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Atmospheric Intelligence for Hybrid Power Advancements (AIHPA): Volume 5 (AIHPA Testbed)

by Gail Vaucher, Sean D'Arcy, Noah Keith, Robert Jane, Michael Lee, and Morris Berman

NOTICES

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14. ABSTRACT
The ever-increasing number of technologies that future Soldiers will need to power on the battlefield demands strategic forethought. As ARL has been pursuing this issue, an Atmospheric Intelligence for Hybrid Power Advancements (AIHPA) Testbed was developed and fielded. Its success in proving the feasibility and value added in hybridizing power has resulted in two, and soon to be three, testbed units dedicated to battlefield power research. The Testbed units have two major elements: 1) a Power Train (PT), which consists of multiple power resources working in concert to satisfy load requirements, and a 2) Meteorological Measuring Tripod (MMT), which is a suite of environmental sensors whose data enable improved power generation model prediction. An automated whole sky imager (WSI) that was designed and built in-house and fills out the current Testbed design. To ensure consistency between research-grade testbed units, the AIHPA project has elected to document the design in this report.

15. SUBJECT TERMS
hybrid power, photovoltaic, PV, atmospheric, Atmospheric Intelligence for Hybrid Power Advancements, AIHPA Testbed, Meteorological Measuring Tripod, MMT, Power Train, PT, Whole Sky Imager, WSI, Military Information Sciences

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1. Introduction

Future battlefields will require an abundance of power resources to support the ever-increasing technologies Soldiers need to employ. By diversifying the power resources, the resiliency and fluidity of provisions not only improve but become more cost-effective (Vaucher et al. 2023b). In 2017, the U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL) created a testbed to experiment with the integration and optimization of multiple power resources. Envisioning the future Soldier scenario as an isolated environment, the design required all data input used to manage the multiple power resources to be in-situ sources only. The initial testbed investigated three power resources: an emulated generator, photovoltaic (PV) panel, and batteries (Vaucher et al. 2019). For this design, acquiring atmospheric data gave a distinct advantage to the optimization routines (Jane et al. 2020). Models were developed to forecast power generation (Vaucher et al. 2020). The uniqueness of this dataset prompted a long-term acquisition of concurrent atmospheric and power datasets. Seasonal patterns were noted, and a second testbed prompted a baseline of design, further solidifying the data's value. Through multiple years of data acquisition in a desert environment, the archived data are poised to service the data-hungry AI tools investigating energy applications in similar environments. An expansion of environmental conditions and locations have also entered the investigation. To support this growing research, the baseline design for the Atmospheric Intelligence for Hybridized Power Advancements (AIHPA) Testbed is being documented.

1.1 AIHPA Testbed General Design

The AIHPA Testbed (hereafter called, "Testbed") was created to run automatically, 24 hour a day, 7 days a week. The Testbed comprised two major elements: 1) a power train (PT) that generated/distributed electricity from multiple resources to support a managed load, and 2) the meteorological measuring tripod (MMT) that characterized the environment using meteorological variables relevant to power generation.

The system optimization depended on power forecasts (Jane et al. 2017). These were determined from both in-situ measurements and quick processing models designed for a stand-alone environment. Supporting model input requirements, the MMT environmental characterization was supplemented with data from a whole sky imager (WSI).

The integrated Testbed is shown in Figure 1. The PT and MMT elements are displayed in Figures 2 and 3, respectively. The white casing of the WSI is attached to the top of the PV panel and can be seen in Figures 1 and 2.

Figure 1. AIHPA Testbed seen from three different angles.

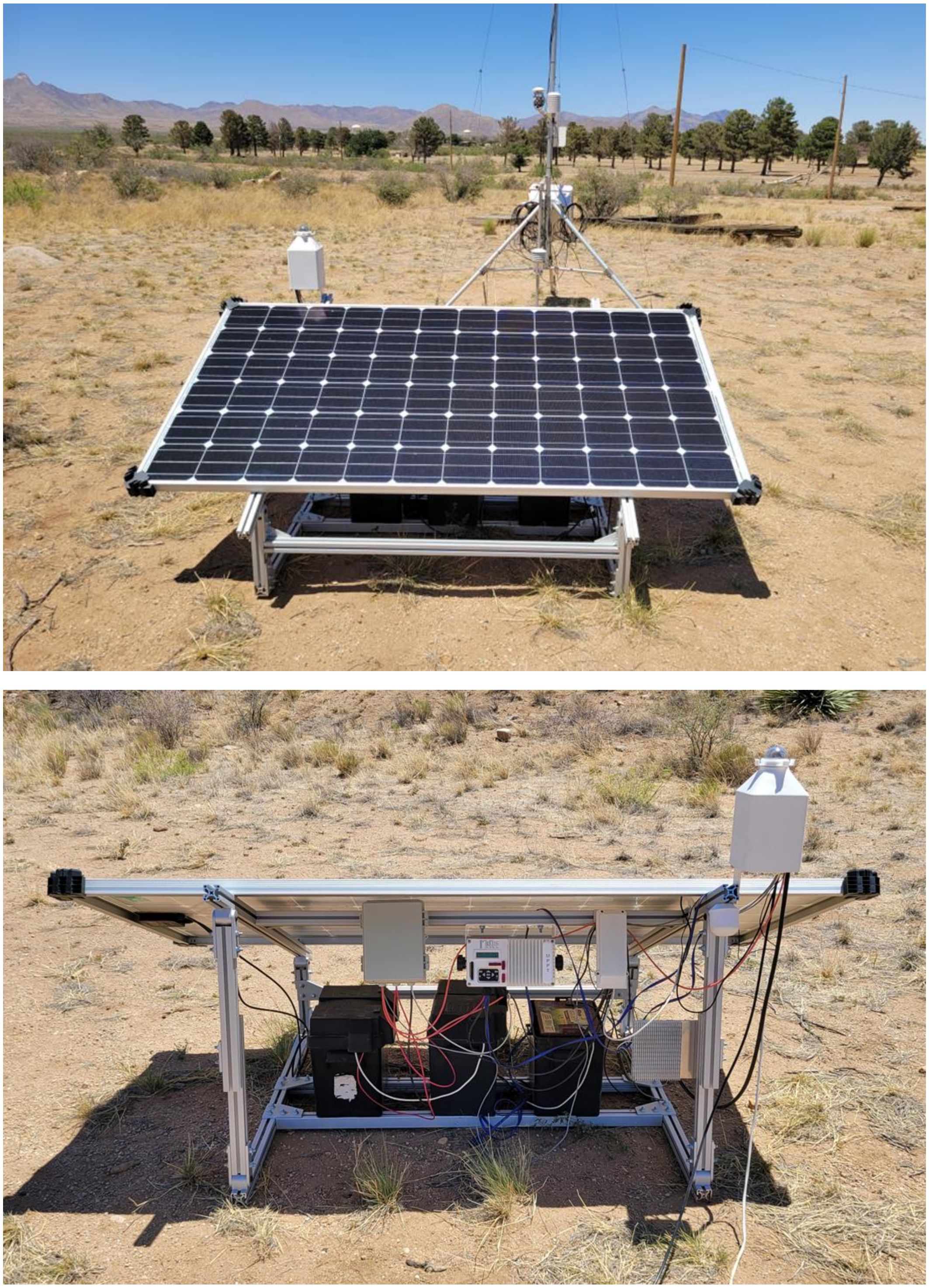

Figure 2. The front (top) and back (bottom) of the AIHPA Testbed PT.

Figure 3. AIHPA Testbed MMT.

1.2 Testbed Elements

Figure 4 shows a more detailed look at the PT (on left) and MMT (on right). The Testbed's three power resources were integrated, in that, the generated PV power was stored in three 8-V batteries, using breakers and a maximum power point tracking (MPPT) charging controller to manage the electrical magnitudes, ensuring maximum power for the current solar conditions. A digital load simulated various load types and, when operating in a "default" mode, was designed to automatically balance the electricity produced. The use of shunts provided the means for measuring large currents in the various circuits, using conventional voltage input data-acquisition hardware.

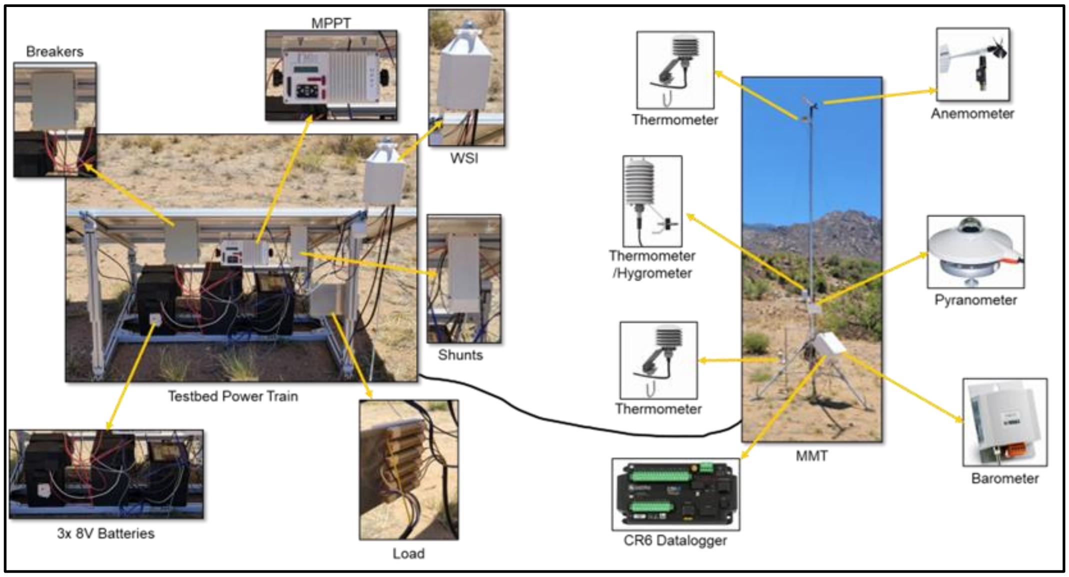

Figure 4. Elements of the AIHPA Testbed.

The environmental input requirements were primarily a function of the PV power generation. Knowing the incoming solar radiation (a.k.a. insolation) and the panel temperature enabled a calculation of PV power. Since bringing research-grade sensors into a battlefield was deemed impractical, a solar radiation model using in-situ data only was developed. The required input included an assessment of the cloud cover, which the WSI, coupled with analyzing routines, provided.

Sections 2–4 detail the three major elements of the Testbed. The purpose is to provide the reader with the ability to construct the Testbed.

2. Meteorological Measurement Tripod

Relevant environmental conditions were documented using in-situ measurements consistent with standard atmospheric parameterization and two additional solar radiation sensors mounted directly on the PV panel for research purposes. The physical MMT unit was positioned north and upwind (using prevailing winds) from the PT, thus better enabling a characterization of the environmental conditions crossing over the Testbed. The physical separation of the MMT and PT ranged between 3 and 16 m.

The variables sampled included pressure (1 m above roof level [ArL]), two temperatures (5.7- and 0.7-m ArL), relative humidity (2-m ArL), wind speed and wind direction (6-m ArL), and solar radiation (2-m ArL). These measurements were sampled every 10 s and reduced to a 1-min average. The dual temperatures were used to calculate a temperature gradient that in turn provided an assessment of atmospheric stability. Figure 4 displays the sensor placement on the 6-m tripod.

Sensors used included, but were not limited to, those shown in Table 1. For additional sensor details, see the Local-Rapid Evaluation of Atmospheric Conditions System (Vaucher et al. 2017).

Table 1. Site A and B sensor suite descriptions and specifications (adapted from Vaucher et al. 2022).

Variable	Sensor	Description	Units	Site A	Site B
Pressure	Barometer	Capacitive sensor measures voltage change; measured using output voltage.	mb	Vaisala PTB-110 (1 m)	Vaisala PTB-110 (1 m)
Temperature	Thermometer	Measured voltage drop across resistor.	deg Celsius	Campbell Scientific T107 (0.7 and 5.7 m)	Rotronics HC2-S3 (2 m)
Temperature/ relative humidity	Thermometer/ Hygrometer	Temperature measured with capacitive sensor. Relative humidity with resistive sensor.	deg Celsius/ %	E+E Elektronik EE181 (2 m)	Rotronics HC2-S3 (2 m)
Solar radiation	Pyranometer	Site A: sensor converts current to voltage. Site B: thermopile heats and temperature difference is converted to voltage.	W/m^2	Kipp/Zonan CMP3 (2 m)	Li-CORLI-2000X (2 m)
Wind speed/ direction	Anemometer	Propeller rotation produces AC sine wave with frequency proportional to wind speed. Output signal is an analog voltage proportional to wind direction.	m/s and deg	RM Young 05305 (6 m)	RM Young 05305 (6 m)

The acquisition of measurements used a Campbell Scientific CR6 Datalogger. An example of one of the Datalogger programs is provided in Appendix A.

Assessing solar radiation via a model required the percentage of cloud cover and cloud type(s). These were determined using a WSI and specialized data processing software that were constructed in-house. Since the power needed to run the WSI was drawn from the PT, this instrument's details are described after the PT.

3. Power Train

The PT is composed of a collection of resources including the following: 1) PV module, 2) PT frame, 3) Relay utility box, 4) MPPT charging controller, 5) Shunt module, 6) Battery bank, and 7) Load bank. These are described in Sections 3.1–3.7, respectively. Figures 5 and 6 show 3D visualizations of the PT assembly.

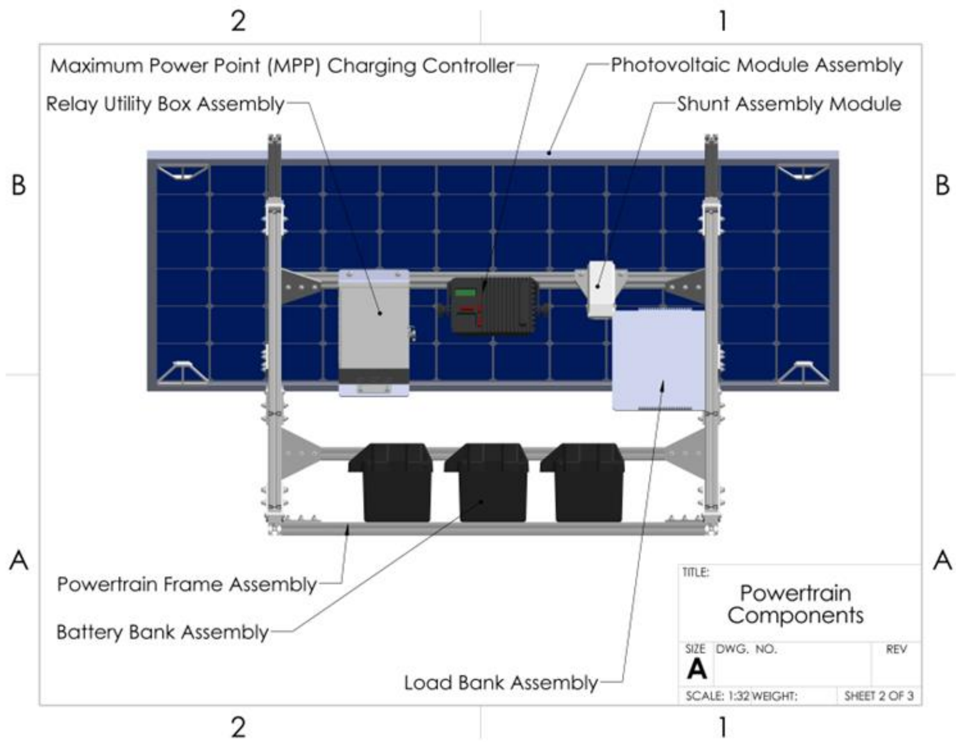

Figure 5. PT component assembly (back).

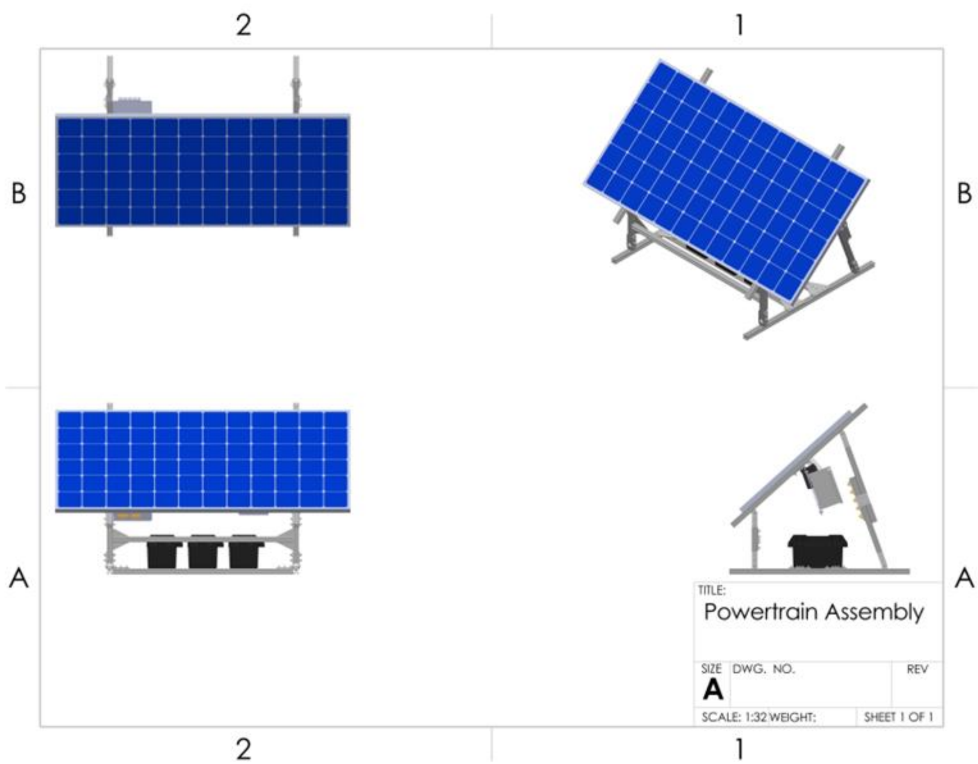

Figure 6. PT assembly (front and sides).

3.1 PV Module

The PV module was composed of a singular 315 W Sunmodule Pro-Series XL Monocrystalline PV module manufactured by Solar World. Figure 7 shows a 2D visualization of the PV module. All Figure 7 units provided are imperial (in inches), with international standard units (millimeters) provided in parentheses. Table 2 describes the PV module at standard test conditions (STC), which includes an irradiance of 1000 W/m^2, ambient temperature of 25 °C and atmospheric pressure of 1.5 air mass (AM). Table 3 shows an alternative parameter data sheet that describes the panel operating at nominal operating cell temperature (NOTC); namely, at an irradiance of 800 W/m^2, ambient temperature of 65 °C and atmospheric pressure of 1.5 AM. The bill of materials describing the individual components is provided in Table 4.

Links to the component websites (active at the time of this publication) are provided with each tabulated part number.

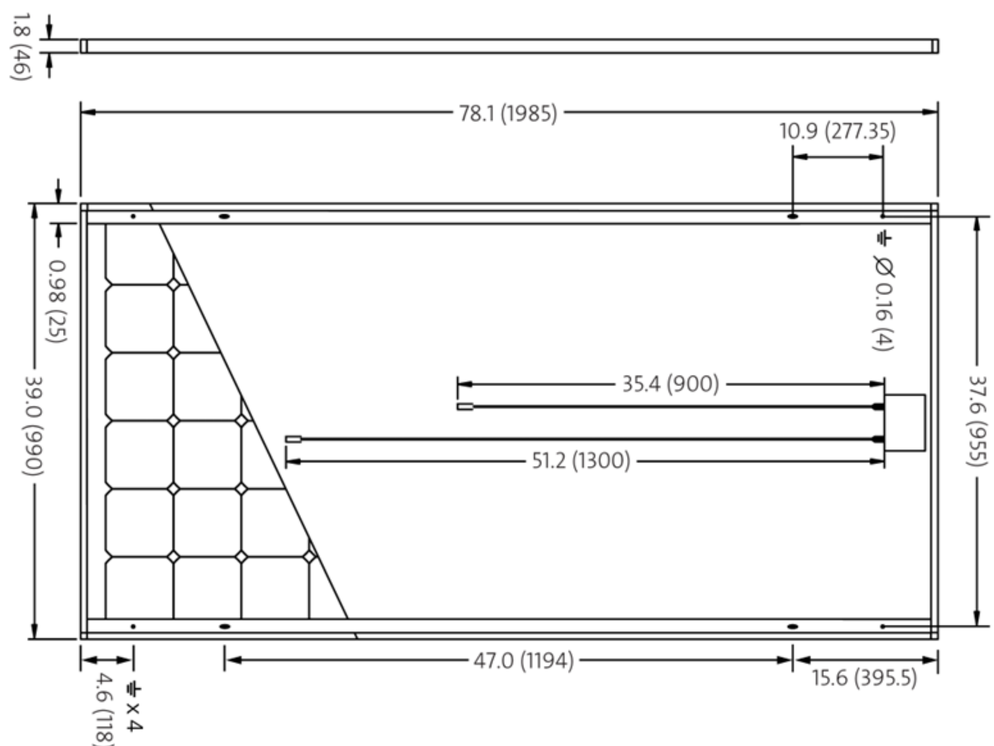

Figure 7. PT: 2D PV module visualization.

Table 2. Data sheet parameters for PV module at STC.

Description	Variable	Value	Units
Maximum power	P_{max}	315	W
Open circuit voltage	V_{oc}	45.6	V
Short circuit current	I_{sc}	9.35	A
Voltage at maximum power point	V_{mp}	36.5	V
Current at maximum power point	I_{mp}	8.71	A
Temperature coefficient at V_{oc}	$\alpha_{V_{oc}}$	-0.304	%/℃
Temperature coefficient at I_{sc}	$\alpha_{I_{sc}}$	0.042	%/℃
NOCT	$NOCT$	76	℃
Number of cells per module	N_{cell}	72	#
Number of series string	N_{ser}	1	#
Number of parallel string	N_{par}	1	#

Table 3. Data sheet parameters for PV module at NOTC.

Description	Variable	Value	Units
Maximum power	P_{max}	240	W
Open circuit voltage	V_{oc}	39.8	V
Short circuit current	I_{sc}	7.77	A
Voltage at maximum power point	V_{mp}	33.6	V
Current at maximum power point	I_{mp}	7.18	A

Table 4. Bill of materials for the PV module.

Part no.	Description	Quantity	Unit price (US$)
3D printed part	Panel temperature mounting bracket	4	…
DS18B20	Raspberry Pi temperature probe kit	4	8.71
315W	PV array	1	350.00

3.2 PT Frame

The PT frame assembly was primarily composed of T-slotted frames and fittings in addition to miscellaneous fasteners. The T-slotted frames and fittings included 8020 extruded aluminum products. Figure 8 shows 3D visualizations of the PT frame assembly. The bill of materials describing the individual components is provided in Table 5.

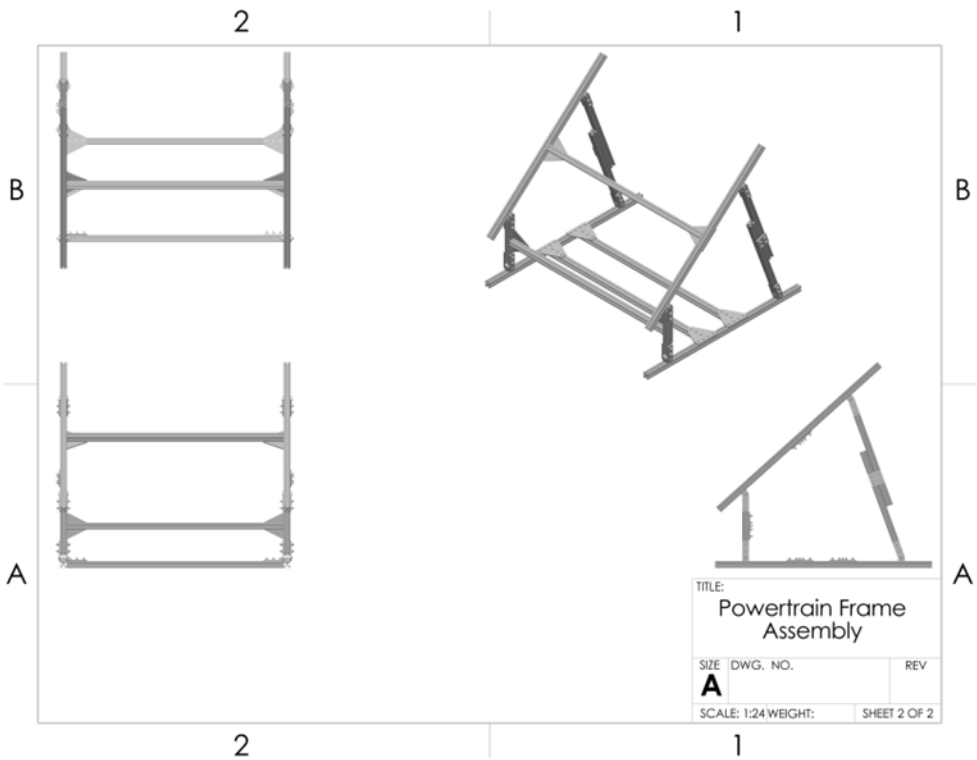

Figure 8. PT: PT frame assembly.

Table 5. Bill of materials for the PT frame assembly.

Part no.	Description	Quantity	Unit price (US$)
92356A583	Fittings/fastener	96	0.41
93776A441	Fittings/fastener	96	0.20
47065T127	T-slotted framing	8	49.29
3136N152	T-slotted framing	8	25.92
47065T13	T-slotted framing	6	27.49
47065T21	T-slotted framing	4	26.37
47065T271	T-slotted framing	2	13.34
47065T414	T-slotted framing	2	14.92

3.3 Relay Utility Box

The relay utility box assembly comprised a custom metal mount, weather resistance enclosure, electrical protection relay components, and multiple fittings and fasteners. 3D visualizations of this component are shown in Figure 9 where the front panel of the weather resistance enclosure has been hidden to visualize the included DIN-rail-mounted electrical protection equipment (relay). Table 6 lists the bill of materials describing the individual components.

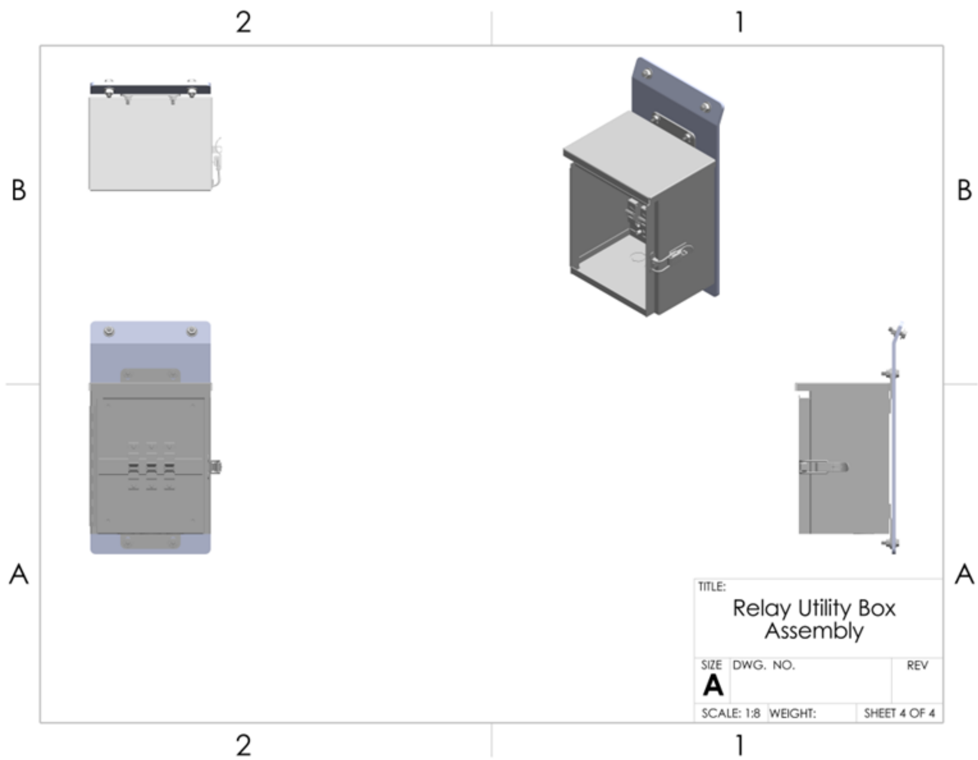

Figure 9. PT: relay utility box assembly.

Table 6. Bill of materials for the relay utility box.

Part no.	Description	Quantity	Unit price (US$)
92141A029	Fittings/fastener	8	0.05
95462A029	Fittings/fastener	4	0.08
91309A542	Relay/breaker	4	0.08
92141A030	Fittings/fastener	4	0.08
7026K615	Fittings/fastener	3	50.48
92356A583	Fittings/fastener	2	0.41
93776A441	Fittings/fastener	2	0.20
8961K102	DIN rail	1	14.92
7649K45	Weather resistance enclosure	1	99.14
89155K11	Mount (requires postprocessing)	1	100.43

3.4 Maximum Power Point Tracking Charging Controller

The MPPT charging controller assembly was composed of a single charge controller manufactured by MidNite Solar, in addition to multiple fittings and fasteners. Approximate 3D visualizations of the component are shown in Figure 10. The bill of materials describing the individual components is listed in Table 7.

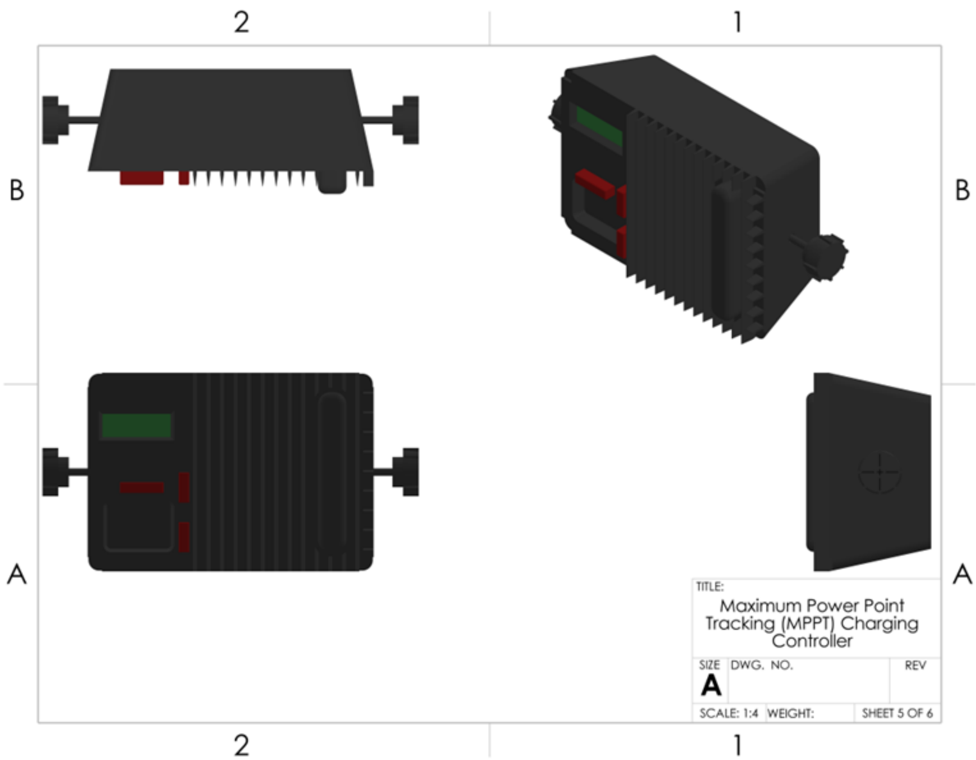

Figure 10. PT: approximate MPPT charging controller visualization.

Table 7. Bill of materials for MPPT charging controller.

Part no.	Description	Quantity	Unit price (US$)
92141A030	Fittings/fastener	4	0.08
93810A220	Fittings/fastener	2	2.51
93827A219	Fittings/fastener	2	0.21
MNKID-M-B	Charging controller	1	499.00

3.5 Shunt Module

The shunt module assembly was composed of multiple industry standard shunt resistors, custom 3D printed shunt housing and shunt mount, and multiple fittings and fasteners. 3D component visualizations are shown in Figure 11; the shunt cover was hidden to visualize electrical equipment (shunt resistors). Table 8 lists the bill of materials describing the individual components.

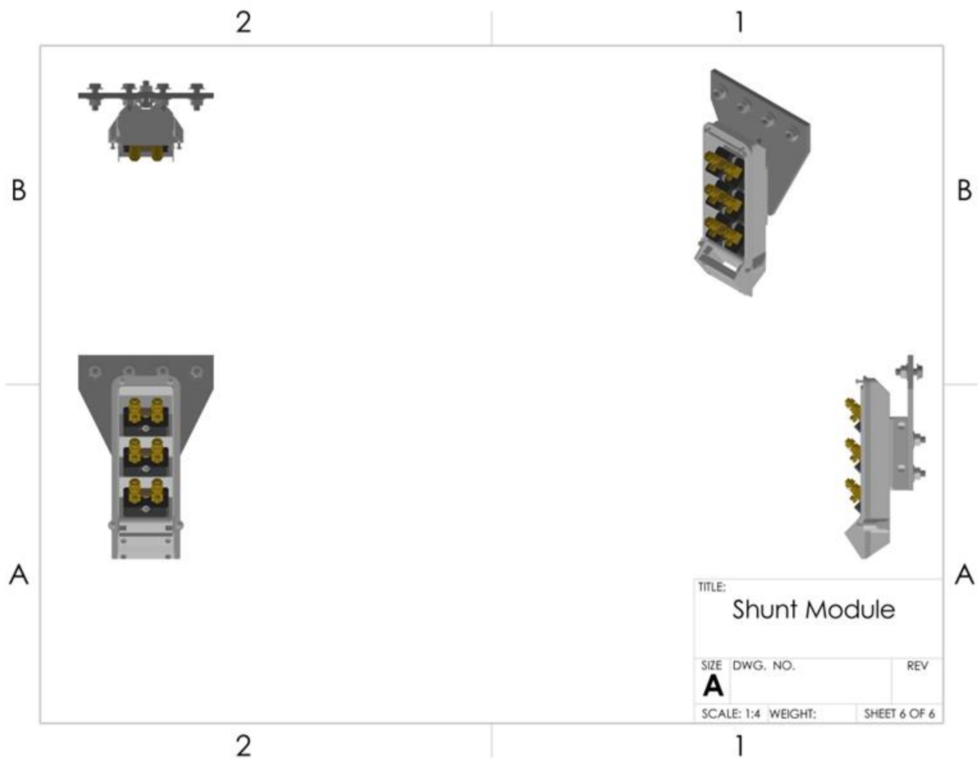

Figure 11. PT: shunt module. Cover hidden to visualize shunt resistors.

Table 8. Bill of materials for the shunt module.

Part no.	Description	Quantity	Unit price (US$)
90410A151	Fittings/fastener	12	0.10
92356A583	Fittings/fastener	6	0.41
93776A441	Fittings/fastener	6	0.20
90410A831	Fittings/fastener	6	0.18
118-RSA-10-100-ND	Resistor	2	32.88
118-RSA-20-100-ND	Resistor	1	32.88
3136N152	T-slotted framing	1	25.92
3D printed	Shunt rail mount	1	. . .
3D printed	Shunt base	1	. . .
3D printed	Shunt cover	1	. . .
3D printed	Shunt wire brace	1	. . .

3.6 Battery Bank

The battery bank assembly was composed of multiple deep discharge cycle batteries (two 12 V or three 8 V) in a serial arrangement with each housed in polypropylene battery boxes. 3D visualizations of the components are shown in Figure 12. Each battery is contained within its own battery box to protect the battery from the elements. One of the battery box tops has been hidden to show the internal electrical equipment (battery). The bill of materials describing the individual components is in Table 9.

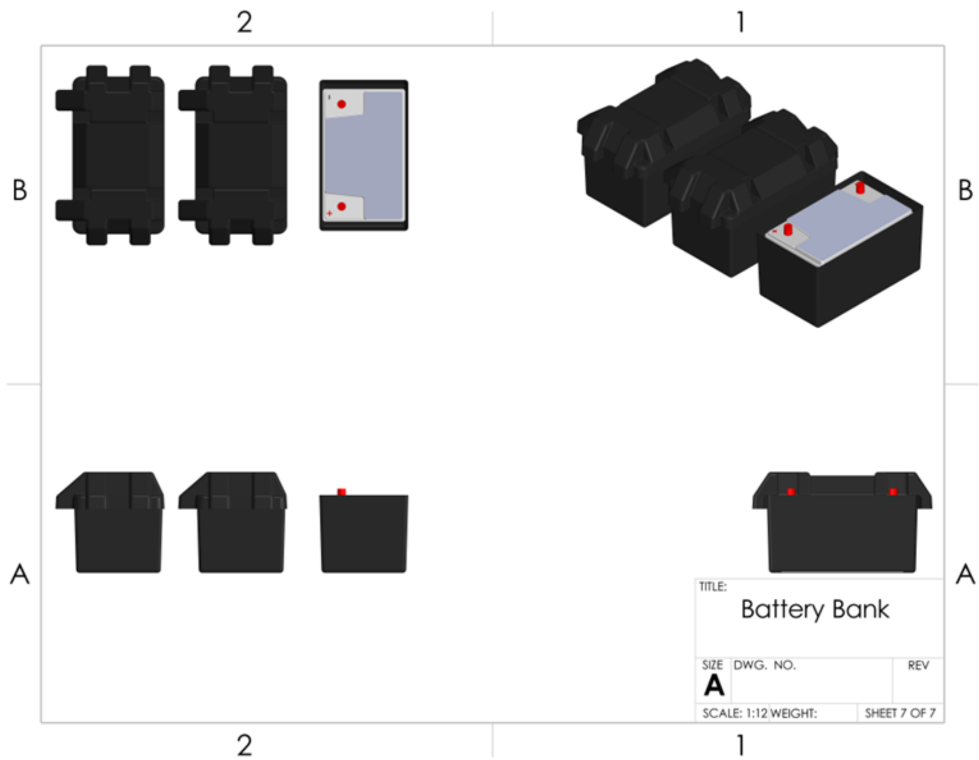

Figure 12. PT: battery bank.

Table 9. Bill of materials for the battery bank.

Part no.	Description	Quantity	Unit price (US$)
71805K15	Deep discharge battery	3	367.14
69995K86	Battery box	3	25.85

3.7 Load Bank

The load bank assembly was composed of a custom metal mount, robust body mounted resistors, a heat sink, and multiple fittings and fasteners. Figure 13 shows 3D visualizations of the component. The load bank was composed of multiple resistors capable of bleeding off excess energy to avoid overcharging the energy storage. The bill of materials that describes the individual components is in Table 10.

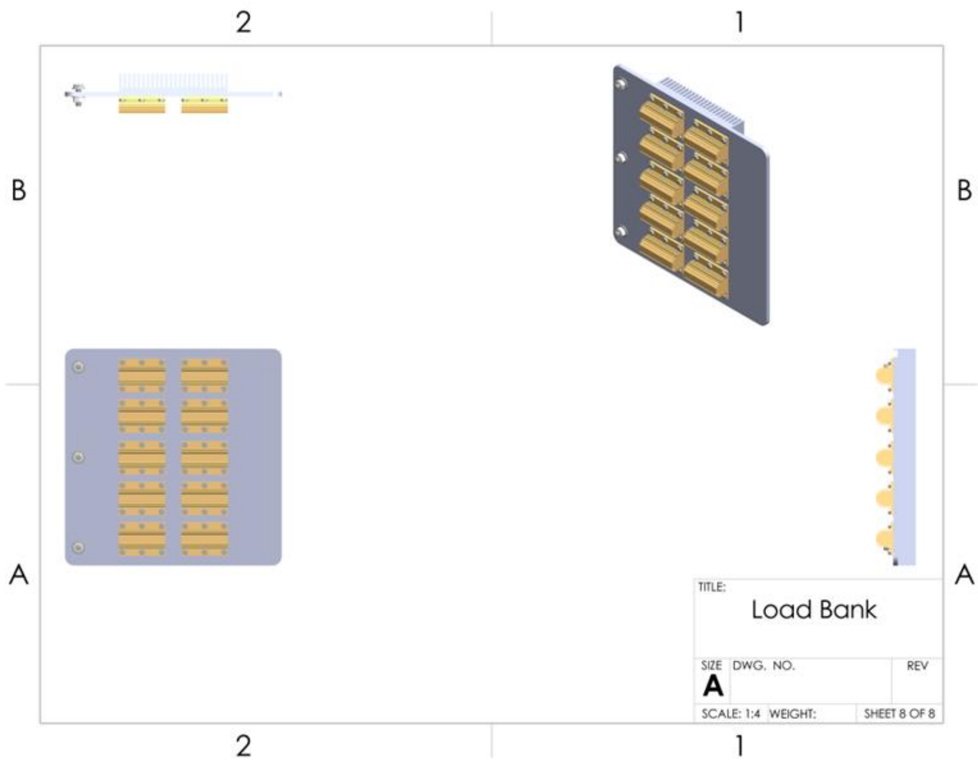

Figure 13. PT: load bank comprising multiple resistors.

Table 10. Bill of materials for the load bank.

Part no.	Description	Quantity
92314A826	Fittings/fastener	60
HS10033RJ-ND	Resistor	10
92356A583	Fittings/fastener	3
93776A441	Fittings/fastener	3
5496-SK44200AL-ND	Heat sink	1
89155K11	Mount (requires postprocessing)	1

4. Whole Sky Imager

Using a model to determine solar radiation required a WSI and specialized software to quantify cloud cover percentage and cloud type/layer. For more information regarding the assessment, see Vaucher et al. (2023a, 2024).

4.1 Testbed WSI History

The original WSI consisted of a Professional NIKON D1X camera with a Sigma 8-mm 180° fisheye lens. A second iteration of the WSI technology used the more versatile NIKON D750 with the same lens. Sky assessments produced by both tools followed a standard three-tiered (high, middle, low) sky observation process, coupled with an automated weather sensor within 40 mi of the field site (Vaucher et al. 2017). The vision for automating this function was finally realized after cellphone-sized cameras confirmed the potential for being powered by the PV panel in its prototype (Curtice 2018). Ultimately, this tool was able to evolve into the automated, stand-alone, miniature camera with fisheye lens that it is today. The hardware encasement and WSI technology will be described next, in the context of constructing a unit. Appendix B provides a list of materials needed to construct the WSI.

4.2 WSI Hardware

The WSI hardware components were attached to the PV panel frame. Figure 14 presents an overview of the five main WSI custom components.

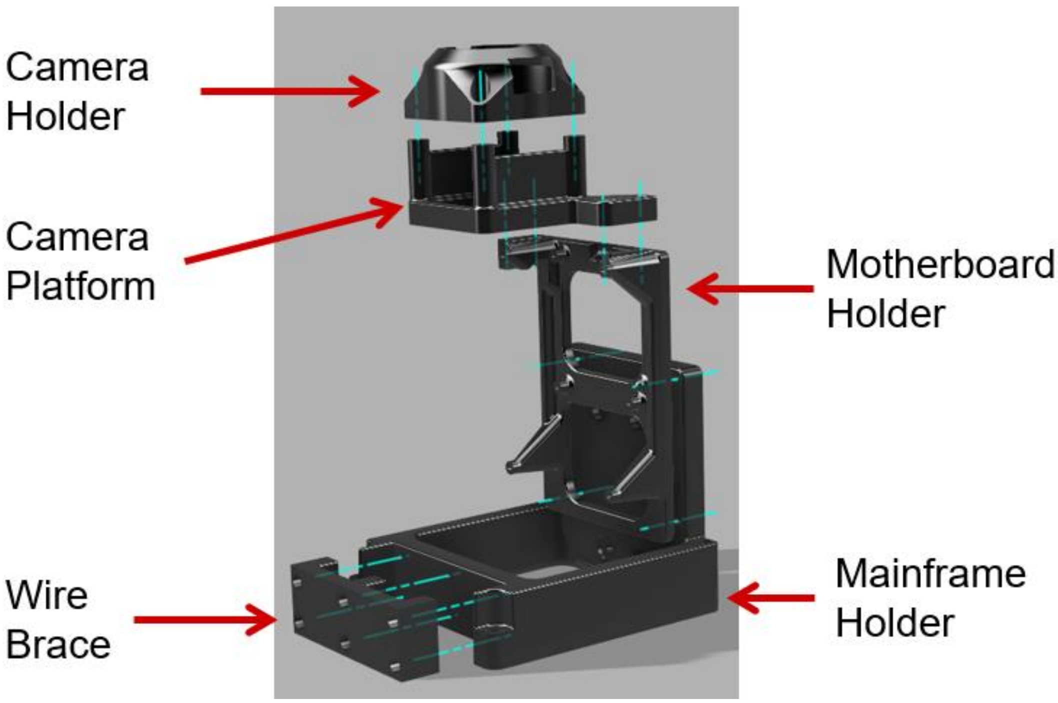

Figure 14. WSI: WSI partial internal component diagram.

Preparation to build the WSI unit includes the following steps:

1) Using a soldering iron to install two M4 × 8- × 6-mm brass Knurled Nuts into the two screw holes found in the inside base of the mainframe holder (Figure 15).
2) Installing four M4 × 8- × 6-mm brass Knurled Nuts into the four screw holes found in the inside of the main cover (Figure 15).

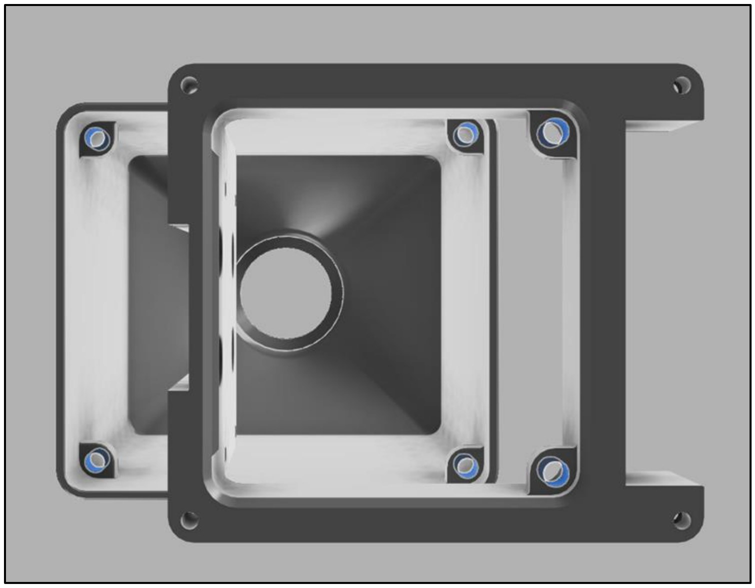

Figure 15. WSI: WSI threaded insert locations.

Prepare the mainframe holder with the following steps:

3) Place the aluminum plate into the indent on the back of the mainframe holder and use a marker to trace the four holes onto the plate. Drill and tap holes into the plate to satisfy a #10-24 × 3/8-inch screw. Connect the mainframe holder to the plate using four of these screws (Figure 16).

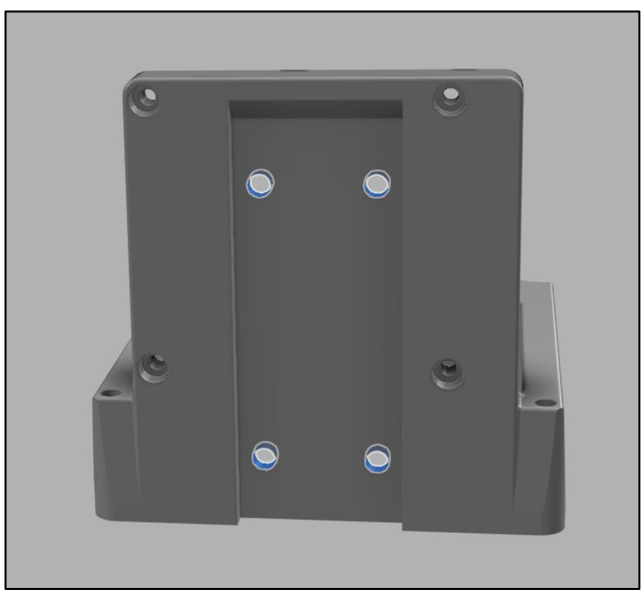

Figure 16. WSI: WSI mounting bar attachment holes.

4) Install two M4 × 25-mm captive screws to the two front outside screw holes. The head should face down (e). See Figure 17.

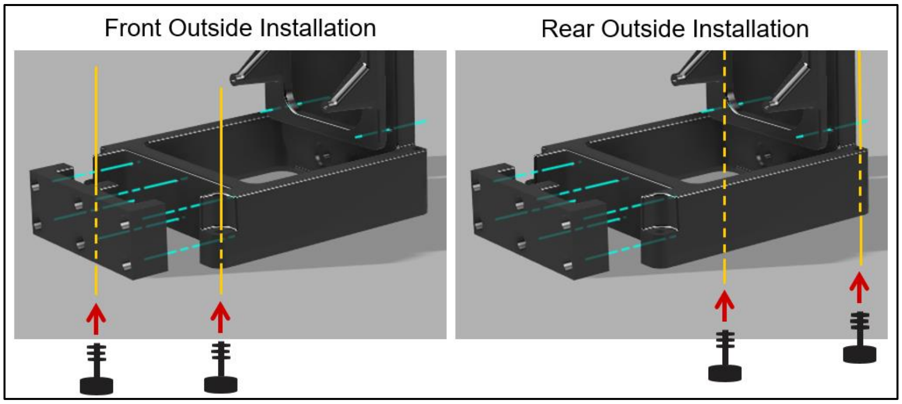

Figure 17. WSI: captive screw installation.

5) Install two M4 × 40-mm captive screws to the two rear outside screw holes. The head should face down.

Prepare the camera and camera holder assembly with the following steps:

6) Remove the tripod mount from the Raspberry Pi camera.
7) Insert the Neutral Density Filter (NDF) into the NDF holder.
8) Install NDF holder system into camera using the custom NDF wrench.
9) Use four M2.6 × 5-mm screws to install camera inside of camera holder, then install the camera lens into the camera.

Next is the motherboard holder assembly:

10) Install the Raspberry Pi (Model 4B) onto the motherboard holder using four M2.6 × 5-mm screws.
    a. Apply the included heat sink to the processor.
    b. Connect the camera ribbon to the Raspberry Pi.
    c. Use an M3 tap on the motherboard holder screw locations.
11) Place the power plate over the Raspberry Pi, ensuring pins are properly connected and the fan is over the Raspberry Pi's processor.
    a. Install included watch battery.
    b. Apply liquid ("brush on") electrical tape to the soldered pins on the power plate located directly above the Raspberry Pi's USB ports.
12) Install four of the included offsets at the power plate corners, then place an analog-to-digital converter (ADC) plate (Figure 18) on top, ensuring pins are properly connected.
13) Install four more offsets at the ADC plate corners, then place another ADC plate on top, ensuring pins are properly connected.
14) Assign this second ADC plate an address of "1" on the board.

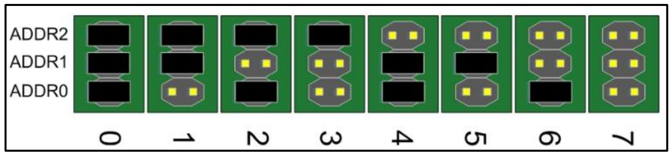

Figure 18. WSI: ADC address assignment (adapted from WallyWare, Inc. 2025).

15) Install four more offsets at the ADC plate corners, then place the relay plate on top, ensuring pins are properly connected (Figure 19).
16) Install the last four offsets to the relay plate corners to keep the plate in place.

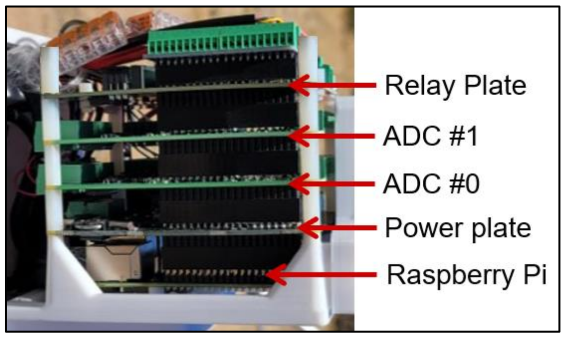

Figure 19. WSI: assembled plates and offsets on motherboard holder.

The main cover assembly can be prepared with the following steps:

17) Set the main cover ring on the lip of the main cover.
18) Set the lens surround ring on top of the main cover ring and on/in the main cover lip.
19) Set the camera cover dome on top of the lens surround ring.
20) Lock the components in place using the dome lock ring.

The whole unit assembly is next:

21) Attach the motherboard holder to the mainframe holder using four #6 × 1/2-inch pan head sheet metal screws (Figure 20).

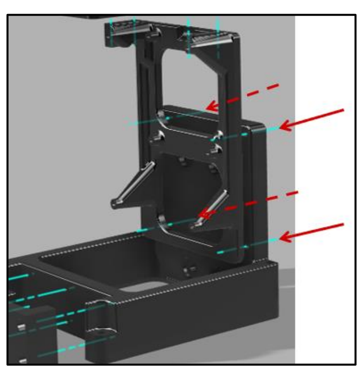

Figure 20. WSI: screw placement for motherboard holder and mainframe holder.

22) Attach the camera platform to the motherboard holder using four M3 × 10-mm screws.
23) Attach camera holder to the camera platform using four #6-5/8-inch flat head screws.
24) Attach wire brace to mainframe holder using six M3 × 12-mm screws. NOTE: Complete this step after wiring the WSI.
25) Place main cover over partial assembly and secure captive screws.
26) Attach the main cover door to the main cover using two M4 × 16-mm captive screws to complete the assembly (Figure 21).

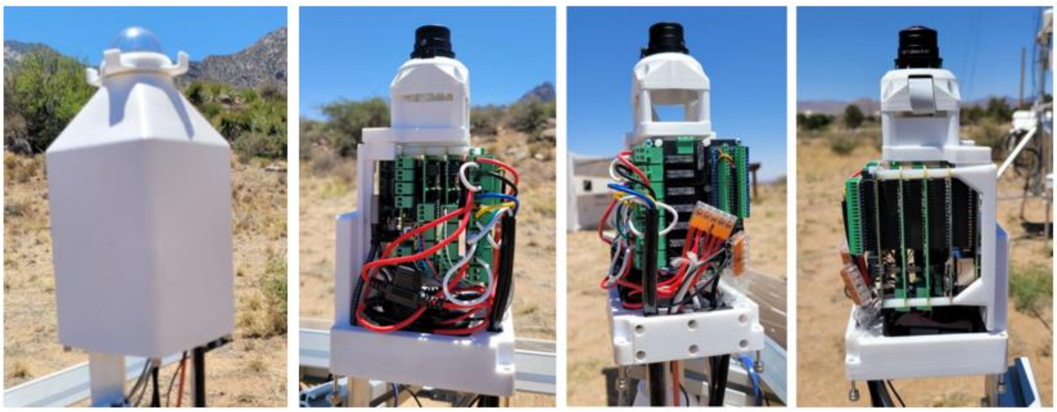

Figure 21. WSI: completed WSI assembly with main cover on and off.

5. Autonomous Data Acquisition

Running 24/7 requires automation in both the acquisition and archiving of the data files. While Testbed details were tailored for the individual sites, the following subsections capture the basic functions.

5.1 System Autonomy

All electrical power requirements of the MMT and PT data acquisition were originally supported by external power. In the latter iterations of the Testbed, however, system power was provided by the PV panel and battery in the PT. The system's minimal power requirements left a surplus of electricity to be managed and dissipated in the digital load, thus enabling the continued option for tactical device and scenario simulations.

5.1 System Software

System software details were tailored to specific network and associated constraints of the individual site. In the absence of on-site internet connectivity, a specialized network associated with the meteorological instrumentation was used to transmit the entire Testbed data payload from the remote site to a central location. The instrumentation network then used a dedicated web server to make the raw data available on an internal data network. While bandwidth was limited, this methodology was sufficient for the given purposes.

To make the complete dataset accessible to all interested researchers, a set of scripts was developed that polled the dedicated web server and then created an organized, validated data archive. The specific form of these scripts was highly dependent on the peculiar data storage and transmission methods. However, several salient features were identified that were implemented by a set of management scripts.

Name conventions were important and, in some cases, formed a critical element of the dataset. Due to the established data format in the MMT and PT data files, the file name was used to identify the recording date of each dataset. It was also important to identify the time zone so that any automated data processing could proceed without time ambiguity.

The system software design was set up for autonomous data collection and transmission. Human intervention and oversight were still occasionally required. Since the Datalogger used local storage, disruption of the basic raw data was very rare. However, it was quite helpful for the management scripts to include the ability to retrieve previously stored data and seamlessly incorporate it into the archive for occasions when there was an unscheduled network interruption and data needed to be moved manually.

The MMT software was designed around a standard Datalogger product. Appendix A provides an example program.

The WSI and PT software were run on a Raspberry Pi 4B single-board computer using Raspberry Pi OS and data collection software written in Python.

The PT software read voltages from six channels of the ADC boards at 1.5-s intervals, averaged all samples within 1 min, and saved the resulting voltages to a file along with the current panel temperature, which was read from the DS18B20 temperature sensor. The system started a new file at midnight, then processed the voltages in the last raw data file (processing shunt voltages to calculate currents and compensating for resistor half-bridges on the voltage side) to produce final current and voltage readings for the system. The software was run daily (around midnight) from a Crontab entry.

The load was controlled by software that checked the most recent battery voltage saved by the PT software and increased or decreased the number of relays activated as voltage went up or down, respectively. The load was adjusted at 15-min intervals by a program running from a Crontab entry.

The WSI images were taken using software that iterated the exposure time. The system started with a minimum exposure time, taking test images and analyzing the image brightness, then it increased exposure until a brightness threshold was achieved. The image was then taken as a Numpy array and multiplied by a 1-bit mask before being saved as a JPEG image. If the maximum exposure was achieved without reaching minimum brightness, no image was taken. Images were taken at 15-min intervals and the program was run from a Crontab entry.

Power optimization routines used the "near real-time" data acquired and were kept on an independent computer platform. This platform served as a partial data archive for current and future optimization applications.

While the WSI served as a routine data resource for solar radiation modeling and 3D dual-image cloud assessment research, it also enabled a quick assessment of onsite conditions for the remote site environment.

5.2 Archiving Software

While not required, organizing the data into monthly subfolders was very convenient. These subfolders were organized under MMT, PT, and WSI folders. This structure provided manageable directory sizes for users to sort through visually as needed and still enabled automated processing of the data for most tasks. This archive was located on a Linux system to which research access was granted with the full complement of Linux system tools and scientific software to review and process the data.

Users were not limited to local access; rather, approved users from over 3000 km away had daily access to the multiple systems through a protected network that supported the daily archival of quantitative system and environmental data. An automated graphical visualization of the atmospheric data was generated on a controlled-access website.

6. Conclusion and Recommendations

Documenting the AIHPA Testbed has brought to light several accomplishments gained through the integration of technologies. The consistent reliability of the MMT data has established a foundational data resource for current AI research. The latter PT design has shown minimal operations and maintenance requirements and has provided constructive guidance to remote-site ARL (and other government agency) projects. The WSI continues to advance into more efficient and effective designs. Finally, the self-powering attribute has opened a wide array of future possibilities. The ultimate direction for the Testbed will be to evolve into a mobilized system, effectively turning it into a smart, automated, hybridized, mobile recharging station.

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Appendix A. Meteorological Measuring Tripod Software

The following is a Meteorological Measuring Tripod Campbell Scientific CR6, Datalogger Program example:

```
CR6 Series
'Created by Short Cut (4.2)
PipeLineMode
PreserveVariables

Const CR_LF = CHR(13) & CHR(10)

'Declare Variables and Units
Public BattV
Public PTemp_C
Public Pressure
Public TempHi
Public TempLow
Public Temp_Vai
Public RH_pct
Public WS_1
Public WD_1
Public SlrW
Public SlrkJ

Units BattV=Volts
Units PTemp_C=Deg C
Units Pressure=mbar
Units TempHi=Deg C
Units TempLow=Deg C
Units Temp_Vai=Deg C
Units RH_pct=%
Units WS_1=meters/Second
Units WD_1=degrees
Units SlrW=W/m^2
'Units SlrkJ=kJ/m^2

'Define Data Tables
DataTable(One_Minute,True,-1)
 DataInterval(0,60,Sec,10)
 Average(1,Pressure,IEEE4,False)
 Average(1,TempHi,FP2,False)
 Average(1,TempLow,FP2,False)
 Average(1,Temp_Vai,FP2,False)
 Sample(1,RH_pct,FP2)
 WindVector(1,WS_1,WD_1,FP2,False,0,0,1)
 FieldNames("WS_1,WD_1")
 Average(1,SlrW,FP2,False)
 Average(1,BattV,FP2,False)
```

```
 Average(1,PTemp_C,FP2,False)
EndTable

Dim LnuxSec(10)
Alias LnuxSec(1) = SmplPressure
Alias LnuxSec(2) = SmplTempHi
Alias LnuxSec(3) = SmplTempLow
Alias LnuxSec(4) = SmplTemp_Vai
Alias LnuxSec(5) = SmplRH_pct
Alias LnuxSec(6) = SmplWS_1
Alias LnuxSec(7) = SmplWD_1
Alias LnuxSec(8) = SmplSlrW
Alias LnuxSec(9) = SmplBattV
Alias LnuxSec(10) = SmplPTemp

Dim rTime(9)
Alias rTime(1) = Year
Alias rTime(2) = Month
Alias rTime(3) = DOM
Alias rTime(4) = Hour
Alias rTime(5) = Minute
Alias rTime(6) = Second
Alias rTime(7) = uSecond
Alias rTime(8) = WeekDay
Alias rTime(9) = Day_of_Year

Dim HHMMss As Long

Public DataOutStr As String * 150

'Main Program
BeginProg
 SerialOpen (ComRS232,-115200,0,0,50)
 SW12 (SW12_1,1 )
 'Main Scan
 Scan(5,Sec,2,0)
 'Default CR6 Datalogger Battery Voltage measurement
'BattV'
 Battery(BattV)
 'Default CR6 Datalogger Wiring Panel Temperature
measurement 'PTemp_C'
 PanelTemp(PTemp_C,60)
 'CS106 Barometric Pressure Sensor measurement
'Pressure'
 PortSet(U3,1)
 VoltSe(Pressure,1,mV5000,U1,True,0,60,0.240,500)
 '107 Temperature Probe measurement 'TempHi'
```

```
 Therm107(TempHi,1,U5,U2,0,60,1,0)
 '107 Temperature Probe measurement 'TempLow'
 Therm107(TempLow,1,U6,U2,0,60,1,0)
 'EE181 (constant power) Temperature & Relative
Humidity Sensor measurements 'Temp_Vai' and 'RH_pct'
 VoltSe(Temp_Vai,1,mV1000,U7,False,0,60,0.1,-40)
 VoltSe(RH_pct,1,mV1000,U8,False,0,60,0.1,0)
 If RH_pct>100 AND RH_pct<103 Then RH_pct=100
 '05103 Wind Speed & Direction Sensor measurements
'WS_1' and 'WD_1'
 PulseCount(WS_1,1,U4,5,1,0.098,0)

BrHalf(WD_1,1,mV5000,U9,U2,1,2500,True,20000,60,355,0)
 If WD_1>=355 OR WD_1<0 Then WD_1=0
 'CMP3/CMP6/CMP11 Pyranometer measurements 'SlrkJ' and
'SlrW'
 VoltDiff(SlrW,1,mV200,U11,True,0,60,1,0)
 If SlrW<0 Then SlrW=0
 'Calculate total flux
 'The multiplier to calculate total flux was
calculated by Short Cut
 'and based on a program execution rate (scan rate) of
5 Seconds.
 'If you change the program execution rate outside of
Short Cut with the CRBasic Editor
 'you will need to recalculate this multiplier. See
the sensor manual for more details.
 SlrkJ=SlrW*0.4078303
 'Calculate flux density
 SlrW=SlrW*81.56607
 'Call Data Tables and Store Data
 CallTable One_Minute

 RealTime(rTime())
 HHMMss = Hour * 100 + Minute

 If One_Minute.OutPut(1,1) Then
 GetRecord(LnuxSec(), One_Minute, 1)
 DataOutStr = Year & "," & Day_of_Year & "," & HHMMss
& "," & Pressure & "," & TempHi & "," & TempLow & ","
& Temp_Vai & "," & RH_pct & "," & WS_1 & "," & WD_1 &
"," & SlrW & "," & BattV & "," & PTemp_C & CR_LF
 SerialOut (ComRS232,DataOutStr,"",1,0)
 EndIf

 NextScan
EndProg
```

Appendix B. Testbed Construction Materials

The following materials are needed to construct the whole sky imager.

- Six M4 × 8- × 6-mm brass Knurled Nuts
- Four #10-24 × 3/8-inch screws
- 1/2- × 3/16- × approximately 7-inch aluminum plate

    a. Length not specific but needs at least 3.75 inches (the length of the mainframe holder indentation) plus the length necessary for mounting.
    b. Success was found with an approximate 7-inch length, but a longer plate may be needed based on mounting needs.

- Mainframe holder: 3D print using polyethylene terephthalate glycol (PETG) filament
- 2× M4 × 25-mm captive screws
- 2× M4 ×40-mm captive screws
- Raspberry Pi high quality camera with CS mount
- Neutral-density filter (NDF)
- NDF holder: 3D print using thermoplastic polyurethane (TPU) filament
- Raspberry Pi model 4B
- Motherboard holder: 3D print using PETG filament
- Eight M2.6 × 5-mm screws
- POWERplate24 rev. 1.0 (https://pi-plates.com/product/powerplate24/)
- Liquid ("brush-on") electrical tape
- 12 offsets: Included with plate packaging from Pi plates
- ADC plate rev. 1.0 (https://pi-plates.com/adcplate/)
- Relay plate 2 (https://pi-plates.com/relayplate2/)
- Main cover ring: 3D print using TPU filament
- Lens surround ring: 3D print using PETG filament
- Camera cover dome
- Dome lock ring: 3D print using PETG filament
- Screws for "whole unit assembly"

List of Symbols, Abbreviations, and Acronyms

2/3D	two-/three-dimensional
ADC	analog-to-digital converter
AI	artificial intelligence
AIHPA	Atmospheric Intelligence for Hybrid Power Advancements
AM	air mass
ARL	Army Research Laboratory
ArL	above roof level
DEVCOM	U.S. Army Combat Capabilities Development Command
MMT	meteorological measuring tripod
MPPT	maximum power point tracking
NDF	neutral-density filter
NOTC	nominal operating cell temperature
PETG	polyethylene terephthalate glycol
PT	power train
PV	photovoltaic
STC	standard test conditions
TPU	thermoplastic polyurethane
USB	Universal Serial Bus
WSI	whole sky imager

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