NAU
NORTHERN ARIZONA UNIVERSITY

Renewable Energy Lab Weather Station

By:

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Description

The goal of this project is to make a weather station for the RE Lab at NAU that will last for years. This station will provide accurate and current measurements for various weather conditions and will be accessible from anywhere with an internet connection.

Measure:

- Temperature
- Humidity
- Wind Speed/Direction
- Barometric Pressure
- Solar Irradiance
- Possibly Rainfall

Purpose:

The RE Lab currently does not have a weather station, their old equipment no longer feeds into functional devices. We need a weather station for future classes for environmental engineers and other such fields.

Benchmarking

1. Flagstaff Pulliam Airport (KFLG) [7]

    a. This is an airport weather station in Flagstaff. It provides multi-day forecasts.

    b. Automated Surface Observing System (ASOS)

Humidity
Wind Speed
Barometric Pressure
Dewpoint
Visibility
Heat Index
Last Updated Time

There is also an easy-to-access 7 day history on the website.

This displays temperature, dewpoint, and humidity in a graph, as well as much more information in table form below.

Benchmarking

2. Tempest Home Weather Station [9]

Personal home weather station which broadcasts to a phone app. Features an auto-calibration self-learning system.

Measurements:

- Air Temperature
- Relative Humidity
- Wind Chill
- Barometric Pressure
- Wind Speed and Direction
- Lightning Activity
- Rain Intensity and Duration
- UV Index and Solar Radiation

Cost- $350

Key Features:

- Custom weather alerts through Tempest Home app
- 10 day forecast
- Requires WiFi Connection

Benchmarking

3.Davis Vantage Pro2 is a high-end professional weather station launched by Davis Instruments in the United States. It is widely used in agriculture, scientific research, universities and meteorological stations.

Its main features include:

Sensor integration: integrated with temperature, humidity, wind speed, wind direction, air pressure, rainfall and other sensors.

Wireless transmission: supports 900 MHz or 2.4 GHz wireless communication, up to 300 meters.

Solar power supply system: with solar panels and backup batteries, suitable for long-term deployment in the field.

Strong scalability: users can choose modules such as ultraviolet light and light intensity.

Structural design:

The module adopts a tower installation structure, and the anemometer is installed on the top to minimize interference. The overall shell is made of ABS material, which is waterproof and anti-aging. All parts can be quickly disassembled for easy maintenance and transportation.

Customer Needs

- Measurement of Key Weather Parameters - Station will measure temperature, humidity, wind speed and direction, barometric pressure and solar irradiance. Will potentially measure rainfall as well
- Data Transmission - Data collected will be transmitted via internet
- Remote Data Access - Live and stored data should be accessible through a web interface
- Renewable Power Supply - Any components which require power must run on solar energy
- Weather Durability - Station must withstand outdoor weather conditions
- Low Maintenance - Station should require less than 2 hours of maintenance per year
- Sensor Accuracy - Sensor readings should be properly calibrated
- User Friendly - User interface should be easily navigable
- Ease of Installation - Installation should require minimal tools or training
- Low Cost - Station should be cost effective and within budget
- Safety Compliance - Must comply with relevant electrical and operational safety standards
- Data Storage - Data should be stored in an accessible and organized database for at least one year.

Engineering Requirements

- Long Term Data Storage - Database should log data in an organized manner over the course of 4 years
- Increased Data Accuracy - Sensor readings should be highly accurate, within 3% or less. Data average calculations should be properly computed
- Multiple Wind Speed Readings - Wind speed and direction should be measured at both standard height and atop existing tower at lab providing at least 2 readings.
- Measured at Industry Standards - Sensors should be properly positioned according to industry standards
- Proper Calibration - Sensors should be properly calibrated to upload accurate data from raw readings within 3% of true values
- Measurement of All Data Types - Station should record 5 data types including temperature, pressure, humidity, solar irradiation and wind data
- Low Power Requirement - Station should be capable of fully operating under existing solar generated power means located at lab, with a target of 0.2 kWh per day or less.

QFD

- Customer needs weighted based on client input.
- Technical requirements importance and relationship to each other and to customer needs weighted based off team discussion.
- Customer opinion survey of similar products based on available information.

Results:

- Highest absolute technical importance is proper calibration, closely followed by increased data accuracy and long-term storage.
- Lowest technical importance is the low power requirement.

System QFD

Project: RE Weather Station QFD
Date: 6/16/2025

	Technical Requirement	1	2	3	4	5	6
1	Long Term Data Storage						
2	Increased Data Accuracy	1					
3	Multiple Windspeed Readings	1	3				
4	Measured at Industry Standards	1	9	9			
5	Proper Callibration	3	9	3	9		
6	Temp, Pressure, Humidity, Wind spd/dir, Solar Irradiance	3	9	3	9	9	
7	Low Power Requirement	3	1	1	1	1	9

Legend

A	KFLG
B	Tempest
C	Davis Vantage

	Customer Needs	Customer Weights	Long Term Data Storage	Increased Data Accuracy	Multiple Windspeed Readings	Measured at Industry Standards	Proper Callibration	Temp, Pressure, Humidity, Wind spd/dir, Solar Irr	Low Power Requirement	1 Poor	2	3 Acceptable	4	5 Excellent
			Technical Requirements							Customer Opinion Survey				
1	Data Transmission	5	9	1	3			9	9			A	B	C
2	Data Storage	3	9	1	1	1		9	3		AB		C	
3	Weather Durability	5	1				3		1		B	A		C
4	Safety Compliance	5	3				1	3	3			C	B	A
5	Low Maintenance	3	3	1	3	1	9	3	1			A	BC	
6	Low Cost	3	1	3	3	3	1	9	3		A	C		B
7	User Friendly	3	9	1	1		9	3					ABC	
8	Easy Installation	3			9	1	9	3	1		A		C	B
9	Remote Data Access	5	9	1	1			1					B	AC
10	Measurement of Weather Parameters	5	3	1	3	3	9	9	9				B	AC
11	Renewable Power Supply	5	1					3	9	B		A	C	
	Technical Requirement Units		years	%	Readings	N/A	%	Readings	kWh					
	Technical Requirement Targets		4	3	2	N/A	3	5	0.2					
	Absolute Technical Importance		82	88	75	12	1223	80	8					
	Relative Technical Importance		4	5	1	3	6	7	2					

Barometric Pressure

Barometric pressure is the measurement of air pressure in the atmosphere, specifically the measurement of the weight exerted by air molecules at a given point on Earth.

It enables prediction of weather patterns, altitude calculation, optimal equipment operation, and informed decision-making in various applications and industries. [1]

- Barometers
  - Barometric Pressure is measured with electronic barometers, aneroid barometers or hypsometers
  - Typically measured in Pa and hPa
  - To set up:
    - Good light exposure
    - No artificial wind currents
    - Solid, non-vibrating mount
    - Protection against rough handling [3]

Solar Irradiance

- Pyranometer
  - Measure global solar radiation
  - Essential for monitoring energy efficiency, weather patterns, and climate change.
  - It records the amount of solar energy reaching a surface per unit area, typically measured in watts per square meter (W/m^2). [4]
  - Capture both direct sunlight and diffuse sunlight
  - Degrade over time due to environmental factors, usage, and component wear
  - Must be robust in design and resist the corrosive effects of humid air [3]
  - Set up away from obstructions and along north/south to get the most sun
- Types:
  - Thermopile Pyranometers [4]
    - Convert temperature differences between a black absorber and a reference into an electrical signal
    - Known for Accuracy
  - Silicon Photocell Pyranometers [4]
    - More common, less accurate. Especially on a cloudy day
    - Use a silicon sensor to convert solar radiation into an electrical signal

Air Temperature

- Air Temperature [2]
  - Measured by Thermometers
  - Air temperature is the temperature of the free air conditions surrounding the station at a height between 4 and 6 feet above ground level
  - Freely exposed to sunshine and wind and not close to or shielded by trees, buildings, or other obstructions.
  - Over level ground and at least 100 m from extensive concrete or paved surface
  - The instrument should be no closer than four times the estimated height of any nearby building, tree, fence, or similar obstruction. Determined by 10 degree measurement from the instrument

Air Temperature Measurement Performance Requirements				
Observed Element	**Range - Fahrenheit**	**Reference Temperature**	**Time Constant**	**Accuracy At Reference Temperature (F)**
Air Temperature	−20° to +115°	+ 50°	25 sec	± 1.0° 95% confidence
Air Temperature, Maximum*	-20° to +115°	+ 50°	25 sec	± 1.0° 95% confidence
	+115° to +140°	+ 120°	25 sec	± 2.0° 90% confidence
Air Temperature, Minimum*	−80° to −20°	- 30°	25 sec	± 2.0° 90% confidence
	−20° to +110°	+ 50°	25 sec	± 1.0° 95% confidence

Table 3.1. Performance Standards for Air Temperature Measurements.

Air Temperature Data Requirements					
Observed Element	**Data Output Resolution**	**Data Average**	**Calculation Update**	**Time Stamped**	**Memory Recall**
Air Temperature - Maximum Daily	0.1-degree F	15 seconds	1 minute	Yes	33 days
				No *	1 day
Air Temperature - Minimum Daily	0.1-degree F	15 seconds	1 minute	Yes	33 days
				No *	1 day
Air Temperature - Current Reading	0.1-degree F	15 seconds	1 minute	No	1 minute

Table 3.2. Data Requirements for Air Temperature.

Precipitation

- Two Types [2]
  - Manual
    - The Standard Rain Gauge consists of an eight-inch diameter metal overflow can, a funnel, a clear plastic collection tube and a measuring stick with marked gradations in hundredths of an inch.
  - Recording
    - The ASOS Program and the COOP Program use recording rain gauge that measure the weight of collected precipitation and convert the weight into equivalent hundredths of an inch of liquid precipitation
- Set up [2]
  - 3 feet above the ground for manual, 6 feet for recording.
  - The gauge should be sited no closer to the nearest obstruction than a distance that is twice the height of the obstruction

Performance Requirements for Manually Observed Precipitation			
Parameter	**Range**	**Resolution**	**Measurement Accuracy**
Precipitation, Rain	0 to 20 inches	0.01 inches	±0.02 inches
Precipitation, Frozen (Liquid Equivalent)	0 to 24 inches of snow	0.01 inches melted	±0.04 inches melted
	0 to 12 inches of snow	0.01 inches melted	±0.04 inches melted

Table 4.1. Performance Requirements for Manually Observed Precipitation.

Performance Requirements for Recorded Precipitation			
Parameter	**Range**	**Resolution**	**System Accuracy**
Precipitation, Rain (Hourly)	0 to 20 inches	0.1 inches	±0.1 inches, from 0 to 20 inches
Precipitation, Frozen (Hourly) Liquid Equivalent	0 to 20 inches	0.1 inches	±0.1 inches, from 0 to 20 inches

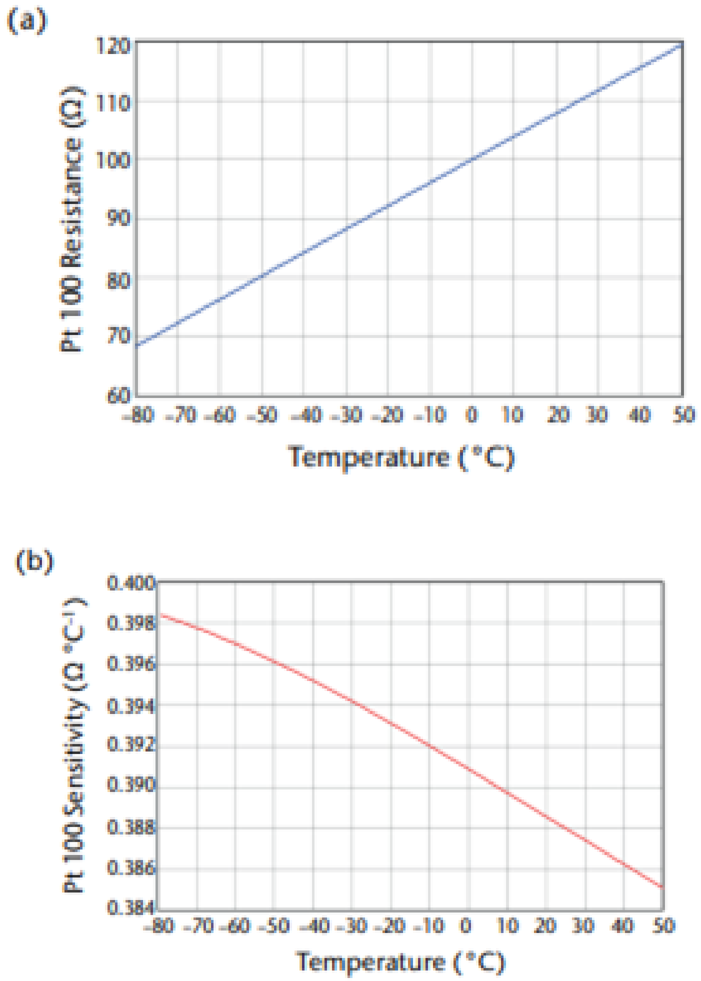
Table 4.2. Performance Requirements for Recorded Precipitation.

Thermometers

Electrical Thermometers (PRTs):

- The electrical resistance of pure metals is an almost linear function of temperature across the meteorological range. [3]
- Most common field thermometers known as Pt100 with an electrical resistance R_0 close to 100Ω at 0^oC.
- Pt100 sensors are categorized by standard tolerances such as IEC 60751 or ASTM E1137 [3] [13].
- These standards define the resistance and sensitivity curves which are used to interpret the readings from the sensor into temperature values.

Other less commonly used thermometer types include thermistors (semiconductor thermometer), and thermocouples.



Resistance vs temperature and resistance vs sensitivity for an IEC 60751-compliant Pt100 sensor

Thermometer Output Calculation

Between the temperatures of -80 °C and 60 °C, the electrical resistance of a PRT can be represented by the Callender-van Dusen equation [3] [13]:

$$R = R_0\left(1 + At + Bt^2 + C(t-100)t^3\right)$$

Where R_0 represents the resistance at 0 °C and t represents the temperature in °C.The coefficients will depend on the specification.

Until we learn the exact specification of our thermometer, we will use the IEC 60751 specification where R_0=100Ω, A=3.908x10^{-3} °C, B=-5.80x10^{-7} °C and C=4.27x10^{-12} °C when temperatures are below zero and C=0 °C when above zero. In temperatures above -40 °C, the C term is negligible and thus the inverse equation for temperature can be simplified to:

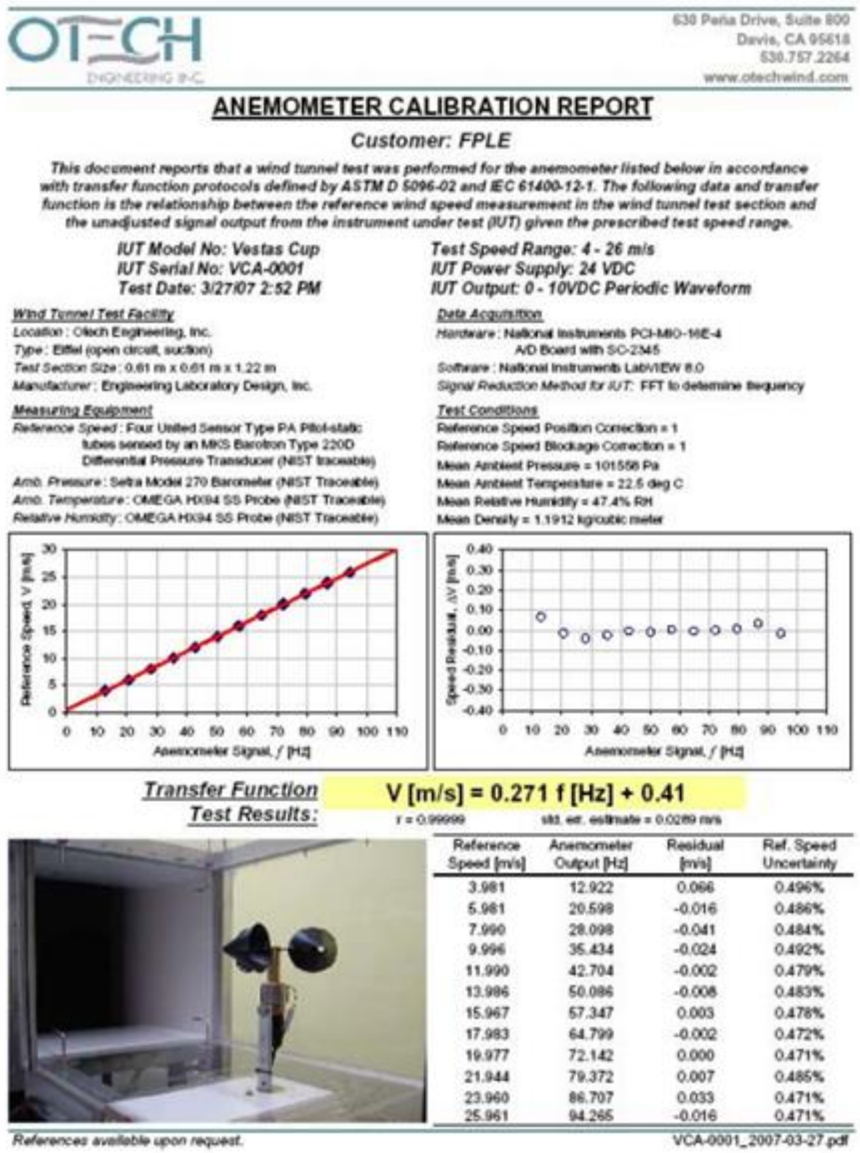
$$t = -\frac{A}{2B} + \frac{A}{2B}\sqrt{1 - \frac{4B}{A^2}\left(1 - \frac{R}{R_0}\right)}$$

Therefore, given an output reading of 110Ω, our temperature reading would be approximately 25.34 °C

Anemometers

Measurement of wind:

- Primary data types include average horizontal wind speed and direction from which the wind blows, measured clockwise from true north [10].
- Wind vanes are used to measure direction and must be well balanced as to not have a preferred position.
- The standard height for an anemometer free of obstructions is 10m [3].
- While wind speed is directly proportional in relation to angular velocity in well-designed systems, speeds near the starting threshold can often deviate from linearity [3].
- Response is significantly faster for acceleration vs deceleration and can cause overestimation in averages.


OTECH ENGINEERING INC.

630 Peña Drive, Suite 800
Davis, CA 95618
530.757.2264
www.otechwind.com

ANEMOMETER CALIBRATION REPORT

Customer: FPLE

This document reports that a wind tunnel test was performed for the anemometer listed below in accordance with transfer function protocols defined by ASTM D 5096-02 and IEC 61400-12-1. The following data and transfer function is the relationship between the reference wind speed measurement in the wind tunnel test section and the unadjusted signal output from the instrument under test (IUT) given the prescribed test speed range.

IUT Model No: Vestas Cup
IUT Serial No: VCA-0001
Test Date: 3/27/07 2:52 PM

Test Speed Range: 4 - 26 m/s
IUT Power Supply: 24 VDC
IUT Output: 0 - 10VDC Periodic Waveform

Wind Tunnel Test Facility
Location : Otech Engineering, Inc.
Type : Eiffel (open circuit, suction)
Test Section Size : 0.61 m x 0.61 m x 1.22 m
Manufacturer : Engineering Laboratory Design, Inc.

Measuring Equipment
Reference Speed : Four United Sensor Type PA Pitot-static tubes sensed by an MKS Barotron Type 220D Differential Pressure Transducer (NIST traceable)
Amb. Pressure : Setra Model 270 Barometer (NIST Traceable)
Amb. Temperature : OMEGA HX94 SS Probe (NIST Traceable)
Relative Humidity : OMEGA HX94 SS Probe (NIST Traceable)

Data Acquisition
Hardware : National Instruments PCI-MIO-16E-4 A/D Board with SC-2345
Software : National Instruments LabVIEW 8.0
Signal Reduction Method for IUT: FFT to determine frequency

Test Conditions
Reference Speed Position Correction = 1
Reference Speed Blockage Correction = 1
Mean Ambient Pressure = 101558 Pa
Mean Ambient Temperature = 22.5 deg C
Mean Relative Humidity = 47.4% RH
Mean Density = 1.1912 kg/cubic meter

Transfer Function V [m/s] = 0.271 f [Hz] + 0.41
Test Results: r = 0.99999 std. err. estimate = 0.0289 m/s

Reference Speed [m/s]	Anemometer Output [Hz]	Residual [m/s]	Ref. Speed Uncertainty
3.981	12.922	0.066	0.496%
5.981	20.598	-0.016	0.486%
7.990	28.098	-0.041	0.484%
9.996	35.434	-0.024	0.492%
11.990	42.704	-0.002	0.479%
13.986	50.086	-0.008	0.483%
15.967	57.347	0.003	0.478%
17.983	64.799	-0.002	0.472%
19.977	72.142	0.000	0.471%
21.944	79.372	0.007	0.485%
23.960	86.707	0.033	0.471%
25.961	94.265	-0.016	0.471%

References available upon request. VCA-0001_2007-03-27.pdf

Wind Tunnel Anemometer Calibration Report [12]

Weatherproofing and Environmental Design

- Weather sensors need to be well protected against water and dust in outdoor environments.
- Ambient Weather's open source description lists effective housing designs for outdoor protection [8].

Design Aspect	Recommendation / Detail
Enclosure Material	Use UV-resistant polycarbonate to withstand sun exposure and aging.
Ingress Protection	Ensure IP65 or higher waterproof/dustproof rating.
Ventilation / Condensation Control	Install breather vents (membrane vents) to prevent internal condensation.
Cable Sealing	Use IP-rated cable glands (e.g., PG7, IP68) and apply heat shrink tubing.
Mounting Position	Wind sensors should be mounted 3–10 meters above ground, away from obstructions.
Lightning Protection	Ground metal parts; consider surge protectors or ESD protection for electronics.
Maintenance Tips	Check seals, sensor surfaces, battery status regularly; clean any debris buildup.

Thermal Management Considerations

Outdoor electronic devices are prone to internal temperature increases due to direct sunlight, temperature fluctuations, and insufficient airflow. Excessive heat can affect sensor accuracy and accelerate component aging.

Joule heating

The internal temperature rise caused by total power loss can be estimated using the following thermal resistance model:

$$\Delta T = P * R\_\theta JA$$

ΔT: Device temperature rise (°C)
P: Total power consumption (W)
R _θ JA; Device or system junction-to-ambient thermal resistance (°C/W)

Result:
If the total power consumption of the sensor is 7.1W and the thermal resistance is 10°C/W, the temperature rise will be approximately 71°C. If the ambient temperature is 35°C, the internal temperature of the housing may reach as high as 106°C.

Solar Radiation Heating

In exposed areas, solar radiation can significantly heat equipment:

$$Q\_solar = G*A*\alpha$$

G: Solar radiation intensity (typical: 800–1000 W/m^2)
A: Light-receiving area (m^2)
α： Material absorption coefficient (black: almost 0.9, white almost 0.3)

Result:
A 0.1m^2 black box receives:
Q=1000*0.1*0.9=90W
Reflective coating or sunshade design is required.

Humidity

Measurement of humidity:

- Humidity is typically measured using capacitive, resistive or printed sensors.[14]
- Performance parameters and comparison of the three sensors. (See the picture on the right)[15][16][17]
- Humidity data should be recorded at the same rate as temperature to allow for humidity analysis. Drift is a major issue for long term deployments and requires either regular reference checks or the use of an automated calibration protocol.[18][19]
- Humidity sensors should be mounted 1.25-2 meters above the ground and away from direct heat sources or reflective surfaces. A ventilated radiation shield is also required to prevent direct sunlight or precipitation from affecting the readings. It is also important to stay away from areas prone to condensation, such as under trees or next to shrubs, as water droplets may distort the readings.[20][21]

Feature	Capacitive Sensor	Resistive Sensor	Printed Sensor (Flexible)
Measurement Range	0–100% RH	~10–90% RH	~20–90% RH
Accuracy	±2–3% RH typical	±5% RH typical	±5–10% RH depending on substrate
Response Time	Fast (2–10 seconds)	Slower (10–30 seconds)	Medium (1–30 seconds)
Temperature Dependence	Low	Higher	Medium
Cost	Moderate (~$5–20)	Low (~$1–10)	Very Low (<$1 in bulk)
Durability	High; suitable for long-term deployment	Moderate; may degrade with moisture cycles	Low–moderate; often disposable or short-term use
Power Consumption	Low	Low	Very low
Size/Form Factor	Small; PCB-mountable	Small; PCB-mountable	Customizable; suitable for wearables/flexible PCBs
Best Use Case	Environmental monitoring, HVAC systems	Home/office use, low-cost devices	Smart textiles, IoT, temporary deployments

Humidity sensor output calculation

For capacitive humidity sensors, relative humidity (%RH) is typically determined by the change in capacitance:

$$RH = \frac{C - C_{dry}}{C_{wet} - C_{dry}} \times 100$$

Where:

- C is the measured capacitance
- C_dry = capacitance at 0% RH
- C_wet = capacitance at 100% RH

Example Sensor:

- C_dry = 180 pF, C_wet = 250 pF, Measured C = 216pF

$$RH = \frac{216-180}{250-180} \times 100 = \frac{36}{70} \times 100 = 51.4\%$$

Validation was accomplished by comparing the values to the manufacturer's calibration curve.

This modeling allowed us to validate sensor sensitivity to meet the sensor tolerance of ±2–3% RH and guided us in performing automated calibration to compensate for drift over time.

Power Requirement

Each sensor takes around .3W of power to run. [6] Our station has a potential total of 7 sensors. The raspberry pi uses around 5W with normal load.

24 hours/day: 24hours * 7(.3W) + (24hours*5W) = 170.4 (Wh) = 0.1704 (kWh)

365 days/year: .1704 kWh * 365 days = 62.196 (kWh)

Per day: 0.1704 (kWh)

Per year: 62.196 (kWh)

A 60W solar panel would produce about 300 Wh daily with only 5 hours of direct sunlight assumed in the calculation. For reference, most solar panels on houses are between 250 W to 450 W.

A 60W is enough to power the entire station every day.

Budget

~$3000 worth of existing equipment.

Around ~$500 from client for expected additional costs.

Expected $300 contribution from the team.

Current plans:

- Family/Friends donations
- Local business sponsorship
- Other fundraising
- Possible Car Wash

Schedule

Weather Station

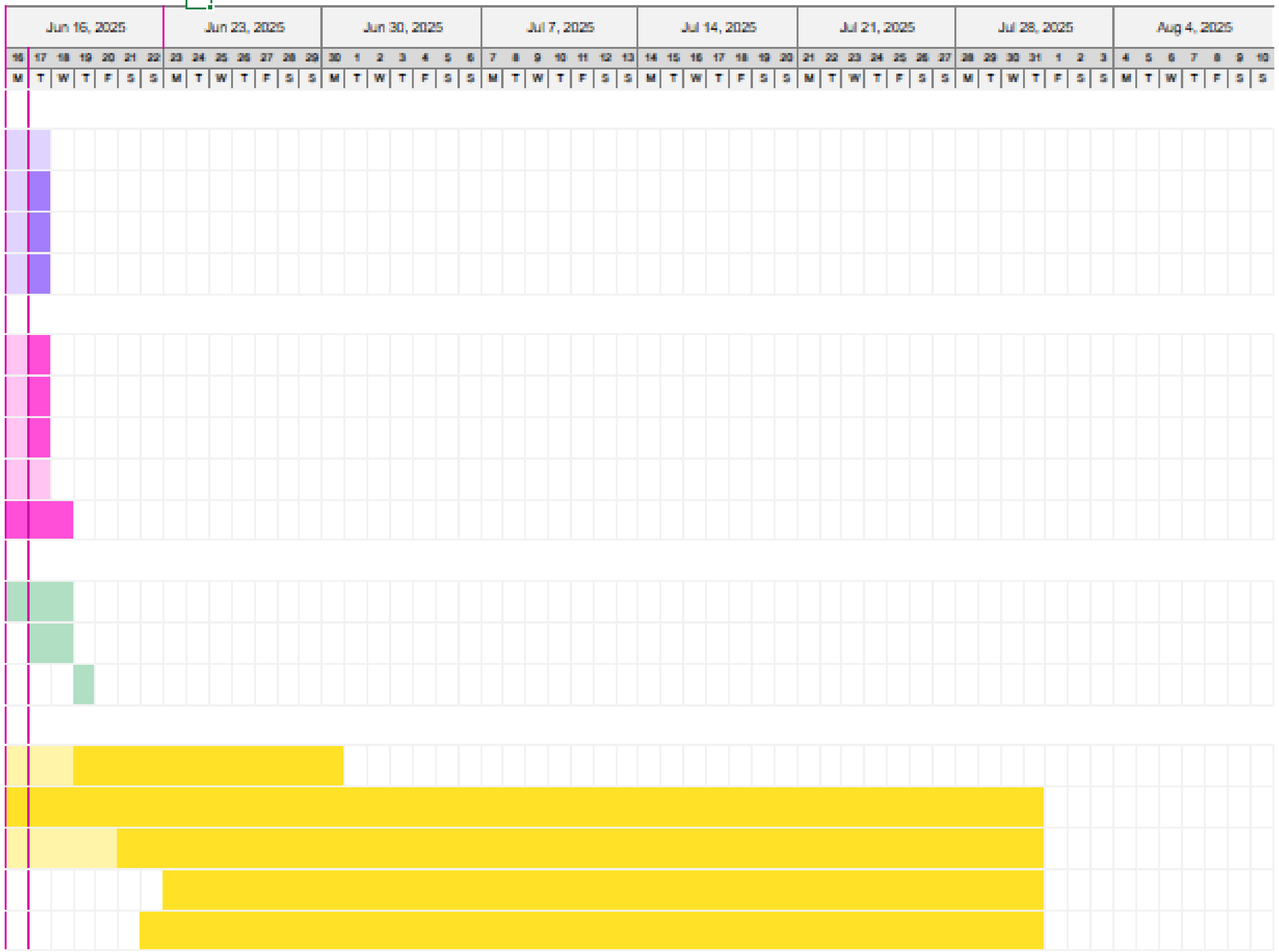
NAU Capstone   Project lead

Project start: **Mon, 6/16/2025**

Display week: **1**

SIMPLE GANTT CHART by Vertex42.com
https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

TASK	ASSIGNED TO	PROGRESS	START	END
Solid Works				
Tutorial 1	Everyone	100%	6/16/25	6/17/25
Tutorial 2	Everyone	50%	6/16/25	6/17/25
Tutorial 3	Everyone	50%	6/16/25	6/17/25
Turn in	Everyone	50%	6/16/25	6/17/25
Rough Draft Pres 1				
QFD	Rowan B McCullogh	50%	6/16/25	6/17/25
Research	Everyone	50%	6/16/25	6/17/25
Math Research	Everyone	50%	6/16/25	6/17/25
Gannt Chart Creation	Ian Torp	100%	6/16/25	6/17/25
Discuss with Client	Everyone	0%	6/16/25	6/18/25
Presentation 1				
Discuss with Client	Everyone	0%	6/16/25	6/18/25
Finalize document	Everyone	0%	6/17/25	6/18/25
Present	Everyone	0%	6/19/25	6/19/25
Future				
Establish Technical Advisor	Ian Torp	25%	6/16/25	6/30/25
Track expenses	Rowan B McCullogh	0%	6/16/25	7/31/25
Evaluate progress	Ian Torp	12%	6/16/25	7/31/25
Website	Shutong Wang	0%	6/23/25	7/31/25
CAD design	Cheroi Dong	0%	6/22/25	7/31/25



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Thank You & Questions?