Cloud Liquid Water Measurements

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Why Measure Cloud Liquid Water Content?

- Determines the Potential of Enhancing Precipitation using Cloud Seed Techniques (Mali, Saudi Arabia)
- Basic Cloud Parameter (MPACE)
- Icing Studies (WISP04, Sikorsky)
- Comparison with Remote Sensing Measurements (THORpex, IOP1)

Forward Scattering Spectrometer Probe (FSSP) On the Left Wing of the King Air 200 Research Aircraft

Liquid Water Content Calculation

The amount of liquid water for a given volume of air may be determined through mass integration of the cloud droplet distribution.

$$LWC = \left(\frac{\pi}{6}\right) \rho_w \sum_{i=1}^{m} N_i d_i^3$$

LWC – Cloud Liquid Water Content

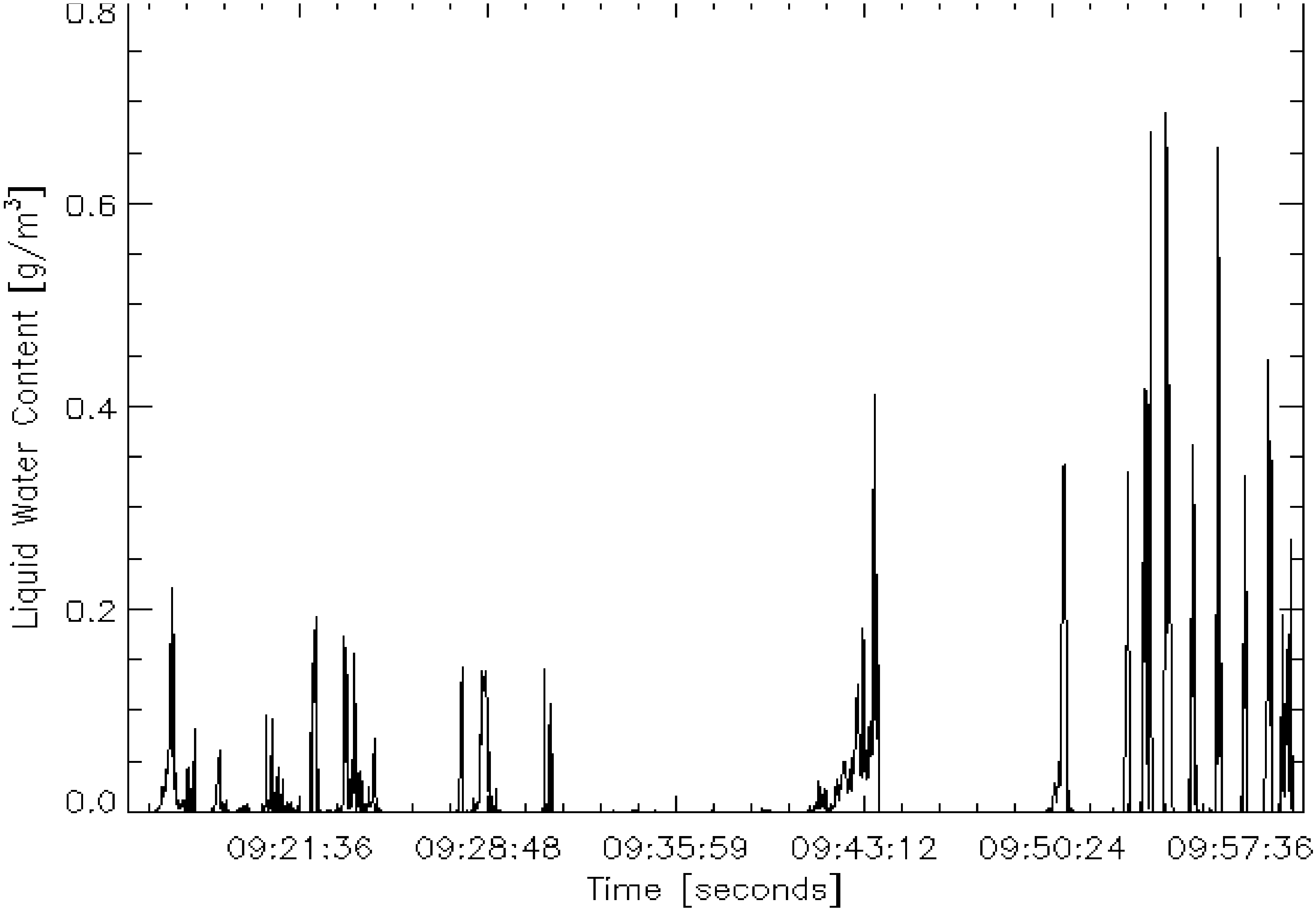
ρ_w – Density of Water

N_i – Concentration of Droplets in Size Channel i

d_i – Droplet Diameter in Size Channel i

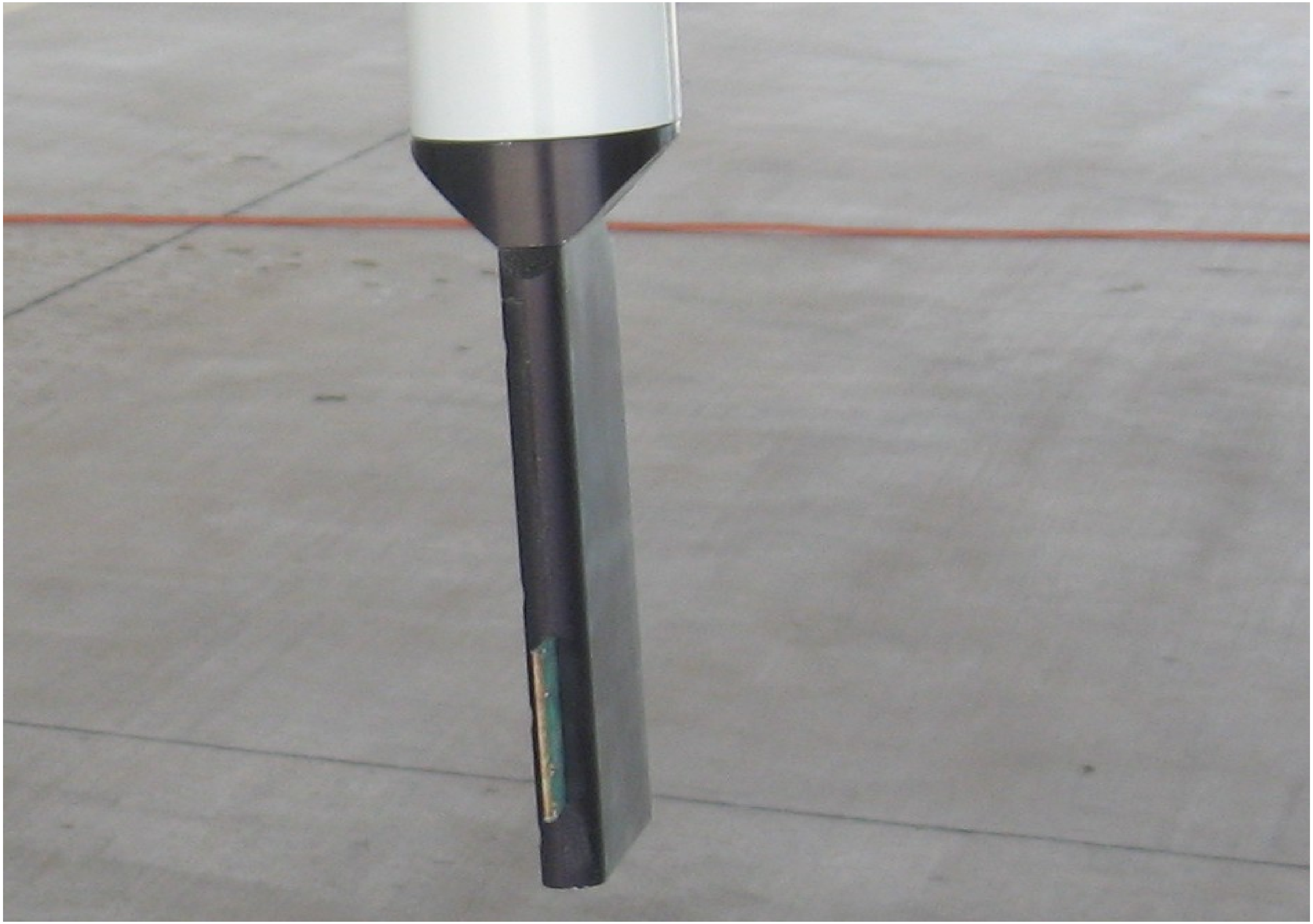
m – Total Number of Size Channels

March 13, 2008 Flight



FSSP cloud liquid water content measurements near Hail, Saudi Arabia at -16 C and 19,000 ft.

Liquid Water Content Probe on the King Air 200 Research Aircraft



Liquid Water Content Probe

- Coil is heated to given temperature ~185 °C.
- Coil supplies energy in the form of heat to vaporize drops.
- Power is supplied to coil to maintain a constant temperature.

$$P = P_{dry} + P_{wet}$$

P – Total Power

P_{dry} – Dry Power Term

P_{wet} – Wet Power Term

Dry Power Term

- Energy is transferred to passing air molecules due to thermal conduction.
- Energy transferred is a function of air speed, pressure, and temperature

$$P_{dry} \approx C(T_s - T_a) * (pv)^x$$

King et. al, 1981

- C – Calibration Constant
- x - Calibration Constant
- T_s - Wire Temperature
- T_a - Ambient Air Temperature
- p - Ambient Atmospheric Pressure
- v - True Air Speed

Wet Power Term

- Energy is transferred to heat droplets to to the boiling point and vaporize the droplet.
- Function of the mass of droplets.

$$P_{wet} \approx Mldv\left[L_v + c_w\left(T_v - T_a\right)\right]$$ King et. al, 1981

- M - Liquid Water Content
- l - Length of Wire
- d - Diameter of Wire
- v – True Air Speed
- L_v - Latent Heat of Vaporization
- c_w - Specific Heat of Water
- T_v - Boiling Temperature of Water
- T_a – Ambient Temperature

Liquid Water Content Formula

Combine the Wet and Dry Power Terms

$$P \approx C(T_s - T_a) * (Pv)^x + Mldv[L_v + c_w(T_v - T_a)]$$

Solve for Liquid Water Content

$$M \approx \frac{P - C(T_s - T_a) * (pv)^x}{ldv[L_v + c_w(T_v - T_a)]}$$

- P – Total Power
- C – Calibration Constant
- x - Calibration Constant
- T_s - Wire Temperature
- T_a - Ambient Air Temperature
- p - Ambient Atmospheric Pressure
- v - True Air Speed
- M - Liquid Water Content
- l - Length of Wire
- d - Diameter of Wire
- v – True Air Speed
- L_v - Latent Heat of Vaporization
- c_w - Specific Heat of Water
- T_v – Water Boiling Temperature

Objectives

- Create calibration routine to determine calibration coefficients for the Liquid Water Content Probe.
- Create data processing routine to apply offset correction to liquid water measurements.
- Compare measurements of liquid water content from Hot Wire probe and FSSP to validate the offset correction data processing routine.

Calibration Data

- Developed a “king_calib” software routine that calculates coefficients C, x, and the correction factor A.
- Calibration software requires flight measurements of the hot wire voltage and the true air speed.
  - Sample out of cloud in dry air.
  - Vary air speed from maximum to minimum and then back to maximum while maintaining constant altitude.
  - Conduct measurement at altitude typical for liquid water content measurements.

Calibration Algorithm

- Fit a curve to voltage versus airspeed data points with a function of the form:

$$v_a = kv^x + a$$

- Va is hot wire voltage.
- v is true air speed.
- Model coefficients are k, x, and a.
- Calibration coefficients are C, x, and A.
- “A” results from the fact that this model does not pass through (0,0).

Calibration Equation

Dry Term is: $$P_{dry} = C(T_s - \bar{T}_a) * (\bar{p}\, v)^x + A$$

Group Constants: $$P_{dry} = [C(T_s - \bar{T}_a) * \bar{p}^x] v^x + A$$

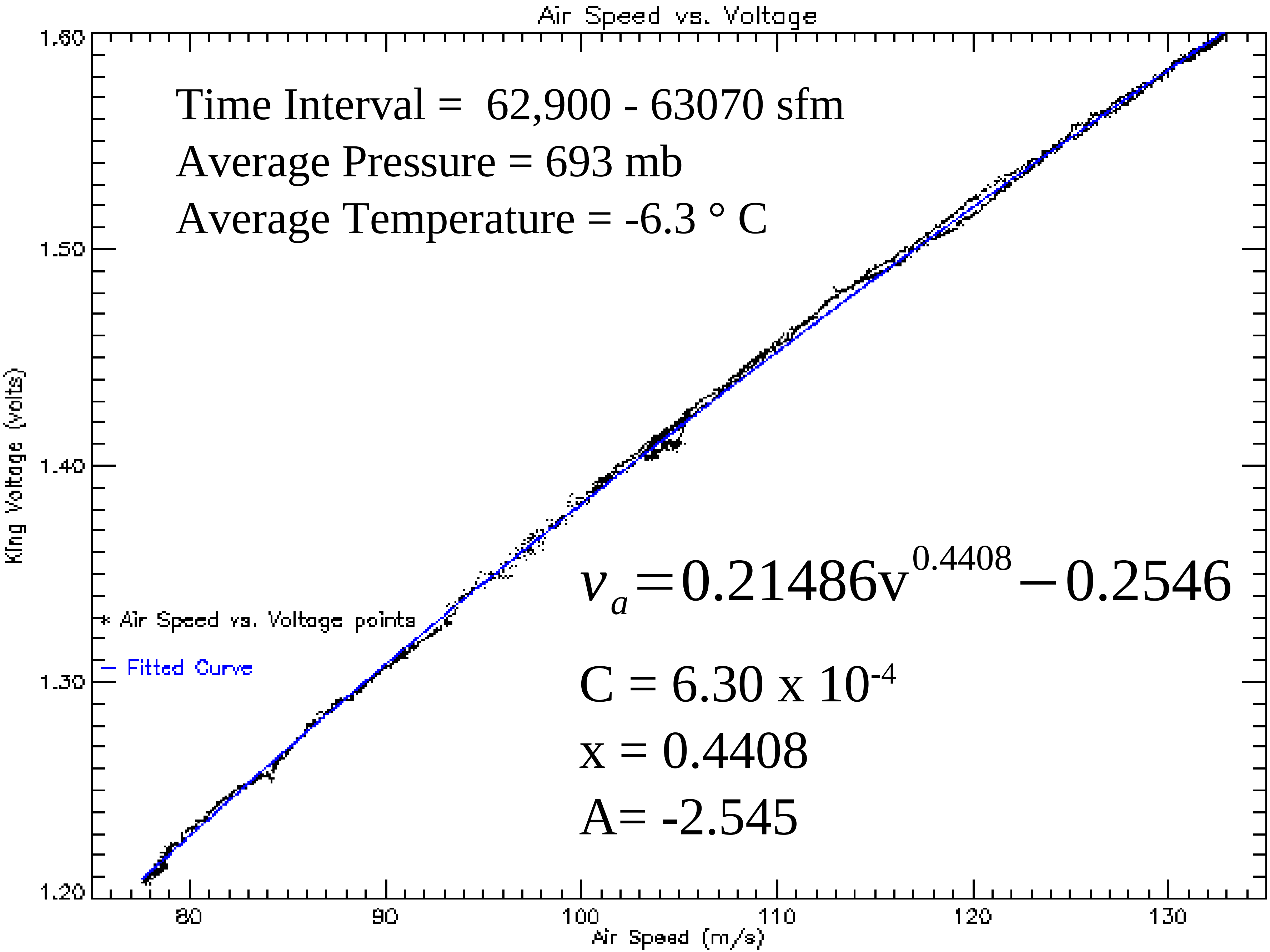
Substitute for P: $$10\mathrm{V}_a = [C(T_s - \bar{T}_a) * \bar{p}^x] v^x + A$$

Define Constants: $$k = \frac{C(T_s - \bar{T}_a) * \bar{p}^x}{10} \qquad a = \frac{A}{10}$$

Solving: $$C = \frac{10 * k}{(T_s - \bar{T}_a) * \bar{p}^x} \qquad A = 10 * a$$

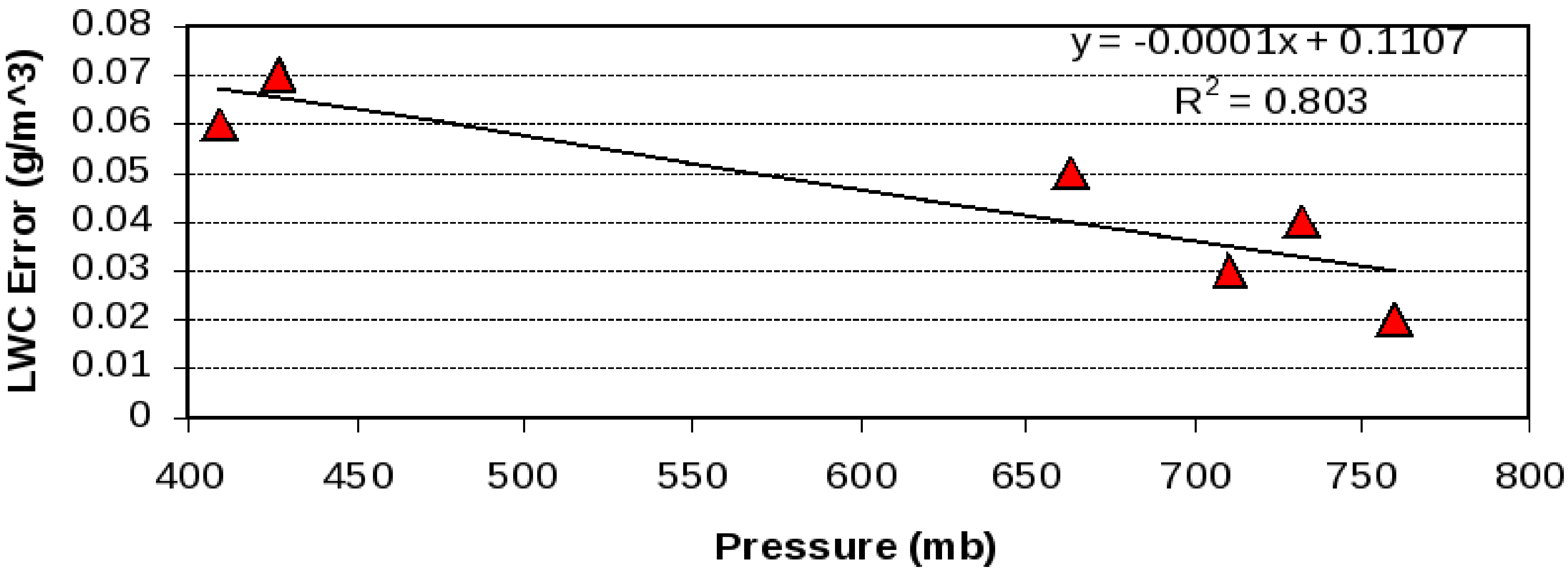
C, A, and x are the calibration constants needed.

Calibration Results: June 21, 2004

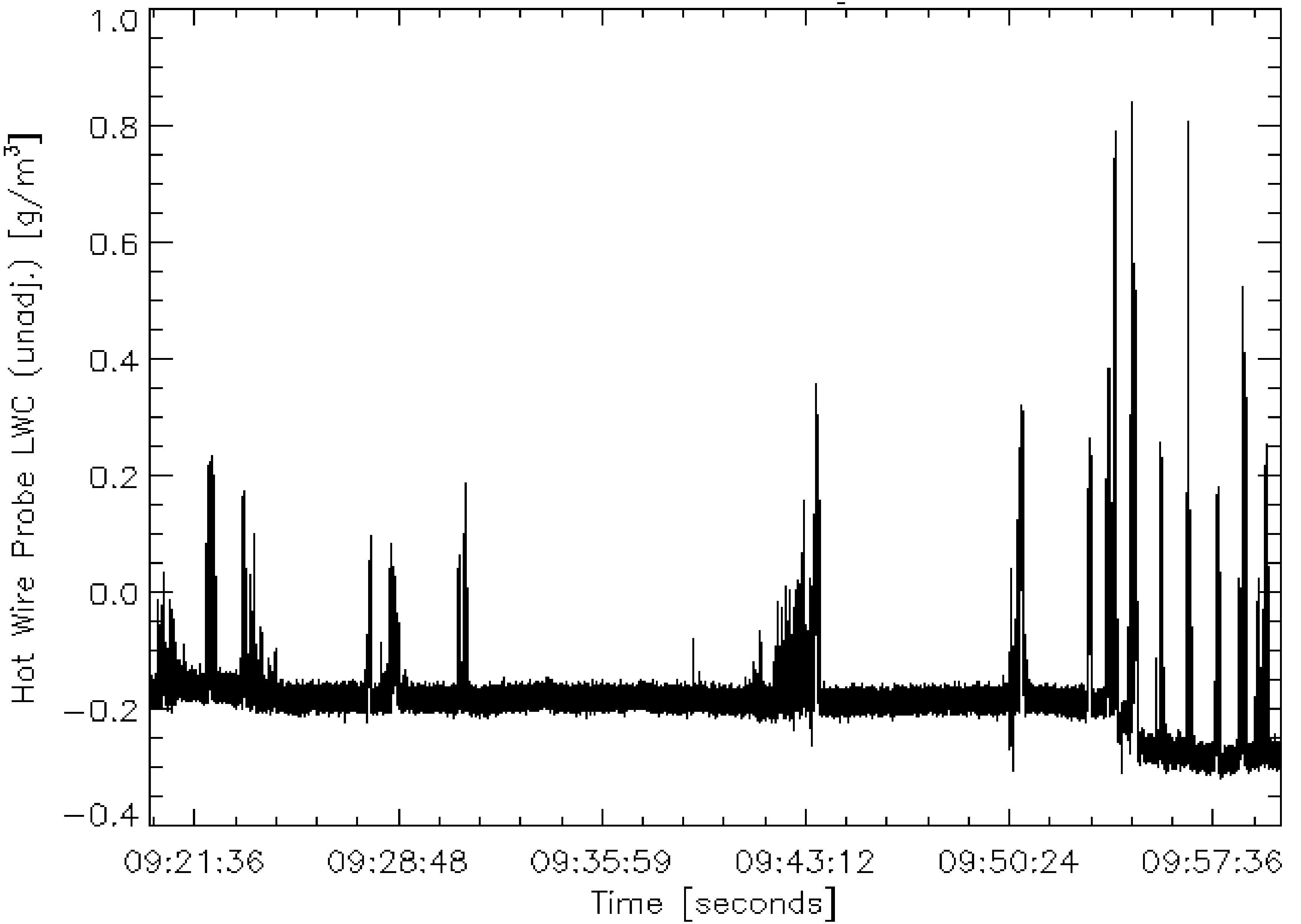


Calibration Summary

Date	Pressure	Temp.	C	X	A
01/25/04	427	-32	9.64E-4	0.3936	-1.968
01/29/04	409	-30	9.00E-4	0.3970	-1.455
02/03/04	732	-7.1	5.59E-4	0.4498	-2.571
02/04/04	760	-3.7	5.56E-4	0.4544	-3.139
02/12/04	663	-18	5.97E-4	0.4435	-2.622
03/08/04	771	-14	5.51E-4	0.4515	-2.588



March 13, 2008 Flight



Hot Wire Probe cloud liquid water content (unadjusted offset) measurements near Hail, Saudi Arabia at -16 C and 19,000 ft.

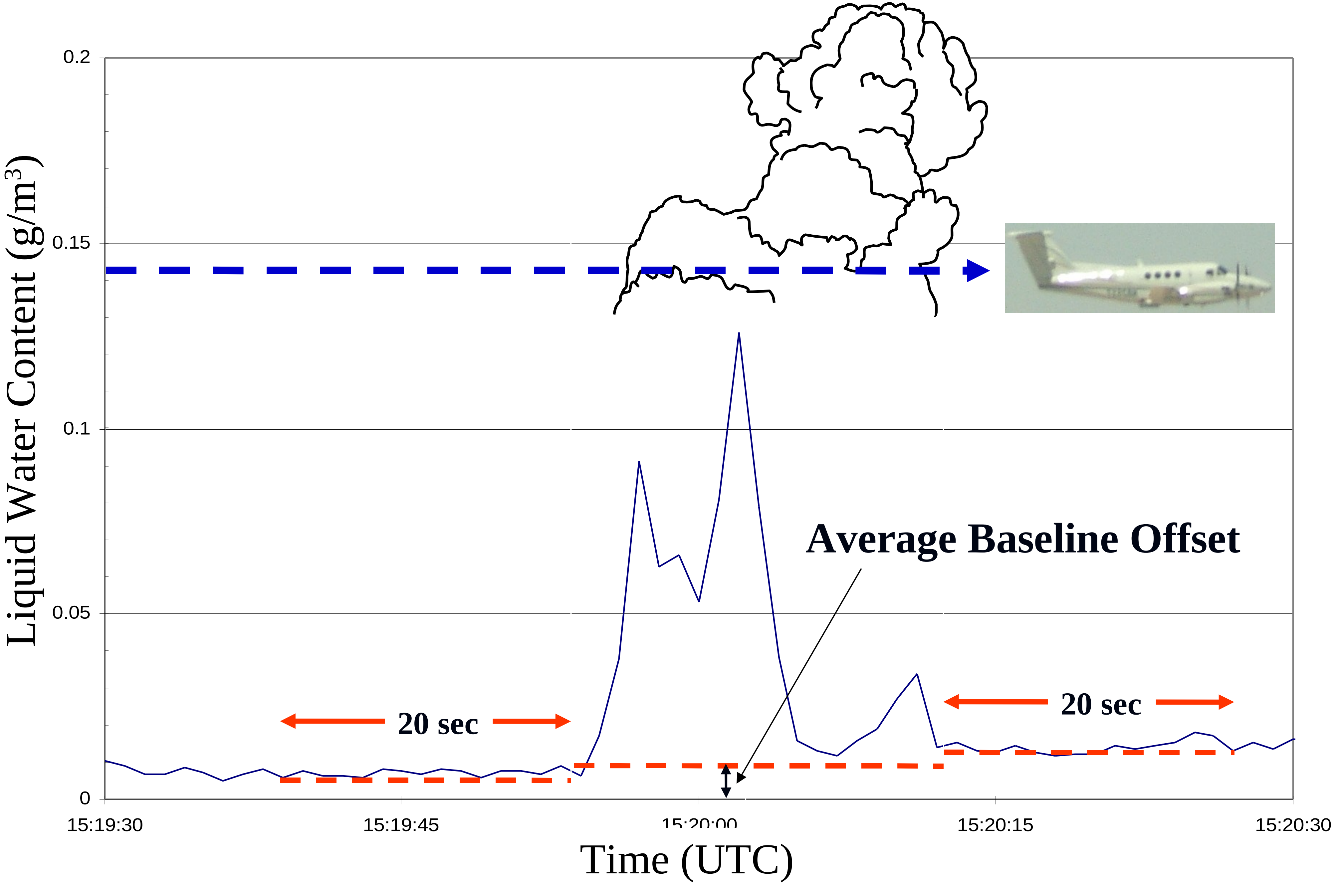
Offset Correction

- In theory, the liquid water content measurement should be zero when out of cloud.
- Calibration error affects the liquid water content measurements and cause the baseline to be offset from zero.
- The “king2lwc” data processing subroutine attempts to adjust the liquid water content data so that the baseline is near zero.
- The offset correction requires FSSP concentration measurements.

Offset Correction Algorithm

- An in cloud parameter based on the FSSP concentration measurement is used to define when sampling in or out of cloud.
- The offset correction is determined right before and right after a cloud measurement.
- An average liquid water content of 20 second interval is for the offset.
- The calculated offset value is subtracted from the in cloud liquid water data.

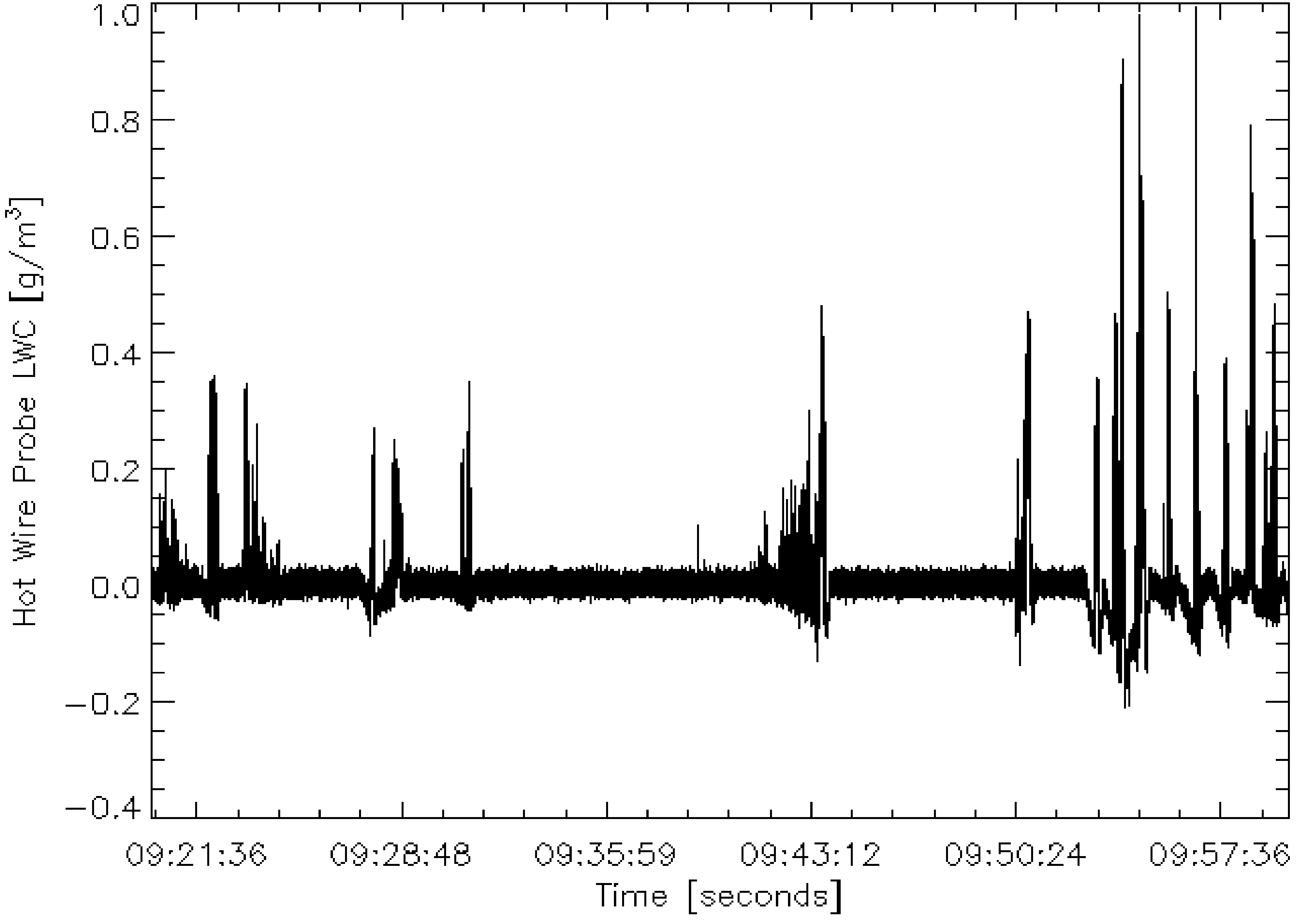
Offset Algorithm Depiction



Offset Correction Conclusions

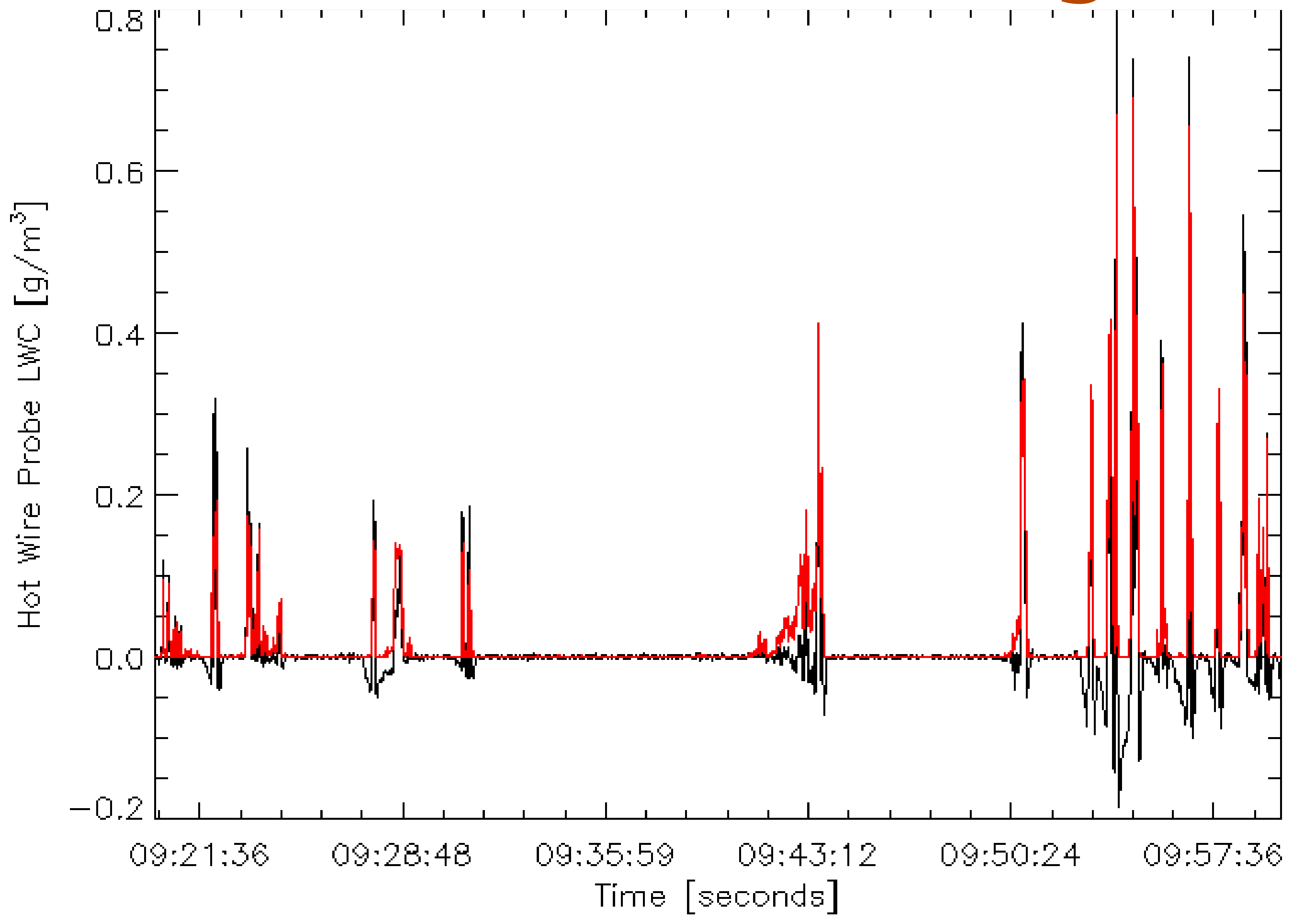
- Most of the time the offset correction algorithm is successful.
- However, the offset correction algorithm can give poor results if:
  - The aircraft takes off in clouds.
  - The aircraft lands in clouds.
  - The aircraft's altitude changes greatly while in cloud.

March 13, 2008 Flight



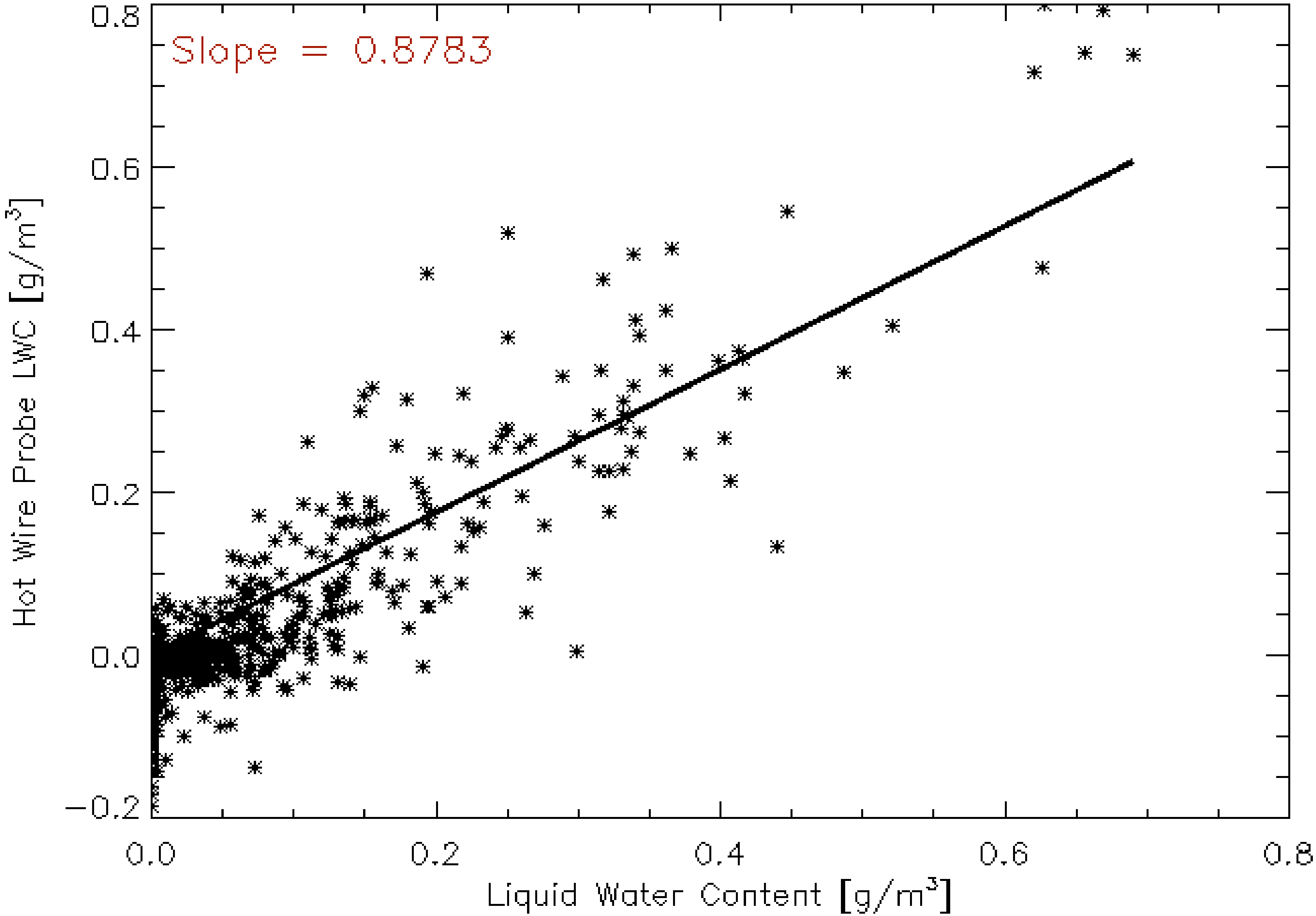
Hot Wire Probe cloud liquid water content (adjusted offset) measurements near Hail, Saudi Arabia at -16 C and 19,000 ft.

March 13, 2008 Flight



Hot Wire Probe (Black) and FSSP (red) cloud liquid water content measurements near Hail, Saudi Arabia at -16 C and 19,000 ft.

March 13, 2008 Flight



FSSP cloud liquid water content versus the Hot Wire Probe cloud liquid water content measurements between 9:20 and 10:00.

Conclusions

- Hot Wire Liquid Water Content Probe can be calibrated during a field project.
- Typical unadjusted Liquid Water Content error is ~0.04 g/m^3.
- Hot Wire Liquid Water Content error has some dependence on altitude and over extreme altitude ranges is approximately 0.07 g/m^3.
- The baseline offset corrections in the Hot Wire Liquid Water Probe can be adjusted during post-processing; however, does not work properly under all circumstances.
- Hot Wire and FSSP Liquid Water Content do agree under some measurement conditions if each instrument is correctly calibrated and processed.

Future Work

- Collect some Hot Probe calibration data during a Research King Air flight.
- Determine calibration coefficients and reprocess the Saudi 2007/2008 data set.
- Lot of work still to do (e.g. AIMMS Probe).

Any Questions?