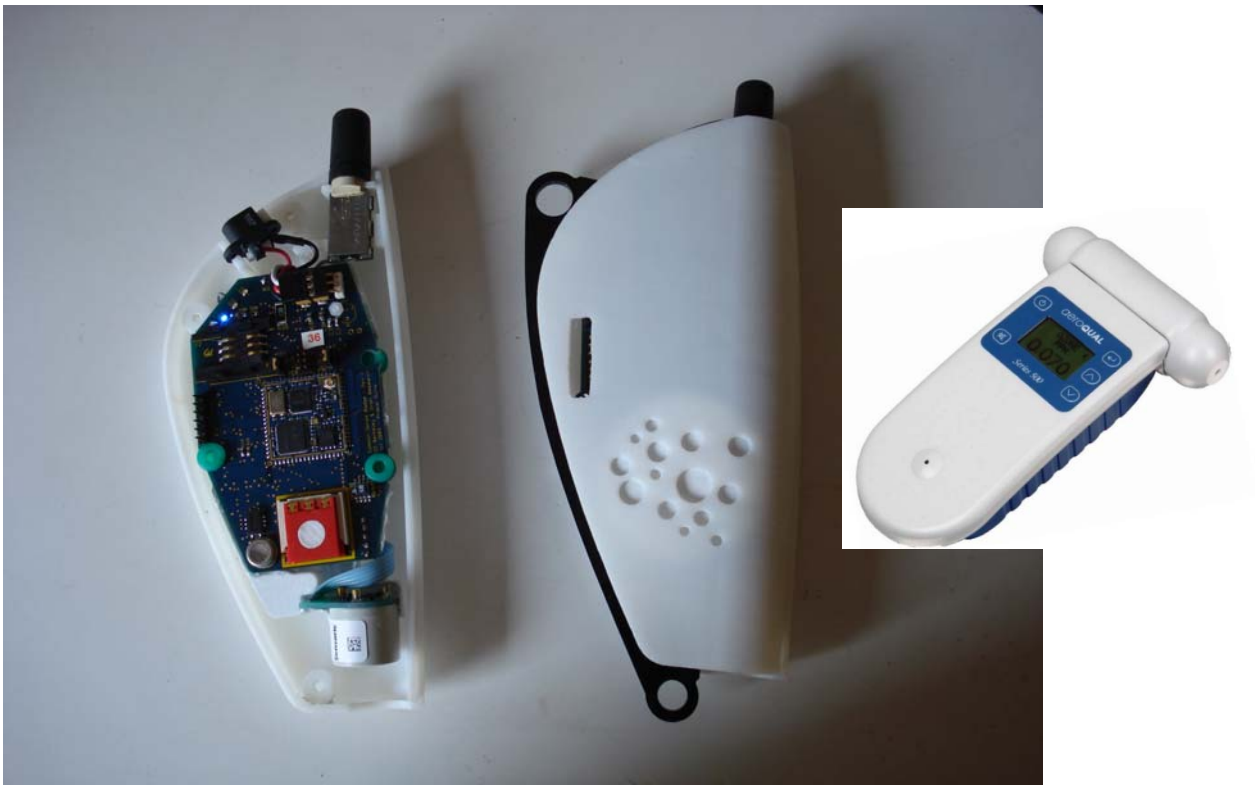
Sonoma Technology, Inc.
Air Quality Research and Innovative Solutions

Characterization of Low-Cost NO_2 Sensors



Draft Final Report Prepared for

U.S. Environmental Protection Agency
Research Triangle Park, North Carolina

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Characterization of Low-Cost NO_2 Sensors

Draft Final Report
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Prepared by

David L. Vaughn
Timothy S. Dye
Paul T. Roberts
Alison E. Ray
Jennifer L. DeWinter
Sonoma Technology, Inc.
1455 N. McDowell Blvd., Suite D
Petaluma, CA 94954-6503
Ph 707.665.9900 | F 707.665.9800
sonomatech.com

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Cover graphic illustrates the Intel Berkeley Badge portable, low-cost sensor and Aeroqual S500 hand-held sensor (inset on right). See Section 2 for more information.

Acknowledgments

The authors would like to acknowledge sensor system manufacturers Intel Berkeley and Aeroqual, which loaned sensors for use in this project. Their cooperation and support during the project are greatly appreciated.

Specifically, we would like to thank Allison Woodruff and Paul Aoki at Intel Berkeley for their ideas, insights, and suggestions regarding the Badge. We wish to thank Geoff Henshaw at Aeroqual for his help and suggestions. Andy Montz at DR DAS made changes to the company's data logging software to accept data from the Intel Berkeley Badges. Again, we wish to thank these individuals for their in-kind help and support with the sensor systems. In addition, we thank the Sonoma Technology, Inc. Publications staff for editing and creating this report.

Table of Contents

Section **Page**

List of Figures

Figure **Page**

Figure **Page**

List of Tables

Table **Page**

Executive Summary

Devices such as mobile phones, electronics, and sensors are shrinking in size and cost. The air quality community is also experiencing this change as manufacturers of air quality instruments and sensors reduce the size and cost of their products. This technology shift has resulted in a wide range of systems being researched and developed by universities, private sector companies, and even the do-it-yourself (e.g., citizen science) community. The lower-cost instruments and sensing systems allow non-government organizations and individuals to monitor and report air quality conditions, a trend that has recently occurred in weather monitoring. The purpose of this study was to begin evaluating the practical application of these smaller, lower-cost sensing systems for specific air quality monitoring tasks.

Interest is increasing in the potential for using small (portable), low-cost nitrogen dioxide (NO_2) sensors for monitoring near roadways and in urban areas. In support of this interest, the current project was performed to evaluate the efficacy of using low-cost, commercially available NO_2 sensor systems to provide data of sufficient quality, accuracy, and precision for diagnosing the major characteristics of pollutant gradients near roadways. The components of the project included: laboratory testing of these NO_2 sensor systems against reference instruments to evaluate the quality of their measurements; a field study to use the sensor systems to make measurements of NO_2 characteristics under a range of traffic and weather conditions; and analysis of the data collected during the field study. Due to performance factors (discussed in Section 2), the project was refocused to evaluate and characterize only the performance of the NO_2 sensor instruments.

At the beginning of the study, we identified two manufacturers of viable sensor systems: Intel Berkeley and Aeroqual. Intel Berkeley has developed a prototype multi-sensor system called the Badge that measures NO_2, O_3, CO, temperature, and humidity. Aeroqual is a commercial air quality instrument company that has developed and sells sensor systems to measure a number of pollutants, including NO_2 and O_3. Both groups loaned sensors to the project, and their cooperation and support during the project are greatly appreciated.

The approach to evaluating and characterizing the sensor systems involved generating a range of concentrations of NO_2 and O_3 in a test chamber and comparing the output from the sensor systems to measurements from standard reference air quality instruments. We conducted a wide range of tests to evaluate response at different concentrations of NO_2 and O_3, evaluated cross-sensitivity and relative humidity effects, and determined the response of sensor systems to changes in concentration.

As discussed in Section 3, several of the sensors produced reasonable and promising results. Yet additional work needs to be performed by the sensor manufacturers and sensor system integrators before “off-the-shelf” systems are capable of producing measurements suitable for the air quality community. Specifically, the conclusions from this study showed

- The electrochemical NO_2 sensor (SensoriC 3E 50) output in the Badge was highly correlated with reference NO_2 levels and had little O_3 cross-sensitivity. Calibration of each individual sensor's output (digitized voltage) to concentration is required for accuracy.

- The handheld Aeroqual S500 O_3 (semiconductor-based, calibrated) sensor showed good correlation with neighborhood-scale O_3 measurements and exhibited similar correlations in the testing chamber, but there were problems with repeatability.
- The uncalibrated semiconductor-based (metal-oxide) sensors in the Badge showed a variable correlation with the reference measurements. This resulted in poor precision in repeated experiments. Cross-sensitivity was evident. The metal-oxide NO_2 sensor in the Badge exhibited cross-sensitivity to O_3, but the degree of sensitivity varied between identical sensors. Some sensors that initially were not cross-sensitive developed sensitivity as testing progressed. The metal-oxide O_3 sensor in the Badge showed low sensitivity to O_3 but responded to NO_2. Fully characterizing the source(s) of various issues (environmental factors, aging, air flow characteristics, and poisoning) was beyond the scope of this study.
- The OEM-style Aeroqual NO_2 and O_3 semiconductor-based sensors (SM50, calibrated) exhibited "random" fluctuations, although correlated responses to reference gas concentrations were measured occasionally. This is the same sensor installed in the company's S500, suggesting that the packaging plays an important role in sensor response.
- The commercially available Aeroqual AQM-60 NO_2 monitor (0-200 ppb calibrated, semiconductor-based, aspirated) showed good correlation with NO_2 reference measurements in early tests but was inaccurate and exhibited significant time lag. Performance (correlation) degraded with repeated testing.

Based on the results and insight gained during this study, as well as knowledge of other studies underway, we offer the following recommendations.

1. EPA should consider conducting a follow-on study in the next two years that further examines the ability of newer sensor systems to make reliable, repeatable, and accurate measurements on both fixed and moving platforms. This study should more closely engage the manufacturers to lessen the steep learning and operational curve that existed for this study. Once that acceptable performance is confirmed, conduct a small, focused field study to examine the operational issues related to field deployments of these low-cost sensor systems.
2. Many efforts are underway at universities, research laboratories, and in the private sector to examine the ability of using lower-cost sensors and sensor systems to make air quality measurements. EPA could help coordinate these many efforts by sponsoring a meeting or workshop to begin integrating this loose-knit community. The workshop would provide an opportunity for EPA to communicate the needs and requirements for measurements that would be suitable for the air quality community. Also, EPA could learn more about how non-air quality agencies and other organizations and individuals are making measurements.
3. Seek to understand the impact of mobile monitoring on EPA programs (e.g., regulatory, AIRNow public outreach) by conducting a field program with higher-cost, more accurate instruments. This would provide data of sufficient accuracy to examine and understand the impact of low-cost, mobile sensors on EPA's programs while reducing the uncertainty about the actual sensors and sensor systems, which hampered this study.

For example, collecting O_3 or $PM_{2.5}$ data from various mobile platforms and then fusing this information with real-time AIRNow data would allow EPA to explore the future impacts of a denser monitoring network on the AIRNow maps and other outreach programs.

4. Increasingly, other organizations are installing mid-cost O_3 and PM instruments and providing real-time and historical data on their websites (Air Alliance Houston, 2009, and Save the Air in Nevada County, 2010). This presents a challenge and an opportunity for EPA and state/local air quality agencies in terms of data representativeness, ownership, consistency, advocacy, measurement conflicts, non-attainment boundaries, public outreach, etc. With several nascent networks already measuring routine air quality conditions, we recommend that EPA engage these groups and local air quality agencies to better understand the future implications for air quality management. In addition, this engagement would provide an opportunity to explore collaborative monitoring efforts that seek to ensure comparability, maximize coverage, and reduce costs.

1. Objective

1.1 Original Objective

The overall objective of the project was to evaluate the efficacy of using low-cost, commercially available nitrogen dioxide (NO_2) sensor systems to provide data of sufficient quality, accuracy, and precision for diagnosing the major characteristics of pollutant gradients near roadways. The components of the project, designed to meet the overall objective, included: laboratory testing of NO_2 sensor systems against reference instruments to evaluate the quality of their measurements; a field study to use the sensor systems to make measurements of NO_2 characteristics under a range of traffic and weather conditions; and analysis of the data collected during the field study. The underlying assumption of the entire study was that the sensor systems would reliably provide reasonable measurements for conducting the field study, yielding data suitable for analysis of NO_2 gradients.

1.2 Challenges

Although there is significant research and development of low-cost sensors for pollutant monitoring (for example, Aoki et al., 2009; Williams et al., 2009), understanding and interpreting sensor signals in real-world environments remains limited and challenging. We encountered a number of problems that ultimately required us to focus all the project's resources on the first component: comparison of the NO_2 sensor systems against reference instruments in the laboratory to evaluate the quality of their measurements.

1.3 Revised Objective

Based on the performance issues outlined in Section 2, and after consultation with EPA, we decided to focus solely on the lab evaluations to better characterize the sensor systems and to forgo the field study.

2. Approach

The evaluation procedure included the selection of sensor systems for testing; development of the experimental approach (characterization tests), including construction of the physical facilities needed to conduct the evaluations; and an iterative process of testing, data review, and retesting guided by the previous results.

2.1 Instruments Tested

The selection criteria, measurement methodologies, manufacturer specifications, and photographs of the sensor systems are provided here.

2.1.1 Sensor System Selection

The criteria for selecting the systems to test were based on the planned use of the sensors in real-world environments.

- Size: Sensor systems must be small and portable, preferably deployable on persons or in areas where sophisticated (heated/cooled) support enclosures are not available.
- Power: Preferably, the sensor systems have the option for battery operation for up to several hours.
- Communications and data storage: The devices should support real-time data communications and/or the ability to store data locally for later export.
- Cost: To assess gradients near roadways, spatially separated arrays of sensors are required, making cost an important consideration. The sensor systems evaluated would preferably be priced in the range of a few hundred dollars.
- Detection limit and measurement range: The sensor systems should be capable of measuring gas concentrations in the ranges commonly encountered under ambient atmospheric conditions near roadways.
- Availability: In addition to low cost, the sensors must be commercially available, or amenable to commercialization.

The sensor systems selected for the evaluation included the multi-sensor Badge (Intel Berkeley) and four single-sensor systems from Aeroqual, two of which were tested in OEM configuration (the SM50 NO_2 and the SM50 O_3) and two of which were in commercially available packages (the AQM 60 NO_2 and S500 O_3).

2.1.2 Sensor Measurement Methodology

The sensor systems selected employed one of two sensor methodologies: electrochemical or semiconductor (metal oxide). The summary of the sensors in **Table 2-1** lists their type, parameter measured, packaging, and air flow characteristics.

Table 2-1. Sensors that underwent testing, their type, parameter(s) measured, whether they were packaged or OEM components, and air flow characteristics.

	Intel Berkeley Badge							Aeroqual			
	SensoriC NO_2 3E 50	SensoriC O_3 3E 1	e2v MiCS 4514	e2v MiCS 2610	MICROceL CF	Sensirion SHT1x	Sensirion SHT1x	SM50	AQM 60	SM50	S500
Sensor Type	Electro-chemical	Electro-chemical	Metal oxide	Metal oxide	Metal oxide	Capacitive	Band-gap (silicon diode)	Metal oxide (GSS[1])	Metal oxide (GSS[1])	Metal oxide (GSS[1])	Metal oxide (GSS[1])
Parameter	NO_2	O_3	NO_2 and CO	O_3	CO	RH	Temperature	NO_2	NO_2	O_3	O_3
Packaged	Yes[2]	Yes[2]	Yes[2]	Yes[2]	Yes[2]	Yes[2]	Yes[2]	No[3]	Yes[3]	No[3]	Yes[3]
Air flow	Passive							Aspirated			

[1] Gas-sensitive semiconductor
[2] Packaged in the Intel Berkeley Badge
[3] Aeroqual sensors were all single-sensor systems

Electrochemical Sensors

Electrochemical sensors are comprised of two electrodes separated by a thin layer of electrolyte and enclosed in a plastic housing. A small capillary allows gas to enter the sensing electrode and includes pins electrically attached to both electrodes. These pins may be connected to a simple resistor circuit that allows the voltage drop resulting from any current flow to be measured. Gas diffusing into the sensor is either oxidized or reduced at the sensing electrode. Coupled with a corresponding counter-reaction at the other electrode, a current is generated through the external circuit. Since the rate of gas entry into the sensor is controlled by the capillary, the current generated is proportional to the concentration of gas present outside the sensor, which gives a direct measure of the gas present.

Metal-Oxide Sensors

Metal oxides, deposited by using thin-film techniques, are used as sensor elements. A structure for a heated electrode is integrated into the chip to achieve a desirable operating temperature. (The conductivity of these semiconductor electrical sensors is affected by atmospheric gases at temperatures between 150° C and 900° C.) Gases are adsorbed and desorbed, which affects the conductance/resistance of the metal oxides. The selectivity of the sensor can theoretically be “tuned” over a wide range depending on the metal-oxide structure and morphology, dopants, contact geometries, mode of operation, and other factors. However, this makes it difficult to understand real sensor signals, as measured in practical applications.

2.1.3 Photographs

The Intel Berkeley Badge is pictured in **Figure 2-1.** The upper portion of the picture shows the Badge enclosure and circuit board. This is a multi-component sensor system; the individual sensor components are shown in the bottom portion of Figure 2-1.

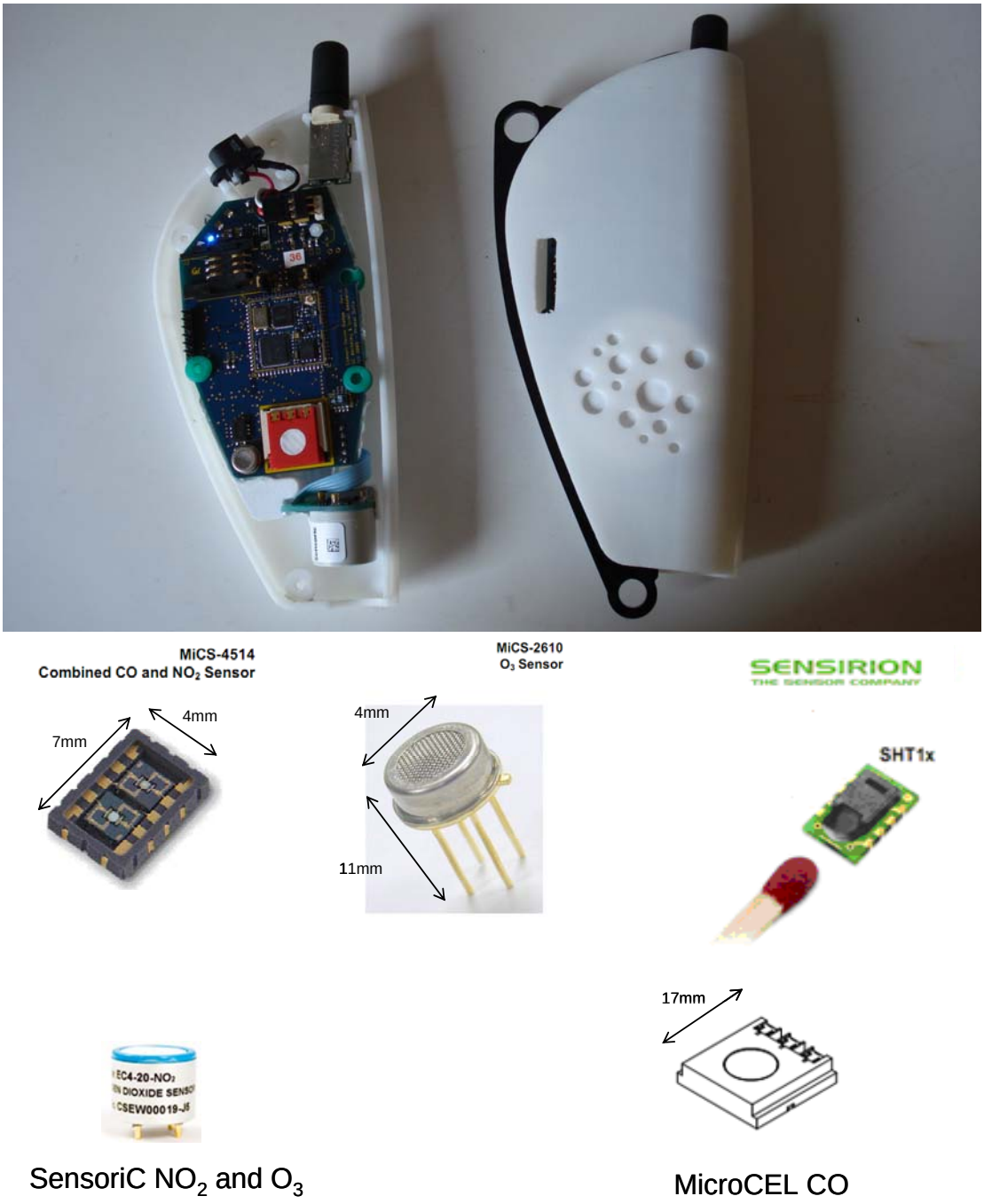

Figure 2-1. The Intel Berkeley Badge and component sensors.

The Aeroqual sensor systems are pictured in **Figure 2-2.** The SM50 board is an OEM-style product; the NO_2 and O_3 versions were included in the tests. The AQM 60 NO_2 instrument is a larger system that comes as an integrated package with an enclosure (pictured) that houses a pump and Aeroqual proprietary components. The Aeroqual S500 is a handheld unit with interchangeable sensor heads; the O_3 version was tested.

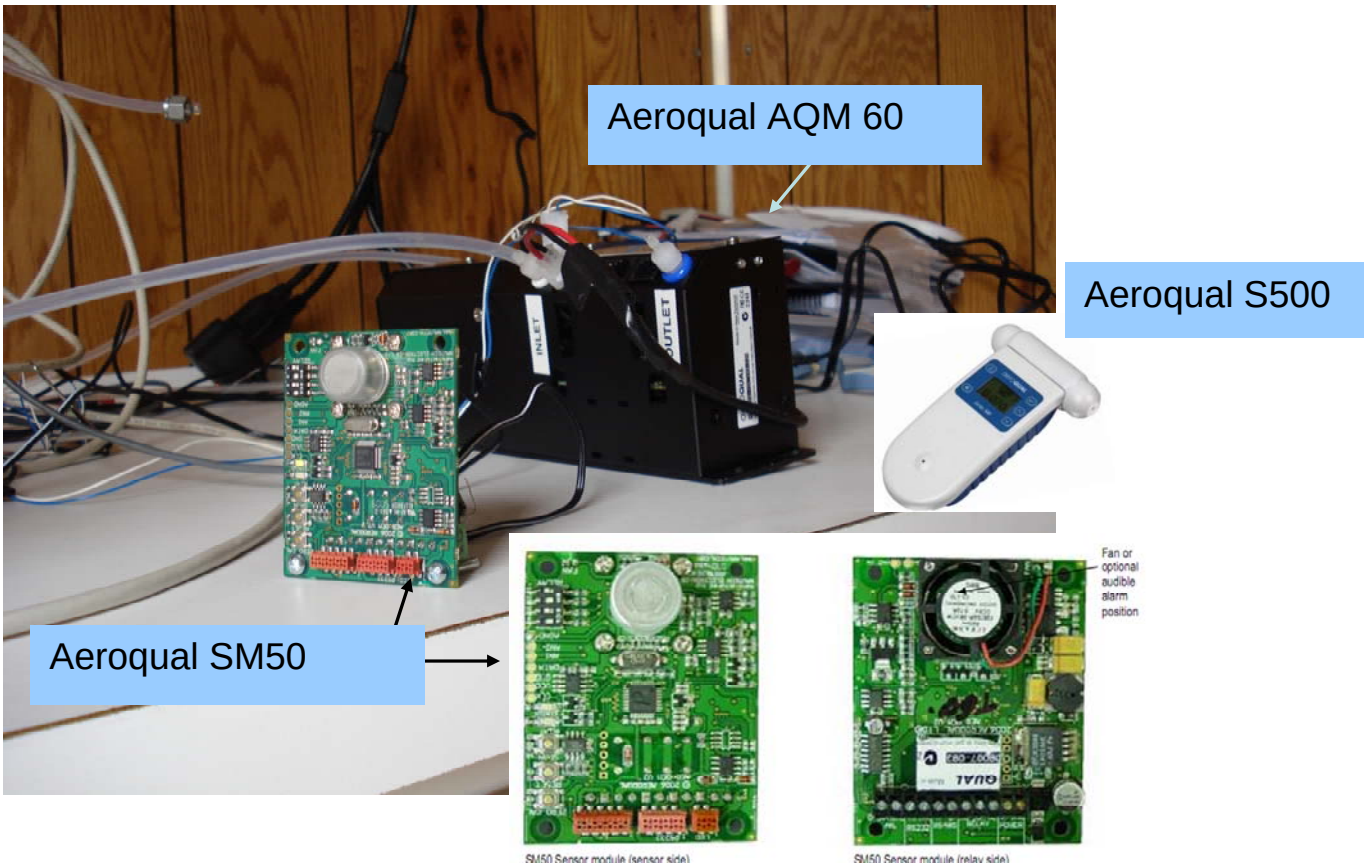

Figure 2-2. The Aeroqual sensor systems. The SM50 has both NO_2 and O_3 versions. The larger AQM 60 package measures NO_2. The S500 was set up to test O_3.

2.2 Characterization Experiments

Following the initial setup of the laboratory evaluation, most of the project resources were focused on experiments to characterize the response of the sensor systems in bench testing protocols. The overall experimental approach, a description of the facilities, and a list of the specific tests are given below.

2.2.1 General Approach

Our general approach for evaluating the inexpensive sensors relied on the accepted and basic experimental practice of quantifying the effect of a single factor (e.g., NO_2 concentration or humidity) while keeping other factors constant. By varying the levels of one input at a time, we sought to develop a data set to characterize sensor response. This approach was made increasingly complex because of the array of sensor types being tested and the large number of environmental variables that could potentially impact the sensors' response.

While technical specifications were available from the metal-oxide and electrochemical sensor manufacturers, the information sheets were frequently laden with caveats pertaining to the specifications. For example, a footnote in a specification sheet for the MICROceL sensor in

the Intel Berkeley Badge stated "The data is given for guidance only. It does not constitute a specification.… It is the clients' responsibility to carry out the necessary tests to determine the usefulness of the products.…" At best, this guidance represents estimates quantifying temperature, humidity, cross-sensitivities, aging, and "poisoning" effect. The real-world characteristics of sensor response were unknown. This contrasts with existing (expensive) reference or equivalent monitors where, given appropriate shelter characteristics, specifications are fairly exact.

2.2.2 Facilities

One of Sonoma Technology, Inc.'s mobile monitoring trailers was moved on site in Petaluma to facilitate the sensor evaluation. The trailer is temperature controlled and has a work bench, work table, and equipment rack that houses the reference monitoring instruments and the PC-based data acquisition system (DAS, see **Figure 2-3**). The reference instruments included a Thermo Scientific Model 111 zero-air system and a Model 146i dilution calibrator that were used to provide 5 lpm of zero air, or known compositions of O_3 and/or NO/NO_2 air via gas phase titration (GPT) utilizing a NIST-traceable tank of NO. Instruments for providing reference measurements of source gases included a Thermo Scientific Model 42i for measuring $NO/NO_2/NO_x$, a Dasibi Model 1008 O_3 analyzer, and a Thermo Scientific Model 48i CO analyzer to provide auxiliary measurements of CO.

The DAS employed PC-based DR DAS software (EnvidasFW) with both analog and digital monitoring capabilities. The DAS required special modifications to correctly read the digital output from the Badge sensor system. A Plexiglas® glove box was modified to serve as a ventilated hood (see **Figure 2-4**). The sensor systems were placed inside a large Tedlar bag, and the bag was put in the ventilated hood. Teflon lines carried source air from the dilution calibrator to the inside of the Tedlar bag. Teflon sampling lines carried air from the bag back to the reference NO_x and O_3 analyzers. Electrical power cables were routed through a small opening in the bag to the sensor systems, and sensor signal cables (analog or RS232) were routed from inside the bag to the DAS. In addition to the Tedlar bag/ventilated hood, a special chamber was constructed to provide the needed flow characteristics to allow some testing of RH effects (see the Figure 2-3 bottom inset). The volume of the RH chamber had to be kept low because the LiCor 610 dew point generator that was used to provide air with a known dew point to the dilution calibrator flow was limited to 0.2 lpm total flow. To minimize the dilution effects of the high flow rate from the dilution calibrator, an in-line needle valve was used to restrict the dilution calibrator flow. A reference temperature and RH sensor monitored chamber conditions. A type T thermocouple was used to measure air flow temperature so that the saturation vapor pressure could be calculated and the set point temperature of the LiCor 610 could be set to reach the appropriate dew point.

Figure 2-3. The system supplying the test gases (NO_2 and O_3) and measuring the reference concentrations. Top inset shows the DAS real-time data display. Bottom inset is the RH test chamber.

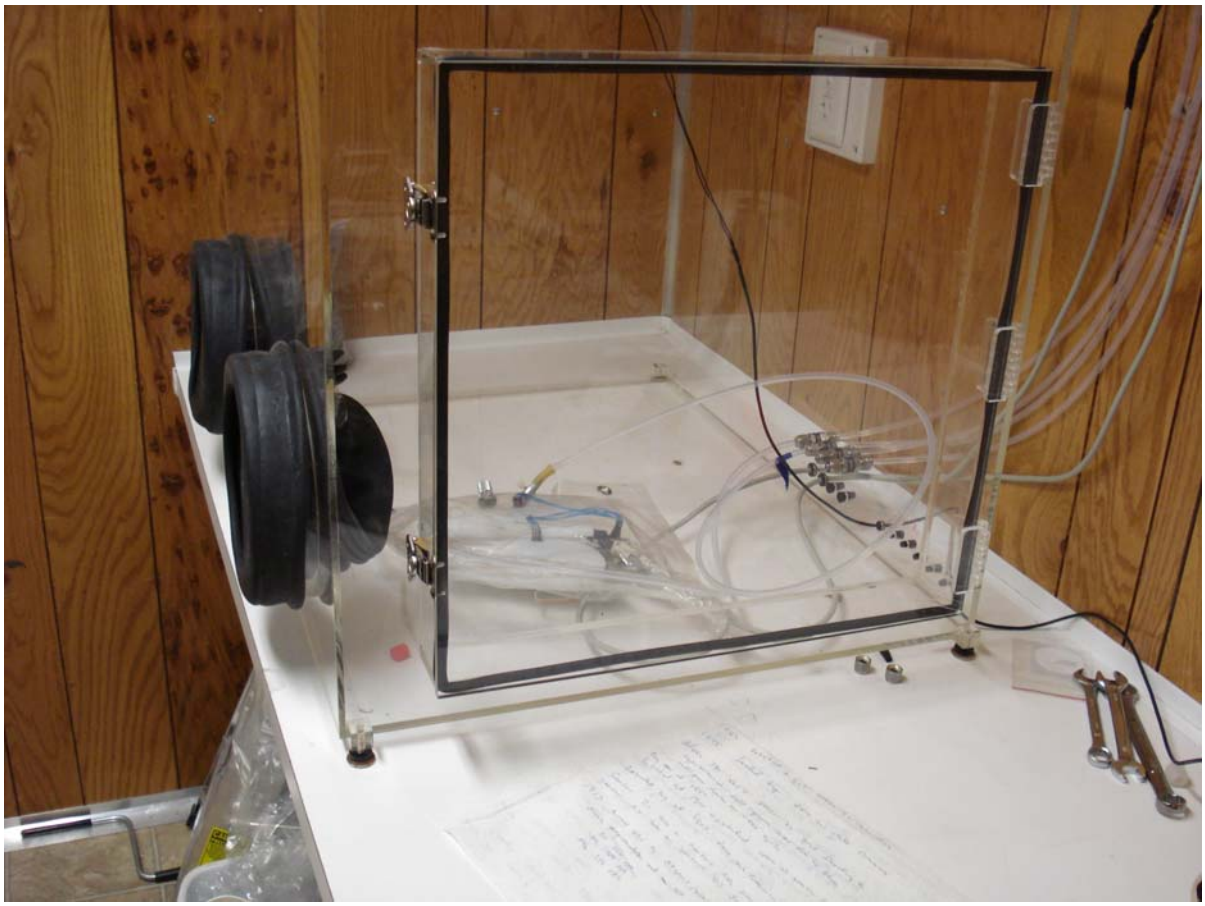

Figure 2-4. A glove box acts as a ventilated hood housing a small Tedlar bag containing two Badges. A larger Tedlar bag was added to accommodate four badges and two SM50 sensors.

2.2.3 Specific Tests

The types of tests conducted are listed in **Table 2-2**.

Table 2-2. Tests of the sensor systems focused on bump tests and step tests of gases in varying concentrations and intervals.

Test Name	Description	Purpose
NO_2 bump tests	Sensors are dosed with one concentration of NO_2 for a nominal time period, followed by zero air; repeated	Used as an initial gauge of NO_2 sensor response, rate of response, and hysteresis; also serves as a check of O_3 sensor cross-sensitivity to NO_2
O_3 bump tests	Sensors are dosed with one concentration of O_3 for a nominal time period, followed by zero air; repeated	Used as an initial gauge of O_3 sensor response, rate of response, and hysteresis; also serves as a check of NO_2 sensor cross-sensitivity to O_3
NO_2 step tests	Similar to the NO_2 bump test, but successive steps vary in NO_2 concentration with no intervening zero air	Response time and saturation effects with stepwise increases in pollutant levels; cross-sensitivity
O_3 step tests	Similar to the O_3 bump test, but successive steps vary in O_3 concentration with no intervening zero air	Response time and saturation effects with stepwise increases in pollutant levels; cross-sensitivity
Step tests with alternating NO_2 and zero air	Similar to the NO_2 step test, but successive steps in NO_2 are alternated with periods of intervening zero air	If saturation effects are evident, can the sensors be “cleansed” by periods of zero air? Hysteresis check
Step tests with alternating O_3 and zero air	Similar to the O_3 step test, but successive steps in O_3 are alternated with periods of intervening zero air	If saturation effects are evident, can the sensors be “cleansed” by periods of zero air? Hysteresis check
Step tests with alternating NO_2 and O_3	Step tests but no zero air	Cross-sensitivity check; saturation effects
Stability tests	Prolonged exposure at steady gas concentration	Stability and drift
RH tests	Multiple RH levels at one gas concentration	Estimate magnitude of RH effect

3. Results

Thirty-one individual experiments were conducted, each lasting from several hours to a few days. The longer trials included repeat or replicate runs. When logistically possible, all available sensor systems were included in each experiment. Sometimes space was limiting: in the case of the RH testing, the RH chamber could accommodate only a single Badge and SM50. Initially, only one Badge was available, but this eventually increased to four. Only one each of the Aeroqual SM50 NO_2, SM50 O_3, S500, and AQM 60 were available at any given time.

3.1 Qualitative Evaluation

Of all tested sensors, only the SensoriC NO_2 3E 50 in the Intel Berkeley Badge showed consistently good results and holds promise for providing useful information for the air quality community. While some other sensors showed initial results that appeared workable, evidence of response drift with time became more apparent as the testing progressed. Time lag was a significant problem with many of the metal-oxide sensors, as was cross-sensitivity. In some cases, the performance of sensors seemed to degrade with time. In other cases, sensors became unresponsive or were erratic in response from the beginning. A qualitative summary of the testing results is given in **Table 3-1**. Detailed quantitative examples are provided in the following sections.

Table 3-1. A qualitative summary of the results from the sensor system evaluations.

	Intel Berkeley Badge							Aeroqual			
	SensoriC NO_2 3E 50	SensoriC O_3 3E 1	e2v MiCS 4514	e2v MiCS 2610	MICROceL CF	Sensirion SHT1x	Sensirion SHT1x	SM50	AQM 60	SM50	S500
Sensor Type	Electrochemical	Electrochemical	Metal oxide	Metal oxide	Metal oxide	Capacitive	Band-gap (silicon diode)	Metal oxide (GSS[1])	Metal oxide (GSS[1])	Metal oxide (GSS[1])	Metal oxide (GSS[1])
Parameter	NO_2	O_3	NO_2 & CO	O_3	CO	RH	Temperature	NO_2	NO_2	O_3	O_3
Qualitative Rating	Good	Not responsive to O_3	Fair, variable	Fair, variable	NA[2]	Good	Good	Fair	Poor	Poor	Good
Repeatability	Good	Good	Poor	Poor	NA[2]	Good	Good	Very poor	NA[3]	NA[3]	Good
Time lag	Minimal	Minimal	Substantial	Substantial	NA[2]	None	None	Substantial	NA[3]	NA[3]	Minimal
Linearity	Good	Not known	Non-linear	Non-linear	NA[2]	Non-linear, Calibrated	Non-linear, Calibrated	Linear	NA[3]	NA[3]	Good
Interferences	RH	NO_2, RH	RH	NO_2, RH	NA[2]	None	None	RH	NA[3]	NA[3]	None detected

[1] Gas-sensitive semiconductors
[2] The MICROceL CF sensor data were not evaluated
[3] The Aeroqual AQM 60 NO_2 response degraded with time, and the SM50 O_3 sensor had frequent errors, resulting in full-scale output signal

3.2 Quantitative Results

The results presented in this section are examples drawn from the collected data that are representative of the observed sensor responses. Individual experiment results may differ from those shown here (some better, some worse), which points out that variability in response was a common thread throughout the evaluation.

3.2.1 The Berkeley Badge Electrochemical SensoriC 3E 50 NO_2 Sensors

The NO_2 version of this electrochemically based sensor responded to ambient-level NO_2 concentrations in a consistent manner throughout the evaluation process (**Figure 3-1**). Time lag was negligible. Cross-sensitivity to O_3 was not prevalent. While the sensor itself is not calibrated, the Analog Digital Conversion (ADC) units showed a linear response over NO_2 concentration ranges of interest. **Figure 3-2** and **Figure 3-3** are scatter plots of Badge 21 and Badge 22 data, respectively. **Figure 3-4** represents a typical calibration curve constructed from Badge 21 data points; each point was chosen after several minutes of equilibration time for each reference NO_2 concentration. The NO_2 version of the sensor essentially requires only a calibration to provide a conversion factor from the ADC units. It would be a reasonably accurate and precise measuring device for NO_2 studies near roadways. The sister SensoriC 3E 1 sensor for O_3, while sensitive to O_3, showed a strong cross-sensitivity to NO_2, limiting its usefulness for O_3 studies (data not shown).

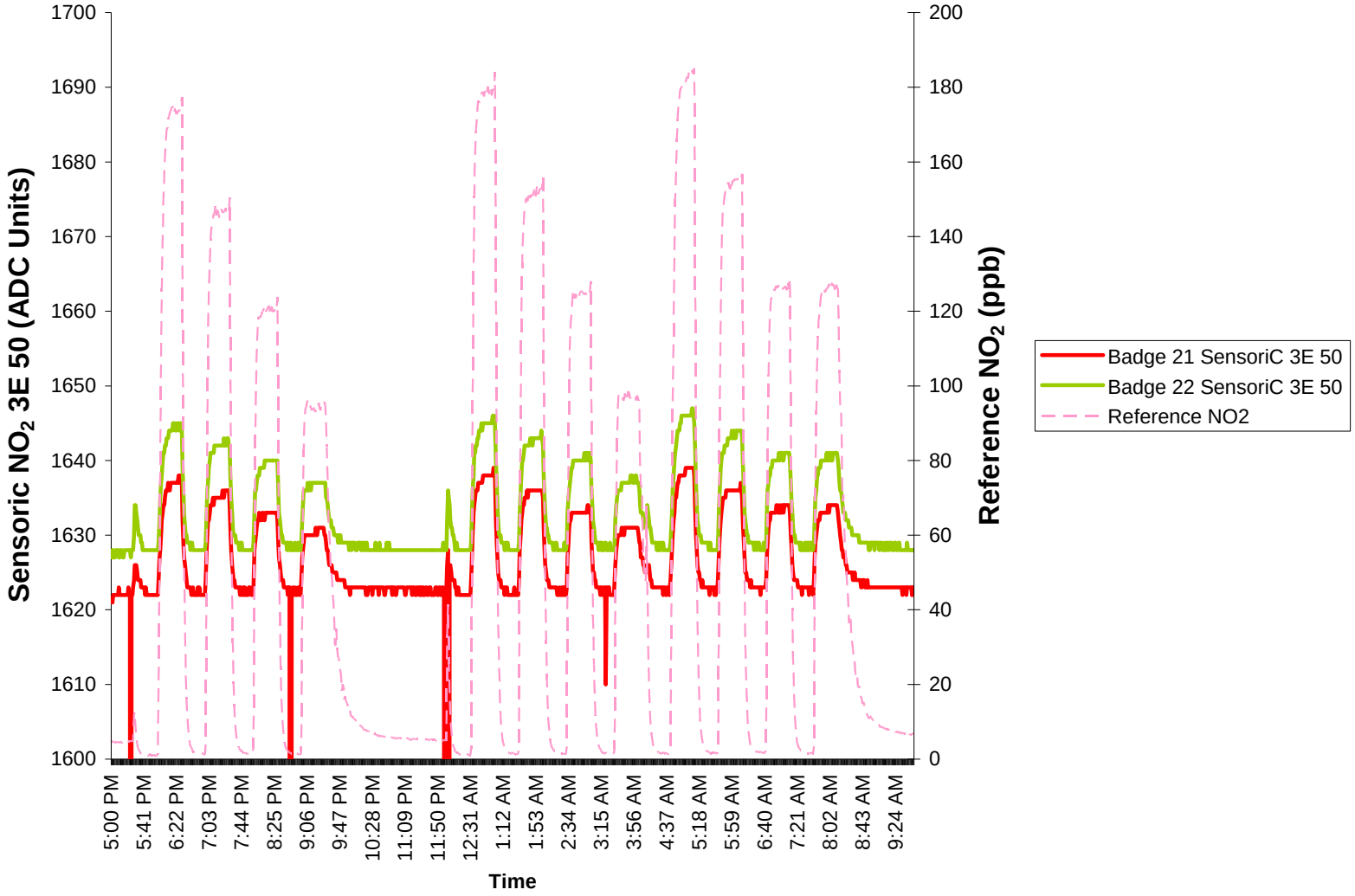

Figure 3-1. The SensoriC 3E 50 NO_2 sensor yielded a correlated response to NO_2 bump tests and step tests over NO_2 concentration ranges of interest. The excursions below baseline (1620 ADC units) for Badge 21 are unexplained. The experiment was conducted on 7/7/10.

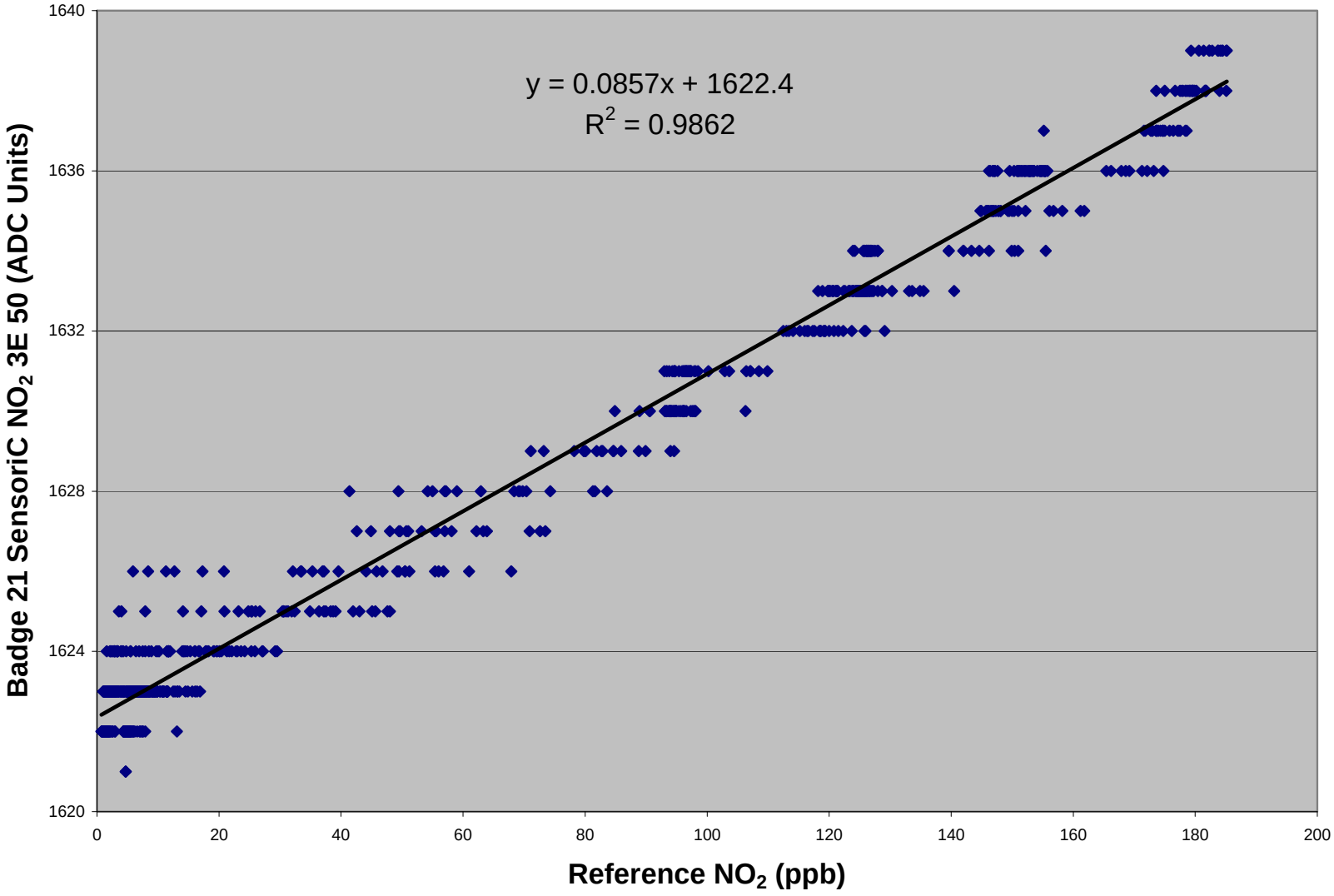

Figure 3-2. Scatter plot of the ADC response of the SensoriC 3E 50 NO_2 sensor of Badge 21. Data are the same as those in the time series of Figure 3-1, but six points representing the excursions below baseline have been removed from the scatter plot.

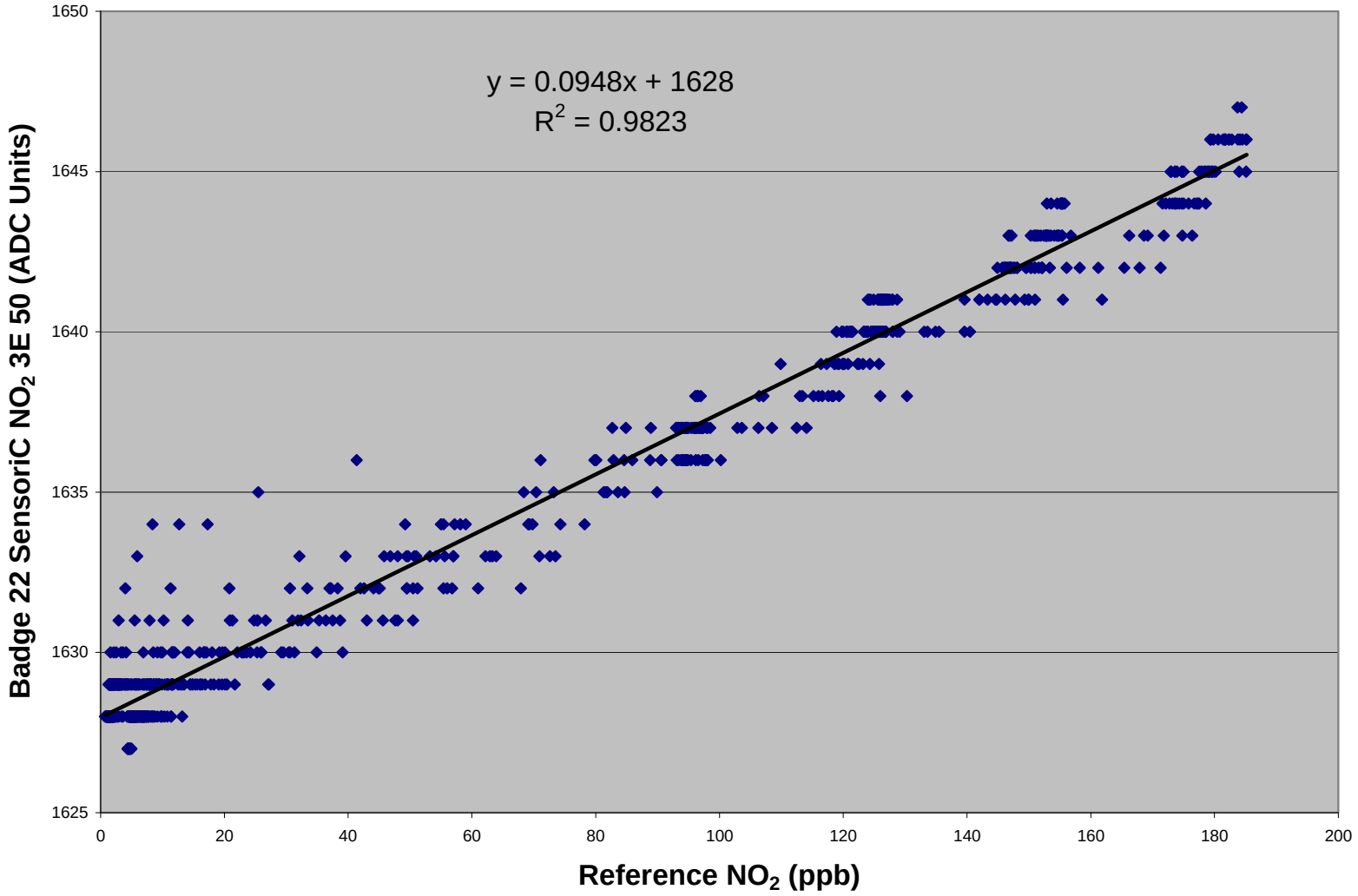

Figure 3-3. Scatter plot of the ADC response of the SensoriC 3E 50 NO_2 sensor of Badge 22. The Badge 22 data are shown in the time series of Figure 3-1.

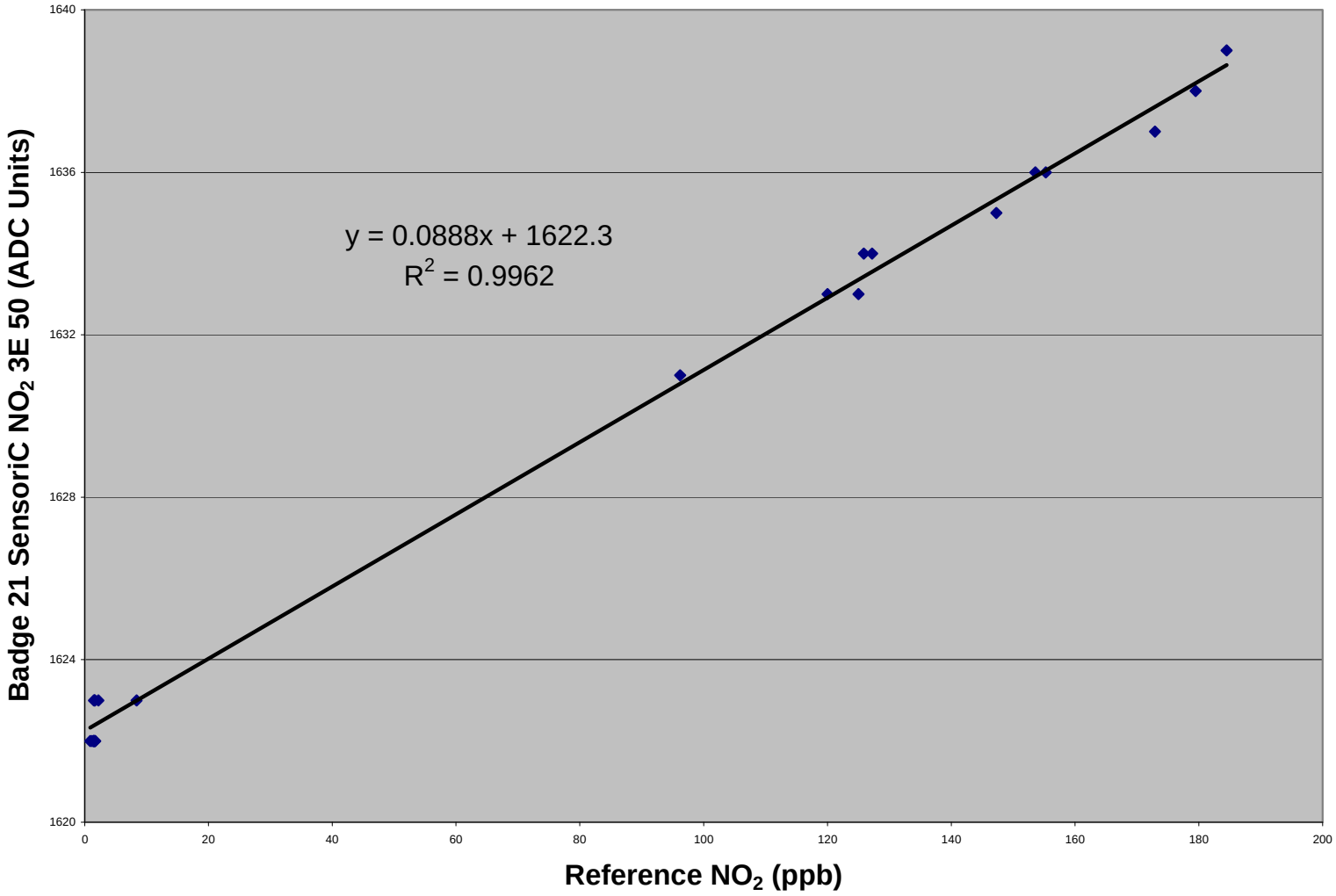

Figure 3-4. Scatter plot of the ADC response of the SensoriC 3E 50 NO_2 sensor of Badge 21. This scatter plot reflects a typically constructed calibration curve using data from Badge 21 and showing data points taken after the sensor was allowed to stabilize for several minutes at each reference NO_2 concentration.

3.2.2 The Aeroqual SM50 NO_2 Sensor

The Aeroqual SM50 NO_2 instrument showed an increasing response to increasing concentrations of NO_2 (**Figure 3-5**). This is a calibrated sensor in the range of 0-200 ppb. Linearity was affected by some lag in rise time as NO_2 increased (data below regression line in **Figure 3-6**) and some lag when NO_2 concentrations dropped (data above regression line in Figure 3-6). This lag effect becomes important in situations where steep concentration gradients may exist, such as in mobile monitoring or near-roadway monitoring where NO_2 levels can change rapidly.

The manufacturer states that the SM50 NO_2 sensor may react to O_3 above concentrations of 50 ppb, but step tests of alternating NO_2 and O_3 suggest that this cross-sensitivity may be expressed at lower O_3 concentrations (**Figure 3-7**). The cross-sensitivity decreased the correlation between the SM50 NO_2 device and reference NO_2 concentrations (**Figure 3-8**).

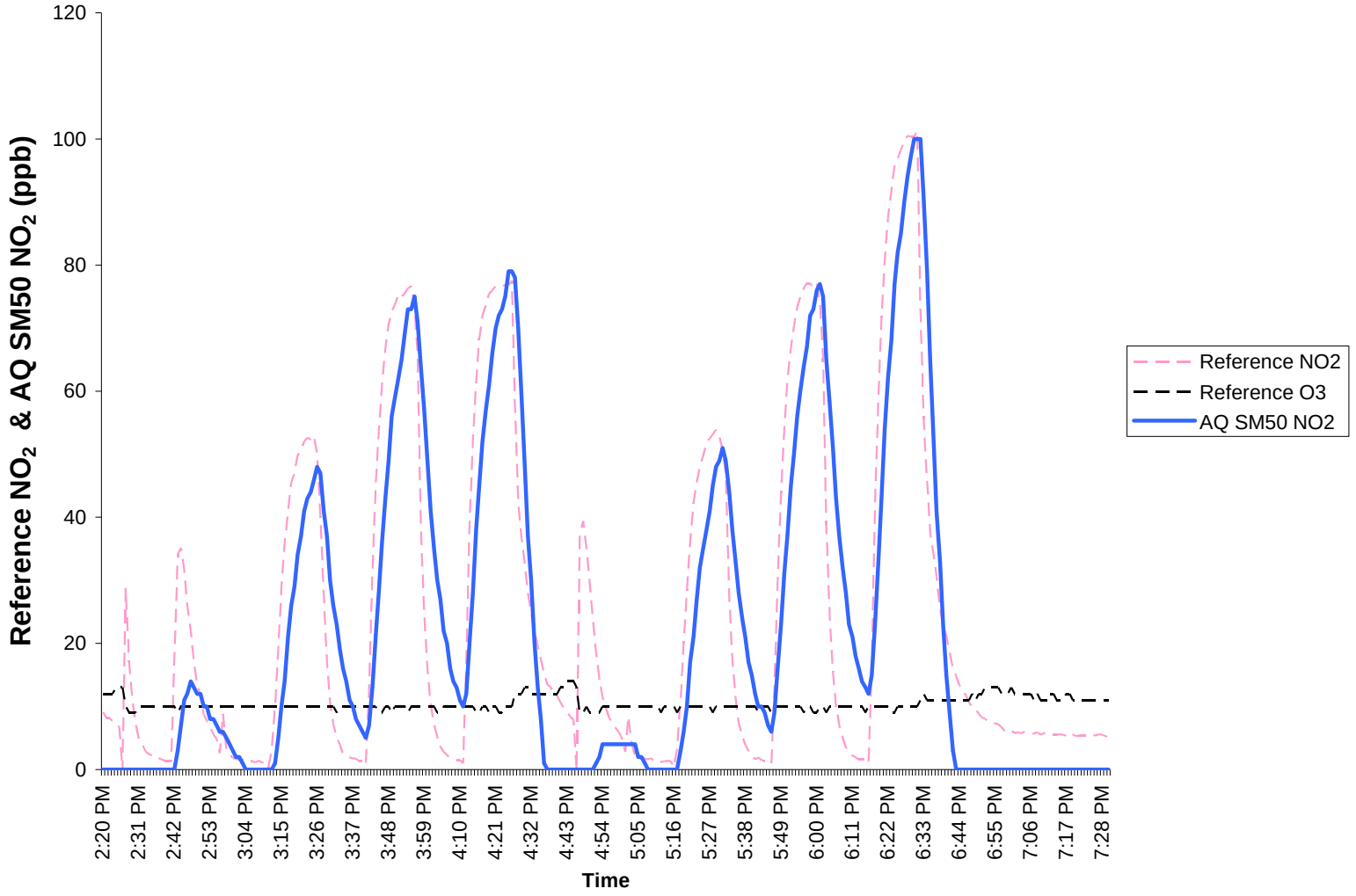

Figure 3-5. The calibrated Aeroqual SM50 NO_2 sensor showed a good correlation with NO_2 concentration but exhibited some hysteresis, illustrated by the delay in rise time and the lag when reference gas levels decreased quickly. The experiment was conducted on 5/26/10.

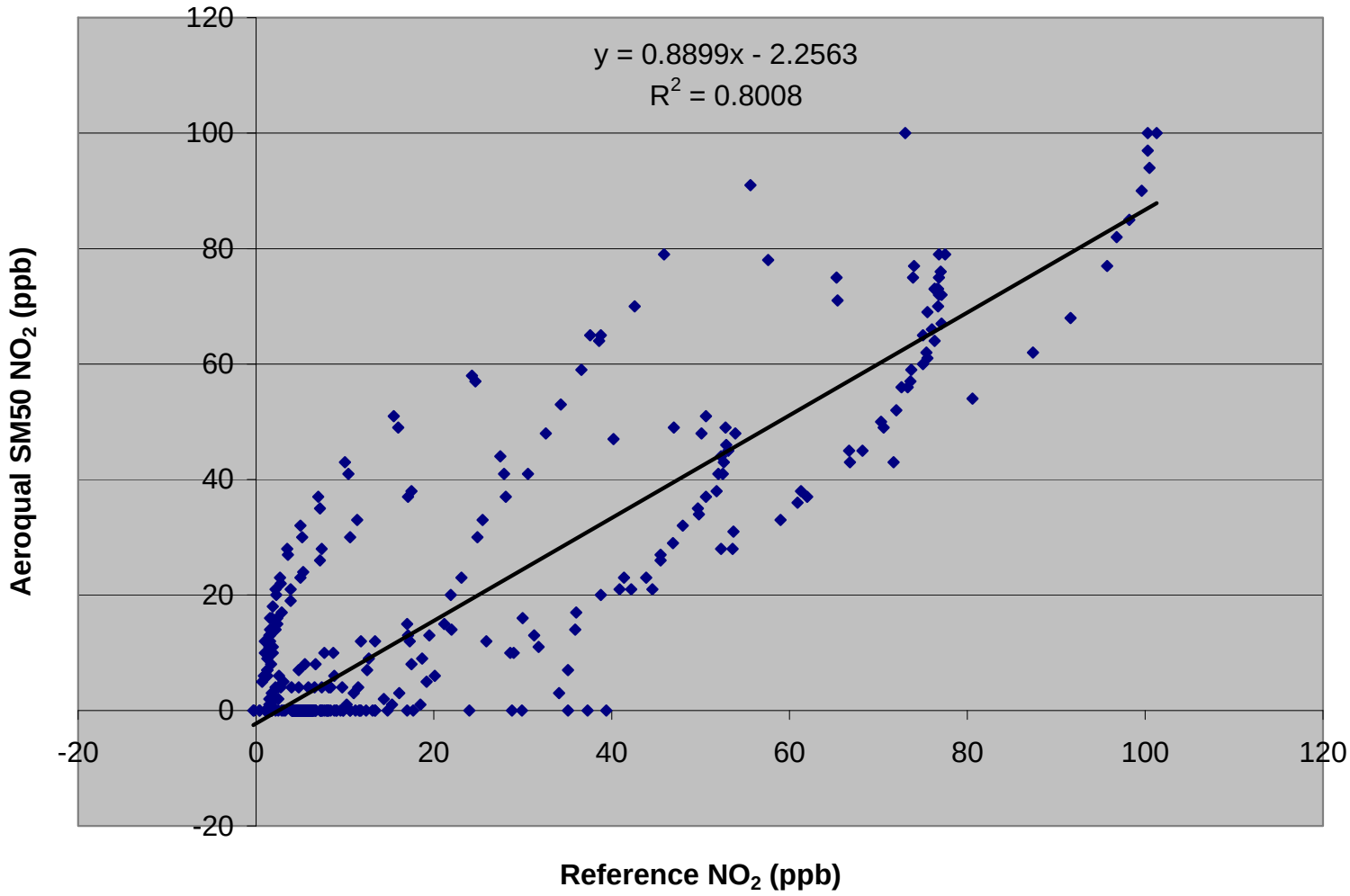

Figure 3-6. A scatter plot of the time series data shown in Figure 3-5 illustrates the time lag observed in the Aeroqual SM50 NO_2 sensor. The experiment was conducted on 5/26/10.

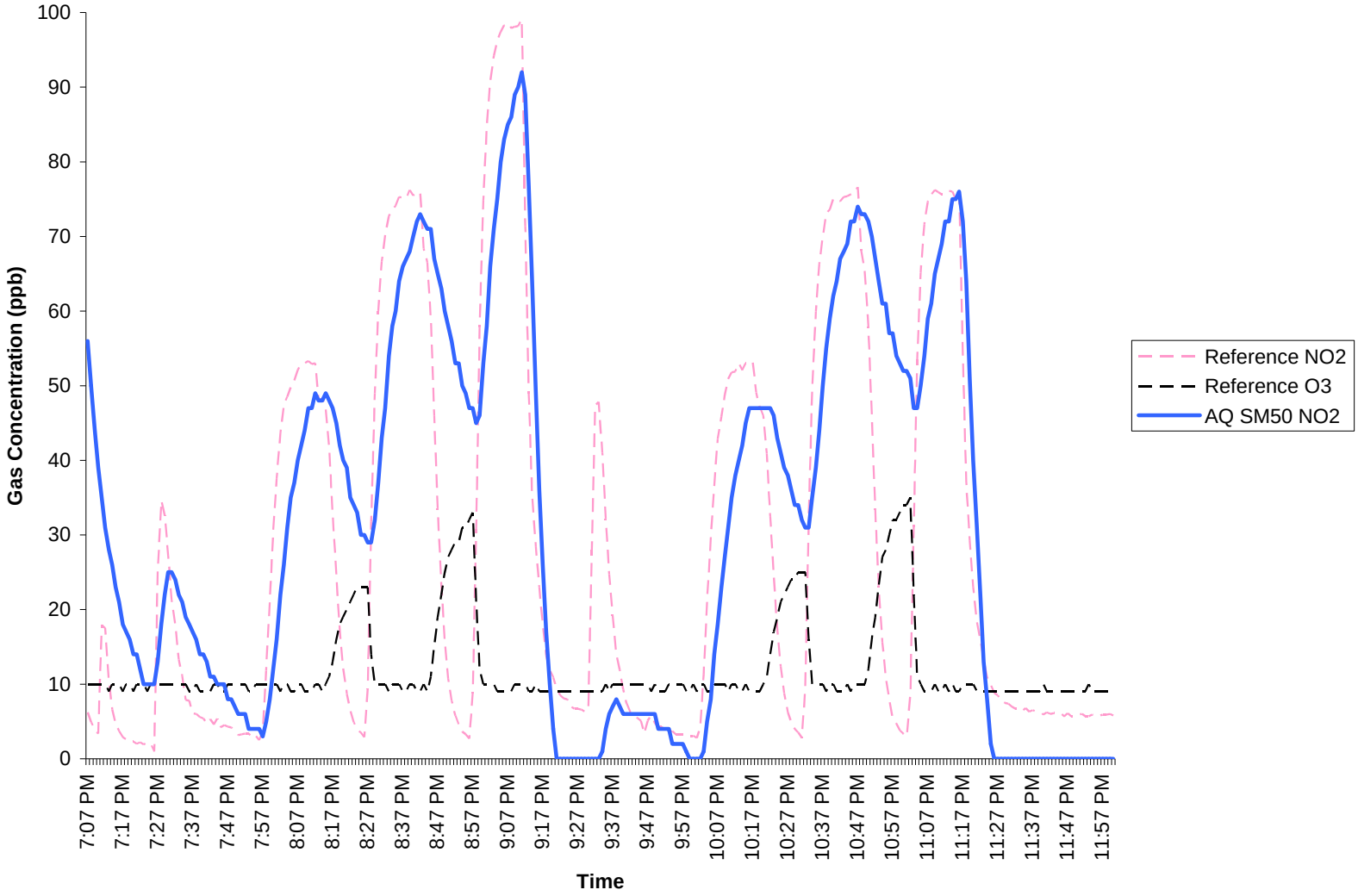

Figure 3-7. When NO_2 step tests were interspersed with bumps in O_3, the recovery of the Aeroqual SM50 NO_2 sensor was negatively impacted. This effect was seen to occur at O_3 concentrations near 25 ppb. The experiment was conducted on 5/24/10.

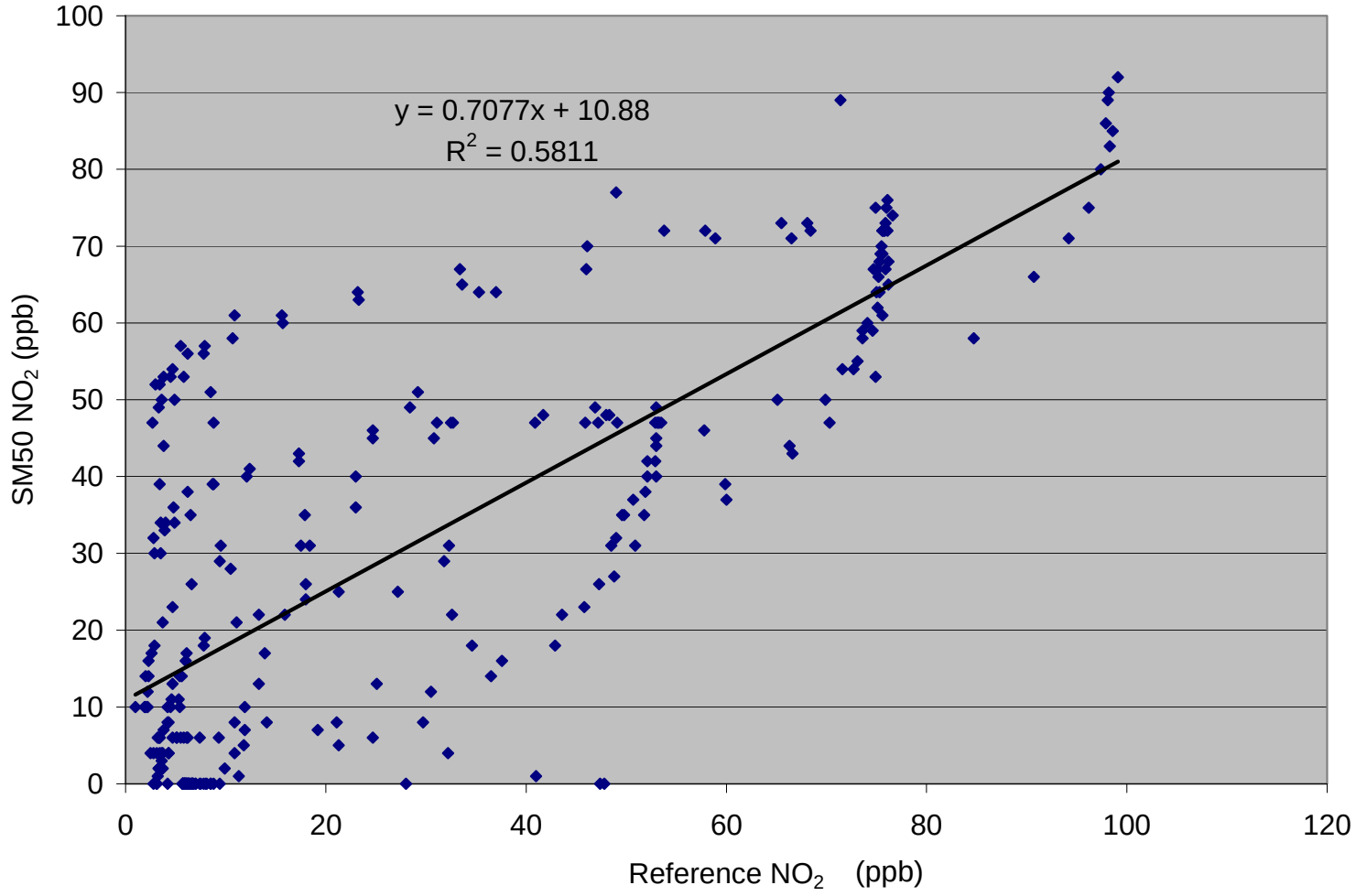

Figure 3-8. The cross-sensitivity illustrated in Figure 3-7 decreased the correlation between the SM50 NO_2 device and reference NO_2 concentrations. The experiment was conducted on 5/24/10.

3.2.3 The Berkeley Badge Metal-Oxide e2v MiCS 4514 NO_2 Sensor

The e2v MiCS 4514 NO_2 sensor also shows some promise and warrants continued development efforts. This is an ucalibrated and non-linear sensor. **Figure 3-9** shows the time series results of one of the early tests with alternating steps of NO_2 and O_3 using Badge 21. The uncalibrated ADC response of the e2v MiCS NO_2 sensor tracks the reference NO_2 very well. Cross-sensitivity to O_3 appears negligible, although sensitivity to O_3 increased with time. In contrast, data collected simultaneously from Badge 23 revealed strong cross-sensitivity to O_3 (data not shown in the time series). **Figure 3-10** illustrates a good fit when the Badge 21 MiCS 4514 sensor response is regressed on the log of reference NO_2 concentration. Also shown on this plot are the scatter and regression results from the Badge 23 MiCS 4514 NO_2 sensor. The strong cross-sensitivity to O_3 for that particular sensor resulted in very high ADC output from Badge 23 when O_3 was present and NO_2 absent. While some early test results looked good, continued testing resulted in less favorable outcomes as the MiCS NO_2 sensor's response varied with time. This resulted in poor precision overall and suggests that each sensor may need frequent recalibration.

Figure 3-11 depicts a sequence of regression plots for a single MiCS NO_2 sensor (Badge 21) that occurred over time. The variation in sensor response that leads to low precision is evident.

The e2v MiCS 4514 sensors in the four Badges that were tested were generally sensitive to the target gas, but they also were temperature- and RH-sensitive, and they either possessed or developed cross-sensitivity to O_3. In simple, repeated experiments, the sensors exhibit variability in response that is hard to separate or attribute to temperature or other environmental variables. They also may be susceptible to "over-exposure" or "poisoning". The sensors exhibited a time lag in response to the test gas, which is an important issue for mobile monitoring since delayed response could result in a transposition or displacement of high or low values of air quality conditions.

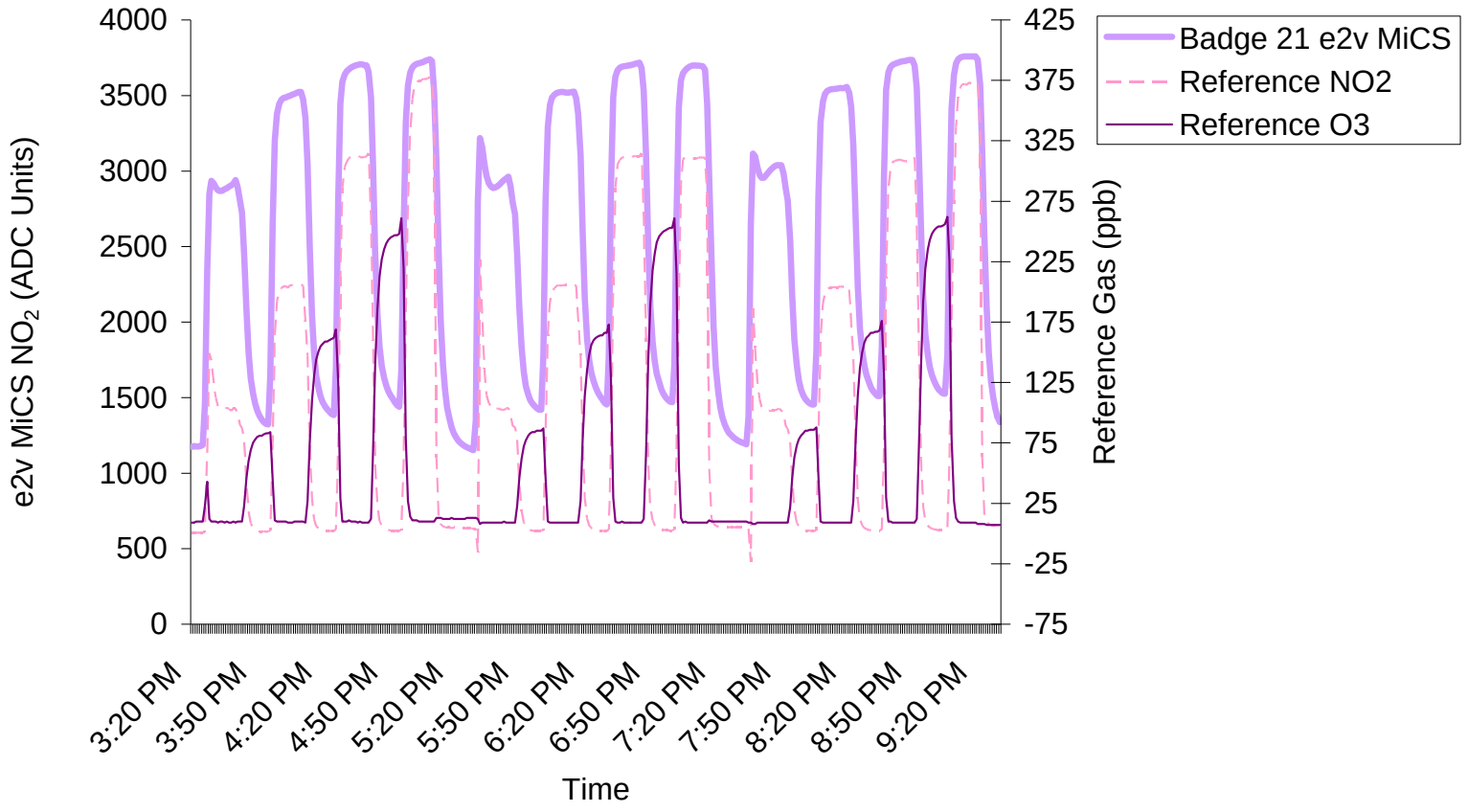

Figure 3-9. Early tests of the MiCS 4514 NO_2 sensor tracked reference NO_2 well. O_3 cross-sensitivity appeared negligible for the Badge 21 e2v MiCS NO_2 sensor. However, the e2v MiCS NO_2 sensor in Badge 23 showed high cross-sensitivity to O_3 (see Figure 3-10). The experiment was conducted on 4/27/10.

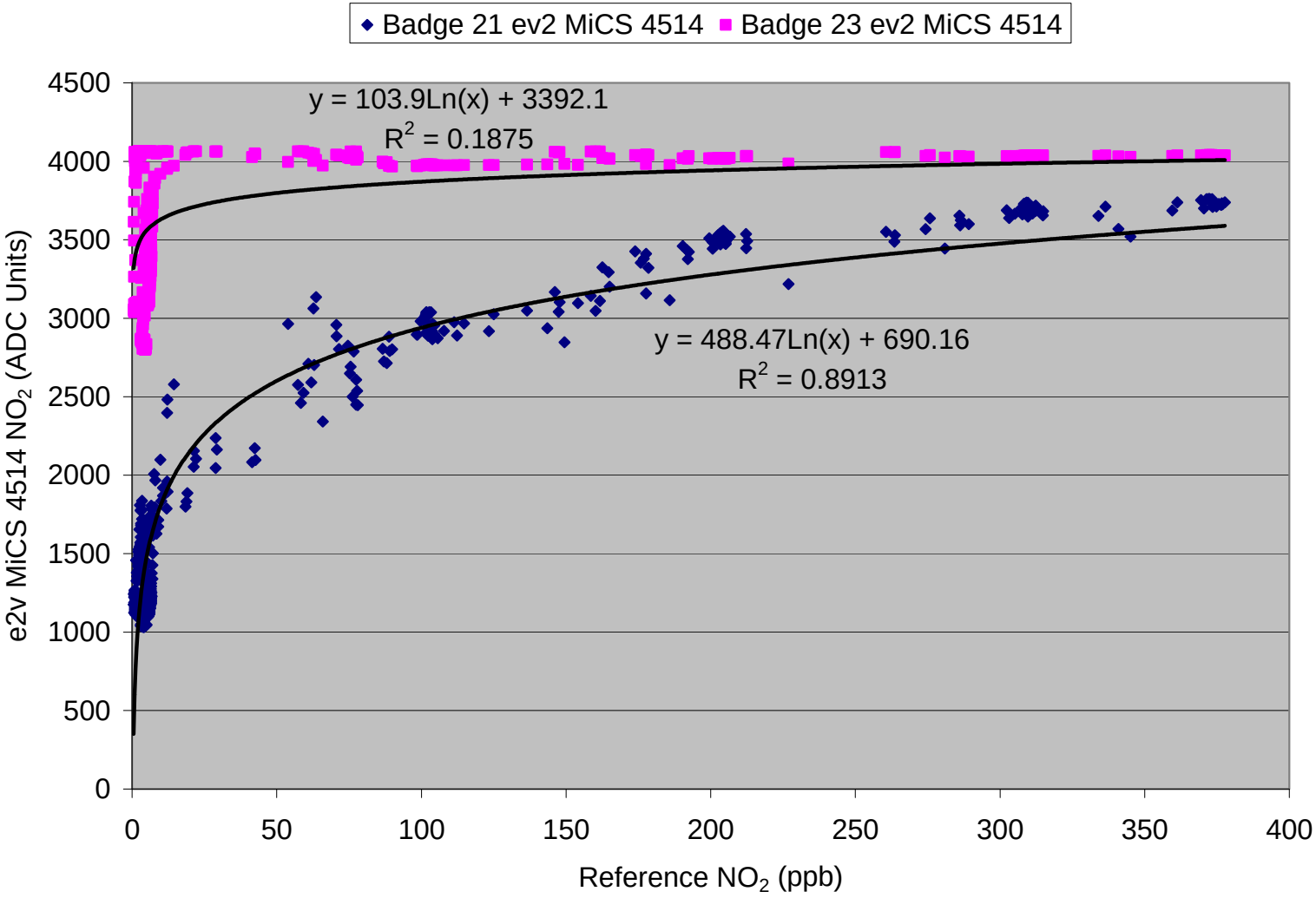

Figure 3-10. In some early experiments of the e2v MiCS NO_2 sensor, response was good for some units. Repeated experiments revealed substantial drift in sensor response with time, suggesting low precision and the potential for frequent recalibrations. Cross-sensitivity to O_3 was a problem for some units, but not for all of them. The response of Badge 23 in this figure was elevated but flat and caused by high sensitivity to O_3 at zero NO_2 concentrations. The two Badges were tested simultaneously on 4/27/10.

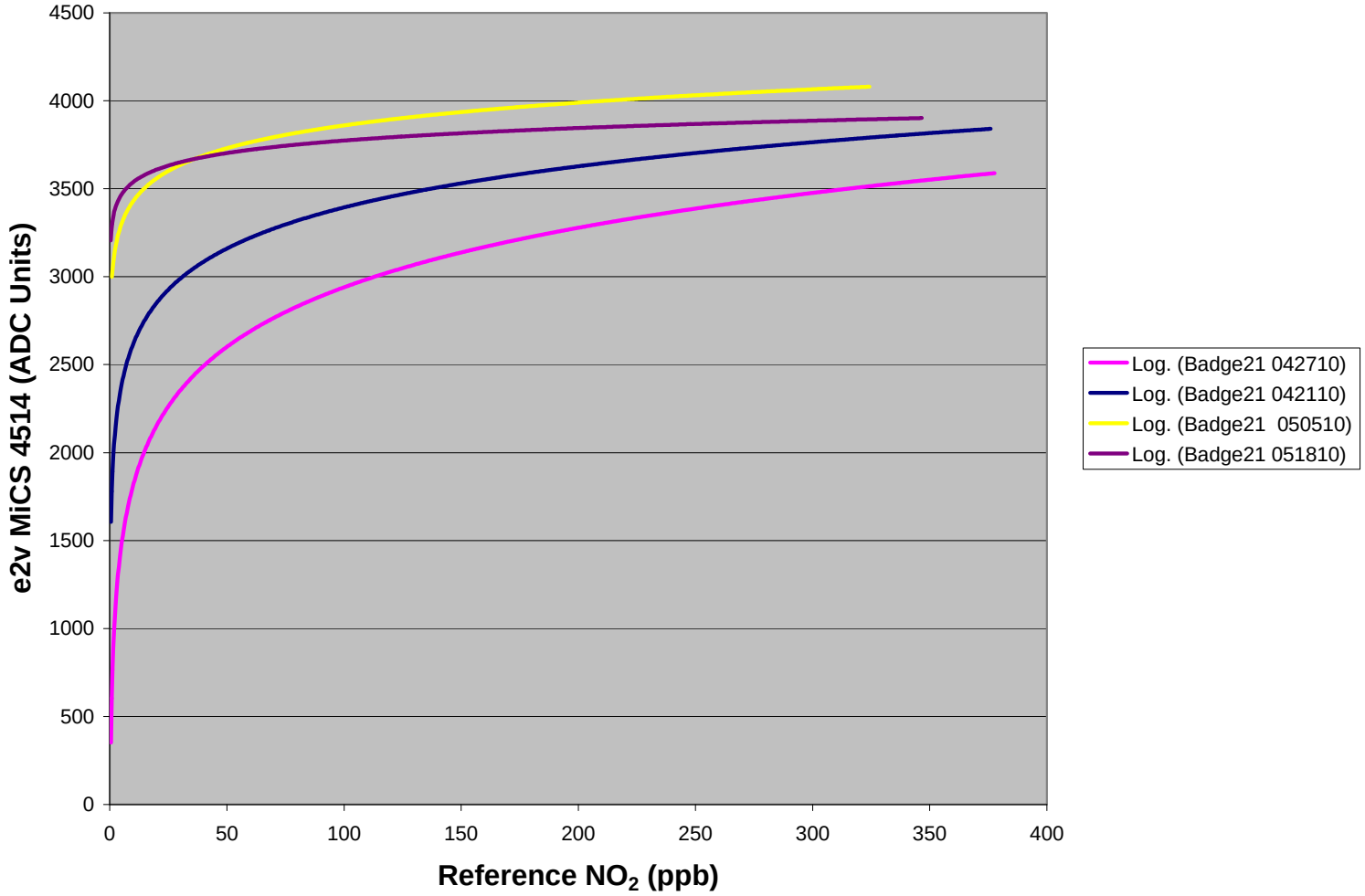

Figure 3-11. The e2v MiCS 4514 NO_2 in Badge 21 exhibited variable responses between experiments. Part of the variability may be attributable to an increased sensitivity to O_3 over time, causing increased ADC output under zero NO_2 concentrations. Dates of the experiments are given in the symbol legend.

3.2.4 The Berkeley Badge Metal-Oxide e2v MiCS 2610 O_3 Sensor

The Berkeley Badge metal-oxide e2v MiCS 2610 sensor is sensitive to O_3 but has significant cross-sensitivities to NO_2. **Figure 3-12** shows an example of NO_2 interfering with O_3 concentrations measured by the e2v MiCS 2610 O_3 sensor. While the MiCS O_3 sensor shows a correlated response to O_3 concentrations, the presence of NO_2 also elicits a response in the absence of O_3. Note that when neither NO_2 nor O_3 is present, the MiCS response returns to baseline levels. Figure 3-12 also illustrates the production spread in sensitivity that can exist between sensors.

A scatter plot of the MiCS O_3 data from Badge 23 (**Figure 3-13**) shows a high correlation in a non-linear regression curve. The stacked data at zero O_3 concentrations (an O_3 offset of 9 ppb is shown) is the MiCS 2610 O_3 sensor response due to the presence of NO_2.

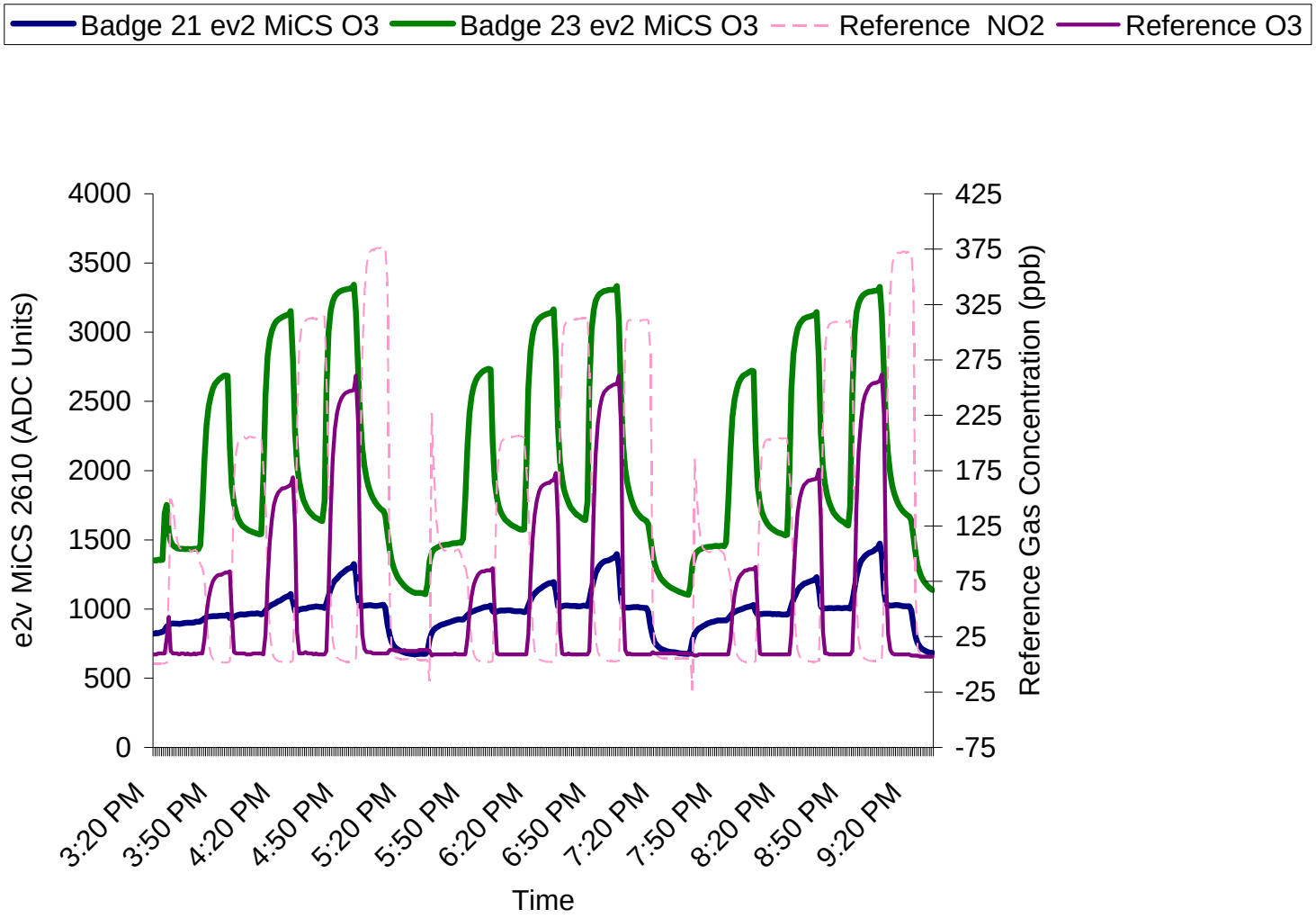

Figure 3-12. The ADC output from two e2v MiCS 2610 O_3 sensors (blue line and green line) is correlated with reference O_3 concentrations. The figure illustrates that (1) production spread in sensor sensitivity can be substantial (compare Badge 21 and Badge 23); and (2) the sensors are cross-sensitive to NO_2, and their ADC response approaches baseline only when both O_3 and NO_2 are absent. The experiment was conducted on 4/27/10.

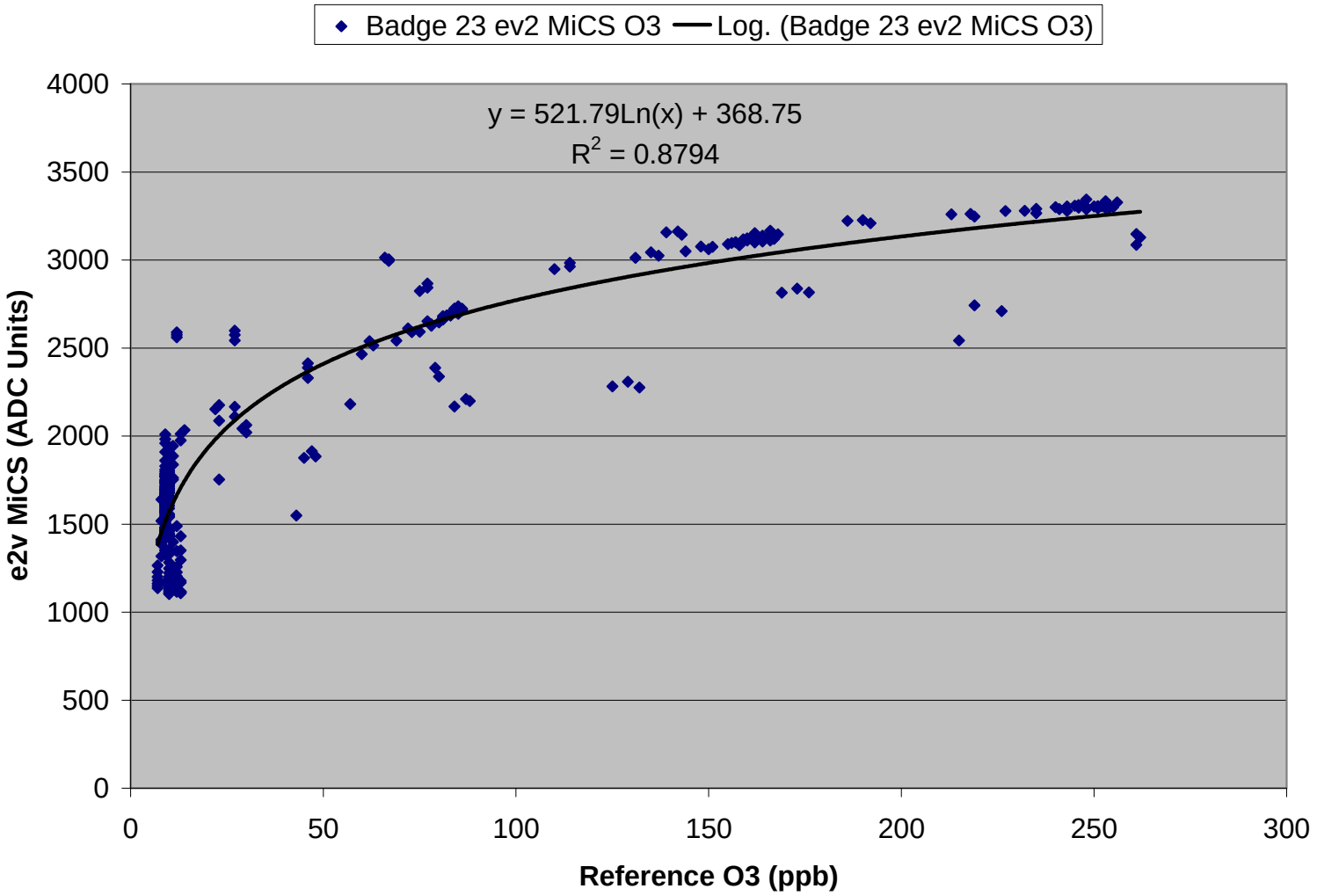

Figure 3-13. The regression of e2v MiCS ADC units on the log of reference O_3 concentration shows a good fit. The stacked ADC units at zero O_3 (offset of 9 ppb) illustrate the cross-sensitivity to NO_2. Data are from the 4/27/10 experiment shown in Figure 3-12.

3.2.5 The Aeroqual AQM 60 NO_2 Sensor System

The Aeroqual AQM 60 NO_2 instrument is a relatively small (but bigger than hand-held) commercially available NO_2 monitor, aspirated at 60 ccm. It is calibrated for 0-200 ppb NO_2 and has a linearized voltage output. Once initial issues with power supply problems were resolved, the instrument exhibited a highly correlated response, but its accuracy was poor (the slope was off by a factor of ten). As testing continued, the correlation grew progressively worse until the unit became essentially non-responsive (flat-lined). **Figure 3-14** shows a time series of one of the highly correlated but inaccurate trials. The scatter plot shown in **Figure 3-15** illustrates that the slope was off by about an order of magnitude.

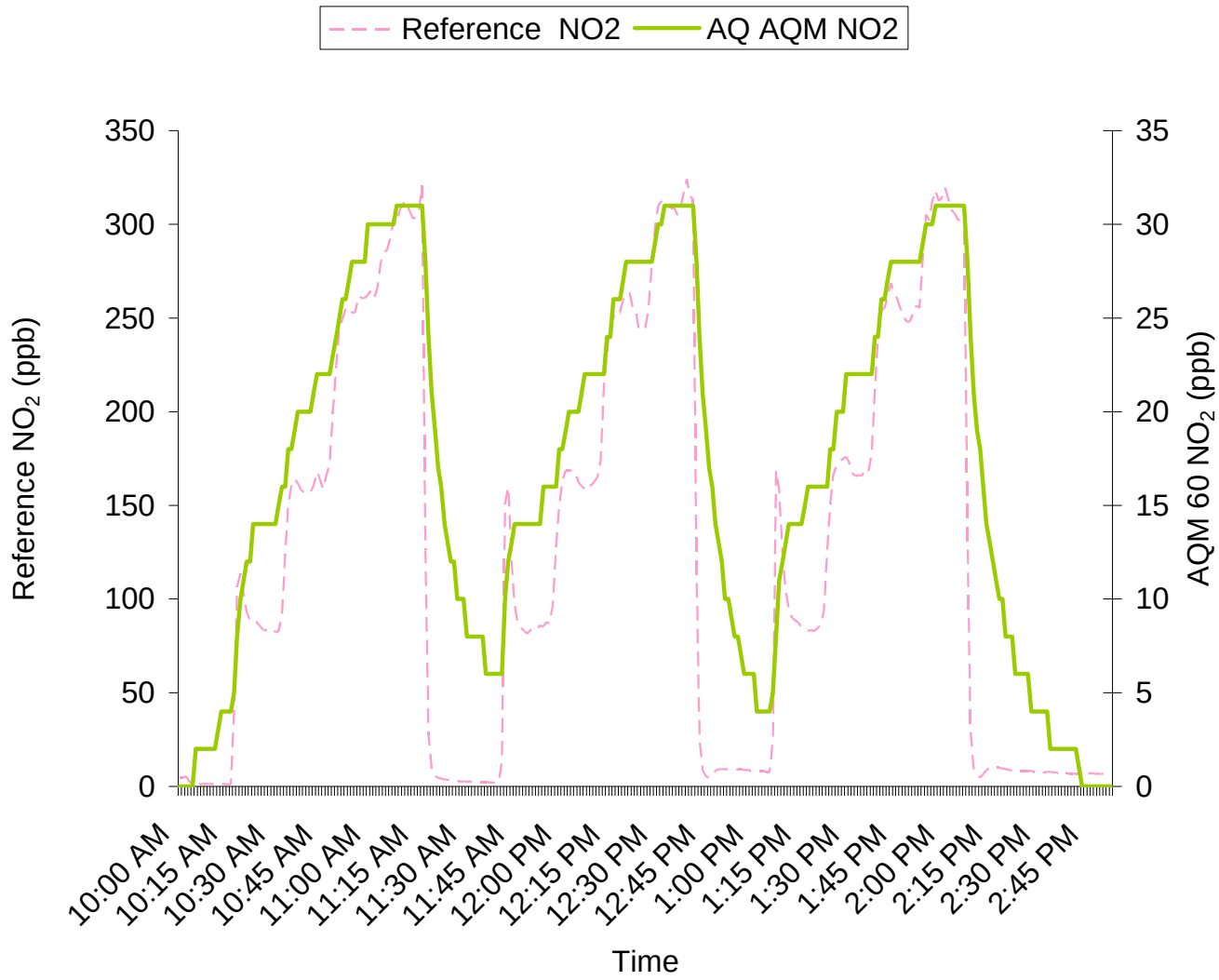

Figure 3-14. The time series of the AQM 60 instrument with reference NO_2 shows good correlation but low accuracy (note the Y-axis scale differences).

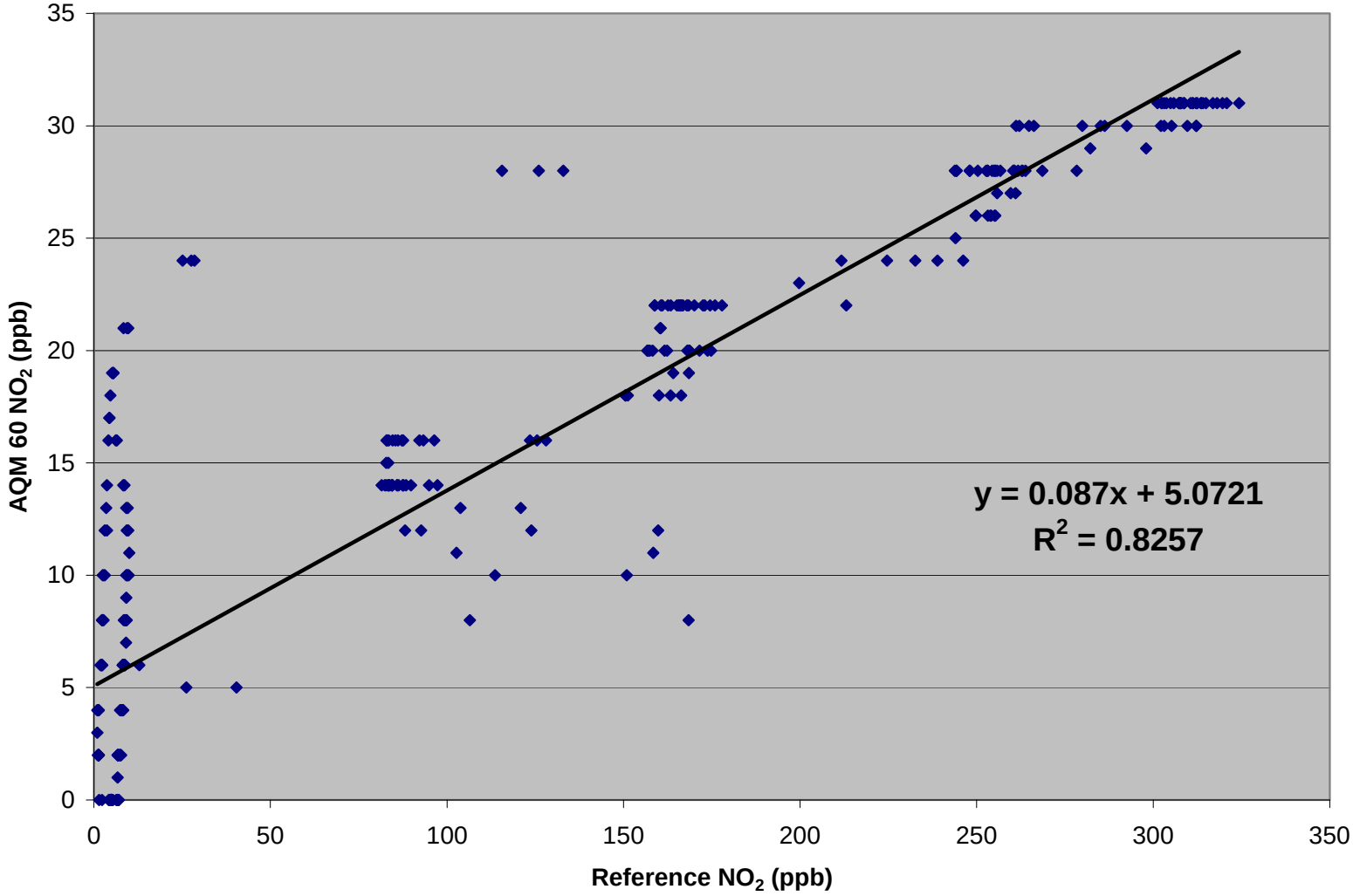

Figure 3-15. A scatter plot of the AQM 60 response and reference NO_2 concentrations shows that the linearly calibrated instrument's slope was off by a factor of about 10. Some time lag is seen by the stacked AQM 60 data near zero reference NO_2 levels. The experiment was conducted on 5/5/10.

3.2.6 The Aeroqual S500 O_3 Instrument

The Aeroqual S500 is a commercially available, calibrated hand-held instrument with an interchangeable sensor head that allows monitoring of different target gases. The S500 unit that was tested was set up for O_3. This instrument was tested in ambient air in Fresno, California, and results were compared to regional O_3 concentrations measured by a reference monitor located a few miles away. **Figure 3-16** shows the hourly results from four days of testing. The correlation is good, but the scatter is still substantial. An offset exists but may be attributable to the geographic separation of the two monitors. A similar relationship was shown in the test chamber, but accuracy there was not as good, recording a slope of about 50% (**Figure 3-17**).

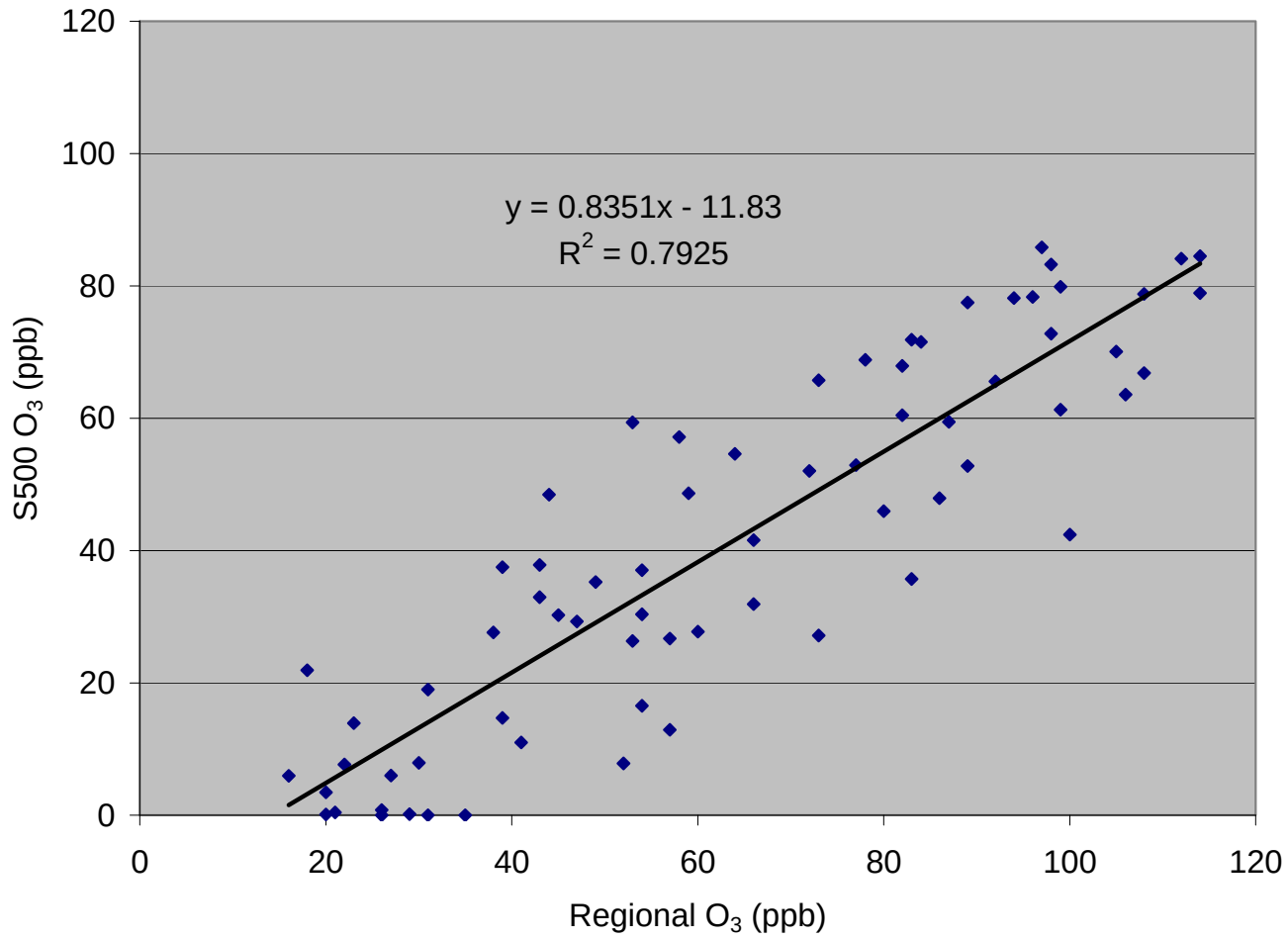

Figure 3-16. The Aeroqual S500 O_3 monitor compared favorably with O_3 concentrations measured by a regional O_3 monitor over a four-day period in Fresno, California. The regional monitor was located a few miles from the S500.

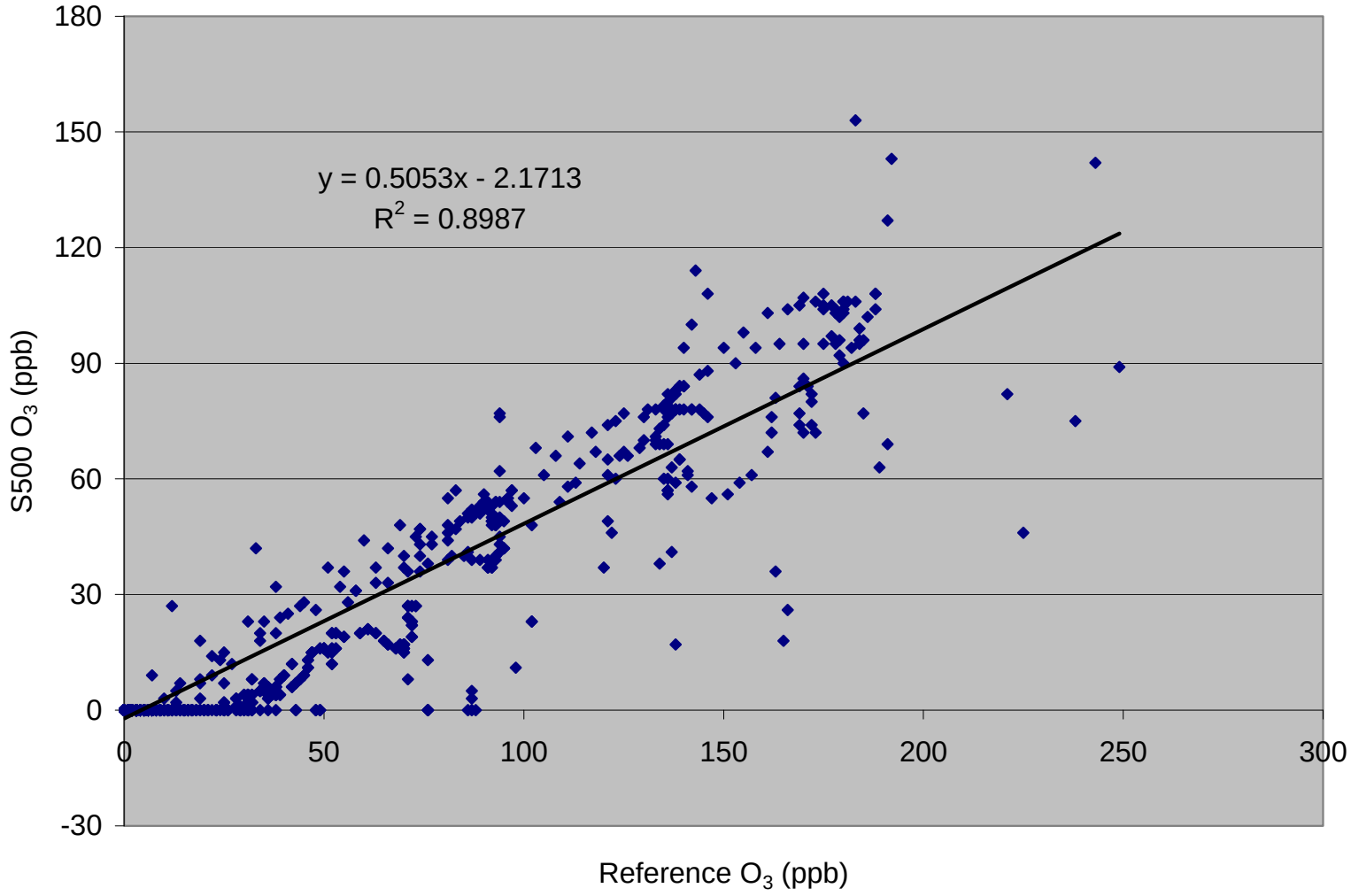

Figure 3-17. In the test chamber, the S500 showed a good correlation with reference O_3 concentrations but underestimated concentrations by about 50%.

3.2.7 Relative Humidity Effects

The SensoriC 3E50 NO_2 electrochemical sensors' ADC signals showed some oscillations in response to changing humidity levels, but the average value of the response tended to remain correlated with the average pollutant level. **Figure 3-18** illustrates that relatively quick changes in ambient RH can cause both upward and downward excursions around a mean ADC value. The effect of varying RH on the response of the SensoriC 3E 50 NO_2 sensor is minimal.

In contrast, the metal-oxide sensors showed a significant response to changing humidity levels at a constant pollutant concentration. Both the e2v MiCS 4514 NO_2 sensor (**Figure 3-19)** and the e2v MiCS 2610 O_3 sensor (**Figure 3-20**) exhibit RH dependence.

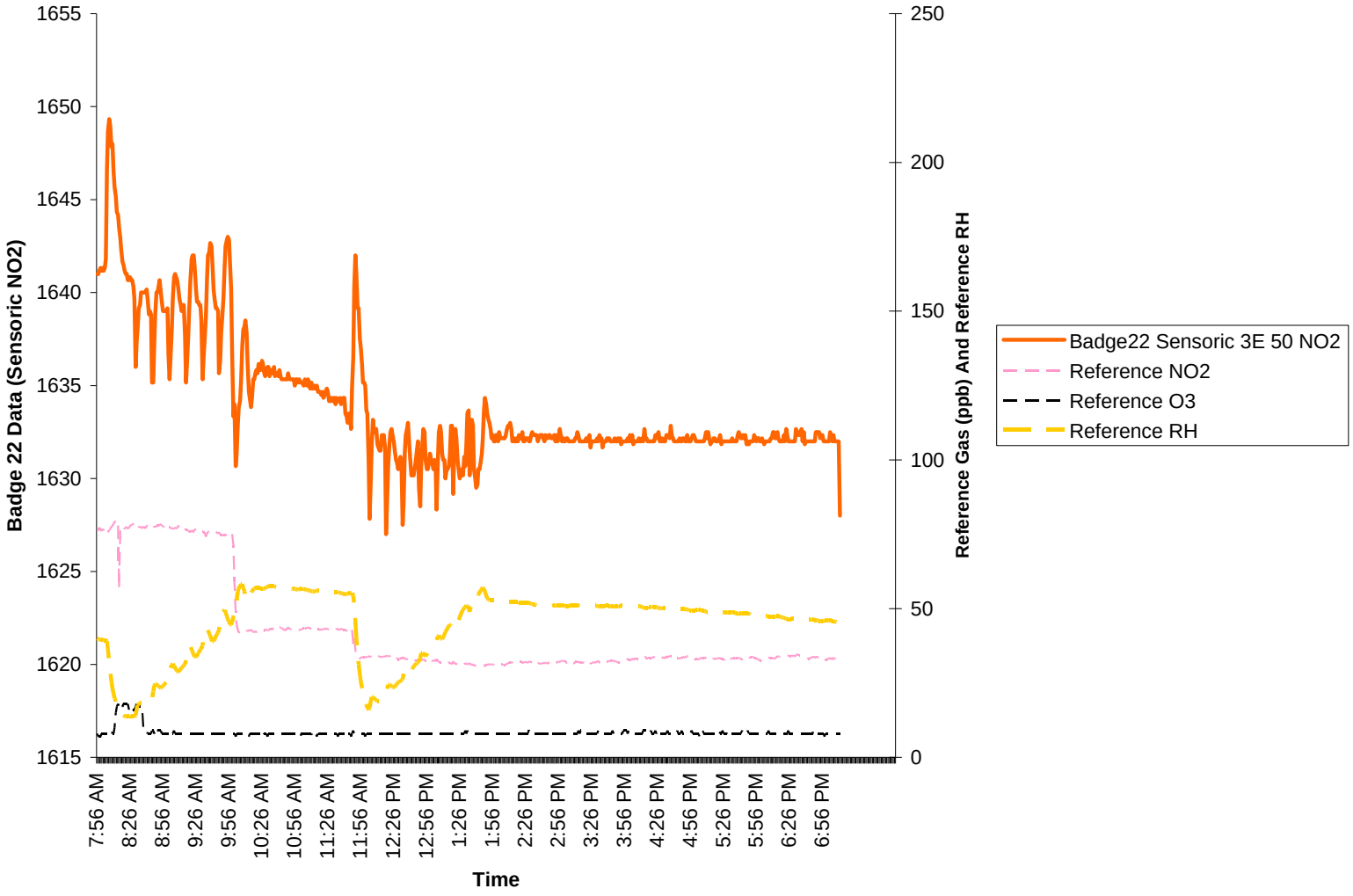

Figure 3-18. The SensoriC 3E 50 electrochemical sensor exhibited upward and downward responses to RH, oscillating about a relatively constant mean ADC output. The experiment was conducted on 6/4/10.

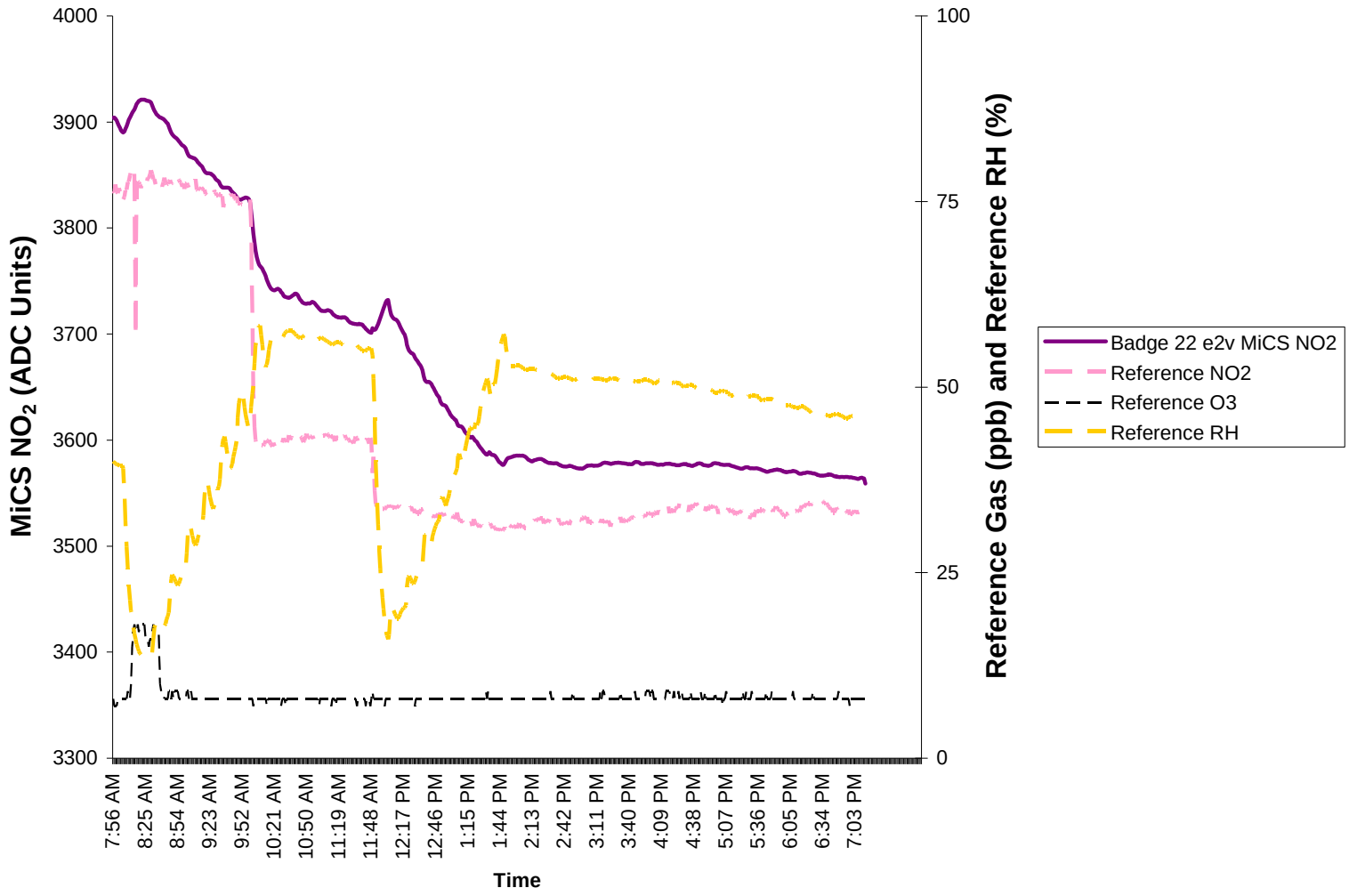

Figure 3-19. The e2v MiCS 4514 NO_2 sensor shows an inverse response to varying RH levels at constant NO_2 concentrations. The experiment was conducted on 6/4/10.

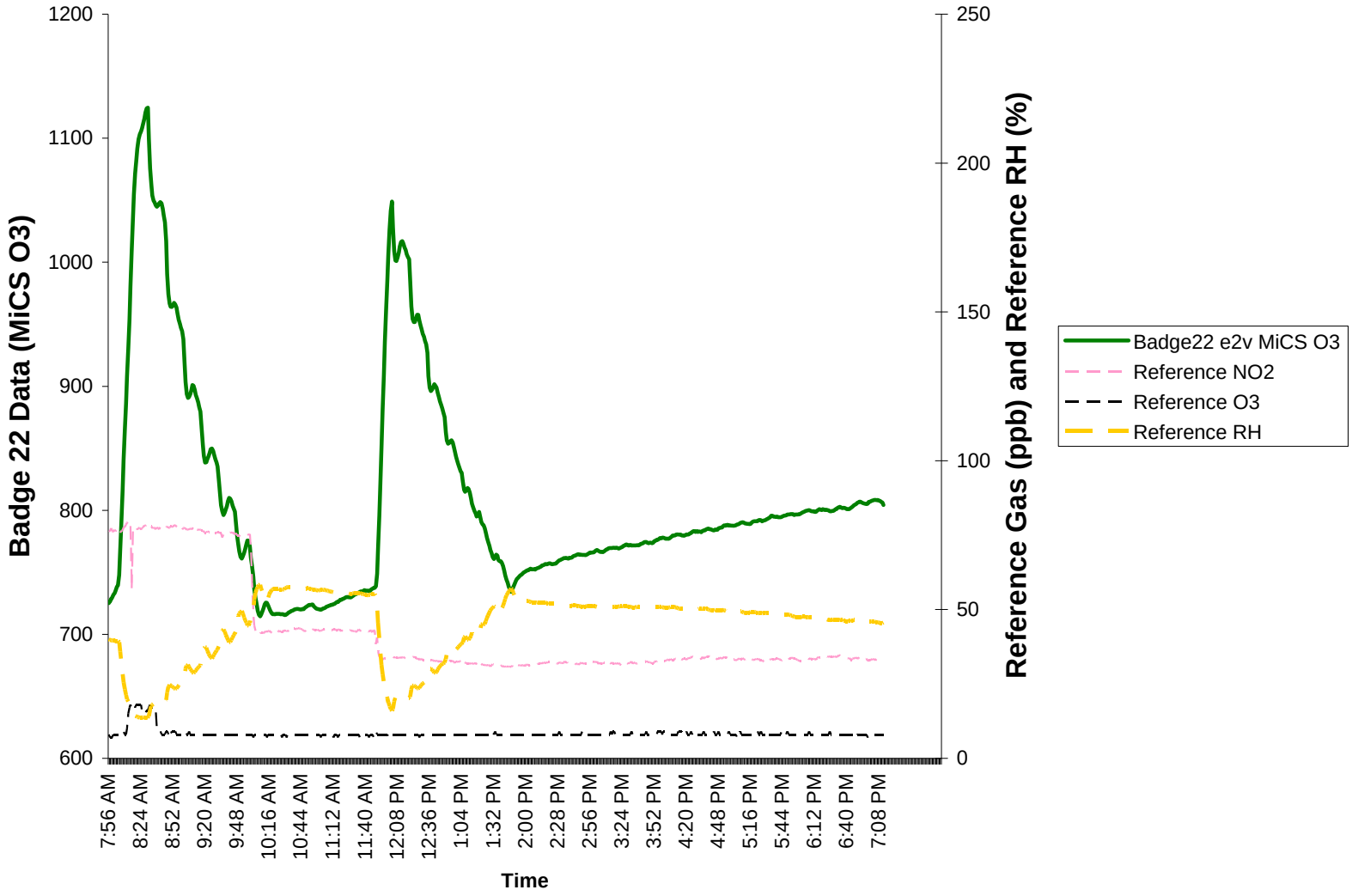

Figure 3-20. The e2v MiCS 2610 O_3 sensor shows an inverse response to varying RH levels at zero O_3 concentrations. NO_2 cross-sensitivity does not seem to play a significant role in this outcome. The experiment was conducted on 6/4/10.

4. Conclusions

This pilot characterization study provided a useful, yet limited, evaluation of these sensor systems. As we found, many factors can affect the sensor performance (temperature, relativity humidity, gas cross-contamination, electrical interferences, etc.). With additional effort by the sensor manufacturers and researchers on the sensors, signal processing, and data mining, the performance of these types of sensor systems will likely improve in the future. In this project, the existence of the potential for multi-factor interactions made full characterization of the response of any given sensor difficult at best. Our efforts focused primarily on dose-response relationships using variable concentrations of NO_2 and O_3, alone or in combination, under a temperature range of a few degrees bracketing room temperature and at ambient humidity levels (except during specific relative humidity tests).

Based on the tests we conducted, the following conclusions are made:

1. For uncalibrated sensor and sensor packages, calibrations for each individual sensor would be required to achieve accurate (true) results.
2. For evaluations of *relative concentrations* only, using uncalibrated sensors or sensor packages would require a collocated evaluation of the sensors to characterize the production spread in sensitivity between sensor units.
3. The electrochemical SensoriC 3E 50 NO_2 sensor (packaged in the Badge) showed highly correlated responses to NO_2 levels with little or no O_3 cross-sensitivity and offers potential for applied field measurements of NO_2. Sensor-specific calibrations (for accuracy) or collocated evaluations (for evaluation of relative concentrations only) would be required.
4. The handheld Aeroqual S500 O_3 (semiconductor-based, calibrated) sensor showed correlation with neighborhood-scale O_3 measurements and similar correlations in the testing chamber that was used, but there were problems with repeatability.
5. The uncalibrated semiconductor-based (metal-oxide) sensors exhibited variable correlations, resulting in low precision in repeated measurements with the same sensor. This suggests that even for relative measurements of concentration, the sensors are not suitable because the variability within the sensor would preclude the use of collocated measurements to characterize relative differences between sensors. The contribution of various environmental factors, aging, air flow characteristics, and poisoning were not sufficiently quantified to infer any causal relationship for the low precision.
6. The OEM-style Aeroqual NO_2 and O_3 sensors (SM50, calibrated) exhibited “random” fluctuations between full-scale and zero-voltage output, though correlated responses to reference gas concentrations were measured occasionally. This is the same sensor installed in the company's S500 model (described above), suggesting that packaging plays an important role in sensor response.
7. The commercially available Aeroqual AQM 60 NO_2 instrument exhibited high correlations in early tests but underestimated NO_2 concentrations by a factor of 10. The correlations degraded with time, suggesting either a “poisoning” effect or sensor aging.

5. Recommendations

As discussed in Section 3, several of the sensors produced reasonable and promising results. Yet additional work needs to be performed by the sensor manufacturers and sensor system integrators before "off-the-shelf" systems are capable of producing measurements suitable for use by the air quality community. We offer several recommendations based on this study and knowledge of other studies underway.

1. EPA should consider conducting a follow-on study within two years that further examines the ability of newer sensor systems to make reliable, repeatable, and accurate measurements on both fixed and moving platforms. The future study should more closely engage the manufacturers to lessen the steep learning and operational curve that existed for the current study. The subsequent study should also get the manufacturers to demonstrate that the performance of their sensor systems is suitable for air quality measurements, or to share data demonstrating the suitability of their sensor systems for such measurements. Once the required level of performance is confirmed, conduct a small, focused field study to examine the operational issues associated with field deployment of these low-cost sensor systems.
2. Many efforts are underway at universities, research laboratories, and in the private sector to examine the efficacy of using lower-cost sensors and sensor systems to make air quality measurements. EPA could provide some coordination to these various projects by sponsoring a meeting or workshop to help integrate this loose-knit community. This workshop would provide an opportunity for EPA to communicate the needs and requirements for measurements that would be suitable for the air quality community. Also, EPA could learn more about how non-air quality groups or organizations are making measurements.
3. Seek to understand the impact of mobile monitoring on EPA programs (e.g., regulatory, AIRNow public outreach) by conducting a field program with higher-cost, more accurate instruments. This would provide data with sufficient accuracy to examine and understand the impact on EPA's programs while reducing the uncertainty about the actual sensors and sensor systems, which hampered this study. For example, collecting O_3 or $PM_{2.5}$ data from various mobile platforms and then fusing this information with the real-time AIRNow data would allow EPA to explore the future impacts of a denser monitoring network on the AIRNow maps.
4. Increasingly, non-air quality organizations are installing mid-cost O_3 and PM instruments and providing real-time and historical data on their websites (Air Alliance Houston, 2009 and Save the Air in Nevada County, 2010). This presents both a challenge and an opportunity for EPA and state/local air quality agencies in terms of data representativeness, ownership, consistency, advocacy, measurement conflicts, non-attainment boundaries, public outreach, etc. With several nascent networks already measuring routine air quality conditions, we recommend that EPA engage these groups and local air quality agencies to better understand the future implications for air quality management. In addition, this engagement would provide an opportunity to explore collaborative monitoring efforts that seek to ensure comparability, maximize coverage, and reduce costs.

6. References

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