

The Free-Stream Anemometer: A laser-Doppler system for the reliable assessment of the aerodynamic performance of surface vehicles

B. Tanguay^{1,*}, P. Cottin², S. Cochard³

1: Aerodynamics Laboratory, National Research Council Canada

2: formerly from Institut National d'Optique (INO[¶]), Québec, Canada

3: Aerodynamics, thermodynamics and acoustics dept., Stadler Rheintal AG, Switzerland

*Corresponding author: bernard.tanguay@nrc-cnrc.gc.ca

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ABSTRACT

The Free-Stream Anemometer (FSA) is a dual-channel laser-Doppler system enabling the non-intrusive, real-time measurement of free-stream velocity forward of traveling vehicles. The FSA is equipped with an ultra-coherent laser emitting at a wavelength of 1550 nm. Each of the two non-parallel FSA laser beams is focused in the free-stream zone, illuminating the microscopic natural aerosols traversing the FSA sensing zone as faithful wind tracers. The FSA was specifically designed for the purpose of assessing a vehicle's aerodynamic performance with enhanced reliability and accuracy during on-road or on-track tests. The physical impossibility of supporting a boom-mounted anemometer "far-enough" into the free-stream region makes the FSA the only known solution for directly probing the free-stream wind velocity non-intrusively and in real-time. Unlike the simulations afforded by wind tunnel testing and CFD, the FSA supports aerodynamic testing in real-life conditions, i.e. in the presence of turbulent terrestrial winds characterizing the atmospheric surface layer. The technology was subjected to several validation phases in the laboratory, in the wind tunnel, and during field tests on board of vehicles. An uncertainty analysis demonstrated that, for typical applications on board vehicles, the FSA measures free-stream speed with an uncertainty level below 0.09 m/s (0.32 km/h) for free-stream yaw angles under 15°. The uncertainty in the free-stream yaw angle measurement is below 0.4° for free-stream speeds exceeding 30 m/s. Wind tunnel testing also confirmed the FSA's sensitivity at detecting airborne aerosols. It was shown that a concentration of about 500 aerosol particles per litre suffices to ensure the detection of ten Doppler events per second for FSA-detectable particles characterized by aerodynamic diameters above 1 μm . In the wind tunnel, this corresponded to a mass concentration of less than 2 $\mu\text{g}/\text{m}^3$ for particles with diameters ranging from 1 μm to 4 μm , i.e. well below the concentrations observed in urban and inter-urban environments worldwide. Under yaw-inducing crosswind conditions, the FSA enables the determination of a vehicle's yaw-dependent aerodynamic drag coefficient, thereby enabling the evaluation of a vehicle's energy consumption in a variety of wind conditions.

[¶] Following a merger, INO was rebranded as [Luqia](#), as of April 1, 2026

1. Introduction and background

The Free-Stream Anemometer (FSA) was developed in partnership between the Aerodynamics Laboratory of the National Research Council Canada (NRC) and Institut National d'Optique (INO[¶]) based in Québec, Canada. This development project, which spanned a period of four years, was co-sponsored by NRC and Transport Canada, via its ecoTECHNOLOGY for Vehicles (eTV) programme. The purpose of this technology is to directly measure the free-stream velocity ($\vec{U}_\infty$) forward of a traveling vehicle in order to enable the reliable evaluation of its aerodynamic drag coefficient (C_D) during dedicated on-road or on-track experiments, *i.e.* in real-life, operating conditions. The use of the subscript infinity (∞) is intentional, as it indicates that the reference, free-stream velocity needs to be measured 'far enough' forward, beyond the vehicle's zone of aerodynamic disturbance.

The certification process of surface vehicles typically requires that coasting tests* be conducted to determine a vehicle's resistance to motion. For example, in North America, SAE standard J2263 (SAE, 2020) prescribes the procedure to be applied for road vehicles, using on-board anemometry. Similarly, in Europe, trains must be subjected to coasting tests by following procedures prescribed by the European Committee for Standardization (CEN) in norm EN 14067-4:2024+A1:2025 (2025). The SAE guideline, which covers the use of a boom-mounted anemometer, stipulates that "*Calibration of the anemometer shall include corrections for vehicle blockage*", without specifying the correction procedure. The purpose of this correction is to convert the biased anemometer measurements to free-stream velocities. In the previous CEN standard for trains (EN 14067-4:2013, 2013), terrestrial winds were neglected in the analysis (*i.e.* assumed zero) if a single track-side anemometer recorded wind speeds below 2 m/s during a coasting test typically covering a distance of some 20 km. Runs for which this threshold was exceeded were discarded, often leading to unproductive or cancelled test campaigns, inducing unwelcome costs. The involvement of the NRC Aerodynamics Laboratory with the CEN working group on train aerodynamics[†] since 2019, advocating for the use of the FSA technology, resulted in a revised version of the test procedure (2025) authorizing the use of on-board anemometry measuring free-stream velocity directly, in lieu of track-side measurements. The FSA is one implementation satisfying this need.

For such track or road tests, the measurement of free-stream velocity is crucial for the determination of a reliable value of C_D whose value grows with increasing free-stream yaw angle (Ψ_∞). The coefficient of aerodynamic drag, which is a dimensionless measure of a vehicle's aerodynamic efficiency, is defined as:

$$C_D(\Psi_\infty) = \frac{D(\Psi_\infty)}{\frac{1}{2} \rho U_\infty^2 A} \quad (1)$$

*During coasting tests, the vehicle is accelerated to a maximum speed and wheel power is then withdrawn, letting the vehicle decelerate freely by virtue of the combined action of aerodynamic and mechanical resistances. The unknown resistance parameters are obtained by fitting the equation of motion to the vehicle deceleration trace.

[†]CEN working group on train aerodynamics: CEN/TC 256/SC 4/WG 6.

Where D is the yaw-dependent[‡] aerodynamic drag force, ρ is the air density and A is the vehicle's frontal area. The problem of determining the free-stream velocity is illustrated in **Figure 1**. The drawing illustrates a vehicle traveling at velocity $\vec{V}$ in the presence of a terrestrial wind with a transverse component. The horizontal flow-field slice at vehicle mid-height (in the vehicle reference frame) highlights the distorted streamlines in proximity to the vehicle and, further upwind, the free-stream zone where the apparent wind velocity ($\vec{U}_\infty$) distribution displays consistency. Within the perturbed zone, both the magnitude and direction of the apparent wind deviate from the sought free-stream conditions. Thus, measuring the reference wind velocity too close to the vehicle can induce a significant bias in C_D . This is quantified by differentiating **equation 1** with respect to U_∞ to obtain the relative error on C_D induced by a bias in U_∞ :

$$\epsilon(C_D) \approx \frac{1}{C_D} \frac{\partial C_D}{\partial U_\infty} \delta U_\infty = -2 \frac{\delta U_\infty}{U_\infty} = -2 \epsilon(U_\infty) \quad (2)$$

equation 2 reveals that a 10% underestimate of the free-stream speed (U_∞) yields a 20% overestimate of C_D . As can be inferred from the drawing of **Figure 1**, a velocity measured along the centreline within the perturbed zone, *i.e.* at a distance less than d_∞ , has a lower magnitude than the free-stream speed and a yaw angle of larger absolute-value. This bias is illustrated in the inset graph, emphasizing the vertical shift of the biased C_D -curve and its reduced yaw angle sensitivity (*i.e.* its flattening). Such an error is not amenable to a sound evaluation of a vehicle's aerodynamic performance.

[‡]In theory, C_D is also Reynolds-number-dependent. However, above a threshold value (typically $Re_\infty \gtrsim 1 \cdot 10^6$ based on vehicle width), C_D can be considered independent of Re_∞ [K. R. Cooper (1985) ; Storms et al. (2004)]

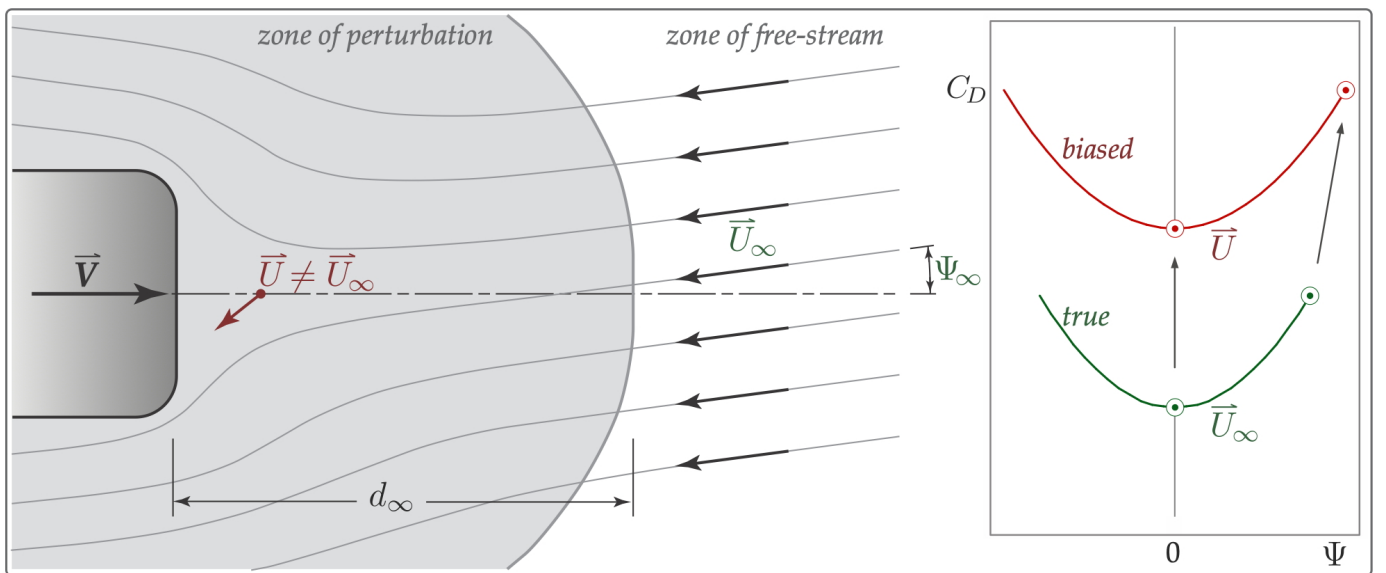


Figure 1. Schematic diagram of the flow field surrounding a traveling vehicle and of the C_D -bias resulting from the inadequate measurement of the reference apparent-wind velocity too close to the vehicle.

The above considerations, combined with the potential of the FSA technology to resolve the "free-stream deficiency", prompted [Stadler Rheintal AG](#) of Switzerland to solicit the NRC Aerodynamics Laboratory to conduct an extensive coasting-test campaign using the FSA in 2019, in Sweden [[Tanguay \(2019\)](#) ; [Cochard & Tanguay \(2020\)](#)]. The quality of the test results, despite the presence of strong winds, convinced Stadler to acquire the first commercial FSA prototype in 2022. Stadler utilizes its FSA system on a regular basis for all coasting-tests of its trains to obtain reliable evaluations of energy consumption in any environmental condition.

2. The quest for free-stream conditions

Although wind tunnel testing and computational fluid dynamics (CFD) are used to evaluate the aerodynamic performance of surface vehicles, these two methods provide aerodynamic simulations that do not replicate the actual wind environment that vehicles experience during operation. For example, in the wind tunnel, the free-stream wind speed and yaw angle are approximated by applying empirical blockage and wake corrections ([Hackett & Cooper, 2001](#)) to compensate for the constraining effect of the wind tunnel boundaries. Notwithstanding, the wind tunnel is the ideal tool to quantify differentials (e.g. ΔC_D) resulting from changes in vehicle configuration, but the absolute values of the aerodynamic coefficients (e.g. C_D) are biased due to the aforementioned simulation deficiency ([Patten et al., 2012](#)). This shortcoming is best exposed by [R. K. Cooper \(1980\)](#):

"The true effects of wind shear, turbulence and the relative motion between the model and ground can be correctly simulated only by a moving-model experiment"

Although track-testing offers the potential to obtain reliable absolute values of C_D in real operating conditions, the main challenge is indeed the characterization of the turbulent wind environment, in particular the reference free-stream velocity ([Tanguay, 2016](#)) which underpins the coefficient of aerodynamic drag (see *equations 1* and *2*). Over the years, several attempts at measuring or evaluating free-stream wind velocity forward of traveling vehicles were undertaken. Two examples are illustrated in *Figure 2*. In the experiments described by [R. K. Cooper \(1980\)](#), a boom-mounted anemometer was used on a $1/5^{th}$ -scale moving-model of a train to "estimate" free-stream velocity. Cooper's own analysis reveals the shortcomings of this approach:

"The aerodynamic forces will depend on the boundary layer profile and turbulence intensity of the wind and the gradient of wind velocity in the direction of travel. The flow is strongly affected by embankments, viaducts and topographical features (hills, valleys, etc) and ground roughness (trees, hedges, buildings, etc.) ... In any case it is expected that they would introduce much smaller errors than those associated with the estimation of the reference wind speed"

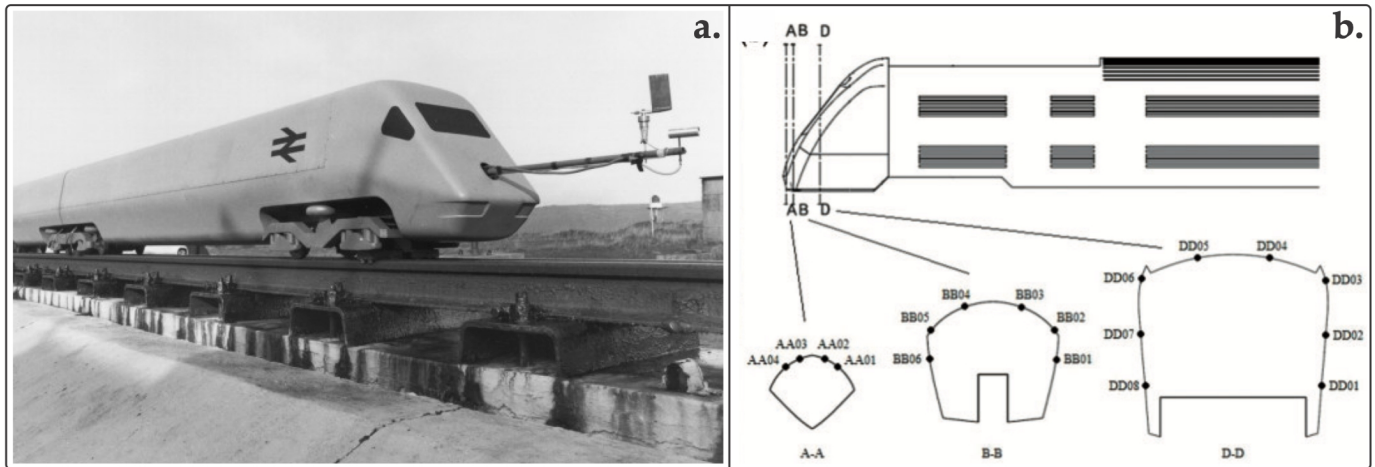


Figure 2. Alternative methods to estimate free-stream velocity **a.** Boom-mounted anemometer on a one-fifth scale passenger train model at the Pendine test track in South Wales (UK) (R. K. Cooper, 1980) **b.** Nose of a wind-tunnel train model equipped with pressure taps (Cheli et al., 2016). Both images reproduced with permissions.

A similar approach was implemented by DB Systemtechnik[§] whereby a boom-mounted wind probe was installed off the nose of a full-scale train operating on the national railway network, as shown in **Figure 3**. Although this set-up was believed to enable the direct sensing of free-stream velocity, the distance to free-stream (d_∞) is not physically attainable by means of a boom, as will be shown below. Besides, such an appendage would only be authorized by railway authorities on a very exceptional basis (Cochard, 2019), due to the risk of breakage and accidents. Such a massive boom also induces its own drag and perturbs the flow field. Thus, this solution is not practical for the aerodynamic testing of trains on national railways. Notwithstanding, a comparable method was implemented in the framework of the TRANSAERO project (Lienhart, 2002).

A less intrusive, alternative method proposed and tested by Cheli et al. (2016) is illustrated in **Figure 2b**, showing the nose of a scaled train model equipped with an array of pressure taps, effectively transforming the nose into a multi-hole probe responding to the direction and magnitude of the local apparent wind. This exact distribution of pressure taps would also be replicated on the real train, such that pressure coefficients obtained at full-scale would be converted to free-stream speed (U_∞) and yaw angle (Ψ_∞). Although the approach deserves some merit, the fact that the pressure-coefficient database is derived from model-scale wind tunnel results raises some doubts and concerns:

- The design and fabrication of an elaborate scale-model is required for each train
- Do the reference static pressures (p_∞) correspond between full- and model-scale ?
- What is the effect of the Reynolds number discrepancy: model Re_∞ is 7% of full-scale ?
- What is the effect of the surrounding terrain (e.g. embankment) on the pressure signature ?

[§]DB: Deutsche Bahn, state-owned national railway operator of Germany



Figure 3. Boom-mounted wind probe used on the German national railway (1982). Title translation: "Measurement of the dynamic pressure from the driver's cabin". [Image graciously provided by Dr. Thorsten Tielkes (DB Systemtechnik, Germany)]

More recently, [Tanguay \(2016\)](#) devised a technique based on Taylor's "frozen turbulence" hypothesis ([Taylor, 1938](#)) which remains a reference for converting temporal turbulent signals into spatial propagation of turbulent patterns. The approach is illustrated in the drawing of **Figure 4**. The method relies on ground-based anemometric measurements on the windward side of the track and on the use of an anemometer mounted on the nose of the test vehicle measuring $\vec{U}_a(t)$. A turbulent wind pattern $\vec{W}(t)$ measured at point **A** is advected toward point **C** at the mean wind speed $\bar{W}$ and at angle γ relative to the vehicle travel direction. At the instant when the vehicle-mounted anemometer reaches point **C**, an instantaneous value of the wind vector $\vec{W}(t)$ originating from a measurement recorded earlier at point **A** is obtained, providing one calibration point $(U_a, \Psi_a) \Rightarrow (U, \Psi)$ by virtue of the simple vectorial equation:

$$\vec{U} = \vec{W} - \vec{V} \quad (3)$$

Vector $\vec{U}$ is the unperturbed (free-stream) velocity correcting the biased wind velocity $\vec{U}_a$ measured by the vehicle-mounted anemometer. One calibration point is obtained every time the vehicle passes by a weather station. The calibration function displayed in the inset graph of **Figure 4** was obtained by post-processing of the entire data set. This specific result indicates that the vehicle

anemometer, located 3.3 metres forward of the vehicle nose, sensed a wind speed that is about 11% lower than the free-stream value. This correction method has been the standard at the NRC Aerodynamics Laboratory since 2013. Notwithstanding, the technique has its drawbacks and the scatter of the data presented in the inset graph points to some limitations:

- The assumption that the turbulent patterns travel at the local mean wind speed is not a certainty [[Higgins et al. \(2012\)](#) ; [Horst et al. \(2004\)](#) ; [Powell & Elderkin \(1974\)](#)]
- The persistence and consistency of a turbulent pattern is not guaranteed for long fetches
- Ground-based anemometers and a vehicle-mounted anemometer are necessary

Through the present work, as will be shown below, it was discovered that the distance to free-stream is considerable, such that no vehicle-nose-mounted boom is sturdy enough to provide a steady and safe support to a wind probe at this distance. This realization provided the impetus to develop the FSA solution, designed specifically to probe the free-stream velocity directly, without assumptions nor compromise.

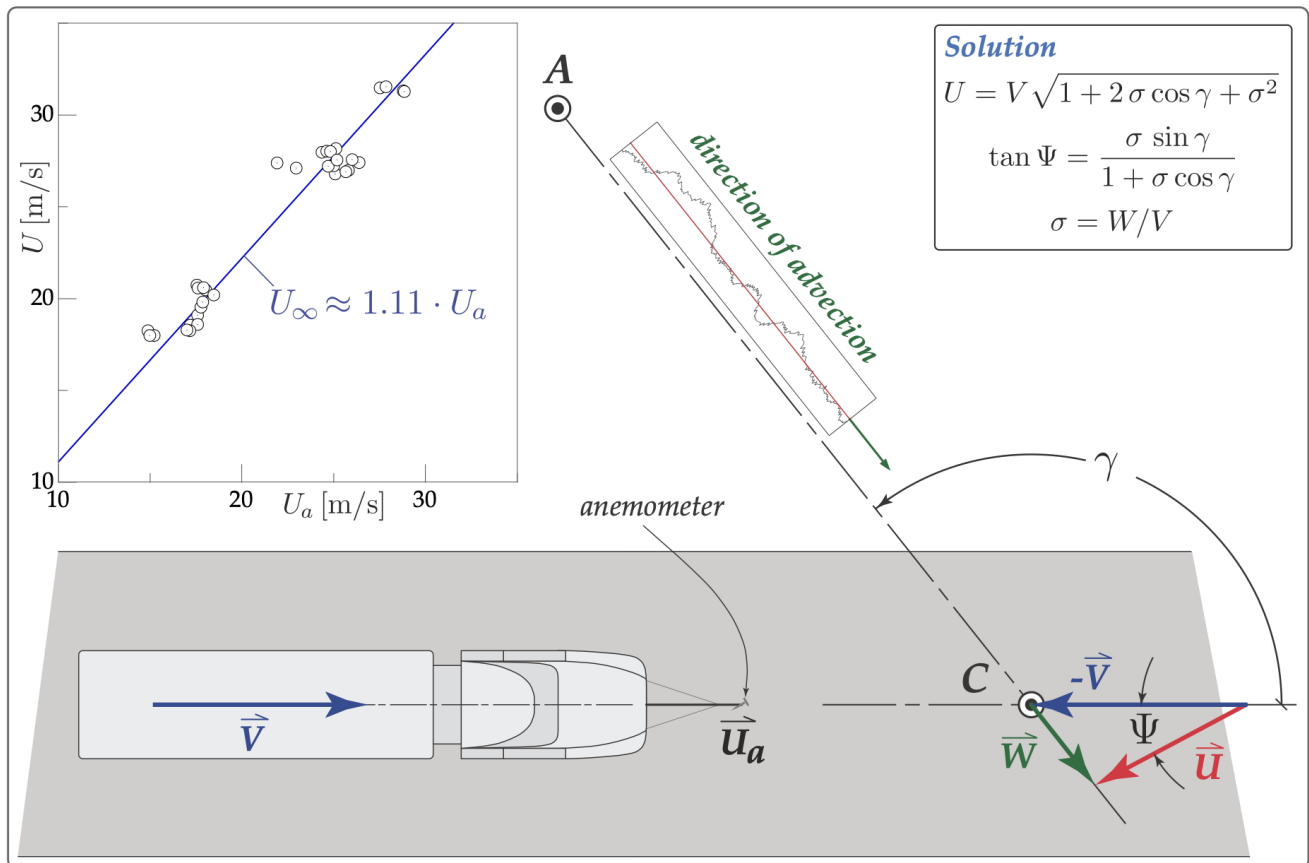


Figure 4. Schematic of the application of Taylor's hypothesis for the calibration to free-stream of a vehicle-mounted anemometer, with key results ([Tanguay, 2016](#))

3. The FSA technology

The FSA is a modular, non-intrusive laser-Doppler velocimetry system designed specifically to probe the apparent wind velocity forward of traveling vehicles, within the “free-stream region”, *i.e.* beyond the vehicle’s zone of aerodynamic perturbation, as illustrated in the drawing of **Figure 5a**. In practice, as will be shown below, the flow field is not as idealized as displayed in this diagram because the turbulent wind is characterized by space-time fluctuations, but the concept of free-stream boundary remains valid. The red segments of the two FSA laser beams depict the two independent sensing zones of the FSA, each located beyond the free-stream boundary. Because the overwhelming contribution to the apparent wind results from the vehicle speed itself (horizontal) and because the vertical component of turbulent fluctuations is attenuated near the ground [[Watkins et al. \(2006\)](#) ; [ESDU International \(1986\)](#)], the free-stream flow field at vehicle mid-height is considered as two-dimensional and horizontal. On this basis, only two non-parallel laser beams are required to resolve the free-stream velocity vector $\vec{U}_\infty$ (*i.e.* magnitude U_∞ and direction Ψ_∞) in a horizontal plane. If the flow were three-dimensional, *e.g.* for an aircraft or drone, then a third channel (and FSA laser beam) would be necessary. Before delving into more details, the schematics of **Figure 5b** and **5c** provide information on the aiming of the FSA laser beams. With the objective of characterizing the oncoming free-stream flow field, the two FSA sensing zones are positioned at range $R > d_\infty$ from the vehicle nose and centred about the centroid of the vehicle frontal area, *i.e.* at vehicle mid-height and on either side of the vertical symmetry plane, as shown in **Figure 5b,c**. The side view emphasizes the pitch angle α . In practice, each FSA laser beam is characterized by its own pitch angle which is measured separately: α_p on the port side and α_s on

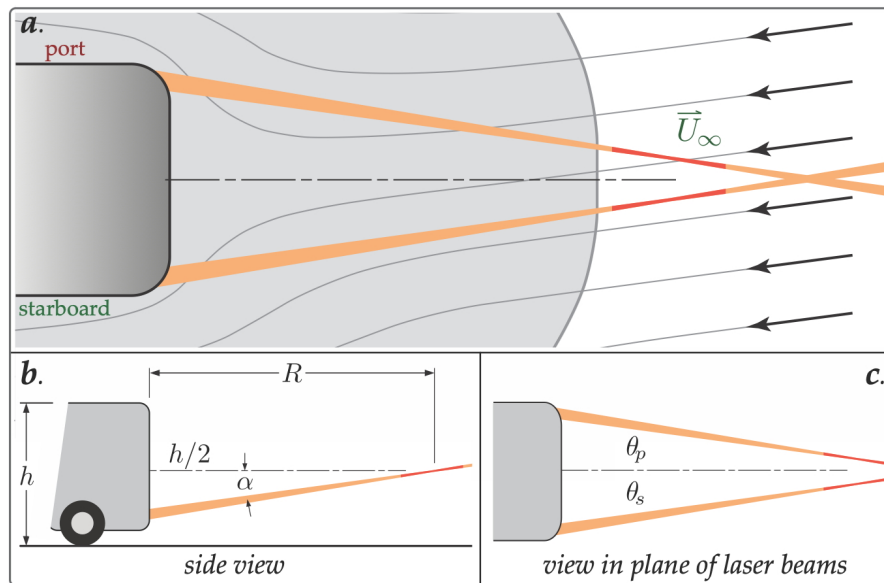


Figure 5. Schematic of the FSA measurement configuration and definition of the laser beam aiming angles.

the starboard side[¶]. Similarly, as shown in the diagram of *Figure 5c*, the angles θ_p and θ_s are the measure of the convergence of the two laser beams toward the FSA sensing area.

The simplified diagram of **Figure 6** depicts the operating principle of the FSA. The ultra-coherent laser emits in the short-wave infrared region of the electromagnetic spectrum, at a wavelength of $\lambda_e \approx 1550$ nm. This is the standard wavelength used in high-performance fibre-optic communications due to the low signal loss through silica composing the core of the optical fibre. Besides, the availability of a wide range of fibre-coupled components at moderate cost made this eye-safe wavelength^{||} the ideal choice for this application. The light emitted by the laser is evenly distributed between the two channels. For each channel (losses aside), about 99% of the input laser power is conveyed via a polarization-maintaining fibre-optic cable to the objective which focuses

¹¹To avoid the left/right ambiguity, port/starboard are used, consistent with these unequivocal maritime terms

^{||}Unlike laser wavelengths around 1 μm , the FSA wavelength of 1.55 μm has a much higher maximum permissible exposure because it is retina-safe.

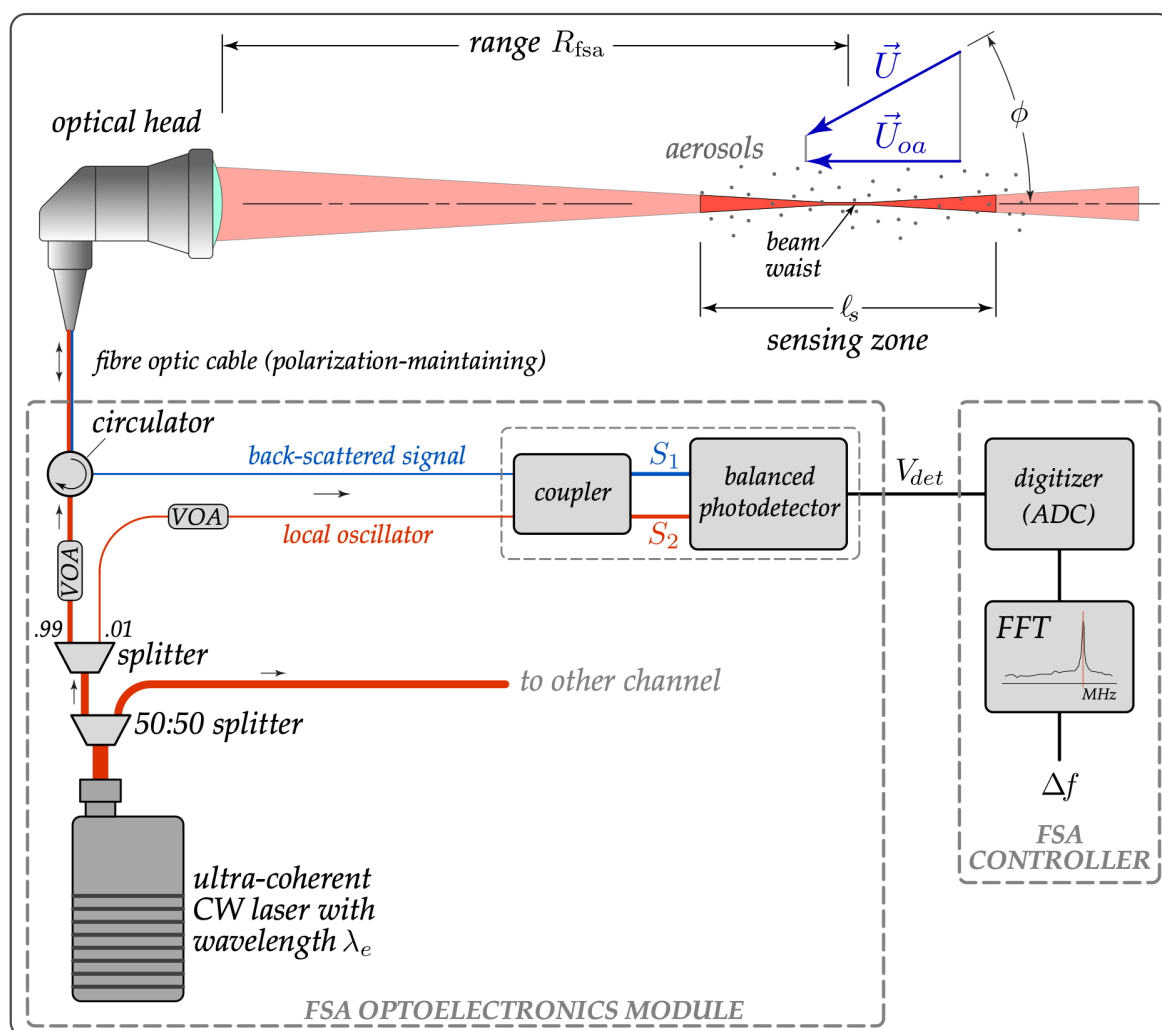


Figure 6. Schematic diagram of the FSA operational principle.

the light toward the sensing zone, with the waist of the laser beam located at range R_{fsa} . The remaining 1% will be used as a reference called the local oscillator. When aerosols traverse the FSA sensing zone, a minute fraction of the incident light is back-scattered toward the objective, where it is focused into the same optical fibre, thereby following the reverse path. The optical circulator combining a polarizing beam splitter and a quarter-wave plate has the ability to redirect the light to the coupler, where it is combined with the local oscillator. By virtue of the Doppler effect, the frequency of the back-scattered light is greater than the frequency of the emitted light, thus the composite optical signal is characterized by a beat frequency equal to the difference between the frequencies of the back-scattered light and local oscillator, *i.e.* the Doppler frequency shift Δf . This optical signal is then converted to a fluctuating analogue voltage by the photodetector and digitized by the acquisition module. Of note, the FSA uses a homodyne detection scheme, meaning that it cannot differentiate whether the aerosols are moving toward or away from the optics. This being said, the vehicle speed is typically much greater than the wind speed, resulting in a relative wind moving toward the optics.

As illustrated in **Figure 6**, the Doppler frequency shift Δf results from the apparent velocity ($\vec{U}$) of the particle traveling toward the vehicle at angle ϕ relative to the FSA optical axis. This frequency is proportional to the projection of the velocity vector $\vec{U}$ onto the optical axis and is given by:

$$\Delta f = 2 \frac{U_{oa}}{\lambda_e} = 2 \frac{U \cos \phi}{\lambda_e} \quad (4)$$

The factor of two in **equation 4** results from two successive frequency shifts. First, the aerosol particle receives light that is frequency-shifted by U_{oa}/λ_e because of its relative motion toward the light source. Similarly, the light that is back-scattered toward the objective emanates from the particle traveling at the effective relative speed U_{oa} , thereby inducing a second frequency shift of the same magnitude. The Doppler frequency shifts detected on both channels independently, provide two optical-axis velocity vectors ($\vec{U}_{oa}^{(p)}$ and $\vec{U}_{oa}^{(s)}$) which, when projected onto the horizontal plane, are combined to yield the free-stream velocity vector $\vec{U}_{\infty}$. Although the FSA uses a continuous-wave (CW) laser, the FSA signals are actually broken down into contiguous temporal segments of user-selectable duration (Δt_d) called detection periods. During each such period (typically 100 ms), thousands of power spectra are computed and Doppler-peaks are searched in real-time. The Doppler frequency $\Delta f(i)$ associated with the i^{th} detection period is the weighted mean of all valid peak frequencies detected.

Of note, the maximum speed that the FSA can detect is limited by the sampling rate of the digitizer module. At the maximum sampling rate of 250 MS/s, the maximum frequency that can be measured is 125 MHz and corresponds to a speed along the FSA optical axis, of $U_{oa}^{(max)} \approx 96.9$ m/s or about 349 km/h, in accordance with **equation 4**. In general terms, the maximum detectable speed and the speed resolution (dU_{oa}) are given by:

$$U_{oa}^{(max)} = \frac{f_s \cdot \lambda_e}{4} \quad \text{and} \quad dU_{oa} = \frac{df \cdot \lambda_e}{2} \quad (5)$$

Where f_s and df are the user-selectable sampling frequency and frequency resolution, respectively. The list of available sampling frequencies and associated maximum speeds and optimal resolutions are presented in **Table 1**.

Table 1. FSA sampling frequencies and associated speeds and resolutions

<i>conf.</i>	f_s [MS/s]	$U_{oa}^{(max)}$ [m/s]	$U_{oa}^{(max)}$ [km/h]	df [kHz]	dU_{oa} [m/s]
A	50	19.4	69.8	12.2	0.009
B	100	38.8	139.5	24.4	0.019
C	125	48.4	174.4	30.5	0.024
D	200	77.5	279.0	48.8	0.038
E	250	96.9	348.8	61.0	0.047

It must be emphasized that the signal received by each FSA channel during one detection period (time interval Δt_d) does not result from particles traversing the laser beam at a single-point (*i.e.* the beam waist). Rather, it is the result of one or several particles crossing the detection zone, which is a hyperboloidal volume of length ℓ_s centred about the beam waist position, as illustrated in **Figure 6**. The longitudinal extent of the sensing zone (ℓ_s) is a linear function of the FSA range (R_{fsa}) which the user sets using the focusing knob of each FSA objective. The greater longitudinal extent of the FSA detection volume (> 1 metre) at ranges typical of train testing, affords the advantage of increasing the probability of detecting a larger number of valid Doppler peaks (increased sensitivity), as the FSA laser beams travel through the air.

As shown in **Figure 7**, the FSA was designed with modularity in mind. It is composed of four main elements: a pair of adjustable-focus optical heads, a pair of polarization-maintaining fibre-optic cables, the optoelectronic module and the FSA controller. The optoelectronic module houses the ultra-coherent continuous-wave (CW) laser, two fibre-coupled optical circuits, two photodetectors and the electronic control circuit. The FSA controller is a Windows-based computer running the FSA server software that is communicating with the user's computer via a gigabit ethernet link, receiving commands and sending data for real-time display and local storage. The controller incorporates a dual-channel high-speed digitizer module, an acquisition and control module and a Graphics Processing Unit (GPU) that computes thousands of frequency spectra per second and identifies Doppler frequencies and related statistics in real-time. The GPU is critical because the amount of raw data generated by the digitizer amounts to 60 Gigabytes per minute at $f_s = 250$ MS/s (at 2 bytes per sample). For a typical train coast lasting 20 minutes, this would amount to 1.2 Terabytes of raw data for a single run. In contrast, the pre-processed GPU data, which contains all essential information, streams only about 1.4 Megabytes of data per minute, or only 28 MB for the same run, *i.e.* about 0.002% of the raw data throughput.

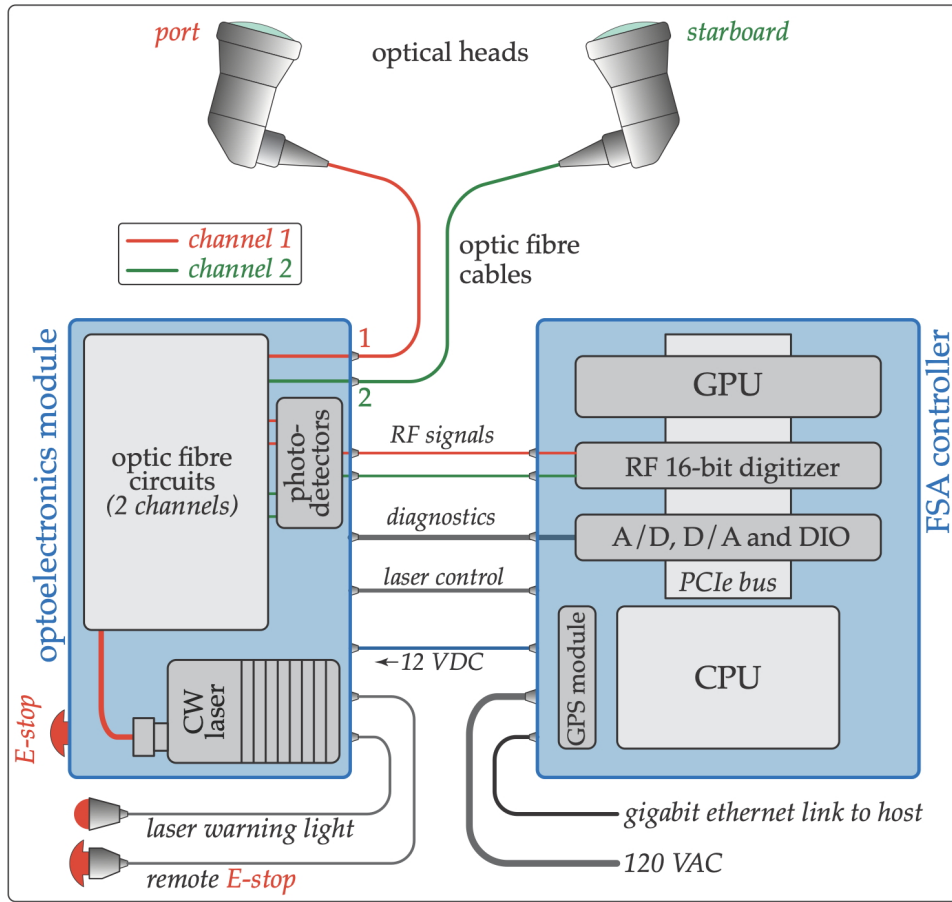


Figure 7. Configuration of the FSA

The FSA controller also includes a GPS module whose data is transmitted to the host computer. The GPS-derived vehicle speed is used as a trigger to turn the FSA laser on or off, upon crossing of a user-defined speed threshold, for laser-safety reasons. The physical elements of the FSA are shown in the two photographs of **Figure 8**. The FSA controller and optoelectronic module are rack-mount components fitting in a standard 19-inch instrumentation rack enclosed within a sturdy, protective Pelican case. The two long-range objectives shown in **Figure 8b** are sufficiently compact to be concealed behind a vehicle bumper, *e.g.* in lieu of fog lamps.

The FSA was designed to achieve a detection rate of at least ten valid Doppler peaks per second and per channel, that is, ten pairs of $\{U_\infty, \Psi_\infty\}$ every second. But the achievable detection frequency (f_{det}) is modulated by the aerosol concentration. For each channel, the continuous FSA signal is broken down into contiguous “detection periods” of duration T_{det} (typically 100 ms). Although the Doppler frequency is the key value required to calculate wind velocity, the amplitude of the optical signal received is its underlying determinant, in the form of the Signal-to-Noise Ratio (SNR) which is used to identify valid spectral peaks. This is illustrated in the simplified diagram of **Figure 9a** defining graphically the SNR . The FSA computes in real-time, several thousands of spectra per second and calculates spectral averages in order to attenuate the noise. The averaged

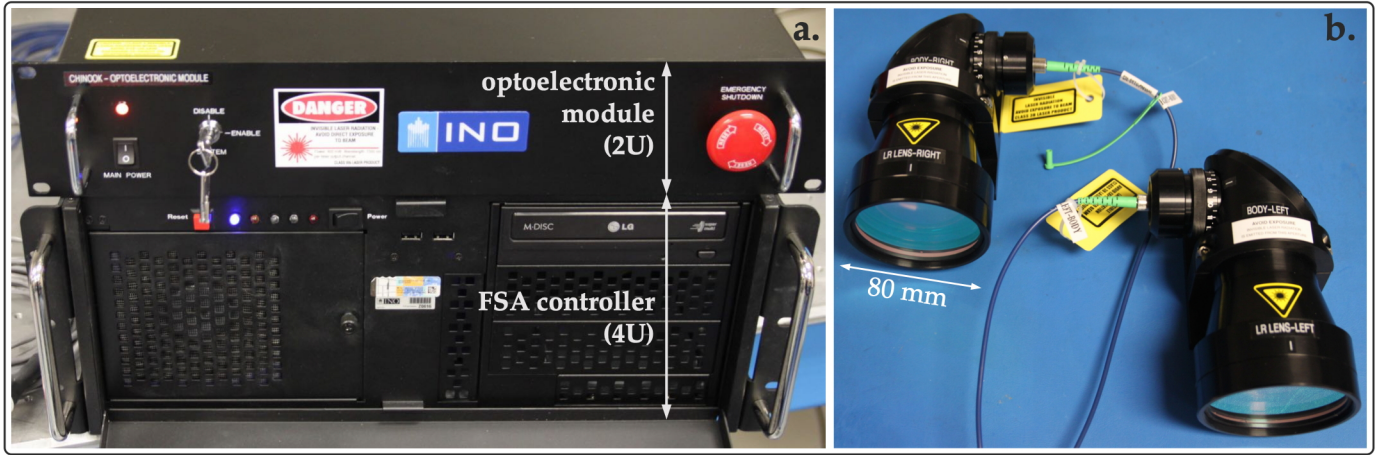


Figure 8. The key elements of the FSA

spectrum depicted in the diagram emphasizes a peak of amplitude A_{pk} occurring at frequency Δf_{pk} . The validity of a spectral peak is quantified by the extent of its emergence above the spectral noise characterized by standard deviation σ . It can be expected that the spectral noise is characterized by a gaussian distribution, which means that a Signal-to-Noise Ratio of $SNR_{pk} \approx 5$ would imply a peak at the noise margin. Consequently, the SNR -threshold applied to discern valid peaks is typically set to a value of 6 or more. The time series of free-stream velocity are obtained by means of a statistical analysis of the $\{\Delta f_{pk}, SNR_{pk}\}$ sets of all detection periods, using the FSA post-processing software.

Figure 9b presents a typical example of peaks that were detected during a vehicle coasting test, for one specific 100 ms period on one FSA channel. The cluster of 25 Doppler peaks is a characteristic signature of aerosols. And the distribution width of about 2 m/s attests to the turbulent nature of the wind. For each channel, a single value of U_{oa} is calculated per detection period. As shown

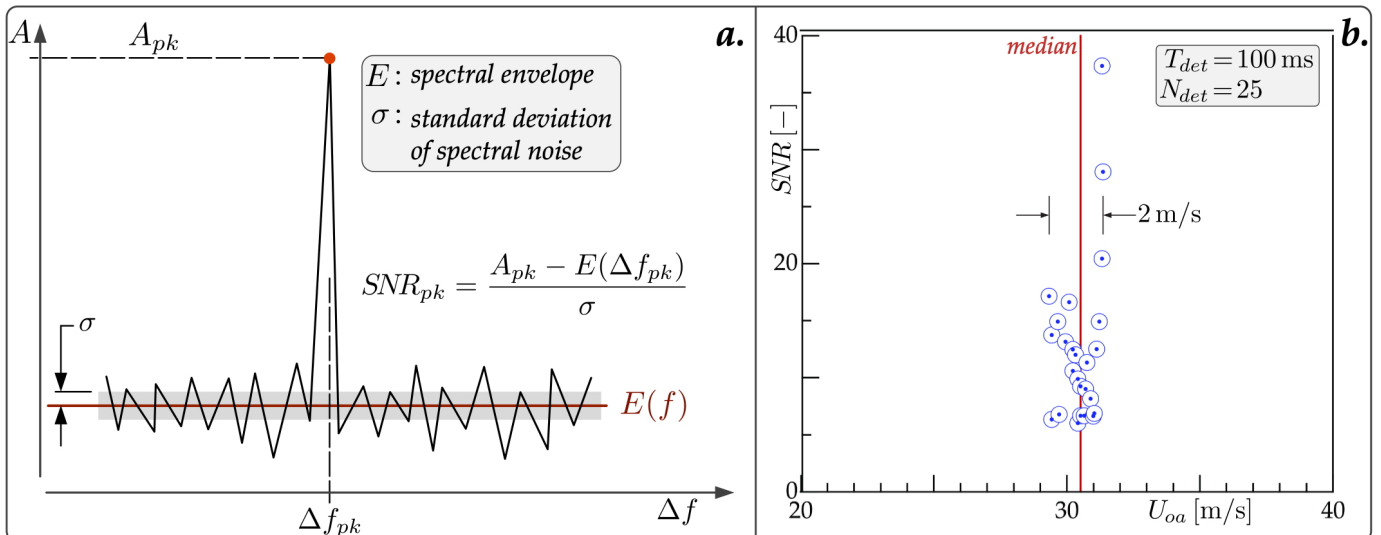


Figure 9. a. Definition of the Signal-to-Noise ratio (SNR) b. Cluster of Doppler peaks typical of an aerosol signature.

in **Figure 9b**, the median value can be used, but other options are available via the FSA post-processing software. Of note, for this specific case, the large number of Doppler peaks is amenable to increasing the detection frequency in order to improve the temporal resolution of $\vec{U}_\infty(t)$.

Because the orientation of each FSA laser beam relative to the vehicle axis is known with precision via a pre-calibration (pitch and convergence angles), the velocity vector $\vec{U}_\infty$ is a known function of the Doppler frequency shifts detected on the port (p) and starboard (s) FSA channels, of the four aiming angles defined in **Figure 5** and of the laser wavelength:

$$\vec{U}_\infty = F(\Delta f_p, \Delta f_s; \alpha_p, \theta_p, \alpha_s, \theta_s, \lambda_e) \quad (6)$$

The FSA measurement uncertainty was examined analytically by determining the sensitivity of the magnitude (U_∞) and direction (Ψ_∞) of the free-stream wind velocity vector to variations in the underlying parameters included in **equation 6**. The first consideration pertains to **equation 4** relating the FSA optical-axis speed to the laser wavelength and the Doppler frequency shift. The laser wavelength has been a constant since the FSA prototype was first commissioned. In 2021, the FSA laser wavelength was verified at the NRC Metrology Research Centre, confirming the stable value of $\lambda_e = 1550121.1 \text{ pm} \pm 0.3 \text{ pm}^{**}$. Hence, λ_e is a constant known within 0.2 parts per million and is therefore not a source of uncertainty. Similarly, the frequency base of the FSA digitizer was verified, confirming that frequencies are measured within about 2.1 parts per million. The limiting factor is the frequency resolution (df) dictated by the selected digitizer sampling frequency combined with the number of spectral bins, as shown in **Table 1**. Thus, the uncertainty in the measurement of the Doppler frequency shift is simply given by:

$$\delta\Delta f = df \quad (7)$$

The other parameters contributing to measurement uncertainty are the four FSA aiming angles. **Figure 10** helps conceptualize the angle measurement process involving the use of the FSA alignment modules (**10b**) emitting fine visible laser beams^{††}. Each alignment module is clamped to its dedicated FSA objective via a precision-milled collar ensuring that the axis of its red laser beam is coincident with the optical axis (infrared) of the FSA objective. The schematic of **Figure 10a** delineates the key features of the FSA alignment target. The horizontal reference laser beam (bottom) is propagating along the vehicle symmetry plane, with the FSA alignment target normal to this beam. Once the FSA aiming directions are fixed, the target is installed at a specific longitudinal station ($x = x_1$ in **Figure 10a**) and the (y, z) -coordinates of the two impact points on the target are measured. The operation is repeated after moving the target longitudinally to its second position, at some distance D (e.g. $x_2 = x_1 + D$). The resulting four points enable the calculation of the four FSA aiming angles. For tests of trains or heavy-duty road vehicles, the distance between the two target planes is typically $D \approx 10$ metres and the uncertainty in the measurements of the (y, z) -coordinates was evaluated to $\pm 25 \text{ mm}$ (a conservative estimate). The measurement uncertainties

**pm: picometre (10^{-12} m or 0.001 nm)

††beam with a wavelength of 635 nm (bright red)

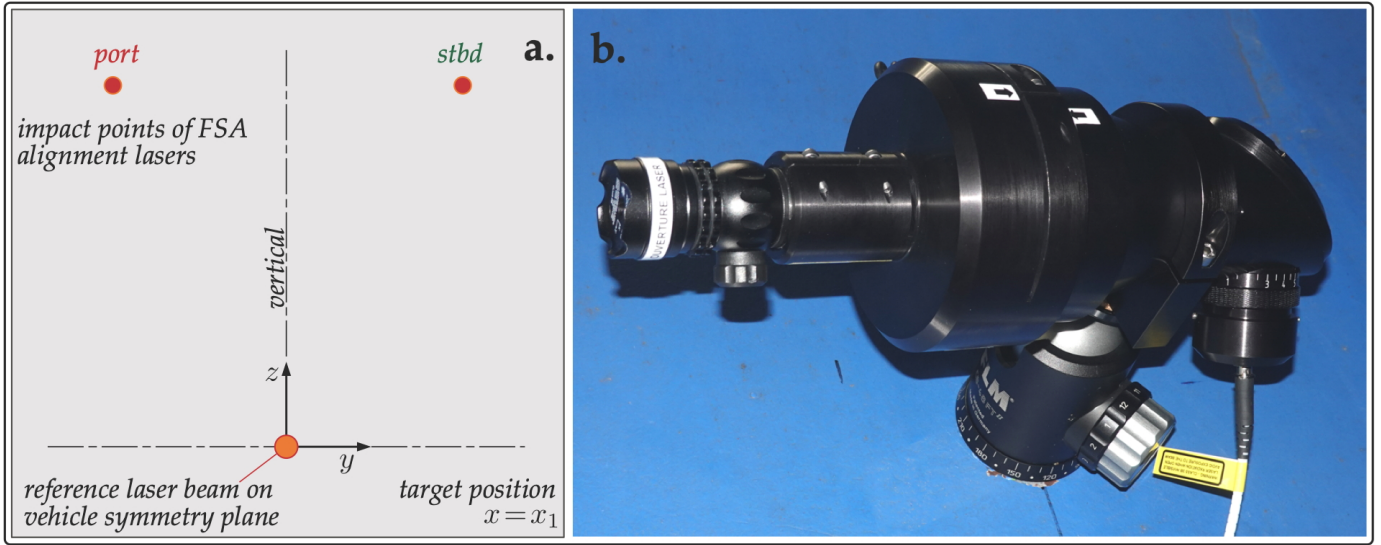


Figure 10. a. Schematic of the alignment target b. Alignment laser (visible light) coupled to FSA objective.

associated with the six underlying parameters are compiled in **Table 2**. For the sake of simplicity, the uncertainty analysis considered that both pitch angles were equal and that both convergence angle were also equal^{††}, that is:

$$\alpha = \alpha_p = \alpha_s \quad ; \quad \theta = \theta_p = \theta_s \quad (8)$$

Besides, the aiming angles were set to values typical of such vehicle tests. The uncertainty analysis proceeds by considering that the underlying measurements are the source of random and independent errors (uncertainties) propagating via **equation 6** to induce a composite uncertainty in $\vec{U}_\infty$. Therefore (Lyons, 1991), the underlying uncertainties are added in quadrature, as follows:

$$\Delta U_\infty = \sqrt{\sum_{i=1}^6 \left[\frac{\partial U_\infty}{\partial \mathfrak{Y}_i} \delta \mathfrak{Y}_i \right]^2} \quad \text{and} \quad \Delta \Psi_\infty = \sqrt{\sum_{i=1}^6 \left[\frac{\partial \Psi_\infty}{\partial \mathfrak{Y}_i} \delta \mathfrak{Y}_i \right]^2} \quad (9)$$

^{††}Note that this is typically the case, within a fraction of a degree.

Table 2. Underlying parameter values and uncertainties

<i>i</i>	parameter	value	uncertainty		units
1	Δf_p	variable	$\pm \delta f$	± 0.061	[MHz]
2	Δf_s	variable	$\pm \delta f$	± 0.061	[MHz]
3	α_p	5	$\pm \delta \alpha$	± 0.15	[°]
4	θ_p	5	$\pm \delta \theta$	± 0.15	[°]
5	α_s	10	$\pm \delta \alpha$	± 0.15	[°]
6	θ_s	10	$\pm \delta \theta$	± 0.15	[°]
These values pertain to train and HDV tests					

Where $\mathfrak{V}_i$, $i = 1, \dots, 6$ represents the six parameters of **Table 2** and the partial derivatives are applied to **equation 6**. Regrouping terms with respect to the three underlying measurement uncertainties $(\delta f, \delta \alpha, \delta \theta)$, the uncertainty level of the free-stream speed is given by^{§§}:

$$\begin{aligned} (\Delta U_\infty)^2 &= \left[\left(\frac{\partial U_\infty}{\partial f_p} \right)^2 + \left(\frac{\partial U_\infty}{\partial f_s} \right)^2 \right] \delta f^2 + \left[\left(\frac{\partial U_\infty}{\partial \alpha_p} \right)^2 + \left(\frac{\partial U_\infty}{\partial \alpha_s} \right)^2 \right] \delta \alpha^2 + \left[\left(\frac{\partial U_\infty}{\partial \theta_p} \right)^2 + \left(\frac{\partial U_\infty}{\partial \theta_s} \right)^2 \right] \delta \theta^2 \\ &= E_f^2(U_\infty) + E_\alpha^2(U_\infty) + E_\theta^2(U_\infty) \end{aligned} \quad (10)$$

Where $E_\kappa^2(\eta)$ represents the contribution of parameter κ to the total uncertainty squared of variable η . Similarly, the uncertainty level of the free-stream yaw angle is defined as follows:

$$\begin{aligned} (\Delta \Psi_\infty)^2 &= \left[\left(\frac{\partial \Psi_\infty}{\partial f_p} \right)^2 + \left(\frac{\partial \Psi_\infty}{\partial f_s} \right)^2 \right] \delta f^2 + \left[\left(\frac{\partial \Psi_\infty}{\partial \alpha_p} \right)^2 + \left(\frac{\partial \Psi_\infty}{\partial \alpha_s} \right)^2 \right] \delta \alpha^2 + \left[\left(\frac{\partial \Psi_\infty}{\partial \theta_p} \right)^2 + \left(\frac{\partial \Psi_\infty}{\partial \theta_s} \right)^2 \right] \delta \theta^2 \\ &= E_f^2(\Psi_\infty) + E_\alpha^2(\Psi_\infty) + E_\theta^2(\Psi_\infty) \end{aligned} \quad (11)$$

Figure 11 presents key results obtained by applying **equation 10**. The absolute uncertainty in free-stream speed (**11a**) is displayed as a function of Ψ_∞ for five values of U_∞ , revealing a systematic rise in the overall uncertainty level with increasing speed. The uncertainty is below 0.09 m/s for all speeds and for yaw angles below 15° . The relative contributions of the three fundamental uncertainty levels (f, α, θ) are illustrated in **Figure 11b**, highlighting the negligible impact of the pitch angle (α) on the overall uncertainty level. For $U_\infty = 30$ m/s, the contribution of the frequency resolution (δf) dominates at low yaw angles, but diminishes in favour of $E_\theta^2(U_\infty)$ for higher values of Ψ_∞ . This trend intensifies with increasing speed, explaining the fan-shaped curves of **Figure 11a**. The relative uncertainty level, $\epsilon(U_\infty)$, is displayed in **Figure 12**, emphasizing its expected reduction with increasing free-stream speed. For yaw angles below 15° and speeds above 30 m/s, the relative uncertainty remains below 0.25%.

Finally, the absolute uncertainty in free-stream yaw angle is illustrated in **Figure 13a**, delineating the reduction in $\Delta \Psi_\infty$ with increasing free-stream speed and the moderate influence of Ψ_∞ . For speeds above 30 m/s, the uncertainty level remains below 0.4° but exceeds 1° for speeds below 10 m/s. The foregoing analysis confirmed the remarkable accuracy of the FSA free-stream velocity measurements, for real-life applications onboard surface vehicles. The key characteristics of the FSA system are summarized in **Table 3** below.

^{§§}To simplify the notation, the symbol of the Doppler frequency shift was changed from Δf to f

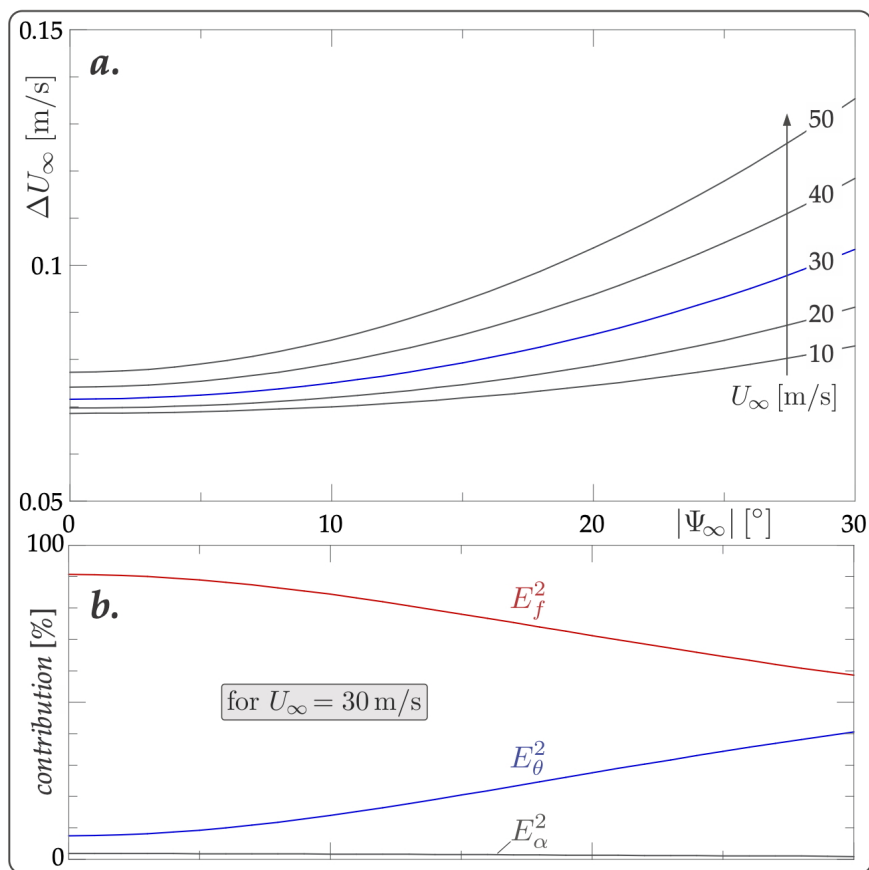


Figure 11. a. Absolute uncertainty in U_∞ b. Uncertainty contributions.

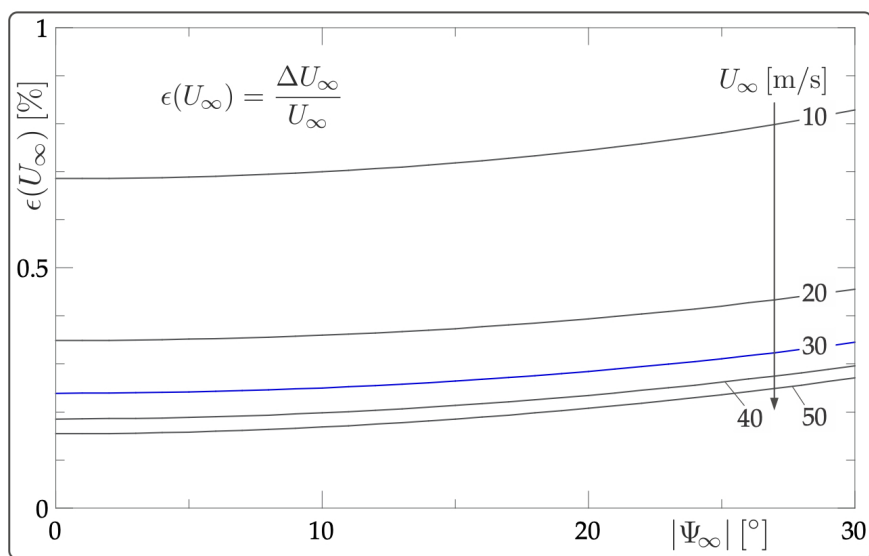


Figure 12. Relative uncertainty in U_∞

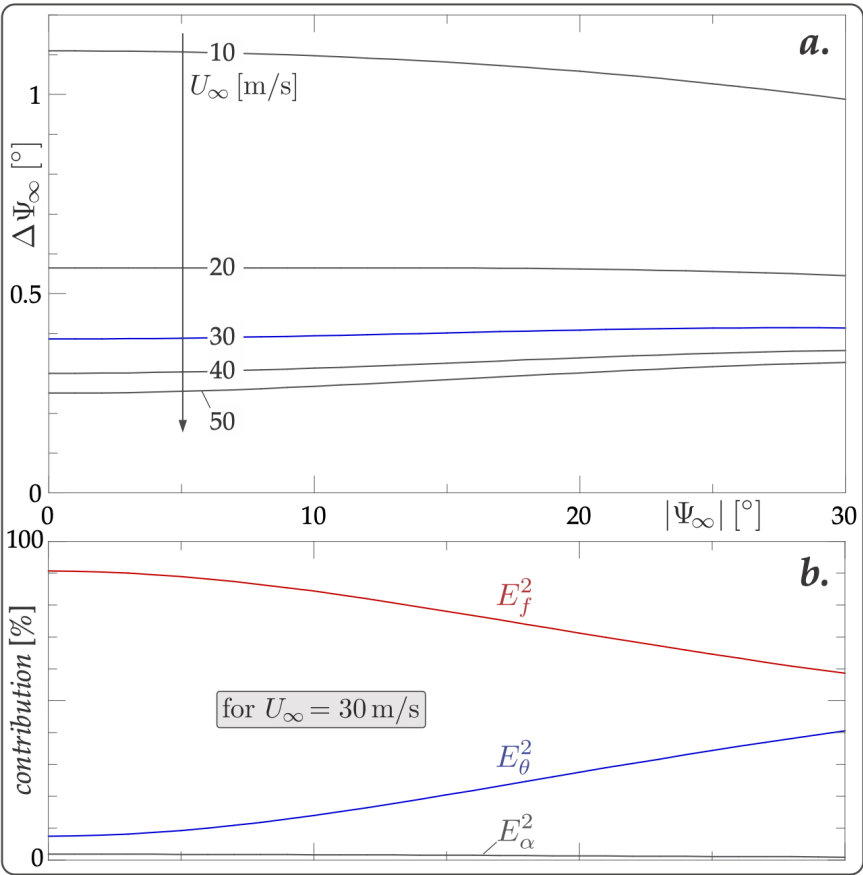


Figure 13. a. Absolute uncertainty in Ψ_∞ b. Uncertainty contributions.

Table 3. Key characteristics of the Free-Stream Anemometer

Laser type	CW, infrared $\lambda_e = 1550$ nm
Detection mode	homodyne
Maximum speed range	$0 < U_{ba} \leq 96.9$ m/s
Maximum yaw angle range	$ \Psi_\infty \lesssim 90^\circ - \theta$
Optimal resolution at maximum speed range	$dU_{ba} = 0.047$ m/s
Aerodynamic diameter of detectable particles	$d_a \gtrsim 1 \mu\text{m}$
Estimated concentration** to achieve $f_{det} = 10$ Hz	$C_{min} \approx 2 \mu\text{g}/\text{m}^3$
Estimated particle-number concentration** to achieve $f_{det} = 10$ Hz	$\mathcal{N}_{min} \approx 500 \text{ L}^{-1}$
** of particles with aerodynamic diameter $d_a \gtrsim 1 \mu\text{m}$	

4. Key validation steps in the laboratory

The NRC Free-Stream Anemometer was subjected to several validation phases in the laboratory, of which four are presented below. The very first experiment was aimed at determining the distance-to-free-stream labeled d_∞ in **Figure 1**. This parameter was of central importance for the design of the FSA, in terms of measurement range, optics design and laser power. This was achieved by conducting PIV^{¶¶} measurements using a $1/10^{th}$ -scale bus model in the NRC Aerodynamics Laboratory's 2 m x 3 m wind tunnel. This model was considered the "worst case" that would yield a conservative value of d_∞ due to its blunt nose and large frontal area. Besides, because viscous effects are confined to the immediate vicinity of the model's surface, it was expected that the results would be scalable because the approach flow forward of the vehicle nose is Reynolds-number-independent (*i.e.* inviscid). Following the image calibrations of several overlapping PIV planes located at model mid-height, several wind-tunnel runs were conducted at a number of yaw angle and wind speed combinations. The key result is presented in **Figure 14** displaying a typical contour plot (isotachs) measured at zero yaw angle, and the corresponding graph of the wind speed profile ($U(x)$) on the centreline ($y = 0$). The value of the distance-to-free-stream was obtained by fitting the asymptotic speed distribution with the following function:

$$U(x) = U_\infty \left(1 - e^{-x/\lambda_u} \right) \quad (12)$$

¶¶PIV: Particle Image Velocimetry

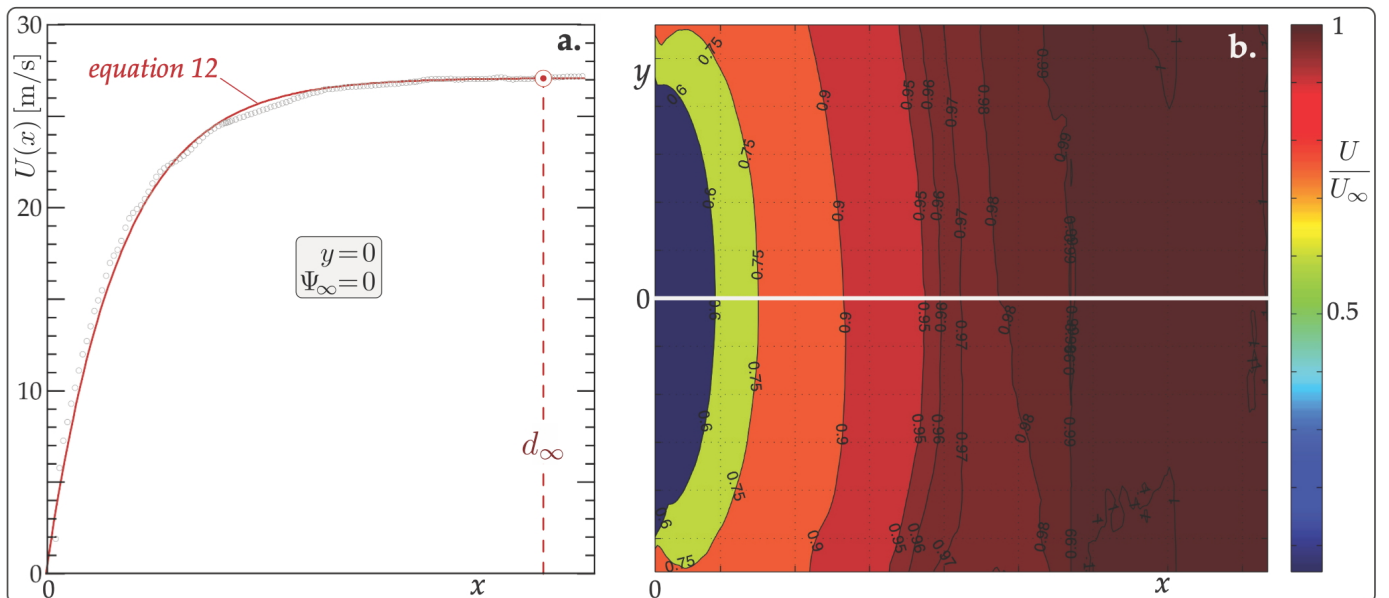


Figure 14. Key result of the PIV experiments conducted in the NRC 2 m x 3 m wind tunnel.

Where λ_u is an unknown length scale. The curve fit (in red) yields the two unknown parameters U_∞ and λ_u . After arbitrarily defining d_∞ as the distance at which $U(d_\infty)/U_\infty = 0.999$, one obtains the following expression for d_∞ ^{***}:

$$d_\infty = -\ln(0.001) \lambda_u \approx 6.9 \lambda_u \quad (13)$$

A second set of experiments was conducted using the “Tube Générateur de Vent”^{†††} (TGV) which was designed specifically for testing the FSA performance. As shown in **Figure 15a**, this open-return wind tunnel is composed of a 100 mm diameter tubular test section and is equipped with cylindrical filters (1 μm porosity) at the inlet and outlet to ensure that aerosols introduced into the airstream remain contained within the facility. The TGV, which can produce wind speeds reaching 45 m/s, was used to subject one FSA laser beam propagating on the tube centreline, to aerosol-containing flows of controlled concentration and size distribution.

The first experiment was aimed at validating the wind speed reported by the FSA, as a means of verifying the proper functioning of its hardware and software. To that effect, a laser-Doppler velocimeter^{‡‡‡}) was used to probe the centre point of the transparent TGV test section, coincident with the waist of the FSA laser beam, as shown in **Figure 15b**. A summary of the results obtained is presented in **Table 4**, confirming the remarkable correspondence of the data, with differentials within the measurement resolutions.

The second experiment was focused on replicating typical atmospheric conditions within the TGV, in terms of aerosol concentration, in order to ensure that the FSA is sufficiently sensitive to detect low aerosol concentrations. To that effect, calibrated aerosols [Arizona Test Dust [ISO 12103-1:2024 \(2024\)](#)] were introduced into the TGV inlet filter by means of a specialized powder disperser^{§§§}

^{***}For reasons of confidentiality, the actual physical distance cannot be provided.

^{†††}*i.e.* Wind-Generating Tube

^{‡‡‡}A miniLDV, rented from Measurement Science Enterprise, Inc. (USA)

^{§§§}TSI Small-Scale Powder Disperser, model 3433

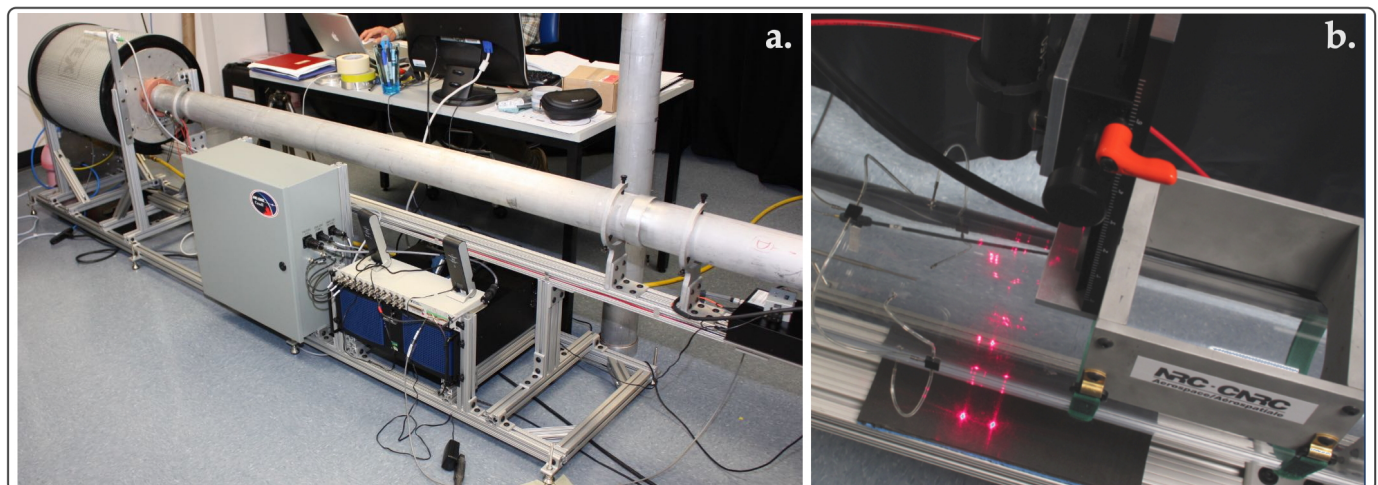


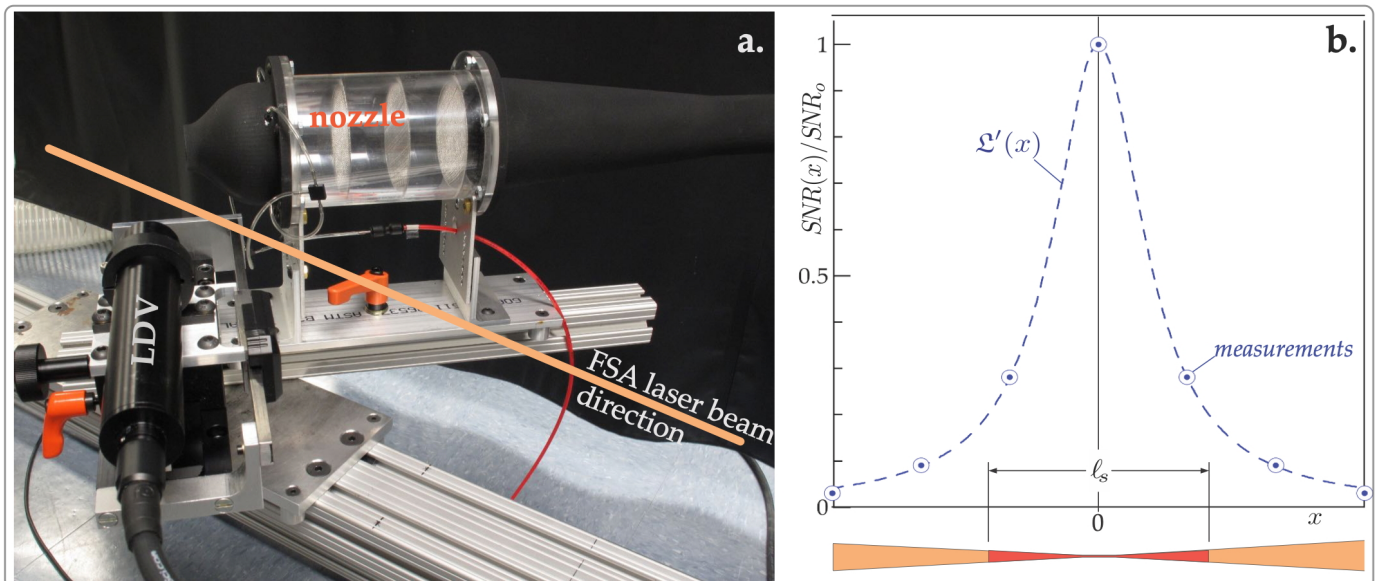
Figure 15. Tube Générateur de Vent (TGV) and its test section.

Table 4. FSA-LDV comparison.

U_{ldv} [m/s]	U_{fsa} [m/s]	ΔU [m/s]
15.44	15.44	0.00
20.53	20.58	0.05
30.92	30.93	0.01
35.62	35.57	-0.05
40.42	40.42	-0.00

capable of delivering precise particle fluxes in the microgrammes per second. The aerosol concentration was obtained by dividing the particle flux by the calibrated TGV flow rate (m^3/s). The aerosol experiment revealed that the FSA was able to detect 10 Doppler events per second in axial flow, at a PM_{10} concentration of about $25 \mu\text{g}/\text{m}^3$, an aerosol concentration typical of urban environments.

A third type of experiment was aimed at characterizing the longitudinal extent (ℓ_s) of the FSA sensing zone. This was achieved by exposing the FSA laser beam to a localized, oblique aerosol-containing jet generated by a purpose-built nozzle, as shown in **Figure 16a**. The nozzle was shifted along the FSA laser beam on either side of its waist to evaluate the FSA response as a function of its distance from the waist position. **Figure 16b** displays the Signal-to-Noise Ratio measured by the FSA as a function of the position of the 25 mm diameter round jet relative to the beam waist

**Figure 16.** Oblique nozzle and longitudinal extent of the FSA sensing zone.

position ($x = 0$). The SNR values are normalized by the maximum value (SNR_o) measured at the waist. As expected, the SNR ratio is consistent with the normalized Lorentz function $\mathcal{L}'(x)$, which is akin to the variation of the illuminance along the laser-beam axis:

$$\mathcal{L}'(x) = \frac{1}{1 + (x/z_R)^2} \quad (14)$$

Where z_R is the Rayleigh length. The extent of the FSA sensing zone was defined as four Rayleigh lengths, that is, $\ell_s = 4 z_R$. The ultimate validation before field testing was to subject both FSA optical channels to controlled and steady wind conditions. This was accomplished in the NRC Aerodynamics Laboratory's 2 m x 3 m wind tunnel during two separate entries [[Tanguay \(2015\)](#) ; [Tanguay \(2026\)](#)]. A view of the experimental arrangement is presented in **Figure 17a**. The two FSA optical heads were fastened to either end of a carbon-fibre tube mounted on a precision rotary table secured atop of a guyed steel tube. The laser beam aiming configuration was comparable to the typical arrangement used on board of vehicles, as illustrated in the two drawings, **Figures 5b,c**. The apparatus was installed within the wind-tunnel diffuser, and the two FSA beams were aligned and focused, such that the beam waists were located at the test section centre (at zero yaw). With this set-up, the yaw angle could be set within the range -7° to $+7^\circ$. A total of 120 combinations of wind speeds, pitch and yaw angles were tested. For each yaw angle setting, the angle measured by the FSA was well within 0.2° , which corresponds to the documented flow angularity in the test section. **Figure 17b** compares the wind speed measured by the FSA with the wind tunnel reference speed, during a speed ramp-up to about 95 m/s. It was observed that the wind tunnel reference speed signal slightly lagged the FSA signal. The FSA measured a speed 0.43% greater than the test section reference, indicative of a slight bias in the test section calibration.

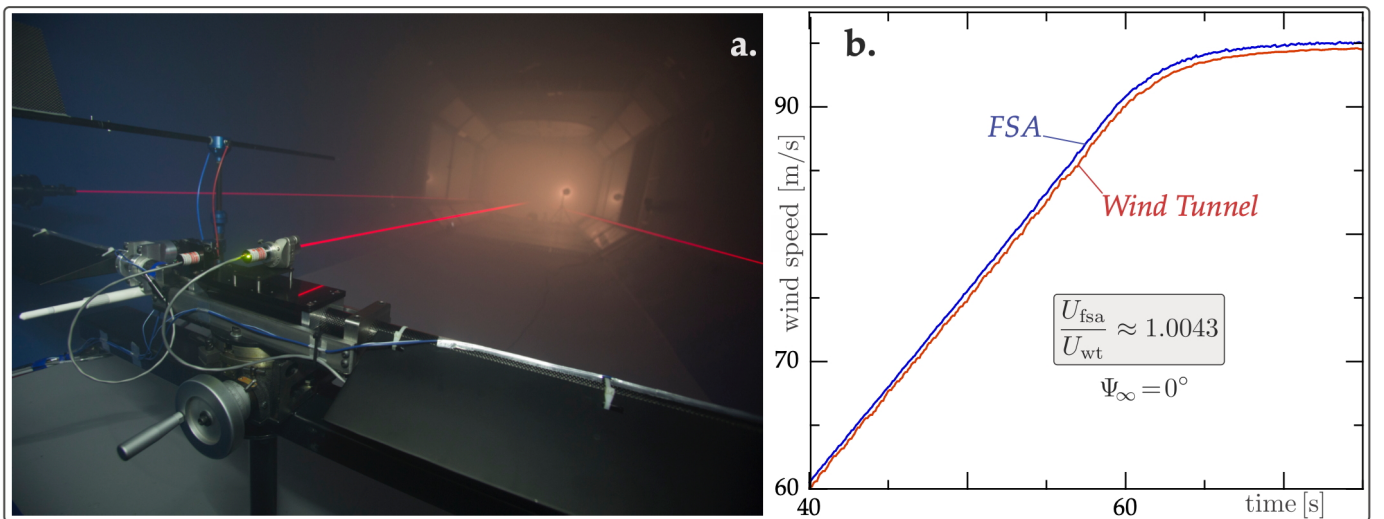


Figure 17. a. FSA objectives mounted within the diffuser **b.** FSA and wind tunnel reference speeds during ramp-up.

The uncertainty analysis presented at the end of *Section 3* was applied specifically to the FSA configuration used for the ramp-up test displayed in *Figure 17b*. The results are presented in *Figure 18*, emphasizing an absolute uncertainty level (ΔU_∞) below 0.075 m/s for all speeds up to 95 m/s. This translates into a relative uncertainty level ranging from 0.08% to 0.12% over the speed range of *Figure 17b*, thereby confirming that the observed difference of 0.43% relative to the wind tunnel reference speed exceeds the FSA measurement uncertainty.

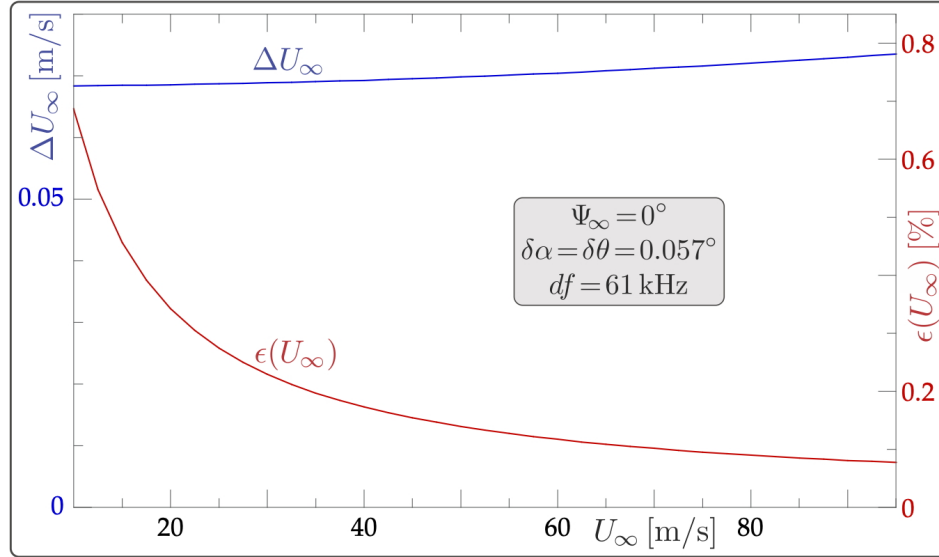


Figure 18. Absolute and relative uncertainty on U_∞ in the wind tunnel.

The wind tunnel also enabled the FSA detection sensitivity to be tested. Immediately before the wind-on tests, the ambient air in the test section was sampled using an aerosol spectrometer^{¶¶¶}, as shown in *Figure 19a*. These measurements revealed a concentration of FSA-detectable aerosols (*i.e.* with $d_a > 1 \mu\text{m}$) of 456 particles per litre, corresponding to a mass-concentration of $1.8 \mu\text{g}/\text{m}^3$, as illustrated in *Figure 19b*. Under these conditions, the FSA was able to measure wind velocity reliably at the target detection rate of 10 Hz. This concentration contrasts sharply with the larger value of $25 \mu\text{g}/\text{m}^3$ obtained using the TGV in axial flow. The improved sensitivity results from the favourable configuration whereby the FSA laser beams are inclined relative to the wind velocity vector, thus exposing a larger frontal area of the FSA sensing zones which are crossed by a larger particle flux. This result provides confidence in the FSA's ability to measure wind velocity on board vehicles in typical atmospheric conditions. Indeed, a global survey (Kim et al., 2025) of more than 13,000 urban areas worldwide revealed that the annual average $\text{PM}_{2.5}$ concentration was $37.7 \mu\text{g}/\text{m}^3$. Similarly, the examination of a number of urban and inter-urban environments in Europe reported aerosol concentrations in the range 12 to $38 \mu\text{g}/\text{m}^3$ for $\text{PM}_{2.5}$ and 26 to $52 \mu\text{g}/\text{m}^3$ for PM_{10} (Kassomenos et al., 2014).

^{¶¶¶}Portable aerosol spectrometer, model 11-D by GRIMM Aerosol Technik GmbH, Germany.

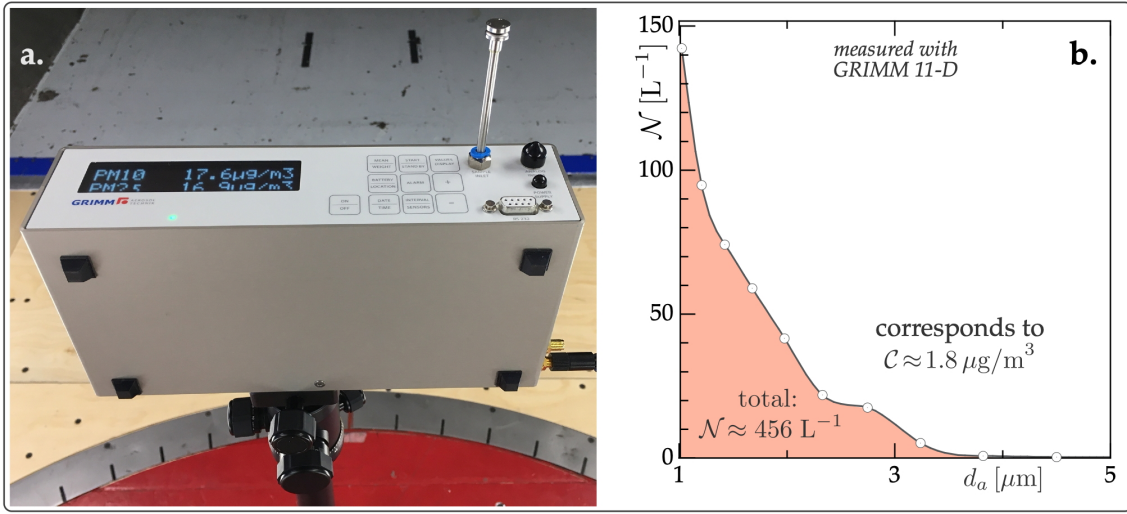


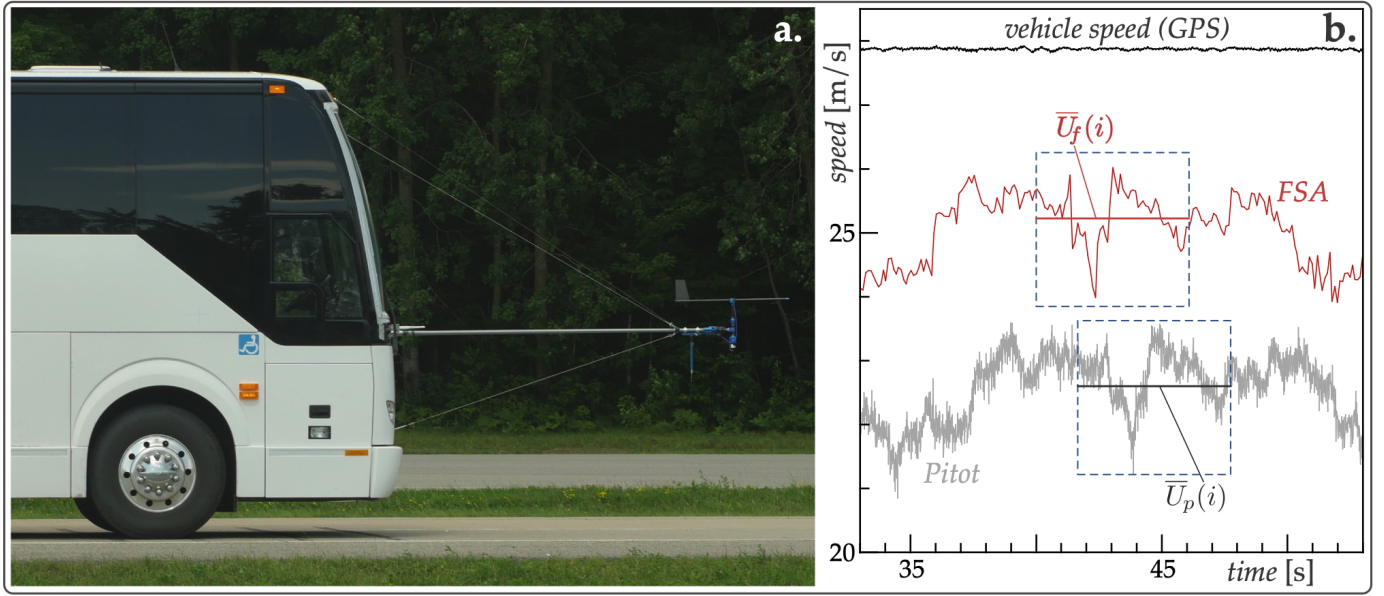
Figure 19. a. Aerosol spectrometer in the test section b. FSA-detectable aerosol concentration.

5. On-vehicle validation

The first FSA field experiments were conducted on board of a Prévost H3-45 intercity bus, depicted in *Figure 20a* (Tanguay, 2018). This vehicle is the full-scale equivalent of the model used during the PIV experiment described earlier. The testing took place on the taxiway of the Oscoda-Wurthsmith airport in Michigan (USA). The test vehicle was equipped with the FSA system and a boom-mounted Prandtl-vane probe sensing the local dynamic pressure and yaw angle at 3.3 m forward of the vehicle nose, within the perturbed region illustrated in *Figure 1*. This probe provided a useful comparison with the FSA measurements. This first on-vehicle experiment enabled the development of a new statistical algorithm to identify reliably the aerosol signatures (*Figure 9b*).

One of the key objectives was to validate the distance-to-free-stream (d_∞) obtained from the PIV experiments. This was achieved by conducting a number of runs whereby the FSA measurement range (R) was varied in seven increments, from the tip of the boom-supported Prandtl tube to a point beyond the PIV-prediction of d_∞ . *Figure 20b* presents a 20-second excerpt of three signals: the vehicle speed and the wind speeds measured by the FSA and by the Prandtl tube. The vehicle was traveling at a constant speed of about 28 m/s in the presence of a terrestrial wind with a tailwind component, which is revealed by the fact that the free-stream speed sensed by the FSA is lower than the vehicle speed. The salient feature is the remarkable similarity between the FSA and Prandtl-tube signals, combined with a time-shift consistent with the fact that the Prandtl tube detects a signal downwind of (*i.e.* later than) the FSA. The two dashed rectangles highlight matching excerpts of each signal. For each value of the FSA range, the ratio $\kappa(R)$ between the FSA- and Prandtl-tube-measured wind speeds was calculated from all matching time series excerpts, as follows:

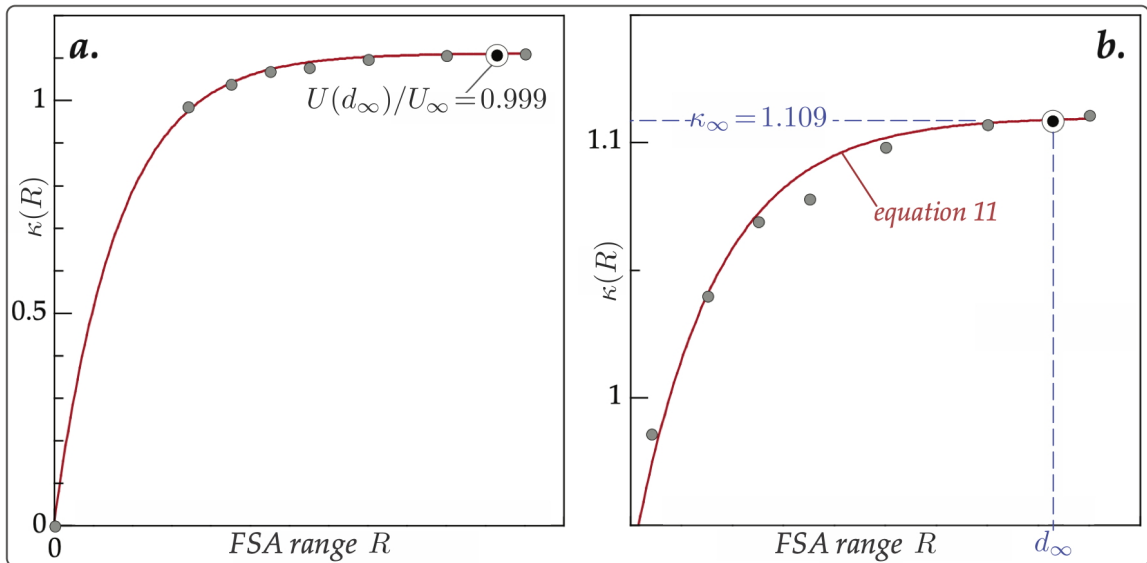
$$\kappa(R) = \frac{1}{n} \sum_{i=1}^n \frac{\overline{U}_f(i)}{\overline{U}_p(i)} \quad (15)$$



Where $\bar{U}_f(i)$ and $\bar{U}_p(i)$ are the mean values of the i^{th} pair of corresponding signal excerpts, depicted as horizontal lines within the dashed rectangles of **Figure 20b**. Each of the n excerpt-pairs was identified by maximizing its cross-correlation coefficient. The process of determining the value of d_∞ followed the principle of **equation 12**, albeit with the following formulation:

$$\kappa(R) = \kappa_\infty (1 - e^{-R/\lambda_u}) \quad (16)$$

The best fit of the set of seven data points comparing the FSA and Prandtl-tube measurements ($\kappa_i(R)$, $i = 1, \dots, 7$) using this asymptotic function is displayed in **Figure 21** (red curve). The optimization yielded $\kappa_\infty \approx 1.11$, indicating that the free-stream speed measured by the FSA is 11%



larger than the speed sensed by the Prandtl tube. Using latter reading as the reference free-stream speed would lead to a +22% overestimate of C_D . The resulting distance-to-free-stream (d_∞) was found to be slightly greater than the value obtained from the PIV experiment (see *Figure 14*). These experiments also confirmed that the FSA was consistently detecting sufficient airborne aerosols to yield ten Doppler measurements every second, the target detection frequency. However, it was observed that the FSA does not operate reliably during or immediately after rainfall, because rain removes airborne aerosols from the air. The FSA is therefore meant to be utilized in dry conditions.

6. Application to high-speed trains

Upon request from Stadler Rheintal AG of Switzerland, the NRC Aerodynamics Laboratory prepared and conducted an aerodynamic test campaign on board of a Stadler KISS intercity train using the FSA technology (Tanguay, 2019). The testing took place in 2019 on a straight 38 km railway segment in the south of Sweden. Stadler had been struggling with inconsistent resistance-to-motion results attributed to the inadequate measurement of the wind conditions during coasting tests. Indeed, the standard test procedure defined in European norm EN 14067-4:2013 (2013) only required that the wind be measured at a few exposed positions at track-side, over a test section with a typical length of 20 km or more. The customary practice was to discard any coasting run during which any of the anemometers recorded a wind speed exceeding a threshold of 2 m/s. This stringent constraint often leads to a small number of valid runs or may require the repeat of an entire test campaign at great cost. The FSA offers the advantage of the non-intrusive, continuous measurement of free-stream wind velocity along the entire test section. Besides, the presence of cross-winds offers a bonus, in that the yaw-angle dependence of the drag coefficient $C_D(\Psi_\infty)$ can be established.

Figure 22 depicts the two FSA optical heads installed atop the train's crash modules. Each head is fastened to a photographic ball-head enabling its aiming direction to be adjusted and firmly locked. A rail-mounted alignment target is used to set and measure the four aiming angles within an uncertainty level of less than 0.15° . A pair of 15-metre-long fibre-optic cables connects the two optical heads to the optoelectronic module located within the first vehicle. A one-minute excerpt of a typical FSA time series of free-stream speed and yaw angle is presented in the graph of *Figure 23*. The presence of strong winds with a prevalent headwind-starboard component is manifest, with yaw angles reaching -20° . The criticality of measuring the wind is exemplified by points **A** and **B**. The instantaneous power required to offset the peak wind speed at point **B** is more than 50% greater than for the no-wind case (**A**). These windy conditions were amenable to the characterization of $C_D(\Psi_\infty)$, as shown in the graph of *Figure 24a* for two train configurations. The knowledge of the C_D -curve enables the prediction of the energy dissipation for various wind conditions, as displayed in *Figure 24b* for the 8-vehicle train set. The aerodynamic dissipative power ($\mathcal{D}_a$) is defined as follows:

$$\mathcal{D}_a = \left[\frac{1}{2} \rho U_\infty^2 A \right] \cdot V \cdot C_D(\Psi_\infty) \quad (17)$$



Figure 22. FSA objectives mounted atop the KISS crash boxes.

At a train speed of $V = 200$ km/h, between a pure 25 km/h tailwind (tw) and a headwind (hw) inducing a 6° yaw angle, the aerodynamic dissipative power rises by about 77%. For the latter case, aerodynamic dissipation accounts for about 95% of the total dissipative power, highlighting the central importance of aerodynamics in the resistance-to-motion of high-speed trains. To contextualize, for a typical intercity train traveling at 200 km/h through still air, the aerodynamic dissipation represents about 1 MW of power.

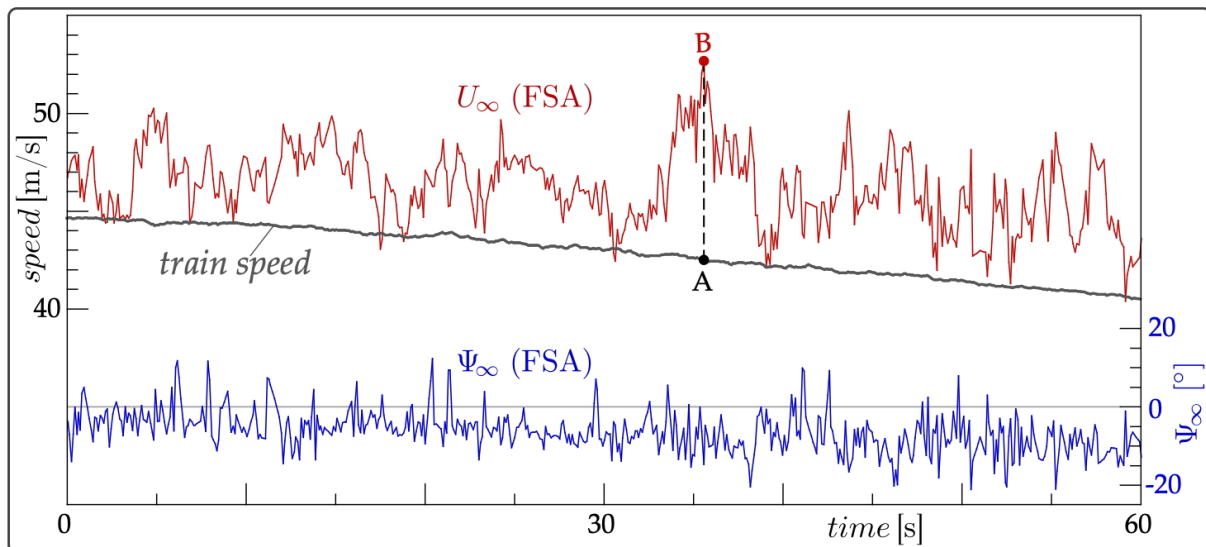


Figure 23. Free-stream velocity and vehicle speed during a typical coasting run.

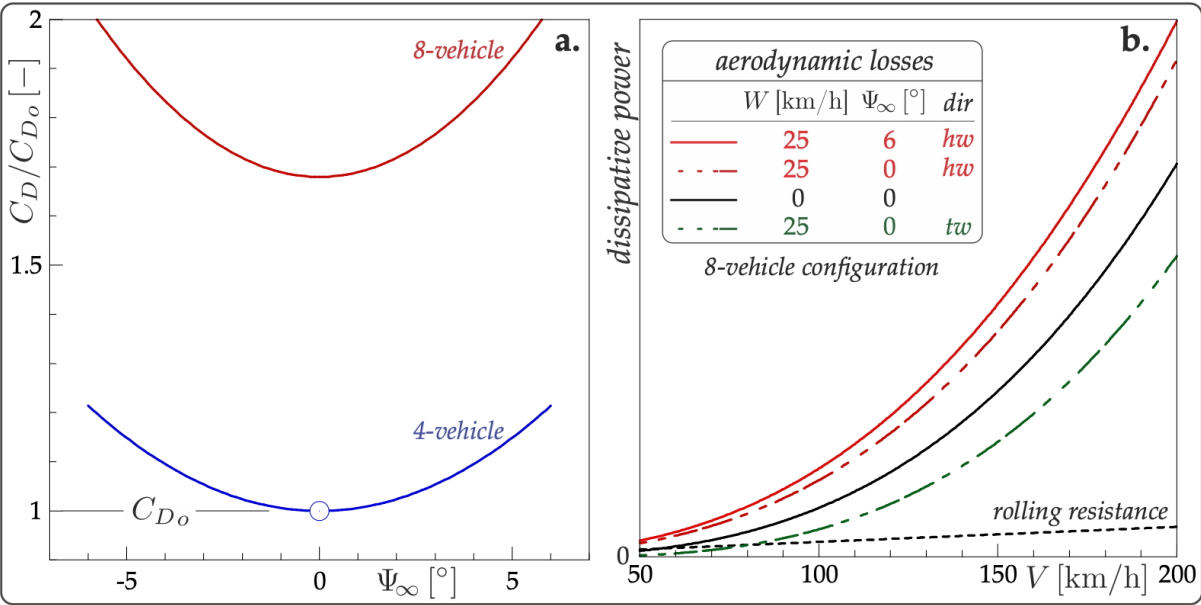


Figure 24. Aerodynamic drag coefficient and corresponding energy dissipation.

7. Conclusions and outlook

Through its various validation stages, the reliability and accuracy of the NRC Free-Stream Anemometer (FSA) were confirmed. The FSA provides an innovative method to measure directly and non-intrusively the free-stream wind velocity forward of traveling vehicles, *i.e.* beyond the vehicle-induced zone of aerodynamic perturbation. Under yaw-inducing crosswind conditions, the FSA enables the determination of a vehicle's yaw-dependent aerodynamic drag coefficient. This game-changing technology has the potential to revolutionize the way the railway and road-vehicle sectors characterize the dominant contributor to a vehicle's resistance-to-motion at cruise speeds, namely aerodynamic drag.

An uncertainty analysis demonstrated that, for typical applications on board vehicles, the FSA measures free-stream speed with an uncertainty level below 0.09 m/s (0.32 km/h) for free-stream yaw angles under 15° . The uncertainty in the free-stream yaw angle measurement is below 0.4° for free-stream speeds exceeding 30 m/s. Wind tunnel testing also confirmed the FSA's sensitivity at detecting airborne aerosols. It was shown that a concentration of about 500 aerosol particles per litre suffices to ensure the detection of ten Doppler events per second for FSA-detectable particles characterized by aerodynamic diameters above $1\ \mu\text{m}$. In the wind tunnel, this corresponded to a mass concentration of less than $2\ \mu\text{g}/\text{m}^3$ for particles with diameters ranging from $1\ \mu\text{m}$ to $4\ \mu\text{m}$, *i.e.* well below the concentrations observed in urban and inter-urban environments worldwide

Several improvements or additions could broaden applicability of the FSA. Examples include the miniaturization of the optoelectronic module and controller and the reduction of the laser power, making the system more compact. Besides, the ability to scan the free-stream area by using beam-steering would be a valuable improvement. As well, adding a third channel would enable the characterization of three-dimensional flows. Alternative applications could include drone operation in extreme wind environments, exterior wind measurements in hard-to-reach areas, calibrations and flow surveys in wind tunnels.

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[¶] Following a merger, INO was rebranded as [Luqia](#), as of April 1, 2026

NOMENCLATURE

NOTE: Units are not provided in the nomenclature since unit consistency within equations is implied. They are provided in Figures and Tables

A	Vehicle frontal area
$C, \mathcal{N}$	mass- and particle-number-concentrations of aerosols
C_D	Coefficient of aerodynamic drag (dimensionless)
D	Aerodynamic drag (force)
$\mathcal{D}_a$	Aerodynamic dissipative power
d_a	Aerodynamic diameter of an aerosol particle
d_o	Waist diameter of FSA beam (<i>i.e.</i> at focal point)
d_∞	Distance from the vehicle nose to the free-stream boundary
df	Resolution of FSA spectra
dU_{oa}	FSA speed resolution
$E_\varkappa^2(\eta)$	Squared uncertainty level of variable η due to uncertainty in parameter $\varkappa$.
f	Doppler frequency shift (used interchangeably with Δf)
f_{det}	FSA detection frequency
f_s	Sampling frequency of digitizer
ℓ_s	Length of the FSA sensing zone, along the optical axis
m	Vehicle mass
N_{det}	Number of detections per period
p_∞	Free-stream static pressure
R	FSA measurement range, from vehicle nose to centre of sensing zone
R_{fsa}	FSA range, measured along optical axis
S_1, S_2	Optical signals entering the photodetector
T_{det}	FSA detection period
$\vec{U}$	Designates an apparent-wind velocity vector (<i>i.e.</i> in vehicle frame of reference)
$\vec{U}_a$	An apparent-wind velocity vector measured by a vehicle-mounted anemometer
$\vec{U}_\infty$	Free-stream wind velocity
$\vec{U}_{oa}$	Projection of the local apparent-wind velocity onto the FSA optical axis
$\vec{U}_x$	Projection onto the x -axis, of the FSA velocity detected on one FSA channel
V_{det}	Photodetector output voltage
$\vec{V}$	Vehicle velocity vector
$\vec{W}$	Velocity vector of the terrestrial wind (<i>i.e.</i> in ground frame of reference)
x	Longitudinal coordinate, on vehicle path
$ \vec{X} $ or X	Magnitude of vector $\vec{X}$

Greek symbols

λ_e	Wavelength of light emitted by the FSA laser
α	Pitch angle of FSA laser beam (optical axis)

θ	Convergence angle of FSA laser beam (optical axis)
δ	Absolute uncertainty (error) level of an underlying parameter
Δ	Designates a difference, a differential or an absolute uncertainty
Δf	Doppler frequency shift (used interchangeably with f)
Δt_d	Duration of one FSA detection period
$\epsilon(X)$	Relative uncertainty of X
γ	Angle between the terrestrial wind vector and the vehicle travel direction
Ψ_a	A yaw angle measured by a vehicle-mounted anemometer
ϕ_{oa}	Angle between local wind vector and FSA optical axis
Ψ	Yaw angle of the apparent wind
Ψ_∞	Free-stream yaw angle
ρ	Density of air
σ	A standard deviation (generic)

Subscripts, superscripts and diacritical marks

a	Designates a measurement by a vehicle-mounted anemometer
$1,2$	Designate start and end points (generic)
$\det$	Refers to the detection of Doppler peaks
fsa	Refers to the Free-Stream Anemometer
min	Refers to a minimum value
max	Refers to a maximum value
pk	Refers to a spectral peak
$\vec{x}$	The arrow designates a vector
$\overline{X}$	Denotes the mean value of variable X
oa	Designates the optical axis of one FSA laser beam
∞	Designates free-stream conditions
p	Refers to the FSA objective mounted on the port side of the vehicle
s	Refers to the FSA objective mounted on the starboard side of the vehicle

Acronyms and abbreviations

ADC	Analogue to Digital Converter
CEN	Comité Européen de Normalisation - European Committee for Standardization
CFD	Computational Fluid Dynamics
CPU	Central Processing Unit
CW	Continuous Wave (laser operational mode)
DIO	Digital Input and Output
EPA	Environmental Protection Agency (USA)
FC/APC	Fibre-optic connector type used by FSA
FFT	Fast Fourier Transform

FSA	Free-Stream Anemometer
HDV	Heavy-Duty vehicle
INO	Institut National d'Optique (rebranded as Luqia in April 2026)
GPU	Graphics Processing Unit
NRC	National Research Council of Canada
eTV	ecoTECHNOLOGY for Vehicles program (Transport Canada)
PIV	Particle-Image Velocimetry
PM	Particulate matter concentration, <i>e.g.</i> PM ₁₀ , PM _{2.5}
RF	Radio-Frequency
SAE	Society of Automotive Engineers
SMA	SubMiniature version A (coaxial RF connector)
<i>SNR</i>	Signal-to-Noise Ratio
stbd	Starboard
TGV	Tube Générateur de Vent (Wind-generating Tube)
VOA	Variable Optical Attenuator

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