

Uninterrupted direct NO₂ and NO_x measurement: Long-term comparison of a new CRDS instrument to existing methods

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Key words: NO₂ measurement, NO_x monitoring, cavity ring-down spectroscopy (CRDS), long-term intercomparison, instrument stability.

Abstract

Ground-based NO_x monitoring networks rely on long-established instruments that have rarely undergone intercomparison across diverse environments, leaving unresolved questions regarding long-term stability, interference, and measurement drift. We report results from a multi-month deployment of a new commercial dual-channel cavity ring-down (CRDS) analyzer (G60, Direct Optics Inc.) designed to directly measure NO₂ and NO_x simultaneously, without valve switching or catalytic conversion. More than 15 analyzers were deployed across North America and Europe, and compared with co-located regulatory instruments, including chemiluminescence (CL) and Cavity Attenuated Phase-shift Spectroscopy (CAPS) systems. Sites spanned pristine background conditions to heavily trafficked urban environments. The findings indicate strong agreement across instruments, while revealing advantages of uninterrupted dual-channel CRDS measurements under rapidly varying emission conditions. In particular, the G60 demonstrates improved stability and response for low-level NO₂ detection and near-road monitoring. These results suggest CRDS-based dual-channel measurements provide a robust path forward for next-generation regulatory air-quality monitoring.

1. Introduction

Ground-based, continuously monitoring NO_x instruments have rarely undergone direct, long-term intercomparison, despite the widespread deployment of well-established sensors (Thornbery et al., 2001; Thornton et al., 2003). Over the past two decades, only a limited number of studies have reported intercomparison spanning several weeks (Pandey Deolal et al., 2012; Ge et al., 2013; Leston and Ollison, 2017; Allen et al., 2018; Li et al., 2019; Landis and Egerton, 2019). Long-term, uninterrupted comparisons are essential to capture variability and identify instrumental drift that may not emerge in short-term (2–3 week) studies.

Regulatory agencies rely on continuous NO_x monitoring to inform policy and assess air quality. For example, the US EPA uses Federal Equivalent Method (FEM) designated NO_x instruments to evaluate

NO₂, a key criteria pollutant. Accurate NO₂ measurements are critical for regulatory compliance, air quality health indexing, emission inventory reporting (e.g., Macdonald et al., 2021), and exposure assessment.

Traditional single-cell NO_x analyzers, widely adopted as reference methods, suffer from chemical interference and unresolved physical limitations (Steinbacher et al., 2007). These instruments typically alternate between NO and NO_x modes using 3-way valves, introducing uncertainties between switching delays, pressure fluctuations, and non-linear response artifacts (Seinfeld & Pandis, 2006; U.S. EPA, 2020). Such limitations affect both direct NO₂ detection systems and indirect chemiluminescence (CL)-based methods, the latter being the global standard, but prone to conversion inefficiencies and cross-interference, particularly under rapidly varying urban emission conditions (Kleffmann et al., 2004; Dunlea et al., 2007).

To address these limitations, we developed a first-of-its-kind commercial dual-channel CRDS analyzer (G60, Direct Optics Inc.) capable of simultaneously measuring NO₂ and NO_x using two independent optical channels. This design eliminates valve switching, catalytic conversion, and single detector artifacts. A self-aligned Direct Optics cavity improves optical stability, overcoming historical barriers to CRDS commercialization. The dual-channel architecture removes delays and non-linear response effects, enabling improved stability, rapid response, and high-resolution detection across diverse environmental conditions. The G60 represents a significant advancement toward real-time, interference-free quantification of NO_x.

Over fifteen G60 analyzers were deployed across North America and Europe as part of the ICE-MAN campaign (Instrument Comparison to Existing NO_x Measurement Techniques Across North America and Europe), and evaluated against co-located regulatory instruments, including Teledyne API T200 (CL-based), N500 series (CAPS-based), and Thermo Fisher Scientific T42i (CL-based) systems. Deployment sites spanned pristine to heavily polluted environments and rural locations.

Preliminary results indicate that uninterrupted dual-channel CRDS measurements improve performance in low-level NO₂ detection and dynamic emission environments, such as near road monitoring. This study evaluates long-term trends in instrument performance through calibration and drift analysis based on daily span checks.

2. Deployment Locations and Monitoring Sites

Multiple ongoing deployments commenced in October 2025 at various sites, and in collaboration with Canadian and US jurisdictional authorities. Table 1 summarizes the deployment sites, sampling periods, type of environment, authorities, co-sampling instruments, and other pertinent information. The deployments were strategically chosen to encompass diverse environments.

G60 analyzers were deployed across select ECCC-NAPS monitoring network locations including Vancouver, Edmonton, Toronto, Port Stanley, Ottawa, Montreal, and Quebec City.

Table 1: NO₂-NO_x co-sampling instruments deployment locales and other characteristics during ICE-MAN.

Site Location	Coordinates	Authority	Environment	Instruments	Period
Vancouver, BC, Canada	49.2603°N 123.0778°W	ECCC-NAPS* network	Direct emissions; heavy urban traffic	2 x G60, T42i	11-Sep-25 – ongoing
Edmonton, AB, Canada	53.4860°N 113.4646°W	WBEA &	Direct emissions; nearby highway	2 x G60, T42i	10-Oct-25 – ongoing
Toronto, ON, Canada	43.7101°N 79.5418°W	OMECP	Mixed (direct and processed)	G60, T42i, N500	5-Nov-25 – ongoing
Port Stanley, ON, Canada	42.6721°N 81.1629°W	ECCC-NAPS network	Rural/agricultural; very light traffic	G60, T42i, N500	5-Jun-25 – ongoing
Ottawa, ON, Canada	45.3166°N 75.6902°W	ECCC-NAPS network	Suburban, within 1 km of YOW airport	2 x G60, T42iQ, N500	01-Apr-25 – ongoing
Montreal, PQ, Canada	45.5773°N 73.5154°W	ECCC-NAPS network	Urban parking lot; diesel trucks	2 x G60, N500	10-Oct-25 – ongoing
Quebec City, PQ, Canada	46.7814°N 71.3087°W	ECCC-NAPS network	Busy highway; direct emissions	G60, N500	10-Oct-25 – ongoing
Quebec City, PQ, Canada	46.7948°N 71.2464°W	ECCC-NAPS network	College campus; urban emissions	G60, N500	10-Oct-25 – ongoing
Tualatin, OR, USA	45.3992°N 122.7455°W	ODEQ #	Urban; heavy highway traffic	G60, T200UP	23-Nov-24 – ongoing
Raleigh, NC, USA	35.8652°N 78.8197°W	US-EPA	Busy highway; by a large airport	G60, 2 x N500, T42i	27-Aug-25 – ongoing
Hyytiälä, Finland	61.8463°N 24.2957°E	University of Helsinki & FMI †	Pristine (forest) background air	G60, N200	10-Oct-25 – ongoing

* ECCC – Environment and Climate Change Canada; NAPS – National Air Pollution Surveillance; # ODEQ – Oregon Department of Environmental Quality; & WBEA – Wood Buffalo Environmental Association; † FMI – Finnish Meteorological Institute

At Vancouver, the monitoring station is primarily impacted by direct highway air mass carrying freshly emitted and unprocessed NO_x. The Edmonton site is embedded within an industrial area and is situated approximately 200 m from two busy roadways, receiving mostly fresh and occasionally processed air mass. The location in Toronto was maintained by the Ontario Ministry of the Environment, Conservation, and Parks (OMECP). There, the deployment was mainly impacted by periods of fresh and processed NO_x-enriched air derived from the busiest highway in North America, HWY-401. Port Stanley's deployment was the only one in the suite characterized by a remote rural environment off of Lake Erie, experiencing very little traffic and therefore NO_x sources. Both Montreal and Quebec City had analyzers situated near direct, local road-traffic emission sources enriched

with NO_x. The locations in Oregon and North Carolina were both urban, characterized by direct NO_x sources and processed air masses.

Finland’s deployment receives mainly clean background air almost free of NO_x with concentration levels normally below 1–2 ppb. Figure 1 shows a G60 analyzer schematic.

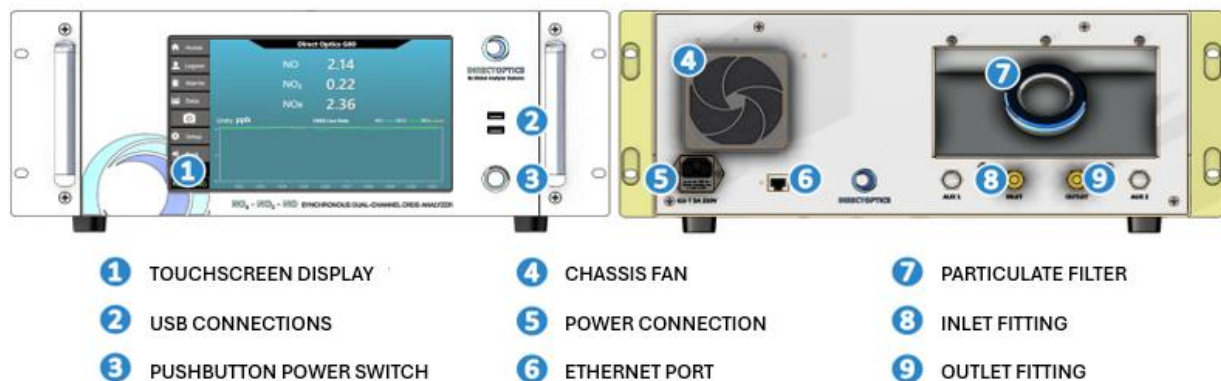


Figure 1: The Direct Optics Inc. G60 dual-channel CRDS analyzer is commercially available, featuring a large touchscreen display with live updates and access to user-friendly and customizable menu options, USB and Ethernet ports, MODBUS communication interface, and Windows OS. The analyzer is equipped with easy-to-service particulate filter, and standard ¼" stainless steel Swagelok fittings at the inlet and exhaust port.

3. Co-located Setups

In this paper, we only describe Vancouver, BC, Toronto, ON, and Greater Portland, OR deployment.

The NAPS location at Vancouver, BC was mainly impacted by direct, unprocessed traffic emissions enriched with fresh NO_x from nearby roads and mixed highway traffic combustion sources, as shown in Fig. 2. This site featured three co-located analyzers: two dual-channel G60 analyzers, and one T42i Federal Reference Method (FRM) designated analyzer. All instruments were located within the same shed and sampled from a common manifold line, without modification to their standard operating routines. Periodic calibrations were either automated or undertaken by the NAPS technical staff. All instruments were periodically calibrated with air (zero grade) and span-checked with a known amount of NO_x to monitor any drifts from linear behavior over the course of the long and ongoing uninterrupted measurement.

Figure 3 shows the relative location of the OMECP-maintained site in the heart of Toronto, ON. The co-located setup consisted of a single G60 analyzer, one T42i, and a Teledyne-API N500 NO-NO₂-NO_x analyzer. Notably, the N500 detects NO₂ based on CAPS spectroscopy, and is yet another FRM-designated class analyzer. All instruments were in proximity to one another and sampled from a common inlet line equipped with particulate matter membrane filters dedicated to each individual instrument. Zero (NO_x-free, zero air grade) and span (NO_x) drift checks were pre-scheduled and performed once every 24 hours to ensure linear data quality.

The location and setup for Portland, OR is not shown here for simplicity. However, in Portland, analyzers were operated in a similar continuous manner with periodic zero and span calibrations.

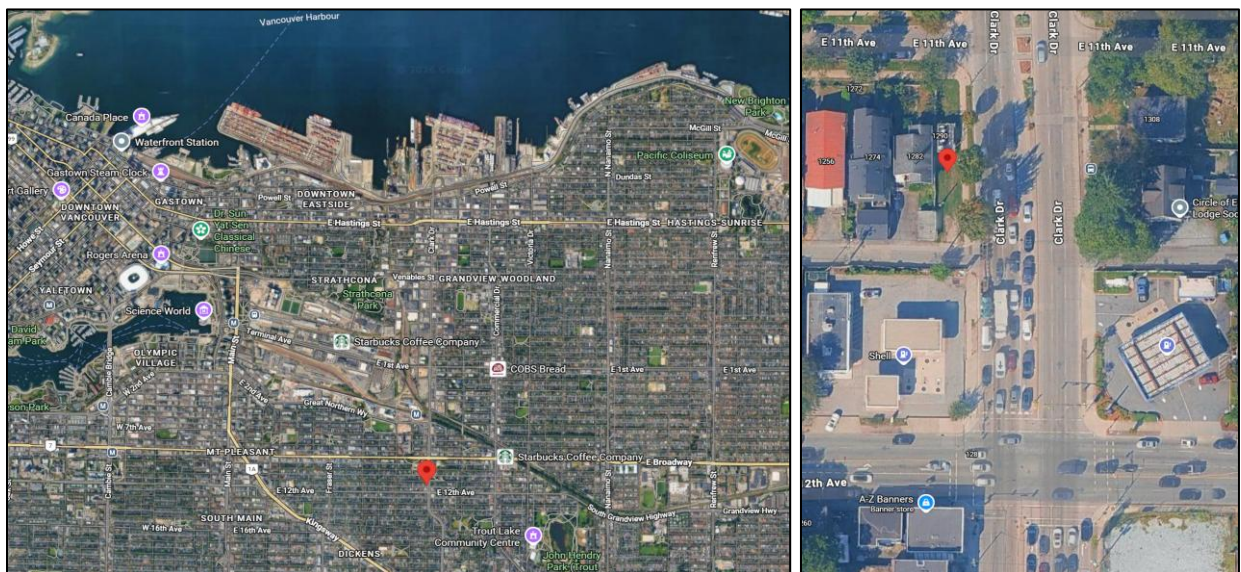


Figure 2: Left side panel shows an aerial view of the Vancouver location relative to major highways and busy residential roads; right panel shows nearby roads. The co-sampling analyzers were situated inside a storage shed and were mounted on a standard rack, sampling from a common manifold inlet line.

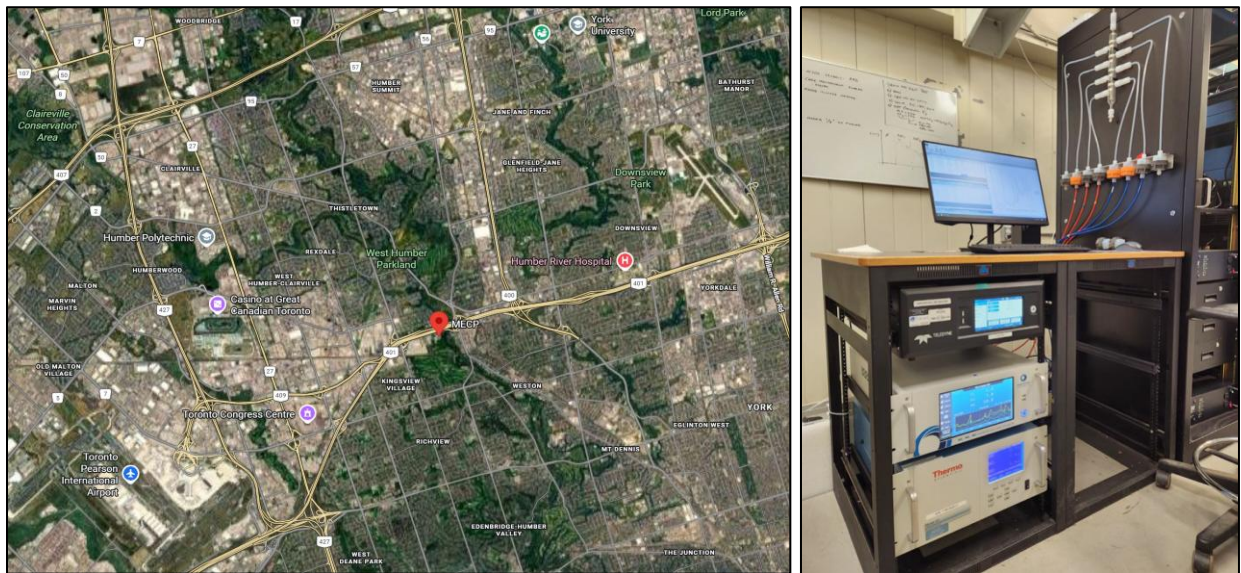


Figure 3: Left side panel shows an aerial view of the Toronto location relative to highway 401 and other nearby emission sources. All co-sampling analyzers were situated inside an OMECP maintained facility, and were mounted on a standard rack (right panel), sampling from a common inlet line equipped with particle filters.

4. Results and Discussion

The ICE-MAN deployments provide a unique opportunity to evaluate long-term instrument behavior under continuous, real-world operating conditions. By examining time series data alongside daily zero and span checks, we assess not only agreement between instruments, but also their stability, response characteristics, and behavior under varying atmospheric regimes.

Vancouver, BC

The Vancouver deployment represents a high-intensity environment dominated by direct, fresh, unprocessed emissions, with NO_x time series shown in Fig. 4. Over the measurement period, all instruments exhibited strong overall agreement in NO_2 and NO_x trends, particularly when data were averaged over longer time intervals. At higher temporal resolution (1-minute data), differences in signal variability were observed between instruments (Fig. 5). These differences became less pronounced when data were aggregated to hourly averages, suggesting that short-timescale variability contributes significantly to apparent disagreement in high-frequency comparisons.

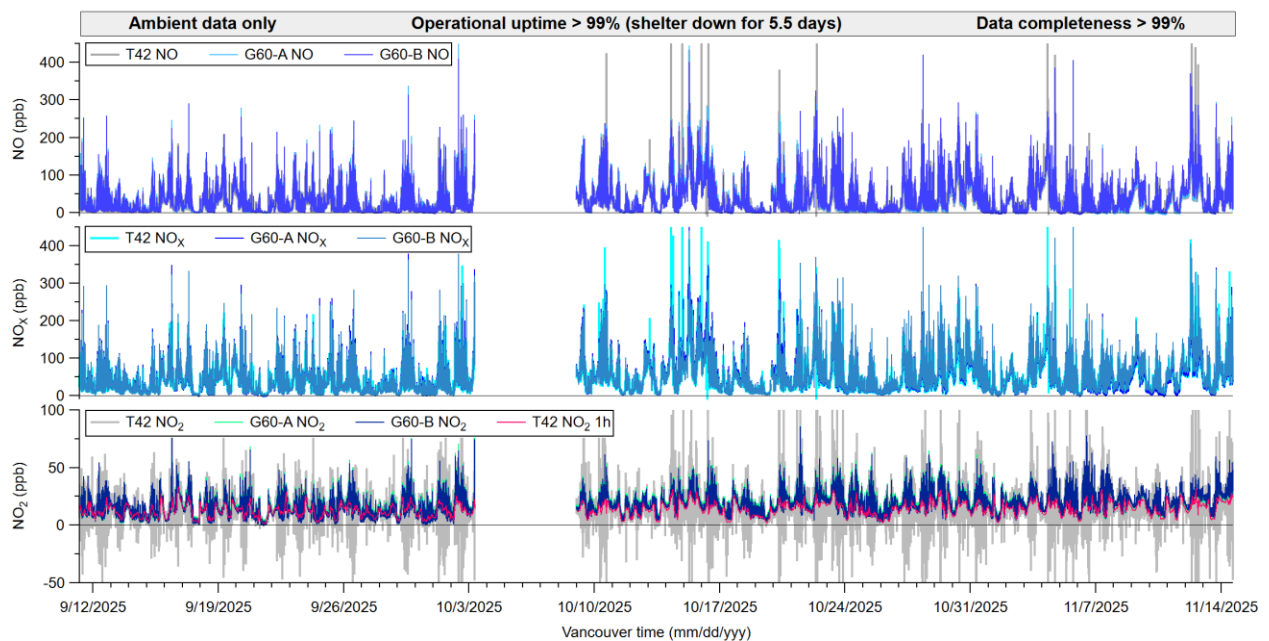


Figure 4: One-minute ambient data only for NO_2 - NO_x - NO measurement by two G60 analyzers and a single T42i for Sep-Nov, 2025. The T42i- NO_2 1-min measurement (grey trace; bottom panel) exhibited high-level noise characteristic to its inherent internal valve switching. A similar artifact appeared in the T42i- NO_x data, as well. The air mass was derived from direct (unprocessed) highway emission sources.

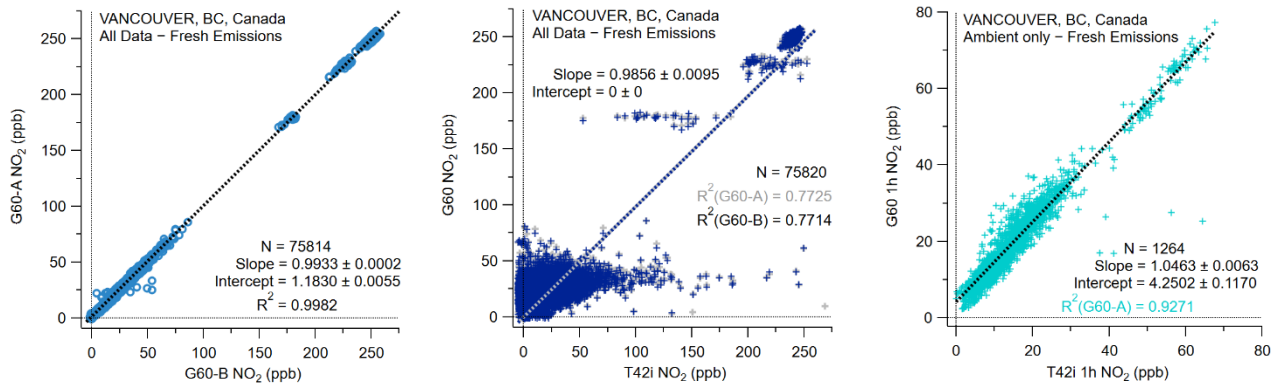


Figure 5: Comparison plots for G60-NO₂ and T42i-NO₂ only. The T42i was not adjusted by a response factor.

Daily zero and span checks (Fig. 6) provide additional insight into instrument stability. Across the deployment period, span responses remained consistent, enabling tracking of long-term drift behavior and confirming stable operation under continuous sampling conditions. Importantly, uninterrupted operation (> 99% uptime) allowed for the capture of transient emission events and evolving atmospheric conditions without data gaps. This continuity provides a more complete picture of ambient NO₂ dynamics, particularly in environments influenced by rapidly changing emission sources.

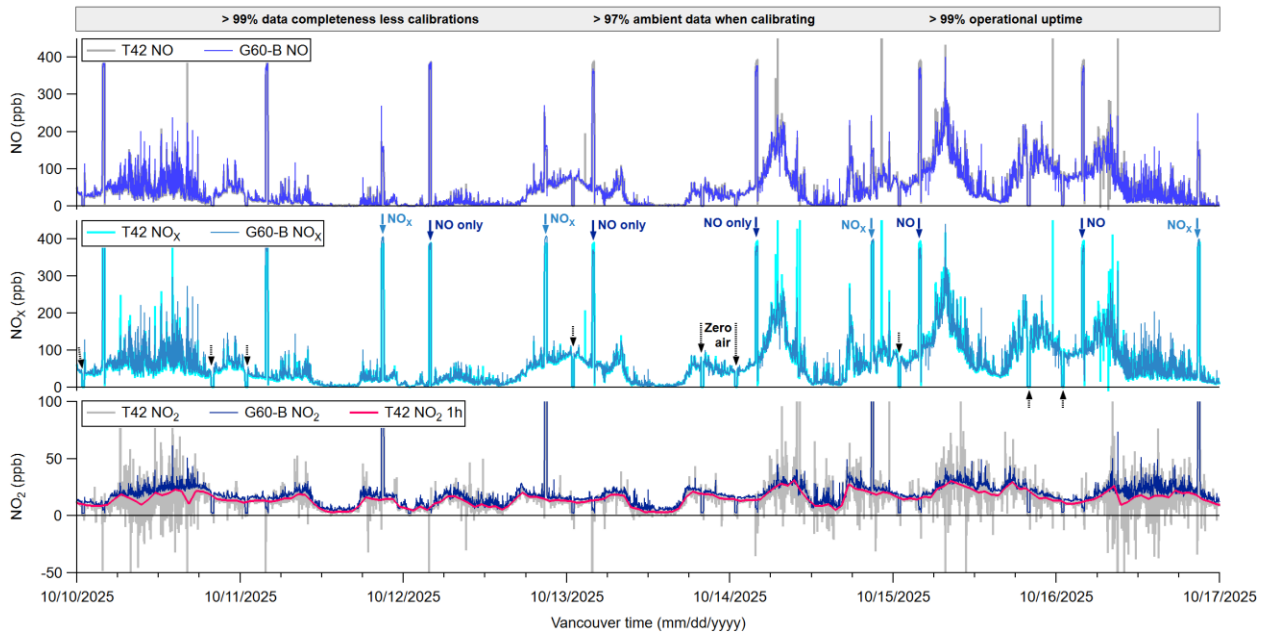


Figure 6: A week-long isolated data set in Oct 2025 showing the analyzers' long-term performance through zero calibrations and span checks for on-line or off-line intervention in calibration and drift analysis.

Toronto, ON

The Toronto site introduces a more complex atmospheric regime, characterized by a mixture of fresh and processed air masses, with NO_2 - NO_x time series shown in Fig. 7 (upper 2 panels). Under these conditions, the instruments again showed strong agreement in long-term trends, with high correlation observed across co-located systems (Fig. 8). Differences between instruments were primarily evident in short-term variability and response to rapidly changing concentrations. As in Vancouver, these differences diminished when data were averaged over longer periods, reinforcing the importance of temporal resolution in intercomparison studies.

Daily calibration checks confirmed stable instrument response over time, supporting the interpretation that observed differences are linked to measurement dynamics rather than systematic drift. The extended deployment period further enabled evaluation of performance consistency across changing environmental conditions.

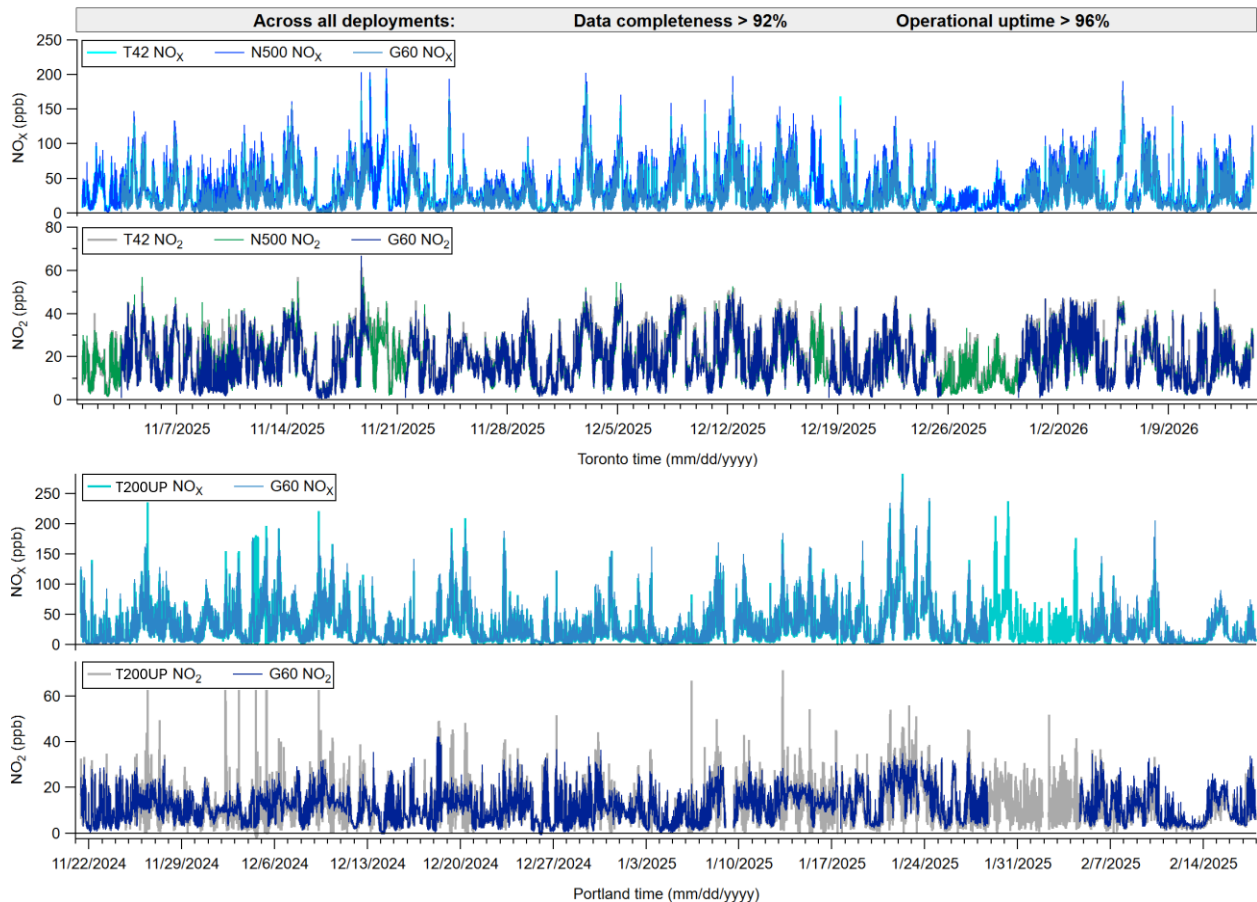


Figure 7: Upper panel shows the NO_2 - NO_x data for three co-located analyzers (G60, N500, and T42i) in Toronto, ON between Nov 1, 2025 and Jan 14, 2026. The lower panel shows NO_2 - NO_x data for two co-located analyzers (G60 and T200UP) deployed in greater Portland area (Tualatin) between Nov 2024 and Feb 2025. All data were collected at 1-min temporal resolution.

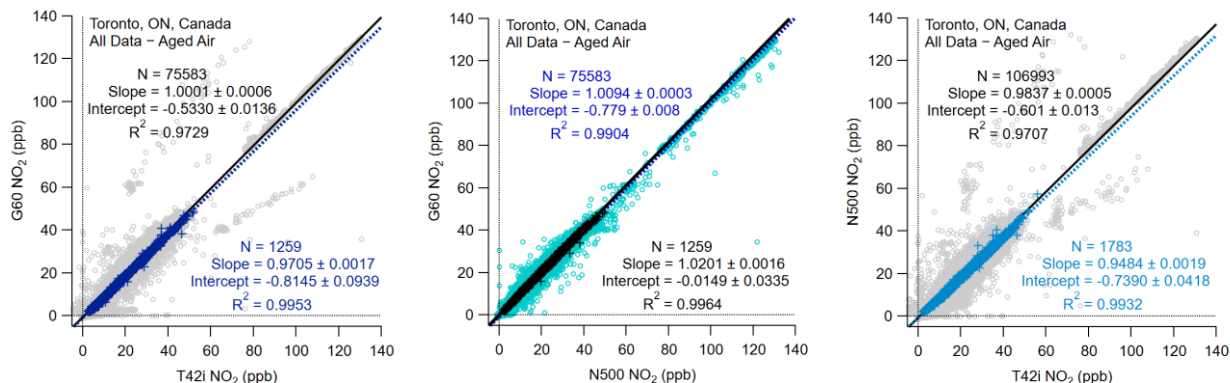


Figure 8: Comparison plots for G60-NO₂, T42i-NO₂, and N500-NO₂ only. The T42i analyzer was adjusted by a small instrument response factor of 4%. The raw (unadjusted) data is given by the grey circles in both the left and right panel. Fit lines show the trends for 1-min and 60-min averaged data. The comparison of G60 to N500 did not apply any response factors.

Tualatin (Portland), OR

Figure 7 shows sample time series (NO₂-NO_x only, 1-min) for the period Nov 22, 2024 – Feb 14, 2025. The Portland deployment, one of the earliest in the campaign, provides an extended record for assessing long-term agreement under continuous operation. The observed correlations between instruments were consistent with those seen at other sites, with moderate-to-strong agreement depending on species and temporal resolution.

As with other deployments, differences in short-term behavior were observed, while longer-term trends remained aligned. These findings highlight the role of measurement approach and temporal averaging in interpreting inter-instrument comparisons.

Cross-Site Observations

So far, across all ICE-MAN deployment locations, several consistent patterns emerged:

- Long-term agreement between instruments is strong across diverse environments;
- Short-term variability contributes significantly to apparent differences at high temporal resolution;
- Daily zero and span checks provide a reliable framework for tracking stability and drift;
- Continuous, uninterrupted measurements enhance the ability to capture real-world atmospheric dynamics;

These observations emphasize that instrument performance cannot be fully characterized through short-term studies alone. Instead, extended deployments with consistent calibration tracking are essential for understanding stability and response behavior under realistic operating conditions.

5. Conclusion

Long-term, uninterrupted intercomparison of NO₂ and NO_x analyzers across diverse environments provides critical insight into instrument behavior that cannot be captured in short-duration studies. Through continuous operation and daily zero and span checks, this work enables direct evaluation of stability, response characteristics, and measurement consistency over extended periods.

Across all deployment sites, strong agreement in long-term trends was observed among co-located instruments, despite differences in measurement approach and operating principles. Variability between instruments was most evident at higher temporal resolution, while longer-term averages showed improved alignment. These observations highlight the importance of considering both temporal resolution and continuous calibration tracking when interpreting intercomparison results.

The use of uninterrupted dual-channel G60-CRDS measurements allowed for continuous tracking of ambient NO₂ and NO_x without reliance on sequential sampling or mode switching. This enabled consistent data capture during rapidly changing emission conditions and contributed to high data completeness across deployments.

Furthermore, daily span and zero checks provided a stable reference framework for assessing drift and ensuring measurement consistency over time. The ability to evaluate instrument behavior within this framework offers a practical approach for understanding long-term performance under real-world operating conditions.

The ICE-MAN campaign represents, to our knowledge, one of the most extensive long-term intercomparison efforts of NO_x monitoring instruments conducted across multiple regions and environmental regimes over the past two decades. The resulting dataset provides a basis for further evaluation by stakeholders across regulatory, academic, and industrial communities, supporting continued refinement of measurement approaches and interpretation of ambient NO₂ data.

6. Acknowledgments

We acknowledge collaboration and support from Environment and Climate Change Canada, United States Environmental Protection Agency, Oregon Department of Environmental Quality, Ontario Ministry of the Environment Conservation and Parks (OMECF), Wood Buffalo Environmental Association, Metro Vancouver, Alberta Environment and Protected Areas, HNU Nordion, Finnish Meteorological Institute, and University of Helsinki.

We thank the individuals responsible for analyzer maintenance, calibration, field operations, and technical support, including Matthew Landis (US-EPA), Zach Koch, Matthew Shrensel, and Ken Moody (ODEQ), Luc White (ECCC), Charley Sever (Metro Vancouver), Nathan Hilker and Teles Furlani (OMECF), Laura Tabor, Emily Nokes and, Jeff McClintock (AEP), Frédéric Bouchard (MELCCFP), Christian Roy (Ville de Montréal), Paavo Pudas (HNU Nordion), Matias Saunamäki (FMI), and Petri Keronen (University of Helsinki), along with others who contributed to the success of these deployments.

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