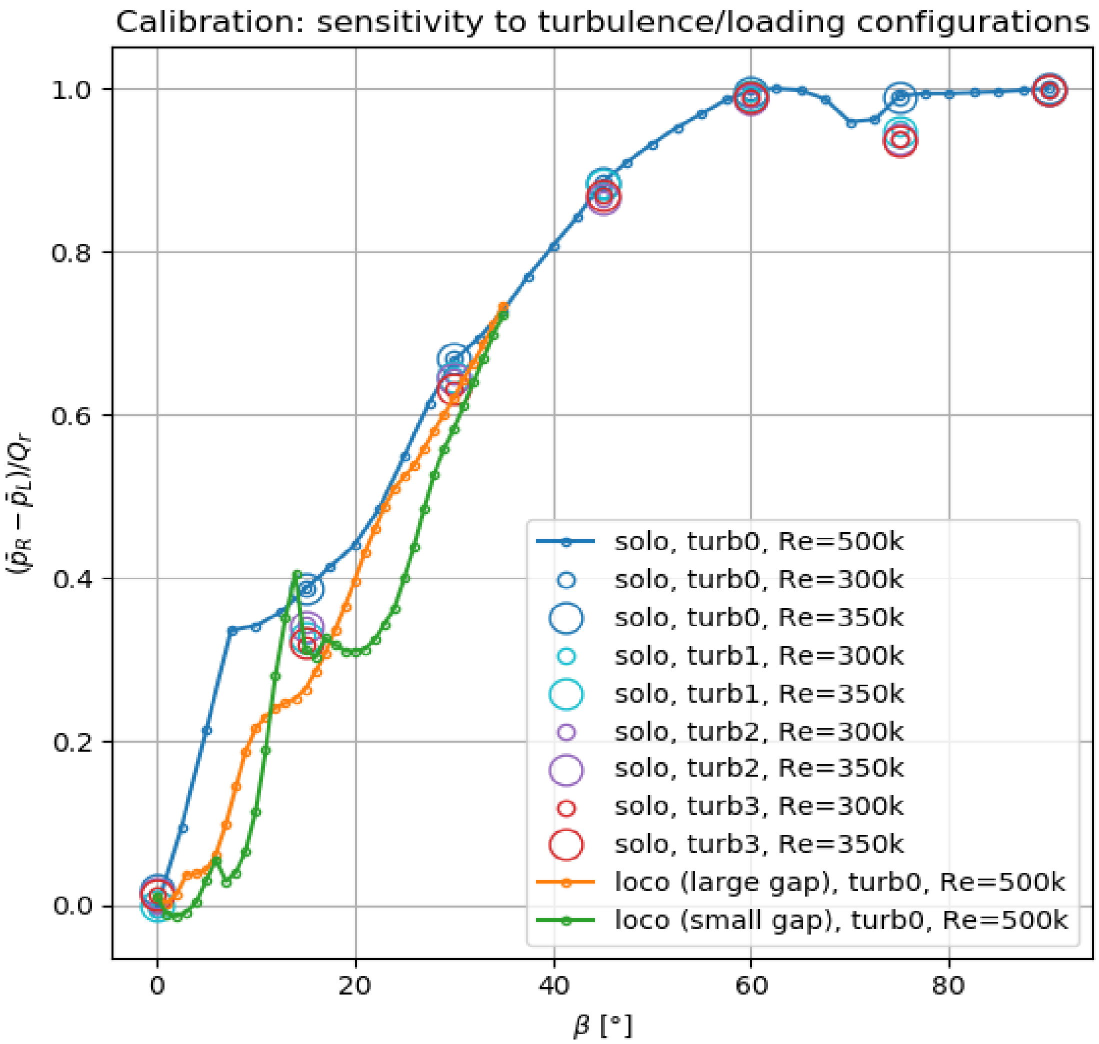
- **Calibration coefficient =(p_left – p_right) / Q_R**
- **Q_R=sqrt((p_front-p_rear)^2+(p_left-p_right)^2)**
- Similar concept as ‘car-as-probe’
  & dynamic-pressure multi-hole probes (wind-tunnel measurement devices) utilized previously



1:15 scale wind-tunnel experiment: Calibration Function

Calibration Profile sensitivity:

- Loading configuration (upstream gap)
  large gap 17.8m, small gap=9.3m
  (full-scale test-configs: 10,17,29,66m)
    - higher sensitity @ low yaw
    - low sensitivity @ medium yaw (priority)
- Turbulence Intenstiy (gustiness of natural wind)
    - low sensitivity @ all yaw
- Repeatabilty (same conditions, repeated)
    - High
- Reynolds number (effect of 1/15 scaled experiment)
    - Low sensitivity



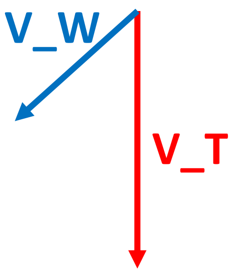
Inferring Atmospheric Wind Magnitude: Vector analysis

Calibration Application – applies Wind-Tunnel calibration results to full-scale measurements

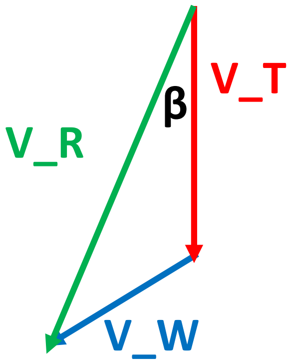
- Infer yaw angle and velocity magnitude experienced in real-world from surface pressure measurements

- **V_T :** train-speed induced-flow (from satellite system: GNSS)
- **V_W :** atmospheric wind (result to infer/find)
- **V_R :** resultant wind train experiences (from pressure combination: Q_R)
  - *Q_R= sqrt[(p_front – p_rear)^2 + (p_left – p_right)^2]*
  - *and Q=0.5*density*V^2,*
  - *therefore V_R=sqrt(2*Q_R/density)   (density from local weather station)*
- **β:** relative angle of wind that train experiences
  - *discretely set in wind-tunnel calibration*

Wind-Vectors affecting train:



Vector Addition:
V_R=V_T + V_W
V_W=V_R - V_T

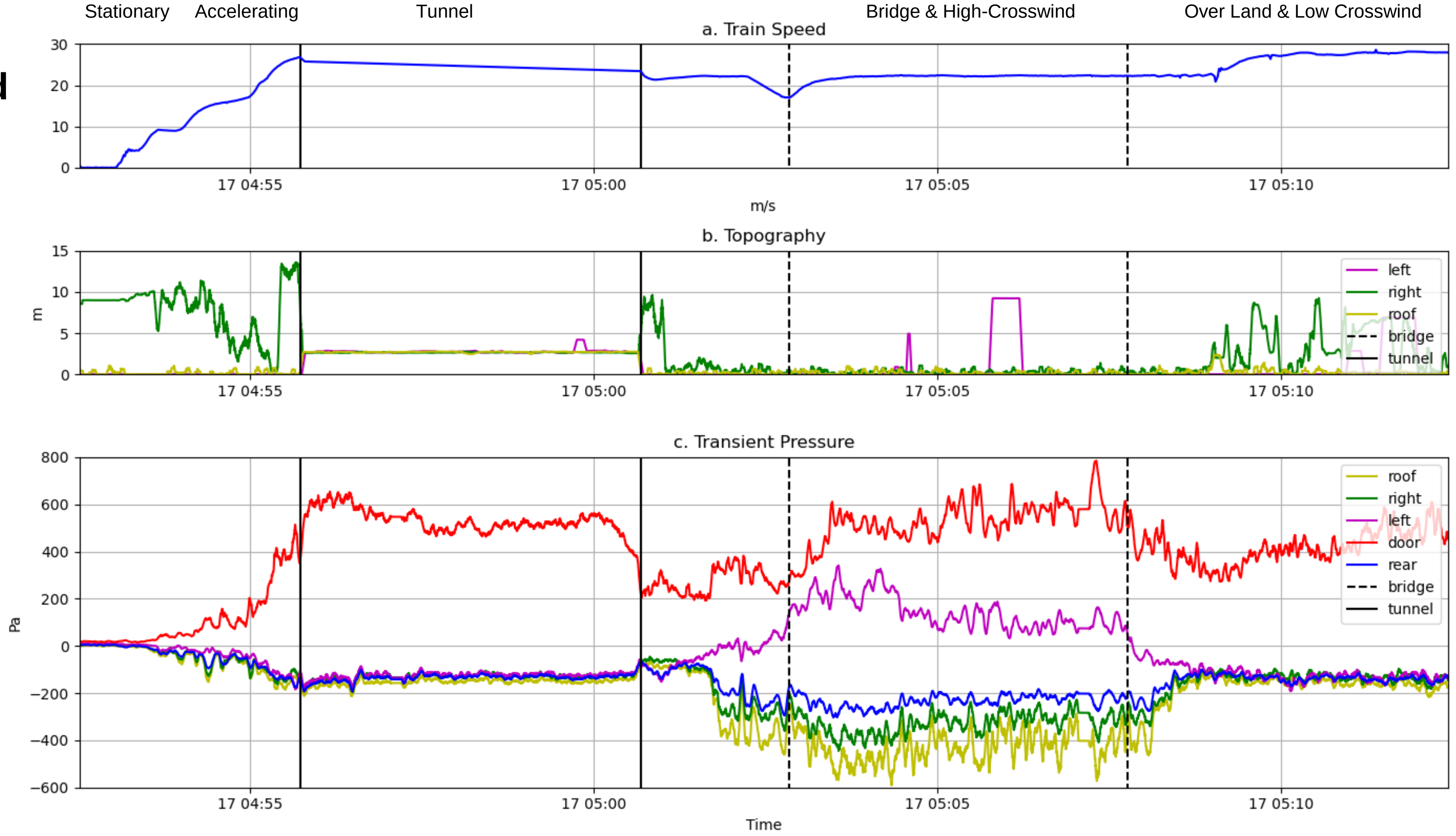


Results: System Functionality

Example High-Crosswind

- 17/1/22
- **a. train speed:** consistent across bridge
- **b. LiDAR:** topography (tunnel)
- **c. transient pressure:** different characteristics visible: acceleration, tunnel, bridge, land

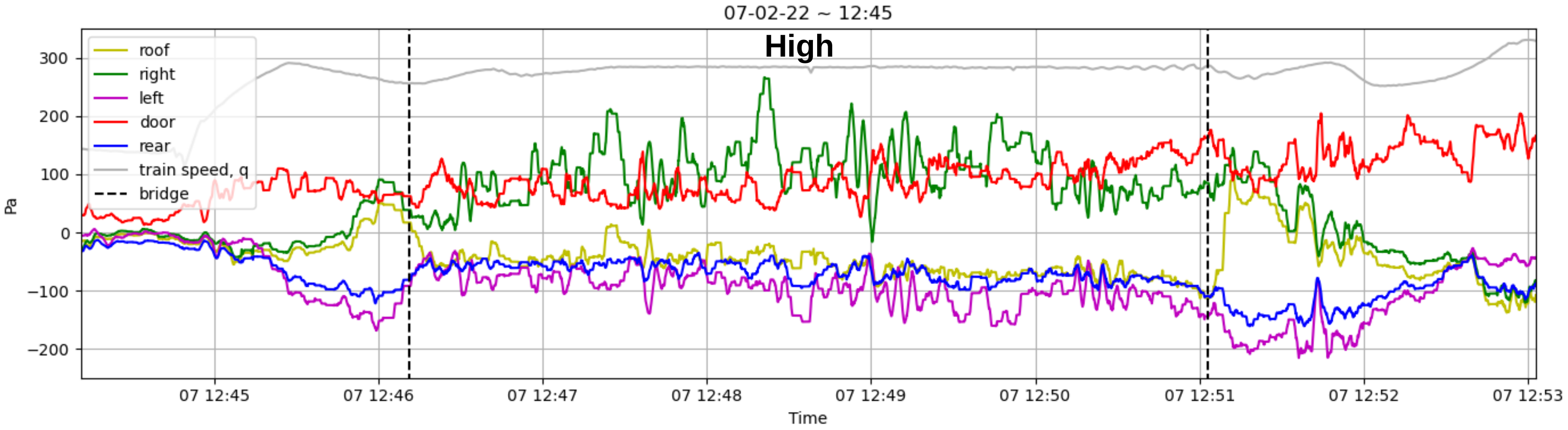
  crosswind effects clear: high pressure difference left-right, transient peaks

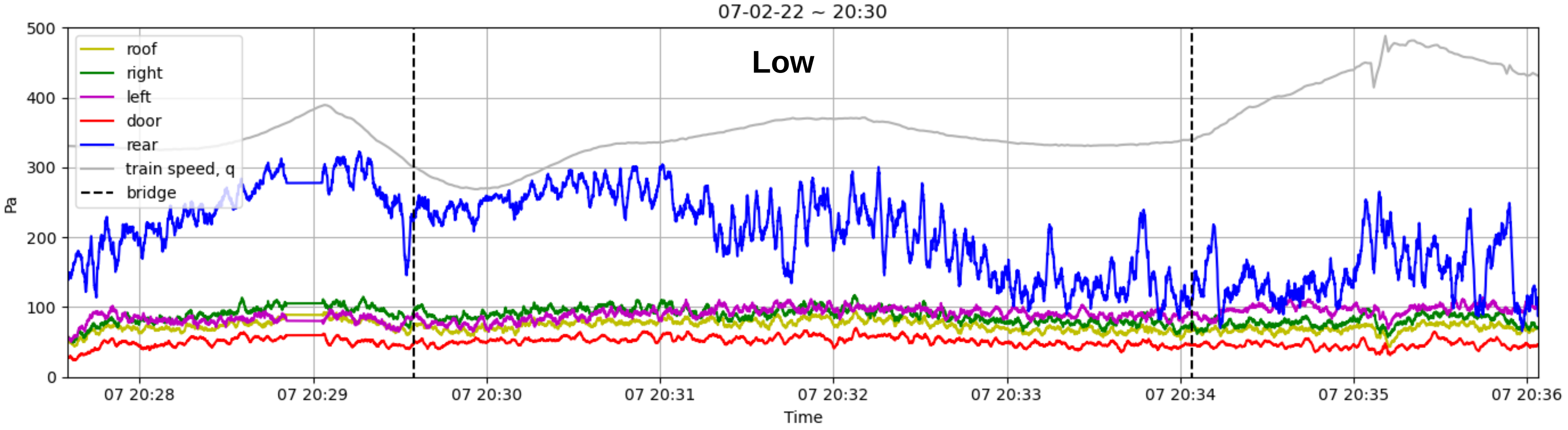


Results: System Functionality

High vs Low Crosswind

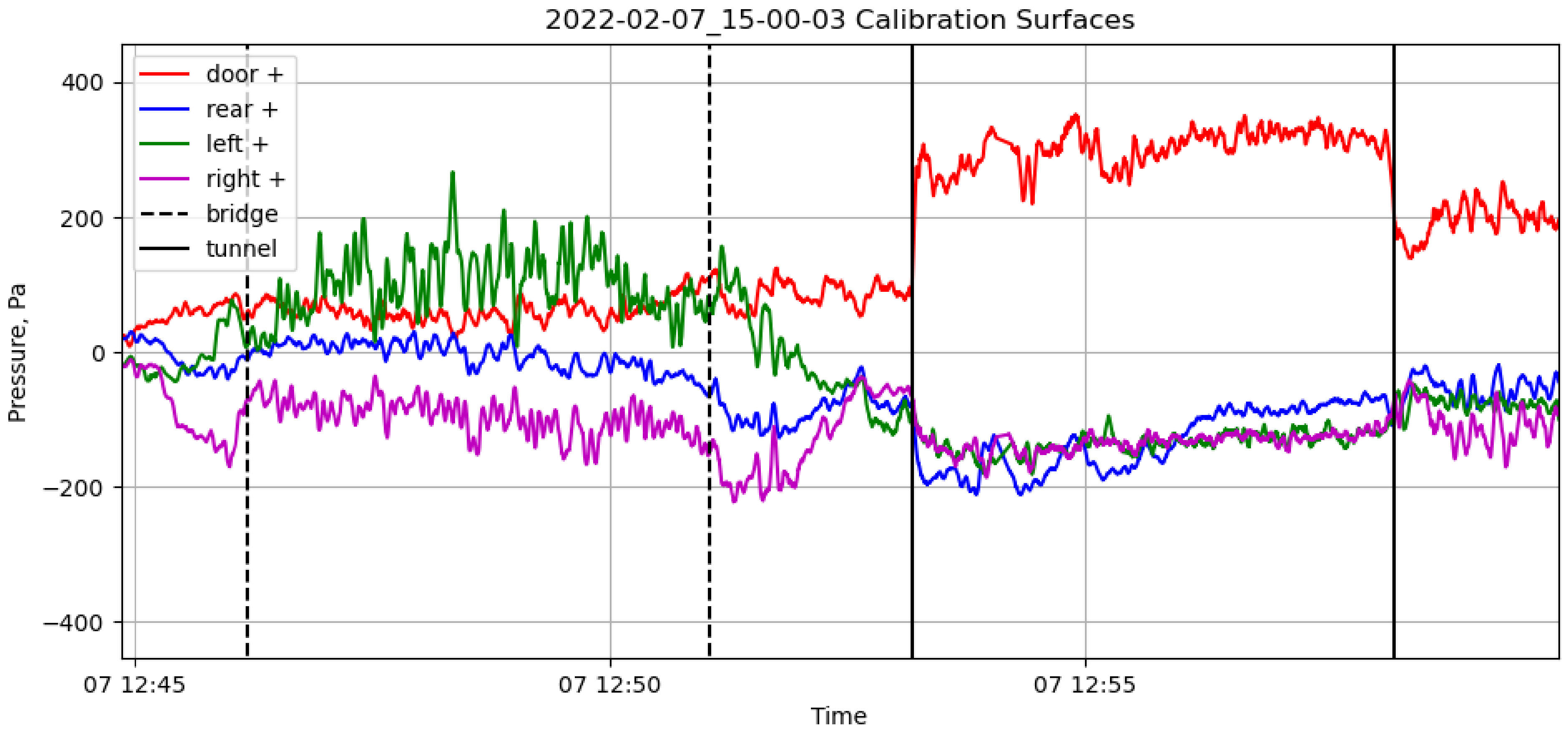
- Bridge Crossings: ~12m/s vs ~4m/s
- **High**: clear fluctuations, high pressure on front/wind-ward side, low pressure on lee-ward side/roof
- **Low**: only high pressure & fluctuations on windward front, rear, sides, roof minimal pressure and fluctuations

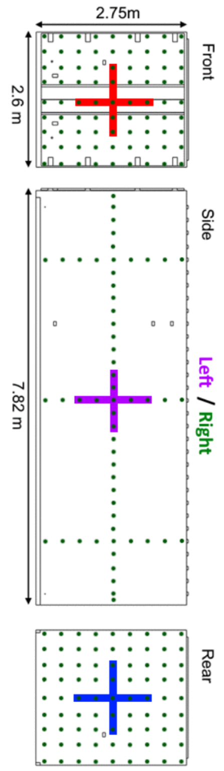




Results: Velocity Derivation – Example Calibration Surfaces

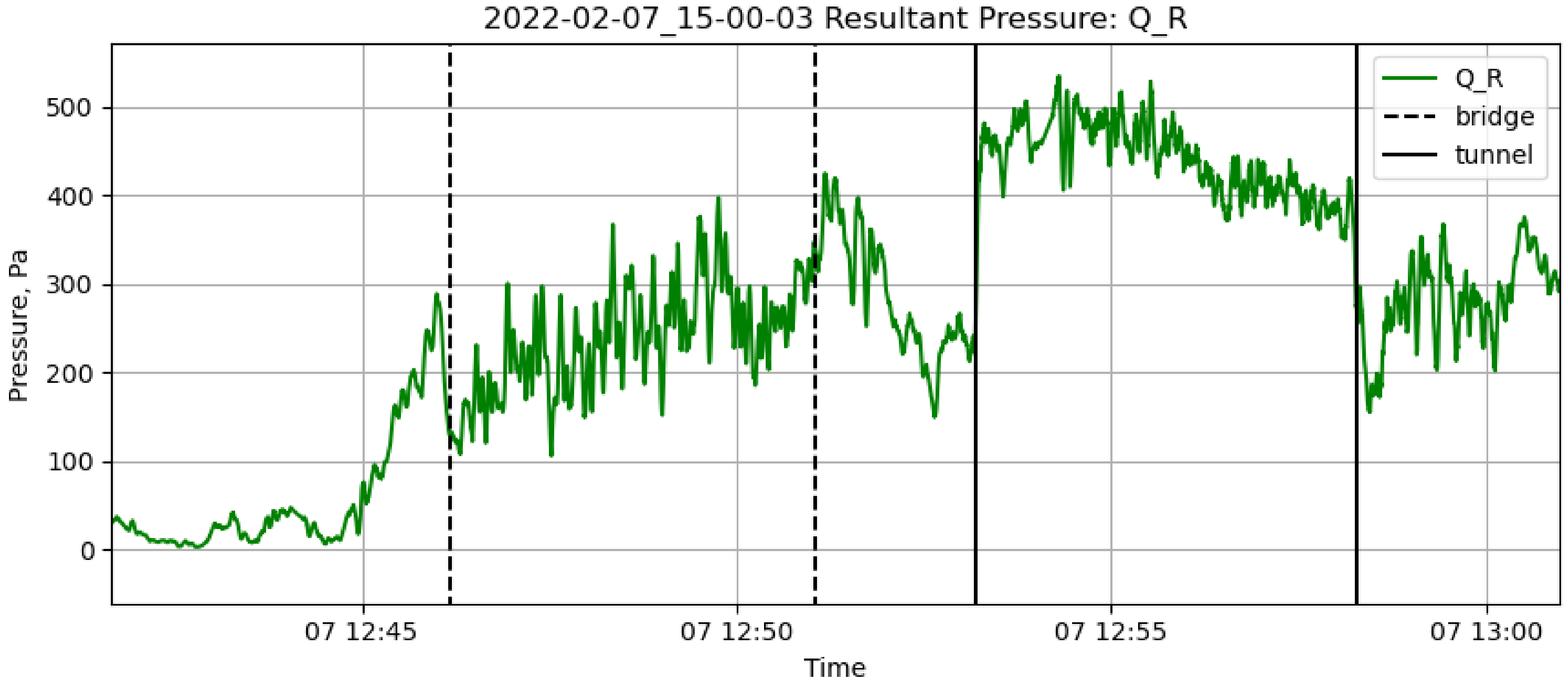
- Different pressures (spatially averaged on each surface) combined to make up the yaw calibration coefficient





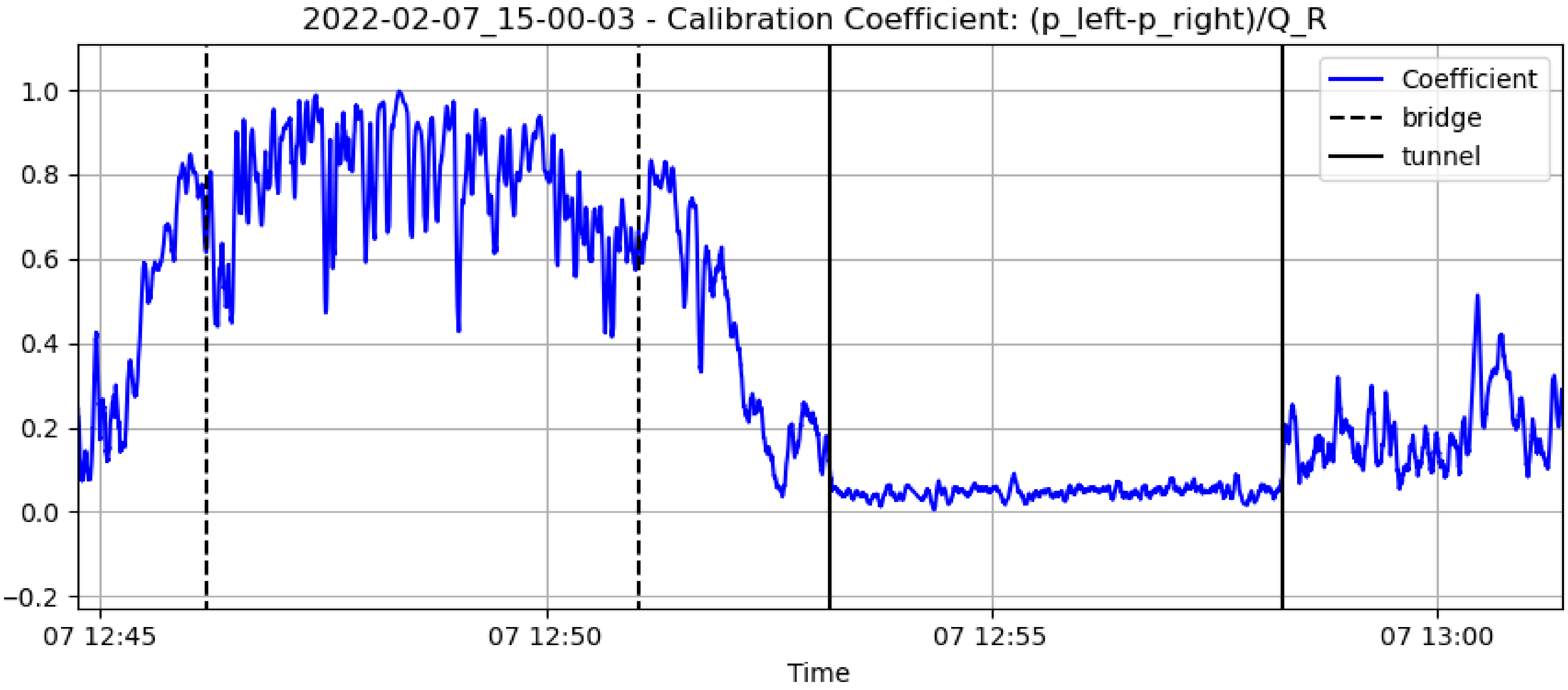
Results: Velocity Derivation – Example Q_R

- Derived ‘resultant’ dynamic pressure, **Q_R** used to derive the resultant velocity, **V_R**
  V_R: Total velocity that the probes experience, contains train speed induced wind **V_T** and atmospheric wind **V_W**
  (**V_R**=**V_T**+**V_W**)



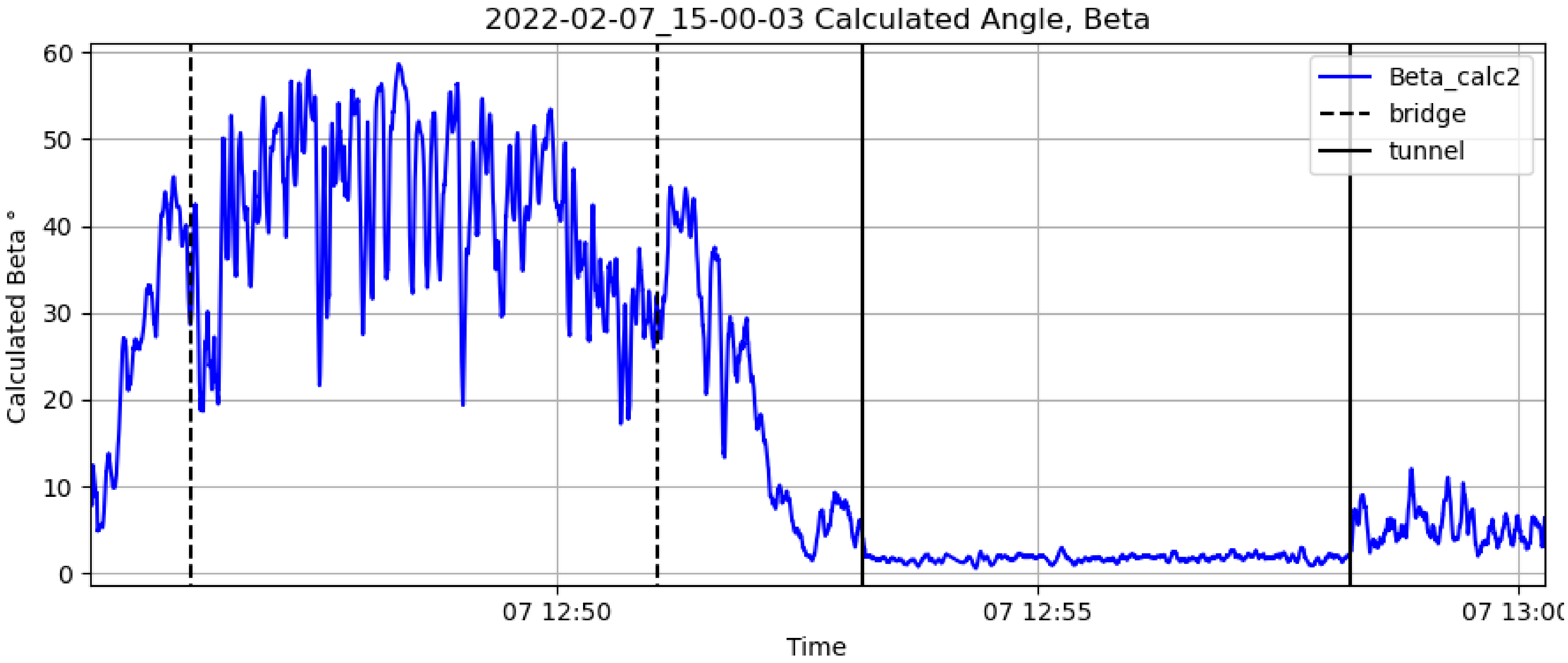
Results: Velocity Derivation – Example Calibration Coefficient

- Calibration coefficient (combined pressures), has a calibrated relationship with Beta, yaw angle
- C=(p_left – p_right) /Q_R
- Q_R= sqrt((p_front-p_rear)^2 + (p_left-p_right)^2)



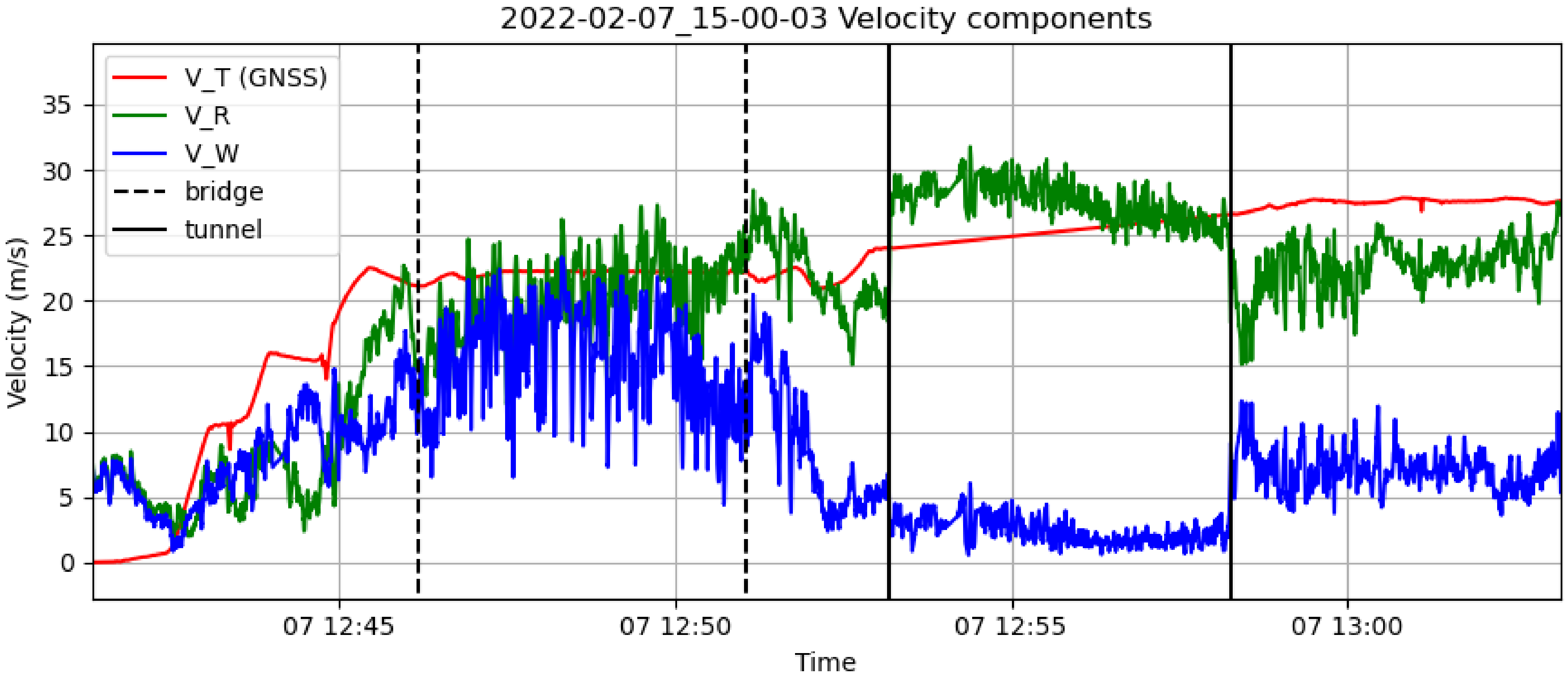
Results: Velocity Derivation – Example Derived Beta (Yaw angle)

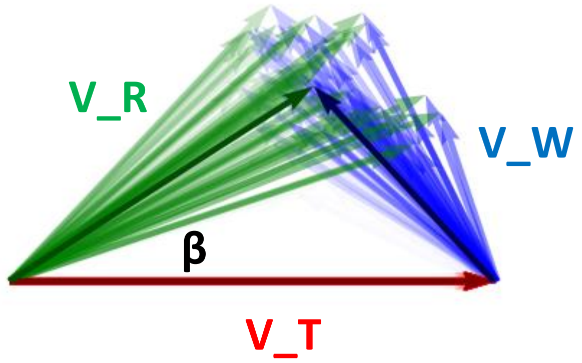
- Derived Yaw angle Beta :
  Determined by applying wind-tunnel calibration relationship to full-scale calibration coefficient data



Results: Velocity Derivation – Example Derived Velocity Components

- Derived velocity components, resultant V_R and atmospheric wind V_W (and train speed V_T)
- Determined using vector mathematics with V_R magnitude, yaw angle, β and V_T





Example Mean and instantaneous vectors during bridge section

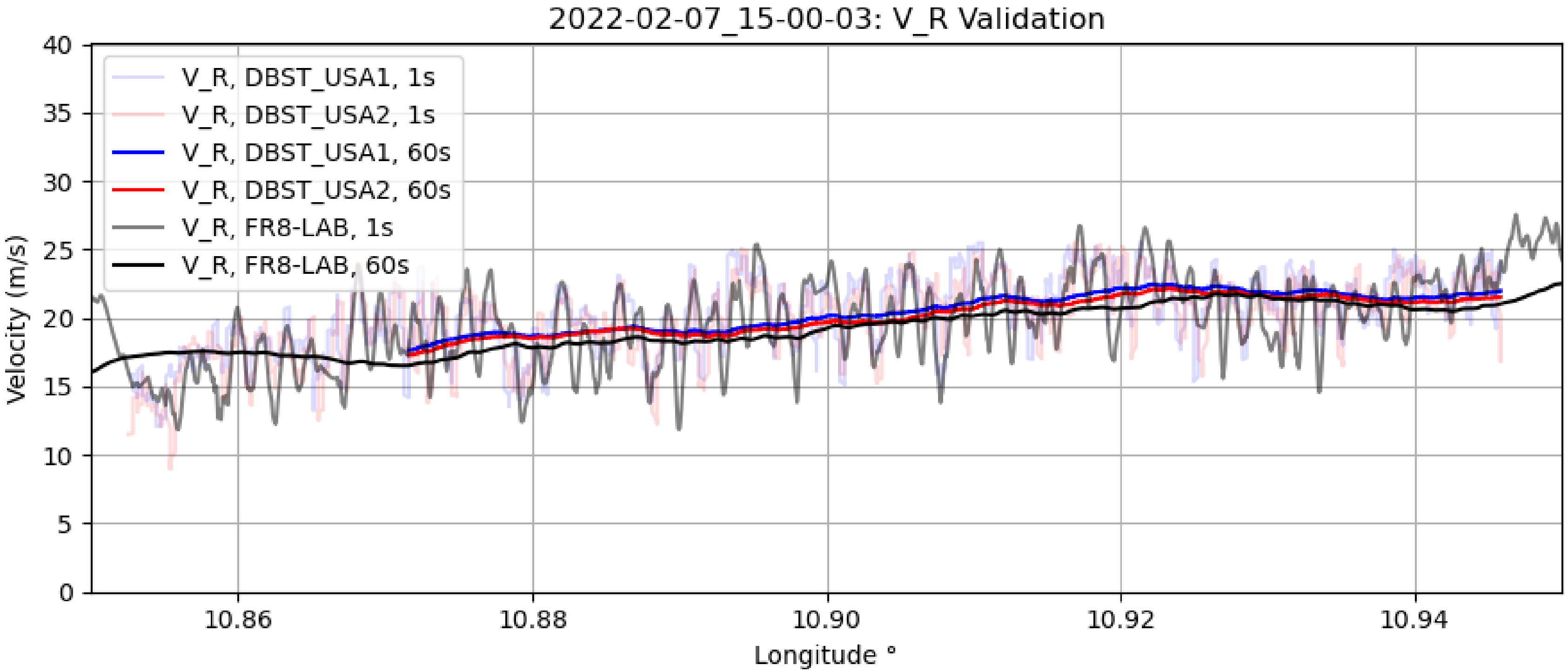
Results: Validation

High wind 07/02/2022: 12am

- Derived velocity from processing of surface-pressure data on FR8-LAB:
  → corresponds well to purpose-built velocity measurement devices: DB ST Ultrasonic Anemometers 1 & 2

V_R: Resultant Velocity:
Total velocity that the probes experience
→Contains train speed and atmospheric wind (V_R=V_T+V_W)

- **FR8-LAB :** derived velocity
- **USA1**, **USA2:** DB STs ultrasonic anemometers 1 & 2



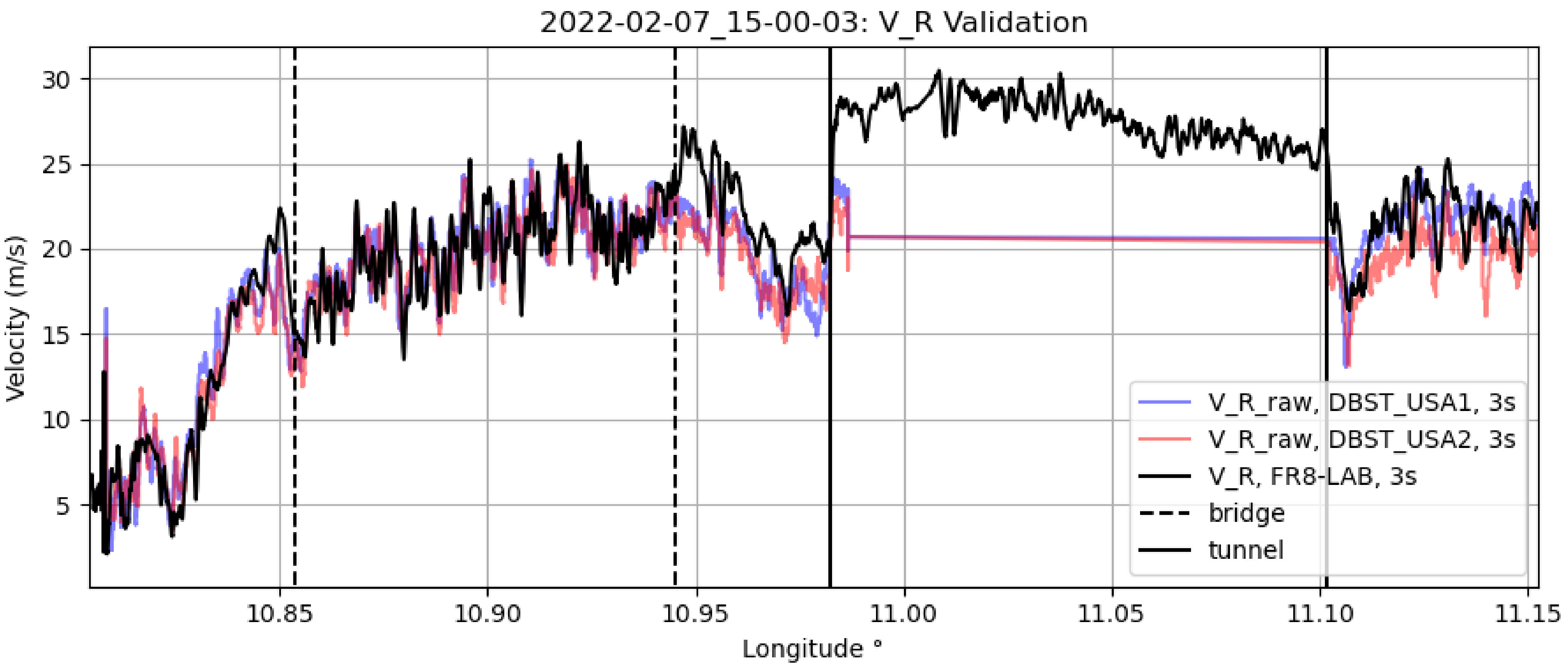
Results: Validation

High wind 07/02/2022: 12am – validation successful beyond bridge section (on land)
(FR8-LAB not calibrated for operation through tunnel, only open air)

- Derived velocity from processing of surface-pressure data on FR8-LAB:
  → corresponds well to purpose-built velocity measurement devices: DB ST Ultrasonic Anemometers 1 & 2

V_R: Resultant Velocity:
Total velocity that the probes experience
→Contains train speed and atmospheric wind (V_R=V_T+V_W)

- **FR8-LAB :** derived velocity
- **USA1**, **USA2:** DB STs ultrasonic anemometers 1 & 2



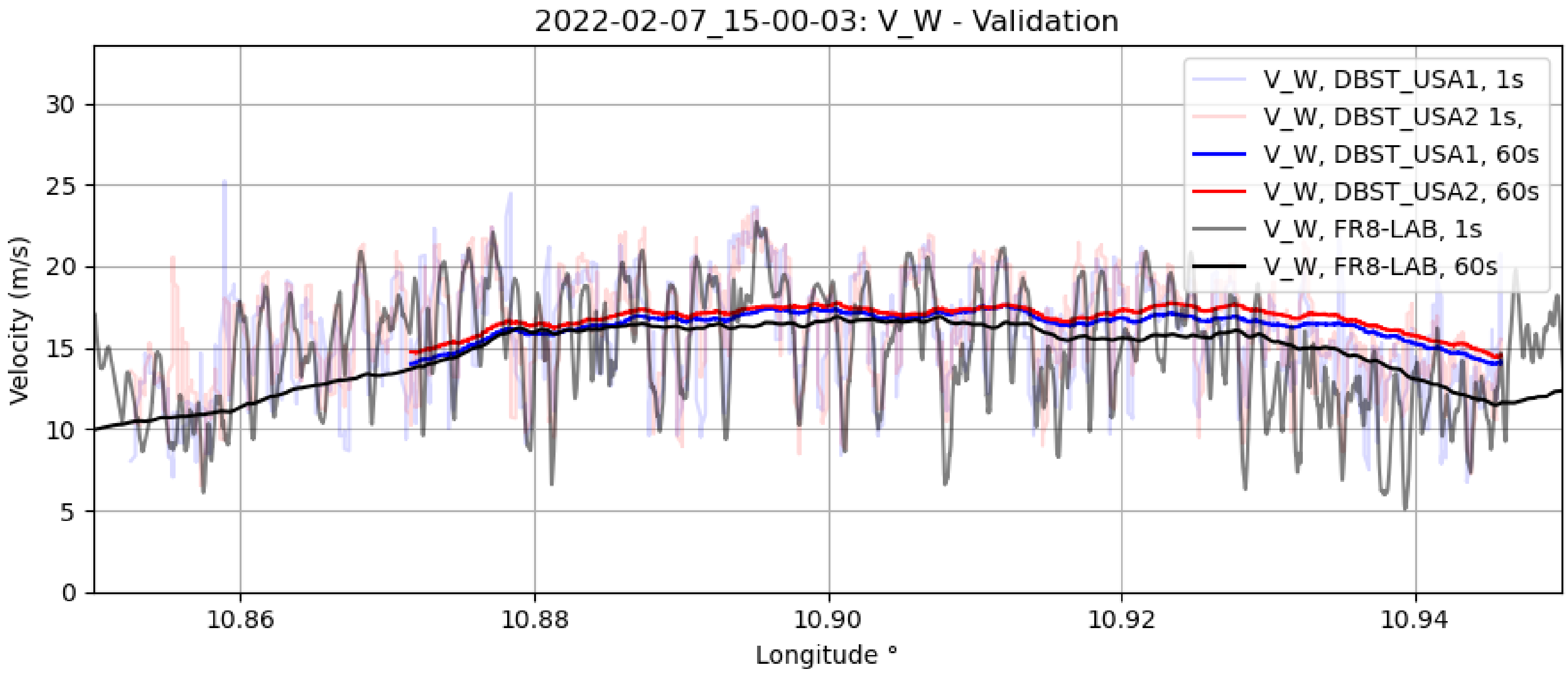
Results: Validation

High wind 07/02/2022: 12am

- Derived velocity from processing of surface-pressure data on FR8-LAB:
  → corresponds well to purpose-built velocity measurement devices: DB ST Ultrasonic Anemometers 1 & 2

V_W: Wind Velocity:
atmospheric wind

- **FR8-LAB :**
  derived velocity
- **USA1**, **USA2:**
  DB STs ultrasonic anemometers 1 & 2



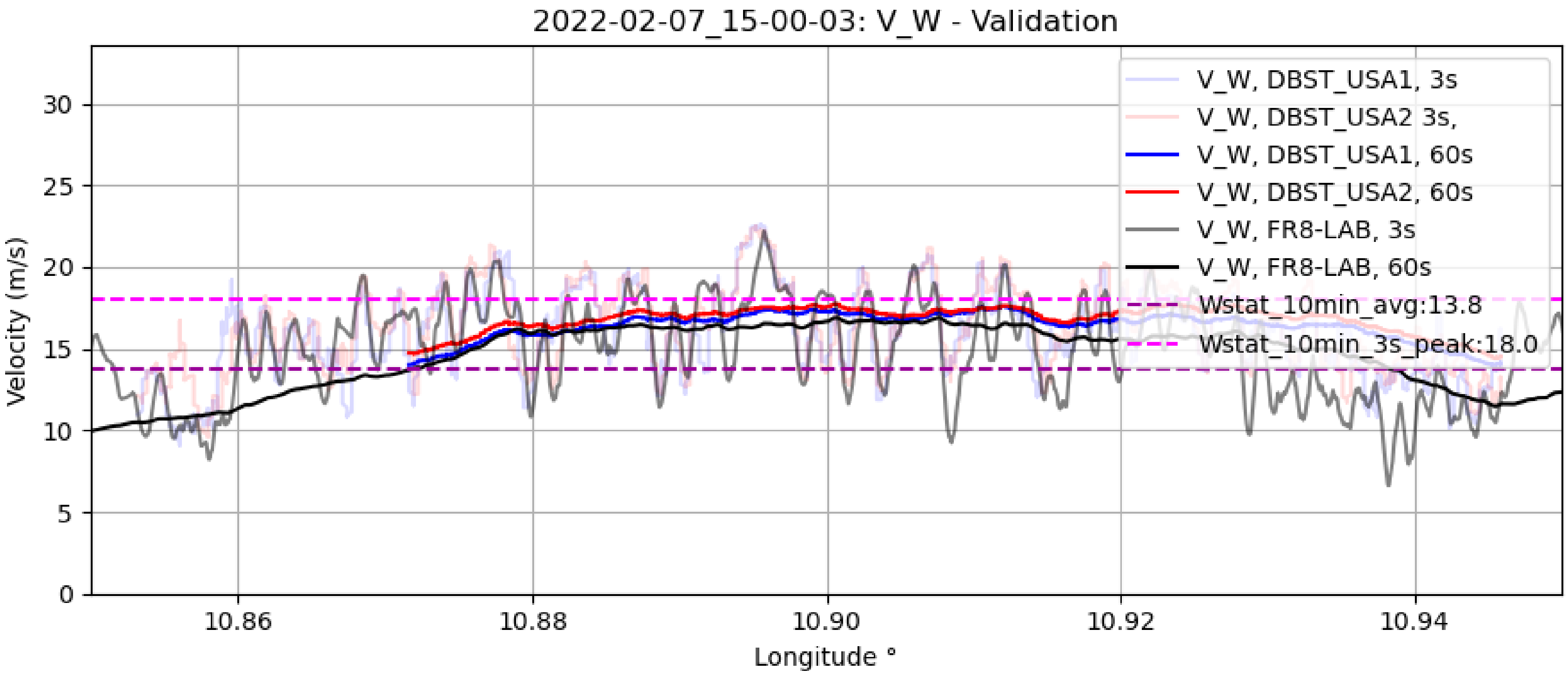
Results: Validation

High wind 07/02/2022: 12am

- Derived velocity from processing of surface-pressure data on FR8-LAB:
  → corresponds well to purpose-built velocity measurement devices: DB ST Ultrasonic Anemometers 1 & 2

V_W: Wind Velocity:
atmospheric wind

- **FR8-LAB :**
  derived velocity
- **USA1**, **USA2:**
  DB STs ultrasonic anemometers 1 & 2
- **Wstat:**
  Local weather station
  - 10min average
  - 3sec peak in 10 min



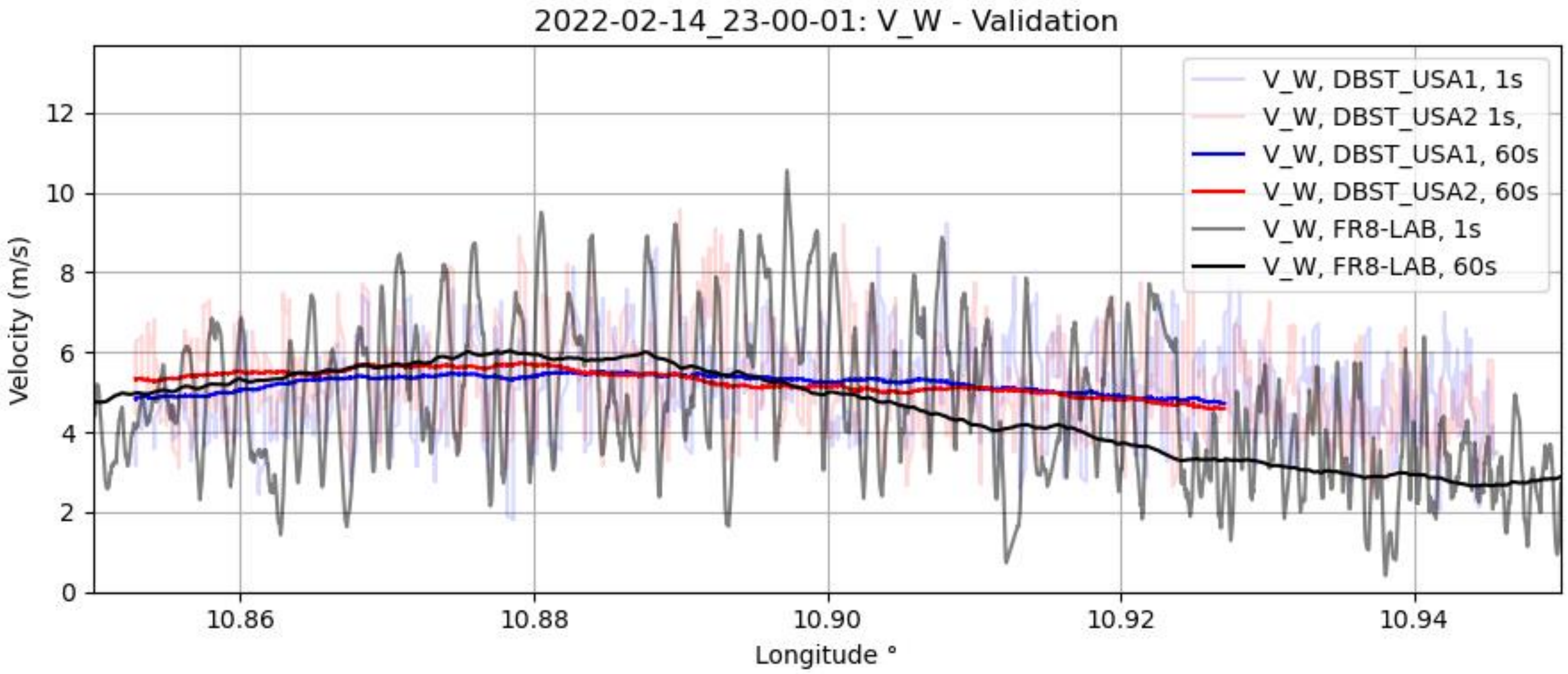
Results: Validation

Medium wind 14/02/2022: 9pm

- Derived velocity from processing of surface-pressure data on FR8-LAB:
  → corresponds well to purpose-built velocity measurement devices: DB ST Ultrasonic Anemometers 1 & 2

V_W: Wind Velocity
atmospheric wind

- **FR8-LAB :**
  derived velocity
- **USA1, USA2:**
  DB STs ultrasonic anemometers 1 & 2



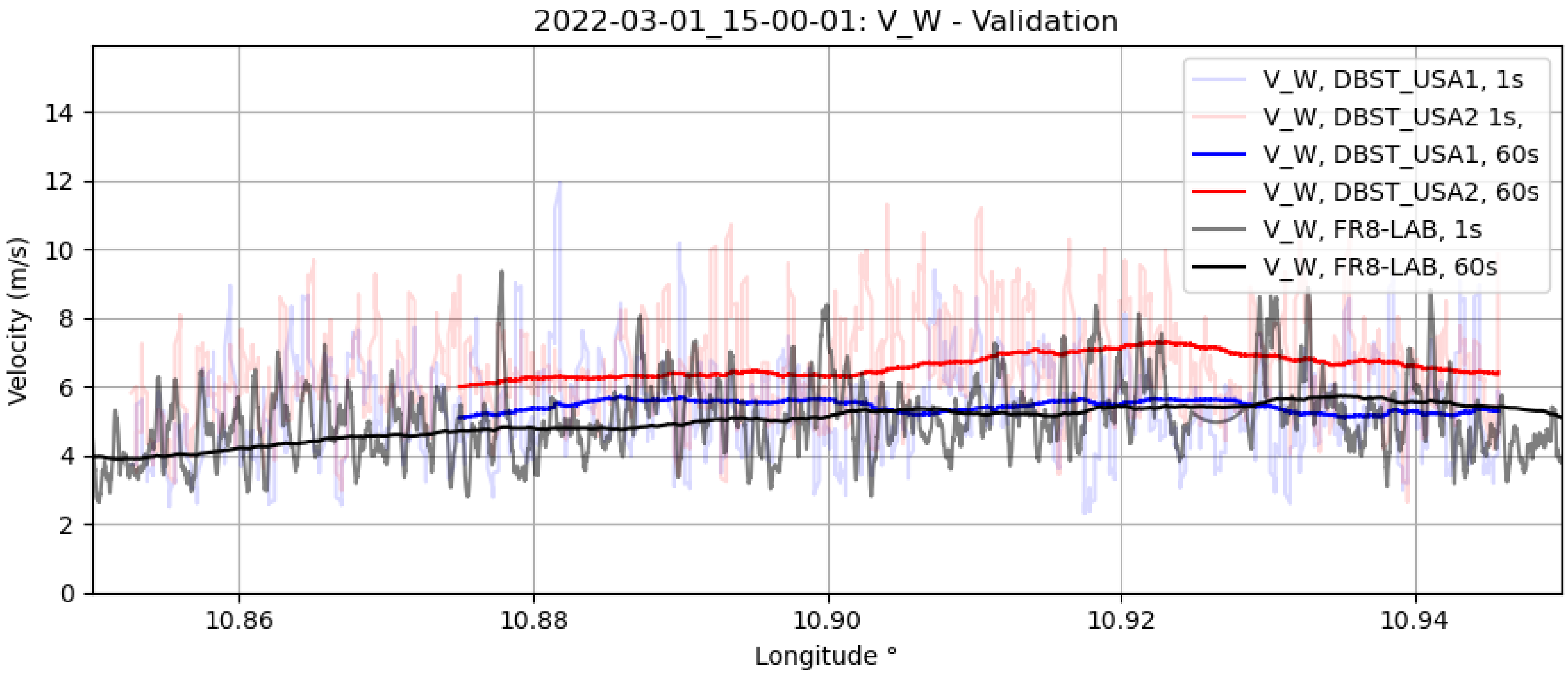
Results: Validation

Medium wind 1/03/2022: 12am

- Derived velocity from processing of surface-pressure data on FR8-LAB:
  → corresponds well to purpose-built velocity measurement devices: DB ST Ultrasonic Anemometers 1 & 2

V_W: Wind Velocity
atmospheric wind

- **FR8-LAB :** derived velocity
- **USA1, USA2:** DB STs ultrasonic anemometers 1 & 2



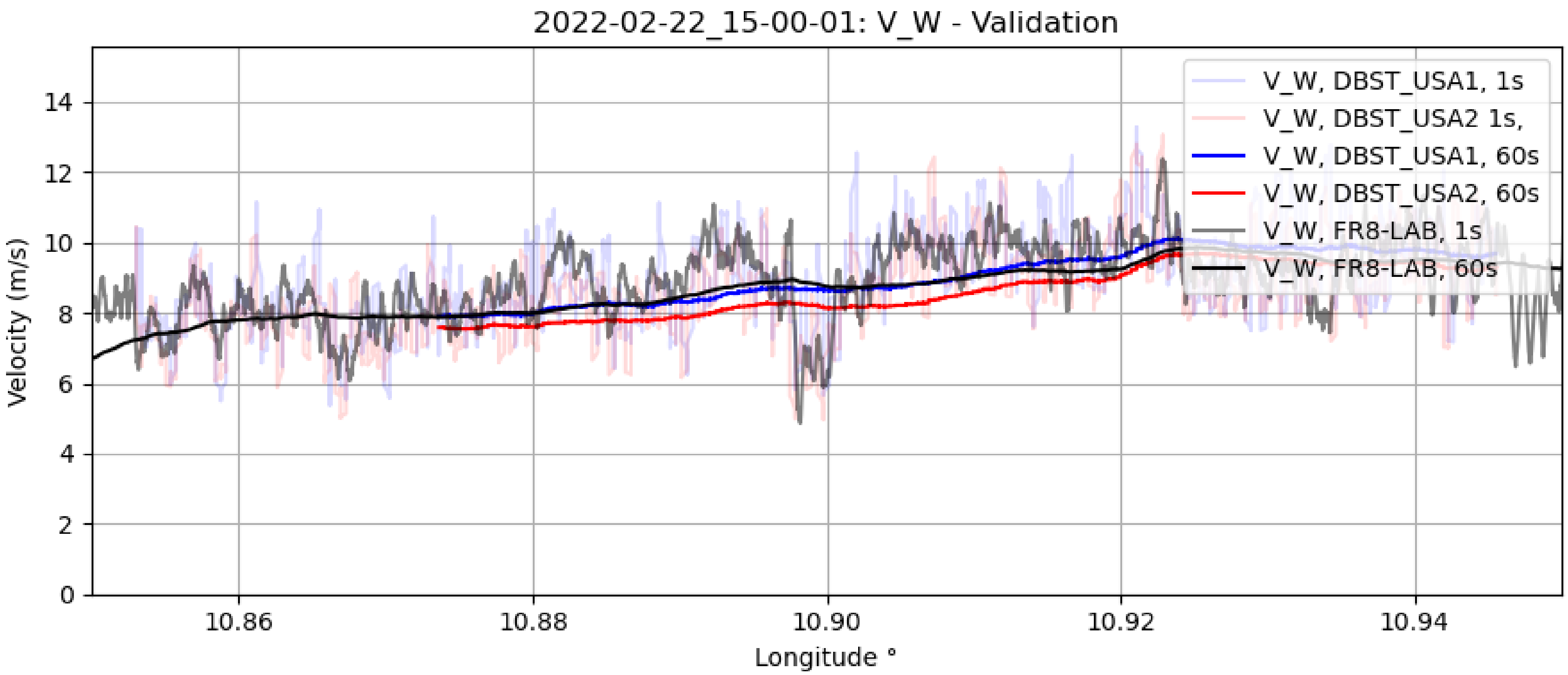
Results: Validation

Medium wind 22/02/2022: 12am

- Derived velocity from processing of surface-pressure data on FR8-LAB:
  → corresponds well to purpose-built velocity measurement devices: DB ST Ultrasonic Anemometers 1 & 2

V_W: Wind Velocity
atmospheric wind

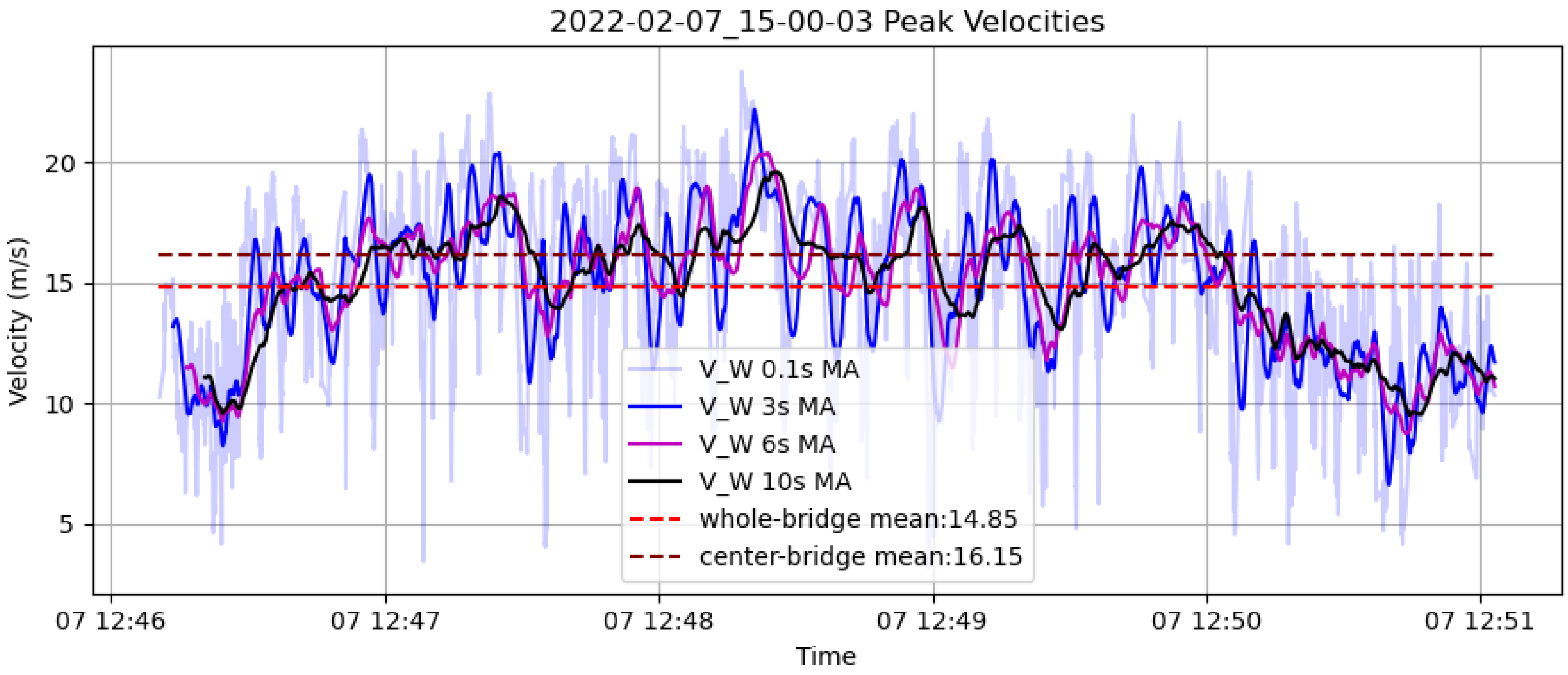
- **FR8-LAB :**
  derived velocity
- **USA1, USA2:**
  DB STs ultrasonic anemometers 1 & 2



Results: Time-Varying Crosswind - Individual Insight #1

High wind 07/02/2022: 12am – Velocity magnitude (m/s)

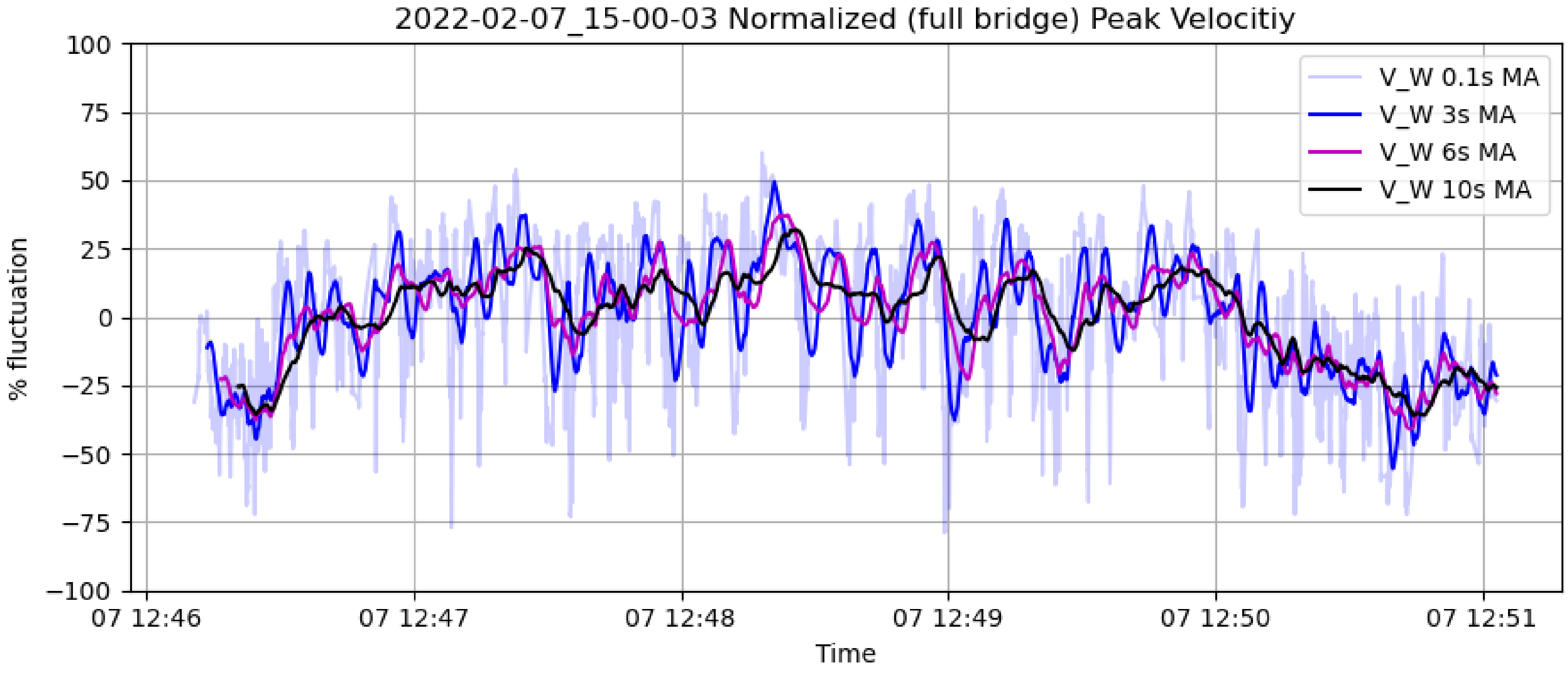
- Characteristics of transient flow ‘gusts’ freight train experiences across bridge
- Different moving averages (MA) durations applied, 0.1s, 3s, 6s, 10s affects gust magnitude
- Visible velocity fluctuations around mean (not 10min mean, ~5min bridge crossing duration)

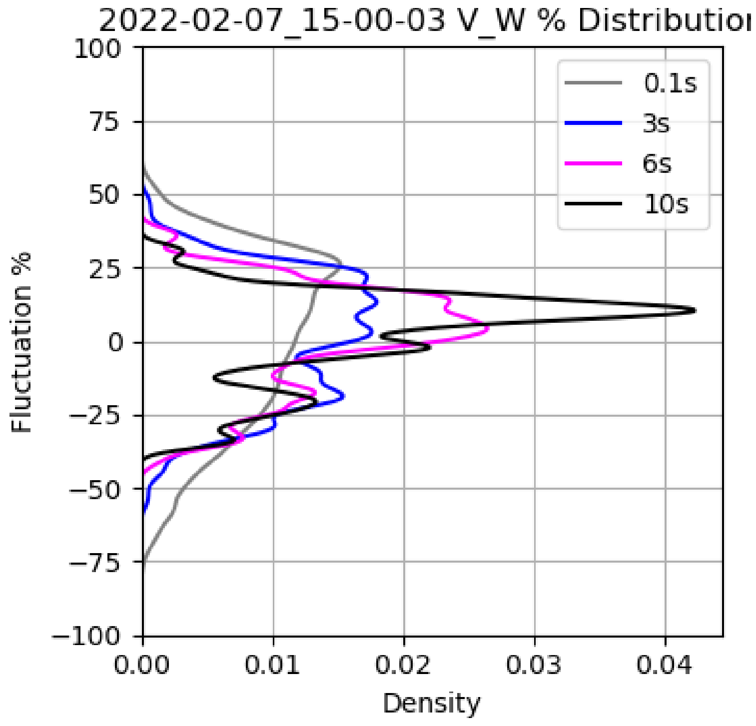


Results: Time-Varying Crosswind - Individual Insight #1

High wind 07/02/2022: 12am – Normalized Velocity (% fluctuation around mean)

- Velocity fluctuations in %: normalized by mean velocity (~5min bridge crossing)
- 25%-50% fluctuations relative to mean, depending on gust duration (0.1-10s MA)

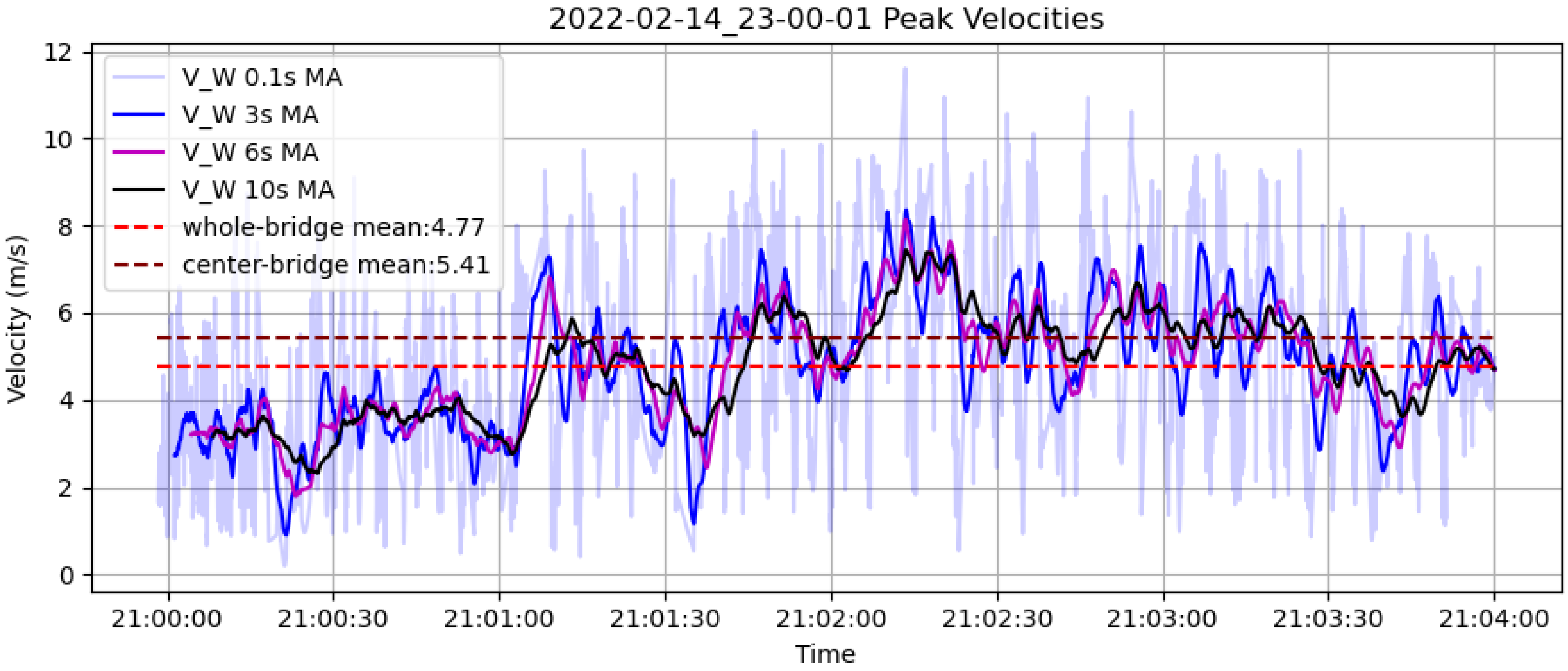




Results: Time-Varying Crosswind - Individual Insight #2

Medium wind 14/02/2022: 9pm – Velocity magnitude (m/s)

- Characteristics of transient flow ‘gusts’ freight train experiences across bridge
- Different moving averages (MA) durations applied, 0.1s, 3s, 6s, 10s affects gust magnitude
- Visible velocity fluctuations around mean (not 10min mean, ~5min bridge crossing duration)

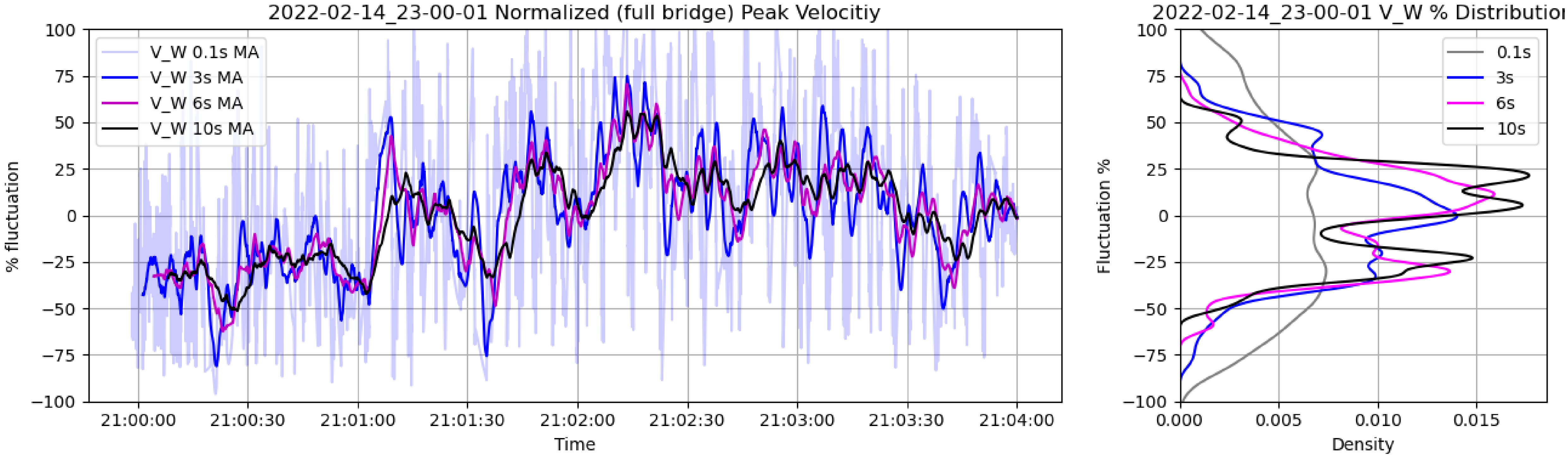


DLR

Results: Time-Varying Crosswind - Individual Insight #2

Medium wind 14/02/2022: 9pm– Normalized Velocity (% fluctuation around mean)

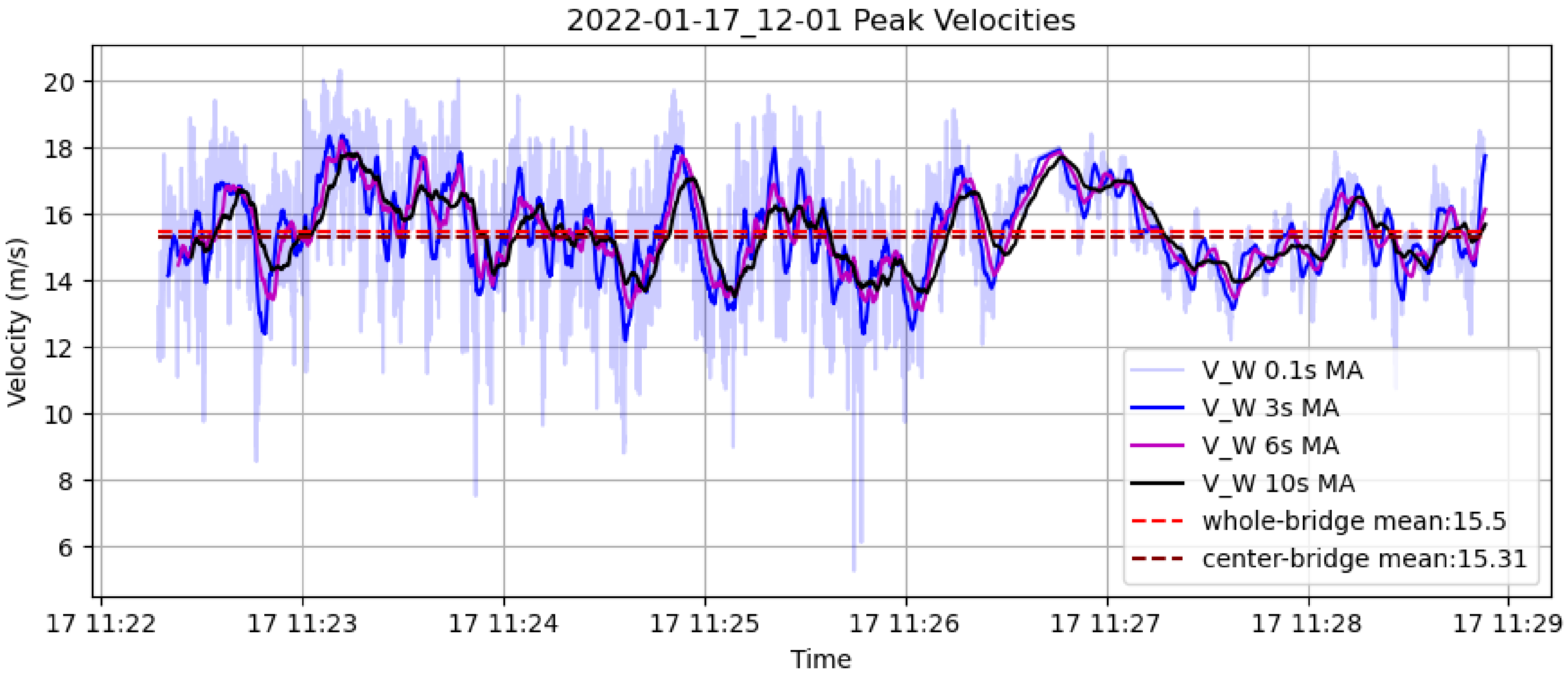
- Velocity fluctuations in %: normalized by mean velocity (~5min bridge crossing)
- 25%-75% fluctuations relative to mean, depending on gust duration (0.1-10s MA)



Results: Time-Varying Crosswind - Individual Insight #3

High wind 17/01/2022: 12am – Velocity magnitude (m/s)

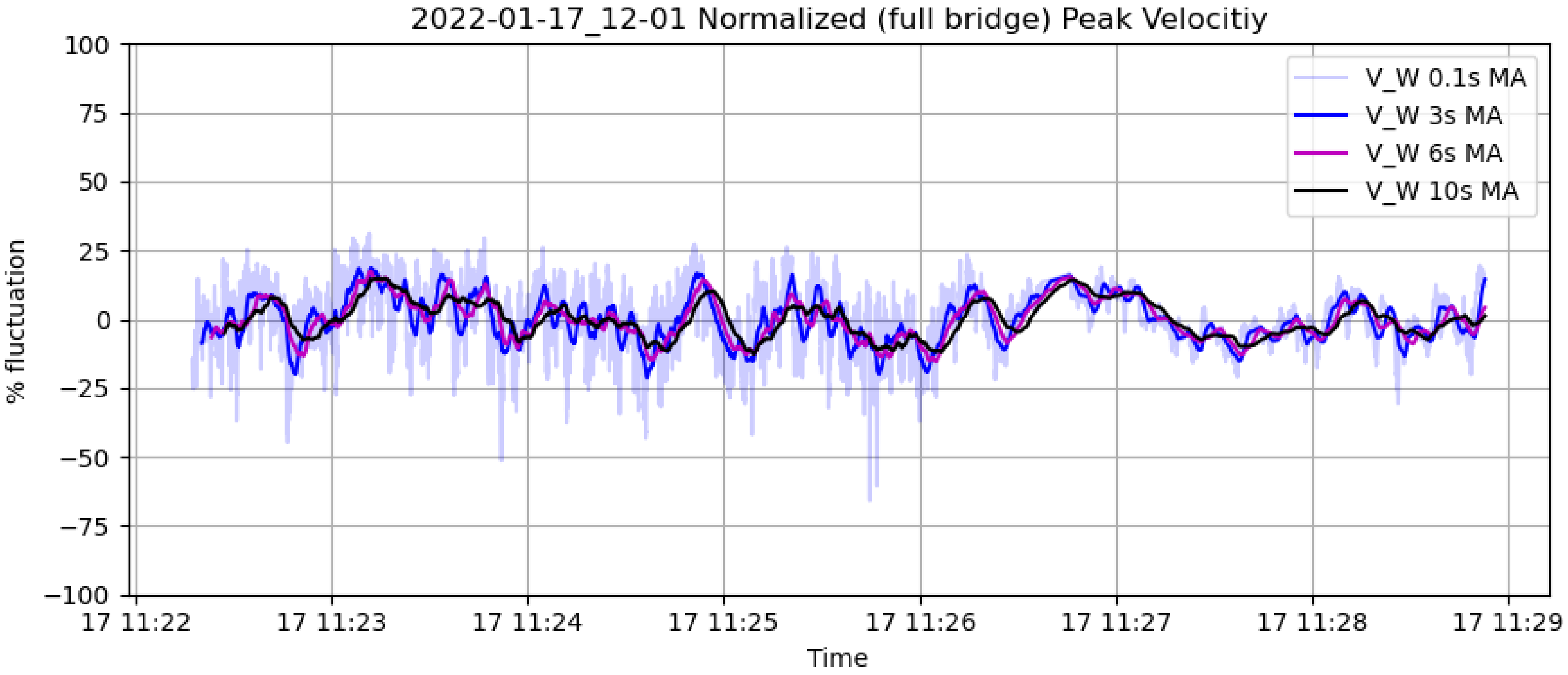
- Characteristics of transient flow ‘gusts’ freight train experiences across bridge
- Different moving averages (MA) durations applied, 0.1s, 3s, 6s, 10s affects gust magnitude
- Visible velocity fluctuations around mean (not 10min mean, ~5min bridge crossing duration)

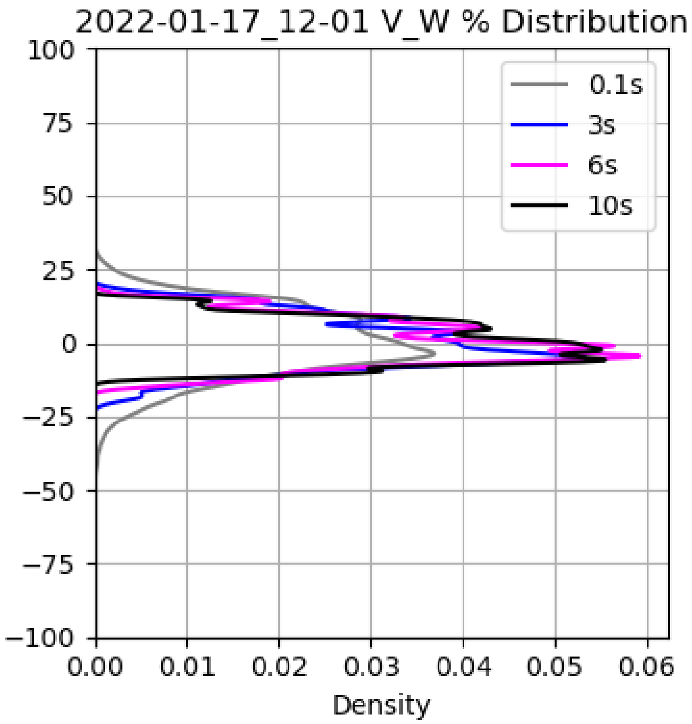


Results: Time-Varying Crosswind - Individual Insight #3

High wind 17/01/2022: 12am – Normalized Velocity (% fluctuation around mean)

- Velocity fluctuations in %: normalized by mean velocity (~5min bridge crossing)
- 10-20% fluctuations relative to mean, depending on gust duration (0.1-10s MA)

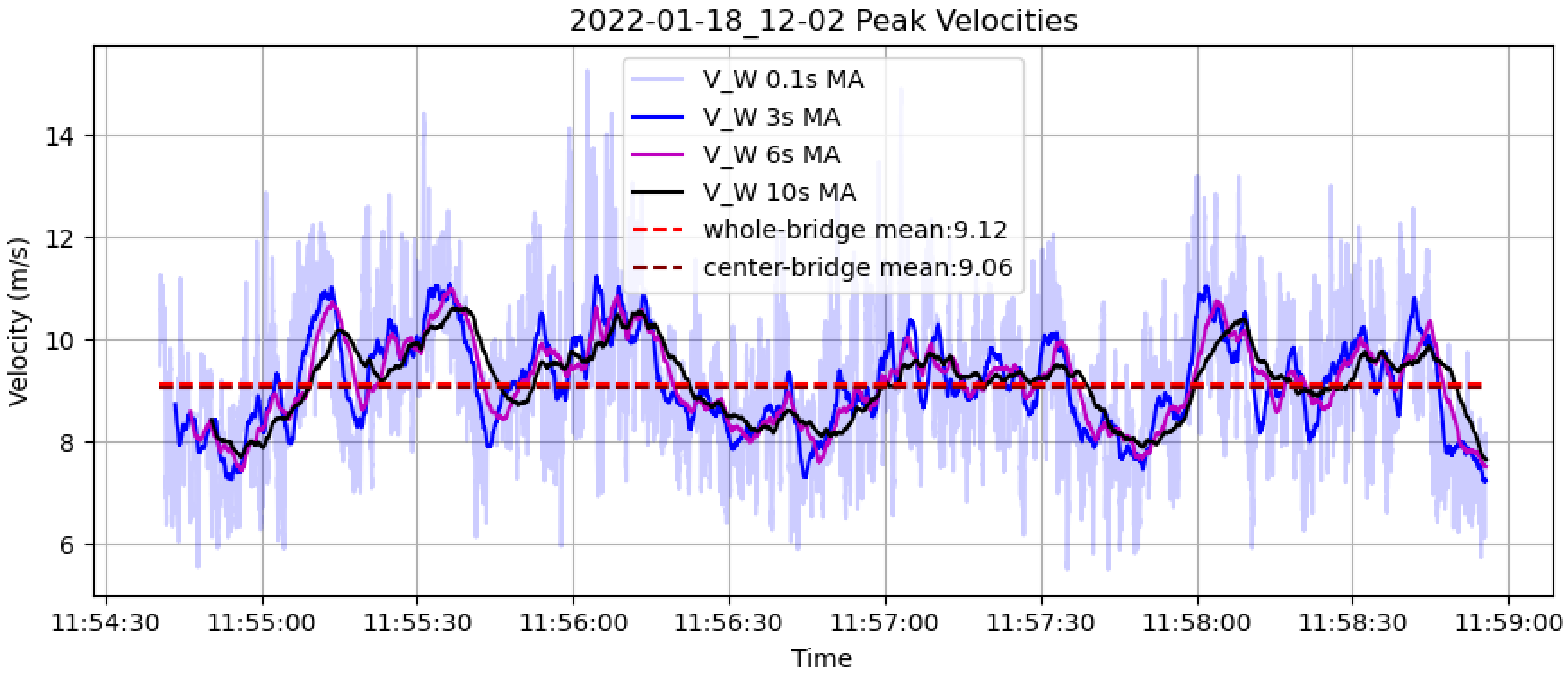




Results: Time-Varying Crosswind - Individual Insight #4

Medium wind 18/01/2022: 12am – Velocity magnitude (m/s)

- Characteristics of transient flow ‘gusts’ freight train experiences across bridge
- Different moving averages (MA) durations applied, 0.1s, 3s, 6s, 10s affects gust magnitude
- Visible velocity fluctuations around mean (not 10min mean, ~5min bridge crossing duration)

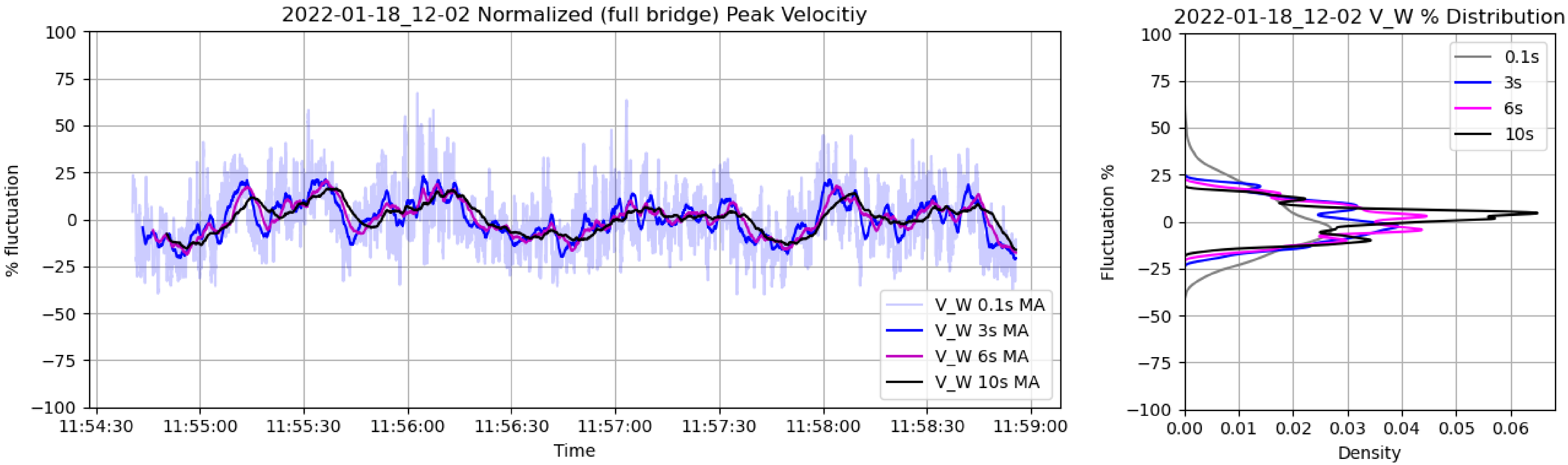


DLR

Results: Time-Varying Crosswind - Individual Insight #4

Medium wind 18/01/2022: 12am – Normalized Velocity (% fluctuation around mean)

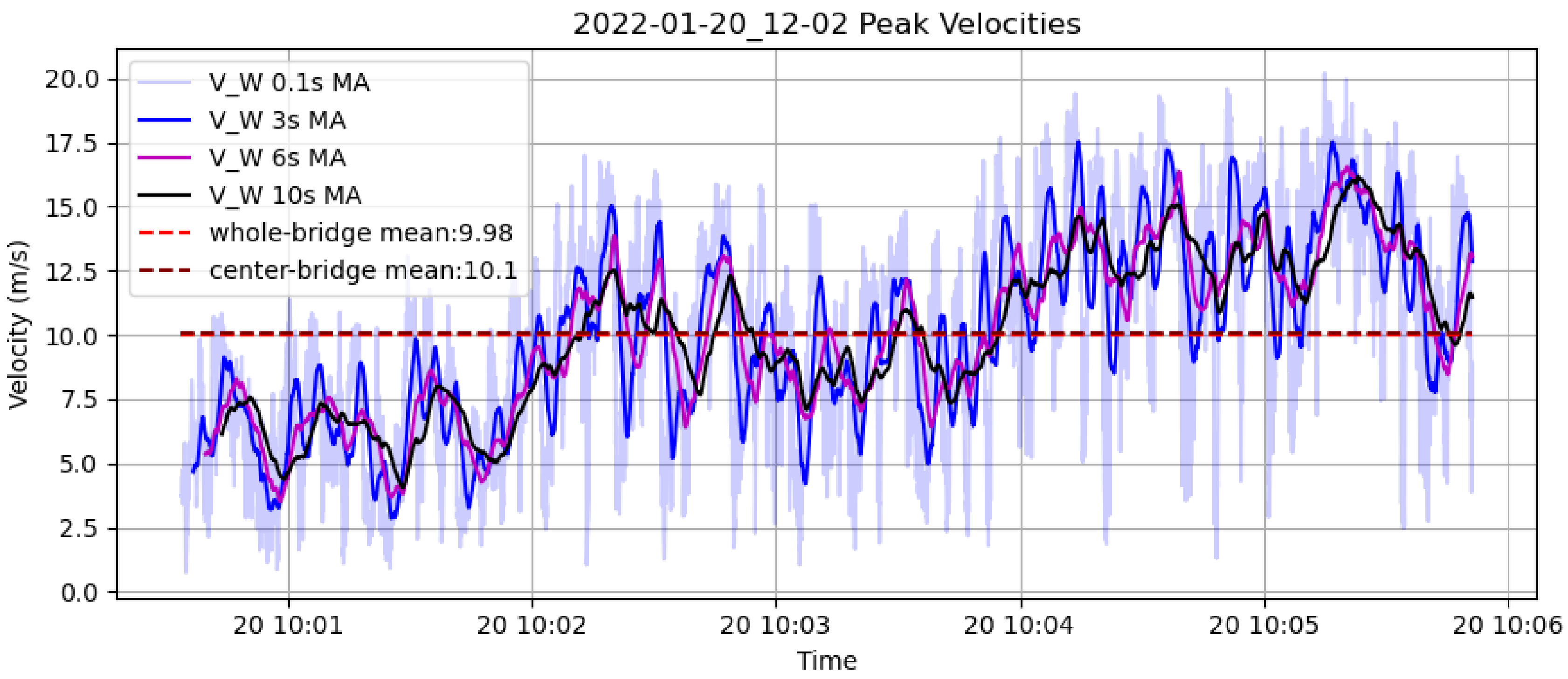
- Velocity fluctuations in %: normalized by mean velocity (~5min bridge crossing)
- 10-25%% fluctuations relative to mean, depending on gust duration (0.1-10s MA)



Results: Time-Varying Crosswind - Individual Insight #5

Medium wind 20/01/2022: 9am – Velocity magnitude (m/s)

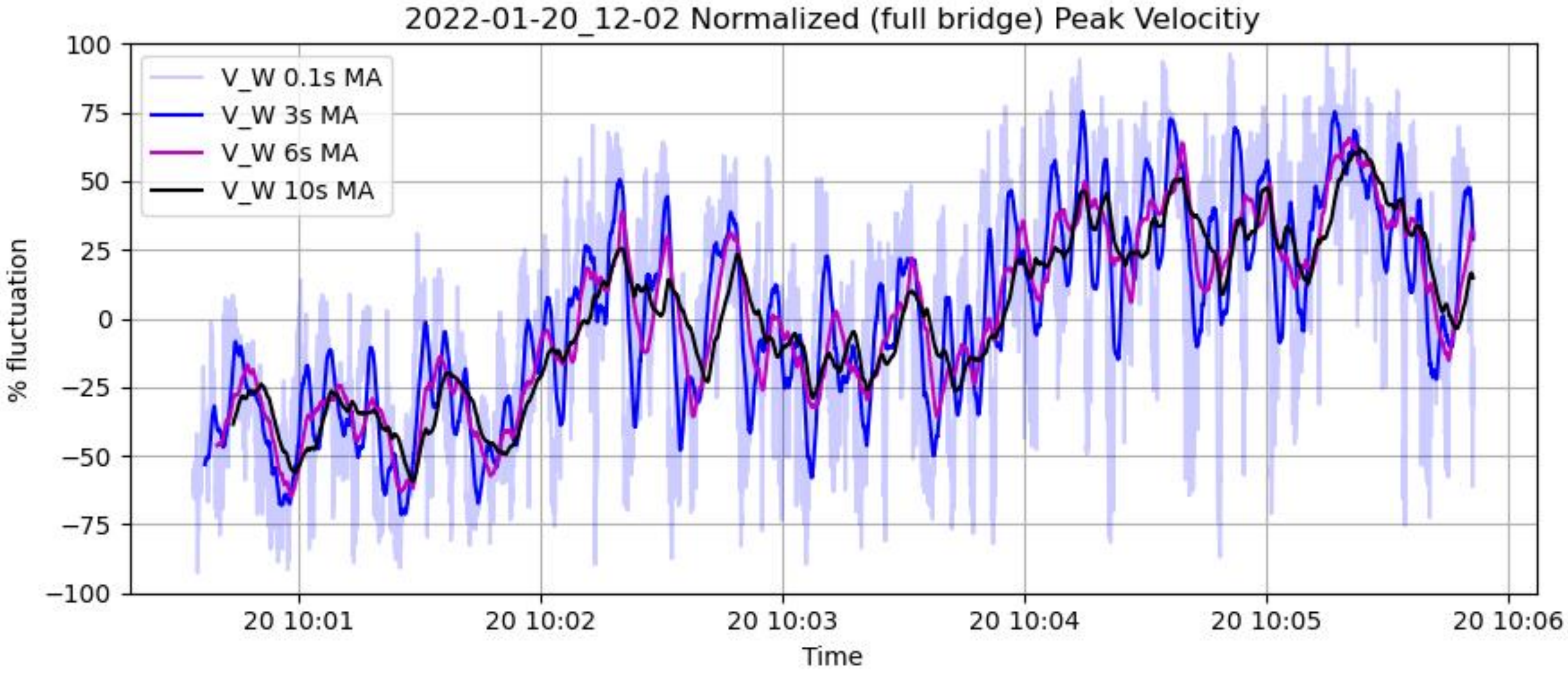
- Characteristics of transient flow ‘gusts’ freight train experiences across bridge
- Different moving averages (MA) durations applied, 0.1s, 3s, 6s, 10s affects gust magnitude
- Visible velocity fluctuations around mean (not 10min mean, ~5min bridge crossing duration)

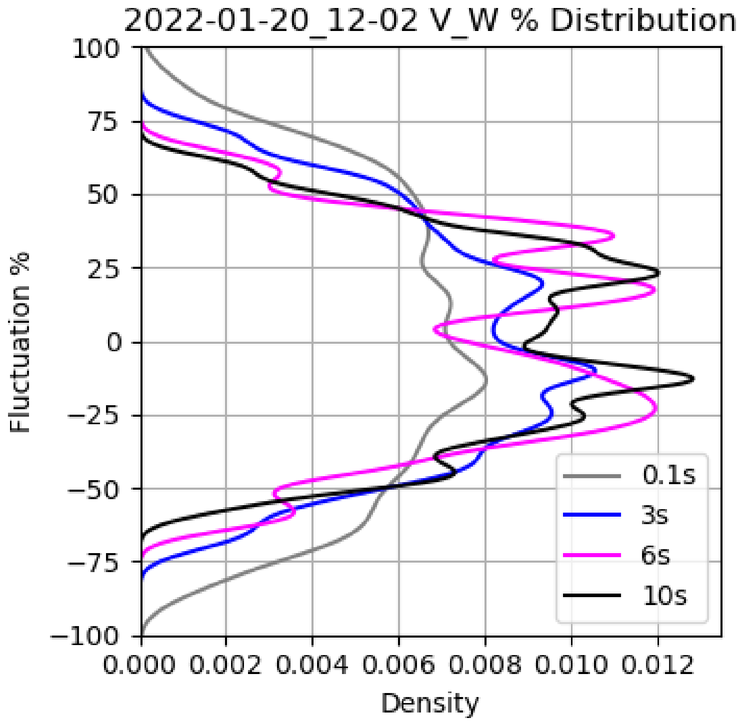


Results: Time-Varying Crosswind - Individual Insight #5

Medium wind 20/01/2022: 9am – Normalized Velocity (% fluctuation around mean)

- Velocity fluctuations in %: normalized by mean velocity (~5min bridge crossing)
- 25%-75% fluctuations relative to mean, depending on gust duration (0.1-10s MA)

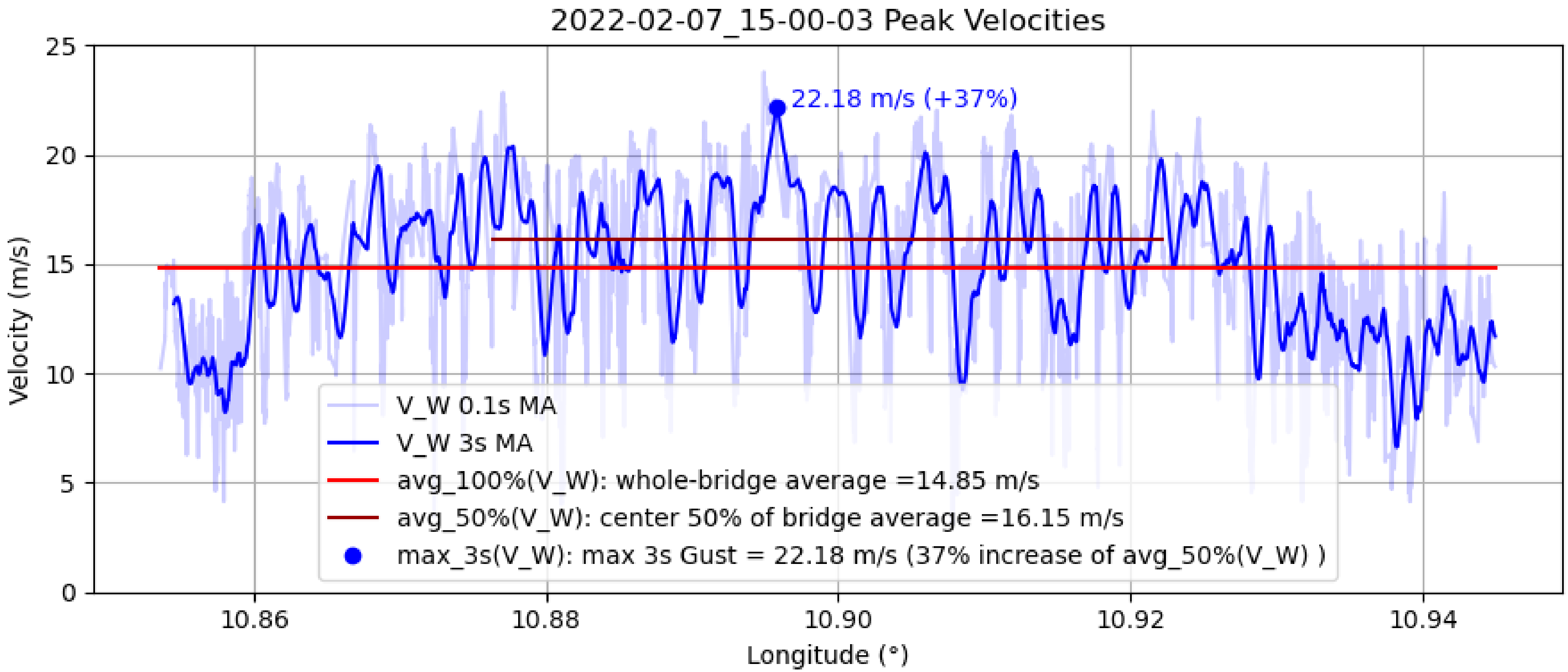




Results: Time-Varying Crosswind – Peak 3 Second Gusts #1

High wind 07/02/2022: 12am – Peak Gust Velocity with 3 second duration

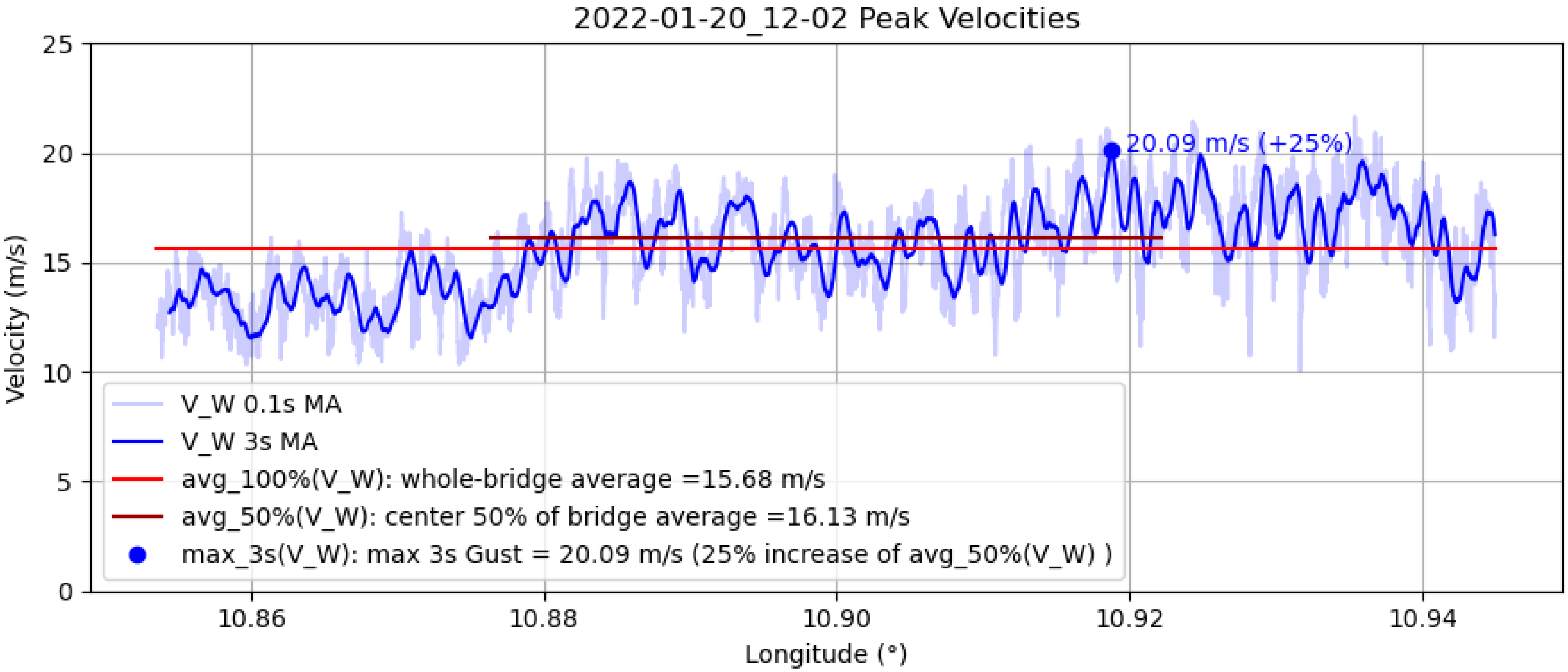
- Peak gust of 22.18m/s (increase of 37% above average wind speed of 16.15 m/s) (average calculated over middle 50% of the bridge)
- Loading configuration: Very Large gap in front of FR8-LAB (66m), High average relative Yaw angle, β~40°



Results: Time-Varying Crosswind – Peak 3 Second Gusts #2

High wind 20/01/2022: 12am – Peak Gust Velocity with 3 second duration

- Peak gust of 20.09m/s (increase of 25% above average wind speed of 16.13 m/s) (average calculated over middle 50% of the bridge)
- Loading configuration: Large gap in front of FR8-LAB (>17m), High average relative Yaw angle, β~30°

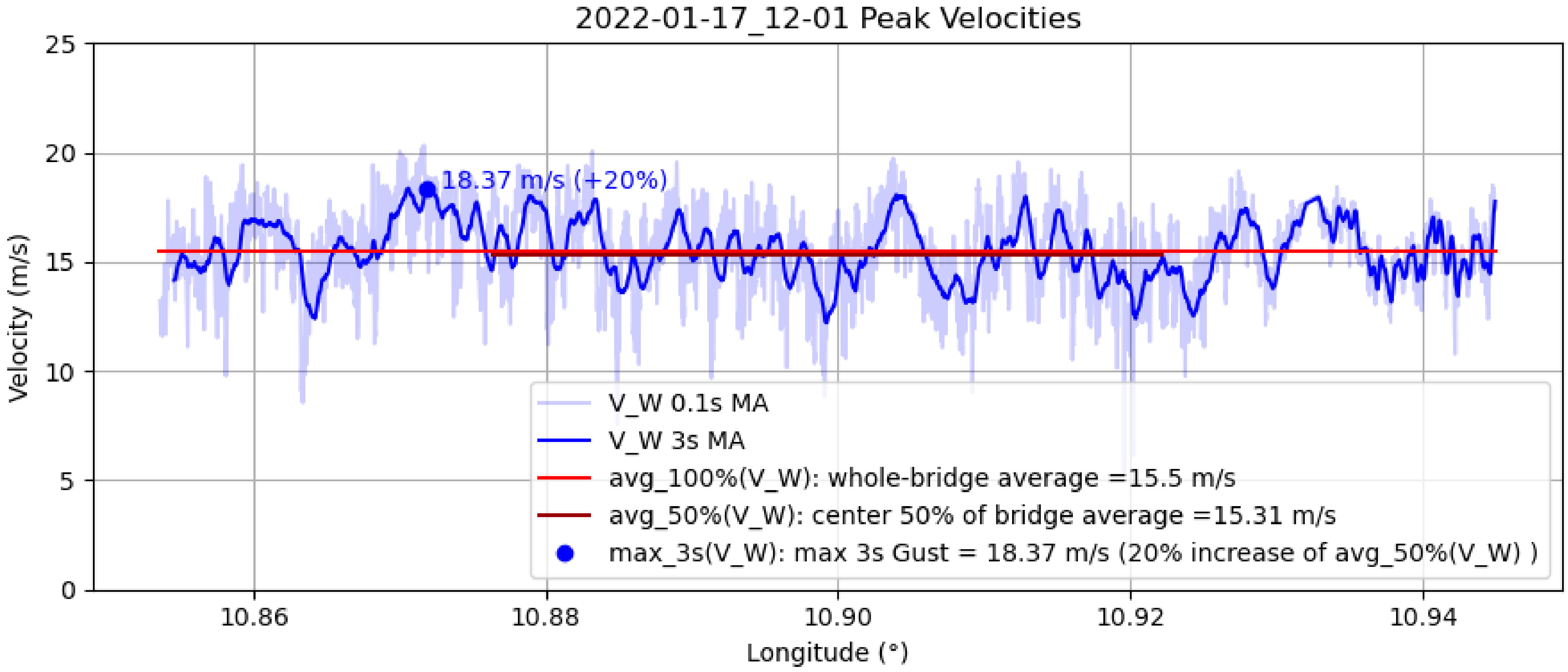


DLR

Results: Time-Varying Crosswind – Peak 3 Second Gusts #3

High wind 17/01/2022: 12am – Peak Gust Velocity with 3 second duration

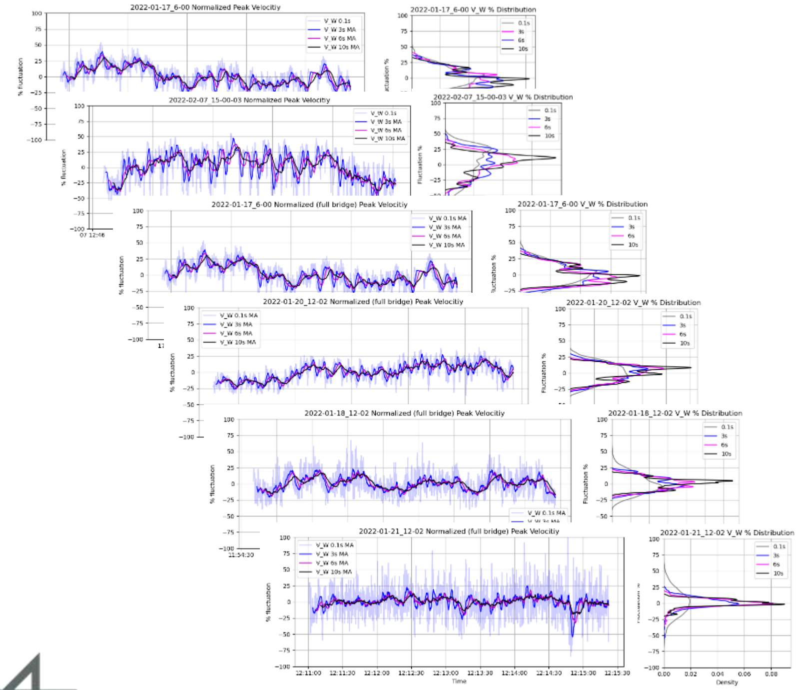
- Peak gust of 18.37m/s (increase of 20% above average wind speed of 15.13 m/s) (average calculated over middle 50% of the bridge)
- Loading configuration: Large gap in front of FR8-LAB (>17m), High average relative Yaw angle, β~40°



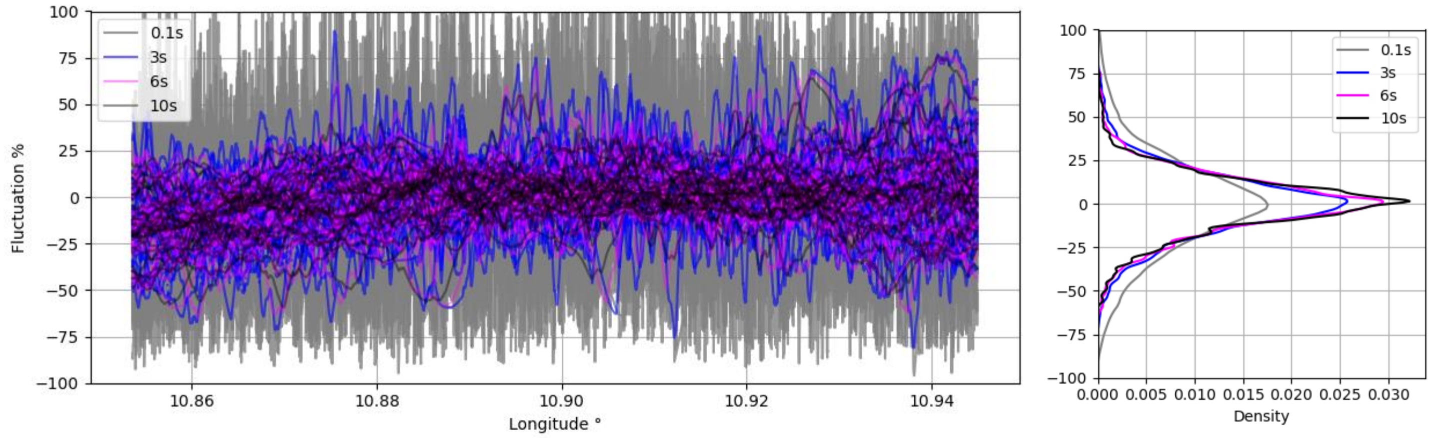
Results: Time-Varying Crosswind - Overview

Development of General Crosswind Characteristics

- All bridge crossings with crosswind (wind > 5m/s), normalized & collated:
  30 individual bridge-crossing measurements
  → provides: general statistical description of (non-negligible: wind > 5m/s) crosswinds
  (not specific to a particular mean wind speed at a given day)



All runs compiled (wind > 5m/s)

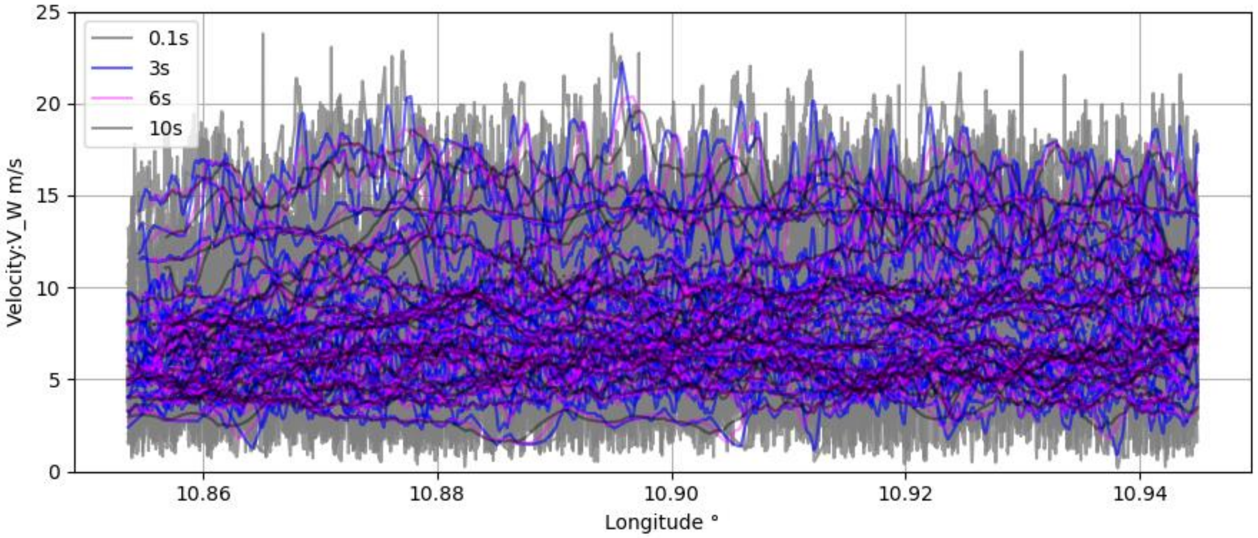


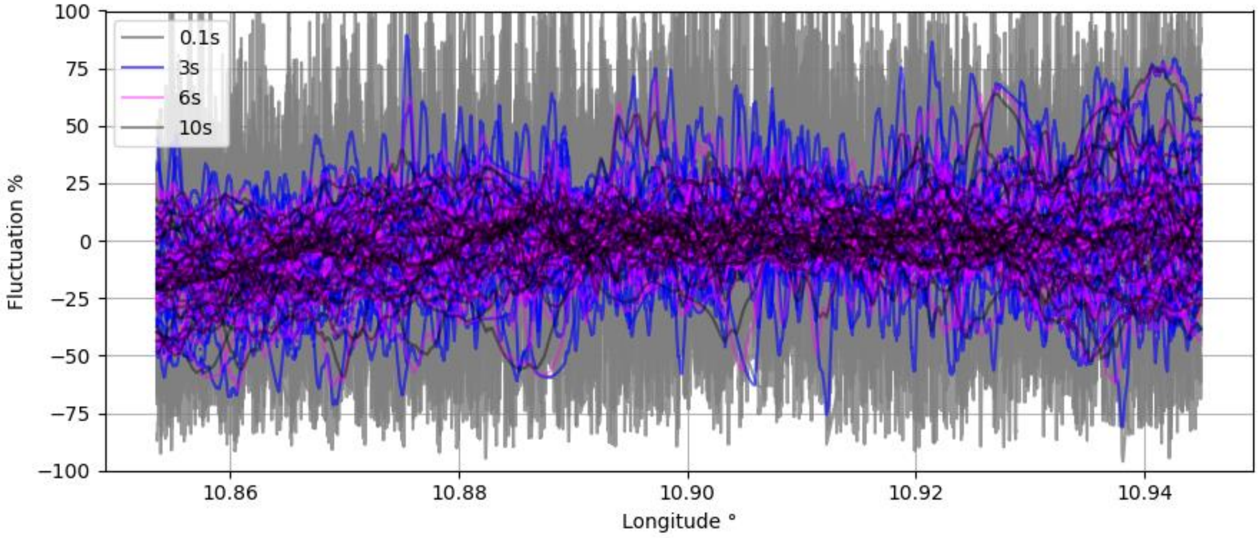
Results: Time-Varying Crosswind - Overview

Development of General Crosswind Characteristics

- All bridge crossings with crosswind (wind > 5m/s): 30 individual bridge-crossing measurements
- Measured results (in velocity m/s), then normalized by each individual mean (during bridge crossing): provides fluctuating velocity in % around mean.

→ Data from each individual measurement now comparable, collatable

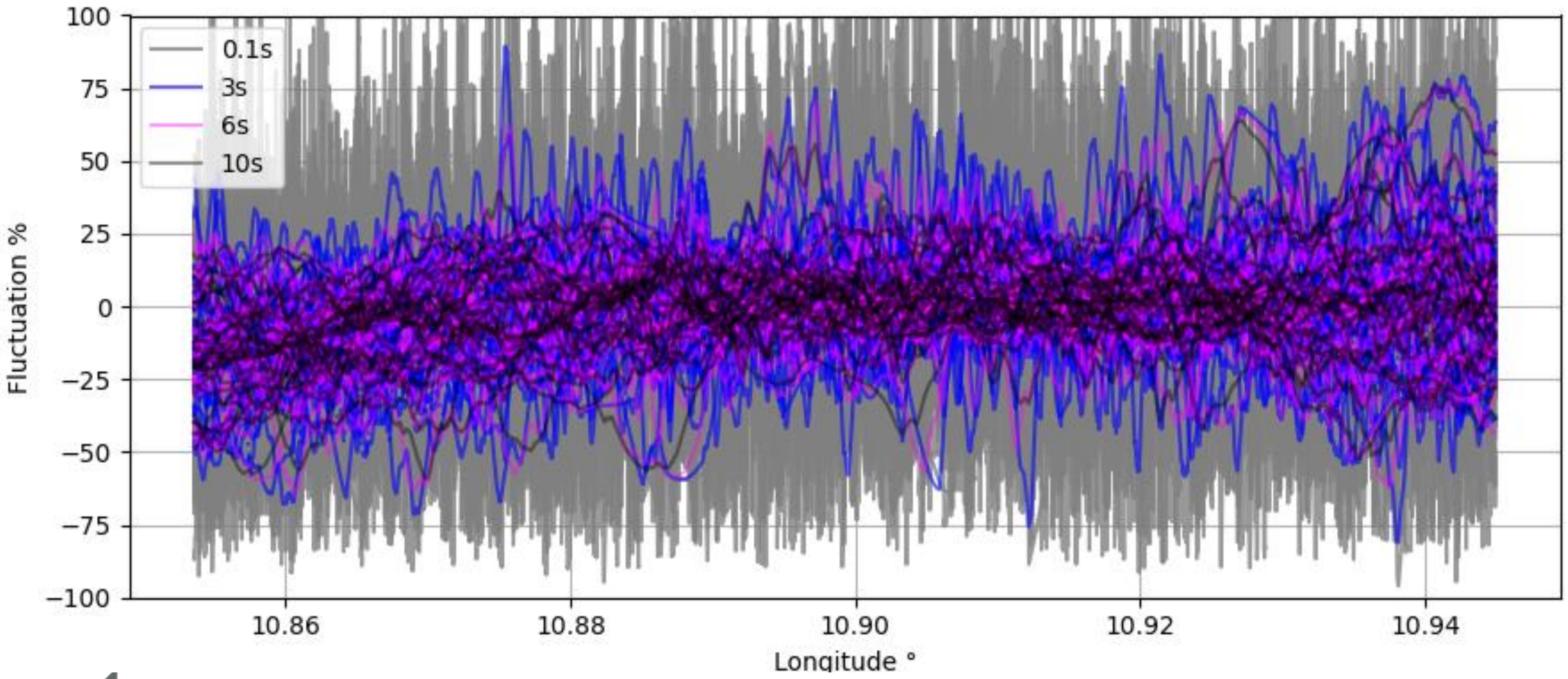


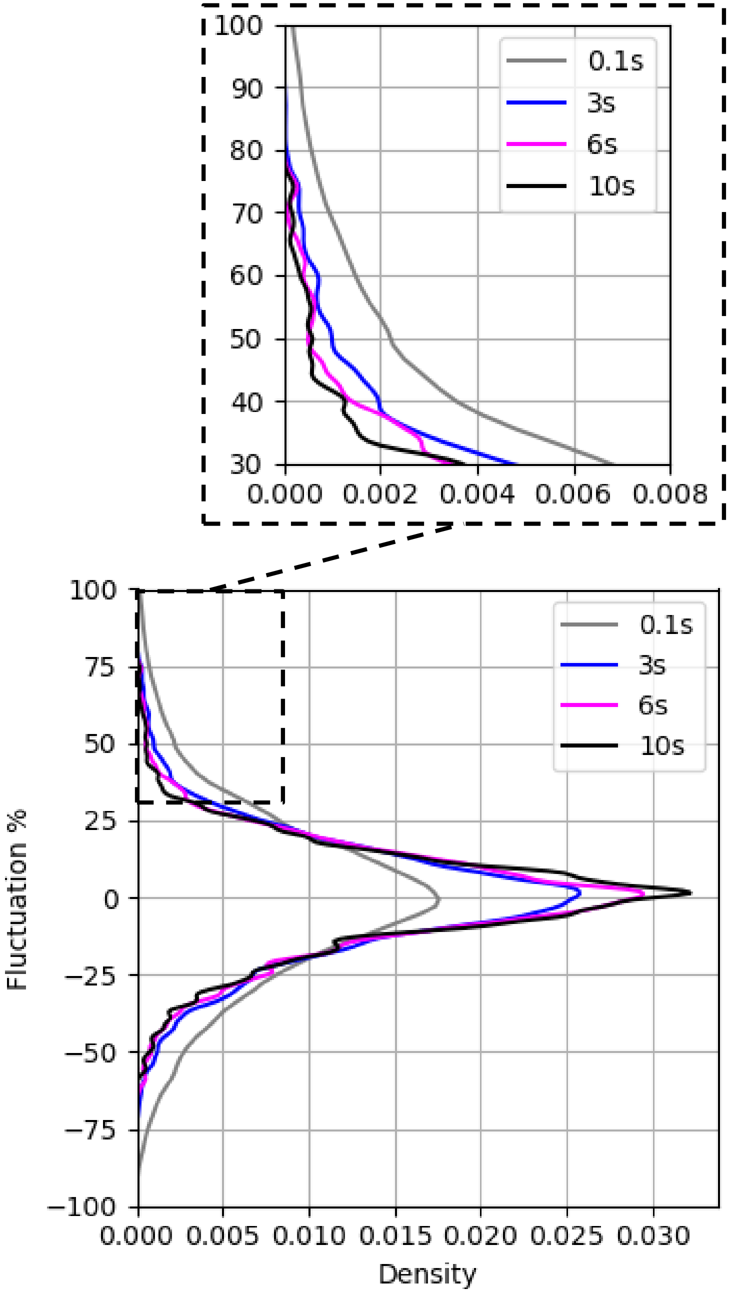


Results: Time-Varying Crosswind - Overview

General Crosswind Characteristics

- From 30 bridge-crossing measurements with wind > 5m/s:
  - Time-varying velocity fluctuates during bridge crossing
  - Fluctuations around mean of +/- 25-75% depending on gust duration (3, 6, 10 seconds)





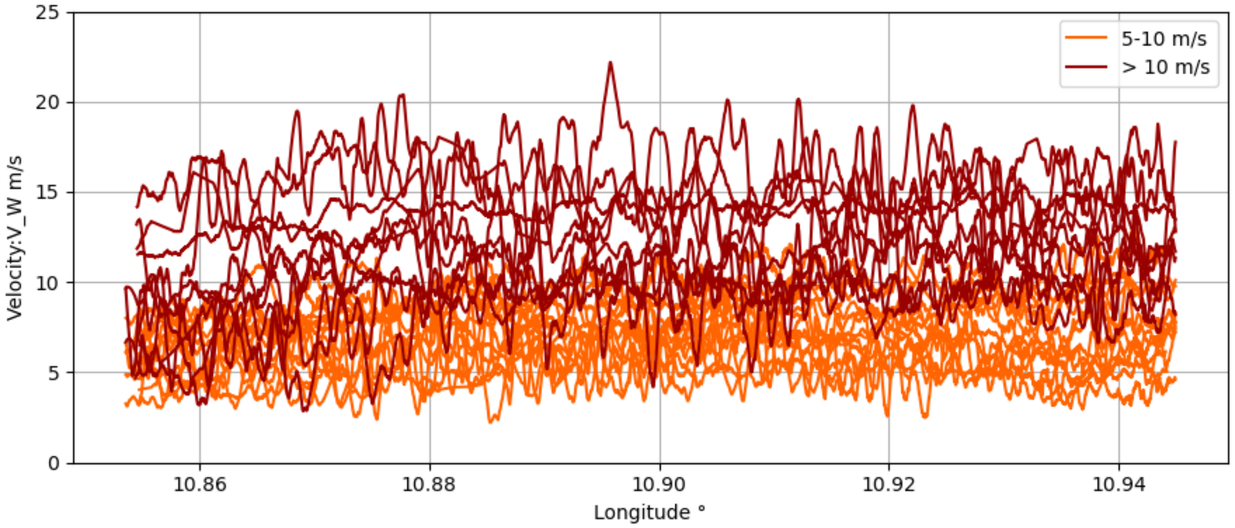
Results: Time-Varying Crosswind - Overview

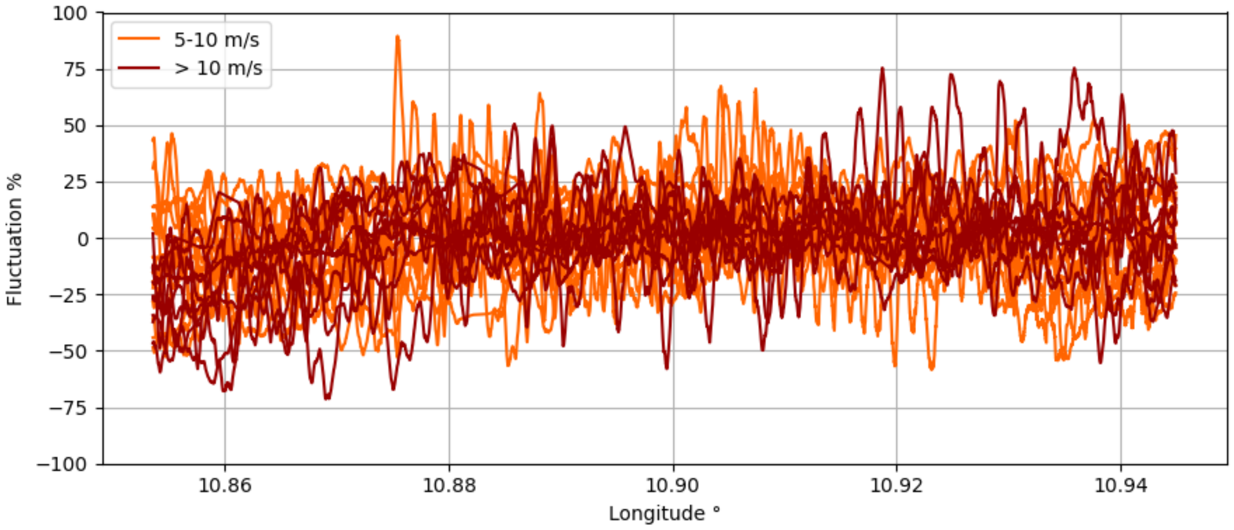
Velocity Range Sensitivity

- 10+ bridge-crossings of two ranges of mean wind velocity : 5-10 m/s & >10 m/s were collated

→ assess sensitivity of characteristics to wind velocity magnitude.

- Measured results (in velocity m/s), again normalized by each individual mean (during bridge crossing): provides fluctuating velocity in % around mean.



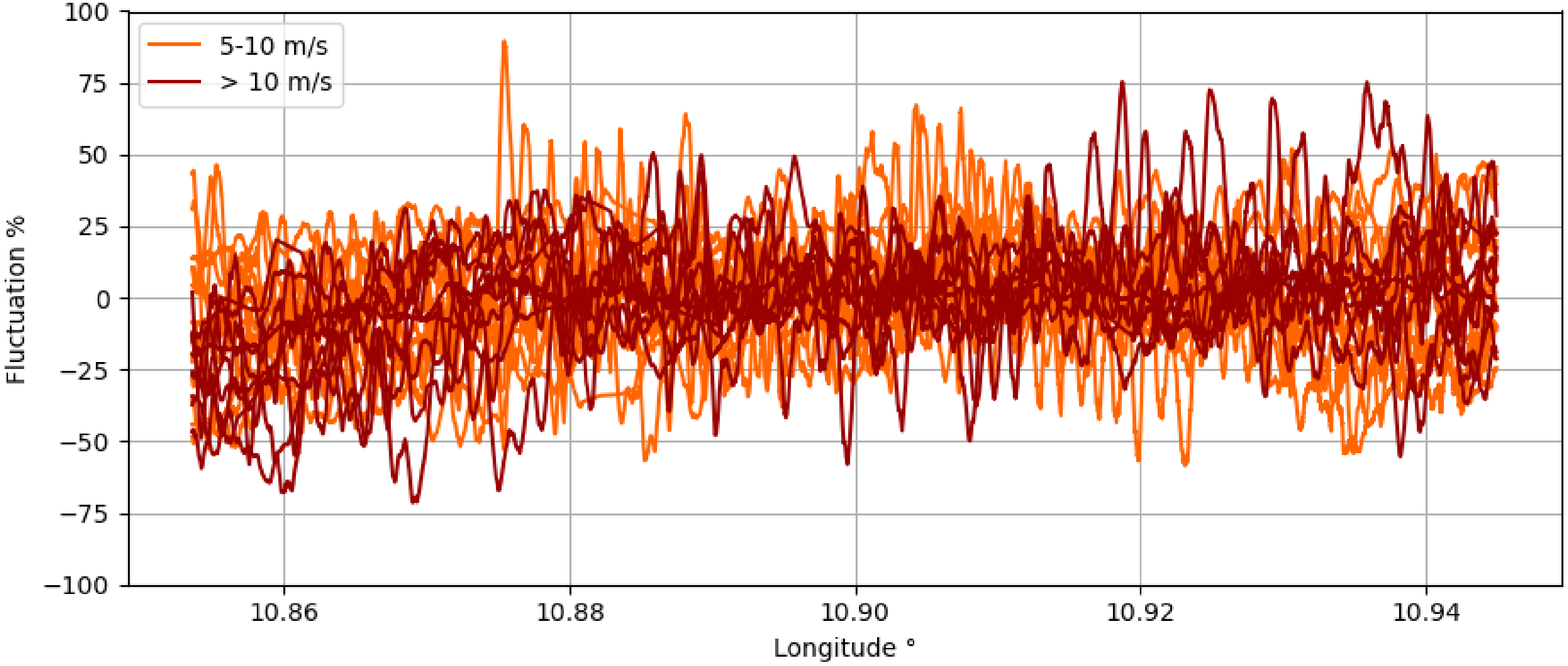


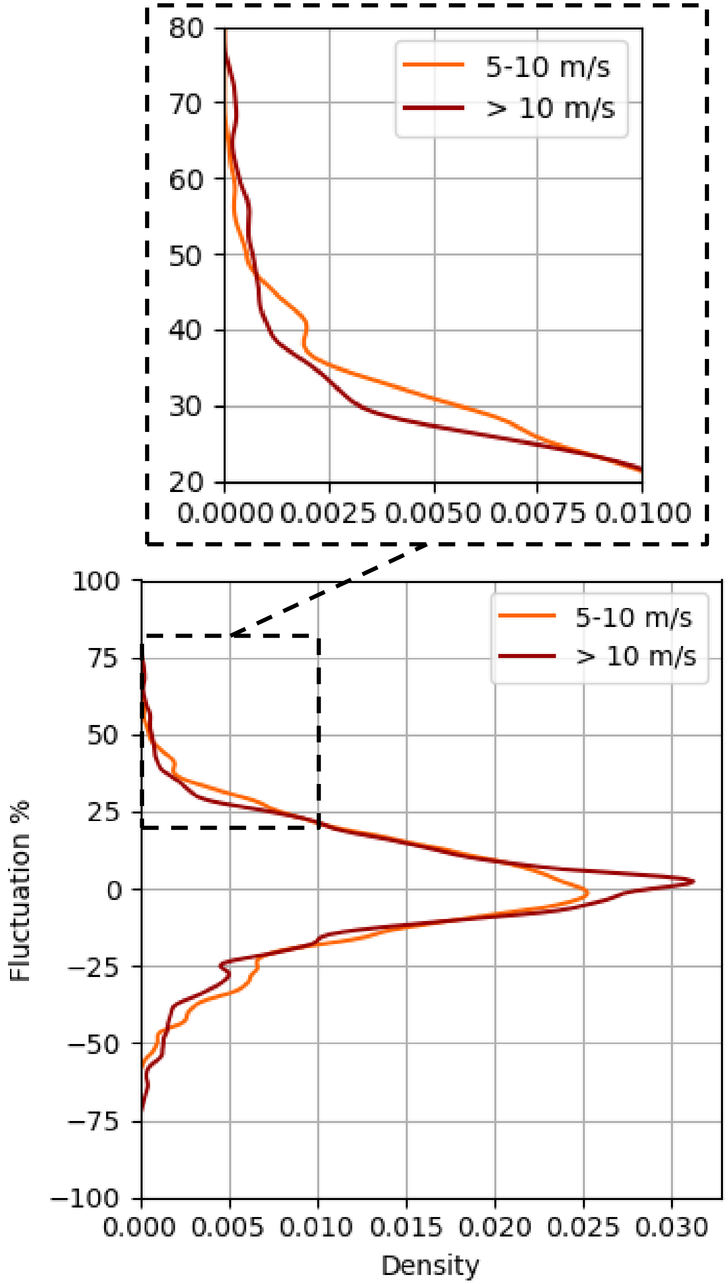
DLR

Results: Time-Varying Crosswind - Overview

Velocity Range Sensitivity

- Minimal difference in time-varying velocity and distribution characteristics between the two mean wind velocity ranges : 5-10 m/s & >10 m/s





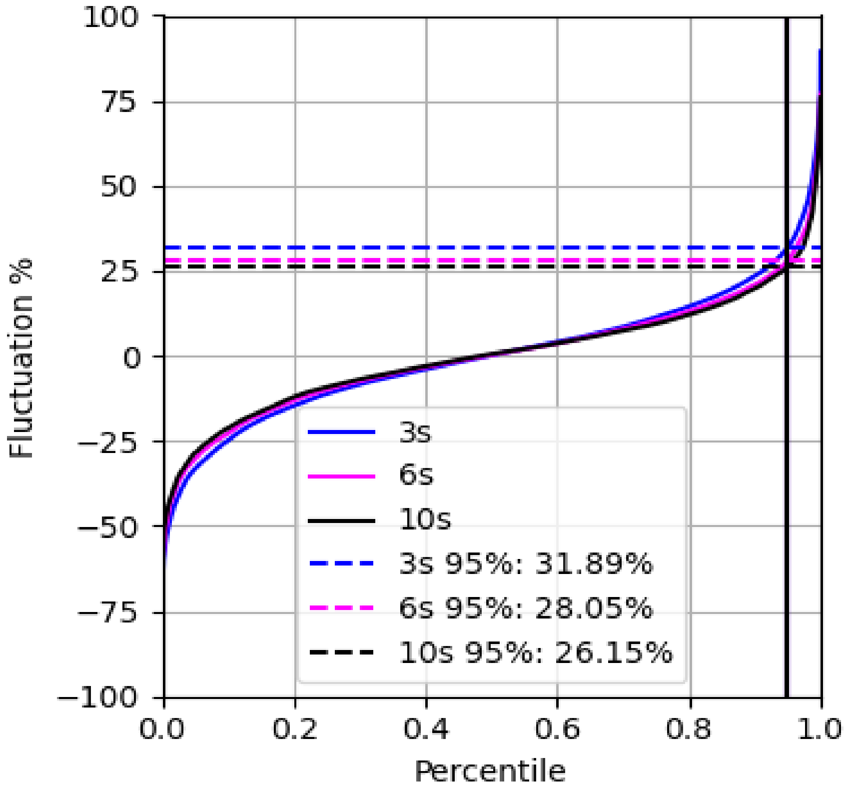
Results: Time-Varying Crosswind - Overview

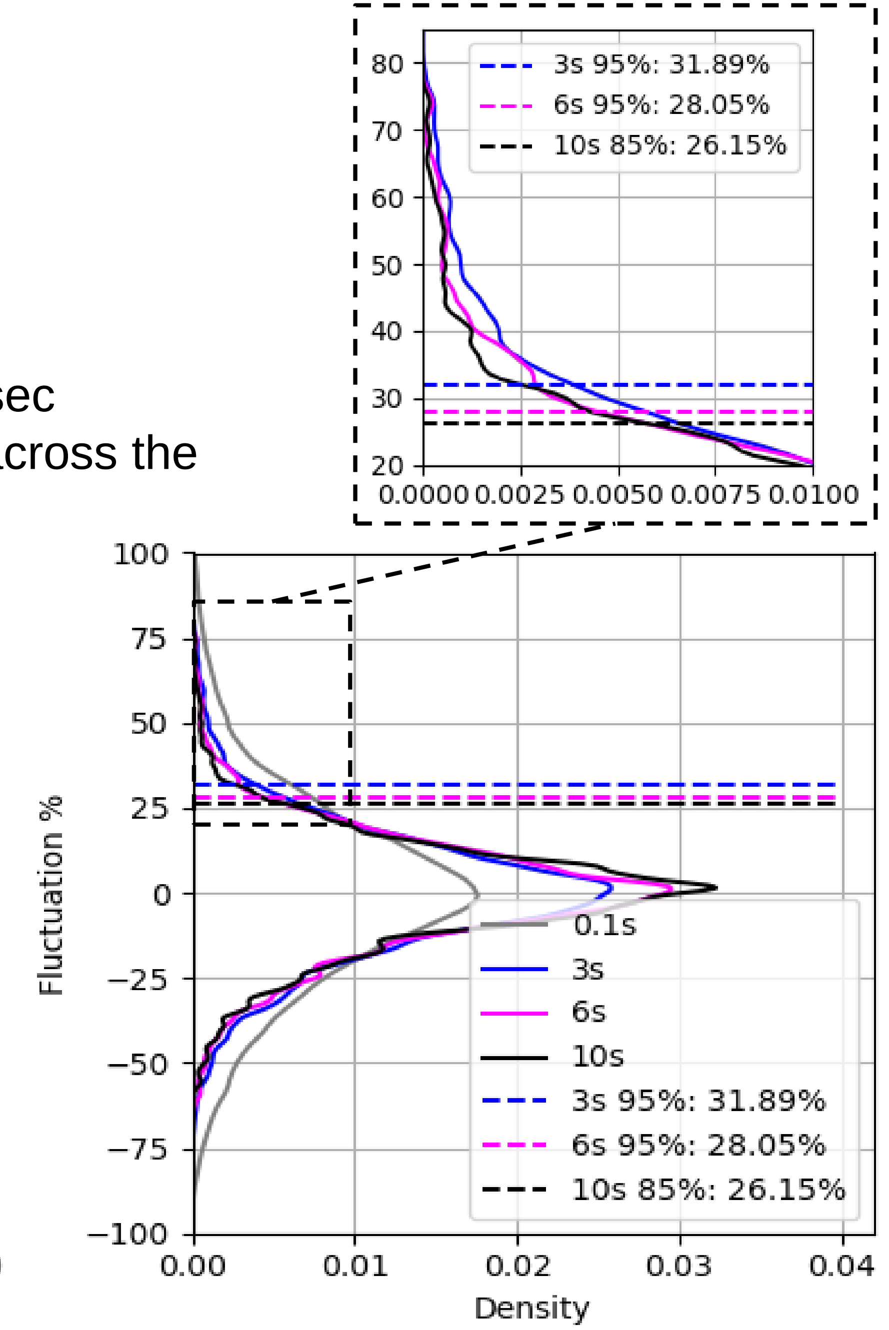
General Crosswind Distribution Characteristics

- **3 sec 95th percentile value: +31.89% fluctuation**
  5% of measurements (where mean crosswind >5m/s) had gusts of 3 sec duration with fluctuation of +31.89% than the mean (~5min duration) across the whole bridge

- **6 sec 95th percentile: +28.05% fluctuation**

- **10 sec 95th percentile: +26.15% fluctuation**

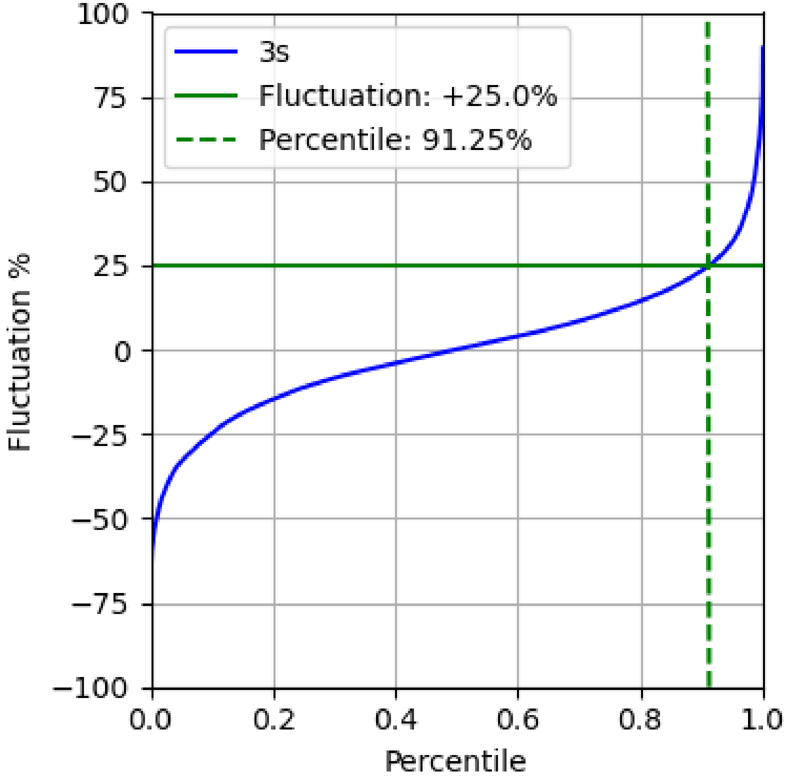


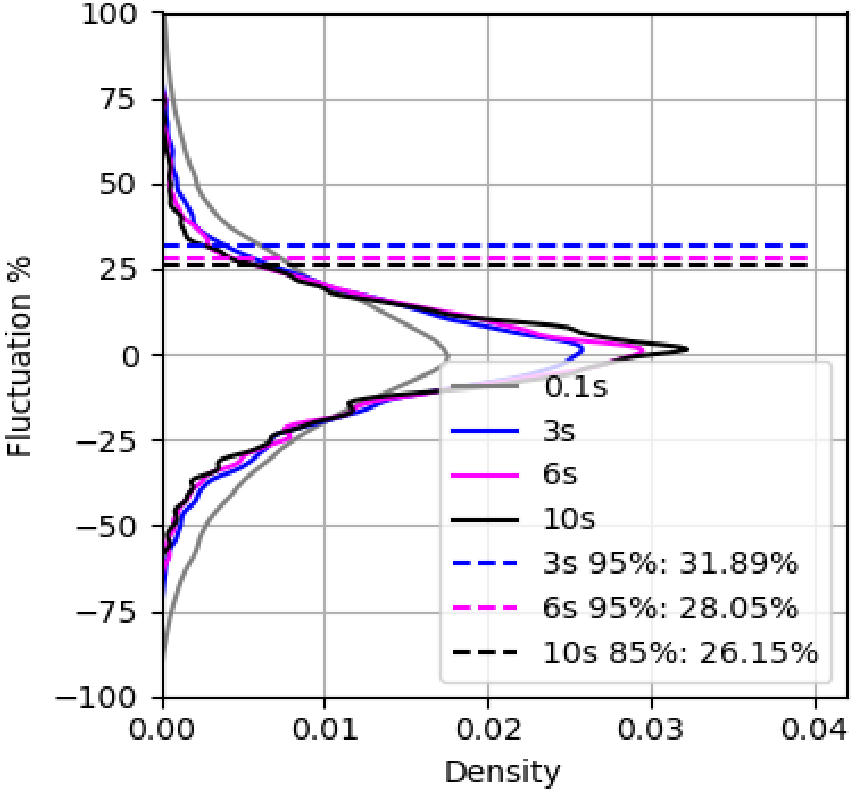


Results: Time-Varying Crosswind - Overview

General Crosswind Distribution Characteristics

- **3 sec +25% fluctuation: 91.25th percentile**
  Fluctuations of +25% higher than the mean (~5min duration) across the whole bridge with a duration of 3 sec or longer, corresponds to the top 8.75 percentile of measurements (where mean crosswind >5m/s)





DLR

Conclusions:

- Full-scale experimental campaign completed: @Bridge Jan 10th – March 4th)
- Wind-tunnel (calibration) experimental campaign completed: April 15th 2022
- FR8-LAB new, novel measurement system: functionality demonstrated
- Validation: FR8-LAB vs DB ST ultrasonic anemometers show good agreement
- Individual runs demonstrate time-varying characteristics:
    - fluctuations around mean during bridge crossing
    - Significant variation between different, individual bridge-crossing measurements
- General crosswind characteristics developed from the collation of 30 bridge measurements (wind>5m/s)
    - Normalized fluctuations (% relative to mean across bridge) of 25-50% observed