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Mission Goal

The purpose of this project is to develop a system to determine orientation of detector instrumentation in three dimensions to less than 2 arc minutes. The goal is to be able to determine where the gamma-ray detectors on the project HARMEnI are pointed at any point during its flight in order to properly analyze the collected data afterwards. HARMEnI's payload flies at a high altitude (around 125,000 ft.) and will rotate and swing below the balloon [2]. The orientation system must be able to account for this motion as well as the translational motion of the balloon by generating the data needed for a pointing direction approximately every second. The HASP flight will serve as a test of the hardware at high altitude. This means minimal telemetry will be required, as the focus is on collecting and holding data in an environment similar to the one in which HARMEnI will fly.

Objectives

- Develop and fabricate orientation system capable of outputting a pointing direction accurate to less than 2 arc minutes every second for analysis after the flight.
- Be able to correct error due to pendulum motion of gondola post-flight; the payload will swing below the balloon about 2 degrees in any direction and rotate by over 360 degrees during float [4]. This needs to be accounted for, so a dual-axis tiltmeter will be used.
- Function in both day and night while retaining desired accuracy of 2 arc minutes.
- Output time-stamped pointing direction for analysis on ground, storing the data onboard until the payload is collected.

Requirements

Functional:

- Needs to switch between day and night systems (sun camera and star tracker) at appropriate times.
- All data will be recorded and time-stamped for ease of use on ground.
- Temperature sensors must measure the temperature of each component and send this information to the ground.
- GPS data must be recorded.

Performance:

- Accuracy to less than 2 arc minutes.
- Take measurements every second.

Environmental:

- Function at near-vacuum pressures (1-5 mbars) as well as atmospheric pressure.

- Function at low temperatures (-70°C) as well as ambient temperature [5].
- The star camera needs to operate to operate below 60°C.
- The sun camera must operate between 0-40°C.
- The tiltmeter must operate between 10-70°C.
- The GPS must operate between -40-85°C.
- The Arduino Uno must operate between -40-85°C.

**All temperature ranges found in respective datasheets.*

Deployment:
- Power and control systems will be activated prior to flight.

Operability:
- Each component will be tested individually as well as together as a system.
- Pressure, thermal, and shock testing will be performed.
- Components will be calibrated when applicable (tiltmeter).

Design:
- The payload shall be powered with voltages of 29 V to 33 V and under 2.5 A.
- The payload shall remain secured to the HASP mounting plate under a 10 g vertical and 5 g horizontal shock.
- Payload shall weigh less than 20 kg.
- The payload shall have a footprint under 38 cm by 30 cm and a height under 30 cm.
- Payload shall have a serial downlink of data under 4800 baud (for this application no serial data transfer will be required) [5].

Science Background

Purpose of HARMEnI:

The High Altitude Rotational Modulator for Energetic Radiation Imaging (HARMEnI) balloon instrument is designed to demonstrate the feasibility of utilizing a Rotational Modulator to detect soft gamma rays. A Rotational Modulator (RM) is an instrument built to image incident gamma ray photons by time modulation of individual events. Figure 1 shows a prototype RM comprised of a grid of lead or tungsten slats (labeled “Grid”) rotating above an array of Lanthanum Bromide (LaBr) scintillation detectors viewed by photomultiplier tubes (labeled “Detector Plane”). The time-dependent shadow of the incoming photons is recorded by the detectors which can then be reconstructed into an image [2].

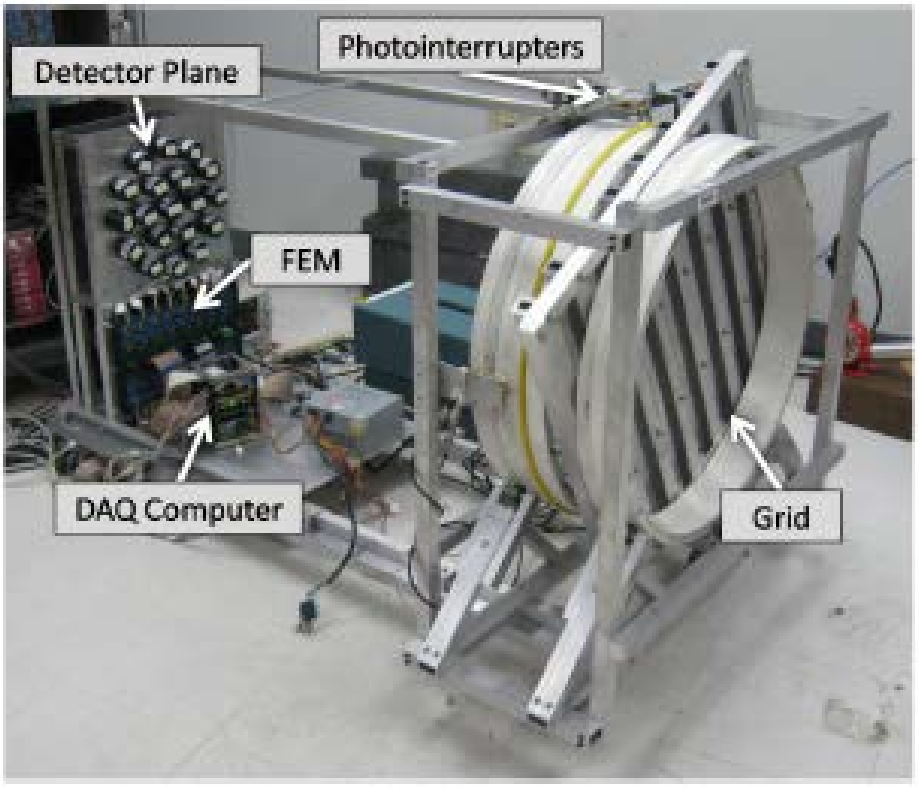

Figure 1: Prototype of a rotating modulator

The prototype HARMEnI instrument will use a RM to detect gamma radiation from the Crab Nebula by taking images of it over approximately 4 hours while suspended from a balloon at 125,000 feet. Over the course of a flight, HARMEnI will potentially transverse a 200 mile flight path while continuously rotating by approximately 3 degrees per second and pitching and rolling by as much as 2 degrees per pendulum swing. A plot of this motion for a typical balloon mission is shown in Figure 2. Since HARMEnI uses incident photons to create an image, it is essential to first deconvolve the RM's motion relative to the incident photons so an image can be constructed. In order to deconvolve the motion, the orientation of HARMEnI must be known to within 2 arc minutes. To identify the orientation of HARMEnI to within 2 arc minutes during the day and night we propose to develop a system which is capable of using the sun and stars to determine instrument pointing. Thus, the star tracker and sun camera systems are essential to the success of HARMEnI.

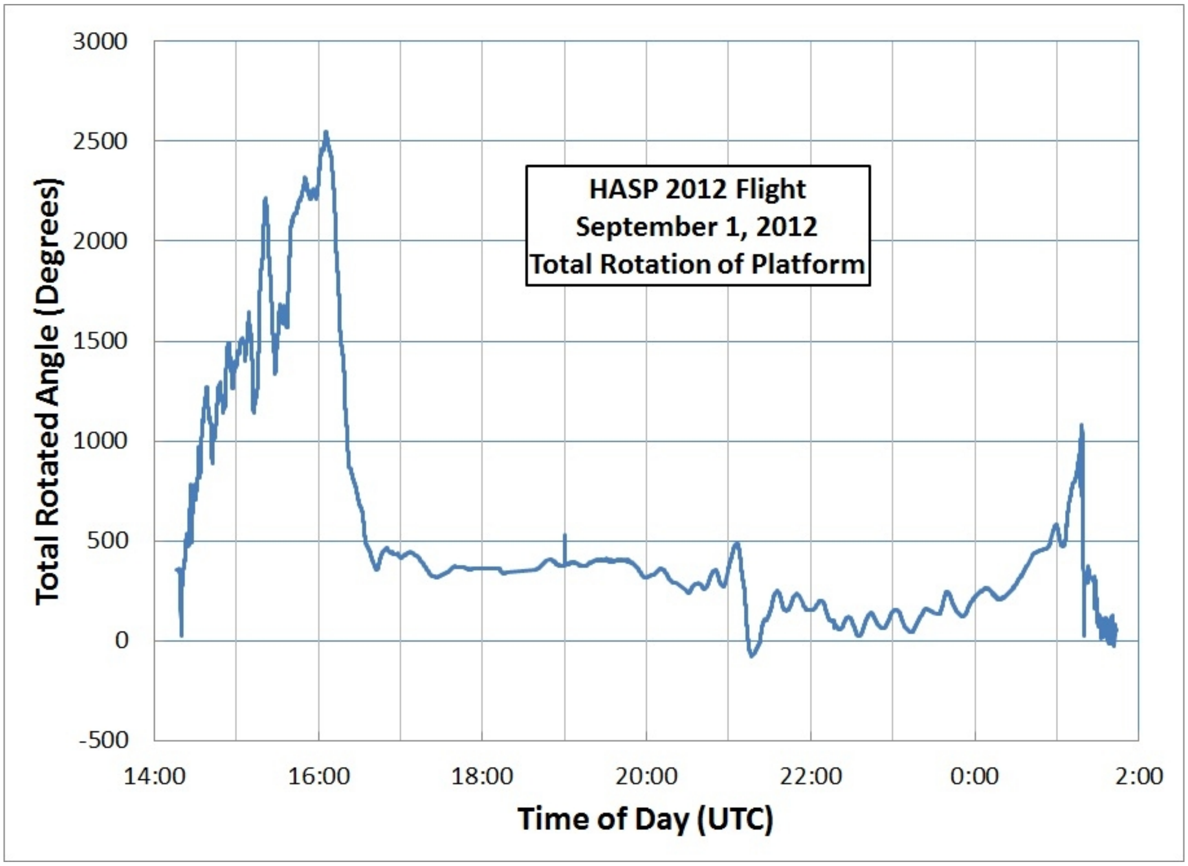

Figure 2: Plot of angular rotation of HASP's payload during a past flight [4]. This shows a typical behavior of a payload suspended below a high-altitude balloon.

Some systems that are used for this purpose include optical gyroscopes and use of the earth's magnetic field. The gyroscope can be very accurate, but it was not cost effective for this project. The magnetic fields do not provide as accurate a measurement unless the instrumentation is very advanced and precise. This causes the cost to increase as well. The solutions that provide the best results within our budget are star trackers and sun cameras.

Position Based on Stars:

At night, the instrument orientation can be determined through star tracking. For this purpose, we will use a Sony ExView HAD ICX429ALL. The CCD will be used to image the sky at a rate of roughly 1 exposure per second. The field of view of each image will be approximately 30-45 degrees to ensure that at least 5-10 bright stars are visible regardless of pointing direction. The depth of exposure can be quantified with a limiting magnitude, that is, a maximum magnitude at which a star can be significantly detected (note that increasing magnitude corresponds to decreasing luminosity). The exposure time for the images has not been firmly decided, but will be in the range of 0.1 – 0.5 seconds. This will depend on the filter used (neutral density, B, V, R, etc.) and the limiting magnitude desired. The field of view was chosen such that a significant number of stars can be identified while minimizing the number of photons detected from atmospheric scattering.

Post flight, programs such as Maxim DL and SAOImage DS9 will be used to determine the orientation of the CCD at the time of each exposure using the corresponding images. The images will be compared to star charts available through digital sky surveys (SAO, Sloan, etc.) in DS9. Right ascension and declination will be found for several stars in the flight images and matched to pixel locations in order to fit the image coordinates linearly to the known coordinates.

Position Based on Sun:

During daylight, position is found using the sun by taking snapshots of the sky at a specified interval. The sun will show up on the CCD as a cluster of bright pixels, so the centroid will need to be found. The path of the centroid can then be traced along the CCD over a full day. By knowing the location, altitude, time of year, and time of day one can find the exact position of the sun with respect to the payload at every time interval. This will create an expected path across the CCD. The variation of the actual path with respect to this expected path will give the horizontal rotation of the payload.

This concept does not, however, account for the pendulum motion of the gondola. From accelerometer data recorded on previous HASP flights, it is known that the gondola and payloads tend to swing back and forth by about ±2 degrees. This motion will cause the plane of the payload to tilt, which in turn induces an uncertainty in the position measurement. By observing the path of the sun, it will be impossible to tell the difference between the variation caused by this tilt and that caused by the payload rotation. This means that the tilt will have to be measured by a separate system and then removed from the data, leaving only the rotational variation. In this application, the system chosen was a dual-axis tiltmeter that could measure the tilt of the payload plane in any direction.

To achieve the 2 arc minute accuracy that is desired, the pixel size and amount of the CCD needs to be addressed. The sun disk measures approximately .5 degrees across its diameter. For a 12 MP DSLR equipped with a 180 degree fisheye lens, this equates to approximately 7.8 pixels. The super resolution is then 1/10 pixel equal to about 23 arc seconds, which is well below the goal of 2 arc minutes [6].

Overall System Design

The system is comprised of two main components: the star tracker and the sun camera. Both of these systems are necessary to determine the pointing direction at all times -- both day and night. The combination of these two systems will achieve this.

The star tracker is made up of a CCD that will take photos at designated time intervals of the night sky. The sun camera is slightly more complicated; it is comprised of a camera, a GPS, and a dual-axis tilt-meter. The camera, like the star tracker, will take photos of the sky, and with the position data from the GPS and the tilt angle data from the tilt-meter the photos can be analyzed after the flight to derive the pointing direction. Both systems will be controlled by an Arduino Uno microcontroller and all data will be stored on-board. The pictures will be held on the cameras' 64 GB SD cards and the position and tilt data will be saved directly to the Arduino's SD card. Power will be distributed to the components via a power system.

All components will be housed in an aluminum and foam container. This will keep the system close to atmospheric pressure and temperature, even in the near vacuum environment in which HASP will be flying.

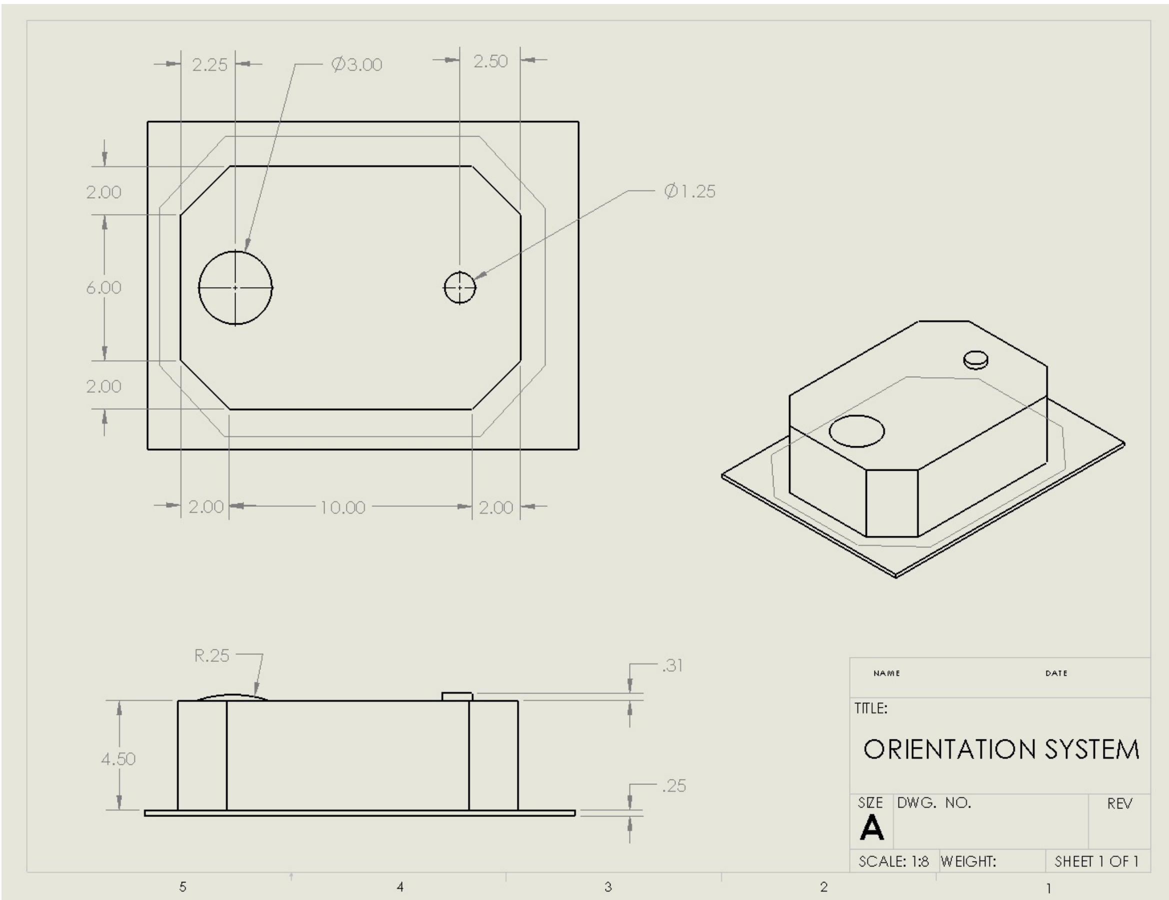

Figure 3: Dimensioned drawing of system including housing [3]

Figure 3 shows the geometry of the housing relative to the HASP plate. The lenses for the cameras protrude from the top of the container, making the effective height slightly over 4.5 inches. Enough room was left on all sides to properly secure the system to the plate using L-brackets.

In Figure 4 below the placement of the major components within the housing is shown. The cameras will be at opposite ends with the tiltmeter, heater, electronics, and power board between them. The heater was placed in such a way that it can effectively heat both the tiltmeter and the sun camera. All components are drawn to scale with the exeception of the heater and power board, which have yet to be sized.

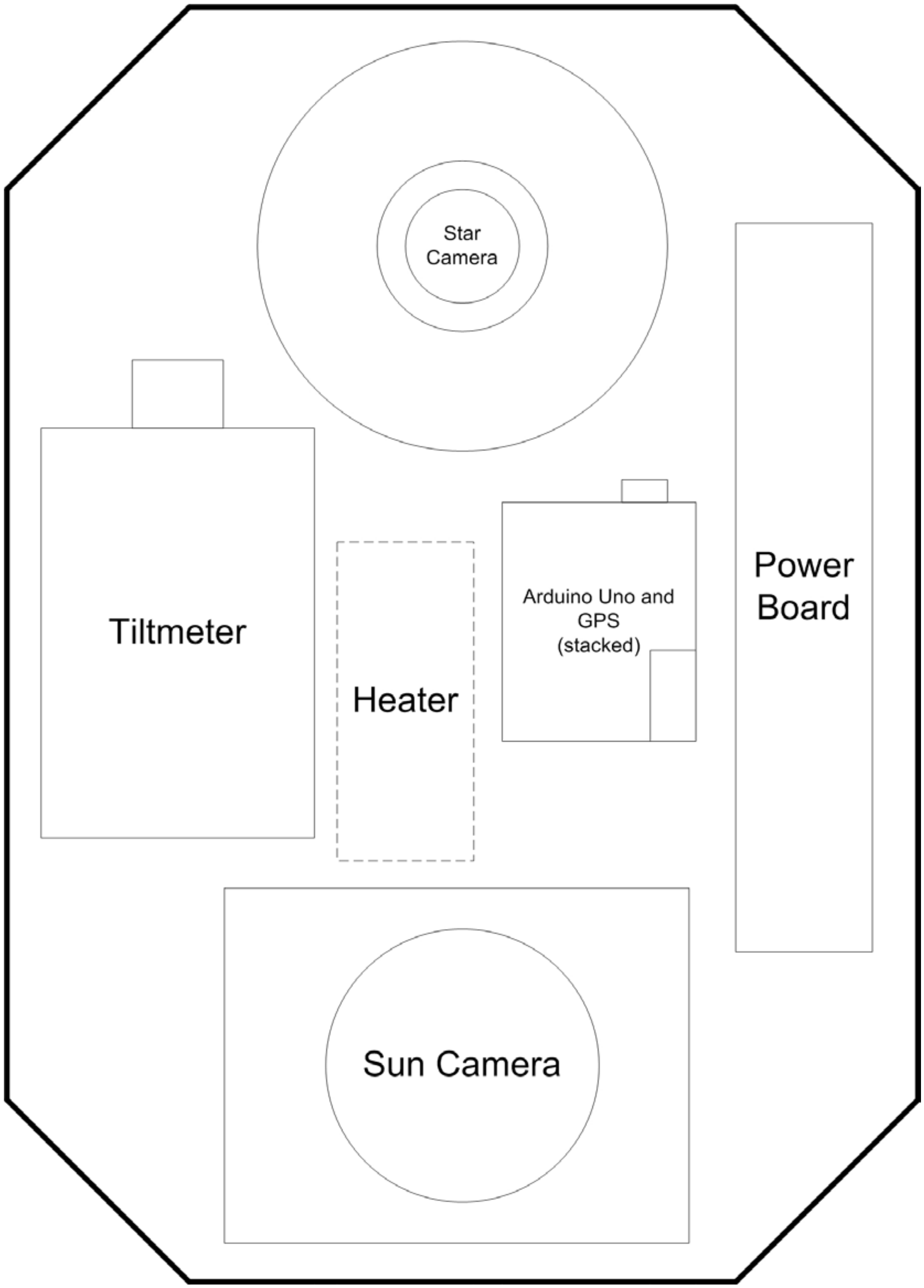

Figure 4: Placement of major components within housing. All components are drawn to 2:1 scale, with the exception of the heater and power board, which still have to be sized.

Star Tracker System:

The star tracker system consists of a CCD equipped with a lens and filter. The CCD that has been selected for this application is the Sony ExView HAD ICX429ALL housed in an Orion Starshoot Deep Space Monochrome Imager II by Meade.

The goal for the limiting magnitude that will be imaged is around 10. As mentioned before, with an exposure time of .1-.5 seconds and a field of view of 30-45 degrees it is possible return enough stars to obtain an accurate pointing direction post-flight. These estimated values are presented as ranges because they will need to be verified through ground-level testing during the Spring. Lens and filter combinations also need to selected after further testing.

For time of year and location of the HASP flight the star Vega will be near zenith. Because the star camera will be vertically oriented this poses a problem with oversaturation; Vega is of magnitude 0 which could make photos unusable for several minutes. A filter will have to be selected that will prevent this while still allowing for stars of the desired magnitude to be visible. Because Vega is so bright in all spectra B, V, and R filters will not suffice. A neutral density filter may serve this purpose, but further analysis will have to be done to determine if the desired visibility is conserved.

The CCD will take photos every second that will be saved to the camera's SD card.

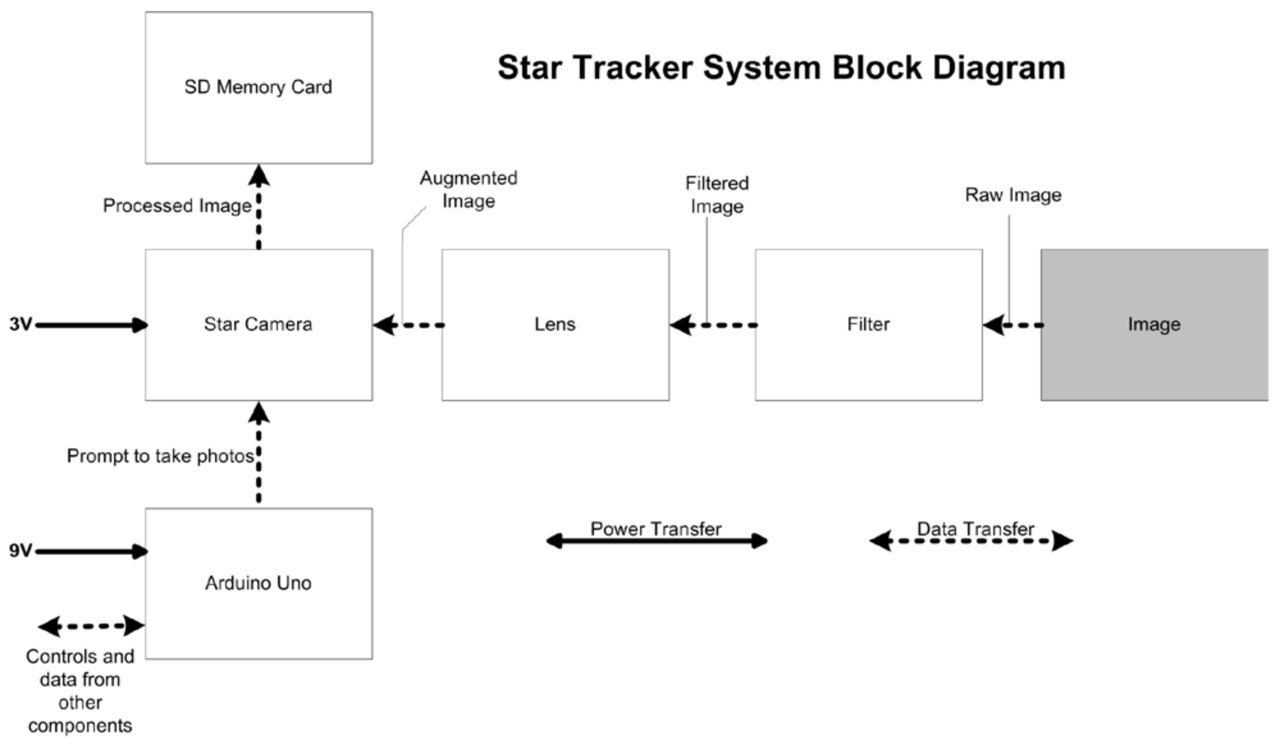

Figure 5: Simplified block diagram of star tracker system. A more detailed power diagram will be shown in Figure 7 to illustrate the sources of power for the camera and Arduino

Sun Camera System:

The sun camera system is comprised of three main components; a sun camera, GPS, and a tilt-meter. The camera will be a 12 MP DSLR to achieve the 1/10 pixel = 23 arc seconds super-resolution as mentioned previously. This will be equipped with a fish-eye lens to extend the field of view to a full 180 degrees. The lens will also be equipped with a neutral density filter to avoid over-saturating the CCD with sunlight.

Black and white images of the sky taken with 12 MP are approximately 600 KB in size. This means that if the camera was equipped with a 64 GB SD card it would be capable of storing approximately 112,000 pictures total. This allows for 1.3 pictures to be taken every second, assuming a 24 hour flight.

A GPS unit will provide the latitude, longitude, and altitude measurements, as well as the time-stamps needed for analysis on the ground. As mentioned before, these values are critical for deriving an expected path of the sun across the CCD.

A dual-axis tilt-meter will account for the pendulum motion of the gondola. The selected model, the 904-T Clinometer from Applied Geomechanics, has a resolution of about 35 arc seconds.

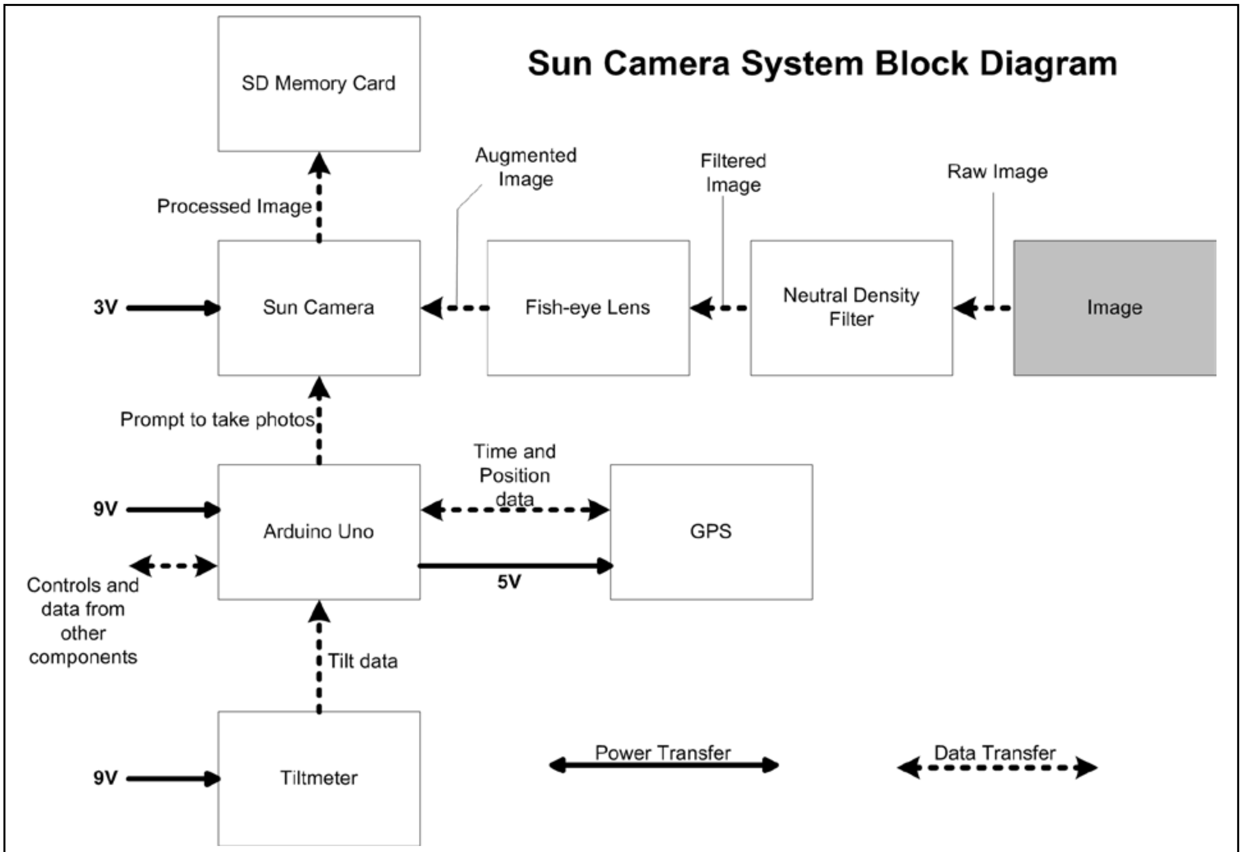

Figure 6: Simplified block diagram of sun camera system. A more detailed power diagram will be shown in Figure 7 to illustrate the sources of power for the camera and Arduino

Control System:

An Arduino Uno microcontroller will control much of the system. It will control functions such as heaters, data acquisition, and camera operation. A thermostat will be implemented to help regulate the heater and let us know if it needs to be turned off manually through a discrete command.

The temperature sensors placed on all components will allow the Arduino to continuously send flight system temperature information to the ground via the analog downlink. This will allow ground to monitor all components to ensure that they are functioning in their proper thermal ranges. If one is not, the heater relay will be sent a command to enable or disable the heaters until the component is in proper thermal range again.

All data from the sun and star camera will be stored on their individual 64 GB SD cards in .jpg format. In .jpg format, an average sun camera picture is 600KB; similarly, the average star camera picture is 430KB. A counter will be applied to the Arduino's coding that will allow the pictures to be synchronized with the data acquisition from the GPS and tiltmeter.

Thermal System:

The system will need to be kept at an appropriate temperature range that satisfies the constraints of each component in the very low temperature environment of the beginning of the flight. Particularly the tiltmeter is only rated for as low as 10°C operating temperature, so it will need to be kept above this threshold to function properly. The sun camera will also need to be kept above 0°C. A combination of insulation and heaters will be used to keep the interior of the housing above the 10°C, which will satisfy the requirements for all components. The heater will be controlled by a thermostat with the option of being turned on or off by discrete commands as a failsafe.

The housing will also be insulated. The housing will be lined with a non-conducting foam type material and will also be surrounded by a thin sheet of aluminum coated with "Appliance White" paint to shield and reduce the heat from the sunlight.

The temperature of each individual component will be monitored via the analog down-link as mentioned previously. This is to ensure that if a temperature drops near its respective limit (either high or low-bound) the heater can be adjusted accordingly.

Power System:

The power supplied by HASP is 30 VDC, with slight variation at startup and landing [5]. Each component has its own voltage requirement as well as an amperage consumption. This means that multiple DC-DC converters will need to be utilized as step-downs. Both cameras operate at 3 V, so they will share a converter. The Arduino and the tiltmeter's required voltage coincide so they can also share a 30 to 9 V converter. The GPS pulls its power directly from the Arduino, so it will not need a converter. The two converters will be connected in series, rather than each connected directly to HASP's power.

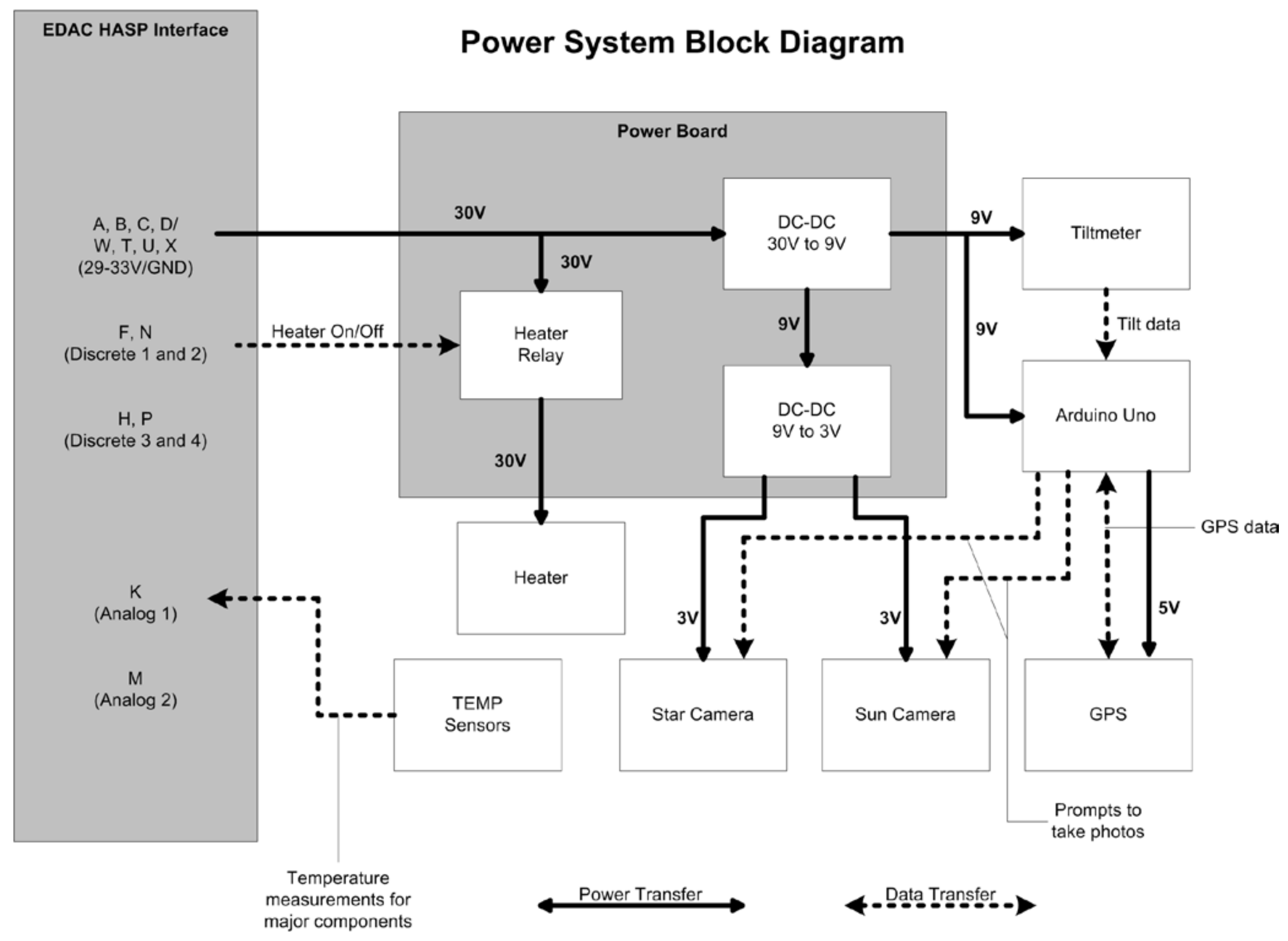

Figure 7: Simplified block diagram of power supply system

Payload Specifications

Power Specifications:

Component	Voltage (V)	Current Draw (mA)	Duty Cycle (%)	Power (W)	Power Consumed (Amp-hrs)
Tiltmeter	9	7	100	0.063	0.112
Star Camera	3	500	65	1.5	5.2
Sun Camera	3	500	65	1.5	5.2
GPS	5	40	100	0.2	0.64
Arduino	9	40	100	0.36	0.64
Heater	30	600	5	18	0.48
Total				21.623	12.272

Table 1: Power budget table for major components

The power supplied by HASP's EDAC is 30 V and 75 W [5]. To calculate each component's requirement and verify that the total was below the allowable their voltage and current needs had to be addressed. These were found in respective datasheets or estimated conservatively. To calculate the power the voltage was multiplied by the current in each case and then summed for a total. Amp-hours were also calculated using an estimated total flight time of 16 hrs and each component's duty cycle. This was needed because some components will not function for the entire length of the flight; in particular, the heater will only be needed periodically to regulate the temperature within the housing. Also, the cameras will switch duty when day turns to night, so neither will run for the entire time. The cameras also draw more power when they take pictures than when they simply sit. This was accounted for in their average amperage consumption seen in the table.

Weight Specifications:

Component	Estimated Weight (g)
Star Camera System	800
Sun Camera System	800
Tiltmeter	450
GPS/Shield	35
Arduino	25
Housing Structure	5000
Foam insulation	100
Heater	50
Electronics	500
Total	**7760**

Table 2: Budget of estimated weights in grams for major components

Table 2 shows the weight specifications of each component. The sun and star camera system both include the combined weights of the camera, lens, and filter. It is shown that we are well within the 20 kg weight requirement by HASP. In addition, both the star and star camera system as well as the housing structure have been conservatively estimated to ensure that we remain within the 20 kg confinements.

Size Specifications:

The housing that contains all components fits within the allowed space for large payload with at least a half inch clearance on all sides for L-braces and insulation. It reaches a maximum height of about 4.75 inches (≈12 cm), so it meets this requirement as well.

Telemetry Specifications:

Discrete Commands

Discrete commands will be used to manually control the heater for the tiltmeter and sun camera. It will be regulated by closed feedback, but the discrete command will serve as a precaution to prevent overheating.

Analog Downlink

The EDAC's analog downlink will be used as a redundant temperature downlink. The individual measurements from each component will be sent to the ground here as well as through the serial downlink.

Uplink/Downlink

Serial uplink and downlink will not be required for this project. All data will be self-contained, with the exception of the thermal data mentioned previously.

Integration and Testing

The housing and will be adhered to the plate via L-shaped brackets on the outside. Enough room was left on all sides to ensure that these will fit without touching the boundary. The cameras and electronics will be secured using tie-downs while the tiltmeter will be bolted into place.

The EDAC will supply 30 V to the heater and relay, but will be stepped down to 9 V for the Arduino and tiltmeter, and then again to 3 V for the cameras. It will also provide the discrete commands and analog downlink that will be used for the heater and temperature sensors, respectively. The power that reaches the components from HASP will be measured prior to the flight to ensure that they are receiving enough to function.

Each component will be tested individually and as a system prior to integration. This will entail taking test photos with the cameras manually as well as automatically with the Arduino. The tiltmeter, GPS, and temperature sensors will also be tested and calibrated to ensure accurate results. Heat transfer calculations will be performed using the heater to ensure that the housing can feasibly remain near room temperature.

Once integrated to HASP, both mechanically and electronically, all components will be tested again to ensure that the results are consisted with expected values.

Project Management

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Table 3: Team members' roles and contact information

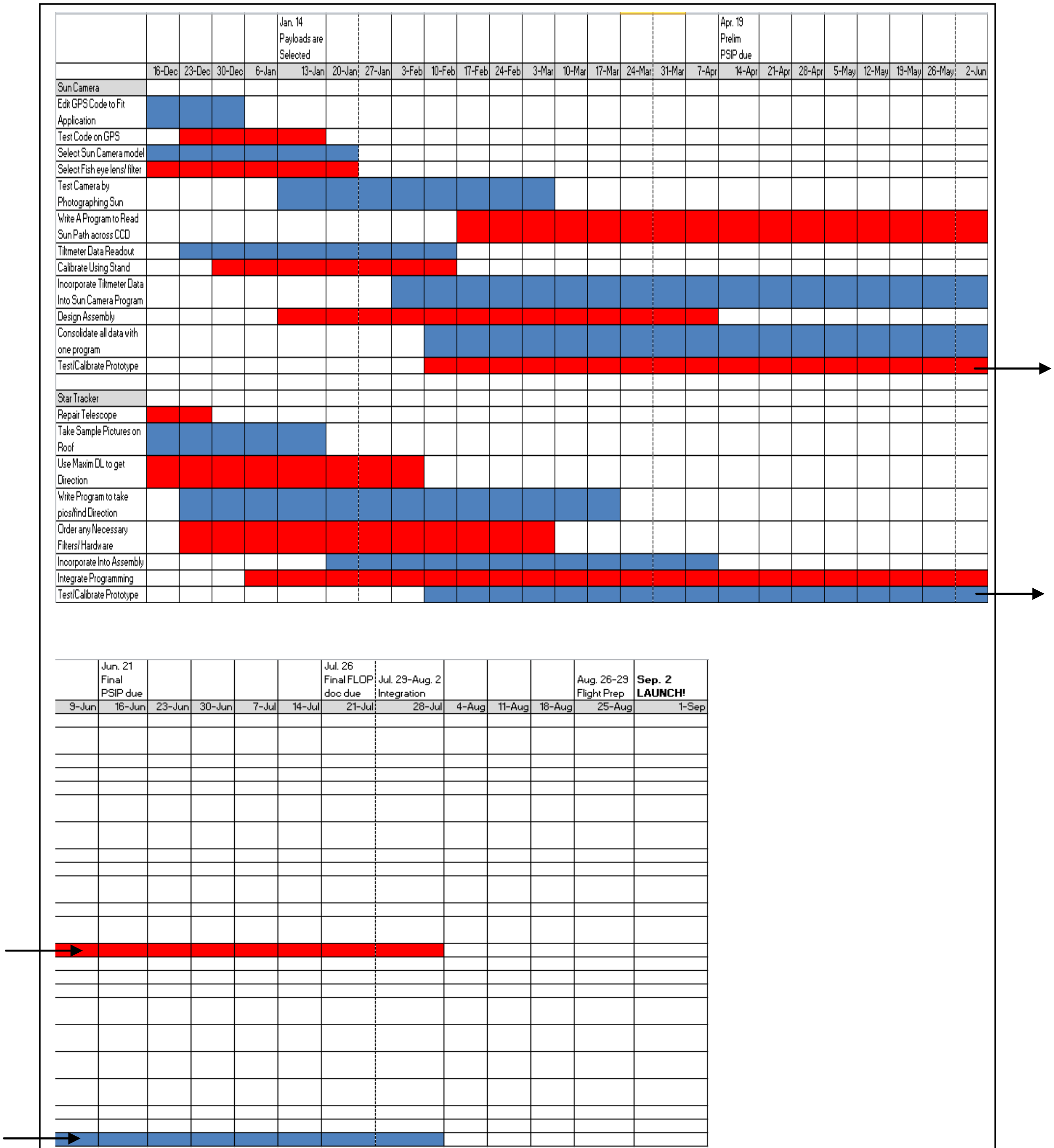

Figure 8: Gantt chart of design and fabrication process

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