VCSEL Hygrometer for use in the Troposphere and Stratosphere

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Figure 1 VCSEL hygrometer

1. Overview

A standalone laser hygrometer was developed for the NSF Gulfstream V research jet that can measure water vapor concentration over the full altitude range of the aircraft (see Fig. 1). During the project, the hygrometer was deployed on the PACDEX, HEFT, and START08 flights. The instrument was also used in the AquaVit intercomparison measurements in Oct. 2007.

The laser hygrometer measures water vapor concentration using optical absorption spectroscopy. The hygrometer is an open path system which mounts in a window sized cutout in the aircraft (see Fig. 2). The exterior portion of the instrument consists of an aerodynamic fin. This fin contains a multipass Herriott cell that provides 375 cm of optical path (25 passes × 15 cm basepath). The electronics system resides inside the aircraft and is attached to the fin baseplate. The physical specifications of the system are noted below:

Fin Dimensions: 30 × 24 × 6 cm
Electronics Dimensions: 25 × 14 × 7 cm
Weight: 3.2 kg
Electrical: 115 VAC, 20 W
Output: RS232, 19.6 kBAUD

A fiberized vertical cavity surface emitting laser (VCSEL) located in the electronics box serves as the light source for the hygrometer. The light is fiber coupled to the multipass cell outside the aircraft. To cover the large dynamic range required, a weak (1853.3 nm) and a strong (1854.0 nm) absorption line are used for the measurement. A combination of wavelength modulation and normal direct absorption spectroscopy are employed. There are three measurement modes. At high concentrations (typically above -20°C frostpoints), second harmonic wavelength modulation is performed with the weak line. At intermediate concentrations (typically -20°C to -50°C frostpoints), the strong line is used in direct absorbance mode. At the lowest concentrations, the strong line is measured using wavelength modulation.

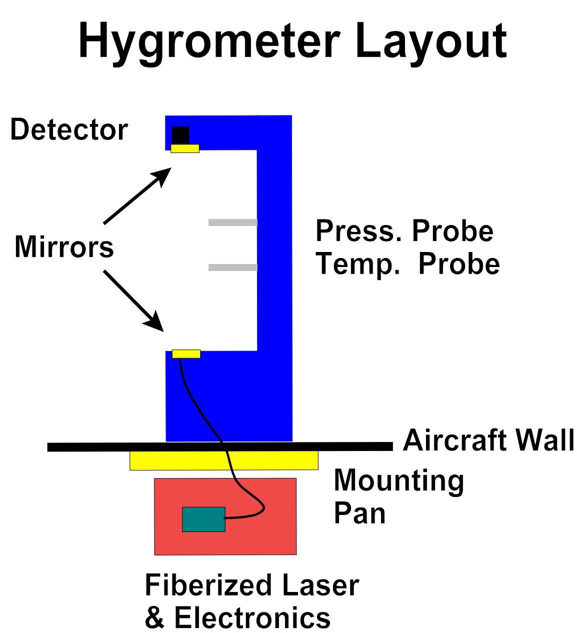

Figure 2 Instrument schematic

Full spectra are measured at a 1.5 kHz rate. The scan width and modulation depth is adjusted once per second according to the calculated line width for ambient conditions. These adjustments are made to keep the trough to trough separation a constant fraction of the total scan width. Gain adjustment of the spectrum amplitude is performed once a second to keep the signal plus noise approximately constant. Spectra are coaveraged for 40 msec prior to analysis. Thus, the instrument reports independent concentration measurements at a rate of 25 Hz. Reference spectra recorded at typical atmospheric conditions are used to fit the sample spectrum. Fitting is performed using singular value decomposition analysis. Data fitting for the wavelength modulation spectra is limited to the region between the troughs. Because of the continuous scan width adjustment with linewidth, this region of the spectra shows virtually no change in shape as a function of pressure and temperature. Thus, reference spectra can be readily compared to sample spectra with only minor correction (<2%) for lineshape changes.

The system outputs measured number density through an RS232 port. Instrument operating parameters are reported once per second. The water vapor concentration is reported 25 times a second as the measurements are made. For convenience, the measured number density is also reported as a dew point for comparison to the plane's chilled mirror system. A synchronization trigger from the plane is used to end each second of data collection. The ambient temperature as measured by the plane's Pitot probe (ATX) is sent to the instrument once a second. This temperature is needed because the instrument's temperature probe experiences dynamic heating.

Calibration

Figure 3 Hygrometer and test chamber.

The instrument was calibrated for each measurement mode. A single calibration constant (a linear span factor) was determined for each mode. The calibrations were performed with the instrument mounted in a 15 l vacuum can (see Fig. 3). Gas was flowed through the vacuum can and then through a General Eastern chilled mirror system. Readings were taken once the chilled mirror reading was stable for 30 minutes. For the weak line, a 0°C saturated stream was prepared by bubbling dry gas through an ice water bath. For the strong line, room air was drawn through a coil submerged in an acetonitrile slush (-45°C). The AC part of the signal is normalized by the DC transmission so changes in the transmitted optical intensity do not impact the calibration. Thus, the calibration of the instrument should be stable over the long term.

Reference spectra used for the fitting process were measured with an identical optical system mounted in a small vacuum can. Reference conditions were created that are typical of the atmospheric region where the specific mode would be employed (see Table 1). The vacuum can was placed in a cold slush bath and filled with moisture saturated air.

Table 1 Reference Spectra Conditions

Mode	T (K)	P (kPa)	Bath
Weak	273.1	78.7	ice/water
Strong Direct	227.4	52.8	Acetonitrile/N_2(l)
Strong	209.6	13.5	Chloroform/N_2(l)

Verification of the spectral model accuracy over pressure and temperature space was attempted using the fin test chamber. At room temperature, the fin outgassing became problematic at frostpoints below -40°C. Thus, for achieving lower frostpoints, cooling of the test chamber and fin became imperative. The test chamber was immersed in various cryogenic slush baths in a large dewar. The top flange of the chamber was kept above the bath. Approximately 60 l of solvent and 60 l of liquid nitrogen were required for forming these baths (the solvent volume contracts when frozen). In addition to the solvents listed in Table 1, other solvents used included benzyl alcohol and 2-butanone. Initial experiments were performed with the test chamber sealed and pumped down to a pressure typical of the atmosphere at the observed temperature. The ambient temperature probe on the fin indicated a temperature differential between the chamber walls and the fin. Table 2 shows the bath temperature and the gas temperature as measured by the ambient temperature probe. In the 2-butanone bath, the gas temperature is similar to that typical in the coldest part of the stratosphere. These sealed chamber experiments revealed that the system is not hermetically sealed. A leak rate of ~1 × 10^{-3} cc/sec was observed. This leak was substantial enough to cause the observed concentration to be twice that expected in the 2-butanone bath. Thus, only atmospheric pressure measurements with this setup are useful, preferably with a gas flow where the gas is introduced from a coil submerged in the cooling bath.

Table 2 Bath temperatures vs gas temperature

Bath	Bath Temp (K)	Probe Temp (K)
Ice/water	273.1	276.6
Benzyl Alcohol	258.0	265.4
Acetonitrile	227.4	243
Chloroform	209.6	233
2-Butanone	186.8	219

Since the gas flow is introduced through the top flange on the test chamber, the part of the gas line that is not submerged in the bath will outgas. Thus, atmospheric pressure experiments with flowing gas were limited to using ice/water, benzyl alcohol, and acetonitrile baths. A cold water bath that provided a stable gas temperature of 281 K was also used. From these measurements, a correction to the HITRAN linestrength for the weak peak has been determined (see Fig. 4). The weak peak is actually a combination of three transitions which are fairly temperature sensitive and it is not surprising that a correction to the HITRAN values is needed.

Measurement with the test chamber fin in a water/ice bath and water inside the chamber showed that the measured concentration varies only 3% as pressure is changed from 50 to 80 kPa. As noted above, the test chamber system does leak, but in this case the difference between the water vapor concentration was rather modest as the ambient frostpoint was ~-5°C. Because the linestrength is constant in these tests, the test indicates that the linewidth model used for the weak peak is accurate. As noted in the section describing the AquaVit measurements, a similar test was performed with the strong peak and this test also showed the linewidth model to be accurate.

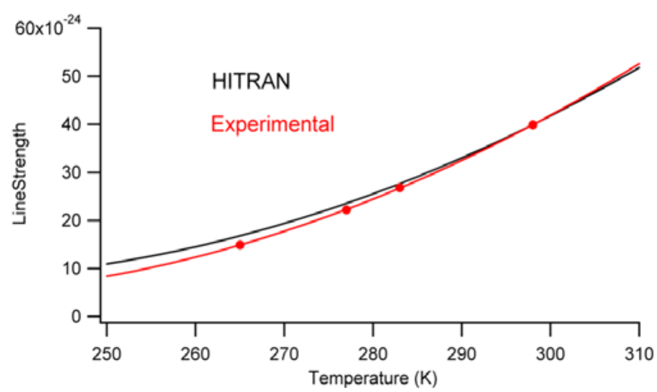

Figure 4 Comparison of HITRAN and experimentally determined linestrength from cold bath measurements at atmospheric pressure.

The thermistor temperature probe was calibrated by dipping the sensor in various slush baths. A chloroform slush bath was the coldest bath used and the ice/water bath the warmest bath. The pressure probe was calibrated by comparing the atmospheric reading to a mercury manometer and measuring the system offset with the test chamber pumped out.

Resolution of issues identified during HEFT and PACDEX

The hygrometer flew in HEFT and PACDEX and worked reasonably well for initial test flights as was discussed in earlier reports. However, the instrument was not fully operational or well calibrated for either set of flights. There were two major problems with the instrument during these flights. These problems included a shortened optical path and laser temperature control issues. The short optical path was caused by using mirrors with incorrect focal lengths. After several iterations, a proper set of mirrors was fabricated in Feb. '08 and they were first deployed in the START08 flights. The consequence of these problems was that the system had between 1 and 17 of the desired 25 passes in the multipass system during HEFT and PACDEX.

The laser temperature must be controlled to within 0.01 °C to keep the spectral peak linelocked. This level of control proved difficult because of laser packaging issues and the instability of the electronics box temperature during flight. The most desirable laser package has the laser chip directly mounted on a thermoelectric cooler (TEC). This is common packaging for fiberized DFB lasers. However, such packaging had not been developed for a single mode VCSEL prior to this project. The first lasers used in this project did not include an internal TEC. An external TEC was used which greatly increases the thermal response time. The thermal response time for the laser used in PACDEX was about 1 minute. The electronics box that contains the laser is mounted on the aluminum pan that seals to the plane cutout. This pan gets very cold during flight and causes the electronics box to become cold (down to 0 °C). During ascents and descents, the rapidly changing temperature of the pan and electronics box made temperature control of the laser difficult. The laser would lose linelocking during these periods.

During this project, the laser manufacturer developed a package that incorporated a TEC and butt-coupled the laser to the fiber. This is the first time such a package had been developed for a VCSEL and was a crucial part of solving the temperature control issue. To keep the electronics box temperature regulated, a 15 W heating strip was put along the bottom of the box and a microcontroller was added to provide heater control. These improvements were made prior to the START08 flights. The heater does not allow the box temperature to fall below 20 °C. Heating the box also prevents condensation from occurring in the box and protects the laser package. Exposure to cold temperature can permanently damage the laser to fiber coupling efficiency. With these improvements, the thermal management problems have been resolved as demonstrated in the START08 flights.

AquaVit

The hygrometer was used in the AquaVit comparisons in Oct. 2007. Single blind comparisons were performed between approximately a dozen hygrometer instruments that are used to measure upper tropospheric and lower stratospheric water vapor. Concentrations in the 1-20 ppm range in the AIDA chamber at the Institute for Meteorology and Climate Research (Karlsruhe, Germany) were measured. Results were blindly submitted to the AquaVIT organizers. A report on the results will be available later this year.

To make the hygrometer suitable for use with the AIDA chamber, an identical multipass optical system was constructed inside a 400 ml vacuum can. The fiberized laser was connected to this cell. Unfortunately, during the experimental setup, the laser and laser driver chip in the hygrometer were destroyed, probably due to an electrostatic discharge. The laser supplier provided a replacement within a few days. However, the system had to be retuned and recalibrated for the new laser. This was done hastily and the system was not optimally tuned. Reference spectra taken with the old laser were used for the fitting procedure and afterward, the modulation depth was discovered to be a factor of two low (which diminishes the signal size). Also, the cell mirrors did not have the correct focal length so the pathlength was only 2/3 of the design pathlength. A quick single point calibration was done using saturated water vapor conditions with the vacuum can submerged in a chloroform/liq. N_2 bath. Despite the less than optimal state of the instrument, it performed well enough to participate in the measurements and measurement results were submitted for comparison.

Fig. 5 shows sample results for two different mixing ratios (4.92 ppm and 14.76 ppm) as a function of pressure. Four different pressures were used: 100, 200, 300, and 500 hPa. The measured absolute concentration showed a linear response with pressure while the mixing ratio (red) remained constant (as it should). At 14.76 ppm, the instrument was accurate to within a few percent with respect to pressure variation. This result is significant as it demonstrates the linewidth model being employed is accurate. (The modulation depth and scan width automatically adjust with ambient pressure.) At 4.92 ppm, the instrument variance was larger – deviating by as much as 1 ppm. However, given the hasty nature of the repair and calibration, the system performance was reasonable.

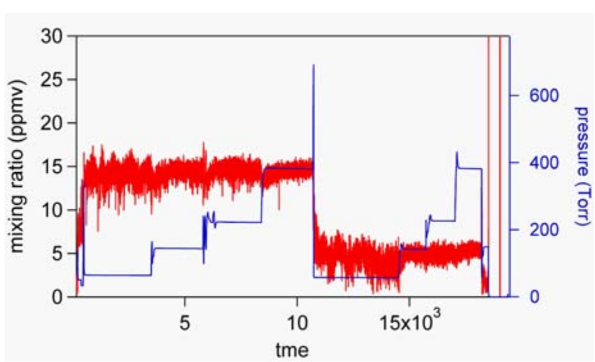

Figure 5 Measured concentration as pressure varies at constant mixing ratio. The mixing ratio is changed halfway through the data set.

START08

The hygrometer was used throughout the START08 campaign. These flights were the first time that the targeted 375 cm optical path was used in the system. During the first test flight, the system operated well and provided reasonable concentration measurements. Midway through the second test flight, the instrument stopped measuring water vapor. Post flight examination revealed that the photodiode and preamp and the temperature probe amplifier circuitry had been blown. An electrostatic event due to static buildup on the fin was believed to be the cause of this problem as these were the only components connected to the fin. To prevent this in the future, a ground wire is attached to the fin from the aircraft frame. The repairs were completed in time for research flight 4. The hygrometer flew on the remaining 14 missions. The only other incident that occurred which caused total measurement dropout was when the plane got iced over while awaiting deployment for research flight 6. The plane was brought back in the hanger to defrost but a significant amount of residue was left on the hygrometer mirrors. The residue was significant enough to block light transmission. Cleaning the mirrors with methanol remedied this problem post flight.

From the early research flights, a concentration mismatch between weak and direct measurement modes became obvious. Comparison between the ambient temperature probe and the plane's Pitot probe revealed that dynamic heating was occurring on the hygrometer probe. The temperature reading ranged from 10 degrees high at low altitude to 30 degrees high at high altitude. The weak peak is very temperature sensitive - a factor of 2 in linestrength change of over 20 degrees - while the strong peak linestrength is far less sensitive to temperature. To rectify this problem, the system was programmed to receive the aircraft Pitot probe temperature measurement over the serial communication line. This improvement was implemented during the second part of the START measurements.

The reported concentrations from the hygrometer were reasonable over all atmospheric conditions and appeared to be the most accurate of all the hygrometers on the G-V. This point is demonstrated by an overlay of the VCSEL readings during the campaign with STRAT/POLARIS data from 1995/1997 (see Fig. 6). During the live data stream reports, the hygrometer readings often were in agreement with the chilled mirror system at dewpoints above -60 C (when the chilled mirror wasn't overshooting). It should be noted that the hygrometer was calibrated prior to the beginning of the research flights and that no changes in the calibration constants were made during the campaign.

An assessment of the precision of the hygrometer readings during the START 08 flights is shown in Fig. 7. These data excerpts taken are regions where the water vapor concentration appeared relatively constant. No trend analysis on the water vapor concentration was performed in assessing the noise statistic (although in some instances, there is an apparent trend). The excerpts were taken from the later flights and thus, are indicative of the instrument state at the end of the campaign. The excerpts in which the strong peak mode is being used are at the lowest water vapor concentrations achieved during the campaign (highest plane altitude). As can been seen from the figure, the noise is in the 1 - 3% of reading range. Averaging the 25 Hz data for 1 second typically only provides a 30% improvement in the noise. The lack of $n^{1/2}$ improvement indicates an underlying noise component that is not White noise. This noise is likely due to baseline artifacts from interference fringes.

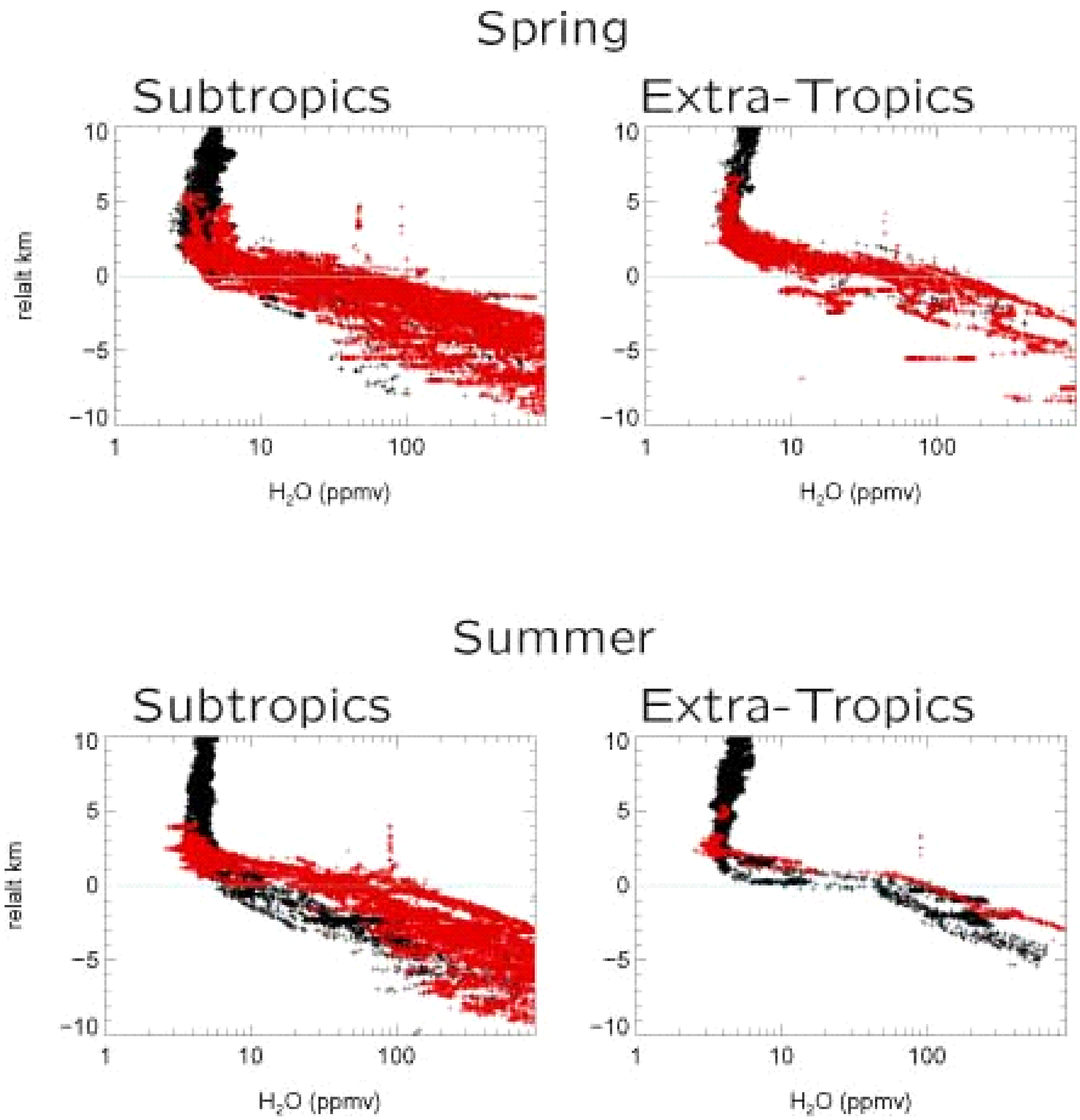

Figure 6 Comparison of VCSEL data from START08 (red) to1995/1997 STRAT/POLAR data (black). The altitude is relative to the tropopause. Plot provided by Simone Tilmes of NCAR.

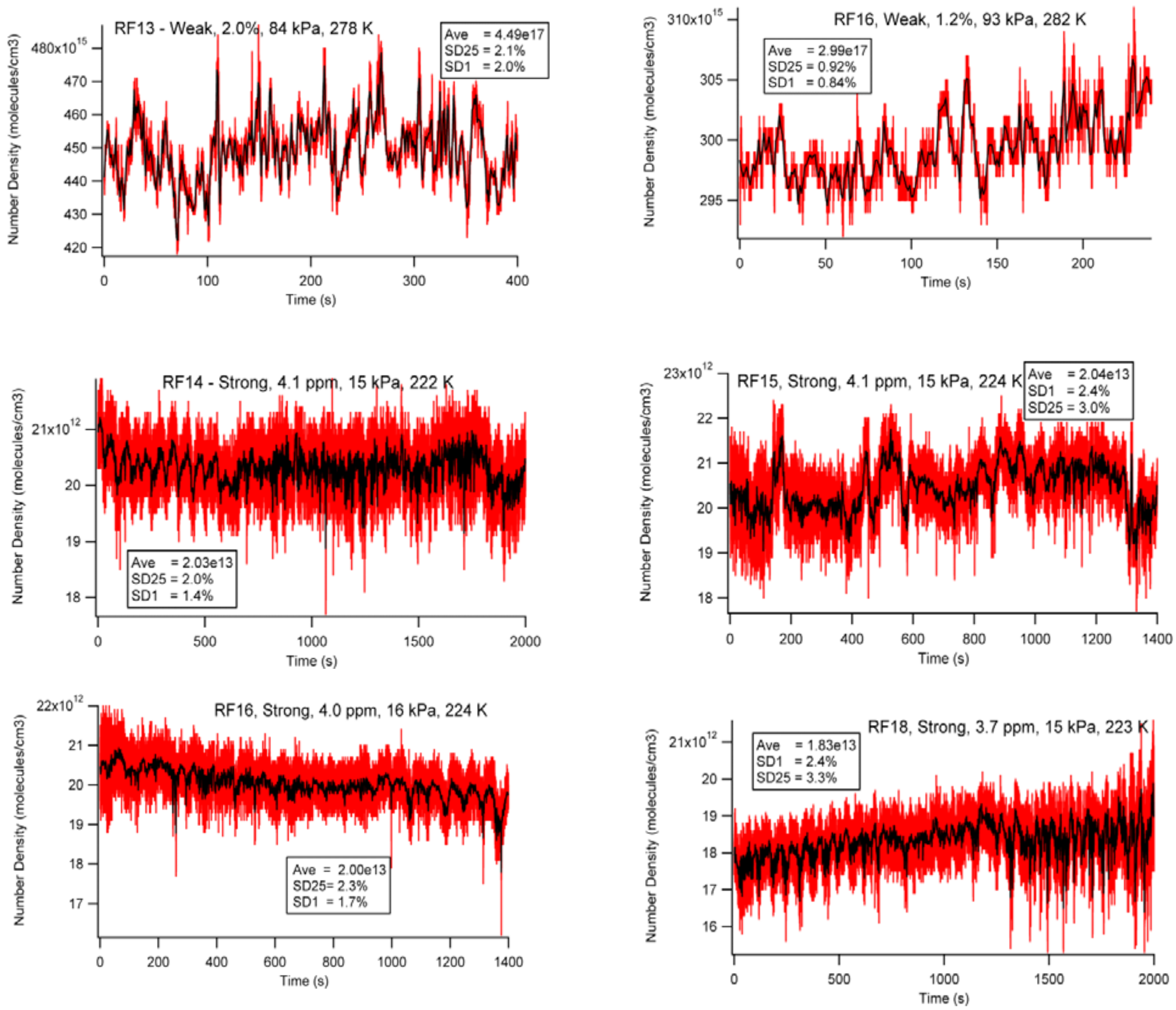

Figure 7 Noise assessment during later START08 research flights. The measurement mode (strong or weak), the water vapor concentration, pressure, temperature, and research flight number are noted. The red curves are the 25 Hz data and the black curves are the 1 second averaged data. In the box, the average concentration is shown along with the standard deviation for 1 Hz averaged data and the normal 25 Hz data. No trend analysis has been applied in determining these statistics.

The VCSEL hygrometer showed superior response and sensitivity compared to the other hygrometers on the aircraft. Fig. 8 shows a graph of the VCSEL response in a Kelvin-Helmholtz wave along with the UCATS water vapor sensor. The closed-path UCATS instrument does not resolve the structure, likely due to outgassing and smearing of the structure as it is pumped inside the plane. Fig. 9 shows all three laser hygrometers onboard START08 at lower stratospheric conditions (133 hPa, 223 K) during Research Flight #10 with the NCAR TDL divided by 25 and NOAA UCATS H_2O mixing ratios divided by 1.67 to put the sensors on a common scale (the absolute values of each sensor are subject to change). The VCSEL data is averaged to the 1 Hz sampling frequencies of the other sensors in order for direct comparison. The higher precision and sensitivity of the VCSEL provides a better understanding of dynamics and chemistry. For example, for this portion of the flight, the VCSEL data showed tight correlations with ozone as shown in blue on the right axis.

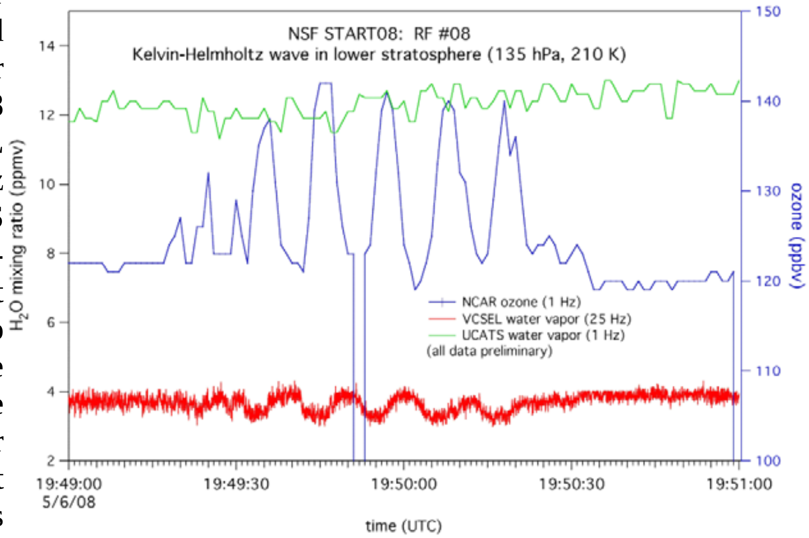

Figure 8 Kelvin-Helmholtz waves during RF #08 for VCSEL (red) and UCATS water vapor (green) and NCAR ozone (blue). The absolute differences between the UCATS and VCSEL were typical for the first deployment.

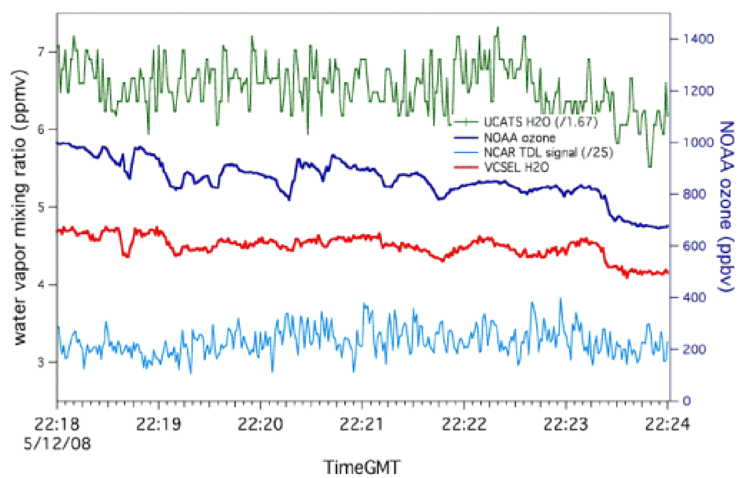

Figure 9 VCSEL, UCATS H_2O, and NCAR TDL preliminary data for lower stratospheric conditions (133 hPa, 223 K) during RF #10. The VCSEL shows correlations with ozone during this leg (blue, right axis) that are not captured by the other laser hygrometers.

Residual Issues

The major issues that still remain with the hygrometer performance are:

1) Difficulty with the weak - direct transition in highly variable water vapor concentration regions.

2) Optical interferences (etalons) in the optical system.

3) Limited accuracy tests

The weak - direct transition performed very poorly at the beginning of the START campaign. There were 10 minute periods where the system would lose linelocking. Much of this poor performance was a consequence of having an inaccurate temperature measurement. This was resolved by using the plane's Pitot probe temperature measurement. Additional improvements were made by jumping the laser temperature setpoint along with the laser injection current during this transition. Initially, only the current was jumped to switch peaks. Watching the transition on an oscilloscope revealed that the laser temperature was impacted by this current jump. Thus, the system was programmed to change the temperature setpoint during the transition along with the current in order to minimize the thermal restabilization time. By the end of the campaign, the transition was much smoother and the data dropouts were greatly reduced. Still, the transition is not always as smooth as it should be. Following the campaign, it was realized that the overlap between the modes was not sufficient. Overlap is required to keep the instrument from constantly switching between modes. This issue has been addressed. An examination of how the autogain level impacts regions of variable concentration may reveal how further improvements can be made. Currently, the autogain is set so that the signal plus noise level is about 30% of the total voltage range. Southwest Sciences will continue to assess this problem from the START data and will monitor it during the HIPPO test flights and campaign. We believe this is a solvable problem.

The existence of an optical interference cavity in the system is evident at smaller absorbance levels while monitoring the spectrum in the laboratory. The periodicity of this interference is approximately 7 times the trough to trough spacing of the weak peak. The origin of this interference is not yet known. This fringe impacts the noise level on the reported concentration. As is common with such problems, the magnitude of the interference greatly varies with time because of thermal and mechanical sensitivity. Whether this fringe is significant in flight is not known. The vibration of the plane may greatly reduce it. There are times in the flight data where the concentration fluctuations and peak position movement suggest that it may be problematic. For peak position determination used in linelocking, a box filter is being employed to smooth this fringe. Southwest Sciences proposes to examine the instrument further to see if this fringe can be eliminated.

With the late assembly of the system in the project, the amount of laboratory checks of the system accuracy over all temperature and pressure space has been rather limited. In addition, repetitive testing is needed. Often with water vapor concentration tests, the measurement variability is related to the testing method rather than the instrument. Building a large data base will increase confidence of the system accuracy. Because of the pressure leaks with the fin system, the duplicate optical system used in AquaVit will likely be more useful in performing further laboratory accuracy tests. If the leaks in the fin system can be fixed, an improved test chamber with a gas inlet on the bottom would be valuable. Future discussions with NCAR personnel will be held to determine an action plan regarding continued testing.

Possible Improvements

In addition to the more substantial issues discussed above, there are a number of improvements that can be made to the hygrometer. These improvements include:

1) Mechanical improvements
   A) Mirror mounts with fine adjustment control
   B) Glass dielectric mirrors instead of gold coated metal mirrors
   C) Cylindrical mirrors instead of spherical mirrors
   D) Reorganization of electronics box and replacement of large components

2) Software improvements
   A) Output of spectra at user request
   B) Interactive control of system parameters via communication port

The far mirror in the system is on an adjustable mount (the near mirror is fixed). This mount is adjusted by loosening some screws and performing a finger adjustment. Thus, it cannot be tweaked back and forth in a repetitive fashion. This mount should be replaced with a kinematic mount modeled after standard commercial mounts. Alignment optimization would be easier and more reliable. In addition, the mount that holds the fiberized lens that delivers the beam into the multipass cell can be altered to improve alignment as well. This mount is a modified commercial kinematic mount. However, because of physical constraints of the mount and the space around the mount, it does not have the desired adjustment range. Replacing both of these mounts with better custom mounts would not be difficult or very costly.

The current mirrors in the hygrometer are gold coated copper mirrors. Copper mirrors were used so that the mirrors could be heated. However, the metal coating is fragile. During PACDEX, the coating was substantially scratched and worn away by the dirty air. The mirrors looked like they had been rubbed with sandpaper. Fortunately, the abrasion occurs more in the center of the mirror than at the edges. With the current multipass configuration, only the edge of the mirrors are used. In contrast to the PACDEX campaign, the mirrors suffered no deterioration during the START08 measurements in which the air was relatively clean.

Dielectric coatings are far more rugged than metal coatings. These coatings can only be applied to glass mirrors. Southwest Sciences has already obtained replacement dielectric coated glass mirrors for the instrument. These mirrors are cylindrical instead of spherical. The current metal mirrors are spherical. The spot pattern for the cylindrical mirrors uses the interior of the mirror and the beam enters and exits through center of the mirror as opposed to the edge of the mirror. An advantage of this configuration is that movement of the input beam causes the spot pattern to expand or contract but does not move the output spot. In contrast, in the current configuration, the output spot will move with the input spot. Also, because of the restricted space around the mirrors, using a central entrance/exit makes mounting issues easier for the fiberized lens and detector. In regard to the mirror heating, currently the mirror heaters are only using 1 W of power. It isn't clear that this heating is actually necessary and the glass mirrors could be heated through the mount if necessary.

Reorganization of the electronics box would provide several benefits. The bend on the laser output and feedthrough fibers could be reduced. Currently, the bend on the laser fiber is too harsh. Another benefit would be to make the DSP electronics more accessible by facing it upward. This would make test points easier to access and allow chip/component to be performed without disassemblying the box. To accomplish this reorganization, space savings would be realized by replacing the pressure sensor and dc converter. NCAR has used accurate pressure sensors that are much smaller than the current MKS sensor. The dc converter is a linear converter, but a smaller switching converter would be adequate.

Software improvements that can be made to the system would utilize the two way serial communication. This communication to the instrument could be used to prompt the system to send out spectra instead of the normal concentration output. It could also be used to adjust system operating parameters such as the laser temperature setpoint or measurement mode or to reinitialize the system. Such control could be very useful if an instrument user is monitoring the live data stream during a flight and realizes that the system is not operating properly.

Instrument Performance Summary

The performance of the instrument during the START08 campaign established that the instrument is functioning fairly well and providing useful data. It also has some superior characteristic in regard to sensitivity and time response compared to other laser hygrometers. The instrument specifications from the proposal are shown in Table 3 along with the demonstrated instrument performance. The specifications were largely achieved. The demonstrated dewpoint range is from the START08 flights. The instrument should work for 30°C dewpoint minumum. Measurements at dewpoints below -85°C have not been demonstrated and are not particularly relevant since the altitude range of the aircraft is not going to increase. The accuracy of the measurements has not been fully established over all P and T space, but the indication from the limited laboratory measurements and the comparison to archival flight data indicates that it is in the 5% range. At room temperature, the system accuracy is closer to a few per cent. The system generally draws less than 5 W under normal operation. It spikes to 20 W when the box heater comes on. The heater is on with a duty factor under 50% during ascent and at the highest flight altitude.

Table 3 - Specifications of VCSEL Hygrometer

Parameter	Proposal	Demonstrated
DewPoint	+35 to -110°C	~ +20 to -85°C
Sensitivity (SNR=1, 1 Hz)	0.05 ppmv	~0.08 ppmv
Detection Bandwidth (all conditions)	25 Hz min.	25 Hz
Accuracy	5%	~5%
Precision	< 3%	~1- 3%
Power	10 W @ 5VDC	20 W max (5 W typical)
Weight: Instrument Housings	 2 lbs ~5 lbs	7 lbs total
Size	8" × 8" ×6"	10" × 6" × 3"
Communication	RS-422, RS-488 or as specified	RS232
Operation	totally stand-alone, no operator required	stand alone

The most significant remaining issues for the instrument are 1) elimination/reduction of the interference fringe, 2) better performance during the weak - direct mode transition, and 3) further accuracy testing in the laboratory. These issues should be resolvable and Southwest Sciences is certainly interested in addressing them.