Open Source Hardware Engineering

Instruction Manual
-
Building a High Performance Fan-Aspirated Radiation Shield

Version 5.0

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Copyright Information

Figure 1. The version 5 coaxial shield

Introduction

The author owns one of the original WMR100 weather stations. This unit has the outdoor temperature/humidity sensor integrated with the anemometer. The first problem with this setup is that the anemometer is supposed to be 30 feet above ground level while the temperature sensor should be 5 feet high. The other problem is that the temperature sensor is not fan aspirated, poorly shielded, and can exhibit significant temperature errors.

The new WMR100N offers a separate shielded temperature sensor (THGN810) – but tests conducted on that unit's radiation shield indicate it has equally poor or perhaps even worse performance. Radiation induced errors as large as 15 degrees Fahrenheit have been documented with that shield.

This document shows how to build a high performance custom, fan-aspirated radiation shield for a wireless remote sensor which. The unit is quite large and fairly expensive due to the use of some 6-inch diameter PVC pipe and fittings. The construction of a smaller, less expensive shield which performs nearly as well as this one is also detailed on the osengr.org web site.

Many weather station software programs such as Weather Station Data Logger can be configured to use any external wireless sensor for the “official” outdoor temperature reading when uploading data to the internet.

Changes in version 5 of this document

There is no conceptual change in the design but it has been made significantly smaller with no apparent decrease in performance. An additional change replaces the mounting cradle with a galvanized steel pipe flange, resulting in a more sturdy mounting system for the shield.

Notes are made in the text where appropriate below. Items no longer needed for the updated version are ~~stricken out, like this~~. New items are marked as version 5 additions.

Note that the original version of this design is available on the osengr web site, although that design is larger, heavier and more difficult to mount.

Features & Benefits

The key to both fan-aspirated designs is a coaxial configuration found on a web site in Greece (http://users.otenet.gr/~meteo/project_radiation-shield.html). While this design is significantly different, the original design provided the idea for the coaxial arrangement, and this is the key to its excellent performance. Another feature of this design is that the exhaust air (which has been warmed by solar heating) is directed ***away*** from the air intake port, thus eliminating another source of error that plagues some designs.

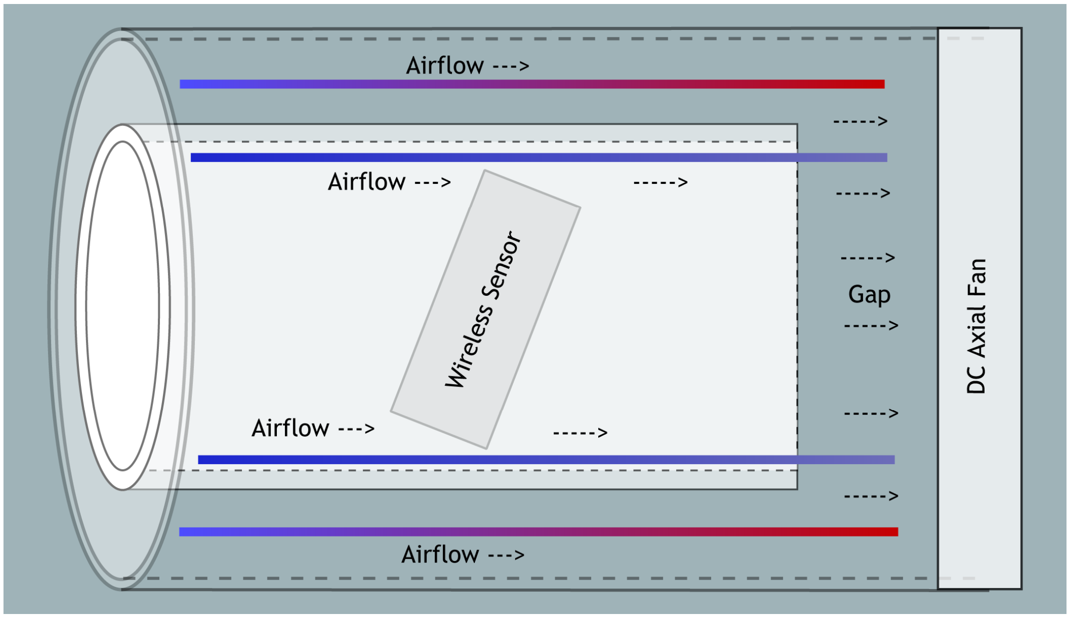


Figure 2. Coaxial Shield Concept

As shown in figure 1 above, this design uses two coaxial-mounted pipes: one smaller pipe is mounted inside a second larger pipe. The smaller pipe is shorter than the large pipe, so there is a gap at one end as shown. A DC powered axial fan mounted at the end of the large pipe sucks air through both pipes at the same time. The temperature sensor is mounted in the small pipe, in the airstream created by the fan.

To have an effect on the measured temperature, solar radiation absorbed by the outer pipe must be first be conducted through the wall of that pipe. The warmed inner wall must then transfer heat by convection across the air gap; this process is hindered by air flow between the two pipes created by the fan. Heat must then conduct through the wall of the inner pipe before finally being able to warm the sensed air temperature (by convection).

The inner pipe in the large design, and both pipes in the small design are designed for irrigation drainage and manufactured by Hancor company. They have a “triple wall” construction (shown in figure 2) which provides additional insulation, reducing the amount of heat that can be conducted through the pipe wall(s). As a result, this shield should perform significantly better than a shield constructed of metal tubes which would conduct much more heat through their walls.

The surface of the outer pipe will be heated by the sun, and will in turn heat some of the nearby air. Another source of error is caused by aspiration of this heated air (around the outside of the outer pipe) into the air intake. This can occur in calm wind conditions or if the intake is pointed downwind with a very light breeze. This design helps minimize this source of error since warmed air near the surface of the outer pipe will tend to get sucked into the gap between pipes instead of into the inner pipe (where the sensor is mounted).

According to the NWS, air should be sampled from an elevation of 5 feet above ground level. Many of the aspirated designs are vertically oriented, with the airflow going upwards. Depending on the speed of airflow, this can result in an *effective* sampling height quite a bit below the intake location – so how high should the intake be located? Sampling air at the wrong height will also cause errors. The larger design reduces this problem since air is aspirated at a 45-degree angle instead of vertically (see figure 2).

Parts List

This design uses a 4-inch pipe for the inner pipe with a 6-inch diameter pipe for the outer shield. Depending on the kind of pipe chosen, the 6-inch pipe can be a bit pricey. Thin-walled galvanized metal vent piping (ducting) might also work for the outer pipe, but that could also hurt performance since it conducts heat much better than PVC.

Parts List:

- 12-volt NMB 4710KL-04W-B10 fan (available from DigiKey)
- 12-volt 6-watt power supply wall wart (made by CUI inc, from DigiKey) -- or any convenient wall-wart supply that produces a 12V DC output at 0.12 amperes or more.
- 4-inch Hancor Triple-wall drain pipe
- 6-inch pipe, PVC or ABS plus two 45-degree elbows
- ¼-20 aluminum, brass or stainless steel screws, various lengths ~~plus two nuts~~.
- ~~1, 1-1/4 or 1-1/2 inch PVC pipe tee~~
- 1/2, 3/4 or 1-inch galvanized steel pipe flange (version 5 addition)
- Mosquito netting
- Tie-wraps (a.k.a. cable ties)
- White plastic primer paint
- Low voltage wiring long enough to reach from sensor location to power supply

Also required are an assortment of tools. Drills, hacksaw, grinder, ¼-20 tap, soldering iron, etc.

Construction Details.

Figure 3. Original assembled Temperature Sensor

The vertical mounting pipe (1-inch PVC) has a smaller metal pipe inside it for stiffening. Version 5 replaces the mounting system with a galvanized steel pipe flange, and the shield is mounted directly onto a galvanized steel pipe. A length of PVC pipe may be slipped over the steel pipe if desired to provide shielding from the sun heating the steel pipe (not sure how much difference that will make).

Figure 4. The smaller version 5 shield

Pipe Lengths

In version 5, the center section is short enough that the two elbows can be pushed completely together, between 4 and 5 inches perhaps. Experiment with the two elbows, sliding a section of pipe in to see how deep it will go without a lot of force as a gauge for cutting this section.

The inlet section is a total length of 9 inches and the inner pipe section is 6 inches long. The photos below show pipes cut for the original design so they are longer than required for the version 5 design.

The exhaust section and mounting cradle are not used in the version 5 design.

~~The center section only needs to be long enough to slide the elbows over and attach to the mounting cradle (about 7 inches is exposed here, plus the length that has been slipped inside the elbow fittings).~~

~~The inlet section is about 18 inches long. The exhaust section is only long enough to keep rain out of the center section even in high winds, about 12 inches in the photo.~~

~~The inner pipe section in this example is 12 inches long. These lengths are longer than really necessary; the inner pipe could be as short as 6-8 inches with the outer pipe (intake section) being maybe 10-14 inches long -- only 4-8 inches longer than the inner pipe~~.

Figure 5. 6-Inch PVC Parts

Below is a photograph of the Hancor double wall pipe's cross section – showing the insulating properties of this pipe.

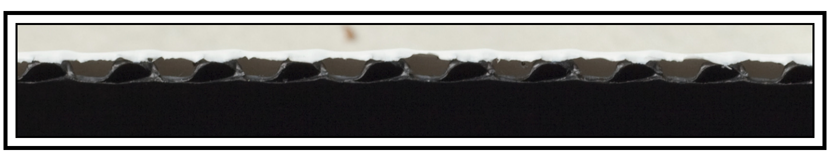


Figure 6. Hancor Triple-Wall Pipe

Sensor Mounting

In the photograph, the sensor is essentially “pinned” between two screws and cannot move inside the pipe. The sensor needs to be back far enough from the inlet end of the pipe that it will not get wet from rain.

The inner pipe does not need to continue very far past the sensor mounting point. In this example, the inner pipe is 12 inches long and the first mounting screw is about 1-2 inches from the inlet end of the pipe. The pipe extends several inches past the upstream end of the sensor which is probably more than necessary. The new version 5 design uses a 6-inch length of inner pipe which works just as well.

Figure 7. Sensor Mounting

Improved Sensor Mounting

By using drilling some small holes (1/16 or smaller) in the inner pipe and threading monofilament fishing line through the holes, a "cage" can be formed of fishing line which holds the sensor in place. The next two photos show this idea. These are from a different shield design but the same idea works here.

Figure 8. Making a sensor cage with monofilament fishing line

Below is shown the routing detail for the fishing line through the ten drilled holes.

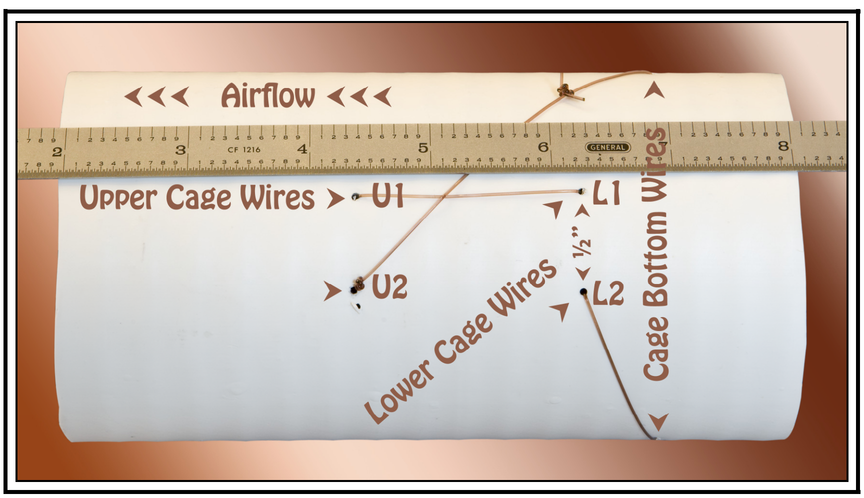


Figure 9. Monofilament routing detail

The next photo shows a sensor mounted in the cage (view from the bottom). This is a different shield design but the cage concept is the same. The line across the bottom, at right angles to the other wires keeps the sensor from falling out of the cage.

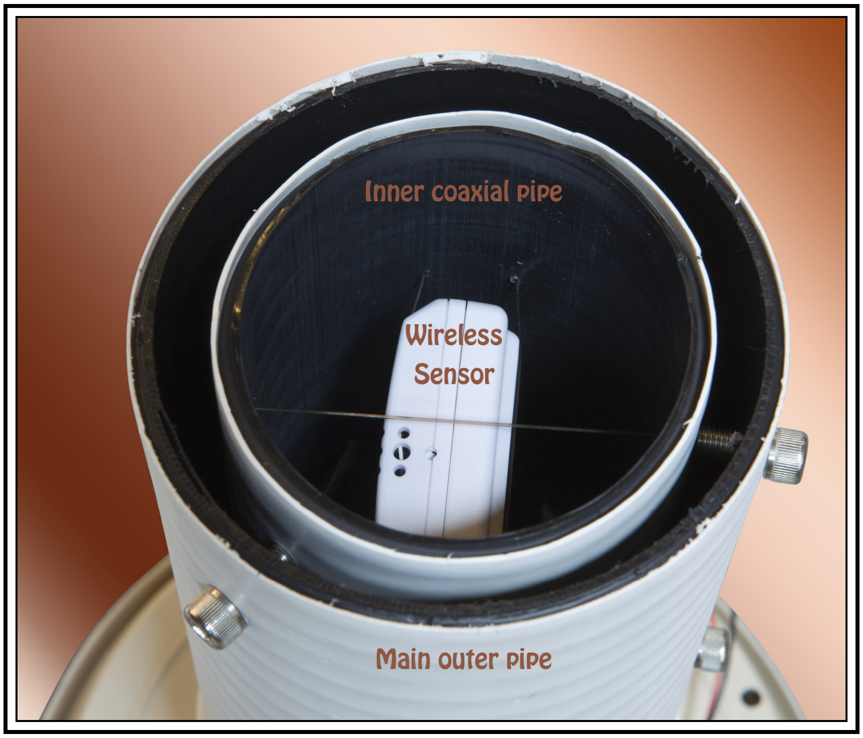


Figure 10. Sensor installed in the monofilament cage

Fan mounting

Be sure to mount the fan so that it sucks air up into the pipe – you don't want to blow air out of the pipe. The mounting ears on the intake side of the fan (not visible in the photo) had to be trimmed back slightly in order to fit inside the pipe. I did this with a grinding wheel. Do not trim the ears on the exhaust end. Cut some pieces of plastic (fiberglass is used in the photo) and use RTV to secure them. These seal the gaps between fan and pipe so air cannot "cheat" and go around the fan. This may not be all that important; no tests have been done to see how much difference it makes.

This fan is fairly "wimpy" and better performance might be achieved with a faster version of the fan (readily available). However, tests seem to indicate the current fan is more than adequate and it doesn't make much noise.

Fan Lifetime

Experience indicates that the fan specified here will have a lifetime of perhaps 2-3 years. It is not designed for the humidity levels it sees during periods of rain and dirt and dust that will be sucked into the shield. The fan will eventually die from exposure these elements. If you can find another fan rated for condensing a condensing environment it will last longer than the one shown here.

Figure 11. Fan Mounting

Mounting the Inner Pipe

Mounting studs are shown in figure 7. Use a ¼-20 tap to thread the holes in all locations; it may also work to simply force-thread the screws into the plastic but a tap is preferable, especially on the PVC pipe. Other screw sizes and materials can be used if desired. Aluminum, brass, stainless steel or nylon is preferred for corrosion resistance. Stainless steel and nylon are a poor conductors of heat so that is another point in their favor.

Figure 12. Mounting Screws for Inner Pipe

Inner Pipe Location

Figure 8 shows the inner pipe secured in place by the mounting studs. The end of the inner pipe is flush with the end of the outer pipe. The inner pipe should be 4-6 inches shorter than the outer pipe. This encourages the fan to suck equally through both pipes.

This view (figure 8) shows how the design minimizes the effects of solar radiation. Here you can see how air is sucked through both the inner pipe, ***and*** the gap between the two pipes: this is the key to the unit's performance.

Solar heating will cause a significant increase in air temperature between the two pipes. However, with aspiration the temperature rise will be minimal (perhaps a few degrees Farenheit). The small temperature rise present on the ***outside*** of the inner pipe will then have much less effect on the air being sucked through the ***inside*** of the inner pipe. This temperature rise is further lessened by the insulating properties of the double-wall inner pipe.

If building the smaller version of this shield, the assembled pipe in figure 8 would be mounted vertically with the top covered with a larger flower pot base which is suspended perhaps a half-inch above the top end of the pipe.

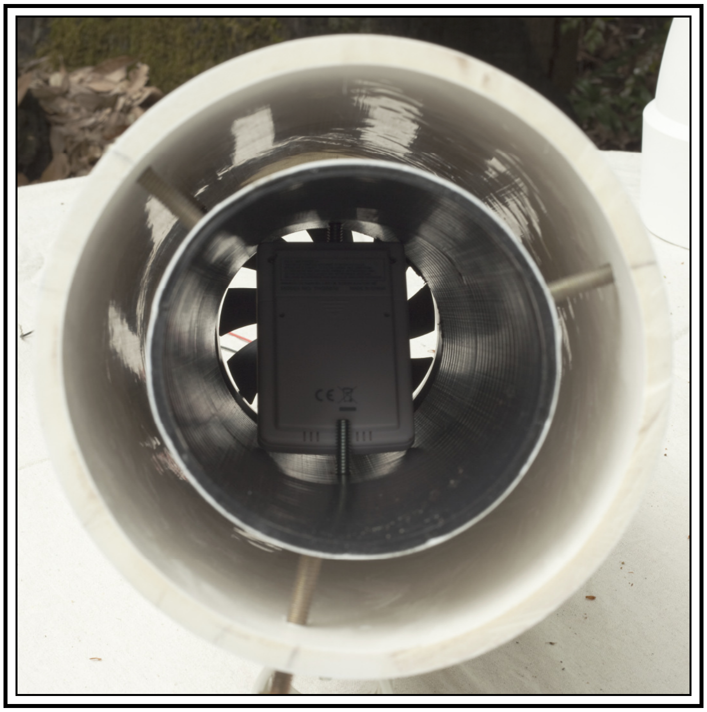


Figure 13. Coaxial Setup

Bug screen or mosquito netting is used to cover intake and exhaust ends. This keeps bugs and spiders out of the unit. In the version 5 shield there is no exhaust section, and the screen is installed directly onto the elbow opening on the exhaust end of the shield.

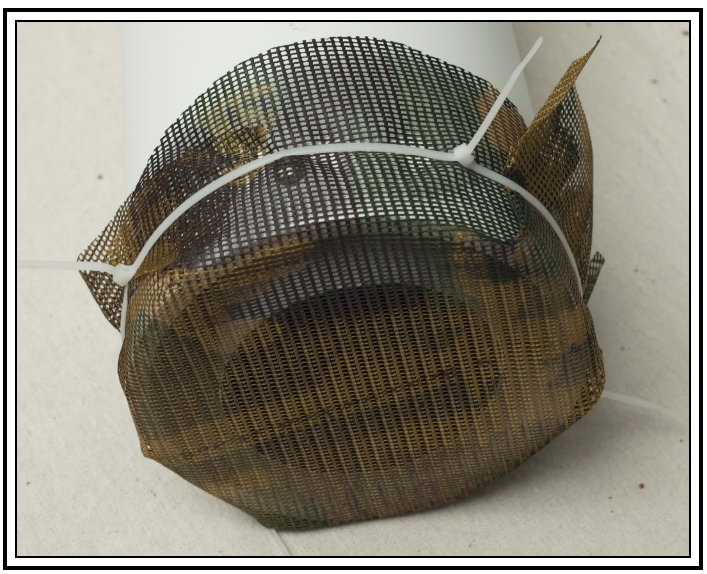


Figure 14. Bug Screen

Fan Wiring

The fan wires can be routed through a small hole drilled in the elbow. Be sure to drill the hole on the underside so that gravity will keep water from entering. Optionally, the wires can be routed down the pipe and through the bug screen.

Figure 15. Fan Wiring Detail

Mounting Flange

The version 5 shield uses a galvanized steel pipe flange for mounting and is shown in the detail photo below. The flange is held against the underside of both elbows with two 1/4-20 stainless steel screws. These screws should be long enough to penetrate both the elbow and the pipe inside the elbow. This not only provides a rigid mount for the shield, it also holds the elbows together. The flange may be used as a template to mark hole locations; then drill two 7/32 diameter holes through the assembled elbows (all the way through the inner pipe). Then tap the holes for a 1/4-20 thread.

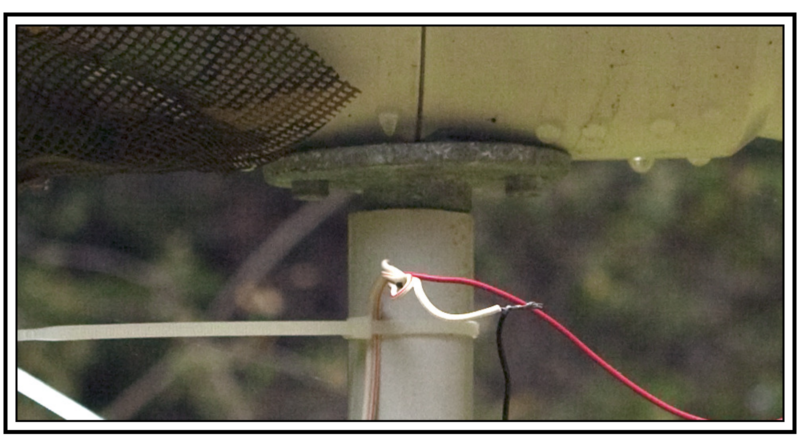


Figure 16. Pipe flange mounting detail

~~Mounting Cradle~~

~~Cut a section of the 6-inch pipe and attach a smaller pipe tee with two bolts and nuts. Use tie-wraps to hold the center section in the cradle. The open end of the smaller pipe tee can then be slipped over a vertical mounting pipe. Other mounting techniques are possible -- use your imagination.~~

~~Figure 17. Mounting Cradle~~

Wrap-Up

Paint the outside of the 6-inch outer pipe with white plastic primer paint. This will help to keep the pipe healthy in the presence of UV from the sun. Depending on the color of the bare pipe, it may also increase the reflectivity which will minimize solar heating. White spray paint looks black in the infra-red portion of the spectrum, which may be more important on a clear night (cooling from the cold sky) but that's what was used in this example.

The outer pipe warmed by the sun (or cooled by the night sky) will be surrounded by heated (or chilled) air. In calm-wind conditions this air will tend to rise, away from the pipe inlet. In light winds, the heated air will have less effect if the unit is oriented with the air intake upwind. One enhancement would be to mount the unit on a pivot and add a wind vane -- using the wind to help orient the air intake upwind. It is not clear how much difference this would make.

When the sensor battery needs changing, the bug netting can be carefully slipped of if the tie-wraps are not overly tight. Then loosen some of the exterior mounting studs and remove the inner pipe. Only one of the screws in the inner pipe needs to be removed to extract the sensor.

Flow Rate Calculations

The 4710KL-B10 fan data sheet shows a flow rate of 53 CFM for a static pressure of 0.02" of water, and about half that for 0.04" static pressure. The ID of the 6" schedule 40 PVC pipe is 6.031". The inner Hancor pipe has OD/wall thickness of 4.200/0.165"

The area inside the main pipe is 28.6 sq-in. The area occupied by the Hancor pipe is 2.1 sq-in. The area occupied by the sensor is (THGR810N) about 2.2 sq-in. Total area available for airflow is then 28.6-2.1-2.2 or 24.3 sq-in or 0.169 sq-ft.

An airflow of 53 cu-ft/min passing through an area of 0.169 sq-ft requires a velocity of roughly 314 ft/min or 5.2 ft/sec. At half the airflow that would be 2.6 ft/sec.

Radiation Shield Performance Tests

Hardware Information

This comparison was performed between the following radiation shields:

- Home-built fan aspirated shield (FARS)
- Davis #07714 naturally aspirated shield
- Ambient Weather LX100 naturally aspirated shield
- AcuRite VN1TX (aka 5n1) shield

The VN1TX unit is fan aspirated when there is enough solar energy on the solar cell to run the fan; at other times it is passive. This is the version that only has a single solar cell. It uses a Sensirion SHT21 temperature sensor which has a typical accuracy of +-0.3C (+-0.54F).

All other shields are fitted with custom-built sensors whose (NIST traceable) accuracy is +-0.08C (+-0.15F).

The test location is at approximately 38 degrees north latitude. Sensors are shaded by trees in the early morning so sun appears rather suddenly on them around 10:30Am local time.

Test Setup

As shown in the photograph, the passive shields and AcuRite sensor were mounted in one cluster while the FARS unit was separately mounted nine feet away from the passive cluster. The VN1TX was oriented approximately north as per AcuRite installation instructions. The FARS air inlet and passive shield temperature sensors were all 64-inches above ground level, and the bottom of the VNT1X (where the temperature sensor is located) was 78 inches above ground level.

All sensors are wireless, with the exception of a DC fan power connection to the FARS. Data was recorded to a CSV log file using the WeatherStationDataLogger (WSDL) windows application.

Discussion

While in many cases it is desirable to locate a weather station's anemometer separate from temperature measurement, in this case having the anemometer integrated with the temperature sensor in the VN1TX is fortuitous. This allows for an examination of the effect of wind on solar shielding effectiveness.

The first six days of the test run were dominated by clear skies, day and night. There was a significant negative offset on VN1TX temperatures at night and I knew from past experience that some of this might be due to radiational cooling to the clear night sky. On the last night of the test run, a thick layer of low stratus moved in, eliminating the effect of cooling to a clear night sky. This provided a 3.6 hour period over which a calibration comparison between sensors was made.

Each of the sensors in this experiment has a different time lag in its response to temperature changes. This results in a difference between readings whenever the air temperature is changing (which is pretty much all the time). It is just a matter of how much and how fast the air temperature is changing. However, these differences will average out to zero if one is careful to avoid certain situations such as a time segment where the temperature is only increasing.

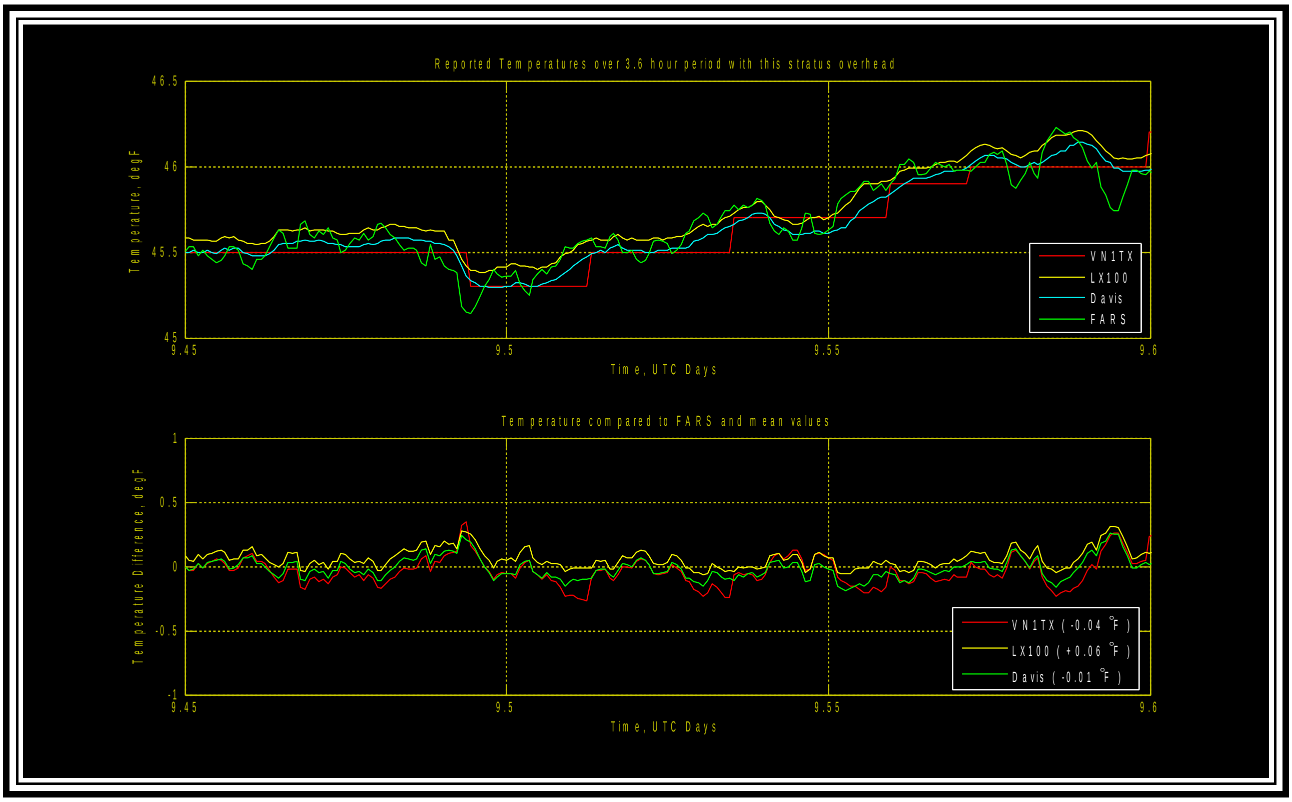
Several graphs of results are presented below. The time axis on each graph is in days, UTC relative to 00 UTC on the first day of the test run. The test location is in the Pacific time zone and daylight savings time was in effect, so midnight UTC occurs at 5PM local time. Temperatures are in degrees Farenheit and wind speed is in knots (MPH = knots * 1.15).

In analyzing overall effects (including that of wind), subsets of data are extracted and averaged for separate day and night periods. The morning and evening intervals where the lack of fan rotation in the VN1TX creates large errors is intentionally excluded from these averages. Obviously, including those times would result in a significant increase in average differences between the VN1TX and FARS readings.

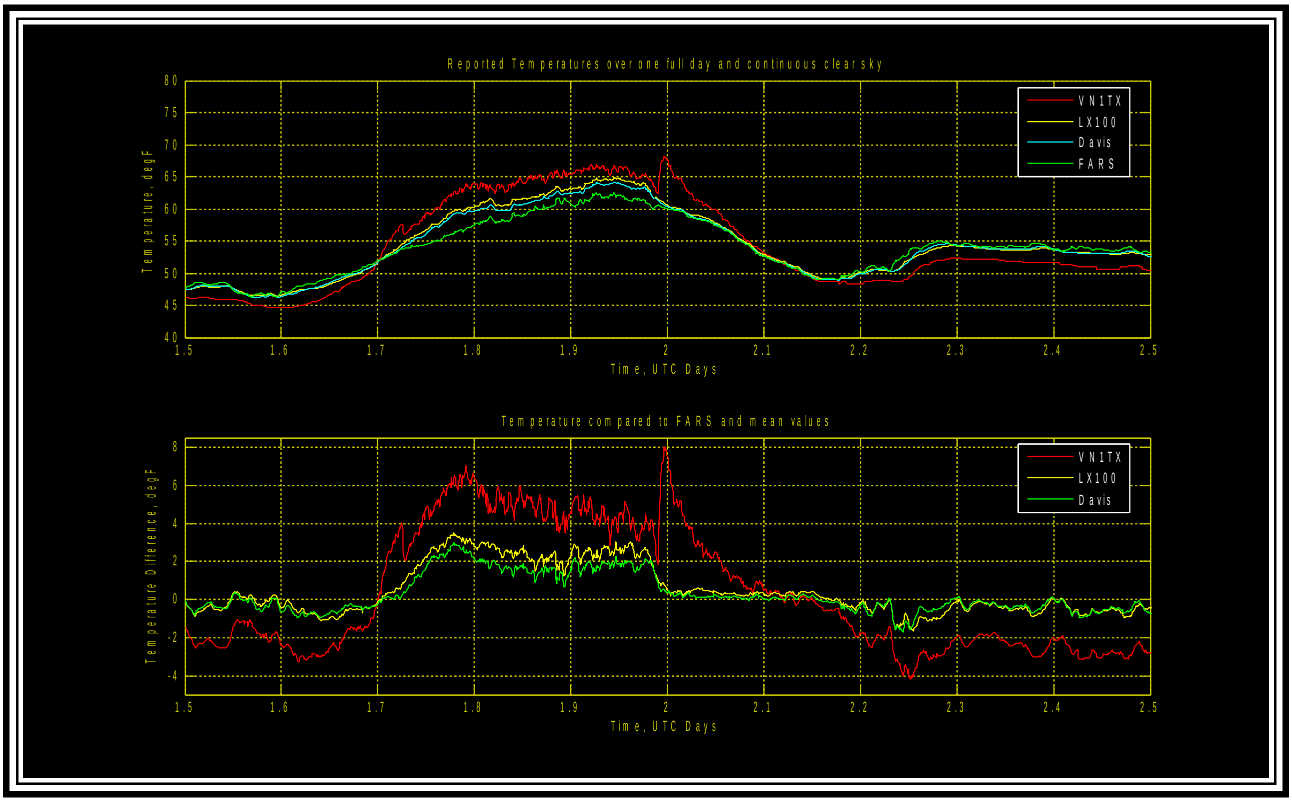
Data extracted for the night period runs from 11PM through 6AM and the day period is from 11AM to 4PM local daylight savings time.

Results

The first data graph image contains two sub-plots. This is the 3.6 hour calibration interval with a thick stratus layer overhead. The top graph shows the temperatures reported by the four sensors. The lower graph shows temperatures reported by the VN1TX, LX100 and Davis units relative to the FARS temperature. The mean differences are also shown in the graph legend. As luck would have it, this particular VN1TX unit has a Sensirion SHT21 sensor with a very small temperature difference compared to FARS. With this difference being so small, no adjustments were made to the VN1TX temperatures for calibration purposes. The remaining graphs below are all showing raw temperatures from each sensor. It is also worth pointing out that a fair portion of the up-and-down variation seen in the lower graph is probably due to differing time lags in each sensors' response to changes.



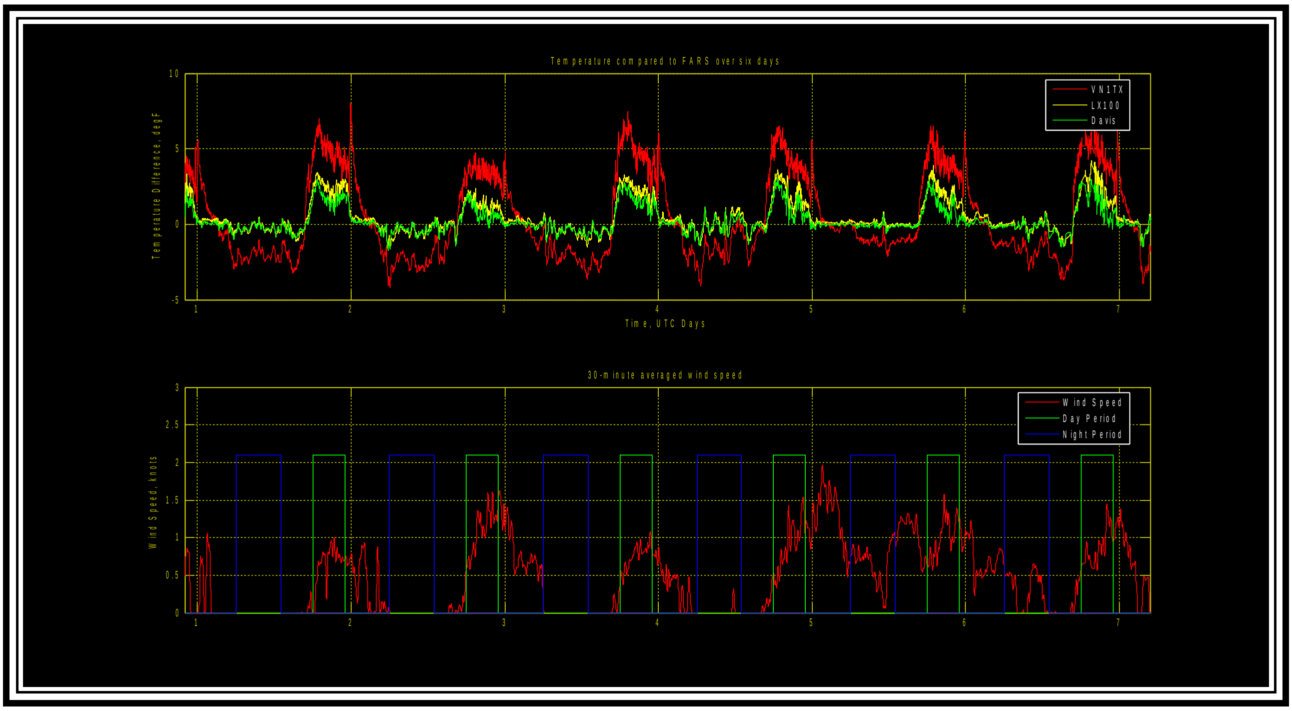
The next graph shows the test run over one full day with clear skies.



Most obvious in the VN1TX data are the "bat ears" at x-axis locations of about 1.73 and 2.0 where the aspirating fan turns off and on. Because morning sun is shaded by trees until about 10:30AM local time, the morning bat-ears are less pronounced -- when the sun finally hits the VN1TX sensor, it is already strong enough to start the fan running. Remember that this is the smaller 5n1 AcuRite sensor with a single solar cell -- the daytime performance of dual-solar cell unit is going to be different (hopefully better). Once the fan is running, solar heating bias is between 4 and 6 degrees F on average on this day. At night, there is somewhere between 2 or 2.5F of cooling bias due to the clear night sky.

The Davis and LX100 passive shields are very close in performance here, running between perhaps 1.7F and 3F of solar heating during the day. At night, these shields are exhibiting a minimal amount of cooling (less than 0.5F) to the clear night sky.

The next graph shows six consecutive days of the test run. Temperatures compared to the FARS and 30-minute averaged wind speed are the two sub-plots here. From this data, numerical averages of day and night temperature differences have been computed and are tabulated below. The day and night time intervals for which data is extracted for numerical averages are shown with green and blue boxes respectively on the graph.



Wind clearly (and not unexpectedly) has a significant effect here. For example compare the daytime performance of day 1 to day 2. Average wind is nearly double (1.10 on day 2 versus 0.65 on day 1) and the temperature difference between FARS and all othere sensors is much less on day 2 compared to day 1. The effect is especially noticeable with the VN1TX where the difference drops from 5F to 3.5F with the higher average wind.

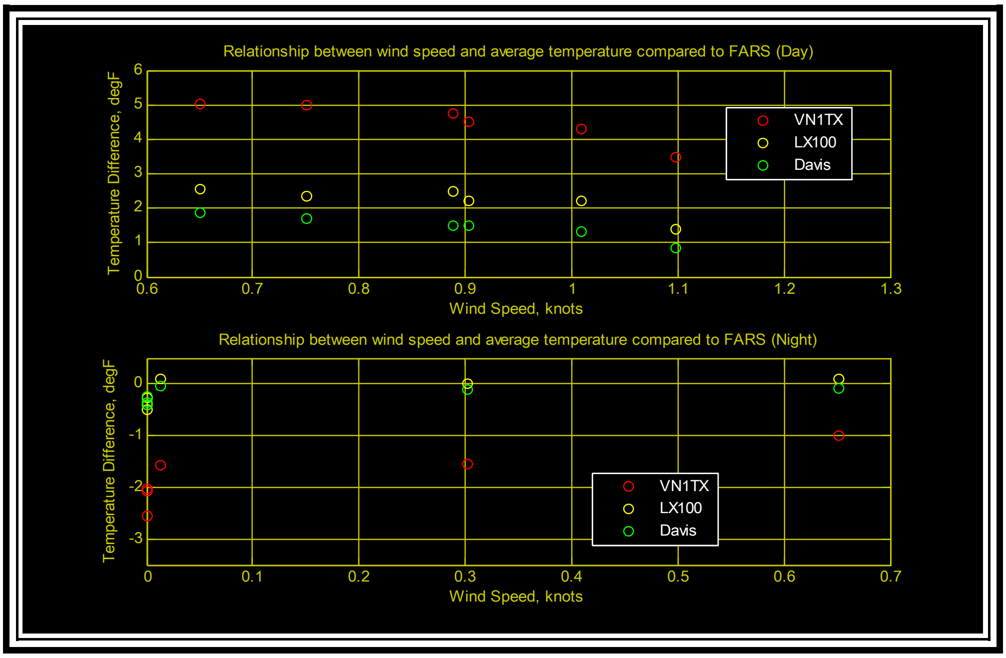
At night, wind is also well correlated with temperature differences in all sensors and is especially obvious with the VN1TX sensor. Differences are typically around 2 to 2.5F on calm nights and drop to 1F with only 0.65 knots of average wind.

Below are the tabulated average data extracted for day and night periods on each of the six days. The first table shows daytime averages, and the second is night.

To aid in visualizing the relationship between wind speed and the amount of temperature difference due to solar heating and radiational cooling, two scatter plots are also shown below in which the trends are clearly visible.

Daytime average differences (degF)				
Day	Wind (knots)	VN1TX	LX100	Davis
1	0.65	+5.02	+2.55	+1.85
2	1.10	+3.48	+1.38	+0.84
3	0.75	+4.98	+2.34	+1.71
4	0.90	+4.51	+2.22	+1.50
5	1.01	+4.30	+2.20	+1.31
6	0.89	+4.74	+2.49	+1.48

Nighttime average differences (degF)				
Day	Wind (knots)	VN1TX	LX100	Davis
1	0.00	-2.08	-0.28	-0.24
2	0.00	-2.55	-0.49	-0.40
3	0.00	-2.03	-0.40	-0.37
4	0.01	-1.57	+0.09	-0.04
5	0.65	-1.01	+0.08	-0.08
6	0.30	-1.55	-0.01	-0.10



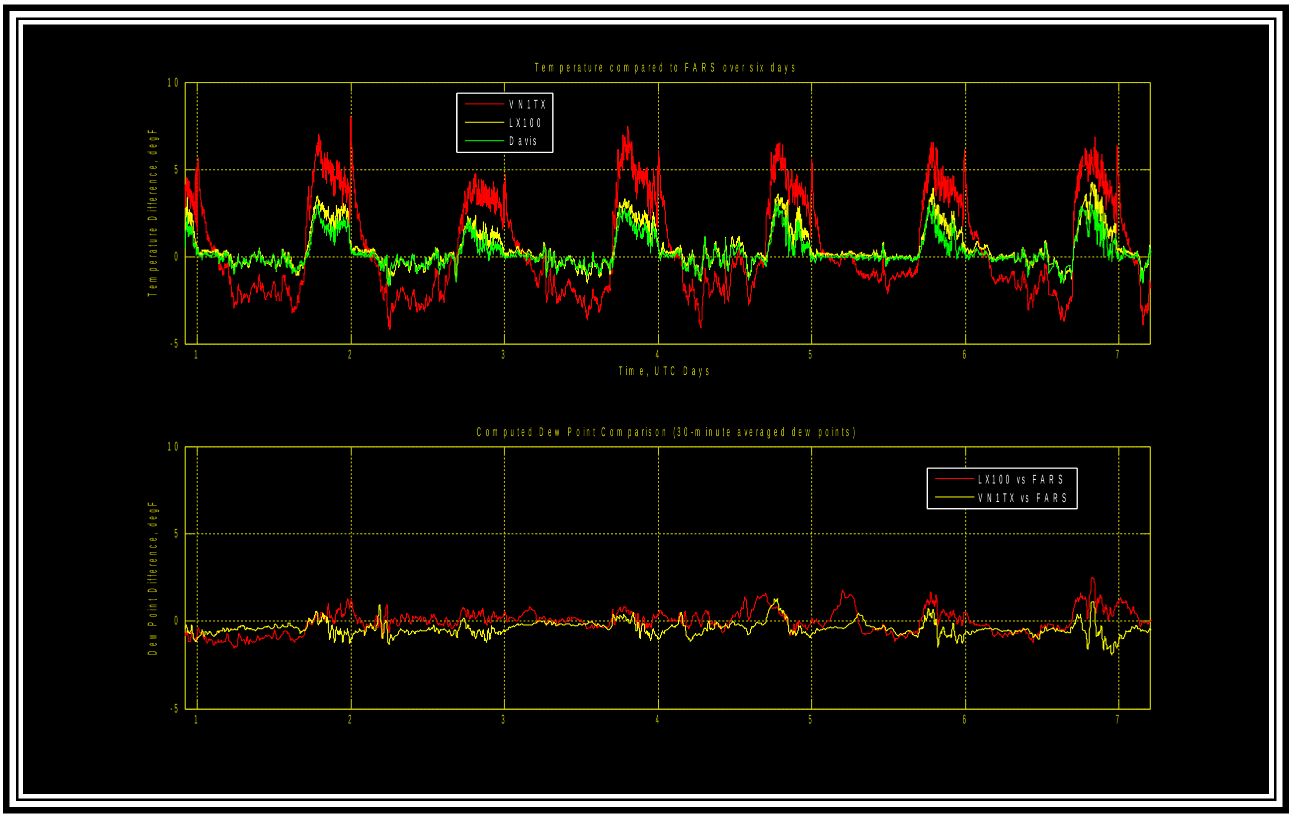
Dew Point Comparison

This report is about measuring temperature. However, the sensors used also measured relative humidity, and it is of perhaps passing interest to examine their performance in the presence of solar heating and radiational cooling.

Only three of the shield setups had humidity measurement capability; the FARS and LX100 shields used Sensirion SHT15 sensors and the VN1TX uses an SHT21 sensor (same manufacturer).

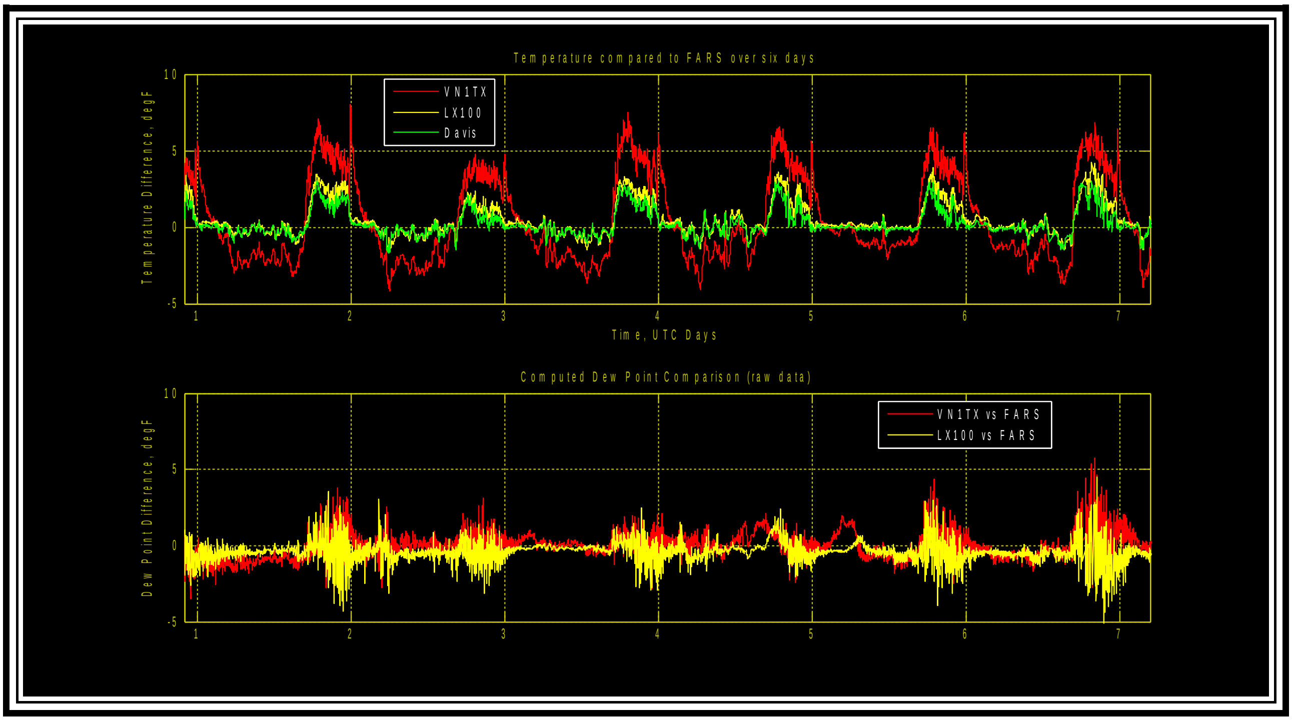
Since all humidity sensors are exposed to air with the same dew point it is interesting to compare computed dew points. The sensors only report relative humidity so it is necessary to compute dew point from the temperature and humidity reported by each sensor.

A properly functioning humidity sensor would be expected to measure the same dew poitn value, even if it is warmed by solar radiation compared to another sensor in the same parcel of air.



Computed RH data turns out to be very noisy and direct comparison of dew points is easier to comprehend if the dew point data is low-pass filtered. A 30-minute averaging filter was used to reduce the noise on this data before comparison. Such a filter introduces a 15-minute delay in the result, and that has been compensated by shifting the data by the amount of delay; thus it aligns properly with the temperature graph above it.The result graphed above shows that the dew points are indeed relatively insensitive to variations in temperature between sensors.

For the sake of completeness, below is the same graph, but with un-filtered dew point data.



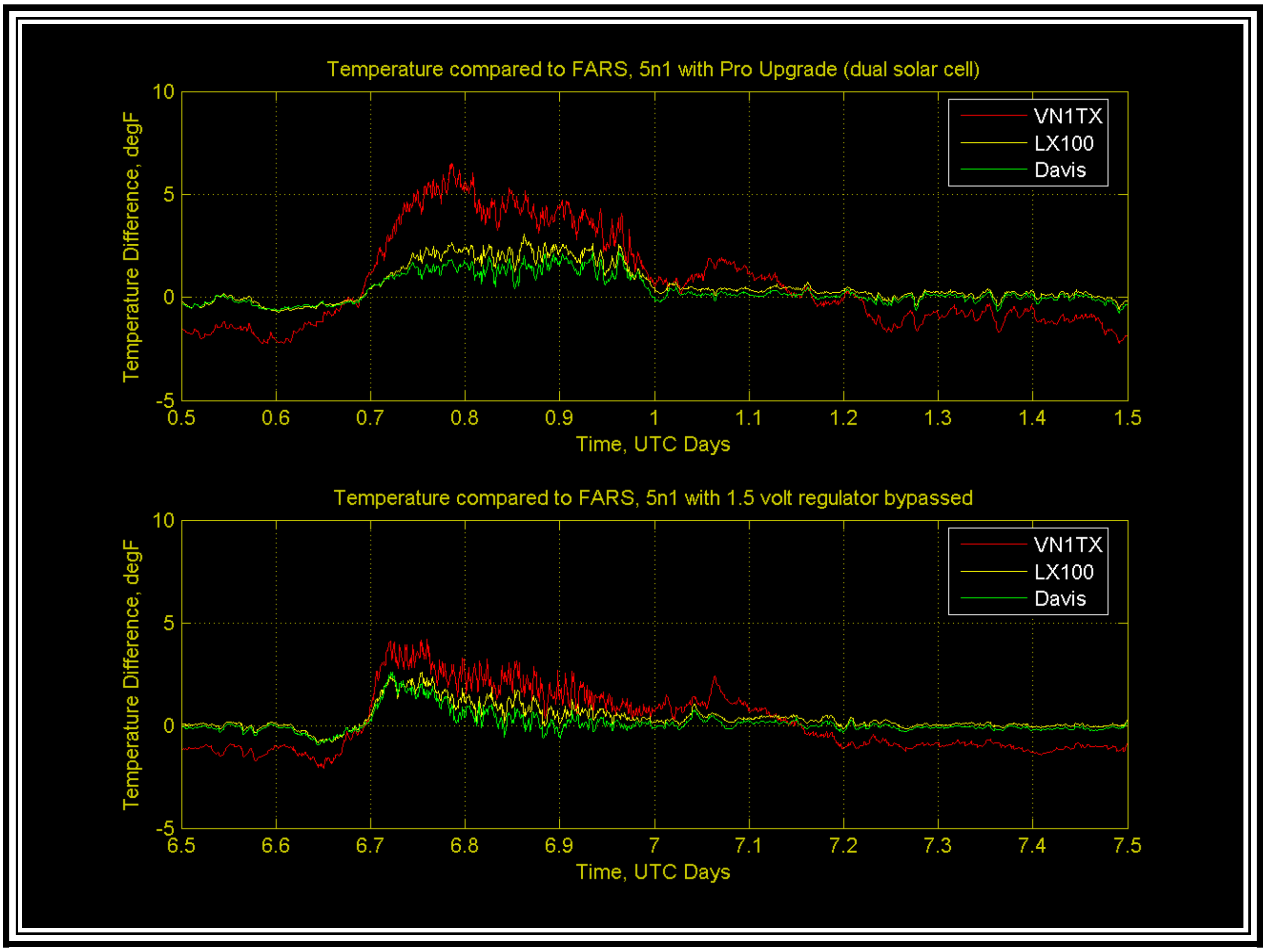
VN1TX Update

The VN1TX is now supplied with two solar cells mounted at angles to each other instead of a single cell. This modification was presumably introduced to deal with the "bat ears" which which occur at sunrise and sunset. There is now one cell pointed in the direction of sunrise and another towards sunset so they will be more efficient at collecting early morning and late evening solar energy.

Both solar cells are connected in parallel and their output voltage is limited to a maximum of 1.5 volts by an electronic voltage regulator. This limits the maximum speed of the fan and was presumably done due to voltage limits on the fan.

An upgraded solar cell cover was obtained and installed to find out how much impact this would have on the radiation shield's performance. An additional test run was performed with the voltage regulator bypassed -- this allowed much more voltage to be applied to the fan resulting in increased fan speed and airflow. This modification obviously voids the AcuRite warranty and others who do this do so at their own risk.

Below is a graph showing the results of the two modifications -- solar cell upgrade and fan voltage increase.



The solar cell upgrade largely removed the bat-ear problem at sunrise and sunset, but errors due to solar heating are about the same. Bypassing the voltage regulator significantly reduces errors from solar heating, but the performance is still worse than the LX100 and Davis non-aspirated shields.