Kansas State University

Remote Weather Station

ECE 590

Coalition of Weather Bois (COW-Bois)

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Executive Summary

Kansas State University oversees a Mesonet System with the plan to collect data and review it over long periods of time. This data is helpful in many models, especially modeling climate change across Kansas over very long periods of time. The station should measure temperature, humidity, solar radiation, wind speed, wind direction, air quality, and precipitation at the minimum. The data also needs to be transmitted across Kansas wirelessly from a remote area. The station will also be able to communicate with smaller stations (micro-stations) around the main station that will use the cell modem.

Extensive research leads to no solution on the market that produces the desired output. The only way micro-station capabilities can be implemented is to implement custom controls but this still does not cut costs down. So, the final decision is to make a design that imitates the Mesonet Station’s measurements while also being small and having easy maintenance.

This design will cost about $600-$800 to make and test. The budget is separated into many categories that range from electronics and sensors to data plans and mechanical designs. Sensors will be tested before implementation using the testing labs of the Mesonet that can do temperature and solar radiation in a controlled environment. Close to the end of development, the plan would be to test the product in the field next to the Mesonet Station here in Manhattan to compare and correlate the custom station’s data with the current Mesonet data and see how close they match. This will check the completeness of the project.

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Project Description

Background and Motivation

Weather has a very large effect on daily life, agriculture, infrastructure planning, and public safety. Having accurate and localized weather data is very important for understanding environmental conditions like temperature, humidity, precipitation, wind, and soil moisture, all of which have an influence on the decisions made by farmers, researchers, and emergency response teams. The Kansas State University (KSU) Mesonet gives these needed measurements through a network of automated weather stations across the state. Each station collects data on air temperature, humidity, wind speed and direction, precipitation, pressure, solar radiation, and soil conditions. The data is transmitted to centralized servers where they are quality checked and made publicly available to support research, agriculture, and environment management [2].

However, the current KSU Mesonet stations are expensive to build and maintain, costing around $19,000 per unit. This cost limits the number of stations that can be used and leaves certain regions of Kansas without coverage. The motivation for this project comes from the need to design a more affordable and mobile weather station that can give reliable, high-quality data at a much cheaper cost. By lowering expenses, the Mesonet could expand its network, improve localized data collection, and improve Kansas's ability to track environmental conditions in real time.

The goal is to design a low-cost remote weather station, estimated at $600-$800, that measures key factors such as temperature, humidity, pressure, wind speed and direction, solar radiation, precipitation, soil temperature, soil moisture, and air quality. The system will be powered using solar power and battery storage, making it good for remote use. Each sensor will be “plug and play”, allowing for simple replacements, and the system will transmit data wirelessly to a centralized database.

The design follows national standards said in the American Association of State Climatologists (AASC) Recommendations and Best Practices for Mesonets, which says that Mesonets must have high quality data, consistent sampling rates, and reliable sensor accuracy to meet both scientific and public needs. [6]. For example, the AASC recommends that Mesonet air temperature sensors maintain an accuracy of ±0.5 °C, relative humidity sensors ±3%, and wind speed sensors ±0.3 m/s below 20 m/s [6]. It also says that reliable Mesonet networks should maintain 95% or higher data availability to ensure completeness of data for climate and forecasting applications [6]. The team aims to meet these standards while keeping the total system cost below $1,000.

Additionally, the AASC stresses that sensor exposure is very important for accurate data collection. Stations should be installed on flat, natural surfaces at least 100 m^2 in area and free from environmental bias like buildings or trees [6]. By making a smaller, more mobile, and cheaper design that can be used in a wide range of terrains, the weather station can help achieve better coverage in neglected regions, improving data coverage and consistency across the Kansas landscape.

By following these best practices, the project supports the KSU Mesonet’s mission to expand weather monitoring across Kansas through innovation and accessibility. This design's ultimate motivation is to close the gap between cost and quality, giving a maintainable and standards-following weather station that gives reliable environment data. Overall, the purpose of the design is to improve Kansas’s agricultural efficiency and weather awareness through innovative and affordable solutions.

Problem Statement

The KSU Mesonet System collects climate data across Kansas using weather stations that are expensive and complicated to do installation and maintenance on. Due to these issues, the Mesonet System can only cover a limited area across Kansas. This problem results in loss of data and limitations with their budget to extend their coverage.

Project Requirements

The project requirements are listed in the table below

ID	Project Requirements	Description
1.0	Cost Efficiency (<19,00)	The current Mesonet station costs $19,000. The budget is $600 to $800
2.0	Wireless Transmission of Data Distance being >= 410 Miles	Data will need to be transferred over the entire state of Kansas
3.0	Easily replaceable sensors (Convenient maintenance)	Ability to make the replacement of sensors as simple as possible, a plug and unplug approach makes this straightforward
4.0	Off Grid Power Capabilities in a remote area	Needs to be a self-sustaining system and be able to power and charge itself
5.0	Size maximum (1.5ft x 1.5ft x 1.5ft)	Overall maximum size that was mentioned to be maximum (cooler sized)
5.1	Size minimization	Though a maximum size is set, the plan is to shoot for a smaller compact system
6.0	Sensor Accuracy	The sensor accuracy varies between the types of sensors
6.1	Temperature	The Temperature sensor needs to meet the Mesonet standard of ~0.3°C - ~0.4°C
6.2	Humidity	The Humidity sensor needs to meet the Mesonet standard of ~2% - ~3%
6.3	Solar Radiation	The Solar Radiation sensor needs to meet the Mesonet standard of ~5% (Resolution 0.2 W/m^2
6.4	Wind Speed Wind Direction	The Wind Speed sensor needs to meet the Mesonet standard of ~0.3 m/s, Wind Direction needs to be ~3°
6.5	Precipitation	The Precipitation sensor needs to meet the Mesonet standard of ~1% - ~5% (Resolution 0.254mm)
6.6	Air Quality	Mesonet does not currently have an Air Quality standard
6.7	Pressure	The Pressure sensor needs to meet the Mesonet standard of (~1mb)
7.0	Weather resistant station of IP54 [1]	Make the station dust-protected and splash resistant

The first requirement is cost efficiency, the current Mesonet setup costs roughly $19,000. This makes it very expensive to have multiple stations across Kansas. The goal is to reduce the cost so the Mesonet can have more stations, giving a clearer picture of the climate across Kansas. The aim is to keep the cost within the $600 to $800 range. The next requirement is wireless transmission capability. The weather station is intended to be in remote locations, so wireless communication is essential. Data needs to be able to be transmitted across the entire state of Kansas, roughly 410 miles. The station also needs to have simple maintenance. If the sensors are simple to replace, like a plug and unplug approach, it would not require a skilled technician to replace. This would reduce costs, as well as make it easily maintainable. The station also needs to be self-sufficient. The location of the station is unknown, but it will be remote, so it should be guaranteed the station will be able to be powered anywhere. This means the stations need to be able to power and charge themselves. The size of the station also needs to be considered. Transportation of the station should be easy and not involve special equipment. The size requirement is a maximum of 1.5ft x 1.5ft x 1.5ft, although a smaller, more compact design is a better outcome.

For sensor accuracy, the Mesonet already has requirements for their current sensors on its website [1]. The goal is to meet these requirements but realize that it may not be possible due to budgeting the project. Regardless, the sensors should be as accurate as possible.

For the weather proofing requirement, the goal is to have the station follow the IEC 60529 standard that will make the station weather resistant. The ingress protection (IP) rating should be IP54 or higher which means the station is dust-protected and water splash protected [1]. If the station can be more water or dust resistant without exceeding the budget, then that will be the desired approach.

Validation and Acceptance Tests

The verification matrix shows the approach that will be used to verify each of the listed requirements mentioned before for successful completion of the project. The cost effectiveness of the design will be evaluated in an analysis once it has been fully constructed. It will be straightforward to complete, only requiring the comparison of the final cost of the project components to the original budget.

Verifying the wireless transmission distance of the design is less straightforward than verifying cost efficiency. Instead of testing whether the design can transmit the full 410-mile radius, it will be demonstrated that it can transmit over a shorter distance (10 – 15 miles). This creates less of a burden on team members, as cellular communication is a method of communication that already has a proven track record of functioning well over long distances.

To verify convenient maintenance of the weather station design, it will be demonstrated that the sensors and other often replaced components in the design can be easily swapped out with minimal background knowledge on electrical engineering. The goal is to create a system that can be maintained by a layman who may not have any experience with the technical side of electronics. Therefore, the concept of "plug-and-play" is one that must be true of the final design. Verification of this will include speed replacement tests by team members, and a test involving a non-electrical engineer prompted by the final written documentation for the weather module.

Verification of off-grid power functionality and design footprint is simply a yes or no question and can be confirmed by inspection upon project completion. Does the design source power from anything connected to the grid? Does the design fit within a 3.375 cubic foot box?

Size minimization is more convoluted. There is not a specific size minimization requirement of course, but a minimized design improves the overall portability and subtlety of the module’s design, allowing for easier transport and less obstruction in the environment, which is why minimizing size is a requirement for the team. Therefore, a simple demonstration of the module’s portability and unobtrusive stature, especially when compared to the current tower design of the Mesonet, will show this requirement complete.

Next, the sensors will be verified by testing once the weather module has been fully constructed. It is essential that the sensors not only work independently but are also implemented in the system as a whole. Therefore, the sensors will be confirmed accurate individually early in the design process. They must be confirmed to be accurate within the Mesonet’s existing sensor accuracies. Once the project is complete, the same test will be complete, and the data quality this time will be measured up against existing Mesonet sensor data. This will be complete by placing the final design next to a pre-existing Mesonet tower and simply comparing the data collected over the period of a few days to a few weeks.

Finally, adherence of the weather station to the IP54 weatherproofing standard will need to be verified by demonstration. The final design will need to be able to withstand the elements, namely rainy and windy conditions, without being damaged or destroyed. This will require, most urgently, fully waterproofing of the design, and will be demonstrated and verified when the sensor testing is performed in the field over the course of several days. The most obvious sign of failure is if the module stops working during this period. Further testing could be done if the team is still unsure of whether the design is fully water or weatherproof after this, and could consist of simulated rain and wind.

Verification and Validation Matrix

ID	Requirement	Verification Method			
		Analysis	**Demonstration**	**Inspection**	**Test**
1.0	Cost Efficient	X			
2.0	Wireless Transmission Distance			X	
3.0	Convenient maintenance		X		
4.0	Off Grid Power				X
5.0	Size maximum			X	
5.1	Size minimization		X		
6.0 - 6.7	Sensor Accuracy				X
7.0	Weather resistant station of IP54 [1]		X		

Data Needed to Support Analysis

To confirm the design meets the required sensor accuracy, the data from the Mesonet's current station is needed at the same time the design that is made is being tested. This will require a field test of the custom weather station near one of the existing towers. The Mesonet's measurements will act as a baseline for the confirmation of the custom station sensor's required accuracy.

Technical Design

Possible Solutions and Design Alternatives

Design parameters and requirements point towards the idea of a commercial weather station. It is small and can perform most of the Mesonet Station measurements and meets the budget and timeline of the available class time given. In Figure 1, it shows the current Mesonet Station. The tower and all the sensors together cost more than $19,000 to produce and as of October 2019 they have installed 62 stations across Kansas [3]. Some of the stations are not 30-foot towers either, some are just tripod stations. To avoid this cost and maintenance of a 30-foot tower, the plan is construction of a smaller commercial station and test the accuracy compared to the Mesonet Station to see how closely it aligns.

Figure 1: KSU Mesonet Current Tower (Ref)

Figure 2: Wireless Remote Weather Station from Amazon by Raddy

Researching design alternatives, most options are like the one pictured in Figure 2. These are good options because they are small, cost efficient and measure some of the required data values up to close accuracy that compare to the Mesonet Stations. They seem like good options except for one of the requirements of easy maintenance. There are no replacements for separate sensors leading to less budget friendly replacements of entire stations. The other addition is micro station modeling. Research shows there is no implementation in commercial stations of what the client is looking for. Stations transmitting to one data server do exist, but they are not cost effective and do not do all the required measurements.

Another idea is implementing custom controls into a design that was already made. The design could be the current stations that are installed, but this does not solve the problem of cost efficiency. A solution to implement controls into an already made commercial station also presents itself, but the feasibility of this would be very difficult to measure.

The final approach is to make a design that is sized similarly to a commercial station with custom hardware that meets the client's requests and requirements. To meet this, the station will most likely need to be a custom casing, which has a higher potential to save on cost.

Selection Process for Preliminary Design Solution

The design that was selected was to create a custom station with a designed casing with sensors and custom hardware implemented inside. Implementing the custom hardware into an already design casing seems to be a good second alternative, but feasibility of this approach might be difficult to measure. The best option for the design to meet all the requirements would be a small station that can be easily installed and has quick maintenance. This selected solution requires individual parts for each requirement that the system must meet. The parameters are as follows:

- Sensors
  - Chips and PCBs for measuring

    - Addition Mechanical Sensors built for budget

- Microcontroller
- Cell Modem/long range communication device
- Some form of power supply or battery with charging system

These decisions will be made in greater depth starting with sensors:

When choosing sensors, the factors that matter are Price, Durability, Accuracy, Connectivity, and if it was a single sensor or a combined sensor package. Adafruit offers a wide variety of sensors that are within the price range, that also fulfills other needs as well. Adafruit offers unique connectivity capabilities on a variety of their sensors. Their “STEMMA QT” connectors allow for users to plug into their sensors instead of soldering [4]. This is beneficial as it would allow for sensors to be easily replaceable. Accuracy of the sensors is also very important, but further testing will be required to confirm their specifications.

Most of sensors are essentially just protoboards with no housing. This means the durability of the sensors will be reliant on the design of the weather station. Some solutions to weatherproof the sensors include a 3D printed housing, covering in resin, and wrapping in plastic. Further testing will be conducted to find the most efficient solution. Another consideration is whether the sensor was a combined sensor package. That would cut costs because there won’t be a need for multiple sensors, as well as allow for a more compact design. However, if the sensor accuracy was compromised due to the combination, the decision would likely be the single sensor. This is another parameter that will ultimately be decided through further testing.

(1 – 5) 1 is worst, 5 is best	Adafruit Temp and Humidity	Adafruit Temp, Humidity, and Pressure	Adafruit Temp	Solar Radiation	Ambient light	Adafruit Air Quality	Adafruit Air Quality Stemma
Price	3	2	4	1	4	2	4
Durability	3	3	3	3	3	3	3
Accuracy	3	1	4	5	5	3	2
Connectivity	5	5	5	2	2	5	5
Combination	3	5	2	1	1	1	1
Total Score	17	16	**18**	12	**15**	14	**15**

The decision matrix above shows some of the choices for the selected sensors. The total score shows the selected sensors by bolding and underlining the numbers. This will be true for all the following decision matrices.

Some sensors will be built instead of purchased. This approach helps make the station more affordable and given the plans, schematics and models for the constructed sensors, the KSU Mesonet can make the constructed sensors themselves for cheaper maintenance. The decision matrix below showcases the choices for the two sensors that can be constructed.

Criteria	Description	Importance (1-5 scale)	Bend senor Anemometer	Sonar Anemometer	Ping Pong Ball Anemometer and fin	Seesaw with weight sensors	Scale water dump method
Feasibility	Is it even possible?	5	4	2	5	3	4
Budget	Does the design fit the budget?	5	5	2	3	4	4
Durability	Will it break easier due to elements?	3	5	5	3	4	3
Accuracy	Will it accurately read what is needed?	4	4	5	3	4	4
Total			**<u>76</u>**	55	61	63	**<u>65</u>**

The matrix is separated by the criteria and its importance, wind speed/direction sensor types and precipitation sensor types. The matrix categories are separated by the bold lines and the final selection for each category is shown in the total row. The underlined and bolded number is the selected type.

For wind speed/direction, the flex sensor anemometer seemed to be the best because it provides less mechanical moving parts and seemed feasible with the timeline. This choice also provided cost effectiveness and less moving parts that could potentially increase the lifespan of the anemometer. This design was made and tested by “Smart Solutions for Home” on YouTube and proves to work quite well [5]. Following a similar design approach makes this more feasible.

For precipitation, the two types of designs are very close score wise. The decision to try the rain gauge that measures the weight of the water was selected due to higher feasibility with the mechanics. According to the American Association of State Climatologists' (AACS) adopted article titled "Recommendations and Best Practices for Mesonets", they mention that weighing rain gauges using load cells is commonly used in high accuracy systems. The AACS also mentions wind shields surrounding the precipitation sensor to help guide the water into the sensor more, but it recommends it but does not require it [6]. This can be implanted to a certain degree using the anemometer as a slight wind shield.

Criteria	**Description**	**Importance (1-5 scale)**	**ESP32-WROOM-32U**	**STM32F407**	**RP2040**
Feasibility	Can it handle sensors & wireless?	5	5	4	3
Budget	Fits within project cost?	4	5	3	4
Capabilities	Processing power, memory, I/O	5	5	4	3
Integration	Ease of adding sensors & communication	5	5	4	3
Reliability	Suitable for outdoor/long-term use	3	4	4	3
Community Support	Libraries & documentation	2	5	4	3
Total			**131**	**101**	**84**

When choosing the best microcontroller for the remote weather station, it was between three different options: the ESP32-WROOM-32U, STM32F407, and RP2040. Each microcontroller was scored based on six factors: feasibility, budget, capabilities, integration, reliability, and community support. These factors were given weight based on how important they are to meeting the project goals, as shown in the decision matrix above.

The ESP32-WROOM-32U scored the highest overall score with 131 points. Coming in second was the STM32F407 with 101 points and the RP2040 was last with 84 points. The ESP32-WROOM-32U scored the best because it is powerful, affordable, and has built-in Wi-Fi and Bluetooth. This allows it to handle multiple sensors and wireless communication without extra hardware. This makes the design simpler, cheaper, and easier to maintain.

The STM32F407 has good processing power and reliability, but it is more expensive and needs extra components for networking. The RP2040 is cheap, but it lacks wireless capability and has less processing power, making it not a great choice for the design.

Another important reason for choosing the ESP32-WROOM-32U is its large community with many well-supported libraries and documentation. This will make development and troubleshooting much faster and easier once the build phase begins. Overall, the ESP32-WROOM-32U gives the best balance of cost, performance, and ease of use, making it the best choice for the remote weather station design.

The modem selection followed a similar pattern. Several options were considered then narrowed down to a top three, which were compared against each other across the categories of feasibility, integration, capabilities, power consumption, and budget. They were then given a weighted score, and the highest score would be selected. These results are summarized in the following table:

Criteria	Description	Importance (1-5 scale)	Notecard Cellular LTE Cat-1	Quectel BG95	LILYGO T-SIM7600G-H R2
Feasibility	Compatibility with planned sensor setup	5	4	4	5
Integration	Ability for integration with ESP32 and I2C	4	4	3	5
Capabilities	4G LTE capability	5	5	5	5
Power Consumption	Does the modem draw an unreasonable amount of power?	4	4	4	4
Budget	<$200 Price	5	4	5	4
Total			97	98	**106**

As can be seen, the LILYGO T-SIM7600G-H R2 scored the highest of the three. While each of the other two options, the Notecard CAT-1 and Quectel BG95 would likely work, the LILYGO fits the project needs the best because it comes pre-integrated with the EPS32. The LILYGO is built onto the same board as the ESP32, which naturally allows it to be streamlined seamlessly. It is compatible with I2C and has 4G LTE capability, along with a very reasonable price of $58.50. This modem will be able to transmit data over long distances and satisfy all of the criteria of the project design.

Criteria	Description	Importance (1-5 scale)	Solar Panel and Battery	Wind Turbine Generator	3 Phase AC Integrated with Solar
Feasibility	Is it even possible?	5	5	0	0
Budget	Does the design fit the budget?	5	4	0	0
Efficiency	Is the design able to provide the needed power efficiently?	4	3	5	5
Consistency	Is the design able to supply the needed power consistently?	5	3	3	5
Total			**72**	35	45

The power system requirements for the remote weather station module are quite robust. The first design choice was the selection of a top-level design route. This consists of how the required energy will be generated, and how it will be stored and transported throughout the system. This device will be operating completely off grid in remote locations in the state of Kansas; therefore, avoiding frequent maintenance trips for things like battery replacement or solar panel repairs is crucial. If the system is too fragile or unreliable, its feasibility for in-field use is close to zero, as the Mesonet team realistically can't make a trip to every station every week.

The initial design idea was a battery and solar panel setup. This would allow the weather module to operate completely off of the grid and, if designed correctly, with little to no maintenance. This design is also budget friendly, the main cost being the battery and solar panel themselves as conversion equipment is cheap to buy or build. The design does fall short in efficiency and consistency. Current solar panel technology is not as efficient as its renewable counterpart wind generation, and it also relies solely on weather conditions to enable its generation capabilities. If the sun is not shining, the solar panel is not generating electricity.

Related of course would be the use of wind generation or a wind turbine. This design immediately falls short in the budget category. While not the most expensive, a wind turbine fitting the size estimate would cost approximately $100-150, a quarter of the budget for the entire system. As stated previously, wind generation is more efficient in some ways, and Kansas is a prime location for generating electricity in this way. However, again, it relies heavily on weather conditions for its reliability.

Related would be the use of a wind generation system, or a wind turbine. Immediately this design choice falls short in the budget category. While not as expensive as the next design option, a wind turbine fitting the rough size estimate would cost $100-150, a quarter of the design budget for one component! Wind generation is more efficient in some ways, and Kansas is certainly a good place to harness the wind. It too, however, is dependent on weather conditions for its reliability.

The last consideration was the incorporation of 3-phase power into the power distribution network. This would increase the efficiency of power delivery but would still require a solar panel or wind turbine to generate the electricity, meaning this is the priciest option. It would also add a large amount of complexity to the design and incorporate problems the team is not currently equipped to solve.

Therefore, the simple battery and solar panel design was selected as the most feasible in the given time frame and budget range as well as what minimizes the risk of an incomplete project come May. What then will this design look like? What must be true of the rest of the system before sizing and designing the power system can commence?

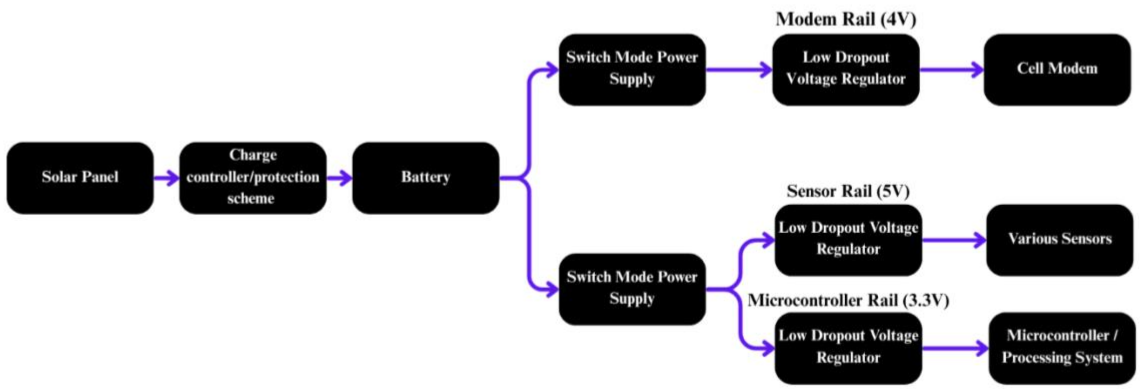


Figure 3: Top Level Design Flow of Power System Design

The figure above details a high-level idea of what the final design will look like. While counterintuitive to the figure's flow, the design process will begin on the right and work left. Before any network can be designed, the amount of current required for each of the three main sections of the design must be determined. The sensor current draw will be calculated when Kennedy tests the sensors. The microcontroller current draw is already known, at around 300-400 mA constant demand. That leaves the complex piece, the modem. Further analysis will be done before the design process begins, but as it stands, it appears that the modem being utilized, the SIM7600E-H, will draw a small 5 mA while in sleep mode, and a much larger 2A while transmitting. This will require some control design to implement.

Regardless of current requirements, a charge controller/MPPT will be required to control and monitor the power generation of the solar panel. At least two switch mode power supplies will be needed to generate a 5V and 4V rail. And finally, low dropout voltage regulators will be needed to fine tune the voltage level to the appropriate required levels (5V, 4V, and 3.3V). The switch mode power supply requirements and low dropout voltage regulator requirements are subject to change as the design process commences.

Data Pre-Processing and Exploratory Data Analysis

The design is not dependent on analyzing data beforehand. The data and measurements required are during the testing phase (testing sensor accuracy in the lab) and after the design is finalized (in the field with the current Mesonet station). The data needed from the Mesonet is on their website and open to use. This data helps correlate whether the custom station's data is up to the Mesonet standard (the requirements). The extracted data will be used during testing at the beginning and then finalized and collected by a home assistant server. The data taken from the final design will be transmitted through an MQTT Broker and stored on a server that can be extracted as CSV files.

Preliminary Design/Solution Description

Global Issues

1. Climate Change and Weather Monitoring
    a. Summary: Climate change is causing harsher weather events like droughts, floods, and heatwaves. This is a worldwide problem, and Kansas is affected by it too. Farmers and researchers need local weather data to help prepare for these events to reduce damage.
    b. Resolution: The weather station design helps with being low cost and mobile. This will allow it to be placed in more rural areas that don't have coverage currently. This will improve weather tracking in Kansas and could help with global climate tracking.
2. Energy Efficiency and Sustainability
    a. Summary: Energy use and sustainability are very big concerns when making a design like this. Remote weather stations need to run continuously, even in areas without reliable power.
    b. Resolution: The system uses solar panels and rechargeable batteries to stay powered without relying on outside electricity. The microcontroller (the ESP32) also can run in low power mode, which helps it last longer and keeps the station environmentally friendly.
3. Data Accuracy and Reliability
    a. Summary: Accurate data is important for scientists, farmers, and safety teams. If data is missing or unreliable, it can lead to wrong decisions.

b. Resolution: Follow the AASC standards for sensor accuracy and data quality. Sensors will be calibrated and tested before implementation and designed for easy maintenance [6].

4. Affordability and Accessibility
   a. Summary: Even though the design is for the KSU Mesonet, many areas around the world still cannot afford expensive weather stations and could use this design. Not being able to afford expensive weather stations limits their ability to collect reliable weather data.
   b. Resolution: The project focuses on making a station under $800, using affordable parts like the ESP32 microcontroller. The station would be easy to repair, making it more cost effective. This would mean more stations could be used, even in developing areas with less money.

System-level Overview

Following the decision matrices, the plan is to make a small station that will include all desired measurements and will be able to be implemented easily. The hardware block diagram for the design is shown in Figure 4:

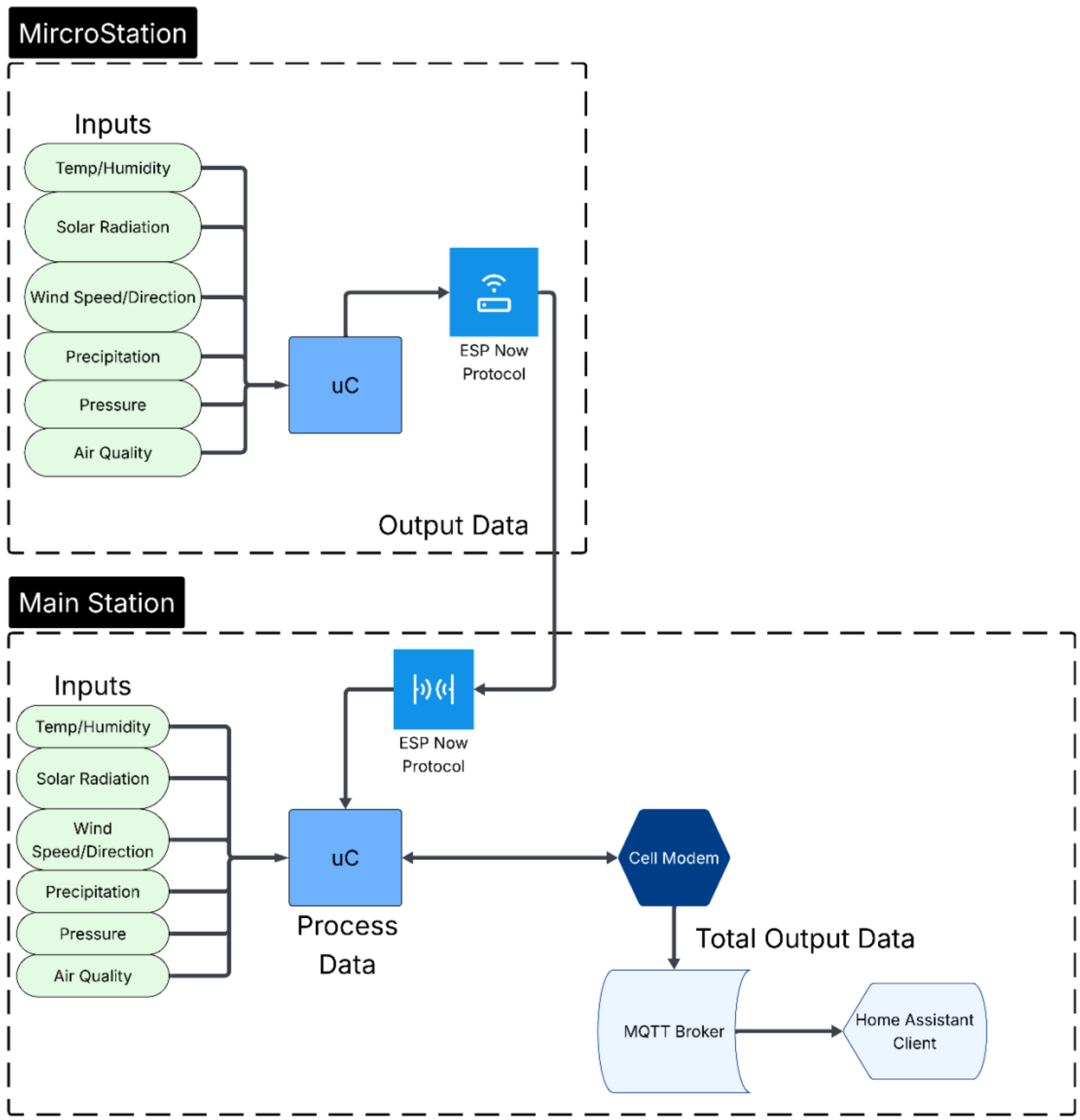


Figure 4: Block Diagram of the Design

This diagram showcases the use of a main station transmitting with a cell modem and SIM card, as well as the micro station that uses ESP Now protocol to communicate with the main station (importance of using the ESP32 microcontroller). This design also showcases the flow of data from the inputs, being processed by the microcontroller and finally being transmitted using a Message Queuing Telemetry Transport (MQTT) protocol (from the main station) to transmit the measured data over a long distance to a receiving client server like home assistant. The inputs will communicate with the microcontroller with I2C or an analog-to-digital converter (ADC). The data will be processed and averaged, then transmitted using ESP Now or the cell modem.

For the mechanical design and casing, the idea is to put the wind gauge anemometer in the middle and have everything be below it. This is so the wind speed and direction measurements are not affected by any of the other sensors. The precipitation and power will be on the sides to have more accurate readings and operate more efficiently. The design sketch of the station is below in Figure 5:

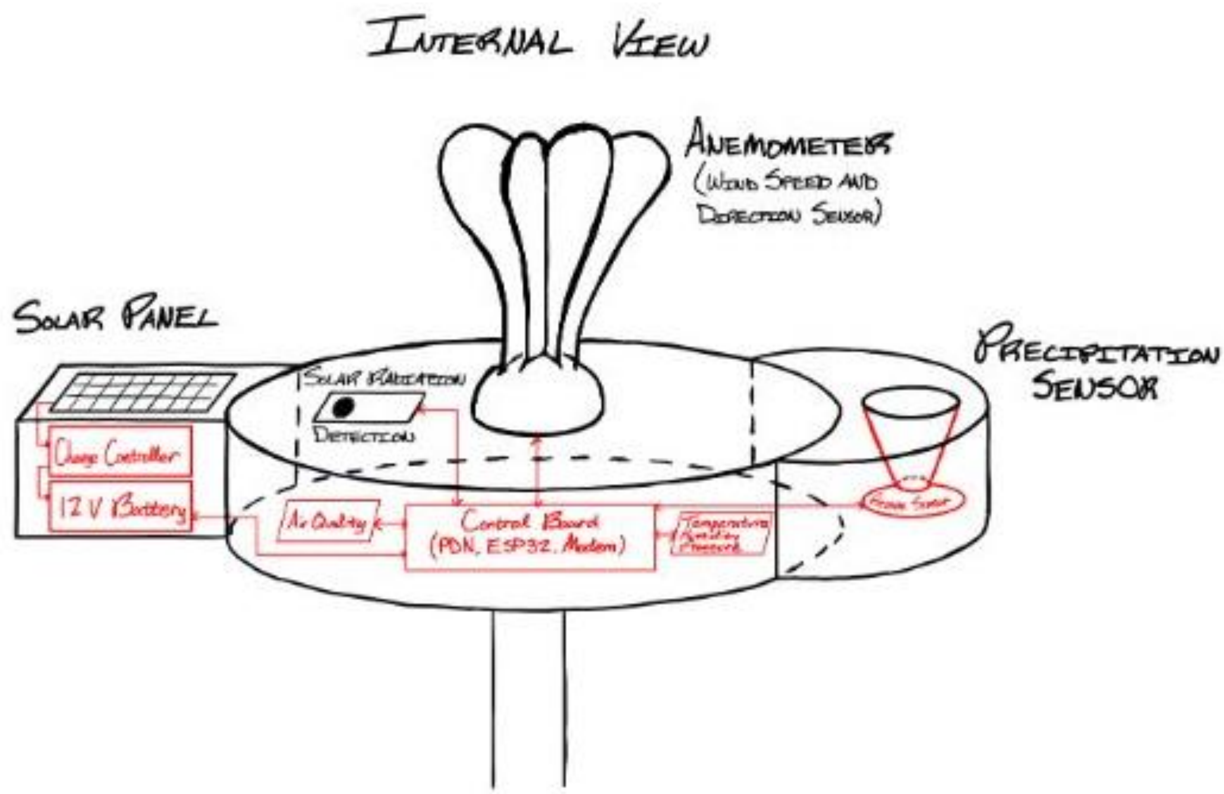


Figure 5: Sketch of Weather Station

The relevant reference is the station pictured in Figure 2. This station is set up on a rod and takes measurements and sends data to an online server.

Applicable Standards

Main System and Communication Standards

JEDEC Standard JESD8-3 – Standard for TTL (Transistor-Transistor Logic) voltages. The interface that will be used in the project is the 5V logic interface for most of the sensors and processing [7].

NXP UM10204: I2C-bus Specification and User Manual – Industry standard of a communication protocol over short distances between chips and devices using two communication lines. One clock line and one data line [8].

FCC Title 47 CFR Part 15 (Unlicensed Transmitters) – Because the device is a radio frequency device, it is necessary to comply with the FCC Regulations and make sure the data can transmit using a cell modem [9].

Adafruit Stemma QT Overview; JST SH Connector Datasheet – Not an industry standard but a connection standard set by Adafruit to connect multiple sensors together with I2C. If made the standard, then maintenance will be a lot easier [4].

3GPP (3rd Generation Partnership Project) System Architecture – International standards for 2G, 3G, 4G, 5G, and LTE communication

- The modem selected must comply with this standard.

IEC 60529 Ingress Protection (IP) Rating – Standard for enclosures for electrical equipment with a rated voltage not exceeding 72.5 kilovolts.

- The enclosure will be rated for an IP54 for dust and water resistance (making it weather resistant) [1].

Power System Standards through IEEE [10]

IEEE Std 1547™-2018 – Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces

- Goes over the common practices and design requirements for voltage converters (switch mode power supplies).

IEEE Std 1547.1-2020 – Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces

- Includes ways to confirm correct functionality of converter design and performance.

IEEE Std 1547.9-2022 – Using IEEE Std 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems

- Outlines how to integrate batteries into small scale power distribution systems.

IEEE Std 2030.2.1-2019 – Design, Operation, and Maintenance of Battery Energy Storage Systems, both Stationary and Mobile, and Applications Integrated with Electric Power Systems

- Will help with battery selection for the needs of the system.

IEEE Std 1679 (family) – Recommended Practice for the Characterization and Evaluation of Energy Storage Technologies in Stationary Applications

- May not be as useful, deals mostly with battery chemistry, could affect selection based on the environment (Kansas).

IEEE Std 519-2014 – Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

- Helps establish harmonic limits (in layman's terms, helps eliminate issues that may arise when using switches and how that may interact with the sensors and other components). This will be useful in controlling the power system's delivery (namely, the modem).

Module-level Descriptions

The module level descriptions will be for the inputs, processing of the data, and receiving the outputs. For the inputs, it takes measurements using the sensors that use Analog-to-Digital Converters (ADCs) and transmitting the data to the microcontroller using I2C for some sensors. Sensors will be purchased trying to have the Stemma QT connector which will make maintenance of the system easier [4]. The wind speed, direction and precipitation sensors are going to be directly connected to the ESP32 ADC. Additionally, connectors can be added to allow for more sensors to be added to the system. This allows the client or customer to add additional sensors later.

Next is the microcontroller. It needs to take measurements every 3 seconds and transmit the data every 5 minutes. This is the recommended timeline for data collection and transmission according to the AASC document [6]. How the data gets transferred depends on whether the station is the main station with the cell modem and SIM card or if it is a micro station that just needs to get the data to the main station using ESP Now. This main station and micro station can be configured with a pin header that is pulled low or high. This selects the output path of the data, and it will follow the programming block diagram in Figure 6.

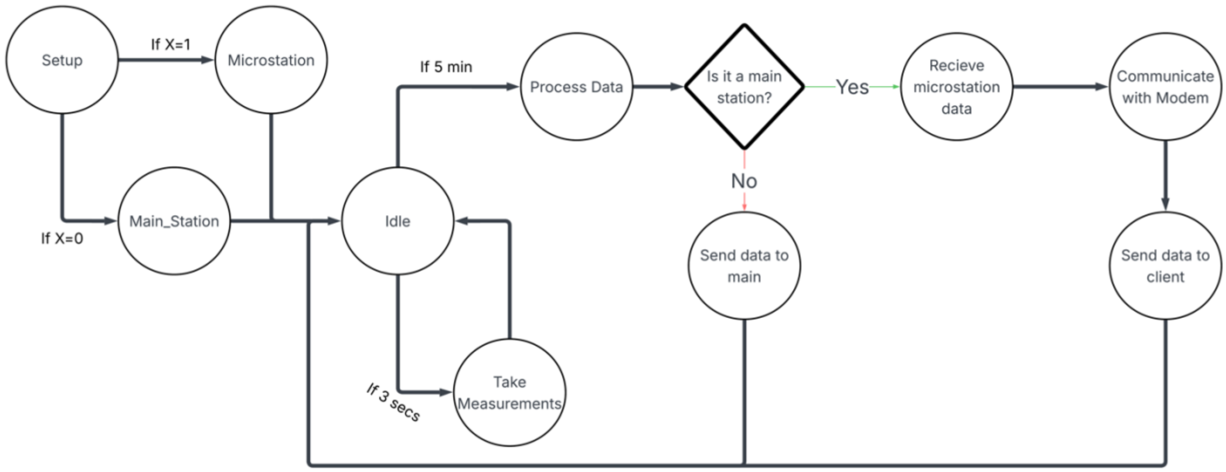


Figure 6: State Machine of Microcontroller

The micro station will transmit data to the main station. For testing purposes, the micro station can just measure temperature and humidity to make sure this process is more cost effective.

The main station first has to receive the data from the micro station(s). Once it receives all the data, it will load it up and send it to the cell modem. The cell modem then transmits the data wirelessly over long distances to be received by a client that can extract and observe the data. The data should also be able to be extracted as a csv file so it can be stored and monitored long term. The overall bullet points of the system modules are as follows:

- Inputs:
  - Sensors using I2C
  - Built Sensors using ADCs from the microcontroller
- Processing:
  - Taking samples every 3 seconds
  - Receiving micro station data using ESP Now
  - Averaging the data over 5 minutes
- Outputs:
  - Organizing data
  - Sending data to the cell modem
  - Sending data to the MQTT Broker
  - Getting the data to a client server that receives the data and can process it
  - Data format can be exported as a csv

Work Plan

Work Breakdown Structure & RACI Chart

The work plan for the product cycle is separated into 4 phases, phase 1 (Designing and Testing), phase 2 (Construction and Build Testing), phase 3 (weather proofing and checkoffs), and finally phase 4 (Field Testing and Data Comparison). The Table below shows the RACI which stands for Responsible, Accountable, Consulted and Informed. These specify which members have which responsibilities. For members that are accountable, they help assist the member that is responsible for the task and make sure that member is on schedule for deadlines. Consulted members are members that need to know the progress of the task being completed. The rest of the members shall be informed of the progress of the responsible member's section.

Each member has a general design style that they are assigned. It is as follows:

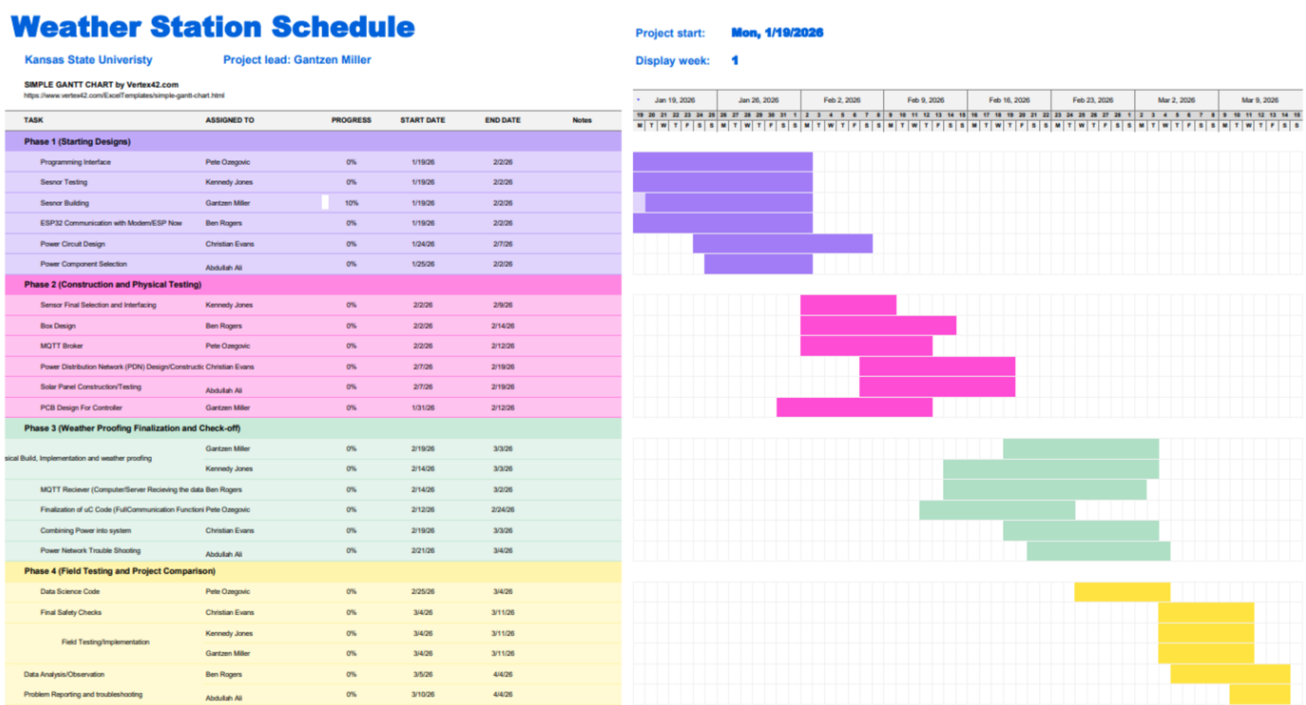
- Gantzen Miller - Hardware/Mechanical Design
- Kennedy Jones - Hardware/Mechanical Design
- Pete Ozegovic - Software Design
- Ben Rogers - Software/Mechanical Design
- Christian Evans - Power System/Hardware Design
- Abdullah Ali - Power System Design

ID	Task	Gantzen Miller	Kennedy Jones	Christian Evans	Abdullah Ali	Pete Ozegovic	Ben Rogers
Phase 1 (Starting Designs)							
#1.0	Program Interface	I	C	I	I	R	A
#2.0	Test Sensor Accuracy	A	R	I	I	C	I
#3.0	Build Sensors	R	A	I	I	C	I
#4.0	Modem Setup (MQTT)	C	I	I	I	A	R
#5.0	Power Circuit Design	C	I	R	A	I	I
#6.0	Power Component Selection	C	I	A	R	I	I
Phase 2 (Construction and Physical Testing)							
#7.0	Sensor Interfacing Plan	C	R	I	I	A	I
#8.0	Test Built Sensors	A	C	I	I	R	I
#9.0	Modem Communication Setup	C	I	I	I	A	R
#10.0	PDN Construction	C	I	R	A	I	I
#11.0	Solar Panel Construction	C	I	A	R	I	I
#12.0	PCB Design of Controller	R	I	I	I	C	A
Phase 3 (Weather Proofing Finalization and Checkoff)							
#13.0	Box Design	C	A	I	I	I	R
#14.0	Sensor Layout Design	A	R	I	I	I	C
#15.0	Weather Proofing Design	R	C	I	I	I	A
#16.0	ESP-Now and Code Finalization	I	I	A	C	R	I
#17.0	Combine Solar Setup and PDN	I	I	R	C	I	A
#18.0	PDN Trouble Shooting	I	I	A	R	I	C
Phase 4 (Field Testing and Project Comparison)							

#19.0	Data Science Code Construction	C	I	I	I	R	A
#20.0	Tying PDN to Station	C	I	R	A	I	I
#21.0	Field Testing	A	R	I	I	I	C
#21.1	Field Install	R	A	I	I	I	C
#22.0	Data Analysis	C	I	I	I	A	R
#23.0	Troubleshooting and Problem Reporting	C	I	A	R	I	I

Schedule (Gantt Chart)

Below in Figure 7 is a picture of the Gantt Chart Schedule. It follows the same format as the RACI Chart and Phases mentioned in the last section. Specific members are responsible for specific parts of each phase and there is overlap in the phase sections and between phases.



TASK	ASSIGNED TO	PROGRESS	START DATE	END DATE	Notes
Phase 1 (Starting Designs)					
Programming Interface	Pete Ozegovic	0%	1/19/26	2/2/26	
Sesnor Testing	Kennedy Jones	0%	1/19/26	2/2/26	
Sesnor Building	Gantzen Miller	10%	1/19/26	2/2/26	
ESP32 Communication with Modem/ESP Now	Ben Rogers	0%	1/19/26	2/2/26	
Power Circuit Design	Christian Evans	0%	1/24/26	2/7/26	
Power Component Selection	Abdullah Ali	0%	1/25/26	2/2/26	
Phase 2 (Construction and Physical Testing)					
Sensor Final Selection and Interfacing	Kennedy Jones	0%	2/2/26	2/9/26	
Box Design	Ben Rogers	0%	2/2/26	2/14/26	
MQTT Broker	Pete Ozegovic	0%	2/2/26	2/12/26	
Power Distribution Network (PDN) Design/Constructic	Christian Evans	0%	2/7/26	2/19/26	
Solar Panel Construction/Testing	Abdullah Ali	0%	2/7/26	2/19/26	
PCB Design For Controller	Gantzen Miller	0%	1/31/26	2/12/26	
Phase 3 (Weather Proofing Finalization and Check-off)					
sical Build, Implementation and weather proofing	Gantzen Miller	0%	2/19/26	3/3/26	
	Kennedy Jones	0%	2/14/26	3/3/26	
MQTT Reciever (Computer/Server Recieving the data	Ben Rogers	0%	2/14/26	3/2/26	
Finalization of uC Code (FullCommunication Functioni	Pete Ozegovic	0%	2/12/26	2/24/26	
Combining Power into system	Christian Evans	0%	2/19/26	3/3/26	
Power Network Trouble Shooting	Abdullah Ali	0%	2/21/26	3/4/26	
Phase 4 (Field Testing and Project Comparison)					
Data Science Code	Pete Ozegovic	0%	2/25/26	3/4/26	
Final Safety Checks	Christian Evans	0%	3/4/26	3/11/26	
Field Testing/Implementation	Kennedy Jones	0%	3/4/26	3/11/26	
	Gantzen Miller	0%	3/4/26	3/11/26	
Data Analysis/Observation	Ben Rogers	0%	3/5/26	4/4/26	
Problem Reporting and troubleshooting	Abdullah Ali	0%	3/10/26	4/4/26	

Figure 7: Gantt Chart Schedule

Prototyping and Testing Protocol

Most of the prototype and testing will be done for the sensor selection. The plan is to purchase a few types of each sensor and do testing in the lab to ensure accurate results. The Kansas State University Mesonet has a laboratory that will be used for testing. This laboratory has equipment that can control variables needed to test the accuracy of the sensors. The equipment can control temperature, humidity, pressure, precipitation, and many other variables. The use of this laboratory will aid in the selection of accurate sensors.

Financial Plan

Proposed Budget

This section will present the proposed budget for the project. The goal is to keep the total cost within the range of $600–$800 while ensuring the use of reliable components and materials. Some costs are still being evaluated, so the values provided are estimated maximums instead of exact values. The costs are organized into two sections: one for the Bill of Materials (BOM), which includes the main components used for the design, and two for Test Equipment/Apparatus, which lists tools and resources needed during testing and prototyping.

1. Bill of Materials (BOM)

Item	Purpose	Estimated Cost (USD)	Priority	Contingency Plan
Sensor Suite	Used to measure temperature, humidity, pressure, rainfall, wind, and solar radiation in the design.	\$150–\$200	High	If not funded, simulation data or university lab sensors will be used.
Hardware (PCB, Modem, charge controller, etc.)	Main electrical hardware for communication and processing	\$150–\$200	High	If necessary, can find a lower-cost controller or connect via wired link temporarily.
Enclosure and Mechanical Frame	Protect electronics and ensures the design is weather resistant and stable.	\$150–\$200	Medium	Can use recycled or 3D-printed materials as a temporary solution.
“Wiggle Room Funds”	Reserved for replacement parts or unexpected expenses during assembly or testing.	\$200 maximum	Low	These funds will only be used if needed.

2. Test Equipment and Apparatus

This section includes the tools and resources that will be used for prototyping, testing, and validation. Most of these items are available in the Kansas State University laboratories, so there will be no significant expenses here.

Item	Purpose	Estimated Cost (USD)	Priority	Contingency Plan
Multimeter and Oscilloscope	Used by the team for circuit testing and debugging.	$0 (Provided by Lab)	Medium	Can share instruments with other teams if needed.
Prototype Breadboards and Wires	Used to build and test the circuit connections.	$0 (Reuse Previous Equipment)	Low	Can reuse existing breadboards from previous labs.
Testing Power Supply	Help simulate the power input from the solar system.	$0 (Provided by Lab)	Medium	Will use the lab power supply or use simulation software.
Software Licenses (MATLAB/Arduino IDE)	Used for programming and data analysis in the project.	$0 (Student License)	High	Will rely on free or open-source versions if licensing becomes an issue.

3. Contingency and Funding Notes

The department provides limited funding to support student projects. If the project does not receive full funding, the plan is to prioritize purchasing critical components such as the sensors, microcontroller, and communication module. The power system will be simulated using lab resources until an affordable alternative is found. The added Wiggle Room Funds will ensure flexibility for unforeseen expenses, such as replacing damaged parts or handling unexpected issues during assembly or design process. Some parts, such as sensors or the enclosure, may be retained by team members after the course, and the parts that fall in this category will be flagged accordingly.

Feasibility Assessment

System Risks and Solutions

Risk 1: Insufficient generation/power in low generation periods (battery sagging)

The solar panel and battery setup faces challenges during extended cloudy periods or winter months when solar radiation is reduced. This risk threatens continuous operation of the weather station. The safety measure requires maintaining adequate safety margins in power needs and battery capacity to ensure the microcontroller, sensors (temperature, humidity, solar radiation, wind speed/direction, precipitation, pressure, and air quality), and cellular modem remain operational.

Recommended Solutions:

- Implement a hybrid power system combining solar panels with a backup battery bank sized for 5-7 days of autonomous operation without sunlight
- Add low-power sleep modes for the ESP32 microcontroller to reduce consumption during low-generation periods
- Install charge controllers with Maximum Power Point Tracking (MPPT) to optimize solar energy harvest even in suboptimal conditions
- Consider adding a small wind turbine generator as supplementary power source, though the Power System Decision Matrix shows these scores lower (8 points) compared to solar-only solutions (15 points) due to feasibility and budget constraints

Risk 2: Overgeneration/Charging during unexpected extended peak hours

During summer months or unexpectedly long sunny periods, the system may experience overcharging, which can damage batteries and reduce their lifespan. This poses both equipment damage risk and potential fire hazards in remote installations.

Recommended Solutions:

- Deploy charge controllers with power protection relay systems to prevent battery overcharging
- Implement voltage regulation circuits with automatic cutoff when batteries reach 100% capacity
- Use lithium-ion batteries with built-in Battery Management Systems (BMS) rather than lead-acid alternatives, as they handle charge cycling more efficiently
- Add dump load resistors to dissipate excess energy safely when batteries are fully charged
- Install temperature monitoring on battery enclosures to detect thermal issues early

Risk 3: Cyber-attacks due to wireless transmission

The weather station transmits data wirelessly across Kansas (≥410 miles range requirement) using cellular modem connectivity via MQTT broker to a Home Assistant client. The IoT network architecture creates vulnerabilities for unauthorized access, data interception, or denial-of-service attacks.

Recommended Solutions:

- Implement end-to-end encryption using TLS/SSL protocols for all data transmission between the cellular modem and MQTT broker

- Use VPN tunneling for additional security layer when transmitting weather data to remote servers
- Enable authentication protocols on the MQTT broker with unique credentials for each weather station deployment
- Ensure FCC compliance with wireless transmission standards and use pre-certified cellular modems (LILYGO T-SIM7600G-H R2 scored highest at 106 points in the decision matrix)
- Implement firewall rules and network segmentation to isolate the weather station system from other network resources
- Regular firmware updates for the ESP32 microcontroller to patch security vulnerabilities
- Deploy intrusion detection systems to monitor unusual network activity patterns

Risk 4: PCB Design Experience

Limited PCB design experience is a risk facing the project. As such, designing a PCB for the power system will be a challenge and risk for the individuals of the team. The PCB is an integral part of the system and must be designed correctly if the system is to perform correctly.

Recommended Solutions:

- Consult resources within the electrical engineering department for assistance on PCB designs
- Online resources
- Backup plan of implementing the LILYGO T-SIM7600G-H R2 in the field

Risk 5: Vulnerability to Climate

This weather station will be small and compact, which fits with the project requirements. However, that also means it could be vulnerable to harsh weather events that can be extreme winds, hail, tornadoes, or flooding. This is especially the case as it will be mounted up in the air to collect accurate measurements. This is a risk that will be considered further when ultimately picking the footprint of the project and the packaging of the station.

Recommended Solutions:

- Ensure structural soundness of design prior to implementation
- 3D print parts with high infill and good material, suitable for long-term outdoor use
- Make the design as compact as possible to limit exposure to wind

Risk 6: Weatherproofing Electronics

The weather station obviously needs to be outside for long periods of time. Weatherproof electronics are thus essential. Since many of the sensors that have been selected are sensors that are not inherently weatherproof, it must be ensured that the strategy to be weatherproofed is actually effective.

Recommended Solutions:

- Seal the sensors with epoxy or a similar material
- Wrap sensors in weatherproofing tape
- Encase sensors securely within weather station housing

Risk 7: Sensor Accuracy

Specifications from the KSU Mesonet have been given for the accuracy these sensors need to be. It must be ensured that the sensors meet this requirement. It will require testing to ensure that the accuracy reported for sensors is consistent with real values. This presents a risk because if the numbers do not line up, a different sensor may need to be purchased.

Recommended Solutions:

- Consult sensor specifications to ensure they meet KSU Mesonet requirements
- Test sensors thoroughly before final use

Risk 8: Anemometer/Precipitation Measurement Design

To measure wind speed and direction as well as precipitation, a measurement device will be designed to test each of these. However, this part of the project is vulnerable to subjectivity for how it will be accomplished. As such, this presents a design risk like the design of the PCB.

Recommended Solutions:

- Design using strong parts which will sustain extreme weather
- Consult knowledgeable people within the engineering department
- Conduct research prior to full design

Strengths of the Design

Strength 1: Cost Relative to Current Design

Currently, the weather station the KSU Mesonet uses costs approximately $19,000. The expected budget for this project is about $600-$800. This is due to using more consumer-grade sensors and electronics as opposed to the precision of the top-of-the-line, industry grade electronics that the Mesonet uses. Additionally, designing precipitation measurement devices and anemometer saves much cost. The expectation is to obtain measurements which are on par with the same accuracy that the KSU Mesonet currently has.

Strength 2: Microclimate

The KSU Mesonet is seeking to get microclimate measurements, which are essentially smaller weather stations near a larger weather station which conduct measurements on specific sections of the area. Examples of those areas could be a low-level spot, something near a body of water, or just more specific weather data to different areas. This data can then be sent to the main weather station of the area to combine with other data. Alternatively, the weather station can be set up as an independent station, and with the use of the cell modem, can be used just as a main station that would transmit its collected data to the KSU Mesonet's main data collection server.

Strength 3: Modularity

One of the goals of the project was to make it modular, so that the KSU Mesonet could add sensors or replace them as needed in the future without much hassle. This will be achieved in the project due to the use of the I2C bus, which allows the sensors to be plugged in and configured easily. Making this project modular makes it simpler for the technicians of the KSU Mesonet to provide maintenance on the system, even if they have little experience of how the system works. The KSU Mesonet also can choose whether they want to set up the cell modem with a data plan which would allow it to transmit as the main station or leave it as a microclimate station.

Lessons Learned

The two major takeaways are:

1. Standards can be applied anywhere in a design. This can be electronically or even mechanically.
2. Teamwork and coordination are crucial for designs like this. Having other members informed about sizes, constraints and progress really helps the project function at the end.

Conclusion

The plan is to make a device following the KSU Mesonet as the standard and talk to Christopher Redmond as the client. The system will be able to measure weather parameters such as temperature, humidity, precipitation, wind speed, wind direction, air quality, solar radiation and pressure. After making some decisions, the solution is to make a station that is similar in size to a commercial station that can be purchased from amazon but meets the accuracies of the KSU Mesonet that was specified in the requirements. The system will also be able to communicate with other stations around it to get measurements from these micro stations to measure microclimates around the main station. The data will be sent across Kansas to a server where the measurements can be better processed and observed. The station will cost around $600-$800 to test and produce and the project schedule is broken down into 4 phases to ensure time for prototyping and construction of the product. This design is within the scope and should be able to be completed by the deadline.

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Appendices