Particle Analysis and Display System (PADS):

Hotwire LWC Module Manual

DOC-0290 Rev A

PADS 3.5

Hotwire LWC Module 3.5.0

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Trademark Information

Risks of Installing Additional Software

Instrument computers from DMT are configured to acquire data in a reliable, robust manner. Typically, such instruments are either not connected to a network or are connected to a small, local network that is isolated from the internet, reducing the risk of viruses. Since anti-virus programs can cause erratic behavior when run in the background on data acquisition computers, DMT does not install anti-virus, anti-spam, or anti-malware programs. If you choose to install these programs, you accept the risk associated with them in terms of potential performance degradation of the software installed by DMT.

For similar reasons, DMT recommends that you do not install or run other software on the dedicated instrument computer. Although the installation of some software may be unavoidable, it is particularly important not to run other software while the computer is acquiring data.

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1.0 Introduction

The Particle Analysis and Display System (PADS) is a software package that interfaces with instruments produced by Droplet Measurement Technologies (DMT) and other leading instruments used in the atmospheric sciences. This manual describes the PADS Hotwire LWC (Hotwire LWC) module version 3.5.0.

For an explanation of the basic PADS setup and instructions on how to acquire data using PADS, consult the *PADS Overview Manual, DOC-0300*. Definitions and calculations used in the Hotwire LWC module are also described in the *PADS Overview Manual*.

2.0 Configuration

Using PADS, you can configure both the software settings for the instrument and the instrument's data display in PADS. The following two sections explain how to do this. Configuring the instrument's software and display affects the default settings PADS uses when starting up. Some parameters can also be changed while PADS is running, but doing so affects the current session only.

2.1 Configuring the Hotwire LWC

Your Hotwire LWC and data system should arrive preconfigured from DMT. In some cases, however, you may want to change the software configuration for the instrument. To do this, follow the steps below. *Note: Droplet Measurement Technologies STRONGLY recommends that customers contact our office prior to changing any of the parameters in the instrument configuration. Improper changes can result in communication failure and/or changes in PADS computation algorithms, which can compromise data validity.*

1. Click on the "Hotwire LWC" tab.

2. From the **Configure** menu, select **Configure Instrument.** You will see the following window.

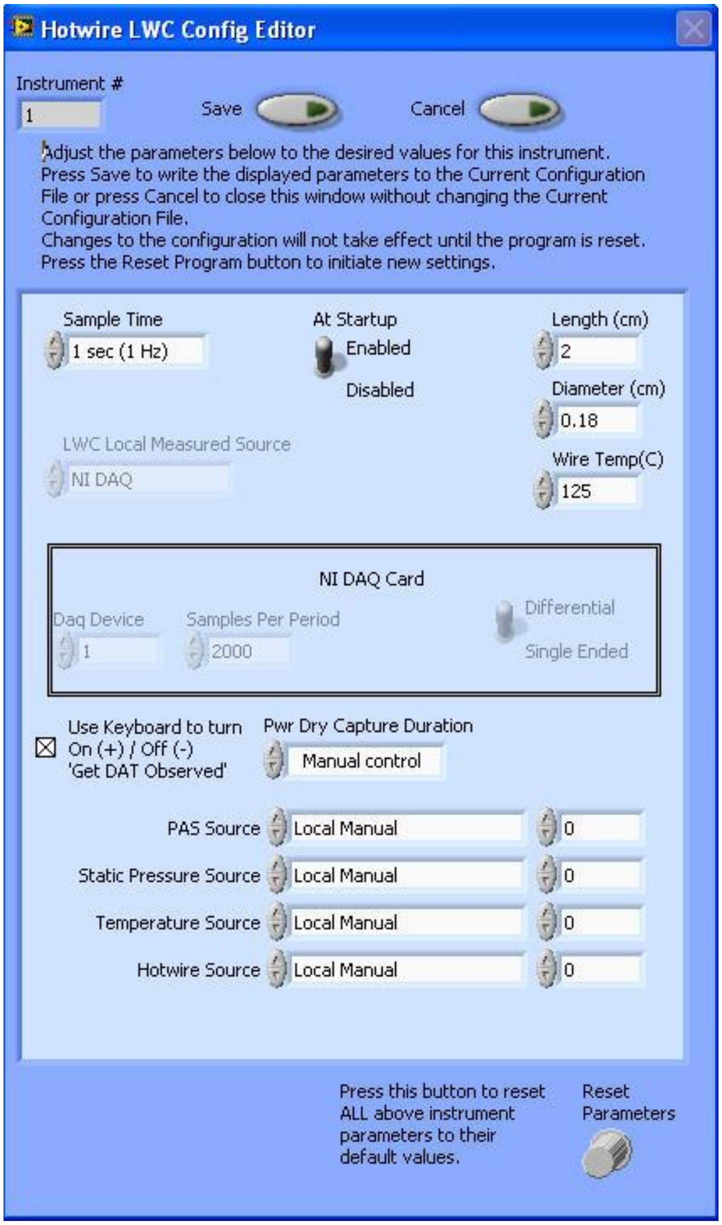

Figure 1: Hotwire LWC Configuration Editor Window

3. Now you can configure the instrument parameters to your desired specifications. See the definitions below for explanations of individual parameters. If at any time you would like to revert to the previously saved values for the Hotwire LWC parameters, press **Cancel** to exit the window without saving changes. Pressing **Reset Parameters** reverts parameters to their DMT-supplied default values.

4. When you are done configuring the Hotwire LWC parameters, press **Save** at the top of the Config editor window. Then press the green **Reset Program** button for the new configuration to take effect. Note that pressing the **Reset Program** button will clear any data currently being displayed.

2.1.1 Hotwire LWC Parameters

Instrument #: This lists the number corresponding to the instrument you are viewing, in this case the Hotwire LWC. If your Hotwire LWC has been assigned instrument number one, you will see "1" in this field. You should not need to modify the instrument number, and in fact you are unable to do so from within PADS.

Sample Time: This parameter shows the time interval you'd like between samples. You can have the probe sample at intervals of .1, .2, .5, 1, 2, 5, or 10 seconds (10, 5, 2, 1, 0.5 or 0.1 Hz).

At Startup Enabled / Disabled: If you want the Hotwire LWC to acquire data when PADS begins sampling, make sure this parameter is in the "Enabled" mode. In some cases, such as if the Hotwire LWC is inoperative, you may want to use this control to disable the probe. Disabling the Hotwire LWC allows data to transmit from other instruments without interference. Data will still be written to the disabled instrument's output file, but PADS will write "NaN" to all fields.

Length: The length of the hotwire sensor in cm. DMT specifies the sensor length at time of manufacture, and this value should not change. Since the formula for LWC (g/m^3) uses sensor length as a variable, setting this parameter to something other than the measured sensor length will give erroneous LWC values.

Diameter: The diameter of the hotwire sensor's master coil in cm. DMT specifies the coil's diameter at time of manufacture, and this value should not change. Since the formula for LWC (g/m^3) uses diameter as a variable, setting this parameter to something other than the measured sensor diameter may give erroneous LWC values.

The **Wire Temp** parameter can be used to shift the value of the Pwr Dry Calculated (W) variable. *Note: this parameter does NOT determine the temperature at which the actual wire is maintained.* Rather, it sets the value of the "wire temperature" variable used in the Pwr Dry Calculated equation.[1] The actual power required to heat the hotwire LWC depends somewhat on variables that are not factored into Pwr Dry Calculated equation, like the hotwire's location on the aircraft. If reported readings of Pwr Dry (e.g., those arrived at through analyzing the velocity and air density) do not exactly match Pwr Dry Calculated, the Wire Temp parameter can be changed slightly so that these readings conform with observed results.

LWC Local Measured Source: This parameter tells PADS how the master and slave hotwire voltages are being measured. If the **Hotwire Source** listed at the bottom of the Config Editor is set to a Hotwire LWC instrument, the LWC Local Measured Source *must* be set to NI DAQ. In other cases, this parameter is irrelevant. This parameter is grayed out so you cannot change it.

The boxed **NI DAQ Card** parameters are only relevant if the LWC source is an NI DAQ card:

Daq Device: This parameter identifies which NI DAQ card is measuring Hotwire LWC data. It helps PADS distinguish the Hotwire inputs in the event that the system uses more than one NI DAQ card.

Samples Per Period: This parameter instructs the Hotwire LWC to take *n* readings during one sample session, where *n* is the number specified in the parameter field. During each reading, the instrument reports values for both LWC Hotwire (V) and LWC Slave (V). PADS then averages hotwire readings and slave readings to come up with the appropriate values for the sample session. This results in less noise than using one instantaneous reading.

Note that the time elapsed between readings is [# of Averages] • [Hotwire Cycle Rate] Hz. For example, if the Hotwire Cycle Time is 1 sec (1 Hz), and the # of Averages is 100, the Hotwire voltage will be measured at a rate of 100 Hz. This is an improvement over PADS 2.X, where the system used faster sample rates but only sampled over part of the cycle.

Differential / Single-Ended Switch: This control tells PADS whether the NI-DAQ device will be used in single-ended mode or differential mode. PADS expects all output channels to be in the same category; you cannot have some channels with a single-ended setup and others with a differential setup. A differential wiring scheme will yield only half the number of input

[1] See Appendix C.

channels of a single-ended setup, but readings may be more accurate. For more information, consult the NI device's hardware manual.

If the **Use Keyboard to Turn On (+) / Off (-) 'Get Pwr Dry Observed'** checkbox is checked, you will be able to use the + and − keys during data acquisition to control when the system takes **Pwr Dry Observed** readings. + enables readings, while − turns it off. For more information about **Get Pwr Dry Observed**, see section 3.1.

Pwr Dry Capture Duration allows you to specify a time limit for **Pwr Dry Observed** readings. If you wish to control this Pwr Dry Observed data acquisition manually, using either the button on the Hotwire_LWC tab or the + and − keys, select "Manual Control."

The **Source controls** allow you to set the source for airspeed-related parameters that can be measured by instruments or entered manually. For instance, the **PAS Source** control specifies from which of the following sources the system should obtain the applied probe air speed (Applied PAS):

1.) A specific instrument in the system (this can be any instrument capable of measuring air speed)
2.) A manually entered value:
    a. A "Local" value, which at start-up is the value entered in the box to the right of the source control. This number can be changed from the instrument display while the program is running.
    b. A "Global" value entered on the **Setup** tab

Applied PAS is used to calculate sample volume. In flight conditions, you will typically want to select an instrument as the air speed source. However, you will need to enter manual air speed values during ground testing. If the PAS source is a manually entered value, PADS will still calculate air speed and store the result in the **PAS (m/s)** channel.

Similarly, you can instruct the system to use different sources for the static pressure, dynamic pressure, and temperature variables used in calculating air speed. For pressure and temperature sources, "Local Measured" uses the instrument's measurement, while "Local Manual" uses manually entered values—initially the ones to the right of the source controls, which can be changed from the instrument display when the program is running.

2.2 Configuring the Hotwire LWC Display

To configure the Hotwire LWC display, click on the Hotwire LWC tab if you have not already done so. Then select **Configure** from the menu bar and click on **Configure Display.** This will bring up the following window.

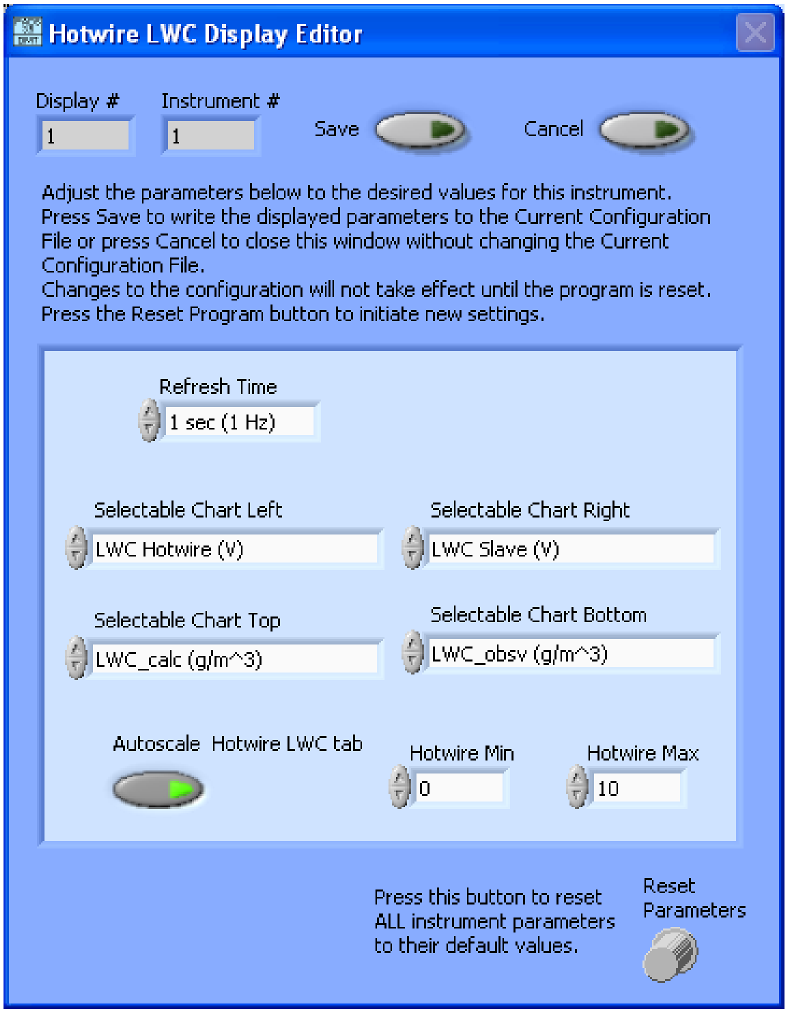

Figure 2: Hotwire LWC Display Editor Window

You do not need to modify the **Display #** or **Instrument #.**

Changing the **Refresh Time** allows you to set the time intervals for data display during acquisition mode; you can choose any time that is equal to or greater than the sample time. (Choosing a time less than the sample time is not useful, since the same data will be displayed multiple times.)

The **Selectable Chart** controls allow you to specify which channels will be graphed on the selectable charts sub-tabs. **Selectable Chart Left** and **Right** determine the channels graphed on the **Dual Selectable Chart** sub-tab, while **Selectable Chart Top** and **Bottom** determine the charts on the **Selectable Charts** tab. To change these channels, click on the arrow buttons to scroll between available options for the channels. You can also click on the white fields to bring up a list of all the available options, from which you can then choose the channel you want.

PADS graphs the channels listed as selectable Channels 1 and 2 together in the Dual Selectable Charts tab. It graphs Channels 3 and 4 separately in the Selectable Charts tab.

If the **Autoscale Hotwire LWC Button** is on, the data for the Hotwire LWC tab will be autoscaled. To disable autoscaling, press the button so it turns off. PADS autoscales data for the remaining four time-series tabs regardless of whether this button is on or off.

The **Hotwire Min** and **Hotwire Max** buttons set the y-axis scale on the **Hotwire LWC** sub-tab chart. The default values for these parameters are -0.5 and 4 g/m^3, respectively.

When you are done, click on **Save** to update the configurations or **Cancel** to revert to the previous configuration. After you reset PADS, you will be able to see any changes. Note that clicking **Reset Program** will clear out any data currently being displayed.

Configuring channels in the **Display Editor** will change the display upon start-up. Once PADS has started, you can change many of these settings from within the main Hotwire LWC tab.

3.0 The Hotwire LWC Window

In the top right of the window, you will see the **Enable** button, **COM Port** indicator, and **Fault/No Fault** button. For explanations of these features, see the "Instrument Tabs" section of the *PADS Overview Manual*.

3.1 "Get Pwr Dry Observed" Controls

In the top left of the window, you will see controls for getting Pwr Dry Observed, as depicted in Figure 3.

Figure 3: "Get Pwr Dry Observed" Controls

The **Get Pwr Dry Observed** button should be used under the following conditions:

1.) There are no clouds present
2.) Airspeed, altitude and temperature are approximately the same as when LWC will be measured

"Pwr Dry Observed" is intended as a measurement of the heat loss term due to dry air. (This loss is a factor in calculated LWC; see Appendix B of this document for more details.) When you press this button, the power currently being measured from the sensor is captured and stored. In a no-cloud "Dry" air environment, most to all of this power is due to dry air term losses. PADS displays the measured power in the Pwr Dry Observed (W) indicator, and it records this value in the Pwr Dry Observed (W) output channel.

When the **Get Pwr Dry Observed** button is on, PADS will average the Pwr Dry Observed values measured since the button was pressed. Note, however, that the value displayed in **Pwr Dry Observed** will be the value after the previous Pwr Dry sampling session; this value does not get updated until the user turns the button off. When the button is off, Pwr Dry Observed indicators will remain at the values they were when the button was last switched from on to off. When the button is turned off and then turned back on, PADS clears out the previously recorded data and begins averaging these values from the time when the button was last turned on.

Pwr Dry Capture Duration allows you to specify a time limit for **Pwr Dry Observed** readings. If you wish to control this Pwr Dry Observed data acquisition manually, using either the button on the Hotwire_LWC tab or the + and − keys, select "Manual Control." (To enable keyboard control of the capture duration, use the checkbox on the Config Editor; see section 2.1.1 for details.)

The **Pwr Dry Observed (W)** indicator lists the Pwr Dry Observed reading from the previous sampling session (i.e., the average over the duration of this session).

3.2 Channel Data

PADS displays Hotwire LWC channel data on the left side of the Hotwire LWC window.

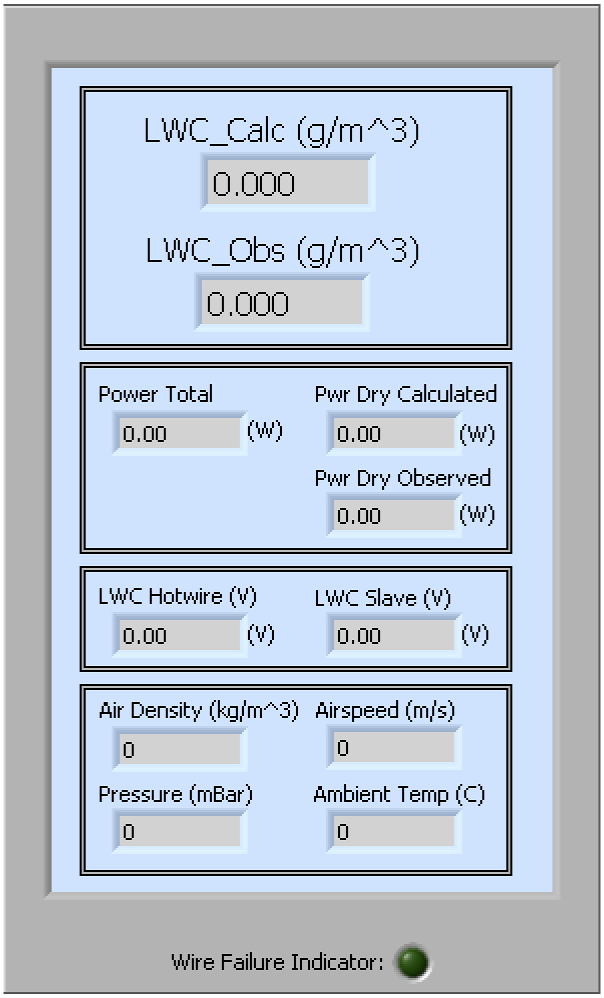

Figure 4: Hotwire LWC Channel Data Window

For information on specific channels, their definitions, and their acceptable ranges, consult *Appendix A: Hotwire LWC Channels* and the PADS Overview Manual's *Appendix A: Definitions*. Note that the **Pwr Dry Observed (W)** reading listed in the channel data is the same as that listed in the box above the channel data, except for the latter is displayed in greater precision.

The **Wire Failure Indicator** illuminates when a problem is detected with the LWC hotwire. This indicates the LWC unit may need to be replaced.

3.3 Sub-tabs

There are five sub-tabs on the **LWC** tab.

3.3.1 Hotwire LWC

This tab shows a time-series chart of LWC_Calc (in green) and LWC_Obs (in blue).

3.3.2 Selectable Charts and Dual Selectable Charts

The **Selectable Charts** tab shows time-series charts of two user-selectable channels. The **Dual Selectable Chart** tab displays a single chart with two channels graphed against time. The left-hand channel is displayed in green, while the right-hand channel is displayed in blue.

All the channels on these two sub-tabs can be changed using the controls above the charts. Changing them from within these windows changes them for the current session only. To change the default values used upon program start up, select **Configure > Configure Display** and modify the appropriate parameters. Then click on **Save** and **Reset Program.**

When you access time-series charts in playback mode, the currently selected moment in time is indicated by a red cursor. The y-axis value for this time is indicated by cross (+) on this cursor. Note that when you display a large range of time-series data, the chart display does not have sufficient resolution to display each individual time point. To increase resolution, zoom in on the data by changing the time interval to a smaller range. You can also change the time scale by typing a different number into the starting and ending values on the x-axis.

3.3.3 Hotwire LWC Collective

The **Hotwire LWC** Collective sub-tab displays a multivariable plot that graphs the following channels against time:

a. LWC_Calc (g/m^3)
b. Airspeed (m/sec)
c. Ambient temperature (C)
d. Pressure (mBar)

Note that air speed, ambient temperature and pressure are used to calculate LWC. See *Appendix B: Calculations* in the *PADS Overview Manual* for details.

3.3.4 Tools

The **Source controls** allow you to set the source for airspeed-related parameters that can be measured by instruments or entered manually. For instance, the **PAS Source** control specifies from which of the following sources the system should obtain the applied probe air speed (Applied PAS):

1.) A specific instrument in the system (this can be any instrument capable of measuring air speed)
2.) A manually entered value:
    a. A "Local" value, which at start-up is the value entered in the box to the right of the source control. This number can be changed from the instrument display while the program is running.
    b. A "Global" value entered on the **Setup** tab

Applied PAS is used to calculate sample volume. In flight conditions, you will typically want to select an instrument as the air speed source. However, you will need to enter manual air speed values during ground testing. If the PAS source is a manually entered value, PADS will still calculate air speed and store the result in the **PAS (m/s)** channel.

Similarly, you can instruct the system to use different sources for the static pressure, dynamic pressure, and temperature variables used in calculating air speed. For pressure and temperature sources, "Local Measured" uses the instrument's measurement, while "Local Manual" uses manually entered values—initially the ones to the right of the source controls, which can be changed from the instrument display when the program is running.

If the Source controls are grayed out, you can enable them by pressing the **Press to Enable Source changes** button.

The **Wire Temp** parameter can be used to shift the value of the Pwr Dry Calculated (W) variable. *Note: this parameter does NOT determine the temperature at which the actual wire is maintained.* Rather, it sets the value of the "wire temperature" variable used in the Pwr Dry Calculated equation.[2] The actual power required to heat the hotwire LWC depends somewhat on variables that are not factored into Pwr Dry Calculated equation, like the hotwire's location on the aircraft. If reported readings of Pwr Dry (e.g., those arrived at through analyzing the velocity and air density) do not exactly match Pwr Dry Calculated, the Wire Temp parameter can be changed slightly so that these readings conform with observed results.

4.0 Zooming In and Out

There are several ways to zoom in or out on Hotwire LWC charts. As described in the *PADS Overview Manual*, you can use the time-range controls (Figure 5) to zoom. To zoom

[2] See Appendix C.

in on the data, move the green and red controls close to the white control, which will narrow the range of displayed data. To zoom out, move the two colored controls away from the white control.

Figure 5: Time-Range Controls

On the chart itself, you can also type numbers directly into the first and last labels on the x and y axis to change the scaling.

Note: Do not right-click on chart and change the auto-scaling using the drop-down menu. This can interfere with the chart display. PADS autoscales most charts automatically. You can turn off autoscaling on the histogram using the buttons in the lower right of the window.

Appendix A: Hotwire LWC Channels

A complete list of Hotwire LWC data channels appears below. The Hotwire LWC output file will contain data values for each channel for each sampling period. You can also plot each of these channels against time using the **Selectable Charts** or **Dual Selectable Chart** sub-tabs.

LWC channels are described in several places. *Appendix C* of this manual describes channels that are used specifically in LWC calculations. This appendix gives a good overview of how PADS derives LWC_Calc and LWC_Obs. Channels that are common to both the Hotwire LWC and other instruments, such as Applied Ambient Temperature, are described in *Appendix A* of the *PADS Overview Manual*. *Appendix B* of the *Overview Manual* provides relevant equations for common channels.

End Seconds	Reynolds Number
Day of Year	Prandtl Numb Dry
Year	Prandtl Numb Wet
Status	Boiling Point Water (K)
LWC Hotwire (V)	Power Total (W)
LWC Slave (V)	Pwr Dry Calculated (W)
Collect P Dry	Pwr Dry Observed (W)
Spare 1 - 8	Wire Temp (C)
LWC_calc (g/m^3)	Quality Indicator

LWC_Obs (g/m^3)	Applied Airspeed (m/s)
Air Density (kg/m^3)	Applied Pressure (mB)
Viscosity Dry (g/sec-cm)	Applied Ambient Temp (C)
Viscosity Wet (g/sec-cm)	UTC Seconds / GPS Time
Thermal Cond Dry (cal/sec-cm-K)	Date
Thermal Cond Wet (cal/sec-cm-K)	Time

If there is no instrument in the system that reports **GPS Time**, or if such an instrument exists but the user has selected on the Hotwire LWC Config Editor to show UTC Seconds, the output channel file will contain **UTC Seconds**. Otherwise, it will report **GPS Time**.

Two additional channels, **Date** and **Time**, may be listed after **GPS Time/ UTC Seconds** if **Write Date & Time Stamp** is enabled on the **Setup** tab.

Hotwire LWC channels fall into several broad categories:

- Time channels
- Hotwire channels (e.g., LWC Hotwire (V) and LWC Slave (V))
- Channels for other statistical data (ambient temperature, etc.)
- Calculated channels

Appendix B: Explanations and Usage of Dry Air Term

The Hotwire LWC instrument measures liquid water content (LWC) using a heated, wire-wound cylinder. The sensor coil maintains a constant temperature, usually 125 °C. The instrument measures the power necessary to maintain the sensor wire at this temperature. More power is needed to maintain the temperature as droplets evaporate on the cylinder surface and cool the surface.

However, the power required to maintain the sensor wire temperature also reflects variables unrelated to LWC. In general, the total power is the sum of three terms: the dry air term, the wet term (LWC), and a radiation term.

In practice, the radiation term is negligible, and PADS assumes it is zero. However, the dry air term—i.e., convective heat loss—is significant. PADS estimates dry air term in two ways. First, it allows users to measure the observed dry air term. This is done by taking readings of the power necessary to maintain the sensor wire temperature in negligible LWC (i.e., out of cloud) conditions. Users can press the “Get Pwr Dry Observed” button to get these readings.[3] The data obtained when this button is pressed should then accurately indicate dry air term, since there will be no heat losses due to vaporization. The dry air term estimate averaged from these readings is stored in **Pwr Dry Observed (W).**

The second way PADS estimates heat loss due to dry air term is by calculating it from the probe air speed, temperature, pressure and the geometry of the sensor wire. For a complete list of these variables and the relevant calculations, see *Appendix C*. The result of this calculation is stored in **Pwr Dry Calculated (W).**

PADS then performs the following subtractions:

Total Power (W) – Pwr Dry Observed (W) = Pwr Wet Observed (W)

Total Power (W) – Pwr Dry Calculated (W) = Pwr Wet Calculated (W)

where Total Power (W) is the total power required to maintain the sensor wire temperature.

Pwr Wet Observed and Pwr Wet Calculated are not stored in the output file. Rather, PADS applies a conversion equation to these values, and then stores the results in **LWC_Obs (g/m^3)** and **LWC_calc (g/m^3)**, respectively. These channels thus give estimates of LWC arrived at by two different techniques.

The theoretical basis for the formulas PADS uses are derived largely from King, W.D., D.A. Parkin, and R.J. Handsworth, 1978: "A hot-wire liquid water device having fully calculable response characteristics," *J. Appl. Met.*, 17, 1809-1813. The theoretical basis for calculating the flow around the cylinder can be found in Zukauskas, A. and Ziugzda, J., 1985, *Heat Transfer of a Cylinder in Crossflow*, Hemisphere Publishing Corporation.

Appendix C: LWC Calculations

Figure 6 shows a diagram of how important LWC channels and variables relate to each other.

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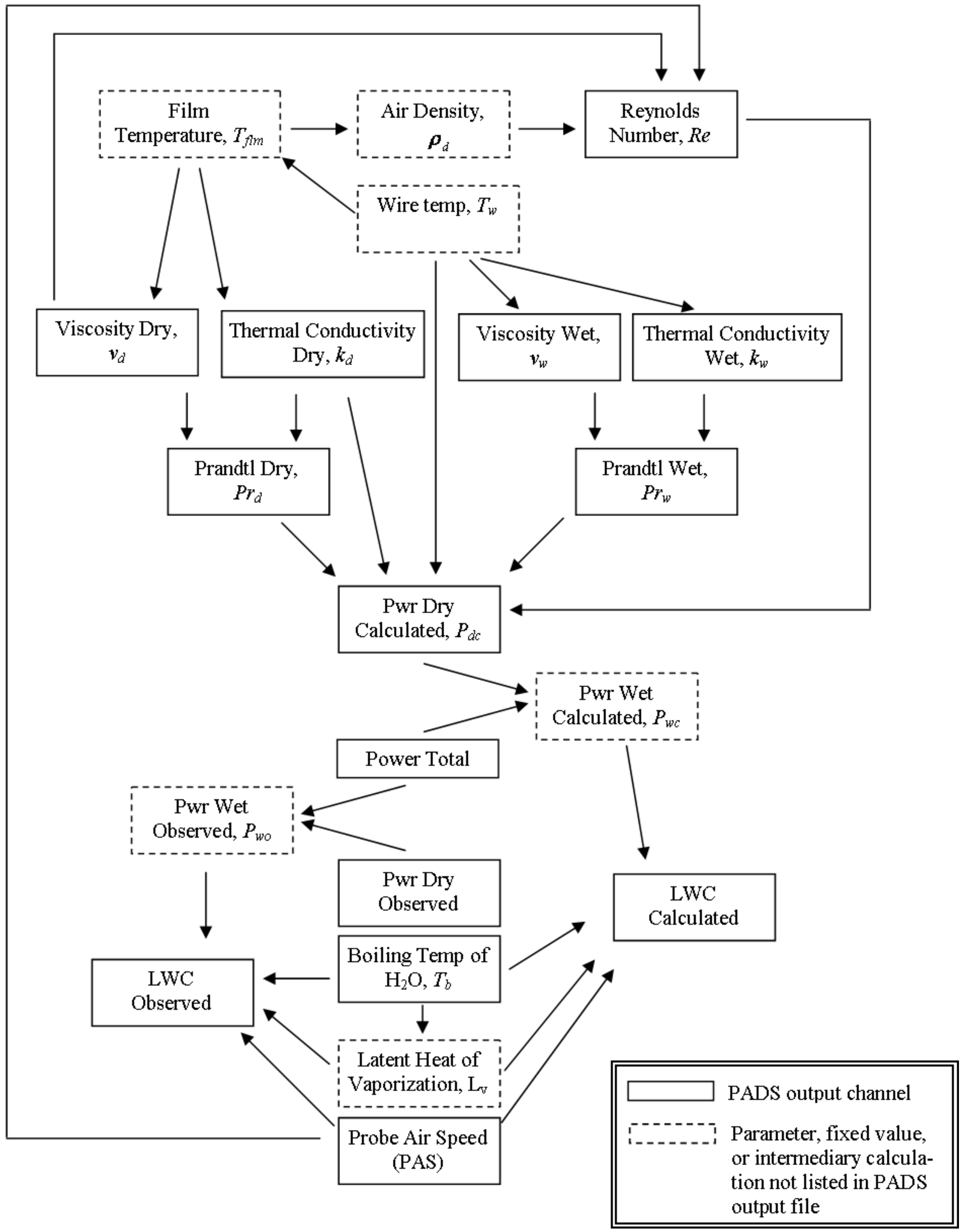
[3] When the button is pressed, there should be no visual clouds. In addition, airspeed, altitude and temperature should be approximately the same as when LWC will be measured.



Notes:

- This diagram provides an overview of how the LWC-specific channels relate to each other. It does not show all input variables for all equations. For complete equations, see the definitions in the following sections.
- While air density is a channel in the output file (ρ_a), this air density calculation differs from ρ_d, the air density used in the Reynolds number calculation. See the **air density** entry for details.

Figure 6: Relationships between Important LWC Output Channels. An arrow from A to B indicates A is a parameter used in calculating B.

Film Temperature (K): On a hotwire sensor instrument, the arithmetic average of the wire temperature and the ambient air temperature. PADS calculates film temperature, T_{flm}, as follows:

$$T_{flm} = \frac{T_a + T_w}{2}$$

where

T_a = Ambient temperature (K)

T_w = Wire temperature (K) specified in PADS

PADS uses film temperature in calculating air density, viscosity, and thermal conductivity. The film temperature is also used when calculating Reynolds number because of the air density and viscosity that are temperature-dependent.

Thermal Cond Dry (cal/sec-cm-K): A channel on the Hotwire LWC output file. It indicates the thermal conductivity of the air as a function of film temperature, T_{flm}. PADS calculates the Thermal Cond Dry, k_d, as follows:

$$k_d = \frac{T_{flm}^{1.5} \bullet 0.00264638}{418.68 \bullet \left(T_{flm} + 245.4 \bullet 10^{-12/T_{flm}} \right)}$$

Thermal Cond Wet (cal/sec-cm-K): A channel on the Hotwire LWC output file. It indicates the thermal conductivity as a function of the wire temperature, T_w. PADS calculates the Thermal Cond Wet, k_w, as follows:

$$k_w = \frac{T_w^{1.5} \bullet 0.00264638}{418.68 \bullet \left(T_w + 245.4 \bullet 10^{-12/T_w} \right)}$$

T_w is the wire temperature (K) specified in PADS.

Viscosity Dry (g/sec-cm): A channel on the Hotwire LWC output file that is used in calculating the Prandtl and Reynolds number and ultimately the LWC. Viscosity measures a fluid's resistance when the fluid is being subjected to shear stress or extensional stress. Viscosity Dry (g/sec-cm), v_d, is a function of the film temperature, T_{flm}. PADS calculates it as follows:

$$v_d \quad = \quad 0.0001718 \bullet \frac{393.16}{120 + T_{flm}} \bullet \left[\frac{T_{flm}}{273.16} \right]^{1.5}$$

Viscosity Wet (g/sec-cm): A channel on the Hotwire LWC output file that is used in calculating the Prandtl and Reynolds number and ultimately the LWC. Viscosity measures a fluid's resistance when the fluid is being subjected to shear stress or extensional stress. Viscosity Wet (g/sec-cm), v_w, is a function of the sensor wire temperature, T_w. PADS calculates it as follows:

$$v_w \quad = \quad 0.0001718 \bullet \frac{393.16}{120 + T_w} \bullet \left[\frac{T_w}{273.16} \right]^{1.5}$$

T_w is the wire temperature (K) specified in PADS.

Prandtl Num Dry: A channel on the Hotwire LWC output file. The Prandtl number is the viscosity divided by the thermal conductivity. PADS calculates **Prandtl Num Dry,** Pr_d, as follows:

$$Pr_d \quad = \quad \frac{v_d}{k_d}$$

where

v_d = Viscosity Dry (g/sec-cm) = $f(T_{flm})$

k_d = Thermal Cond Dry (sec-cm-K) = $f(T_{flm})$

Prandtl Num Wet: A channel on the Hotwire LWC output file. The Prandtl number is the viscosity divided by the thermal conductivity. PADS calculates **Prandtl Num Wet,** Pr_w, as follows:

$$Pr_w = \frac{v_w}{k_w}$$

where

v_w = Viscosity Wet (g/sec-cm)

k_w = Thermal Cond Wet (sec-cm-K)

Air density (kg/m^3): A channel in the Hotwire LWC output file. PADS calculates air density, ρ_a, according to the formula below.

$$\rho_a = \frac{P}{T_a} \bullet 0.348388$$

where

P = Static pressure (mBar)

T_a = Ambient temperature (K)

The ambient temperature (K) is derived from the Applied Ambient Temp (C) channel. The source for this channel can be set on the **Configuration Editor** (for a permanent source change) or the **Tools** tab (for a change that affects the current session only).

This air density reading—i.e., the one stored in the PADS output channel—differs from the air density used in calculating the Hotwire LWC's Reynolds number. The latter air density, ρ_d, depends on film temperature and is calculated as follows:

$$\rho_d = \frac{P}{T_{flm}} \bullet 0.348388$$

where

P	=	Static pressure (mBar)
T_{flm}	=	Film temperature (K) = $(T_w + T_a)/2$

Reynolds Number: A channel on the Hotwire LWC output file. A Reynolds number measures the ratio of inertial forces to viscous forces and thus indicates the relative importance of these two forces under given flow conditions. The Reynolds number, Re, is generally expressed as

$$\mathrm{Re} = \frac{\rho \bullet V \bullet d}{v}$$

where

ρ	=	Air density (kg/m^3) for the film temperature
V	=	Velocity (m/sec)
v	=	Viscosity (g/sec-cm) = $f(T_{flm})$
d	=	Diameter (mm)

PADS calculates the Reynolds number for the LWC hotwire sensor as follows:

$$\mathrm{Re} = \frac{\rho_d \bullet PAS \bullet d \bullet 100}{v_d}$$

where

ρ_d	=	Air density (kg/m^3) for the film temperature
PAS	=	Probe air speed (m/sec)
v_d	=	Viscosity Dry (g/sec-cm)= $f(T_{flm})$
d	=	Diameter of sensor (cm)

Pwr Dry Calculated (W): A channel in the Hotwire LWC output file that tracks the power that the hotwire sensor dissipates due to calculated dry air term. **Pwr Dry Calculated** is the amount of cooling that is caused by air passing the sensor. In cloud-free air, this cooling is measured by the amount of power required to keep the sensor at a constant temperature. When in clouds, the dry air term cannot be directly measured due to the presence of water, but it can be calculated using an empirical equation that has been derived from wind tunnel studies (see Zukauskas and Ziugzda, 1985). Specifically, the heat loss P_d, the dry air term, is expressed by the equation

$$P_d = A_0 \bullet \pi \bullet k \bullet (T_s - T_a) \bullet Re^x \bullet Pr^y$$

where

k = Thermal conductivity of the air (g/sec-cm-K)

T_s = Sensor wire temperature (K)

T_a = Ambient air temperature (K)

Re = Reynolds number

Pr = Prandtl number

A_0, x, y = constants for a heated cylinder at a high Reynolds number

Using this formula, PADS calculates **Pwr Dry Calculated (W)**, P_{dc}, as follows:

$$P_{dc} = \frac{0.26 \bullet \pi \bullet k_d \bullet (T_w' - T_a) \bullet \mathrm{Re}^{0.6} \bullet \mathrm{Pr}_d^{\,0.37} \bullet \left(\mathrm{Pr}_d / \mathrm{Pr}_w \right)^{0.25} \bullet l}{0.23885}$$

where

Re = Reynolds number

Pr_d = Prandtl number dry

Pr_w = Prandtl number wet

k_d = Thermal Cond Dry (cal/sec-cm-K), the thermal conductivity of the air

T_w = Wire temperature (K) specified in PADS

T_a = Ambient air temperature (K)

l = sensor wire length (cm)

Power Total (W): A channel in the Hotwire LWC output file. Power Total is the total power required to keep the hotwire sensor coil at the target temperature set in the hardware (usually 125 °C). Power Total is the power the sensing wire dissipates through both wet term and dry air term heat losses. In theory, radiative heat losses also contribute to Power Total, but these are so negligible that PADS considers them to be zero.

Pwr Dry Observed (W): A channel on the Hotwire LWC output file. This channel should store the power necessary to offset the heat loss currently being caused by the dry air term. PADS uses this channel in calculating liquid water content. It subtracts this power from total power required to heat the LWC sensor, which gives an estimate of power required to offset heat loss due to LWC. In contrast to the **Pwr Dry Calculated (W)** channel, which calculates dry air term from other variables, PADS derives the **Pwr Dry Observed (W)** directly from the measured power in Watts by averaging readings when the **Get Pwr Dry Observed** button is pressed. This button should pressed when no clouds are present and when altitude, airspeed and temperature are similar to LWC-measurement conditions. Under these circumstances, **Get Pwr Dry Observed** will yield accurate readings.

Boiling Point Water (K): The boiling point of water, T_b, which PADS calculates as follows:[4]

$$T_b = \log(P) \bullet 57.579 + 199.53$$

[4] This formula is a curve fit to data presented in *The CRC Handbook of Chemistry and Physics, 62nd Edition*, Ed. Robert C. Weast, CRC Press, Inc.: 1981, D-196.

where

P	=	Static pressure (mBar)

Latent Heat of Vaporization: A variable used in Hotwire LWC calculations for LWC. PADS calculates the latent heat of vaporization, L_v, as a function of the boiling temperature of water, T_b, as follows:[5]

$$L_v\ (\text{cal/g}) = 597.3 \bullet \left[\frac{273.16}{T_b}\right]^{T_b \bullet 0.000367 + 0.167}$$

LWC_calc (g/m³): The liquid water content that is estimated using a calculated estimate of dry air term. PADS calculates LWC_calc (g/m³) as follows:

$$\text{LWC\_calc} = \frac{P_{wc} \bullet 238850}{l \bullet d \bullet PAS \bullet 100 \bullet (L_v + T_b - T_a)}$$

where

P_{wc}	=	Power Wet Calculated (W), or power required to offset heat loss due exclusively to LWC. This is calculated by subtracting **Pwr Dry Calculated (W)** from **Power Total (W).**
l	=	Length of sensor (cm)
d	=	Diameter of sensor (cm)
PAS	=	Probe air speed (m/sec)
L_v	=	Latent heat of vaporization
T_b	=	Boiling temperature of water (K)
T_a	=	Ambient air temperature (K)

[5] Equation 4-85a in Pruppacher, Hans and James Klett, *Microphysics of Clouds and Precipitation*. Holland: D. Reidel Publishing Company, 1978.

LWC_obs (g/m^3): The liquid water content that is calculated using an observed reading of dry air term. PADS calculates LWC_obs (g/m^3) as follows:

$$\text{LWC\_obs} = \frac{P_{wo} \bullet 238850}{l \bullet d \bullet PAS \bullet 100 \bullet (L_v + T_b - T_a)}$$

where

P_{wo}	=	Power Wet Observed (W), or power required to offset heat loss due exclusively to LWC. This is calculated by subtracting **Pwr Dry Observed (W)** from **Power Total (W)**.
l	=	Length of sensor (cm)
d	=	Diameter of sensor (cm)
PAS	=	Probe air speed (m/sec)
L_v	=	Latent heat of vaporization
T_b	=	Boiling temperature of water (K)
T_a	=	Ambient air temperature (K)

This calculation is identical to that for **LWC_calc (g/m^3)** except Pwr Dry is taken from the averaged, observed power measured when out of cloud and when the button is depressed to average these values.

Appendix D: Revisions to Manual

This document replaces DOC-0174, the PADS Hotwire LWC Operator Manual for PADS version 2.X. All sections have been updated.