Sustainable Solar Powered Radiosonde

Team Wepwawet

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Abstract

Weather balloons are used across the world in order to provide accurate weather predictions and data for climate scientists. However, the status quo regarding weather balloons is incredibly unsustainable. It is projected that the United States alone spends nearly 22 million dollars on weather balloons annually, due to the high cost of radiosondes and their lack of reusability (Gonzalez, 2012). Radiosondes are currently powered with expensive, non-reusable batteries, and are not designed to be retrieved after flight (Bamford, 2019). Wepwawet's primary mission was to provide a more cost-effective and sustainable alternative to current radiosondes by utilizing solar power. Extensive research was done via the internet and industry experts to create a low-cost sensor network and telemetry system. The payload is designed to collect humidity, pressure, temperature, and acceleration data to be sent from the payload to a ground receiver through 915Hz radios. To ensure power would be sufficient for the duration of the flight, we used high-efficiency 6V polycrystalline silicon solar panels supported by a backup 3.7 V rechargeable lithium-ion battery and utilized a voltage sensor to measure actual voltage output from the solar panels. Testing thus far has indicated Wepwawet will transmit data packets as expected using solar power through the duration of the flight. All of the subsystems included in the payload were meant to mimic radiosondes currently used in weather balloons. This ensures Wepwawet can be used as a model for more sustainable radiosondes in the professional setting in the future.

Mission Overview

There are currently 92 weather stations in the United States. Each launches two radiosondes per day that are primarily used to collect data for weather prediction purposes. The two primary radiosondes used for atmospheric research in the US are the Lockheed Martin LMS-6 and Vaisala RS92-NGP radiosondes (Ingleby, 2017). Wepwawet was modeled after the LMS-6 as the majority of weather stations in the US use the LMS-6 radiosonde (National Weather Service, *Frequently Asked Questions*…). As it currently stands, the radiosonde network has an extremely high yearly cost and also contributes to wasteful business practices. The widely used LMS-6 requires three, non-rechargeable lithium ion batteries that are then discarded after a single flight (RECESSIM, *LMS-6*…). Wepwawet was designed with the intent to provide a more sustainable and cost-effective alternative to current industry practices. Equipped with telemetry radios and a full weather balloon subsystem, the payload has the capability to provide live weather data similar to an LMS-6 while running off a solar based rechargeable battery system. Wepwawet has the potential to be launched several times before a change of batteries would be needed, reducing overall waste and cost per launch. The payload design could be the basis for a new industry standard that puts sustainability practices first without compromising efficiency or usability.

Payload Design

Weather Balloon Subsystem

Wepwawet was designed to mimic the functions of the LMS-6 to provide the most accurate comparison to an industry standard radiosonde as possible. The LMS-6 collects temperature, barometric pressure, and humidity data and includes a GPS system for tracking and wind speed data purposes (Signal Identification Guide, 2022). Wepwawet similarly contains sensors for temperature, barometric pressure, humidity, and acceleration. Edge of Space Sciences, the facilitators of the balloon launch provide a GPS tracking system for the balloon, so no such device was installed. Each sensor sends live data that is condensed by an Arduino MKR WAN 1310 radio which could then be used for weather prediction purposes.

Solar Power Subsystem

The LMS-6 typically uses three CR-123A lithium battery cells for a total of 9V to power the radiosonde for the duration of the flight. The batteries are then discarded after the short flight, assuming the payload is retrieved. According to the National Weather Service, only 20% of the radiosondes launched annually are found and returned (National Weather Service, *Collecting Meteorological…*). The National Weather Service does not make attempts to locate the radiosondes once they have been released into the environment. We wanted to challenge industry standards by utilizing solar power as a reusable battery system to reduce overall waste and cost per launch.

The first challenge to tackle was to ensure that solar power would be enough for the duration of flight regardless of the immediate weather or conditions. Half of the daily radiosonde launches in the US typically take place around 6:00 am, when it may not yet be particularly sunny depending on the time of year (National Oceanic and Atmospheric Administration, 2023). Since the payload is equipped with a live telemetry system it is possible the battery system would undergo a spike in power usage each time a data packet was sent out. To ensure Wepwawet was powered for the entire flight time the solar power subsystem was backed by two high capacity 3.7V rechargeable lithium ion batteries. When the solar panels failed to provide enough power the rechargeable battery system would make up the slack. Likewise, if the solar panels were outputting too much power, it would be redirected back into charging the rechargeable batteries. Since Wepwawet is an Arduino based system we were able to use its low power capabilities to achieve similar results to that of an LMS-6 with less power.

The second notable issue was whether the solar panels would be durable enough to endure the high acceleration and force the payload initially undergoes at launch. Solar panels are notoriously flimsy and are known for providing variable power. Fortunately, solar panel technology is continually seeing great advancements which provided Wepwawet with the opportunity to utilize solar power as its main source of power. The payload used three weatherproofed 6V polycrystalline silicon solar panels. The solar panels were chosen for their high conversion efficiency while still being a cost-effective option. We also took solar panel placement into consideration when building our payload. Extra supports were added around the faces containing solar panels to help protect the surface of the solar panels from damage when landing. Through the solar panel and drop tests conducted, it was concluded that the solar panels would withstand the substantial force the payload undergoes during flight.

The third challenge with a solar powered system was the possible issue of flooding, or the solar panels drawing in too much power and possibly over-volting the system. To help avoid this issue, Wepwawet was equipped with a DFRobot solar power manager. The solar power manager is a multi-functioning unit that acts as a buck converter and manages the flow of the solar power input. The solar power manager has the capability of accepting up to 30V which is well above the capacity of our solar panels and the power draw of the system. The solar power manager also directs all power flow to and from the solar panels as well as the rechargeable batteries. As it directs power flow to the weather balloon it acts as a voltage regulator to help prevent flooding.

Wepwawet's solar power subsystem was designed with the intent to achieve sufficient solar power output for the duration of the flight, with any extra power generated is stored in the rechargeable batteries for later use. Compared to the lack of reusability of batteries in the LSM-6, Wepwawet has provided a base design for a more cost-effective and sustainable option to the current radiosonde network.

Telemetry Subsystem

Telemetry, or the transmission of live data, is a critical aspect of the radiosondes used in today's weather balloons. Radiosondes have a radio and antenna attached to them so that a ground radio and antenna can receive sensor information from the weather balloon. Telemetry can be quite a complex process because a chosen frequency must not only meet national guidelines, but it also must be able to transmit and receive signals over large distances. In the United States, one must obtain an Amateur Radio License to use a majority of the available frequencies. According to the National Weather Service, their radiosondes either use frequencies ranging from 400 to 405.9 MHz or 1676 to 1682 MHz (National Weather Service, *Education Corner…*, *Radiosonde Observation…*). Different levels of certification are available to use different frequencies. However, the team decided to choose a frequency that did not require one of its members to be licensed.

Another important consideration when using a particular frequency is how effectively it can transmit data. For our project, the frequency selected needed to easily penetrate objects, travel far, and use relatively small, low cost equipment. Multiple options were considered, but the frequency of 915 MHz turned out to be the best option for this project that did not require an Amateur Radio License. This frequency is relatively low, meaning its signals can both travel long distances and will not be blocked by most objects (Plant and Works Engineering, 2023). A larger antenna is needed to transmit at 915 MHz, but it requires less power than higher frequencies (Plant and Works Engineering, 2023). Choosing 915 MHz was also because it is one of three designated Long Range (LoRa) frequencies that are ideal for sending small packets of data (The Things Network, *What is LoRa…*). Due to its popularity, it was also far easier to find compatible equipment at this frequency.

Wepwawet used the Arduino MKR Wan 1310 radio for both the radio on the payload transmitting the data and the radio on the ground receiving the data. The payload radio was also enhanced with an Arduino MKR MEM shield that allowed for the sensor data to be saved on an SD card, as well, in case some of the transmitted data was not received by the ground radio. The Arduino radio's analog pins were connected to the various sensors outlined in the Weather Balloon Subsystem above. Then, the code has all of the data printed into a string that turns into a data "packet" sent from the radio on the payload to the ground radio every 5 seconds.

A 7.68 in. 900-915 MHz 5dBi Gain Omnidirectional Antenna was selected for the payload because it was both the smallest and cheapest antenna with the highest gain that transmitted signals in all directions. Finding an omnidirectional antenna was very important for the payload so that it would be easier for the ground antenna to receive the data. Finally, the ground antenna was a directional 915 MHz General Purpose Ceramic Patch RF Antenna. Each antenna was attached to their respective radio via a cable. During flight, the ground radio would also be connected to a computer with the Arduino IDE to print the received data packets.

Payload Box Design

When designing the box for Wepwawet there were several factors that needed to be taken into consideration. These consisted of having a strong foundational structure that was capable of withstanding an abrupt drop, along with providing structural protection for our solar panels, and insulation inside the payload to support the low temperatures. The process began

Figure 1

with designing the inner box which accommodates the weather balloon subsystem and batteries (Figure 1). This box, measuring 15cm x 12cm x 11cm, was constructed from foam core and insulated with foil faced bubble wrap. The sides of the box were securely attached using hot glue. To accommodate the solar panels on three of the long sides of the box we cut out slits that were 5 cm in length centered in the middle face of each side. These were used to slide the solar panels from the inside of the box to be glued to the outside, then covering these slits.

To provide additional structural support and protect the solar panels, frame like structures were designed and attached to the three outside faces of the inner box containing solar panels (Figure 2). These frames constructed from angled pieces of foam core added approximately 3 cm to each side of the box. Tinfoil was applied to the inside face of the frames to enhance light reflection to the solar panels. The frames were attached using a combination of hot glue and aluminum tape. Finally, 19 cm long rectangular pieces of foam core were used to attach each of the length of the frames to each other, and small triangle pieces of foam core to connect the height of the frames to each other.

Figure 2

The final box design for Wepwawet measured 18.5cm x 18cm x 14cm and weighed 526 grams.

Budget

The project was allowed a budget of $500, however the objective was to stay well under budget. A typical radiosonde costs around $200 (Flores, 2013). Some of Wepwawet's parts were salvaged from previous DemoSat projects such as the pressure, temperature, and humidity sensors. Foam core, aluminum tape, and all other build materials were also available. All parts for the solar and telemetry subsystem were purchased as well as an accelerometer. Build costs amounted to $248.18 while total spent was $302.86 (Figure 3). Individual balloon launches cost around $325 which includes the cost of the radiosonde, the balloon, and labor (Gonzalez, 2012). With 92 weather stations locations in the US launching two balloons daily, the yearly cost for weather balloon soundings amounts to around $22 million dollars. It was found by searching through hardware stores that the CR-123A batteries the LMS-6 cost approximately $3.50 per battery. Using the $3.50 per battery:

Part	Pack Cost	Actual Cost (used parts)
Arduino MKR WAN 1310	$95.60	$95.60
Antenna for Ground	$35.09	$35.09
Antenna for Air	$14.00	$7.00
Solar Power Manger	$38.90	$38.90
IPEX Connector	$7.47	$7.47
Solar Panels	$30.46	$15.21
Battery Holders	$7.99	$2.00
Arudino MKR MEM Shield	$23.99	$23.99
3.7 Li-Ion Batts	$23.99	$12.00
Voltmeters	$5.89	$1.18
Accelerometer	$6.49	$6.49
Pigtail Connectors	$12.99	$3.25
	$302.86	$248.18

Figure 3

$3.50/battery x 3 batteries/flight x 2 flights/day x 365 days/year x 92 locations =

$705,180/year in battery costs. (1)

Ideally, this cost could be drastically reduced if the use of rechargeable and reusable battery systems were invested in. Wepwawet's solar power subsystem, consisting of the solar power manager, solar panels, rechargeable batteries, and battery holders cost a total of $68.11 to build.

Using Equation 1, about $21 per weather station location per day is spent on batteries. If the National Weather Service made more diligent efforts to locate the radiosondes they release, the rechargeable battery system model could pay off in just a little over three days.

Test Plans and Results

Solar Panel Power Testing

The average weather balloon is capable of reaching 100,000ft in altitude and drifting up to 180 miles from the launch site before landing (ABC News, 2023). For the first 35,000ft or so of the balloon's flight, the payload is vulnerable to a variety of weather conditions before it rises above the troposphere and is subject to complete, direct sunlight. Wepwawet's solar power system was tested in a variety of weather conditions at different times of day to predict how it may act during flight if it were to be subject to such conditions.

For each test, the solar panel circuit was connected to a voltage sensor that was read in live time by a computer. The voltage sensor checked solar panel power approximately 70 times per second for about 15 minutes for each test. The total collected voltage data points were averaged out over each minute of run time.

Since half of all daily weather balloon launches occur around 6am, it is possible launch could occur when there is little to no direct sunlight. However, the designated launch time for Wepwawet was scheduled for 7:00 am, allowing for more time for the sun to rise. The Solar Panel Sunrise Test (Figure 4) was conducted around 7:00 am in Boulder, CO at North

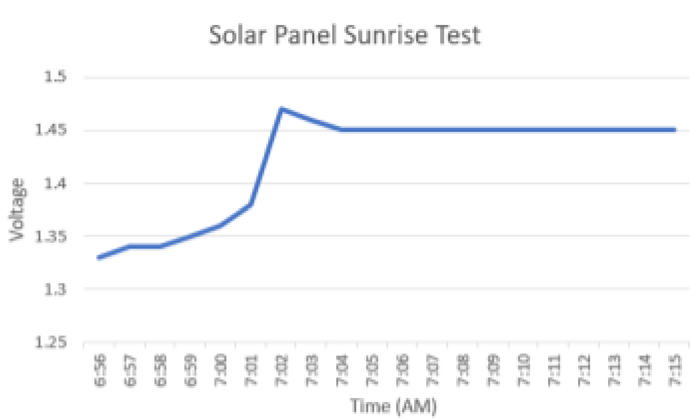

Figure 4

Boulder Park. The payload was placed in the middle of an open field for 15 minutes at dawn. The solar panel circuit was placed facing directly east. There was heavy cloud cover on the east horizon that blocked the majority of the sunrise. A gradual rise in voltage occurred as the sun rose over the horizon until a peak of 1.47V was observed as light briefly broke the cloud cover. The solar panel system then consistently put out 1.45V as the sun remained behind the overcast.

Additional testing was done to see how efficient the solar panels would be if subject to constant, thick cloud cover. For the Solar Panel Cloud Cover Test (Figure 5) the payload was placed in a small grassy yard and tested for 15 minutes. There was thick cloud cover with moderate winds. The solar panel system averaged 1.32V while under consistent cloud cover. Minor changes in voltage were observed as the cloud cover shifted.

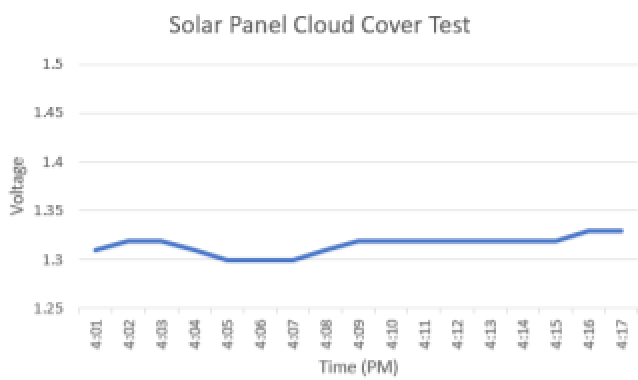

Figure 5

It is concluded from testing the solar panels would not likely provide enough power solely to run the payload at initial launch if it were subject to adverse weather conditions. However, the backup rechargeable battery system is capable of fully supporting payload functions. Once the payload has risen above the altitude at which weather occurs the solar panel system is then exposed to indirect sunlight. The solar panel system then takes over to power the payload and can also replenish charge lost in the batteries. Wepwawet’s battery system had the potential to run for several launches before needing to be changed since the batteries were not being worn out by constantly supporting the payload.

Drop Test

The drop test was conducted to guarantee the payload systems and box design would survive an abrupt stop while traveling at terminal velocity. The payload was taken to a height of about 30 feet, turned on, and was dropped antenna side up where it fell straight down before hitting concrete. Weather conditions were optimal with no rain, wind, or cloud cover. Upon retrieval it was noted Wepwawet had sustained slight damage to two corners, as seen in figure 6. All systems were found functional after the completion of the drop test.

Figure 6

Expected Results

The scheduled launch for Wepwawet was delayed due to high winds and is set to launch in fall 2024. In order to determine what the data collected mid-flight would look like, data from the National Oceanic and Atmospheric Administration National Centers for Environmental Informations' Integrated Global Radiosonde Archive (IGRA) was examined. The IGRA, "consists of radiosonde and pilot balloon observations from more than 2,800 globally distributed stations" (National Centers for Environmental Information, *Integrated Global*…). The sounding data analyzed below is from Grand Junction/Walker Field, CO, station USM00072476, on April 4th, 2024. It is unknown what time of day the radiosonde was launched, but the data spans 95 minutes and 12 seconds since the time it was initially launched. The only data the Wepwawet is capable of collecting that was not found in the IGRA data was acceleration. But, much of why

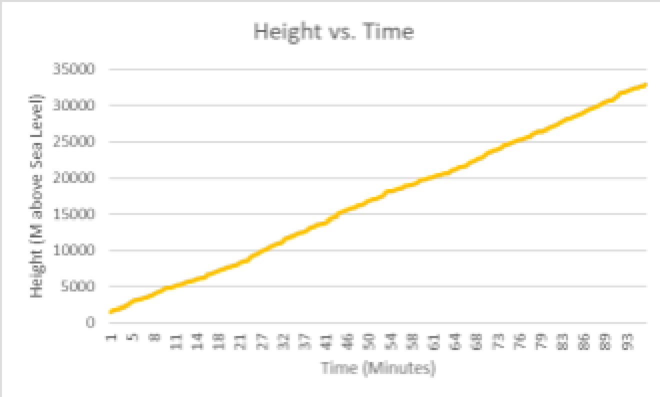

Figure 7

Wepwawet has an accelerometer is to determine altitude during the flight, which is represented from the IGRA data in figure 7. Clearly the IGRA data was only for the radiosonde's ascent, whereas Wepwawet would have data for both the ascent and descent of the balloon. It is also possible that Wepwawet will reach either a higher or lower maximum altitude than what this particular radiosonde from the IGRA reached.

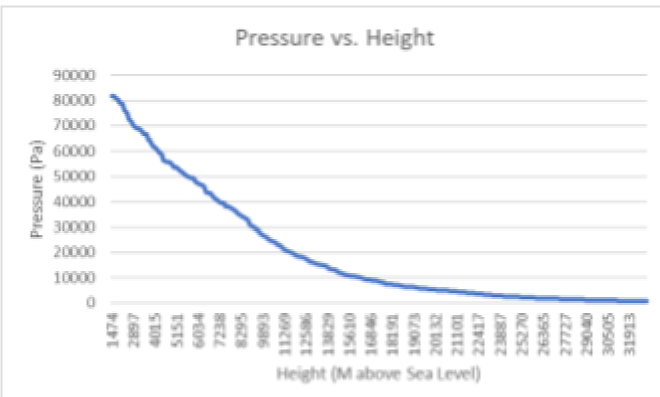

Figure 8

As can be seen in figure 8, pressure decreases as altitude increases because air becomes less dense at higher altitudes, and there is less gravitational force on the air higher in the atmosphere (National Geographic, *Altitude*). Since Wepwawet will also be sending data when the balloon pops, its graph of data will look like figure 8 but with a symmetric increase in pressure afterwards as it drops in altitude.

The next variable shown is temperature with respect to height in figure 9. For approximately the first 10,000 meters, the temperature decreases because the air becomes thinner. Then the radiosonde leaves the

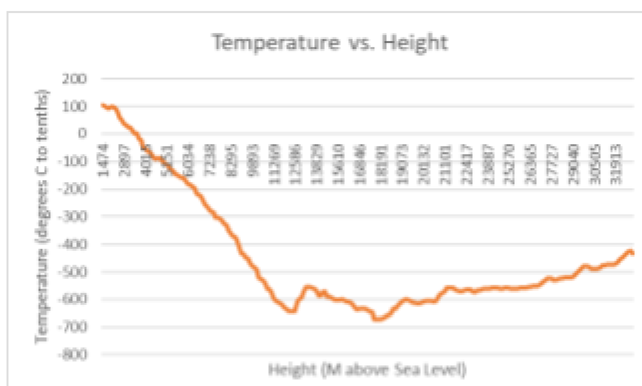

Figure 9

troposphere and enters the stratosphere, where temperature levels out at first but then begins to rise due to the production of ozone in this area (National Oceanic and Atmospheric Administration, *Layers of*…). With the height that Wepwawet is expected to reach, the data will only reflect trends in the troposphere and stratosphere, like the radiosonde from the IGRA data.

Finally, humidity is shown vs. height in figure 10 below. Since the troposphere is where most weather occurs, the humidity will be very dependent on the weather the day Wepwawet is launched. But, it is expected that once in the stratosphere, the humidity will decrease significantly as the air there is known to be dry (Nowack, 2023, p. 577). When Wepwawet re-enters the troposphere, the humidity will again reflect more of the current weather conditions in the area where it will end up landing.

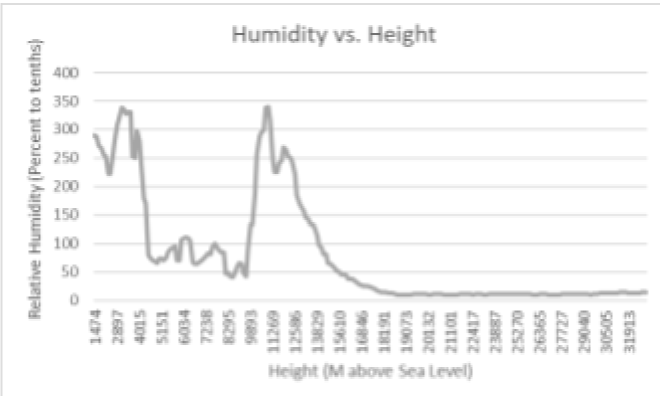

Figure 10

Conclusion

Due to the high winds this spring, Wepwawet's launch was delayed and is expected to launch in the fall of 2024. Considering there is still time to develop the payload, there are numerous factors that can be approved upon. First, we would like to do more experimentation on the solar panel system to test its capabilities in poor weather conditions, such as rain or hail. Another factor to take into consideration is what would happen to the system if the rechargeable batteries were full, and the solar panels were still providing excess voltage. If given the opportunity to build the payload again, the team would consider investing in a compostable build material option since it is common practice to release weather balloons without tracking or locating them.

In summary, the team worked diligently to design Wepwawet, an alternative to current radiosondes that was both cost-effective and sustainable. This project was an incredible experience that taught us the fundamentals of research, design, and time management. Despite numerous challenges, the team overcame them through innovative thinking and problem solving.

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