Global Open Atmospheric Temperature System (GOATS)

Station design for the Global Climate Reference Network (GLCRN)

V2.1 By Anthony Watts, September 20, 2023

Key Takeaways:

- One of the most common problems in temperature reporting is a warm-bias due to poor placement of temperature measurement stations; this project aims to help correct the temperature record by providing parallel and pristine data.
- The system design ensures that reliable daily temperatures are measured and reported – as accurately as the best climate reporting system in existence.
- The data reporting by cellular connection provides instantaneous data logging and accurately captures high and low temperatures for comparison purposes to counter mistaken temperature claims in media reports, based on the National Oceanic and Atmospheric Administration flawed recording network.
- Site selection process ensures temperature data free of localized UHI and other heat sink biases.
- The system does not require human intervention or human recording of data, making it superior to existing systems in use worldwide for reporting temperature data.
- Cost effective and simple deployment – one person setup out of the box using simple hand tools.
- Small footprint – needs only a flat circular area about 16 feet in diameter to accommodate tripod and guy wires.
- Built-in lightning protection.
- Solar powered with battery backup – no local power or services of any kind are required.
- Provides the first independent temperature and climate record, and with 500 stations, it can effectively and representatively cover the globe for a global surface temperature value.

Overview:

As outlined in the 2022 publication Corrupted Climate Stations, one of the most common problems in temperature reporting is a warm-bias due to poor placement of temperature measurement stations by the National Oceanic and Atmospheric Administration (NOAA). Stations have been compromised over time, due to urbanization growing around them. The collection of stations is exclusively part of the U.S. Cooperative Observer Network (COOP) managed by NOAA subsidiary, the National Weather Service (NWS). These stations often report temperatures that are biased significantly higher than the surrounding environment due to their placement. At least 96% of them have been found to be compromised due to their placement.

At the same time, NOAA also operates the U.S. Climate Reference Network (USCRN). A network that uses state-of-the-art temperature measurement technology. These weather stations properly sited around the U.S. at pristine locations to be as accurate and as representative as possible. There are 114 stations in the U.S., but this network is now 20 years old in design, costs about $30,000+ per station, and none have been deployed globally.

The non-compromised USCRN data is never regularly reported to the public. NOAA produces monthly and yearly climate reports with press releases, covering the U.S. and also the world. These reports are based on the temperature biased COOP and GHCN networks. The more accurate USCRN data is never used to counter media reports of record high temperatures in the U.S., even though these USCRN stations almost never experience the same temperature extremes as the COOP networks. There is no "state of the art" weather station network to counter the GHCN network for the rest of the world.

Therefore, almost all surface temperature related data is biased towards warmer values.

Thanks to advances in technology, it is now possible to design and deploy a network of superior private stations that could collect temperature data near the potentially compromised COOP stations that report record high temperatures due to their placement near Urban Heat Islands (UHI) and other local effects. To be clear, by near this means close enough to a compromised site to be representative of temperatures from the same geographic area, but in a location that does not contain features which result in biased temperature readings.

Choosing a good location is paramount to the success of the project, and this project will follow NOAA National Weather Service siting guidelines as defined in *Requirements and Standards for NWS Climate Observations*. Essentially, we will adopt the "100-foot rule" as outlined in that document, to ensure that any station is at least 100 feet (30 meters) away from any artificial influence:

NWSI 10-1302 APRIL 20, 2018

3.1 Air Temperature Measurement

Install the temperature instrument according to the following standards:

1. Over level terrain (earth or sod) typical of the area around the station, and, at least 100 feet from any extensive concrete or paved surface.

The results of the station measurements could then be regularly reported to media to counter temperature alarmism. This document outlines that effort.

Design Criteria:

The GOATS needs to meet the following requirements:

- Accuracy as good as or better than NOAA's USCRN instrumentation – triple redundant sensors with 0.1°C resolution and long-term stability.
- Reporting/logging of temperature every 1 minute, with a 10-minute average calculated – this is to simulate the longer response time of older mercury thermometers in use since 1890, so as to ensure comparative high and low temperature capture. Newer electronic sensors have a much faster response time than mercury thermometers.

- Ability to remote deploy by shipping to and setup by the end-user with simple instructions – essentially a "plug and play" operation out of the box. Some drop-shipping will also be needed.
- Portability - needs to be light enough to be moved by one person.
- Anchoring – needs to be able to withstand high winds equal to a Category 2 hurricane.
- Unattended operation after initial setup plus fully automated remote data transmission.
- Internet cloud access of all reported data – open source of that data.
- Solar powered with battery – capable of operating on battery for at least 5 days of darkness.
- Weatherproofing – IP67 rating or better for all electronics and sensors.
- Remote diagnostics for reporting sensor errors and system health.
- Reasonable cost to deploy – GOATS target cost is under $2000 per station.
- Open public access to all data gathered, both raw and processed.
- Optional reporting of other values in addition to what USCRN reports, such as, incoming solar radiation, wind, soil temperature/moisture, humidity, and rainfall.

Synopsis of the Design:

The USCRN stations use manufacturer-specific components from Campbell Scientific, MetOne, R.M. Young, and Vaisala Inc. and others. These sensors/components are very expensive, and difficult to acquire. For example, the 076B solar radiation shield from MetOne costs $1250.00 and three are needed. That doesn't include the temperature sensor. Additionally, the USCRN sensor support structure is made of concrete, a triangular tower, and ¾" steel pipe and fittings. Shipping costs due to weight are high, and deployment requires a contractor to pour concrete for the tower and to assemble fittings See USCRN document here. Also, the original 21x Campbell Scientific datalogger and its replacement the CR3000 plus the geostationary satellite modem that sends USCRRN data back to NOAA are not intuitive in design or setup, and cannot be shipped in a "plug and play" mode for deployment. Training and/or on-site specialist travel is needed. For an up-close look at the complexity of the USCRN equipment, visit this page.

These factors make private part-for-part duplication of USCRN instrumentation difficult. However, the technical design of the USCRN is circa 2000-2005, and technology has improved a great deal since then. This works in our favor, as new technology provides more and improved features at a lower cost.

A five-month period of design research was undertaken to determine if the USCRN instrumentation could be recreated from widely available, off-the-shelf hardware and software. Hardware was ordered, and testing began. A period of trial and error followed, during which various designs were developed, and electronic components, sensors, solar power, battery systems, support and mounting hardware, plus anchoring hardware for high wind resistance, were tested.

The GOATS weather station, shown in Figure 1, has been successfully created, deployed, and tested and utilizes a variety of off-the-shelf components.

Figure 1. GOATS station in final form, setup for outdoor testing in Sparks, NV. Note, the site is for testing only, and does not represent how these stations will be placed when deployed for actual use. In practice, GOATS stations will be at least 100 feet (30 meters) away from any local heat biasing elements such as structures, concrete, asphalt, etc. Also, not seen are ground screws to anchor the tripod into the soil, and a 3-point guy wire system that will stabilize the pole/tripod assembly, and has screw-in ground anchors for the tripod.

The heart of the system is a self-contained sensor system and datalogger that was originally designed for greenhouse use but has accurate specifications that have been adapted and upgraded for this project with the cooperation of the manufacturer. The choice was a commercially available data logger and sensor suite displayed in an overview below.

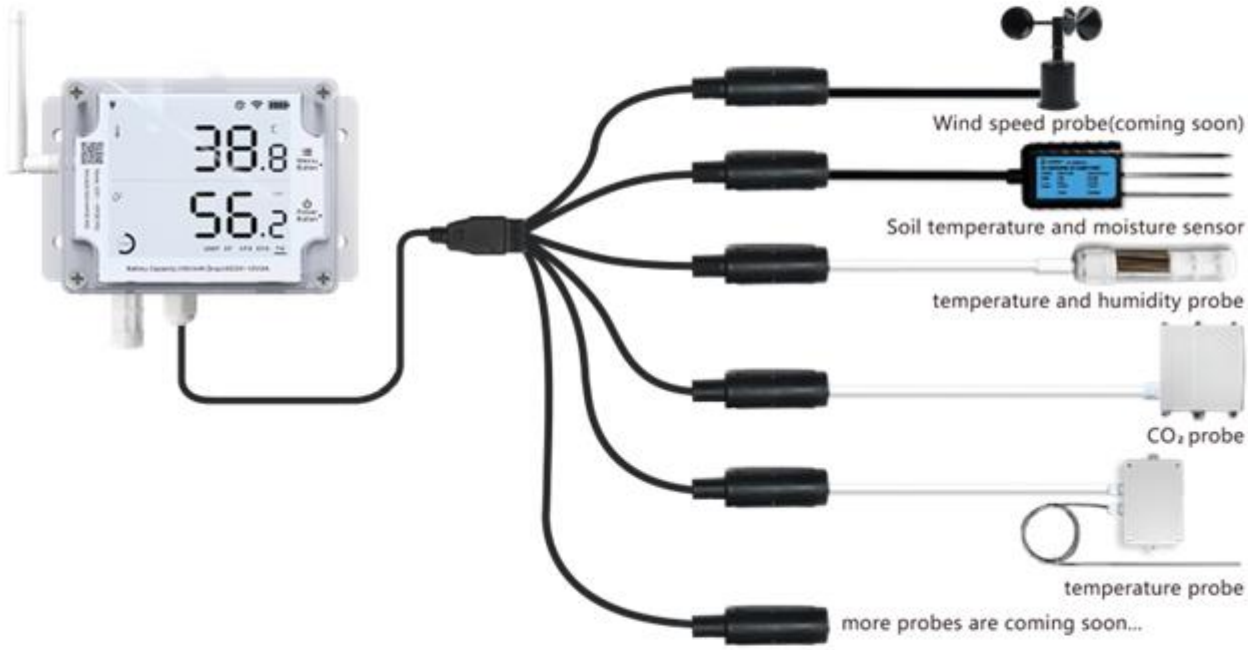


Figure 2. LCD data logger and sensor suite overview. Note the simplicity of cable connections to sensors using a 6 to 1 cable splitter. In practice, 3 cables of the splitter would be in use for the 3 temperature/humidity sensors, leaving 3 connections for optional sensors.

The GOATS design based on the LCD datalogger system meets and, in some cases exceeds, the performance of the USCRN instrumentation. Most importantly, it costs under $2000 to build, and can be shipped ready to run, with some minimal assembly required using only simple hand-tools. Sensors are installed using an "idiot proof" one-wire cabling system (see Figure 2) that is similar to audio cables used in home stereo or television entertainment systems. The sensors can be plugged into the cable splitter in any order, and there is no custom wiring needed.

In the USCRN system design, three electrically fan-aspirated solar radiation shields are used, the MetOne 076B, each costing $1250. The price for three of these greatly exceeded the target deployment cost for a GOATS station. However, a MetOne 076B shield was purchased to do comparative testing and it was determined that it was not practical for several reasons:

1. Excessive costs – three required ($3750) exceeded the target cost for a single GOATS station.
2. Mounting issues – required a more robust structure than a single pole.
3. Maintenance issues – fans require cleaning and/or replacement.
4. Insect intrusion – it has been reported that insects may nest (particularly wasps) in MetOne 076B shields.
5. Electrical requirements – running three fans 24/7/365 required significant electrical power, which is why the majority of USCRN stations use 120VAC grid power. This limits the ability to place both USCRN and GOATS stations away from human related biases.

However, more recent developments have made the original fan aspirated shields used in the USCRN obsolete. Newer passive solar radiation shield devices developed in Europe, represent a superior off-the-shelf solution.

The MeteoShield Pro Gen3 by Barani Design (seen at left) has been chosen as the best solution for GOATS due to its unique passive design actually exceeding performance of fan-aspirated shields according to testing performed by the Royal Meteorological Institute of Belgium.

It requires no electrical power and provides a naturally aspirated airflow due to the helical design. It has been approved by the World Meteorological Organization (WMO) and thus lends credibility to the GOATS design.

The measurement error of the MeteoShield Pro Gen3 has been established by testing at the Royal Meteorological Institute of Belgium to be +/- 0.1°C, making it superior to the MetOne 076B fan-aspirated shield used by the USCRN. See the data analysis depicted in Figure 3.

In an unusual endorsement of a commercial product, the Royal Meteorological Institute of Belgium said this about it in their analysis paper:

> Despite the fact that the Barani shelters are not artificially ventilated, their performances are better than our artificially ventilated compact shelter.

Additionally, it has been reported that the MeteoShield Pro Gen3 has superior dirt, dust, and insect deterrence. The helical surface-sloped design seems to deter insect nesting. It is also simpler to assemble and mount compared to the MetOne 076B, allowing for easier field deployment.

The cost for the MeteoShield Pro Gen3 is approximately $200 per unit, and three are needed for a total cost of approximately $600 allowing meeting the target deployment cost per GOATS station. Considering the WMO endorsed data accuracy, significantly lower cost compared the MetOne 076B fan-aspirated shield, dirt, dust, and insect deterrence, plus no power requirements, it is a superior option to the original MetOne 076B fan-aspirated shields used on USCRN.

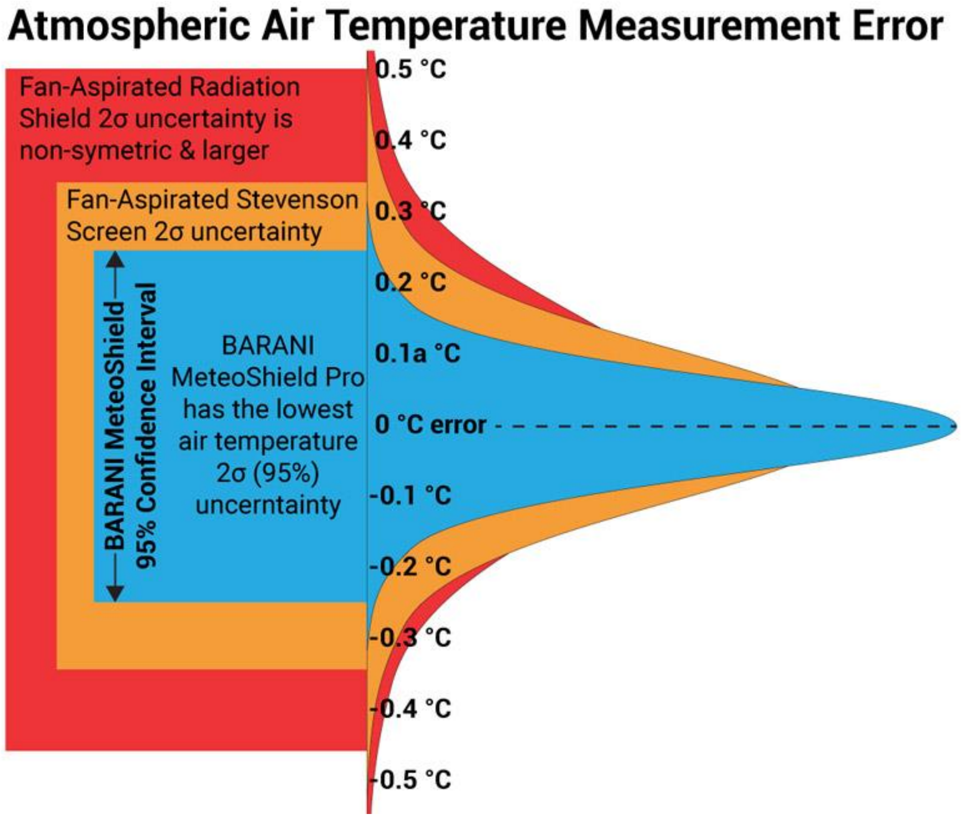


Figure 3. Air temperature measurement comparisons between different solar radiation shields. The Barani MeteoShield is a clear winner with minimal temperature measurement error. Source of data: Royal Meteorological Institute of Belgium, 2018, *"Intercomparison of Shelters in the RMI AWS Network"*

The GOATS LCD datalogger system powers-on using a single power button, will start automatically, and can deliver data to "the cloud" by either a WiFi or cellular data connection. It also features full recovery from "dead mode" if the system becomes disconnected or the battery wears down. It will automatically start reporting data within two minutes of restoration of solar/battery power. It also has a robust wind anchoring system that can be installed for the tripod and pole, using simple hand-tools.

A full suite of optional weather sensors is available. This provides maximum flexibility for duplication of the USCRN instrumentation as well as monitoring the local environment for other meteorological variables of interest.

The LCD datalogger system allows for worldwide communications by WiFi or cellular data connections. All global cellular data formats are supported. See figure 4.

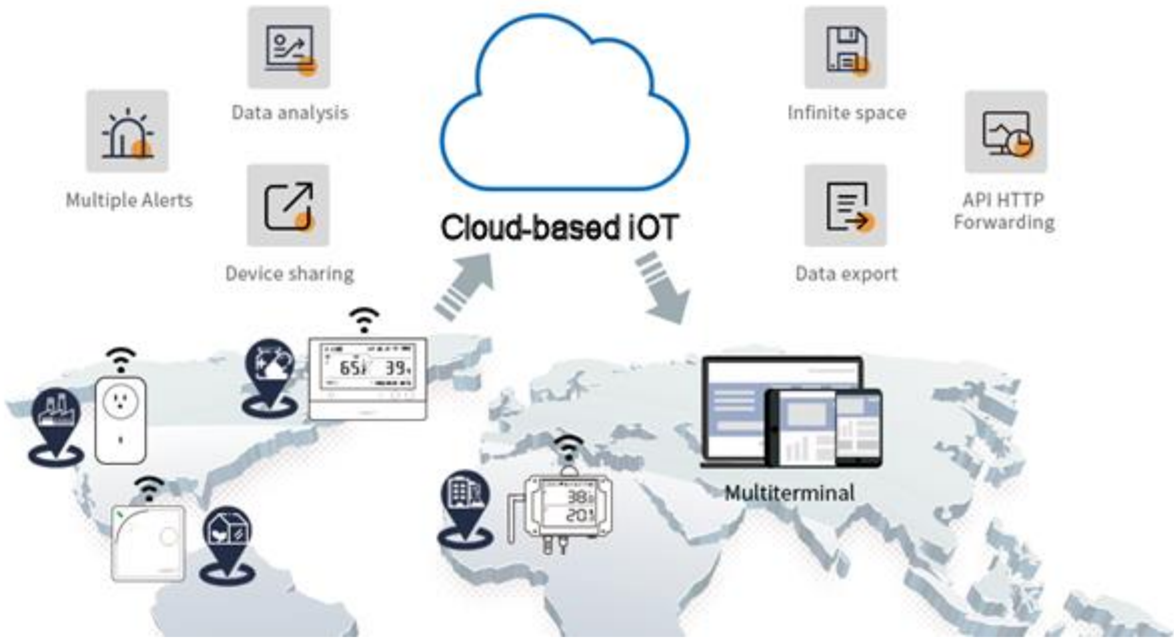


Figure 4. Global deployment using the cloud service.

Features, plus Adaptations/Customizations:

To fully duplicate the USCRN temperature instrumentation, some adaptations to the LCD datalogger system, power, and mounting schemes needed to be done, these are as follows.

- Triple redundant temperature sensor system utilizing three of the TH35S-B temperature and humidity probes, specially programmed for this purpose by the manufacturer.
- +/- 0.1°C accuracy using the SHT35B sensor chip. The LCD datalogger manufacturer has agreed to do this since it is a direct drop-in replacement with better accuracy.
- Passive naturally air-aspirated solar radiation shields, WMO approved. See spec sheet for MeteoShield Pro Gen3.
- Triple redundant temperature sensor system allows for increased accuracy by averaging three temperature measurements made every minute. It ensures capture of high/low temperature events that are not properly captured at airport measurement stations. Data averaging is performed in the cloud/server side so that only the pure raw data is transmitted from the GOATS. Retaining and sharing the raw data ensures full transparency, plus the ability to do post-measurement analysis by anyone interested.
- The LCD datalogger is based on the popular and widely available ESP32 microprocessor, having its own internal 2.8 amp-hour backup battery. See Figure 6. When combined with the external 20 amp-hour battery and solar charger, the LCD datalogger, sensors, and battery monitor require only minimal sustained current in the milliamps range. Testing shows that a GOATS station successfully operated continuously in total darkness for 7 days. Maximum battery life without solar charging may be as long as 14 days.

- Improved power system for the datalogger, combines an internal supercapacitor that is more temperature tolerant with an external 20 amp-hour Sealed Lead-Acid Battery to provide longer run-times in extended darkness and/or low solar periods.
- Built-in battery test and monitoring system in the electronics box.
- Built-in voltage regulator for powering the datalogger.
- The LCD datalogger device has internal sensors for battery voltage and temperature inside the electronics box, allowing remote real-time assessment of system health.
- Wind stability – utilizing off-the-shelf components, three ground screws are placed into the feet of the tripod, plus a 3-point guy-wire system is attached at top just under the solar panel and run to large ground screws via steel cable. Turnbuckles are used to tighten the guy wires.
- Solar power options – 20-, 30-, 50- or 100-watt solar panels are available, at very high geographic latitudes, up to 100-watt solar panels may be required to ensure reliable battery charging and operation.
- GPS integration – the LCD datalogger system has the optional GPS installed, to provide accurate data timestamps from satellite and exact deployment positioning coordinates.
- Internal light sensor can tell us remotely if the electronics enclosure has been opened, which will tell us if theft/tampering may have occurred.
- All temperature probes (as well as other sensors) are easily interchangeable – simply unplug and plug in a new one. This ensures easy service. Temperature probes are pre-calibrated at the factory, but can also be field calibrated using software.
- As needed, a full suite of optional weather sensors is available for the GOATS. This includes incoming solar radiation, wind, soil temperature/moisture, humidity, rainfall. Standard USCRN deployments have rainfall, solar radiation, soil temp/humidity, and sometimes wind.
- A local API software package is provided for remote query of all data from any sensor. This has already been implemented and tested, and allows sending data to a web page from the cloud for real-time display of data, both raw as well as processed/averaged.
- Data is encrypted and follows a closed communications path – minimizing risks for any outside tampering/spoofing. Each device has an internal serial number which is attached to the data.
- Options exist for theft deterrence, including GPS tracking and a local camera, such game cameras used by hunters and wildlife watchers.
- Easy to deploy from kit form using simple hand tools.
- Custom IP68 rated electronics enclosure – pole-mounted and fully weatherproof – houses all electronics and battery/solar charger system, with weatherproof cable ports extend wires to sensors. The electronics box is lockable, and can be insulated against temperature extremes if needed. See Figure 5.
- All-in-one tripod assembly mounting system. Utilizing off-the-shelf components for home satellite dish mounts, a portable and easy to assemble and deploy mounting system with anchors was created. This allows for placement virtually anywhere – meeting siting specifications away from human caused heat biases. See Figure 6.
- Full remote-control console for each station – cloud-based. See Figure 7.
- Data output to website for public consumption at *Global Climate Reference Network (GLCRN.org)* See Figure 8.

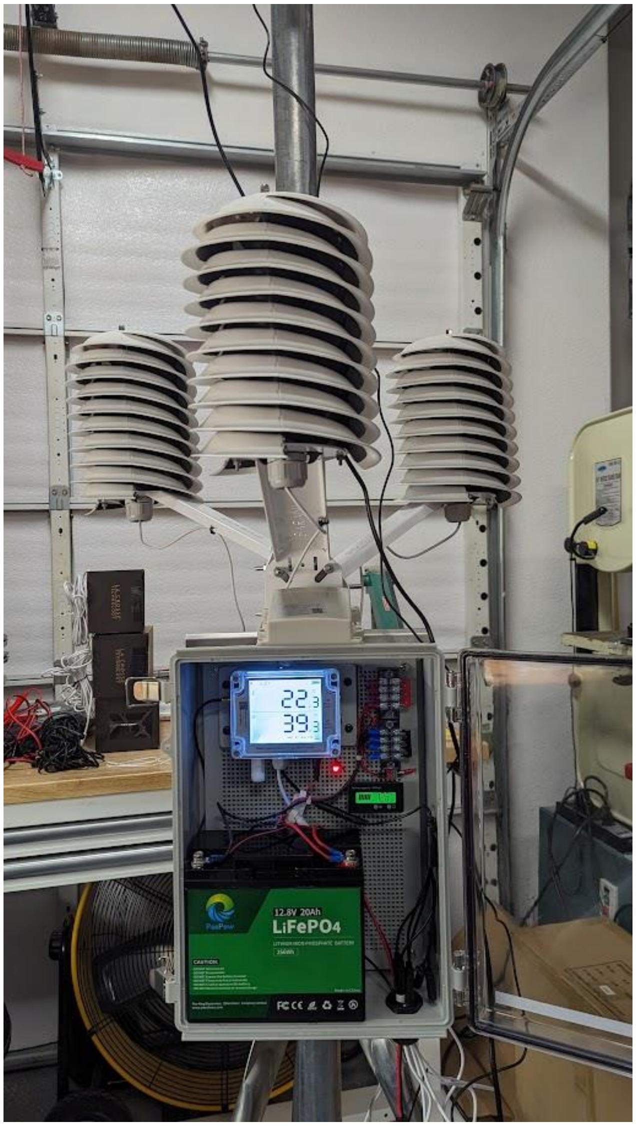


Figure 5: The new GOATS MeteoShield Pro Gen3 temperature sensor shields, shown during assembly and testing plus the GOATS electronics box with clear plastic (for exhibit/demo use only – normally the case is opaque gray). The LCD datalogger LCD backlight/display can be turned off to save power, and then reactivated at the touch of a button. On the right side of the box is the power distribution buss, the power on/off switch, and the LCD display for battery monitoring. Note the large battery for ensuring long-term operation in low/no sunlight. Tests have been performed in total darkness for 7 days and battery state remained high, at nearly 100% and the system continued to function flawlessly.

Figure 6: At left, the GOATS in final prototype form, showing tripod, pole, 30-watt solar panel, electronics box, and three MeteoShield Pro Gen3 temperature sensor shields. Air is drawn in from the sides of the temperature sensor shields, and is not expected to be biased by ground cover. For that reason, the solar panel (which can reach temperatures of 150°F in summer) is placed high above the temperature sensors which are at the standard 1.5-meter measurement height. At right, a USCRN station showing metal tower and three MetOne 076B air aspirated radiation shields and the electronics box. The grey cone is the satellite transmitter antenna. Note also the conduits – this station is powered from the electrical grid. Some other USCRN stations are solar powered.

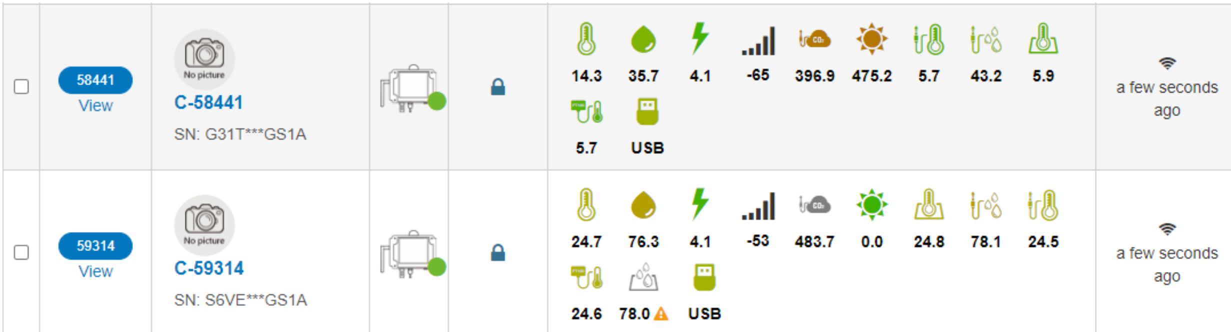
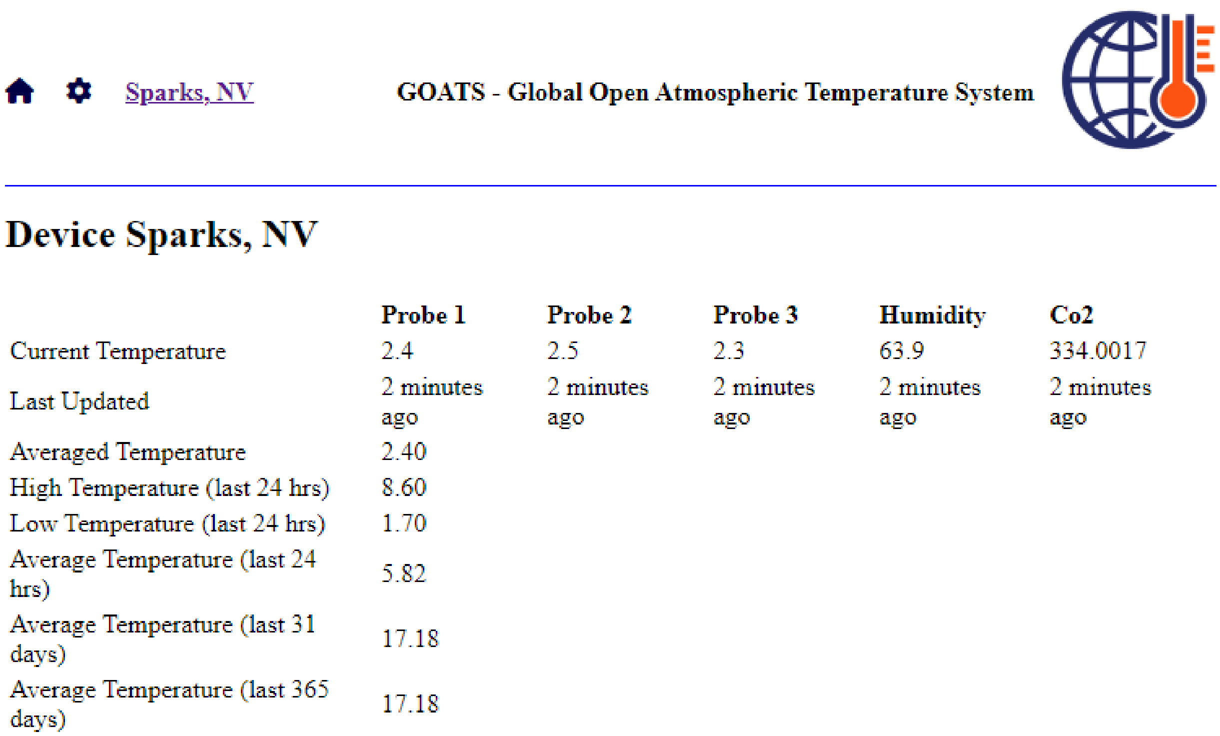


Figure 7: Cloud based remote-control console showing user-interface and data display for two existing test systems – this is for operation and monitoring, the cloud database for sensor data is entirely numerical.


Sparks, NV GOATS - Global Open Atmospheric Temperature System

Device Sparks, NV

	Probe 1	Probe 2	Probe 3	Humidity	Co2
Current Temperature	2.4	2.5	2.3	63.9	334.0017
Last Updated	2 minutes ago	2 minutes ago	2 minutes ago	2 minutes ago	2 minutes ago
Averaged Temperature	2.40				
High Temperature (last 24 hrs)	8.60				
Low Temperature (last 24 hrs)	1.70				
Average Temperature (last 24 hrs)	5.82				
Average Temperature (last 31 days)	17.18				
Average Temperature (last 365 days)	17.18				

Figure 8. Cloud based data output for a single station – preliminary design. Final design will include the ability to graph data as well as download/export all data. The website will be www.glcrn.org (Global Climate Reference Network) and will also have a clickable map and list of all stations worldwide.

System Specifications:

Temperature		
Typ. temperature accuracy	0.1	°C
Operating temperature range	-40 - 125	°C
Response time (τ63%)	> 2	s

Humidity		
Typ. relative humidity accuracy	1.5	%RH
Operating relative humidity range	0 - 100	%RH
Response time (τ63%)	8	s
Protective option	Protective cover	
Calibration certificate	Factory calibration	

Calibration Notes:

The temperature & humidity sensor chips (model number SHT35 by Sensirion) have been fully calibrated, linearized (adjustments to ensure accurate readings over the entire low to high temperature range), and compensated for temperature and supply voltage dependencies by the chip factory. The SHT35 is a digital sensor that shows best performance when operated within recommended normal temperature and humidity range of 5 – 60 °C and 20 – 80 %RH, respectively. Long term exposure to conditions outside normal range, especially at high humidity, may temporarily offset the RH signal (e.g. +3%RH after 60h at >80%RH). After returning to the normal temperature and humidity range the sensor will slowly come back to calibration state by itself. Prolonged exposure to extreme conditions may accelerate aging. A software program exists for field calibration of the temperature and humidity sensor if necessary.

Three sites are currently being solicited for long-term testing and comparison with existing NOAA sensors.

- Butte County, CA – OPERATIONAL
- Yeppon, NSW - OPERATIONAL
- Reno, NV – Reno-Tahoe International Airport. NOAA ASOS station on-site in one of the largest UHI signatures in the nation.
- Palestine, TX – NASA Balloon launch facility with USCRN station on-site.
- Sparks, NV – National Weather Service Office, where a NOAA MMTS sensor exists.

The plan is to write and submit a peer-reviewed paper based on 1 year of comparative testing at these locations.

Site Selection Criteria:

Placement of a GOATS station will follow the guidelines of the USCRN Site Survey Checklist authored by NOAA to choose and document locations for USCRN stations. Selection will also follow NOAA National Weather Service siting guidelines as defined in *Requirements and Standards for NWS Climate Observations*. Essentially, siting choice will be dependent the "100-foot rule" as outlined in that document, to ensure that any station is at least 100 feet (30 meters) away from any artificial influence.

The main site selection criteria are:

- 16 foot diameter flat ground with at least 100 feet (30 meters) clearance from buildings, concrete, asphalt, and any other artificial structures.
- No evidence of water pooling issues from rainfall
- No evidence of cold air drainage or pooling
- No tree line that could cause shade within 100 feet (30 meters)
- No livestock interference that could disrupt the station itself
- Secure location – preferably fenced and gated
- Long term stability of the site, assuring low risk of significant change (new construction)
- Once a year access for maintenance visits (if needed)
- Access to public cellular (4G/3G) services or local WiFi connection

A complete list of criteria and documentation for evaluating and scoring potential sites is contained in the document *Climate Reference Network (CRN) Program Site Acquisition Plan* published by NOAA. While the GOATS program may not be able to meet every criterion listed in that document, neither does NOAA, as they say:

> There will be many sites that are less than ideal. Selecting a site is a series of compromises between a number of factors.

It is expected that any potential GOATS site must be viable for years into the future, so that a long-term signal can be established. A "Site Lease Agreement" (SLA) will be produced and shared with volunteers prior to deployment for signature. It is hoped that such sites can be donated for use at no cost to the GOATS program.

Optional Sensors:

Every station can accommodate a full suite of meteorological sensors, and the reporting software is already configured to detect these and log their data. Some site sponsors may wish to have additional sensors. See the photo below for a station with fully loaded sensor suite.

- Soil Temperature and Moisture Sensor
- Wind Speed Sensor
- Wind Direction Sensor
- Total Incoming Solar Radiation Sensor
- Rainfall Sensor and mounting hardware

Figure 9. GOATS station deployed in Butte County, CA in June 2023, showing a full complement of meteorological sensors for rainfall, wind, and solar radiation, plus a lightning rod assembly. Note the guy wires for wind stability.

Deployment of a 10 Station Test Network:

While the broader long-term goal is for eventual global deployment of 500 or more stations, with at least 125 in the U.S. to mirror the geographic spacing of the USCRN, the short-term goal is to setup and operate a 10-station network to work out unforeseen issues, complications, and bugs.