The NOAA Lyman-α hygrometers

The NOAA balloon-borne Lyman-α fluorescence hygrometer was developed by *Kley and Stone* [1978]. The actual flight instrument for use in the stratosphere has been described and characterised by *Kley et al.* [1979]. This was an open-cell design with a radio-frequency discharge Lyman-α light source. The stray light intensity across the cell and the intensity in the fluorescence region were monitored by nitric oxide ionisation cells. The instrument was flown at night to eliminate solar scatter.

A characteristic of this and successive NOAA Lyman-α fluorescence hygrometers is their method of *in situ* calibration through the simultaneous measurement of water vapour concentration by absorption and OH fluorescence. The *in situ* calibration uses Beer's law at the wavelength of Lyman-α radiation and has two constants, namely the water vapour absorption cross section at Lyman-α [*Kley,* 1984] and the distance between light source and nitric oxide intensity monitor. The balloon instrument makes use of the fact that, during ascent or descent, the absorption by water vapour across the cell changes from >90% in the middle troposphere to <10% in the upper troposphere, allowing the determination of absolute water vapour concentrations and, from the simultaneously-recorded OH fluorescence intensity, the determination of the fluorescence sensitivity constant C over a considerable range of water vapour absorption. Absorption by oxygen at Lyman-α varies between 35 and 20% between 500 and 250 hPa and is numerically considered using the measured cross section of O_2 [*Kley*, 1984]. Table 1 of *Kley et al.* [1979] gives an example for the determination of C for a typical balloon flight. The precision of C obtained from 48 *in situ* calibrations, over the altitude range of 6-10 km with water vapour absorption ranging from 90% to 5%, was 18%, and constituted the single largest error in the overall accuracy of the balloon-borne instrument. The 2σ uncertainty of the water vapour absorption cross section at Lyman-α is 6%. Other error sources are negligible.

The first aircraft instrument was a closed cell design with a microwave discharge lamp. This instrument was operated in a pressurised container for thermal stability. Lyman-α intensity was monitored across the cell with a NO ionisation cell. This instrument was built for the Panama STEP U-2 campaign. The instrument design and calibration procedure are documented by *Kley et al.* [1983]. In short, the *in situ* calibration of the Panama instrument was achieved during level flight in the tropopause region whenever short duration events of large water vapour mixing ratios occurred, superimposed on much smaller background mixing ratios. Thus, the calibration is equivalent to the one described above for the balloon instrument except that the total pressure and, therefore, the oxygen absorption does not change during an absorption event. A disadvantage of the Panama instrument was the irregular and relatively infrequent occurrence of natural absorption events.

The U2 aircraft instrument was modified in 1981 for regular (every 15 minutes) calibration procedures. A small (200 cm^3) cylinder is filled with 100-200 atm of air. The high pressure air is allowed to flow over a frit with a saturated cotton swab, then over a capillary into a second small cylinder, filling it with humidified air over a period of 15 minutes to a pressure of approximately 1000 hPa. A magnetically operated valve then

opens and allows the second cylinder to empty its contents through a second capillary into the main air stream, upstream of the fluorescence chamber. The small pressure increase in the fluorescence chamber is negligible, but the mixing ratio of water is increased, initially to mixing ratios of approximately 500 ppmv. Set by the conductance of the second capillary, the mixing ratio decays exponentially to ambient levels with a time constant of approximately 1 min. From the measurement of transmitted Lyman-α light intensity it is possible to derive absolute water vapour mixing ratios (above ambient background). The calibration was performed every 15 minutes over a wide range of mixing ratios. Water vapour mixing ratios of approximately 500 ppmv at the high end, down to values around 20 ppmv at the low end were used to derive the calibration constant. Accounting for preabsorption of Lyman-α light before entering the field of view of the OH fluorescence detector, the response of the fluorescence signal was extremely linear. The slope of fluorescence intensity versus absolute water vapour mixing ratio yields the sensitivity constant. The precision of the in-flight calibrations (every 15 minutes during a 5 hour flight) was typically 1-2%.

Error sources for the U2 instrument include a negligible error from photon counting statistics from fluorescence and background signal and a contribution from water vapour outgassing. However, the latter contribution would decay to very small amounts after approximately 1.5 hours into the flight and played no role during the final descent profiles. Since the Lyman-α absorption cross section is accurately known with a 2σ standard deviation of 6% [*Kley*, 1984] and the only other parameter (distance between the Lyman-α light source and the nitric oxide ionisation chamber) is measured, it follows that the calibration of the fluorescence instrument must be accurate to the uncertainty of the Lyman-α water vapour absorption cross section.

Since the calibration is always done at ambient conditions of pressure, flow rate, oxygen partial pressure and trace gas composition, errors in the calibration constant that might arise from systematic errors possibly connected to the above parameters are avoided.

The present NOAA Lyman-α instrument is also a closed cell design, optimised for a high flow rate to minimise the effect of trapped water. Heated inlet lines vaporise the ice before reaching the hygrometer. The Lyman-α source is a DC discharge lamp. The Lyman-α intensity is monitored with an iodine ionisation cell that is sensitive from 115 nm to 135 nm. A magnesium fluoride beam splitter samples the source with the ionisation cell placed equidistant from the source and the detected fluorescence region. This arrangement accounts for the preabsorption in the cell from oxygen and water. Water vapour is injected into the air stream and the absorption and fluorescence are measured as above to provide an in-flight calibration. A calcium fluoride filter is inserted during the calibration sequence to measure background radiation from the lamp at 309 nm (about 200 counts per second) and any radiation between 125 and 135 nm. Two hygrometers were built in an attempt to independently measure total water and water vapour. They were flown in the partially pressurised Q bay of the ER-2 [*Kelly et al.*, 1989]. The instrument has since been modified to fly unpressurised on the WB-57.

The main sources of error of the present aircraft instrument are the accuracy of the water Lyman-α absorption cross section and the Poisson counting statistics of the signal and

background. The 2σ uncertainty of the water vapour absorption cross section uncertainty is 6%. The counting period for both instruments is 1 s. Count rates are in the range of 500-1000 counts per second per ppmv of water. For 4 ppmv the 1σ counting error is about 4%. The total 2σ error is 10% at 4 ppmv for 1 second data and 6.6% at 4 ppmv and 10 second data.

Areas of concern in the present NOAA instrument are spectral impurities in the DC lamp and trapped water. Other wavelengths are not as effective as Lyman-α in producing fluorescence. The spectral purity of the lamp is checked during the descents by using the oxygen and the water Lyman-α absorption cross-sections and the measured pressure and water to remove their absorption effects. If the lamp intensity is constant then the result should be independent of pressure unless there are spectral lines with different cross sections. The calcium fluoride cut-off filter gives a second measure of any Lyman-β and contamination, usually less than 0.1%.