Improving Non-dispersive Infrared (NDIR) Sensors for Greenhouse Gas Monitoring

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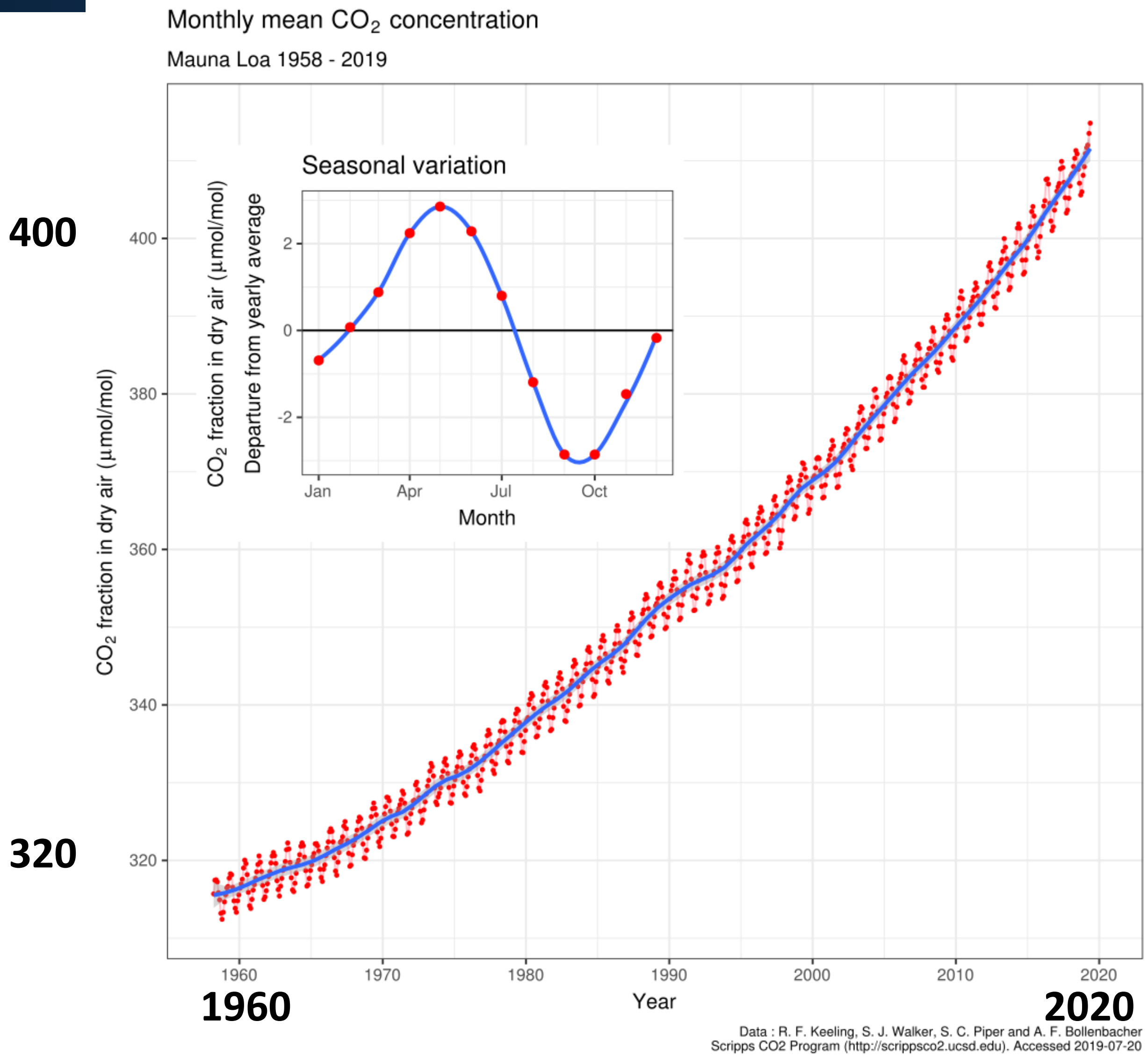
Outline

1. Motivation
2. Basic concepts, technical approach
3. NIST design for NDIR and comparisons to Picarro CRDS
4. Conclusion and future work

Keeling curve (from Mauna Loa)



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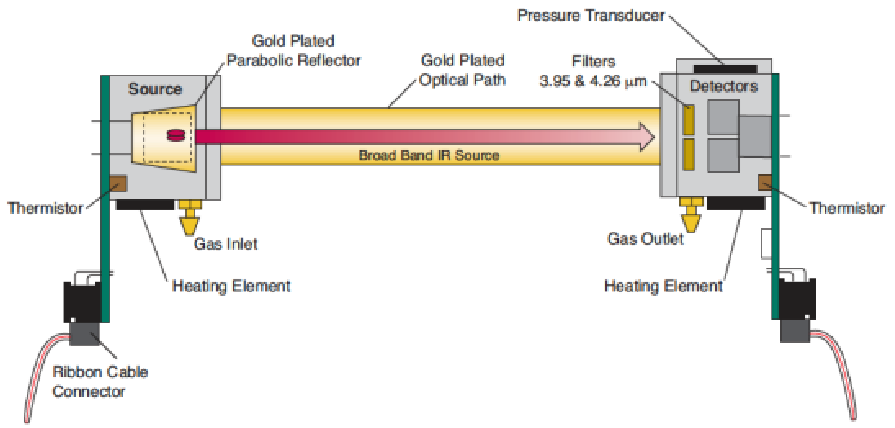
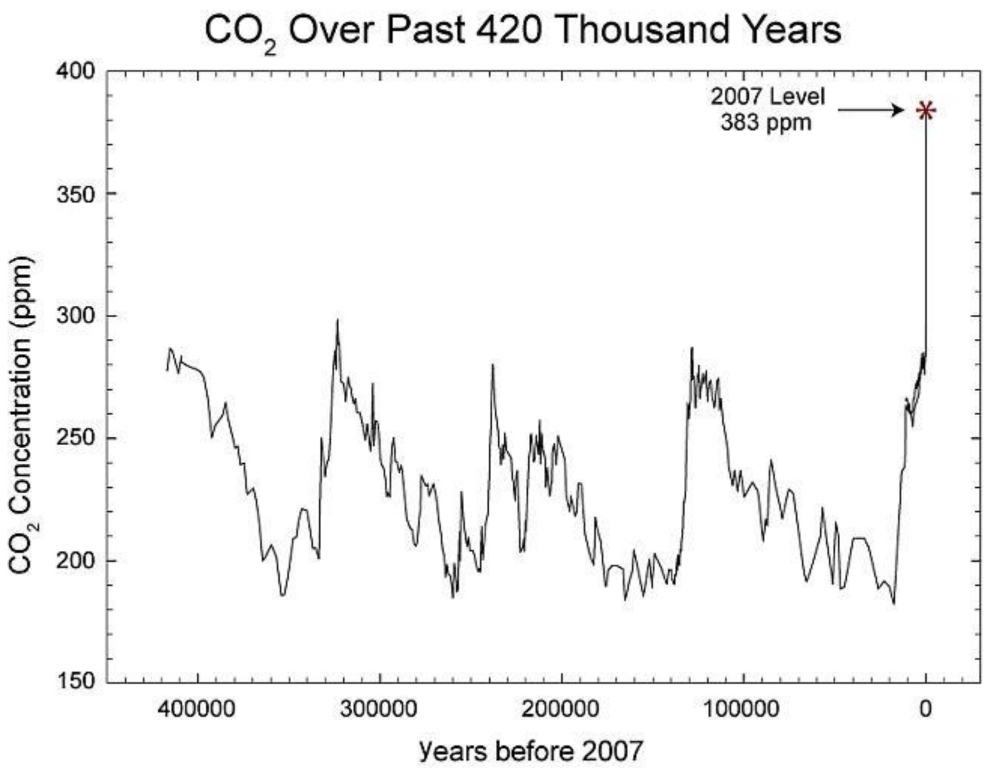
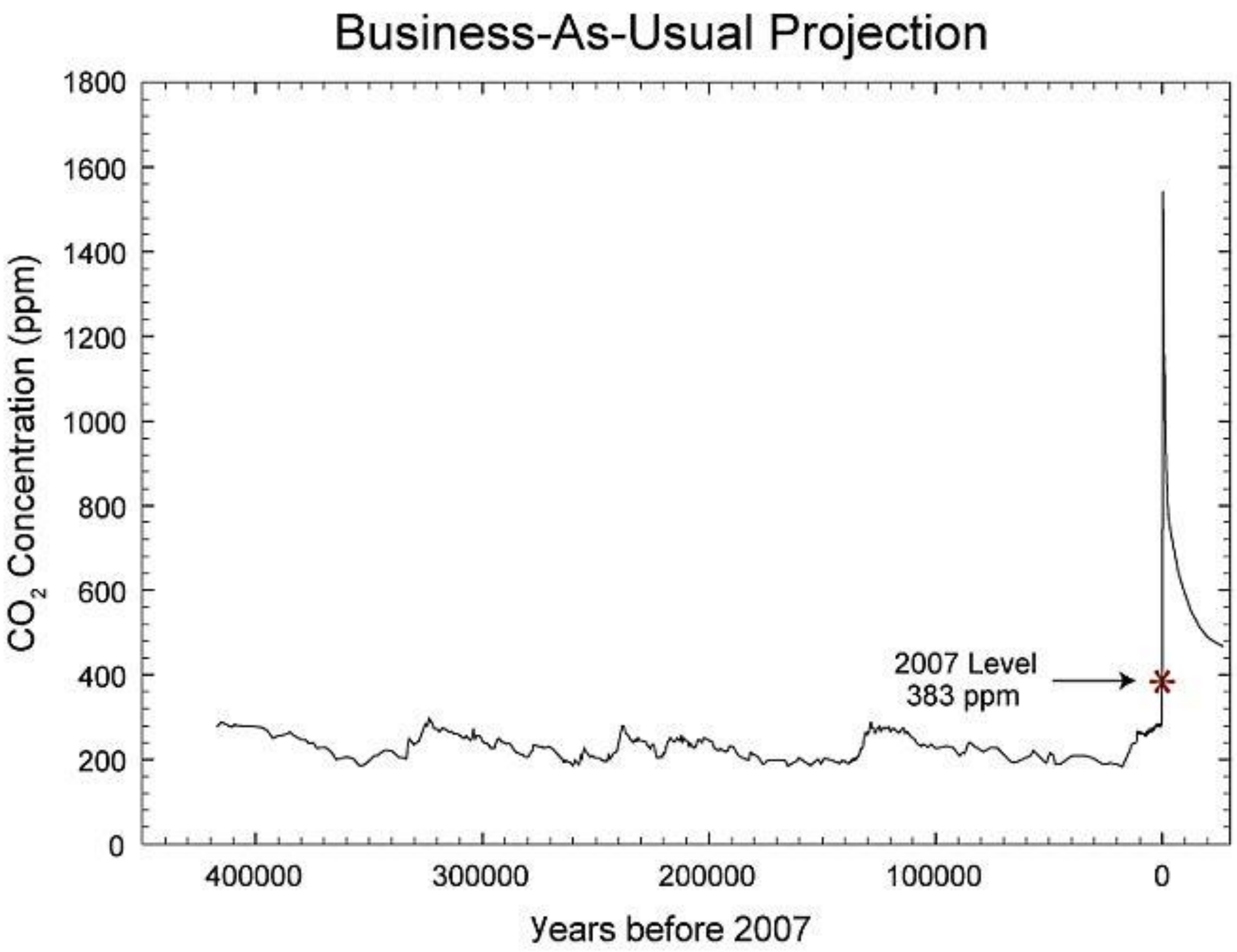


- Measurements using non-dispersive infrared (NDIR) sensor
- Calibrated daily using standard gas bottles
- CO_2 concentrations traceable to manometric techniques

Historical CO_2 levels and projection





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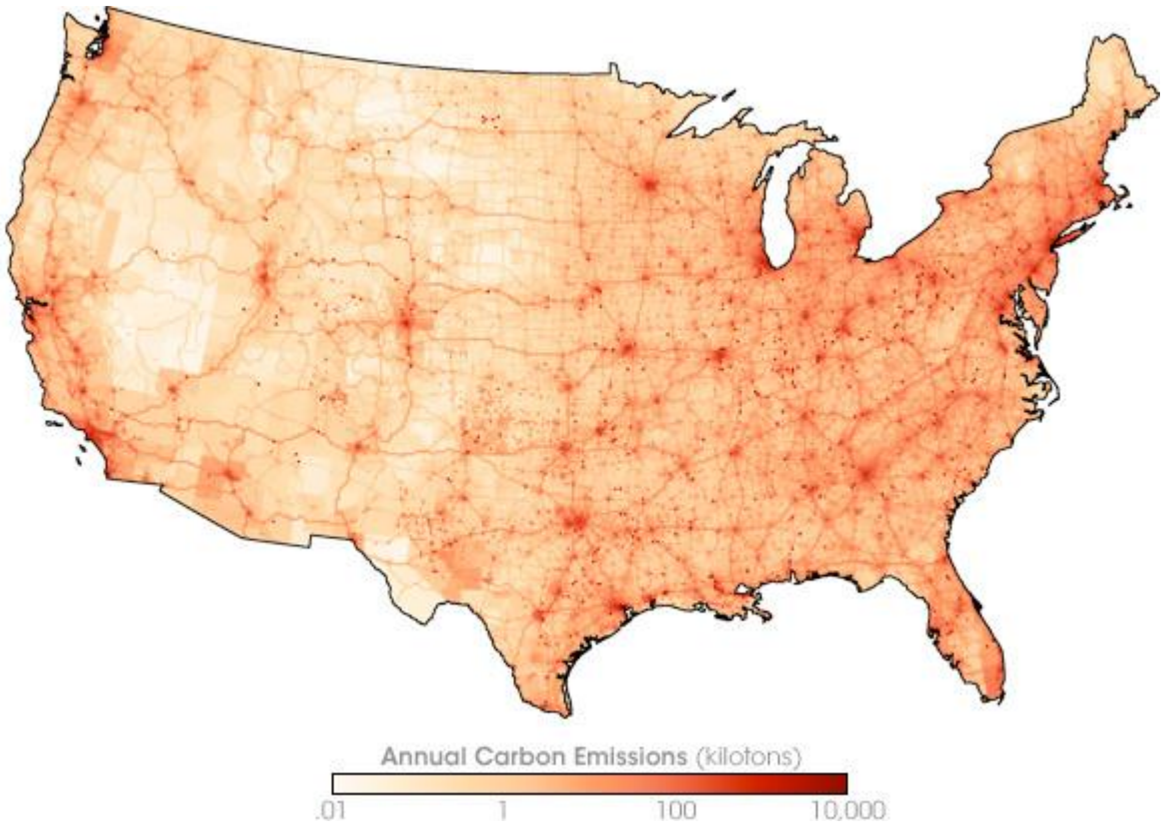
Ultimate goal of real-time CO_2 monitoring using distributed sensor networks



1. In order to reduce CO2 emissions, we need to measure both sources and sinks.
2. Denser sensor grid is needed.
3. Constant calibrations using standard gases are expensive.
4. Better sensors are needed.

(2002 CO_2 emissions map by Jesse Allen, based on data from the Vulcan Project.)

Use of commercial NDIR sensors

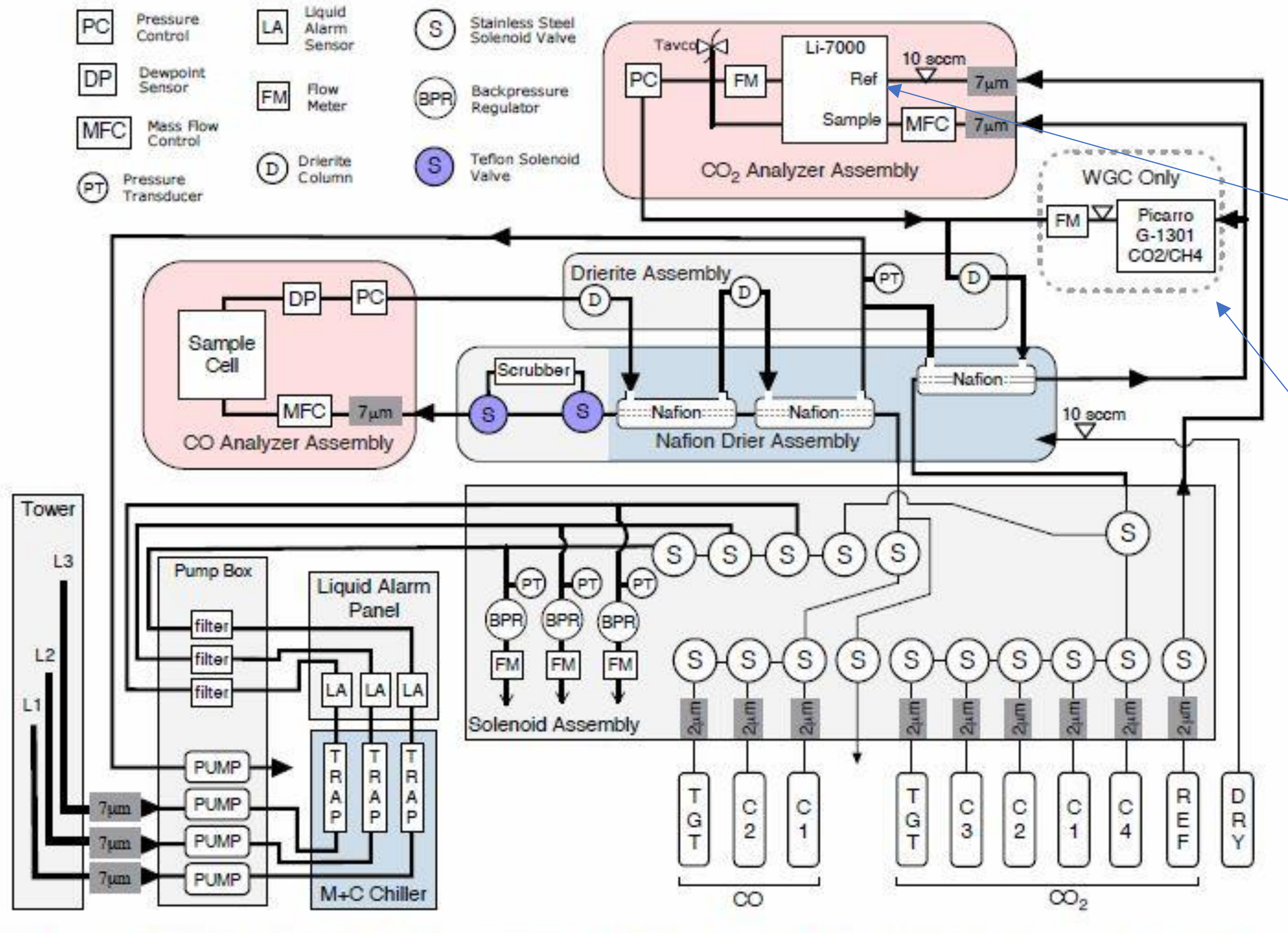
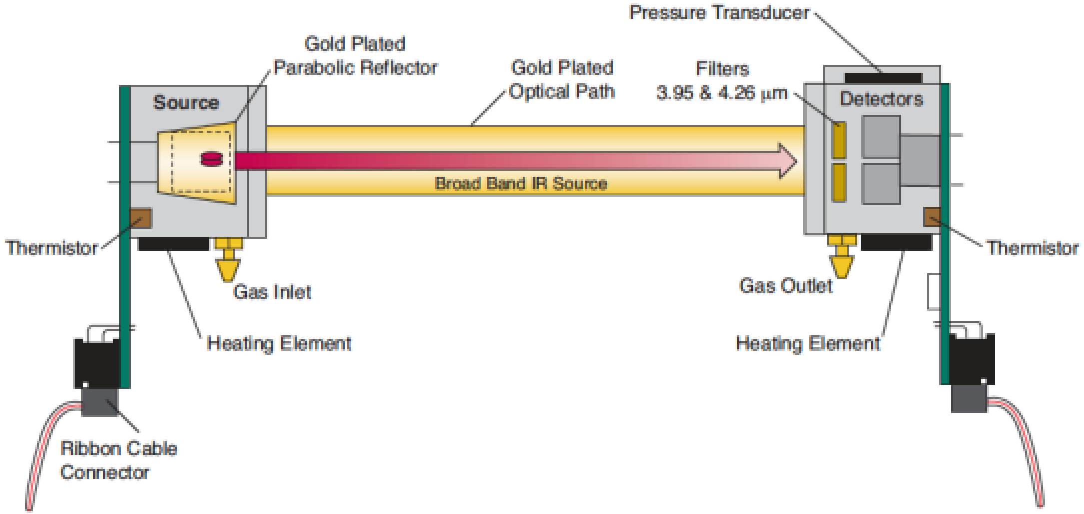


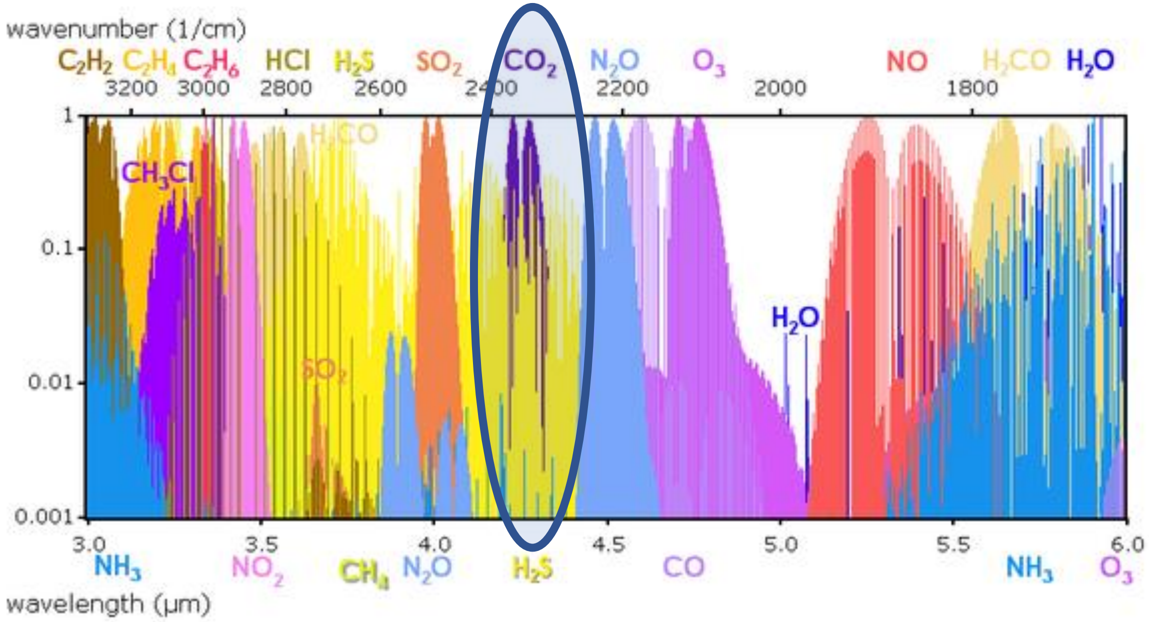
Fig. 1. Schematic diagram of the NOAA ESRL Tall Tower CO_2/CO analysis system. The Picarro G-1301 analyzer is only included at the WGC tall tower site (Walnut Grove, CA). Line thickness indicates tubing diameters of 0.125, 0.25, and 0.375 in. (0.3175, 0.635, 0.9525 cm). Pink and blue shading indicate heated and cooled enclosures. Photos are provided in the supplementary material.

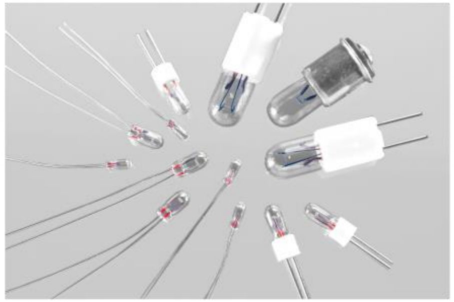
Use of a commercial NDIR at the heart of the
NOAA Tall Tower analysis system

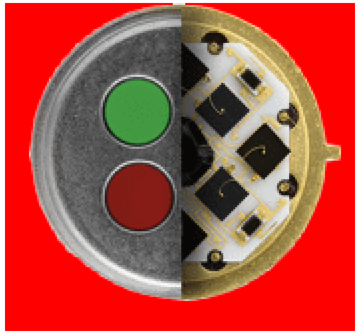
Picarro CRDS system
Limited to NIR where lasers exist

Technical Approach









- Gas concentrations measured using Beer-Lambert law
- Use of broad-band lamp sources
- Dual-band filters (on/off resonance wavelength)
- Typically use pyroelectric detectors with modulated source

Beer-Lambert law

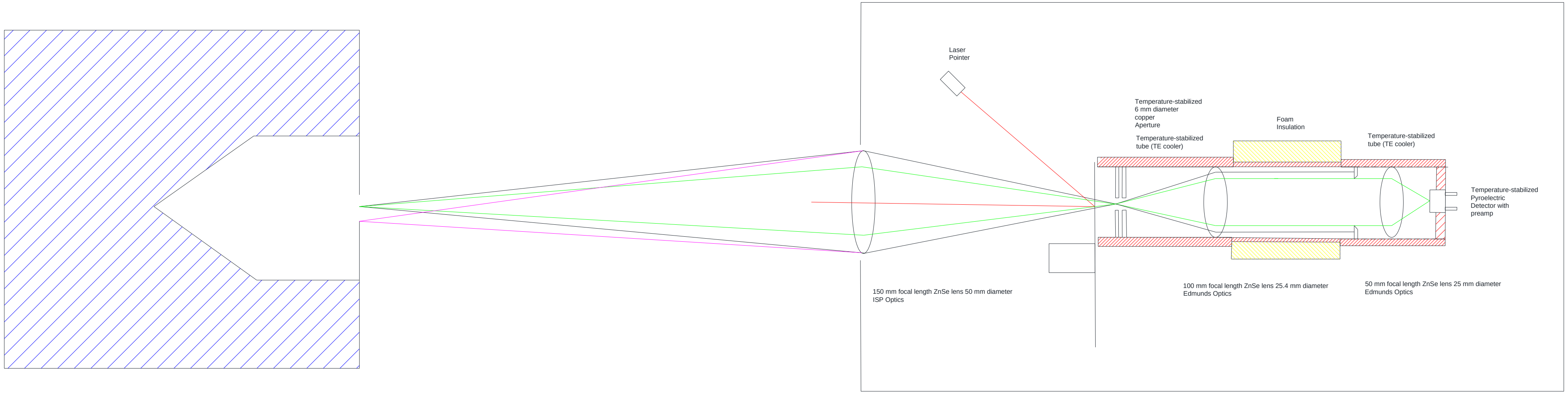
$$A = \varepsilon l c$$

A	absorbance
ε	Molar absorptivity
l	path length of the sample
c	concentration

Need to adjust path length for desired sensitivity (we use a 60 cm path length)

Calibrations using standard gas bottles (traceable to gravimetric or manometric standards)

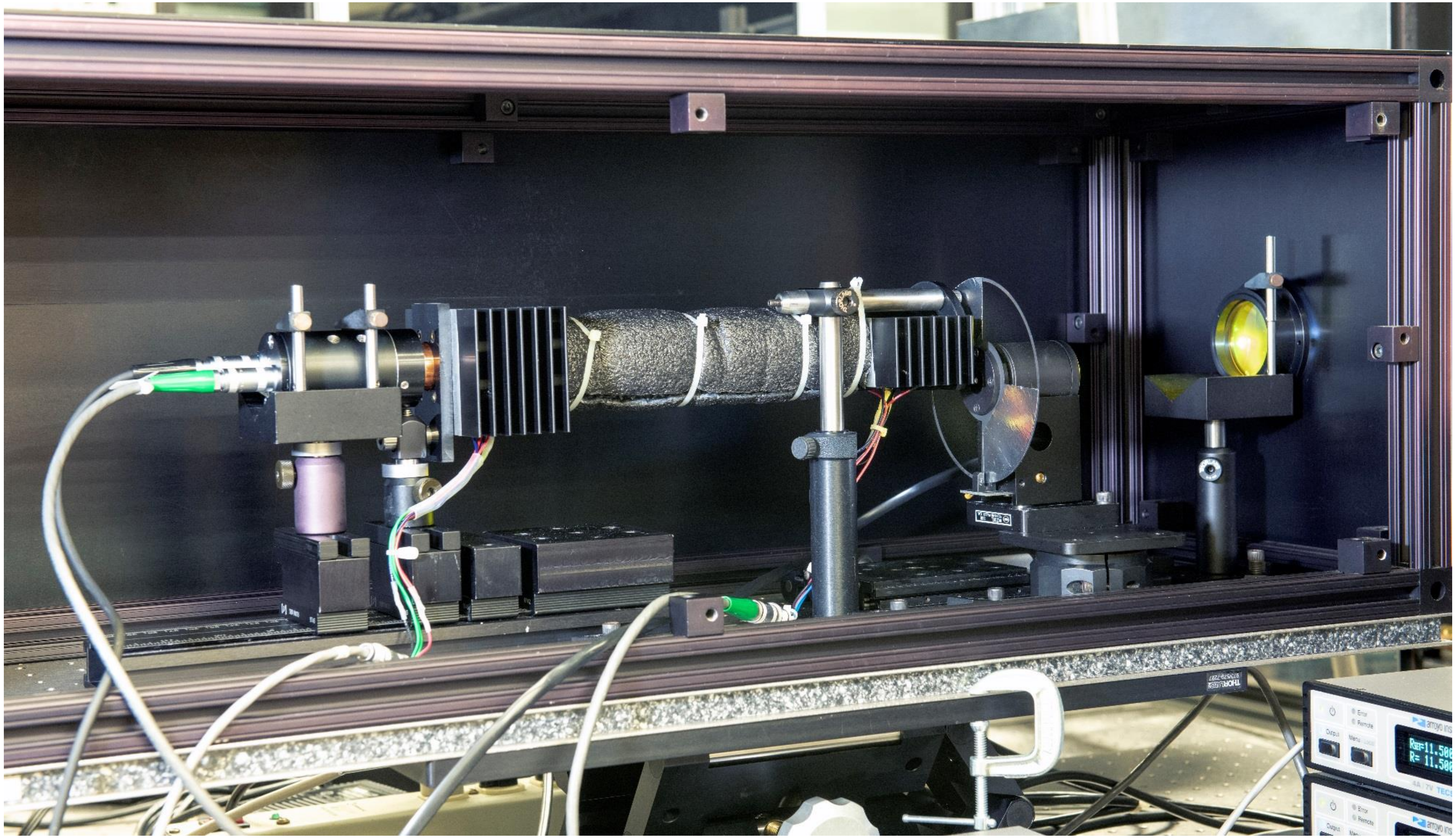
Why now?



Development of the Ambient Radiation Thermometer

- 8 um to 14 um filter
- ZnSe lenses
- Pyroelectric detector

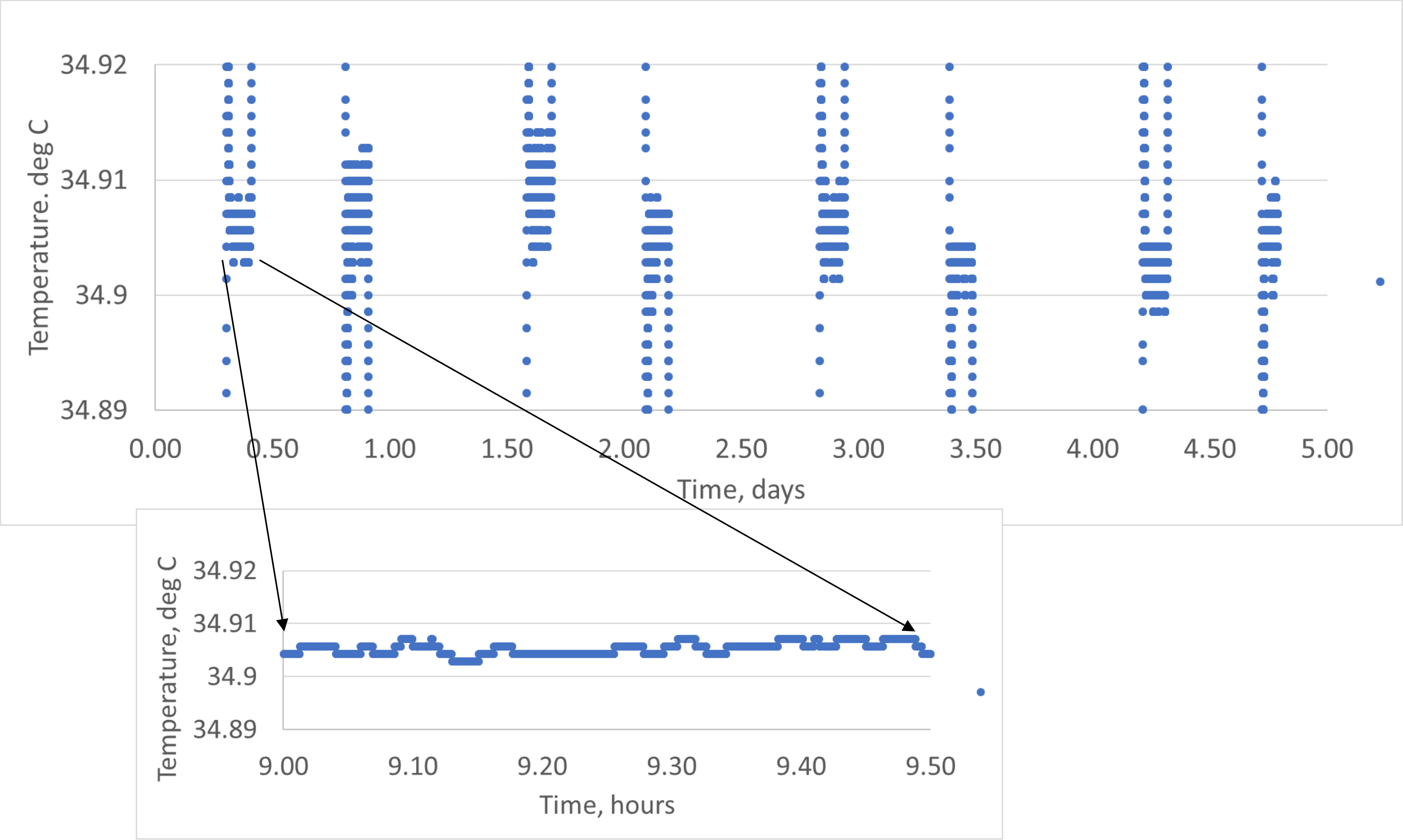
Internal view of the ART



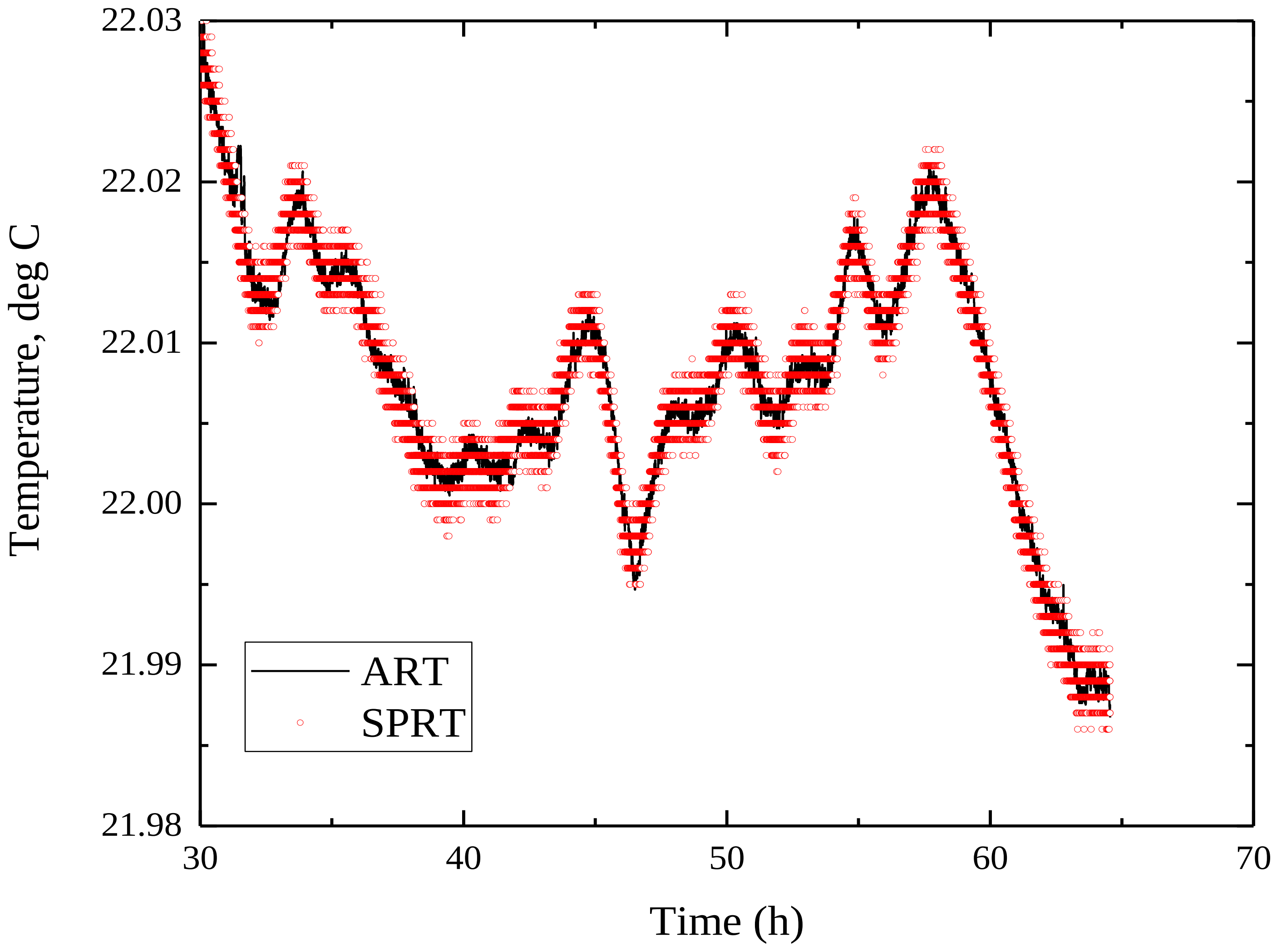
H. W. Yoon, et al. "Improvements in the design of thermal-infrared radiation thermometers and sensors," Opt. Express 27, 14246-14259 (2019)

DN-45 filed May 2019

Repeatability of < 2 mK over 5 days

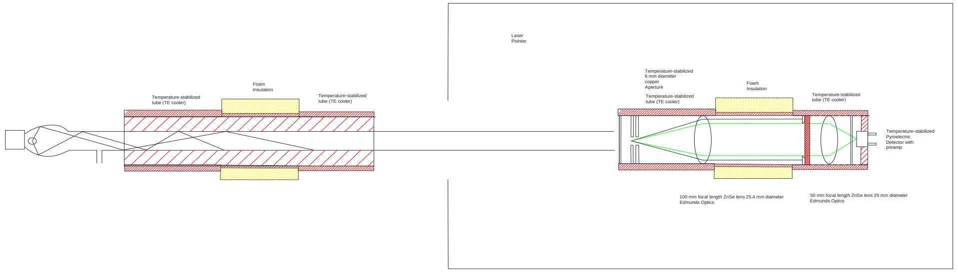


< 1 mK noise-equivalent temperatures close to ambient temperatures



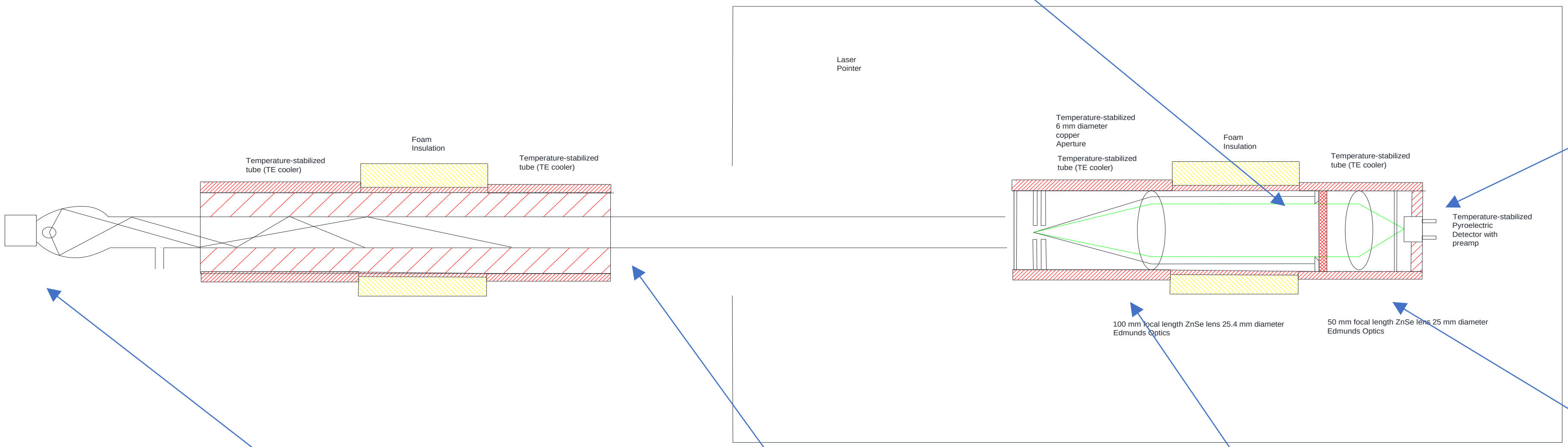
Resolution of < 1 mK temperatures at room temperatures

Modification of the ART design for NDIR



1. Traceable to standard gases
2. Signal of NDIR depends upon
   - Internal set temperatures
   - Detector responsivity
   - Source stability
   - Source frequency
   - Light-pipe stability of transmittance
   - Humidity

Schematic of NDIR sensor



One of two filters at 3.9 um (off) or at 4.26 um (on)

ZnSe windowed TE-cooled pyroelectric detector with preamplifier
Lockin detection system used

Tungsten lamp (5 V 0.06 A) with lifetime of 100,000 hours (11 years of continuous operation)

Pulsed with sine-wave signal from a function generator at 3.9 Hz

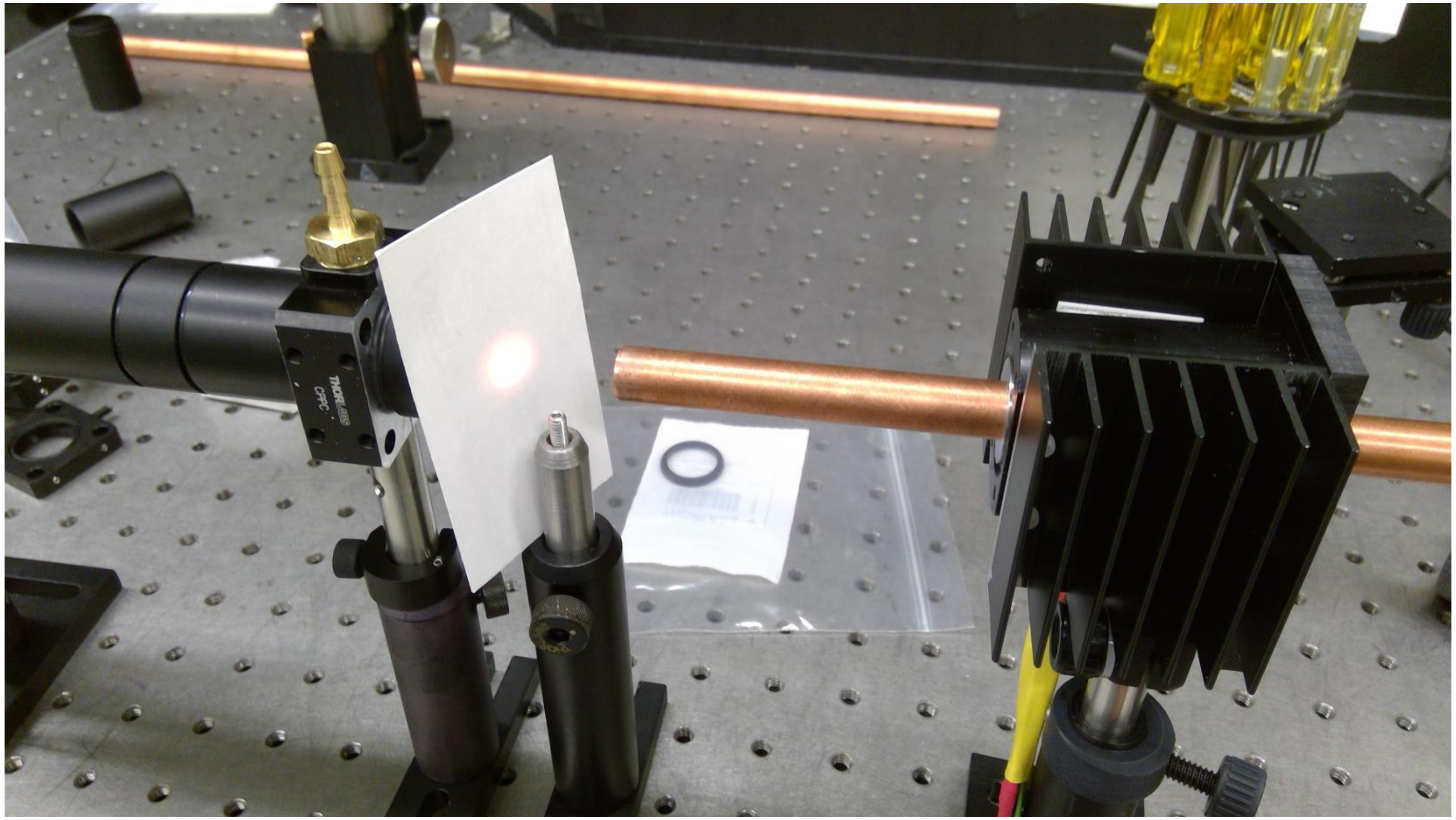
Copper, straight-tubing light pipe (0.5 inch diameter) 60 cm long

CaF lenses inside a temperature-stabilized tube

Sealed using sapphire windows at both end of tube

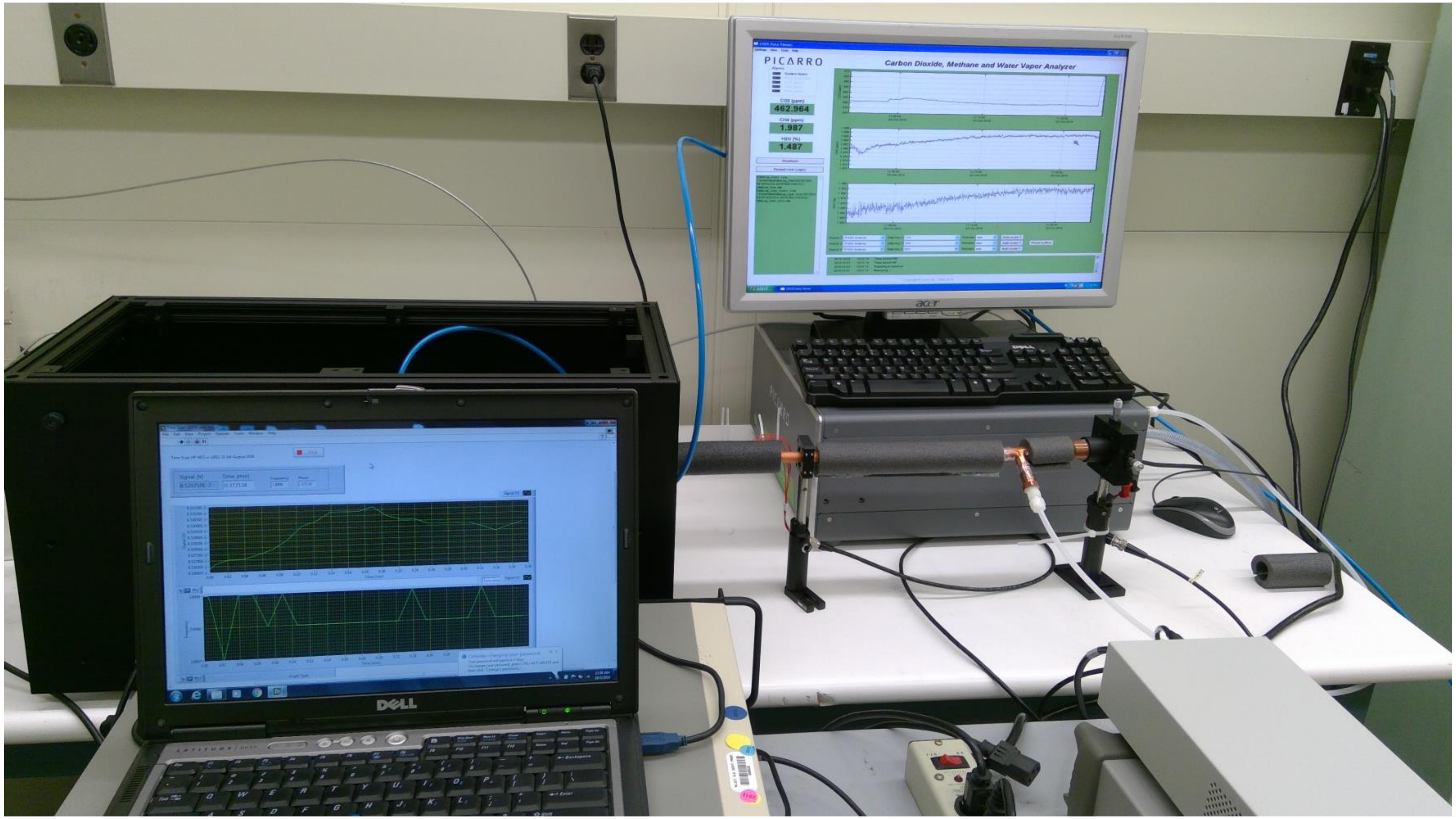
Upper view of setup

Light-pipe effect of tubing



Regular copper straight pipe works well
Will also use ultra-polished SS tube and Au-coated Cu pipe

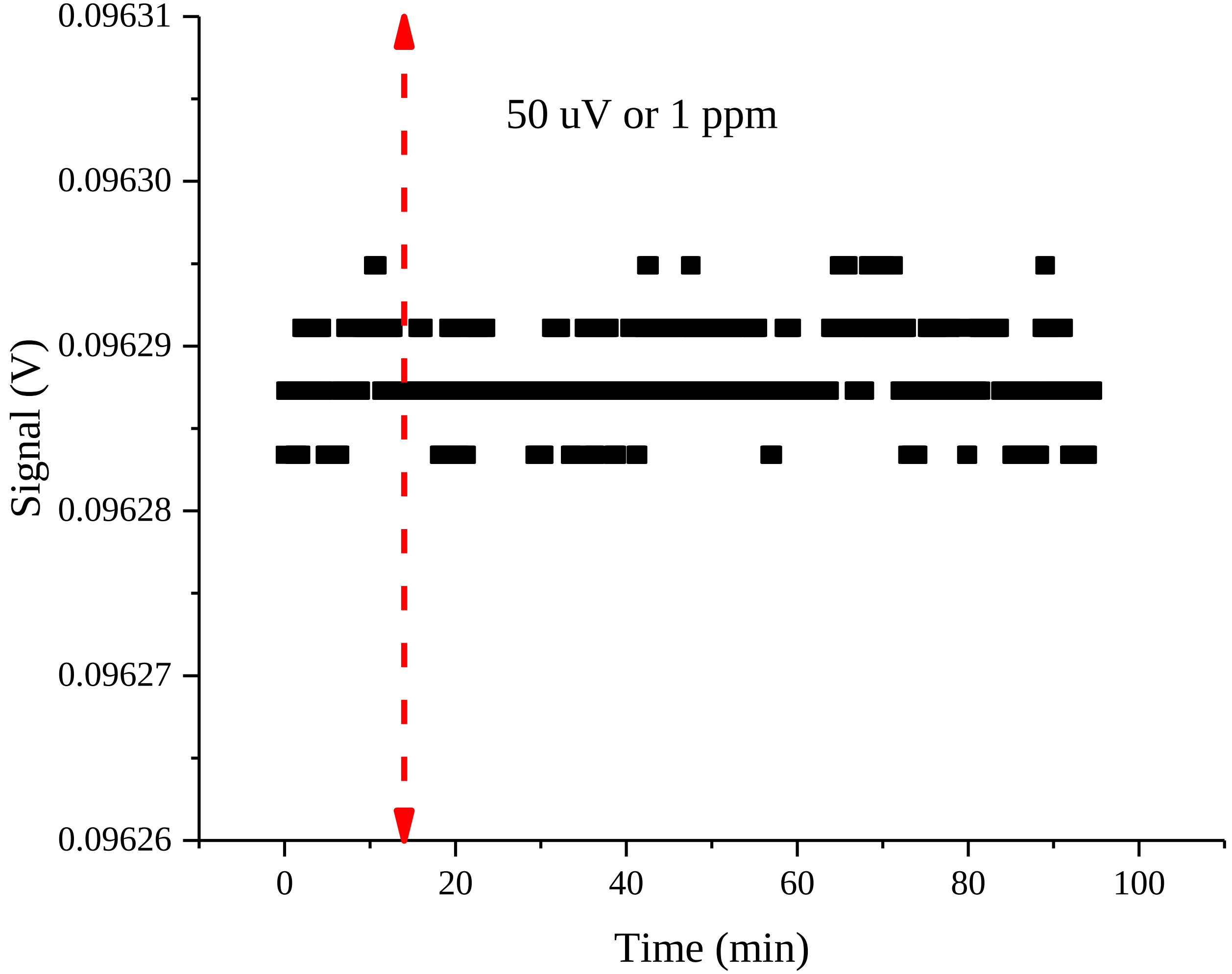
Comparisons to Picarro cavity ring-down spectroscopy (CRDS) instrument



Picarro CRDS
0.05 ppm resolution
0.5 ppm drift over 1 month
$30k/unit

NDIR sensor
0.15 ppm resolution
1.0 ppm over 3 months (TBD)
$2k/unit (TBD)

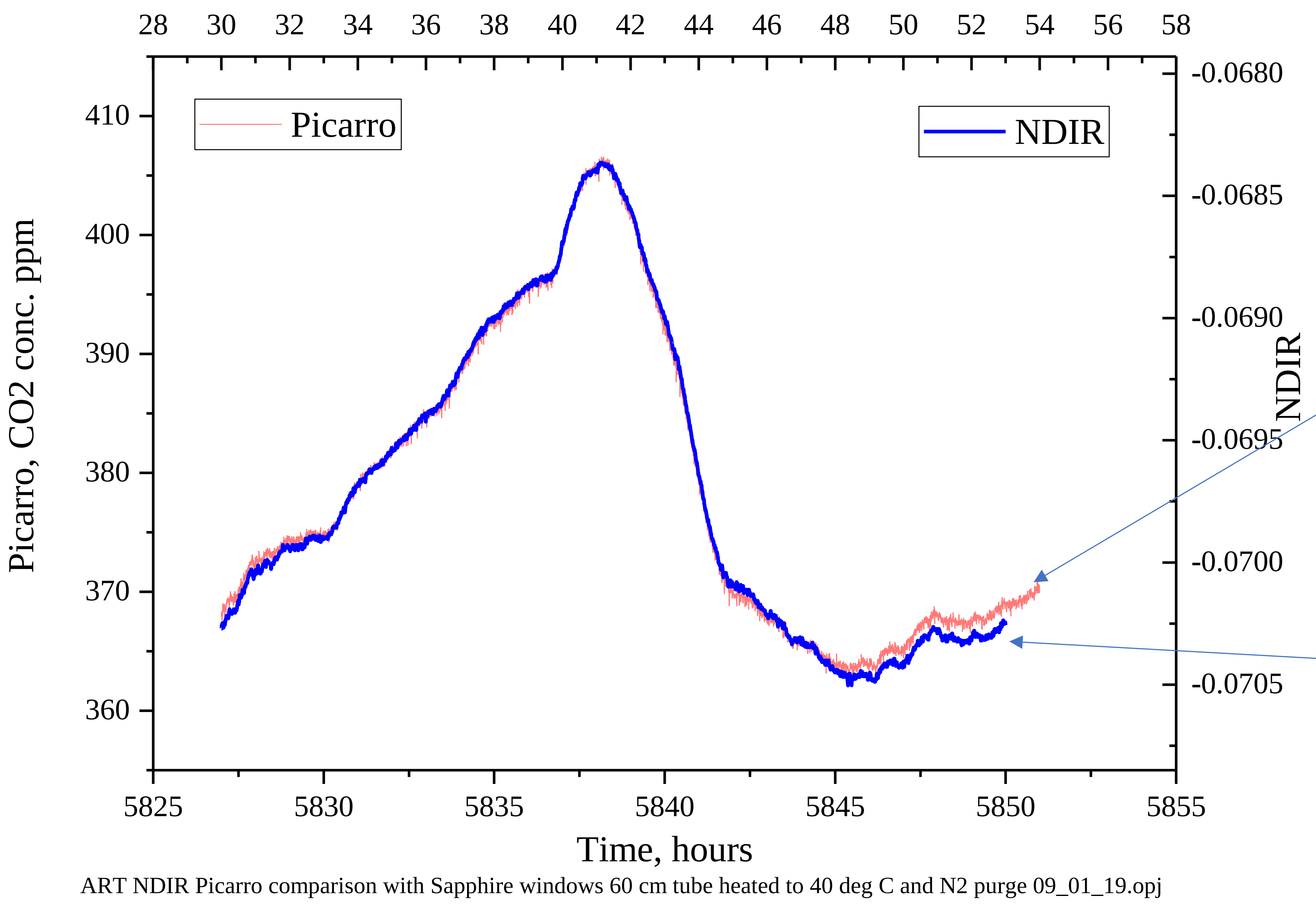
Stability of off-resonance signal at 3.6 um



NDIR 7 Hz off resonance 3_6 um.opj

Off-resonance signal stability is 0.2 ppm of CO2 for hours

NDIR CRDS comparison 1 (30 hour duration)

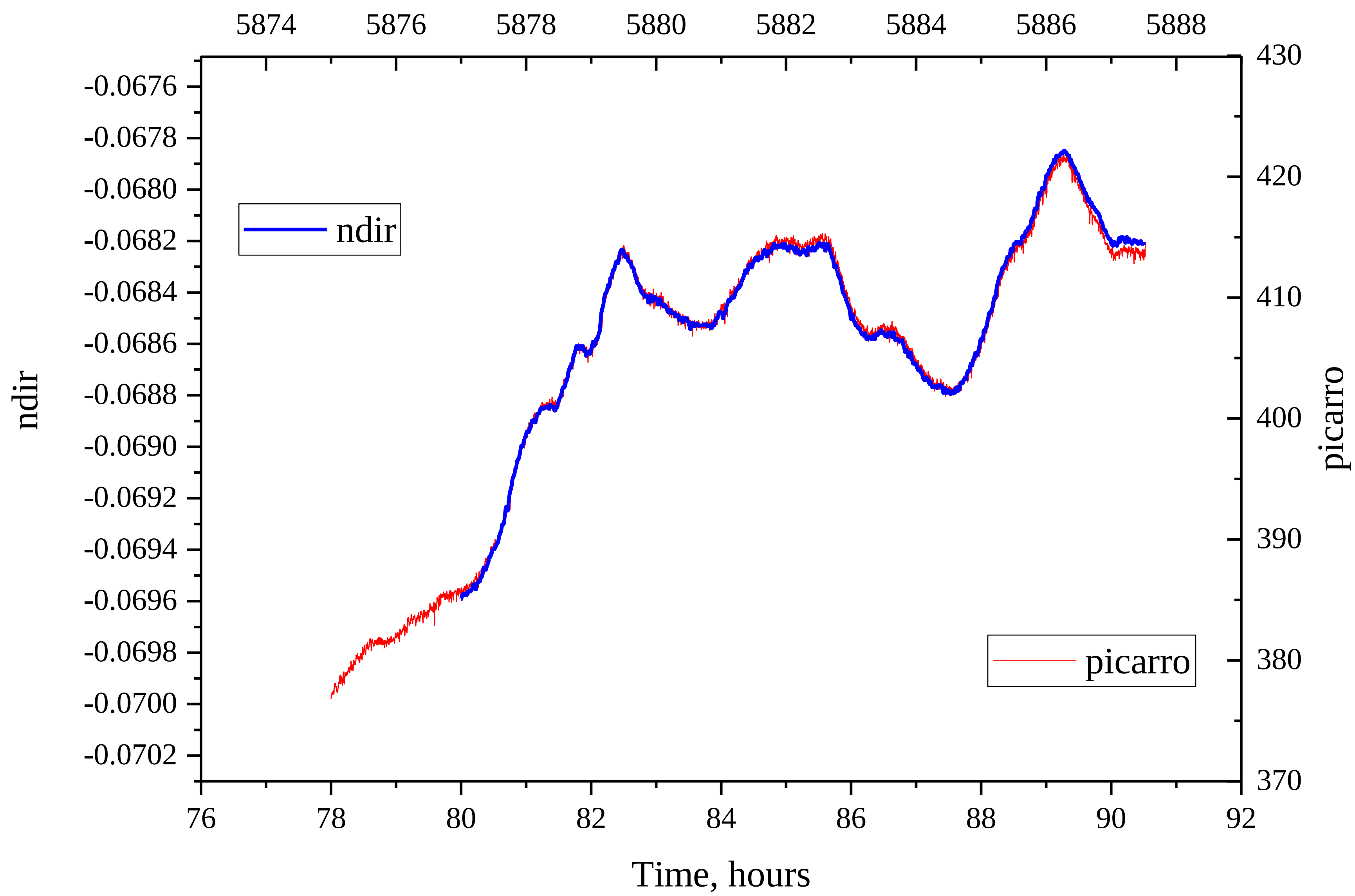


Scaling NDIR vertical axis to have it overlay on Picarro (using Picarro to calibrate the NDIR)

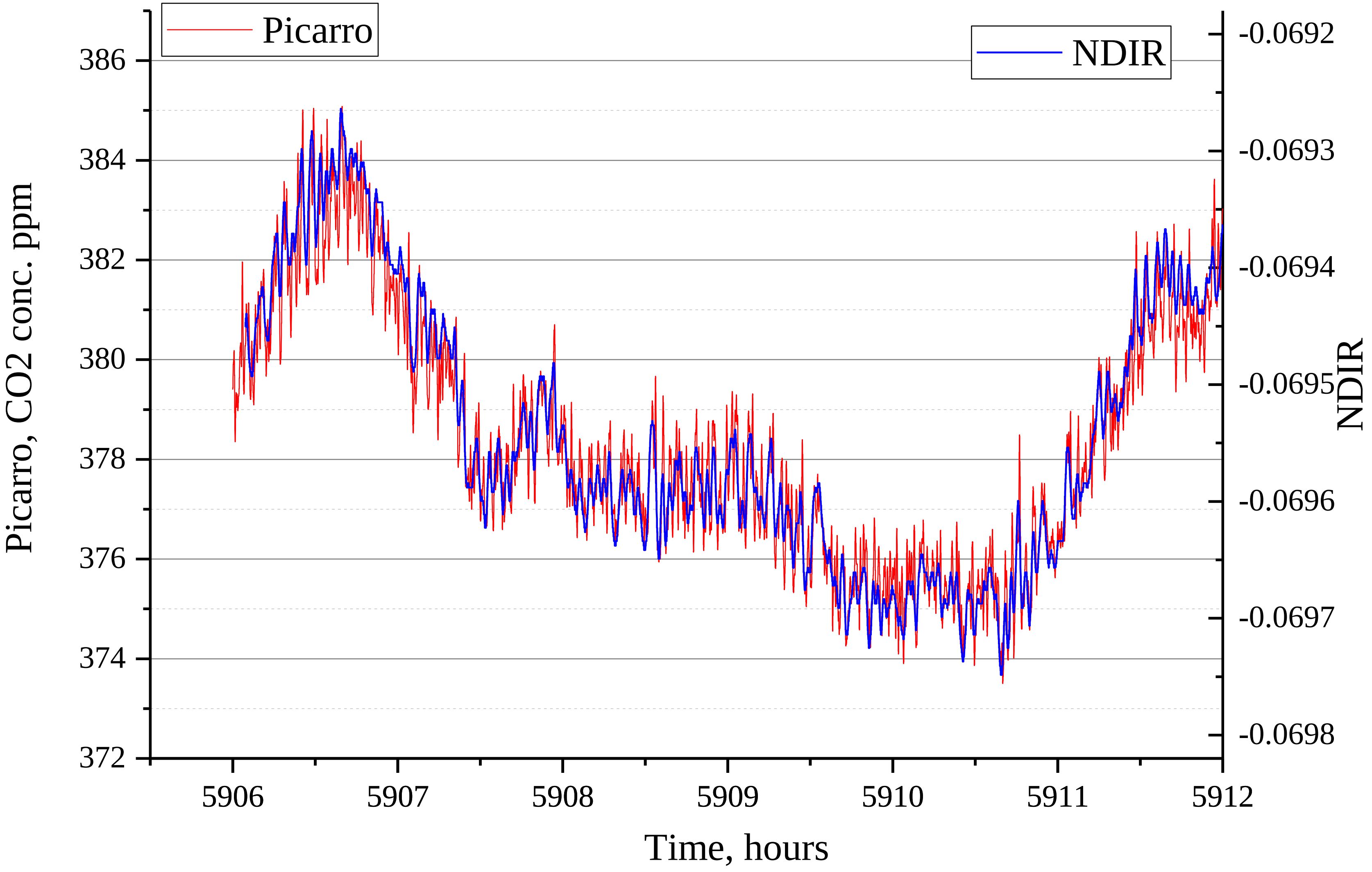
Short-term instability in the Picarro signal due to fluctuations in nitrogen gas purge

Deviation in NDIR due to system drift of ~2 ppm in 12 hours

NDIR CRDS comparison 2



NDIR sub ppm stability and resolution



Constructing a dual-band system

4.26 um 180 nm
3.06 um 160 nm

Lessons learned

NIST

Signal of NDIR depends upon

1. Internal set temperatures (stabilize temperatures of both tube and detector assemblies)
2. Detector responsivity (use interference filters on sapphire substrates and protected pyroelectric detectors)
3. Source stability (use long-life, low-power lamps)
4. Source frequency (use a function generator as a source with sine-wave output)
5. Light-pipe stability of transmittance (use gold-coated Cu pipe or SS pipe)
6. Humidity (condition gas before analysis)

Conclusion

NIST

1. NDIR sensors can be improved with better pyroelectric detectors and an actively stabilized detector compartment
2. The improved designs can be competitive with CRDS over short periods (12 hours)
3. The improved design can measure CO2 with 0.2 ppm noise
4. We expect to achieve 1 ppm stability over 3 months with the dual-band detector and a thermally stable and structurally stable setup
5. Other gas species between 1 um to 14 um can be measured with lower uncertainties with the improved design