Making Sense of Atmospheric Carbon Dioxide Measurements with Low-Cost Sensors

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6/21/2023

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*References are made to certain commercially available products in this presentation to adequately specify the experimental procedures involved. Such identification does not imply recommendation or endorsement by NIST, nor does it imply that these products are the best for the purpose specified.

NIST's Greenhouse Gas Measurement Program

Purpose: Develop internationally recognized, greenhouse gas emissions measurements and standards for reliable and accurate mapping of urban to regional greenhouse gas emissions that inform timely and effective mitigation actions and science-based policy decisions.

Components:

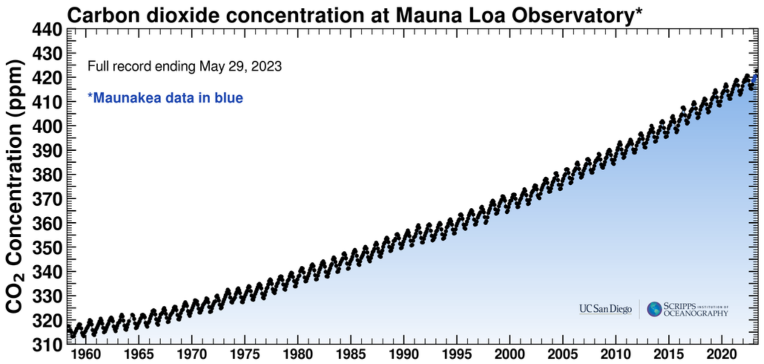
- Urban GHG Measurements Testbed System, Tools, and Methods
- Stationary or Point Source Emission Metrology (advances in smokestack Continuous Emissions Monitoring (CEMs) technology)
- Measurement Tools, Standards and Reference Data
- Satellite Calibration and Atmospheric Carbonaceous Aerosols Measurements & Standards
- International Documentary Standards Development for Urban GHG Flux Measurements

https://www.nist.gov/spo/greenhouse-gas-measurements-program

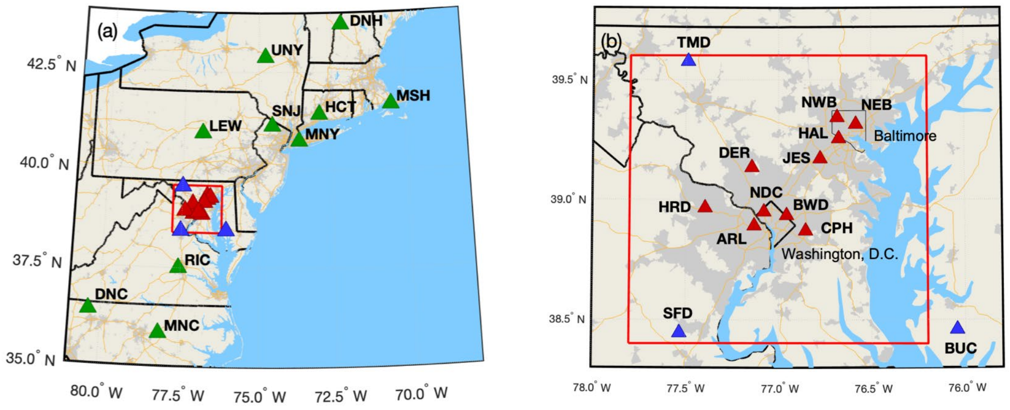
Slide courtesy of Israel Lopez-Coto

Measuring Atmospheric CO_2

- Why measure atmospheric CO_2 concentrations?
  - CO_2 is emitted when burning fossil fuels
  - CO_2 and other greenhouse gases (GHGs) build up in the upper atmosphere, contributing to climate change
  - Measuring CO_2 over time allows us to monitor pollution emissions and target efforts to reduce emissions
  - Typical atmospheric CO_2 range: 400-700 ppm
- Techniques for measuring atmospheric CO_2:
  - Satellites (OCO-2, Carbon Mapper)
  - Aircraft-based analyzers (NASA DC-8)
  - Ground or near-ground (*in-situ*) analyzers
- NIST and other research organizations typically measure *in-situ* atmospheric CO_2 with cavity ring-down (CRDS) spectrometers
  - Many deploy CRDS instruments in networks
  - Instruments are highly precise and accurate (can measure CO_2 within 0.1 ppm)
  - Instruments are expensive (~ $100K, typically mounted to cell towers, requiring additional support infrastructure)



Keeling Curve, showing increase in atmospheric CO_2. CO_2 can vary by ~6 ppm between summer and winter. Figure courtesy of scripps.ucsd.edu



a) Northeast Corridor (NEC) Urban Test Bed
b) Zoomed-in Baltimore/Washington portion of NEC Urban Test Bed

Picarro 2401 CRDS analyzer, courtesy of picarro.com

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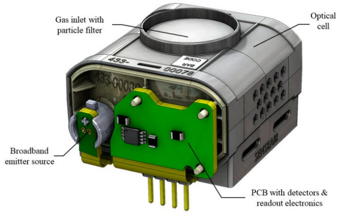
Sensors Converge

Cost-Effective CO_2 Measurement Techniques

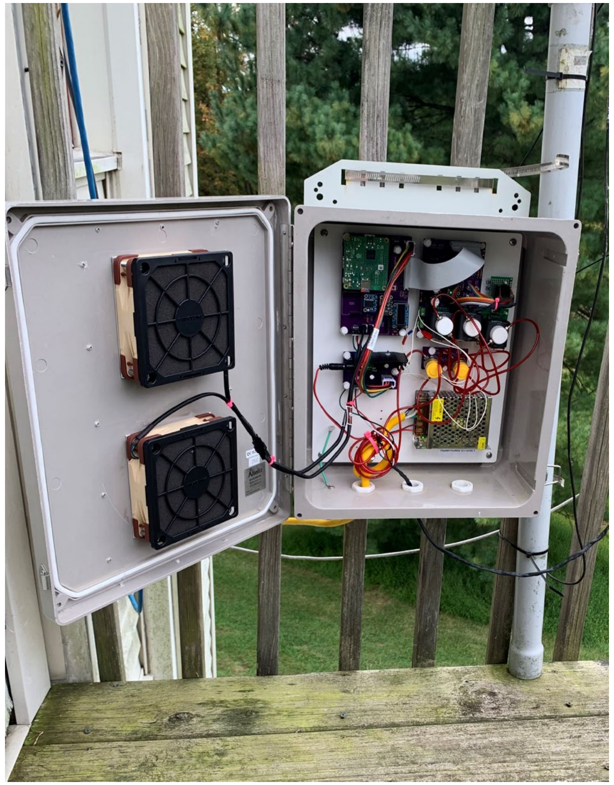
- Large number of commercially-available low-cost GHG sensors have become available in recent years
  - Small size (often credit card size or smaller)
  - Low cost ($10 - $500)
- Most sensors designed for consumer market use
  - Typically designed for indoor air quality CO_2 ranges: 400 – 3000 ppm (K96) or 400 – 10000 ppm (SCD30)
  - Some claim sensitivity ~ 0.1 ppm (K96), or accuracies at $\pm 30\ ppm\ \pm 3\%$ (K30)
- Challenges when using for research applications:
  - Measurements are less accurate/precise than CRDS measurements
  - Sensors are susceptible to long-term (temporal) drift
  - Many sensors require custom solutions/approaches for calibrating
- Despite challenges, research shows that low-cost sensor measurements can be beneficial when coupled with CRDS urban measurement networks (Lopez-Coto et al. 2017)
- NIST's Low-Cost Sensors Project Goals:
  - Characterize low-cost sensor uncertainties over ideal conditions
  - Develop and deploy a network supporting ~50 low-cost GHG sensor stations in Baltimore/Washington region to augment measurements from high-accuracy analyzers



Senseair Prototype K96 (courtesy of Wastine et. al, 2022)

Sensirion SCD30 (courtesy of sensirion.com)

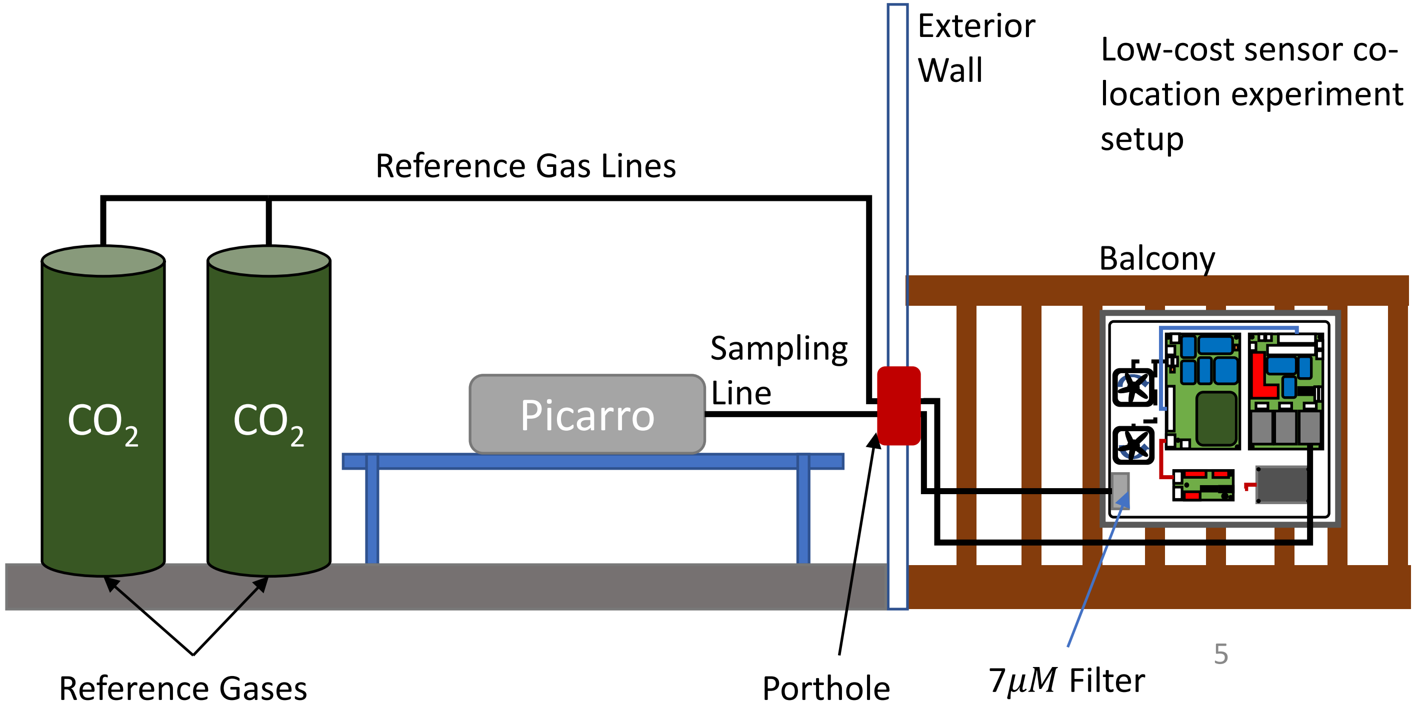
Senseair K30 (courtesy of senseair.com)



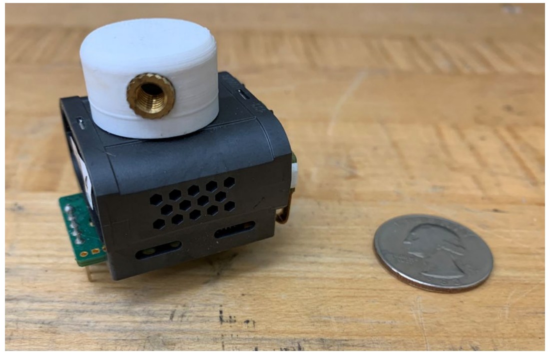
2nd generation low-cost sensor station deployed on campus at NIST

Characterizing Sensor Performance

- Methods for validating sensor measurements
  - Co-location with calibrated reference instrumentation
  - Calibration with known reference gases
- Low-cost sensor validation experiment
  - Deployed a low-cost sensor payload with 3 sensors outside of a building at NIST **(Verify System Design)**
  - Deployed sensor payload alongside a Picarro 2301 CRDS analyzer **(Characterize Sensor Performance)**
  - Automatically calibrated sensors with 400 and 600 ppm reference gases every 12 hours **(Simulate In-Field Calibration)**



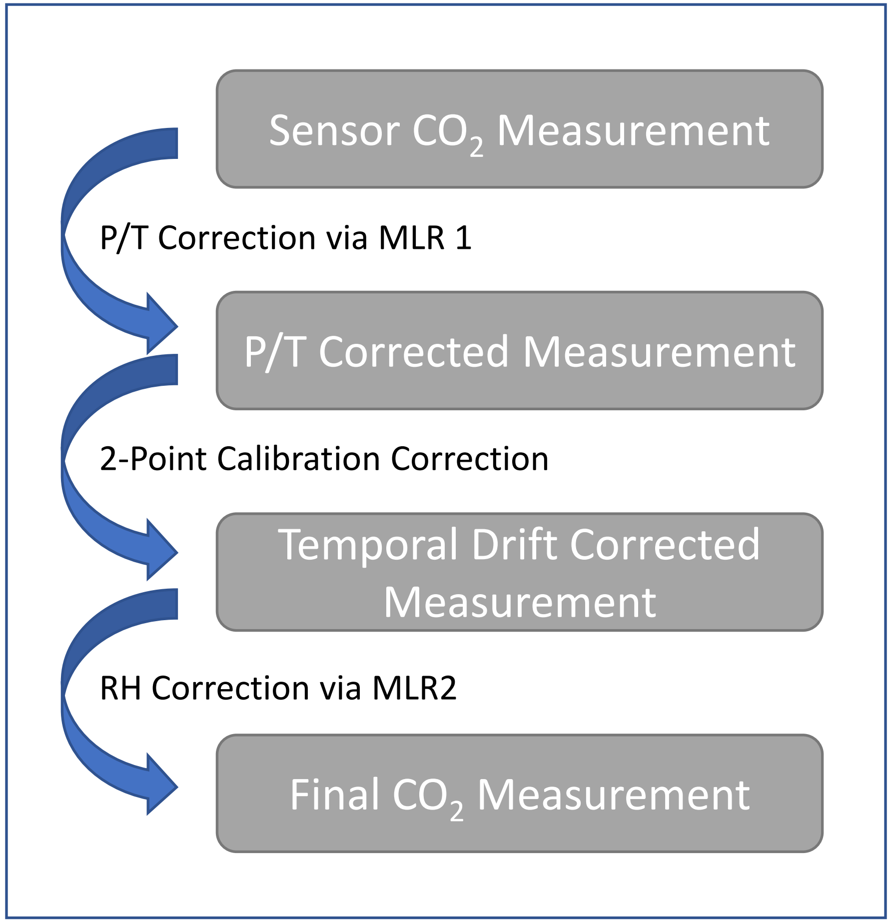
Low-cost sensor co-location experiment setup



Prototype K96 with custom calibration cap

Sensor Validation: Correcting Initial Measurements

- Previous research suggests low-cost sensors are susceptible to temperature/pressure/humidity impacts (C. Martin et al., 2017, Shusterman et al., 2016, Arzoumanian et al, 2019)
- After variety of testing, established a preliminary correction process:
  - Select a fit window with varying P/T/RH/CO_2 conditions (see supplementary slides for details)
  - "Profile" each sensor by calculating coefficients for 2 multiple linear regressions (MLRs) to correct P/T/RH dependencies
  - Use a two-point calibration to correct temporal drift
- Low-cost sensor target measurement accuracy/precision:
  - Mean diff. ~ 0 ppm
  - S. dev ≤ 2 ppm
- Will explore performance through a 2-month deployment outside at NIST



CO_2 Correction Process

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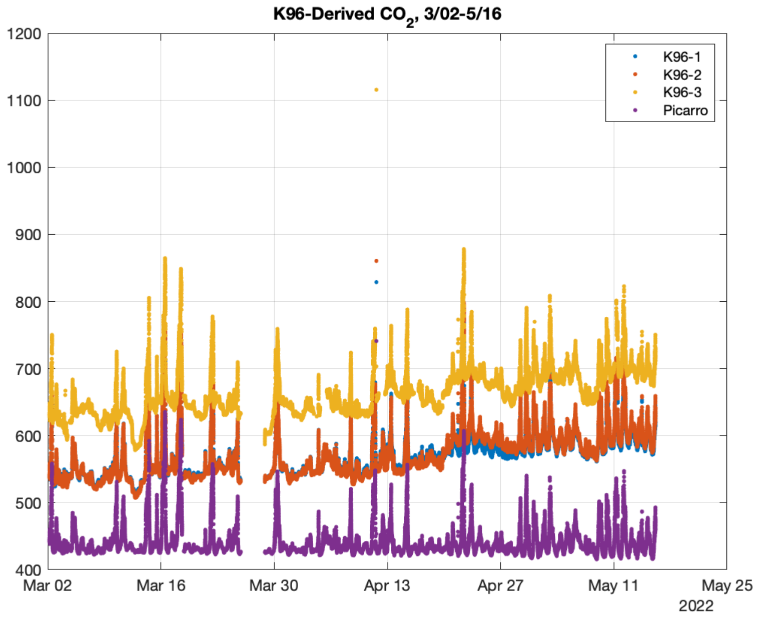
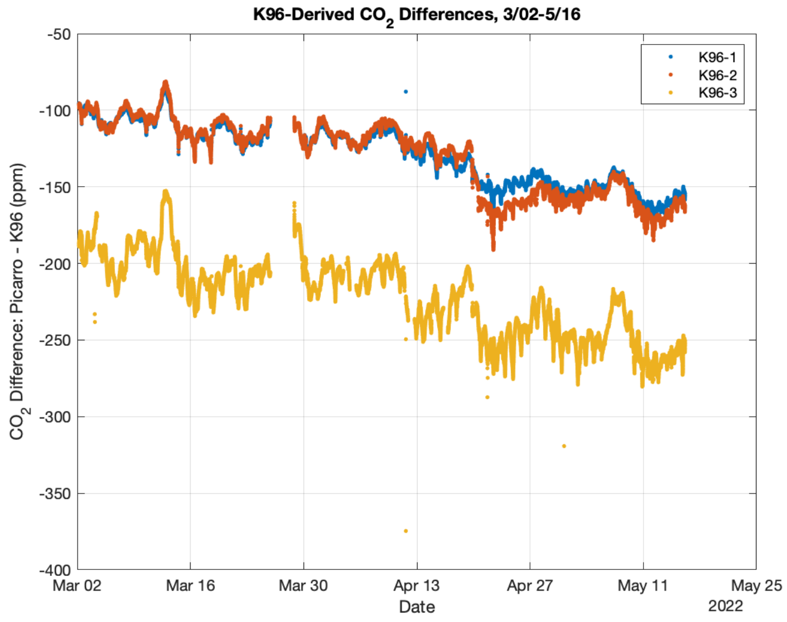
Sensors Converge

Initial Sensor-Derived CO_2 Measurements

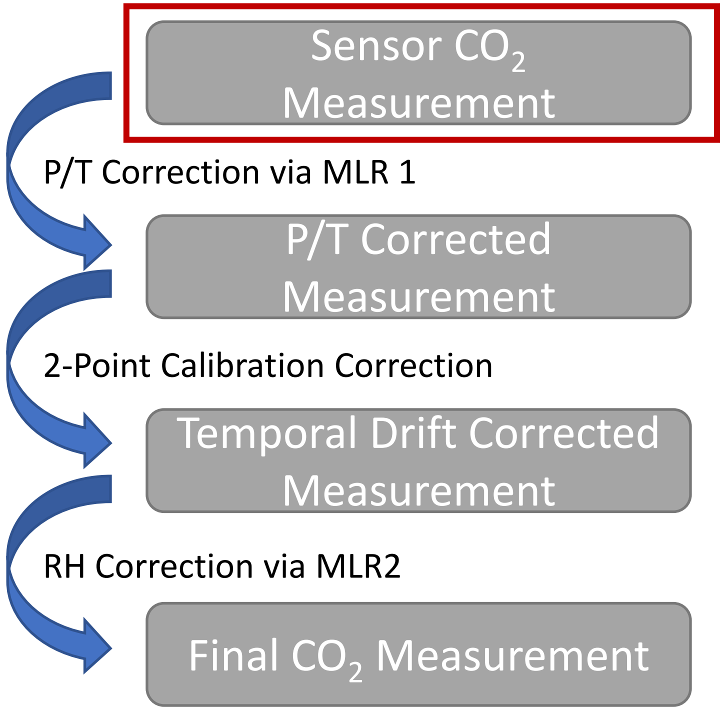
- Large offsets between CRDS and low-cost sensor measurements
- Large offsets between low-cost sensors
- Low-cost sensor sensitivities are within manufacturer specifications, but further corrections needed for our research application



Timeseries of sensor-derived CO_2 measurements



Difference between CRDS sensor-derived CO_2 measurements.



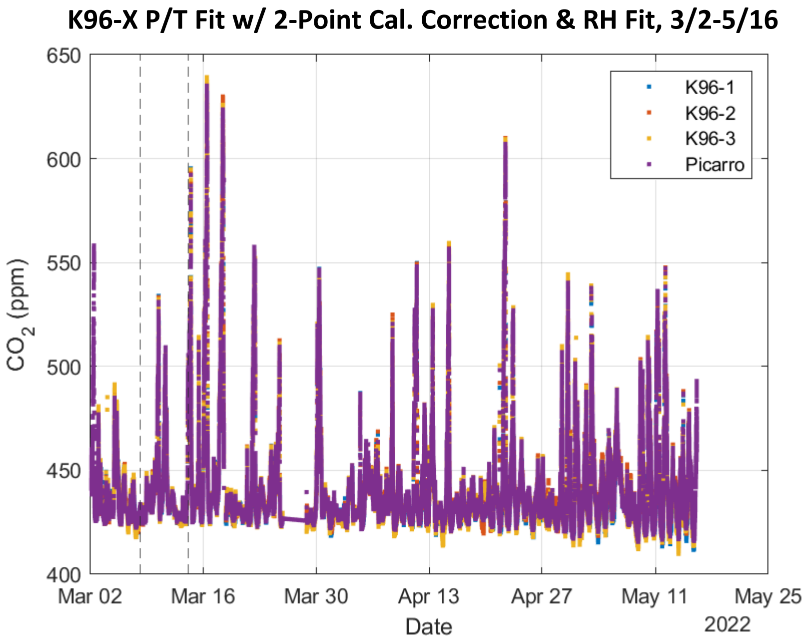
Sensor	Mean (ppm)	S.dev (ppm)
K96-1	-128.84	19.7
K96-2	-129.97	23.82
K96-3	-222.11	25.89

Sensor-derived concentration statistics

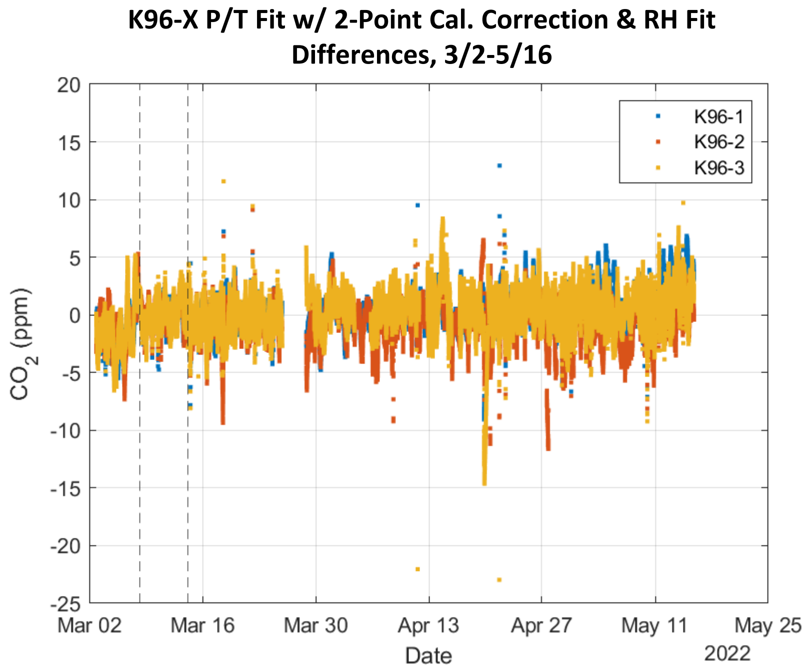
Note: mean and standard deviation calculated for entire timeseries window

Final Corrected CO_2 Measurements

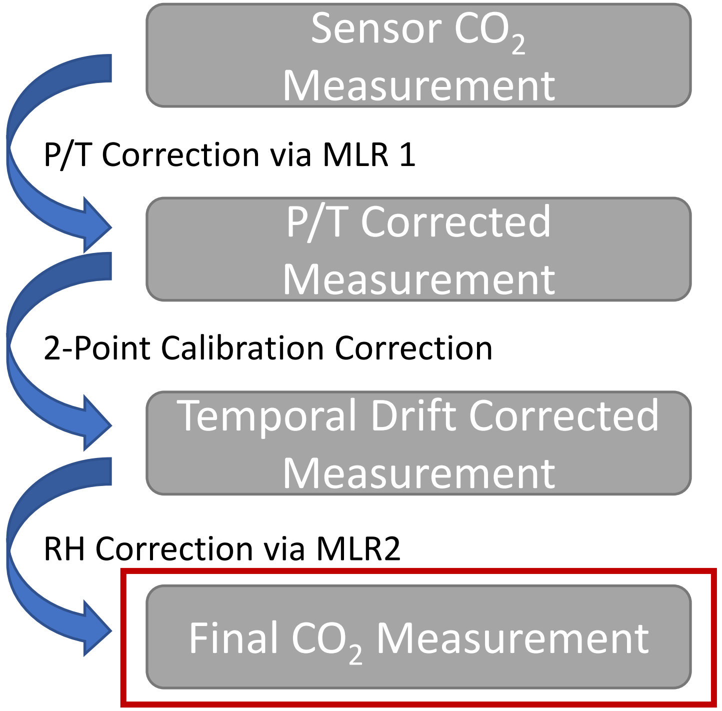
- Applying correction process reduced standard deviation below 2 ppm!
- Mean difference ~ 0 for sensors 1 and 3



Timeseries of P/T/RH/drift corrected CO_2 measurements



Difference between CRDS and P/T/RH/drift corrected CO_2 measurements.



Sensor	Mean (ppm)	S.dev (ppm)
K96-1	0.19	1.79
K96-2	-0.5	1.81
K96-3	0.08	1.92

P/T/RH/drift corrected concentration statistics

Note: mean and standard deviation calculated for entire timeseries window

Experiment Takeaways and Next Steps

- Experiment Takeaways:
  - Sensors performed within manufacturer specifications!
  - Further measurement corrections needed if used for research applications
  - Applying measurement corrections reduced mean and s. dev. within target goals!
  - Current technique for profiling sensors not feasible for large scale deployment
- Next Steps:
  - Revise system to support more sensors **(Completed)**
  - Utilize environmental chamber with T/RH control to simulate wide range of environmental conditions **(Completed)**
  - Redeploy system outside at NIST with CRDS and reference gases to test env. chamber MLR coefficients **(In Progress)**

Profiling station placed inside environmental chamber

Detailed view of profiling station inside the environmental chamber

Final Conclusion and Closing Thoughts

- Consumer-grade low-cost sensors can be useful for scientific research applications if used properly
- Considerations when selecting low-cost sensors for scientific research applications:
  - How important is accuracy? Do sensors need to be calibrated before/during use?
  - Is the target measurement range within sensor specifications?
  - Will all sensors perform similarly?
- Making consumer-grade low-cost sensors feasible for research applications:
  - Providing the ability for users to calibrate their sensors
  - Documenting internal sensor measurement processes - are measurements being corrected internally? Is there access to raw measurements?

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Extra Slides

References

- Lopez-Coto I. Ghosh S. Prasad K. & Whetstone J. (2017). Tower-based greenhouse gas measurement network design—the national institute of standards and technology north east corridor testbed. *Advances in Atmospheric Sciences* 1095–1105. https://doi.org/10.1007/s00376-017-6094-6
- Benoit W. Christine H. Maksym B. Henrik R. Hans M. & Stephan S. (2022). Compact non-dispersive infrared multi-gas sensing platform for large scale deployment with sub-ppm resolution 1789–1789. https://doi.org/10.3390/atmos13111789
- C R. N Z. A K. R R. X R. B N. & K J. (2017). Evaluation and environmental correction of ambient co2 measurements from a low-cost ndir sensor. *Atmospheric Measurement Techniques* 2383–2395. https://doi.org/10.5194/amt-10-2383-2017
- A A. V E. A J. C N. J K. & R C. (2016). The berkeley atmospheric co2 observation network: initial evaluation. *Atmospheric Chemistry and Physics* 13449–13463. https://doi.org/10.5194/acp-16-13449-2016
- E A. F R. A B. B G. O L. M R. & P C. (2019). Characterization of a commercial lower-cost medium-precision non-dispersive infrared sensor for atmospheric co2 monitoring in urban areas. *Atmospheric Measurement Techniques* 2665–2677. https://doi.org/10.5194/amt-12-2665-2019

Collaborators

NIST:
Kevin Cossel, David Long, David Allen, Julia Marrs, Aaron Johnson, Rodney Bryant, David F. Plusquellic, Antonio Possolo, and many more...

Other institutions:
Paul B. Shepson, Colm Sweeney, Eric Kort, Xinrong Ren, Brian McDonald, Russell R. Dickerson, Charles Miller, Riley Duren, Kenneth Davis, Kevin R Gurney, Phillip Decola, Jocelyn Turnbull, Ray Weiss, Ralph Keeling, Alan Brewer, Ariel Stein, Christopher Loughner, Lucy Hutyra, and many more...

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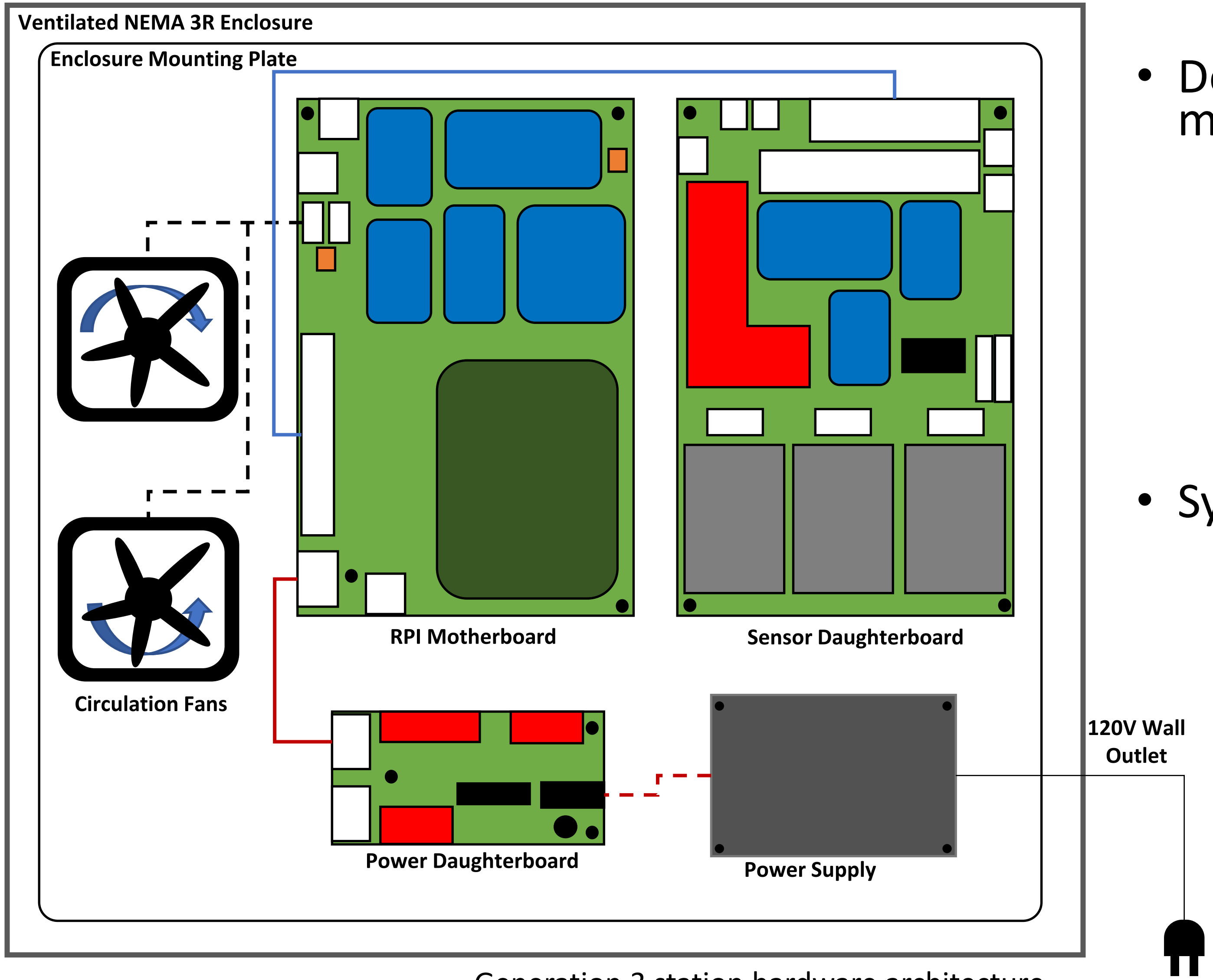
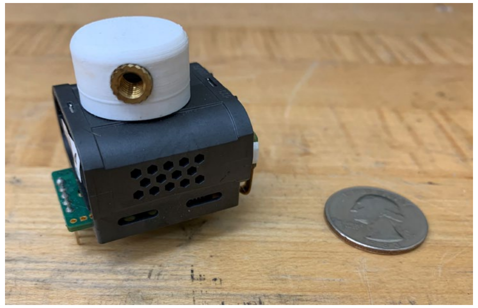
Slide courtesy of Israel Lopez-Coto

Low-Cost CO_2 Station Design



Generation 3 station hardware architecture

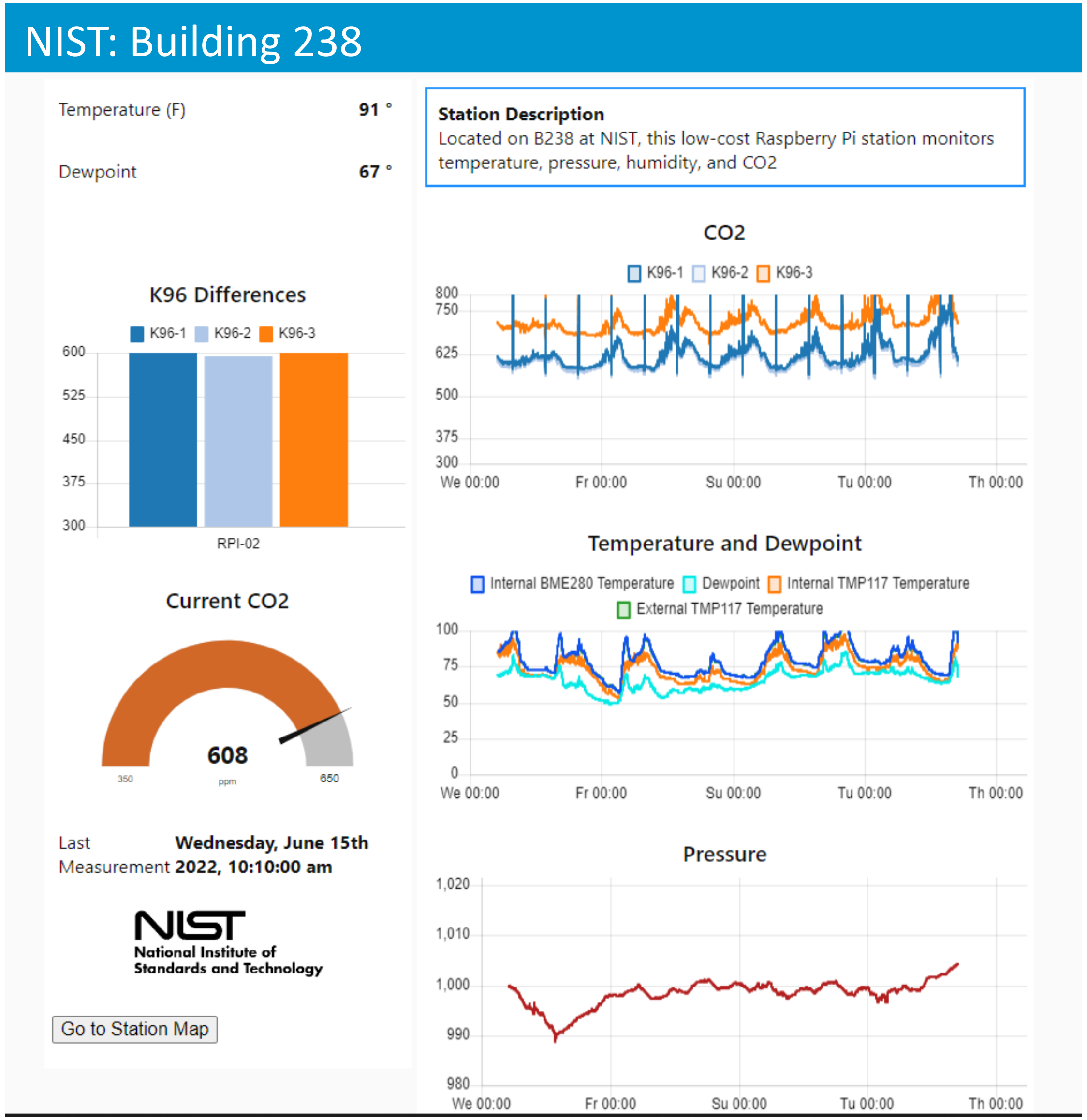
- Design considerations, sampling packages must be:
  - Standardized
  - Compatible with off-the-shelf sensors and microcontrollers
  - Modular
  - Low power
  - Compatible with reference standards for in-field calibration
- System must allow for redundant sensors



K96 with custom calibration cap

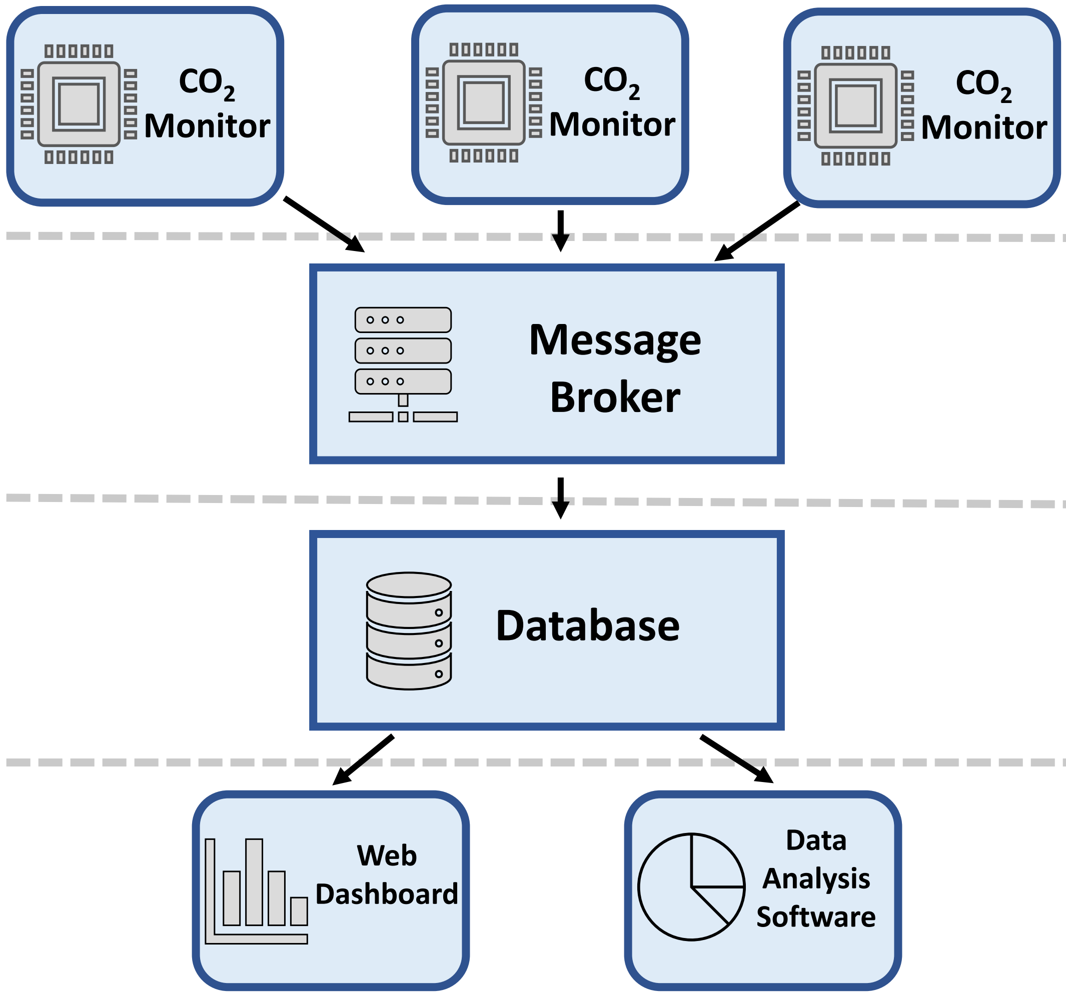
Sensor Package: Supporting Network Infrastructure

- Custom-designed network supporting:
  - Secure real-time data collection from stations to centralized servers
  - Remote accessibility to stations
  - Ability to consolidate measurements from different instruments (Picarro, etc.)
  - Support for real-time calibrations with reference standards
  - An interactive dashboard for data visualization
- Infrastructure designed to be scalable/modular, allowing:
  - Easy addition of new sensor measurements to the database
  - Simple deployment of new stations to the network
- System uses open-source software and protocols in accordance with industry standards



Screenshot of online station dashboard

Sensor Package: Network Architecture



Device Layer

Queries sensors and processes real-time measurements using custom modular shell and python scripts

Messaging Layer

Sends measurements through Mosquitto, an open-source messaging platform that implements the MQTT protocol (mosquitto.org)

Data Storage Layer

Stores measurements using MongoDB, an open-source No-SQL database

Data Presentation Layer

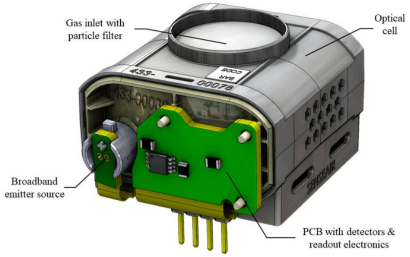
Presents measurements to end-user through platforms like Node-Red or Grafana

Note: images courtesy of PowerPoint

Sensor Package: Device Layer Architecture

Sensor Reading Component
`k96.py, readTMP117.py, etc.`

Queries sensors every 3 seconds



K96 Diagram, courtesy of Wastine et. al, 2022

Data Logging Component
`sensor_to_redis.sh`

Logs messages to Redis open-source, in-memory database (redis.io)

Redis logo, courtesy of redis.io

Data Processing Component
`redis_to_json.py`

Queries Redis, calculates 1-minute averages, outputs a properly-formatted JSON message

```
{“start_epoch”: 1676221133,
“co2”: 450 … }
```

Abbreviated JSON packet

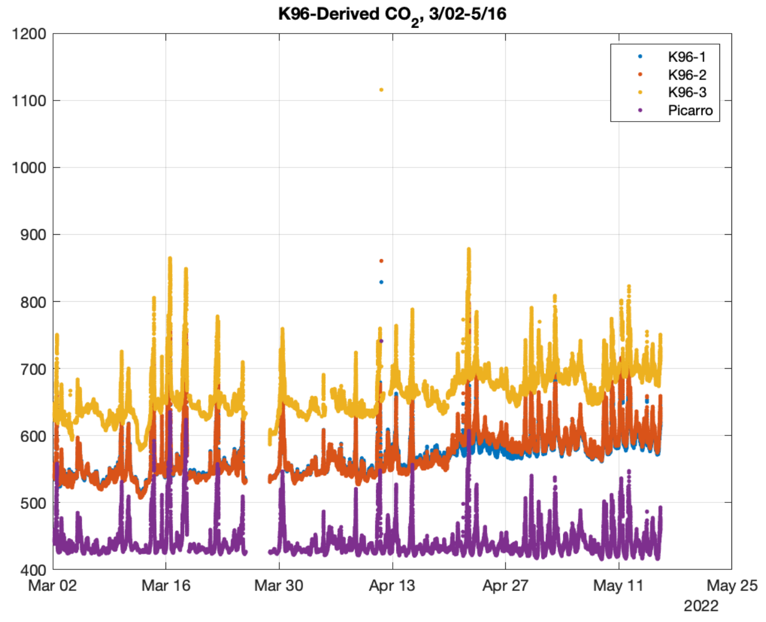
Message Output Component
`json_to_mqtt.sh`

Uses Mosquitto and MQTT to send a JSON message to the messaging layer

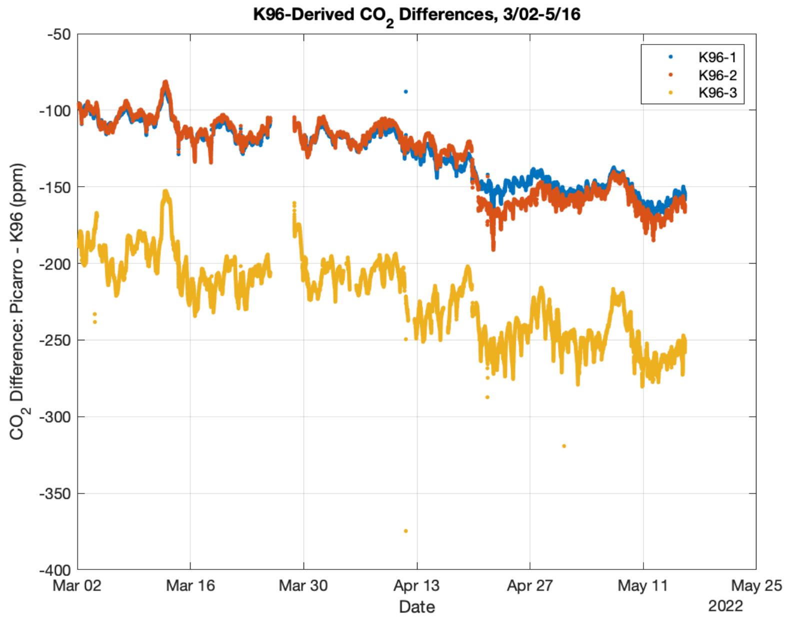
Mosquitto logo, courtesy of mosquitto.org

Initial Sensor-Derived CO_2 Measurements

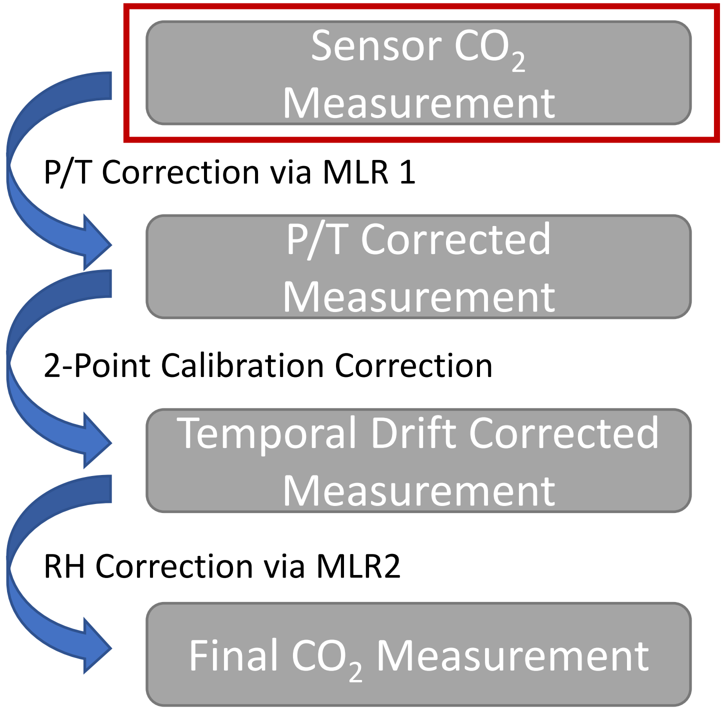
- Large offsets between CRDS and sensor measurements
- Large offset between sensor 3 and sensors 1 and 2
- Precision measurements are within manufacturer specifications, but further corrections needed for research applications



Timeseries of sensor-derived CO_2 measurements



Difference between CRDS and sensor-derived CO_2 measurements.



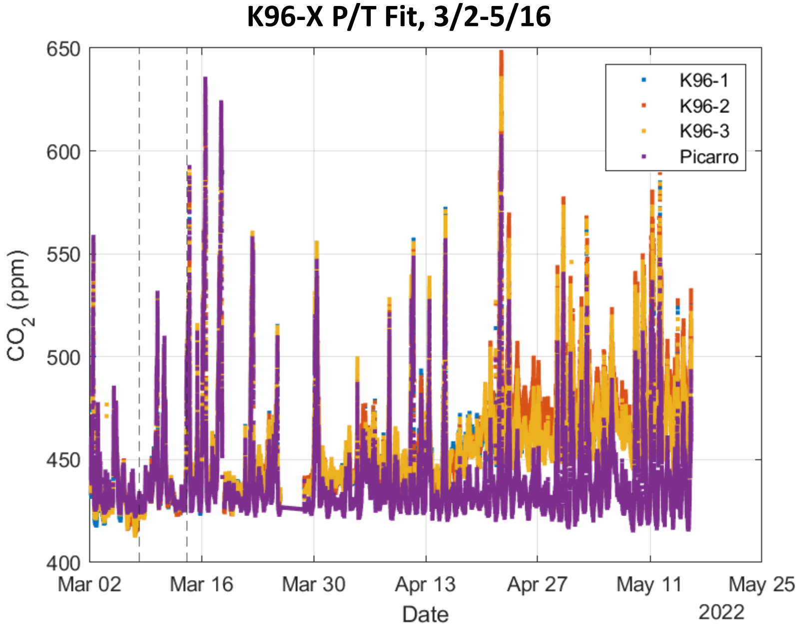
Sensor	Mean (ppm)	S. dev (ppm)
K96-1	-128.84	19.7
K96-2	-129.97	23.82
K96-3	-222.11	25.89

Sensor-derived concentration statistics

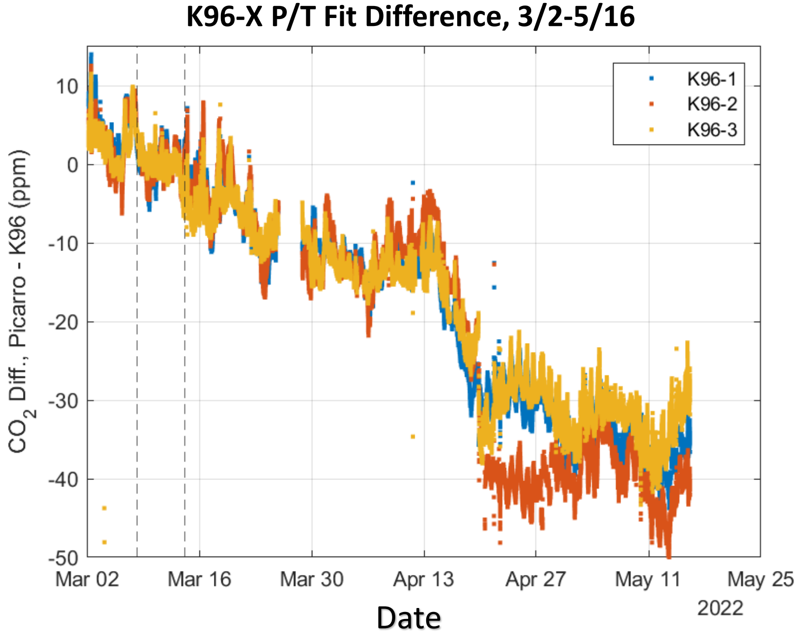
Note: mean and standard deviation calculated for entire timeseries window

Correcting P/T Impacts

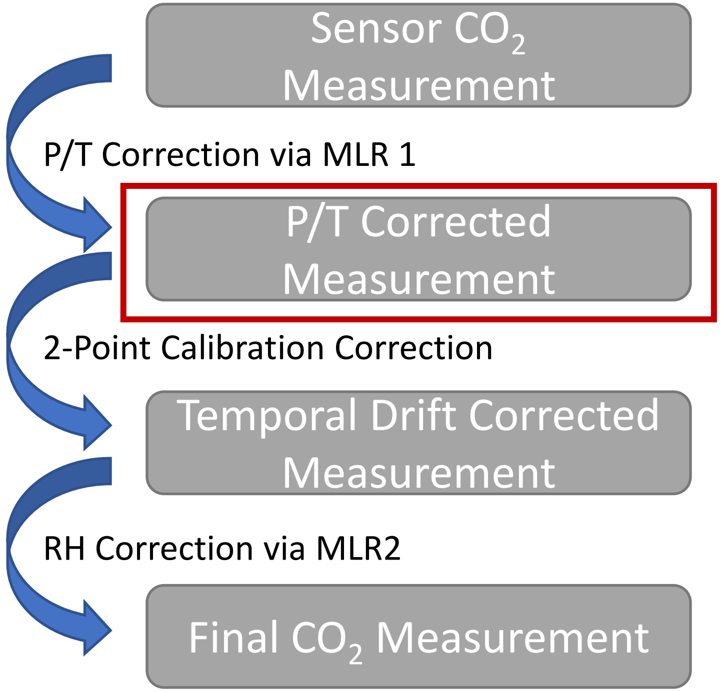
- MLR groups low-cost sensor concentrations together, but further corrections needed to remove temporal drift



Timeseries of P/T corrected CO_2 measurements from 3/2-5/16



Difference between CRDS and low-cost sensor CO_2 measurements. Temporal drift present throughout timeseries



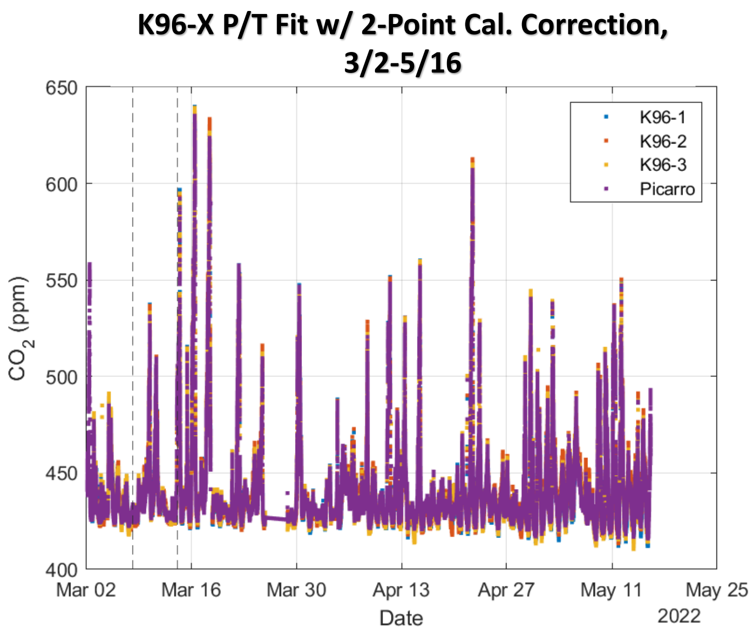
Note: mean and standard deviation calculated for entire timeseries window

Sensor	Mean (ppm)	S. dev (ppm)
K96-1	-17.1	14.26
K96-2	-18.88	16.94
K96-3	-16.92	13.11

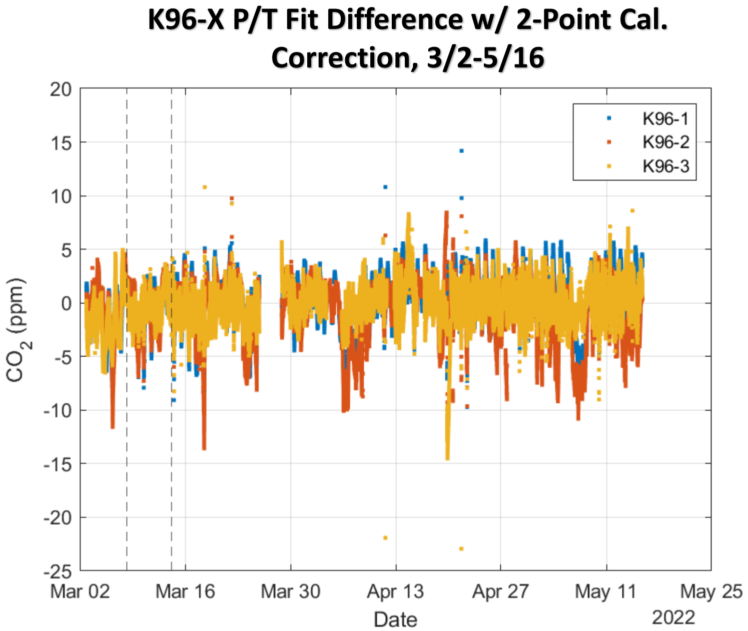
Table 3: P/T corrected concentration statistics

Applying a 2-Point Calibration

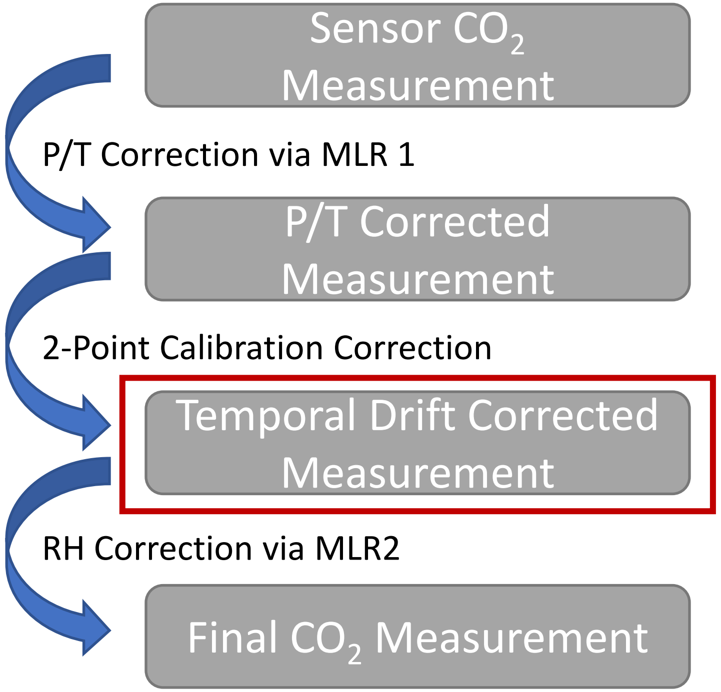
- 2-Point calibration removes temporal drift, but standard deviations are larger than desired



Timeseries of P/T/drift corrected CO_2 measurements from 3/2-5/16



Difference between CRDS and P/T/drift corrected low-cost sensor CO_2 measurements.



Sensor	Mean (ppm)	S. dev (ppm)
K96-1	-0.15	2.54
K96-2	-0.57	2.88
K96-3	-0.33	1.92

2-Point calibrated P/T corrected concentration statistics

Note: mean and standard deviation calculated for entire timeseries window

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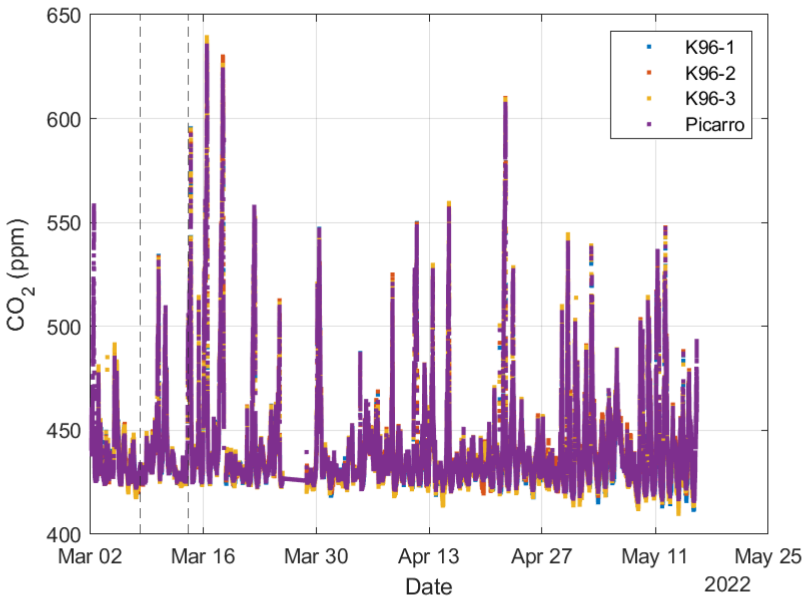
Sensors Converge

Final Corrected CO_2 Measurements

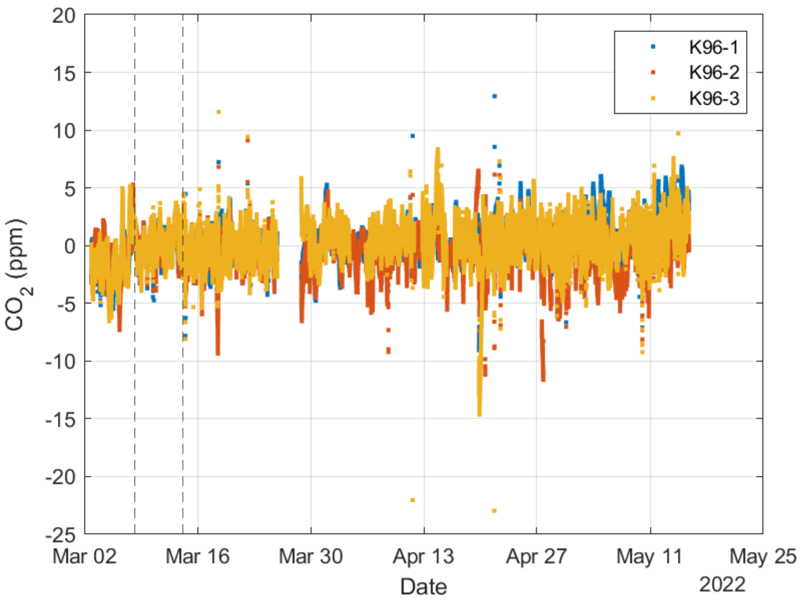
- Applying correction process reduced standard deviation below 2 ppm!
- Mean difference ~ 0 for sensors 1 and 3

K96-X P/T Fit w/ 2-Point Cal. Correction & RH Fit, 3/2-5/16

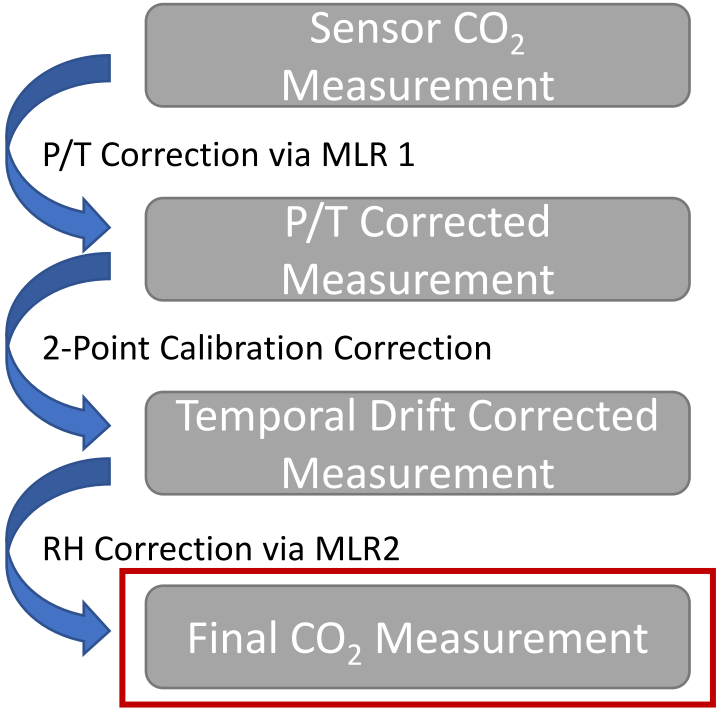


Timeseries of RH corrected CO_2 measurements

K96-X P/T Fit w/ 2-Point Cal. Correction & RH Fit Differences, 3/2-5/16



Difference between CRDS and RH corrected low-cost sensor CO_2 measurements.



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P/T/RH/drift corrected concentration statistics

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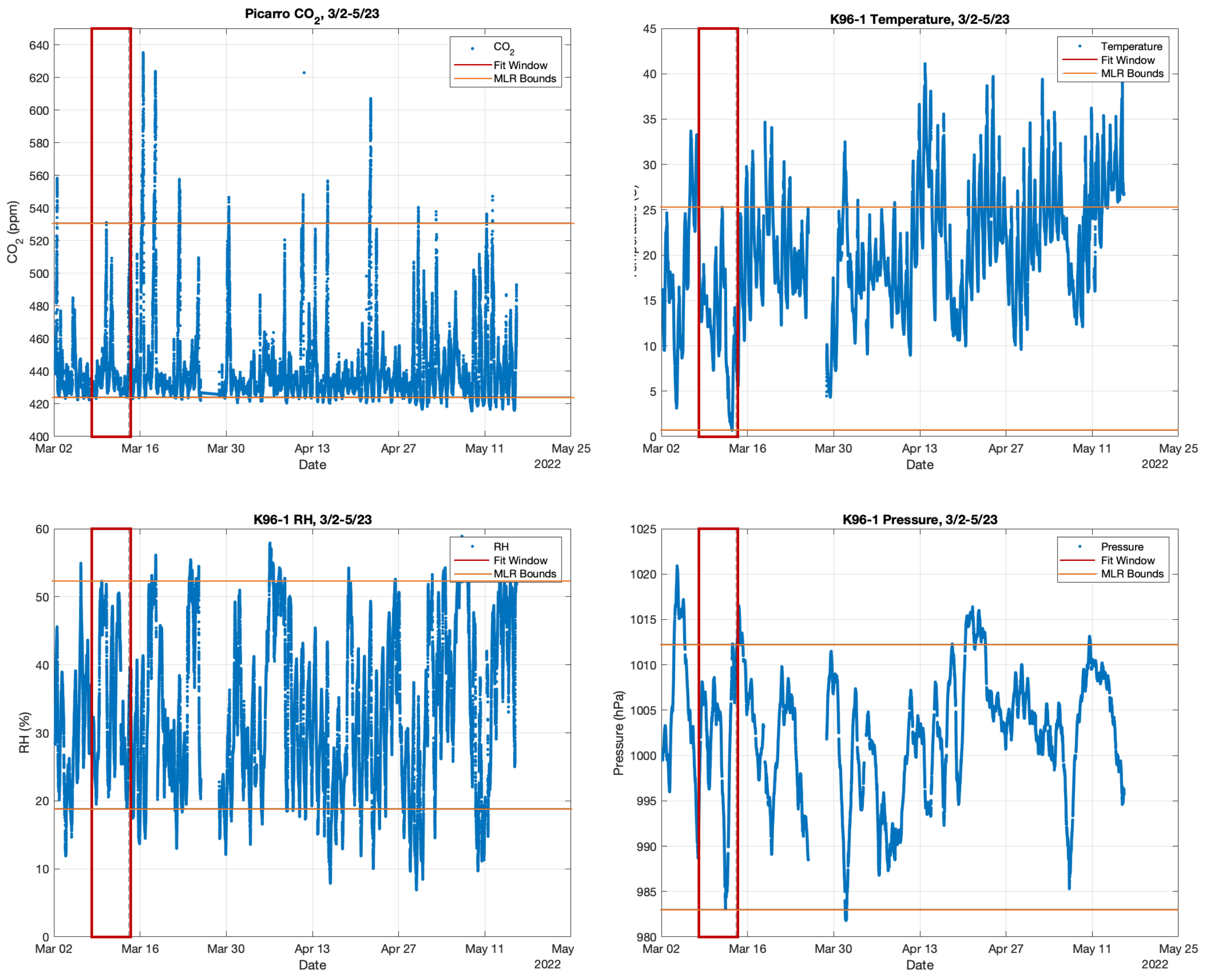
Sensors Converge

Fitting Window

- CO_2, P, T, and RH conditions varied throughout the experiment
- For MLRs, a training window with varying conditions was selected (3/8/22 - 3/14/22)

Parameter	Min	Max
Temp (C)	0.69	25.28
Pres (hPa)	983.1	1012
RH (%)	18.88	52.29
CO_2 (ppm)	424.3	531.3

Training window statistics



CO_2/T/RH/P timeseries throughout experiment