

VCSEL calibration summary report

Minghui Diao diao@princeton.edu

Mark Zondlo mzondlo@princeton.edu

Dept. of Civil and Environmental Engineering, Princeton University

Princeton, NJ, 08544

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Part 1. Calibration system descriptions and diagrams

There are four major calibration systems that we use for calibrating VCSEL hygrometer. Their names and calibration ranges are listed in Table 1. The key point of the calibration system is to get a constant, well-defined water vapor concentration of air in order to compare with the VCSEL reading. Each system has different design and limits. Figure 1 shows the stainless housing we use to seal up the VCSEL hygrometer and immerse into bath. Figure 2 shows the pictures of each system that we use in lab.

Table 1. Calibration system of VCSEL hygrometers and their ranges

Calibration system	Calibration range
Critical orifice dilution flow	3 to 3000 ppmv
Organic slash bath system	-80 (0.5 ppmv) to -10 °C
LAUDA temperature controller	- 80 to 30 °C

RHS chilled mirror instrument	-100 to 40 °C
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Figure 1. VCSEL hygrometer sealed up in the stainless steel housing for calibrations

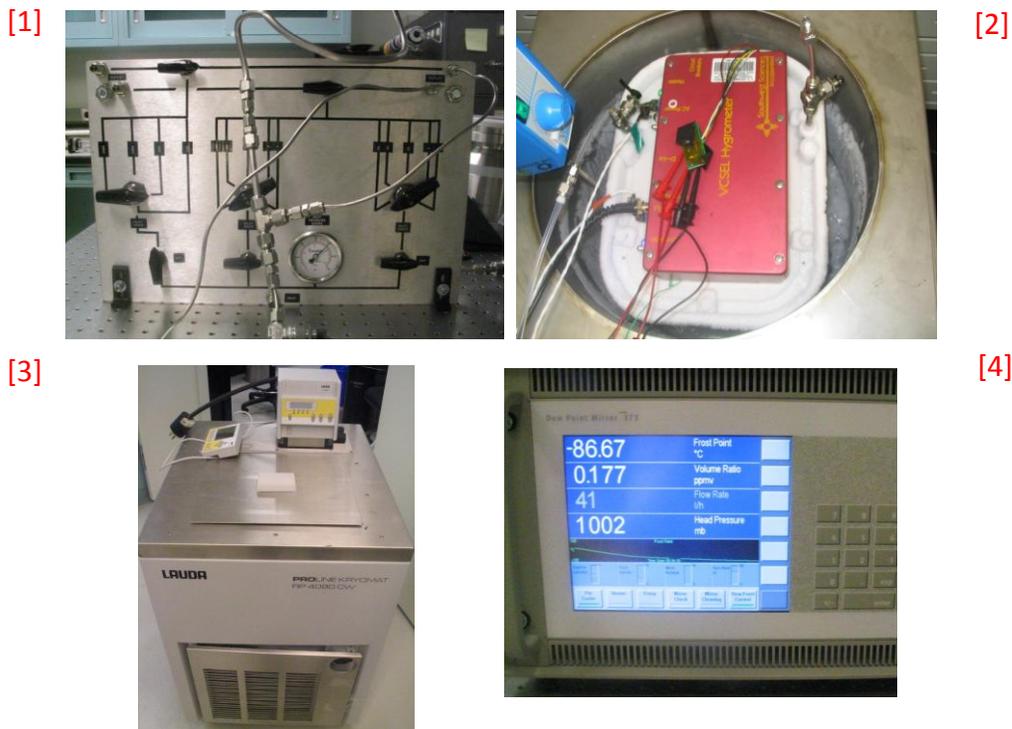


Figure 2. Four calibrations systems that we use to calibration the VCSEL hygrometer

System 1. Critical orifice system

In the critical orifice system, an air flow at higher flow rate can be combined with another flow at lower flow rate. The flow rate is calibrated with the bubbler at standard temperature and pressure (298K, 1013.25mb). The higher flow rate is usually for dry N₂ flow, which flows into the mixer, and then into the sealed cell of VCSEL. The other small flow will go through a cylinder which is filled with distilled

water and immersed in ice/water bath at 0 °C. The smaller flow will be saturated with water vapor and then combined with the dry N₂ flow inside the mixer.

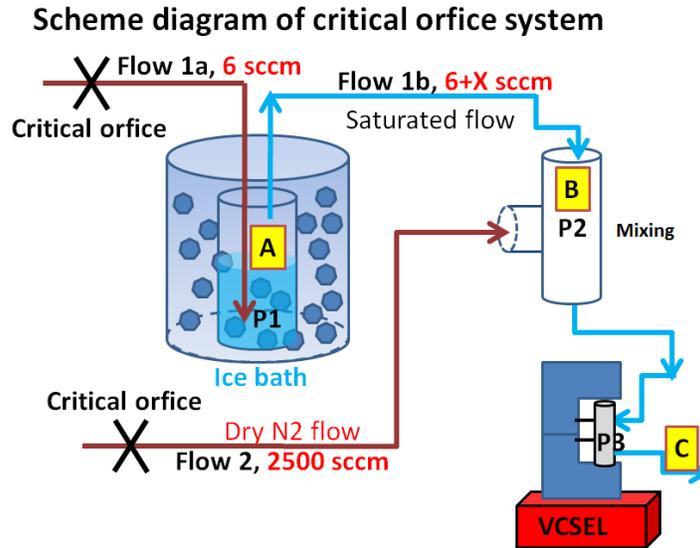


Figure 3. Diagram of the critical orifice system

System 2. Organic slash bath system

In the organic slash bath, we use several organic chemicals to get slash baths of certain freezing temperatures. The diagram of system 2 is shown in Figure 4a. The temperature is maintained steady by adding liquid nitrogen into the bath constantly. The wall temperature of the VCSEL housing is supposed to be equal as the outside bath temperature, which defines the saturation vapor pressure inside VCSEL housing by Clausius-Clapeyron equation.

System 3. Lauda silicon oil bath system

In the Lauda bath, we use silicon oil to control temperature by 0.1K. The diagram is shown in Figure 4b. The temperature is maintained by the Lauda bath instrument, and can be programmed to achieve series of temperature experiments. Similarly as organic slash bath, the wall temperature of the VCSEL housing is supposed to be equal as the outside bath temperature, which defines the saturation vapor pressure inside VCSEL housing by Clausius-Clapeyron equation.

System 4. RHS chiller mirror system

The RHS system is an independent hygrometer we use to intercompare with the other three calibration systems. It provides an estimation of the bracket of the reading. Usually RHS system is linked afterward VCSEL. However, we do not directly use the RHS system's reading to calibrate the reading of VCSEL.

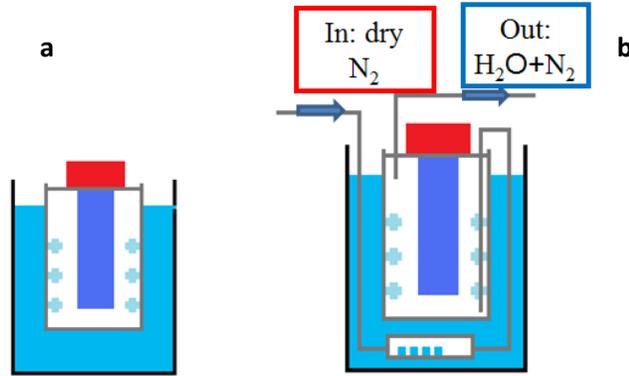


Figure 4. **a**, slash bath system with static system and no flow going through the VCSEL housing. VCSEL can be mostly immersed in the bath. **b**, Lauda bath system where only 2/3 of VCSEL housing is immersed into bath.

Part 2. Evaluation of the advantages and disadvantages of the systems

Each system has its advantages and disadvantages. Therefore the final calibration of VCSEL hygrometer is relied on the synthesis of all systems based on their optimal working conditions. The summary of the systems advantages and disadvantages are shown in Table 2.

Currently the optimal calibration system we use to calibrate the VCSEL is the slash bath system; the next one is the Lauda bath system. The main reason that currently slash bath system is better than Lauda system is because it has a higher bath level, therefore there is less outgassing from the inside wall. We are still working on the pressure gradient inside the critical orifice system in order to narrow down the uncertainties from assumption of constant pressure at the mixer and VCSEL cell.

Table 2. Summary of the calibration systems advantages and disadvantages

Systems	+ Advantages	- Disadvantages
System 1. Critical orifice system	+ Easy to carry into field + Easy to get access to ice/water bath	- Assumes $P_2=P_3$, A is saturated, and mixing ratio of $B=C$, which can add up uncertainties.
System 2. Organic slash bath system	+ Defined saturated water vapor pressure by temperature solely	- Requires immersion into bath - Requires constantly adding liquid N ₂ , but not too much N ₂ otherwise will totally freeze - Large amount of chemical consumption; not easy to get in field - Slow to make slash bath manually - Laser box of VCSEL cannot be immersed into bath
System 3. Lauda silicon oil bath system	+ Defined saturated water vapor pressure by temperature solely	- Slow to reach steady state - Only 2/3 of the housing can be immersed in the bath - Laser box of VCSEL cannot be

		immersed into bath
System 4. RHS chiller mirror system	+ Provides a fast bracket and estimation of the uncertainties of water vapor concentration	- Limited by flow rate, cannot be too fast or too slow; optimal flow rate 20-60L/hr - Uncertainties increases below 5 ppmv

Part 3. Future improvement based on the previous work

In the future we are going to use a small optical cell to mimic the blue fin optical path part of the VCSEL hygrometer. In the past year I designed an optical cell at almost the same pathlength ($L = 3.71\text{m}$) as the VCSEL hygrometer ($L = 3.74\text{m}$). The optical cell reflection pattern and the simulated reflection pattern is show in Figure 5a, b, respectively. The optical cell is sealed up in a stainless steel cylinder which can reach very low pressure, for example, 50 mb, which is low enough to mimic the lower stratosphere pressure that GV aircraft can get into. Then the optical cell uses the same laser and software from the red laser box of the VCSEL hygrometer. Therefore we can use this system to represent the performance of the VCSEL hygrometer. In the past year, the optical cell system I designed has some issues with beam clipping near the detector. But in the next step, a new optical cell will be designed to reach better performance. The optimal calibration would be to use the new optical cell system in the very well sealed cylinder to calibrate in Lauda system or organic bath system. Since the optical cell can be totally immersed into Lauda bath, there will be much lower the outgassing from the inside wall. Pressure can be controlled with very small leakage, and also steady state will be reached much faster.

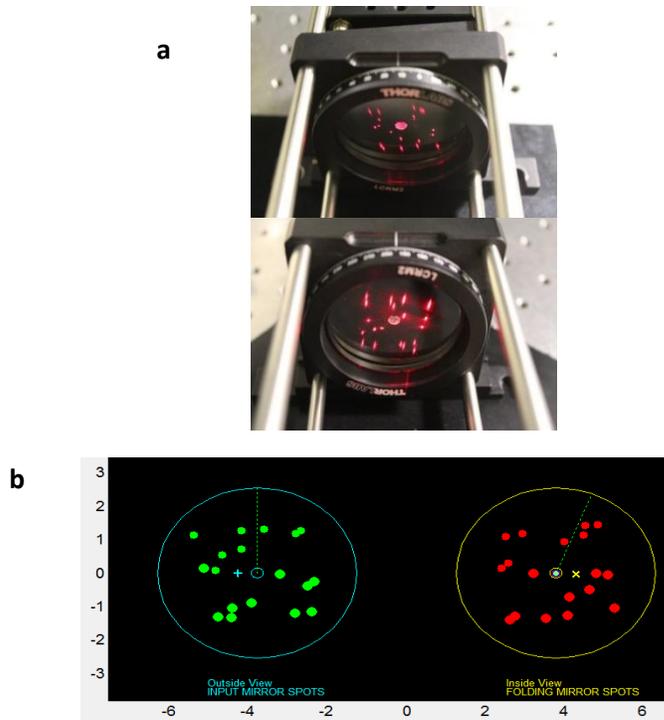


Figure 5. Optical cell pattern and the simulated optical cell pattern to mimic the VCSEL optical pathlength.

Part 4. Calibration parameters and adjustments

The calibration of the VCSEL hygrometer is separated into three modes: strong (2f), direct and weak mode (2f). Each mode is analyzed under a matrix of temperature and pressure in order to get the T-effect and P-effect. Light intensity effect is also tested from light intensity of 1100 down to 200.

T-effect is tested by holding atmospheric pressure, and changing air temperature as well as H₂O partial pressure between the optical paths. Therefore T-effect shows how much the reported value deviates from the true value at different temperature, at atmospheric pressure. We found that for each mode, T-effect is a constant value, which means the VCSEL reading is not varying when temperature or H₂O partial pressure varies within one mode, yet there is a constant deviation within each mode.

P-effect is tested by holding temperature and H₂O partial pressure, and only changing total pressure. Therefore P-effect shows how VCSEL reading changes at different pressure. Since we already know from the T-effect how much VCSEL reading is off at atmospheric pressure, we only need to calculate the **relative changes** of lower pressures with respect to atmospheric pressure, in order to adjust low pressure data. Indeed, the VCSEL reading in strong and direct modes changes with pressure, while weak mode does not vary very much with pressure.

1. Strong mode

P-effect: For 1013.25mb P-effect is always 1, since P-effect shows the relative change with respect to 1013.25 mb. P-effect of strong mode changes from **1.4** to 1.0 for **200** mb to 1013.25 mb. Strong mode has large P-effect.

T-effect: The adjustment factor T-effect is a constant value and not a function of T. I only use the lowest points of slash bath and Lauda bath measurements for strong mode T-effect calibration.

2. Direct mode

P-effect: ranging from **1.07** to 1.0, at **300** to 1013.25 mb.

T-effect: no large T dependent.

3. Weak mode

P-effect: ranging from **1.03** to 1, at **400** to 1013.25 mb.

T-effect: no large T-dependence.

Part 5. Calibration adjustment summary

Each mode has three adjustment coefficients to account for T-effect, P-effect, Lightintensity-effect. The final value of VCSEL water vapor concentration needs to be divided by all of three coefficients in order to get the adjusted value. The coefficient can be constant values, or function of T, P or light intensity.

The submission of the VCSEL final data uses PS_vxl (**mb**) for calculation of P-effect. Please notice that the raw VCSEL pressure data are in **torr**.

Adjusted mixing ratio of H₂O at strong mode = original H₂O value / coeff_T_strong / coeff_P_strong / coeff_light_strong

*Adjusted mixing ratio of H₂O at direct mode = original H₂O value / coeff_T_direct /
coeff_P_direct / coeff_light_direct*

*Adjusted mixing ratio of H₂O at weak mode = original H₂O value / coeff_T_weak / coeff_P_weak
/ coeff_light_weak*

1. Strong mode

T-effect: Assume no change with T, same T-effect coefficient, **coeff_T_strong = 0.788**. This means the VCSEL hygrometer in strong mode needs to be **divided by 0.788** in account for the T-effect. Although this will increase the strong mode reading, later the strong mode will be decreased after P-effect calibration.

P-effect: Use the small cell immersed in Lauda oil for P-effect.

The final P-effect coefficient is a relative value to the atmospheric pressure (1013.25 mb).

Thus the P-effect coefficient is: **Y = (A + B*X) / (A + B*1013.25)**, where Y is **coeff_P_strong**, X is **Ambient pressure (pressure between optical paths) (mb)**.

The linear fitting coefficients are below:

$$\mathbf{A = 0.651 +/- 0.013}$$

$$\mathbf{B = -0.000226 +/- 1.9e-005}$$

2. Direct mode

T-effect: Constant value for T-effect, **coeff_T_direct = 0.876**.

P-effect: Use only the small optical cell calibrations inside Lauda bath as we do for strong mode.

Use linear fitting of **Y = (A + B*X) / (A + B*1013.25)**. Here Y is **coeff_P_direct**, X is **Ambient pressure (mb)**. The linear fitting coefficients are below:

$$\mathbf{A = 0.602 +/- 0.001}$$

$$\mathbf{B = -5.14e-005 +/- 1.54e-006}$$

3. Weak mode

T-effect: constant **coeff_T_weak = 0.805**

P-effect: Use the small optical cell calibration inside Lauda bath.

Use linear fitting of **Y = (A + B*X) / (A + B*1013.25)**. Here Y is **coeff_P_weak**, X is **Ambient pressure (mb)**. The linear fitting coefficients are below:

$$\mathbf{A = 0.800 +/- 0.015}$$

$$\mathbf{B = -3.47e-005 +/- 1.88e-005}$$

4. Light intensity adjustment for three modes

Use the calibrations by adding a light attenuator in order to change light intensity from 1100 to 200.

Only fit to 300 light and below set NaN. But future we will narrow the uncertainty of light intensity so that all the low light readings can be calibrated.

I applied 3-polynomial fitting for the light intensity effects on the water vapor concentration reading in three modes, respectively.

Use **exponential** fitting of $Y = A + B \cdot \exp(-C \cdot X)$.

Here Y is **coeff_Light_mode**, X is **Light intensity**. The fitting coefficients are below:

Strong mode

$$A = 0.997 \pm 0.045$$

$$B = 0.421 \pm 0.091$$

$$C = 0.00277 \pm 0.00138$$

Direct mode

$$A = 1.00 \pm 0.03$$

$$B = 1.71 \pm 0.12$$

$$C = 0.00387 \pm 0.00045$$

Weak mode

$$A = 0.994 \pm 0.051$$

$$B = 0.456 \pm 0.053$$

$$C = 0.00213 \pm 0.00079$$

Part 6. Procedure for calibration

For each mode, T-effect, P-effect as well as Light-effect will be multiplied for the total adjustments. **After calibration, we filter out $\pm 2s$ data when error codes do not equal to 0 or 512, $\pm 2s$ data at peak transitions and $\pm 2s$ data at light intensity < 300 .**

Below are the overall equations for each mode, in current calibration we use PS_vxl (mb) for PS_mb:

Strong mode

$$\text{Mixingratio_calibrated (ppmv)} = \text{Mixingratio_raw (ppmv)} / (0.788 * ((0.651 - 2.26e-4 * \text{PS_mb}) / (0.651 - 2.26e-4 * 1013.25)) * (0.997 + 0.421 * \exp(-0.00277 * \text{laserintensity})))$$

Direct mode

$$\text{Mixingratio_calibrated (ppmv)} = \text{Mixingratio_raw (ppmv)} / (0.876 * ((0.602 - 5.14e-5 * \text{PS_mb}) / (0.602 - 5.14e-5 * 1013.25)) * (1.00 + 1.71 * \exp(-0.00387 * \text{laserintensity})))$$

Weak mode

$$\text{Mixingratio_calibrated (ppmv)} = \text{Mixingratio_raw (ppmv)} / (0.805 * ((0.800 - 3.47e-5 * \text{PS_mb}) / (0.800 - 3.47e-5 * 1013.25)) * (0.994 + 0.456 * \exp(-0.00213 * \text{laserintensity})))$$

After calibration, the strong mode is generally getting slightly lower H₂O mixing ratio than raw data, direct mode does not change very much and weak mode shows higher value than raw data. Most of the flights follow this trend.

For example, at strong mode of 300 mb, 50 ppmv H₂O mixing ratio, light intensity of 800, we would get the calibrated mixing ratio as 44 ppmv; at direct mode of 600 mb, 500 ppmv H₂O mixing ratio, light intensity of 900, we would get the calibrated mixing ratio as 522 ppmv; at weak mode of 900 mb, 10,000 ppmv H₂O mixing ratio, light intensity of 500, we would get the calibrated mixing ratio of 10700 ppmv.

Example of HIPPO2 RF2 final data

HIPPO2 and HIPPO3 final data are recently submitted based on the calibration scheme described above. Figure 6 shows strong, direct, weak mode H₂O mixing ratio of raw data (red) and calibrated data (green).

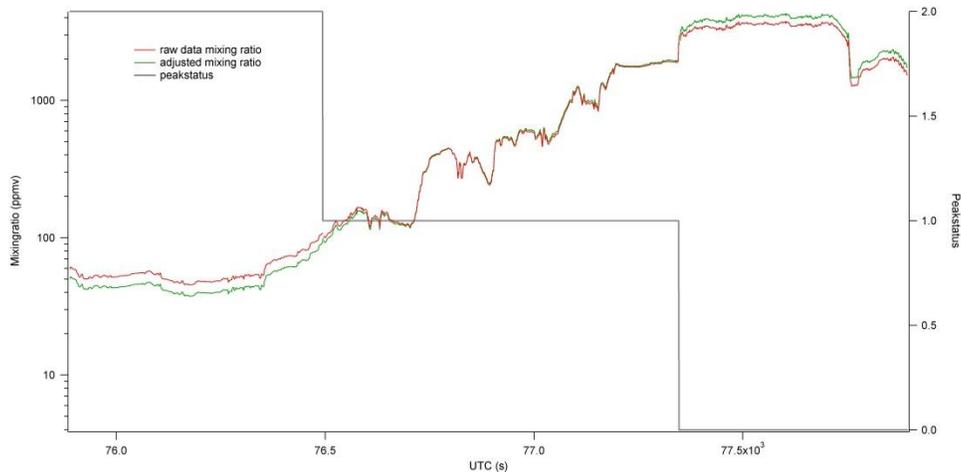


Figure 6. HIPPO2 RF2 final data submission after calibrated with the current scheme