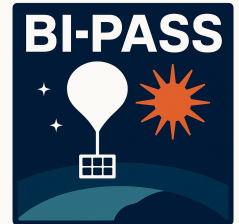


Simulation Framework for Design of Long Duration Balloon Power Systems

JULIA BURTON-HEIBGES

MAY 15, 2025

Colorado School of Mines



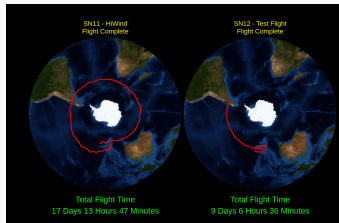
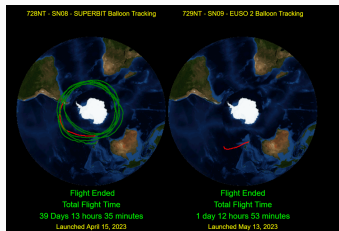
1. Problem space
2. Description of Solar Power Production
3. Battery Bank and Instrument Configuration
4. Simulated Trajectories
5. Single and Multi-trajectory analysis
6. Future Developments

Difficulty in SPB Power System Design

The power system is one of the most critical components of any ULDB payload.

Design constraints include:

- Power-hungry experiments
- Weight Constraints
- Size Constraints
- Environmental Conditions
- Seasonal and location uncertainties



Ballooning Instrument - Power system Analysis Simulation Software (BI-PASS) collects information about these parameters and uses this information to inform future power system design processes.

BI-PASS is a:

- Easy-to-use Python framework
- Easily modifiable
- Highly configurable
- Tested against conditions seen during EUSO-SPB2 flight (limited data, More power system data would be appreciated!)
- Currently in alpha testing
- Will be publicly available by the end of the summer on gitlab along with a paper.



Solar Power Production Theory

Assuming no atmospheric losses at float altitude

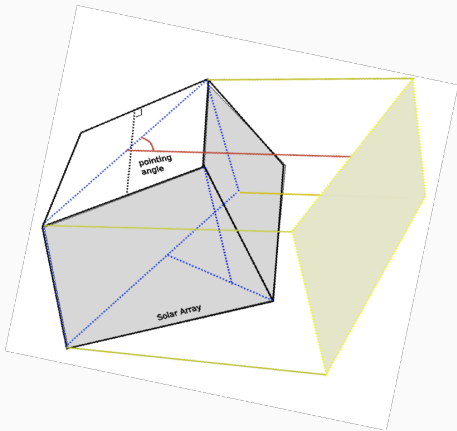
$$\text{Power Production} = \text{Panel}_{\text{eff}} * \text{TSI} * A_{\text{eff}}$$

- $\text{Panel}_{\text{eff}}$ = Solar panel efficiency
- $\text{TSI} \approx 1360 \text{ W/m}^2$ = Total Solar Irradiance at the edge of space

The effective area A_{eff} is calculated based on the angle between the sun and the panels

$$A_{\text{eff}} = A_{\text{panel}} \cdot [\sin(\delta_p) \cdot \sin(\delta_s) + \cos(\delta_p) \cdot \cos(\delta_s) \cdot \cos(\alpha_p)]$$

- A_{panel} = Area of a panel
- δ_s = Solar Elevation Angle
- δ_p = Pointing angle of the given Solar Array
- α_p = Yaw angle of the array relative to zero



Solar Skirt vs Solar Array with Pointing

Solar panel arrangement

- Flexibly configurable through config file
- Defined by pointing direction relative to the sun and tilt angle

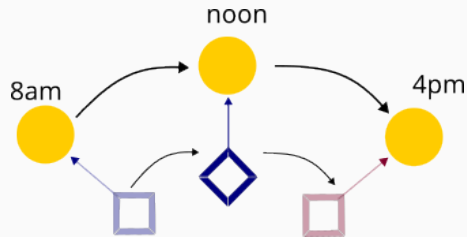
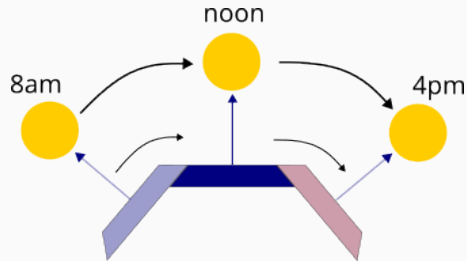
Allow two configurations to be evaluated:

- Sun tracking single solar panel
- Solar skirt (assuming no pointing)

For Solar skirt evaluate two scenarios:

- **Ideal** corner tracking the sun
- **Worst** single panel tracking the sun

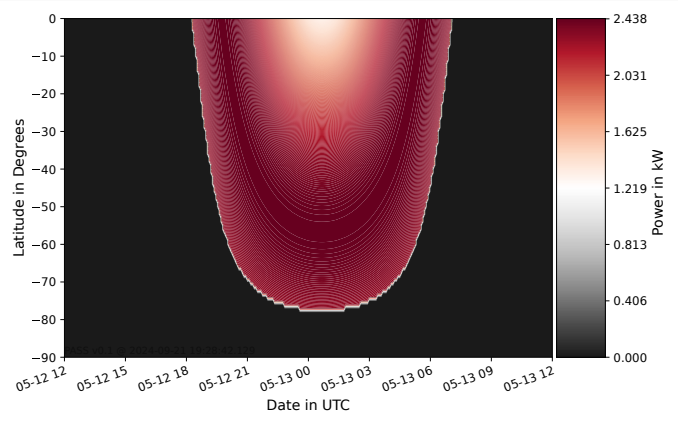
All other configurations are between these two scenarios



Solar Power Production Implementation

Example implementation of single panel design

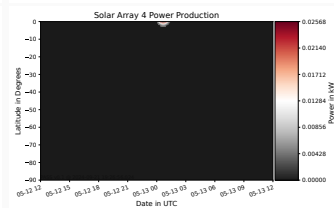
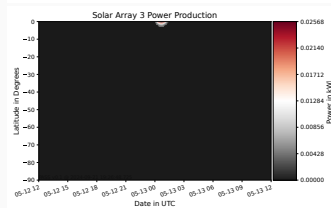
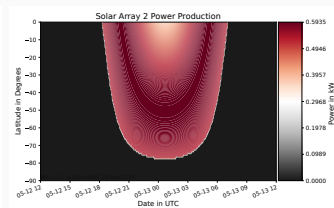
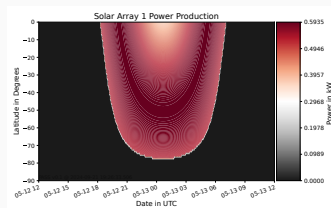
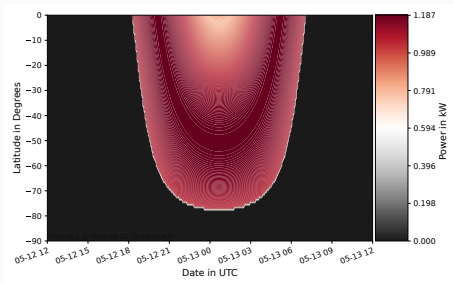
Number of Panels	15
Tilt Angle	15°
Solar Panel Efficiency	22%
Solar Panel Area	0.54 meters



Solar Power Production Implementation

Example implementation of solar skirt design

Number of Panels per Array	5
Number of Arrays in Skirt	4
Tilt Angle	15°
Solar Panel Efficiency	22%
Solar Panel Area	0.54 meters



Battery Bank and Power Consumption

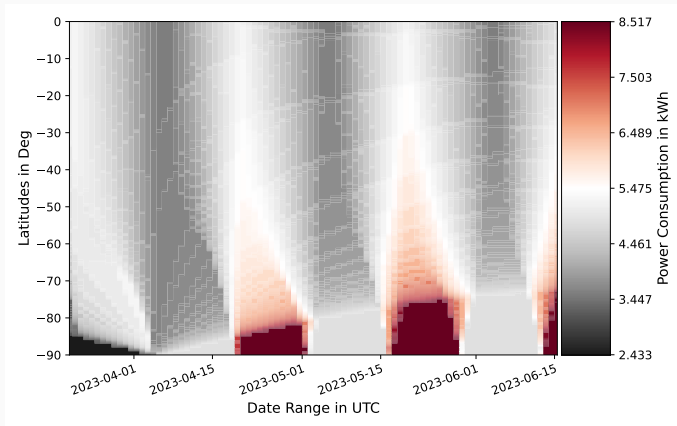
Battery bank fully defined through config file

Battery Type	Lithium ion
Number of Batteries	6
Single Battery Capacitance	1800 Wh

Example power consumption

Daytime Power Consumption	100 W
Nighttime Power Consumption	200 W
Operational Power Consumption	350 W
Loadshedding Power Consumption	80 W

- Nighttime: No sun
- Operational: No sun, no moon



Power Production comparison with EUSO-SPB2

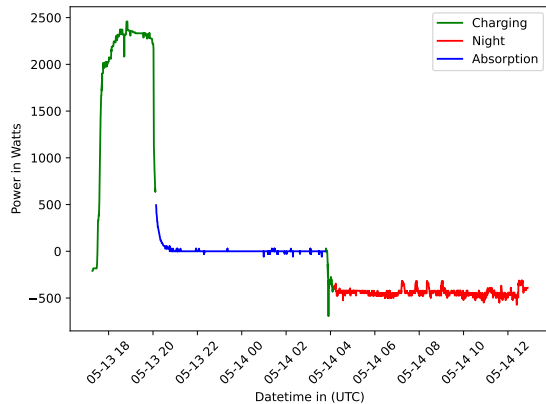


Figure 1: Flight Data

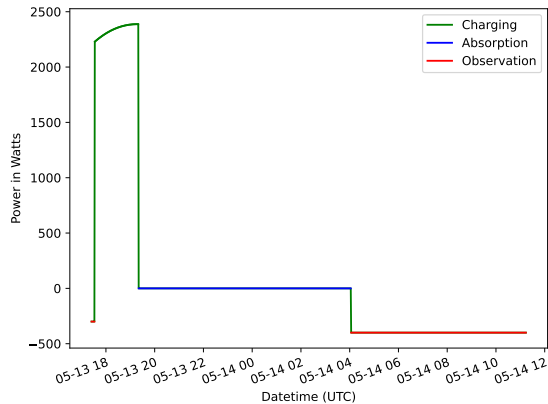


Figure 2: Simulations from BI-PASS

Simulated Trajectories

To project power-system performance, test on many simulated flight trajectories

1. Set starting location to (-44.648, 169.606) Wanaka, NZ
2. Pick the next closest time stamp and altitude to the NASA MERRA2 data [slide 19]
3. For a given coordinate, calculate weighted mean Northward and Eastward wind speeds from four surrounding grid points
4. Convert the velocity to deg moved in lat(red) and long(green).
5. *Add a random component (purple)
6. Repeat from 2

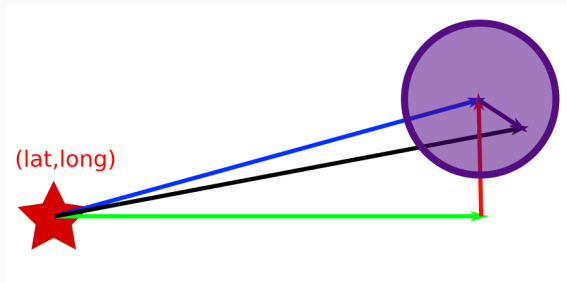


Figure 3: **Note that without a random component, this method will simulate the 'Wind Patterns' while the random component accounts for sporadic wind gusts which can shift the balloon into a different wind zone*

For updates to the simulated trajectory analysis software see "Trajectory Simulation and Wind Gust Analysis for the NASA Super Pressure Balloon" Poster by Xavier Adams

Simulated Trajectory for SuperBIT

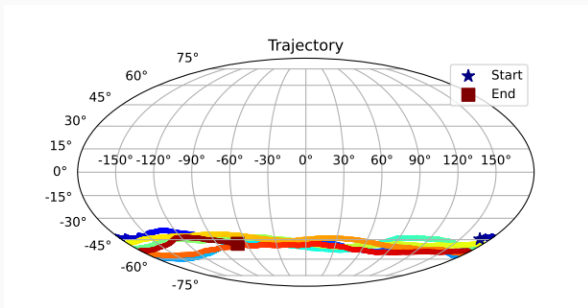


Figure 4: Flight Data

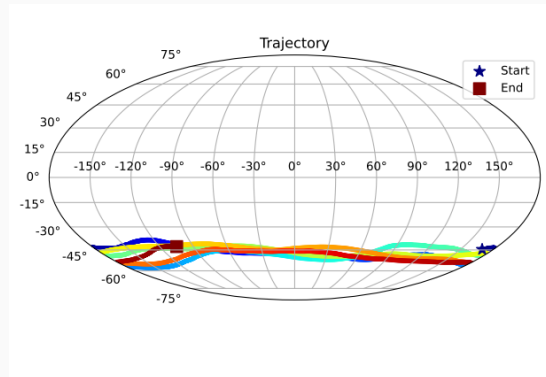


Figure 5: Simulated flight

Single Trajectory Analysis: Minimum and Maximum Case for a Solar Skirt Configuration

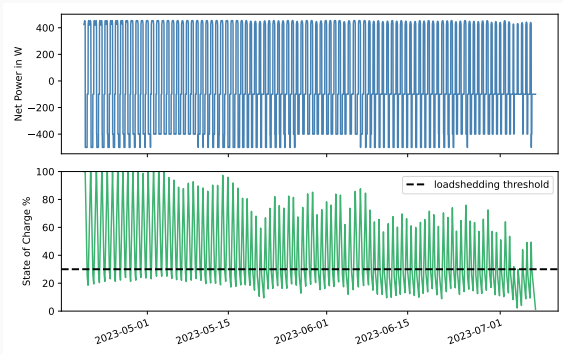


Figure 6: Minimum Case for a Solar Skirt → **Only one side of the Solar Skirt** pointed toward the Sun.

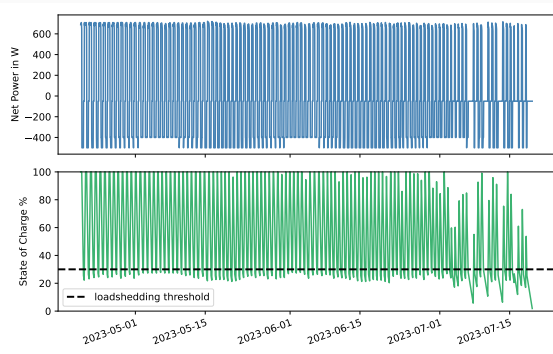


Figure 7: Maximum Case for a Solar Skirt → **Corner of the Solar Skirt** pointed toward the Sun.

Multiple Trajectory Analysis

- Solar Skirt with 3 batteries and 5 panels per side.
- 800 total trajectories each 50 days in length
- Trajectory start days beginning in April - May 2023.
- Average flight length before L2 failure: **47.02 (min)** and **47.04 (max)**

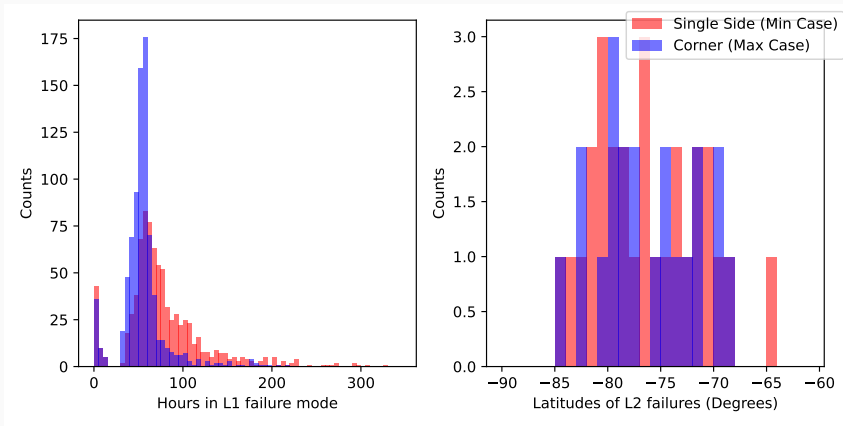


Figure 8: Comparison of the minimum case (single side to the sun) and maximum case (corner to the sun) for a solar skirt configuration.

Multiple Trajectory Analysis: Two Config Analysis

- 1st case: Solar Skirt with 4 batteries and 5 panels per side.
- 2nd case: Solar Skirt with 3 batteries and 10 panels per side.
- 800 total trajectories each 50 days in length
- Trajectory start days beginning in April - May 2023.
- Average flight length before L2 failure: **47.08 (case 1) and 47.04 (case 2)**

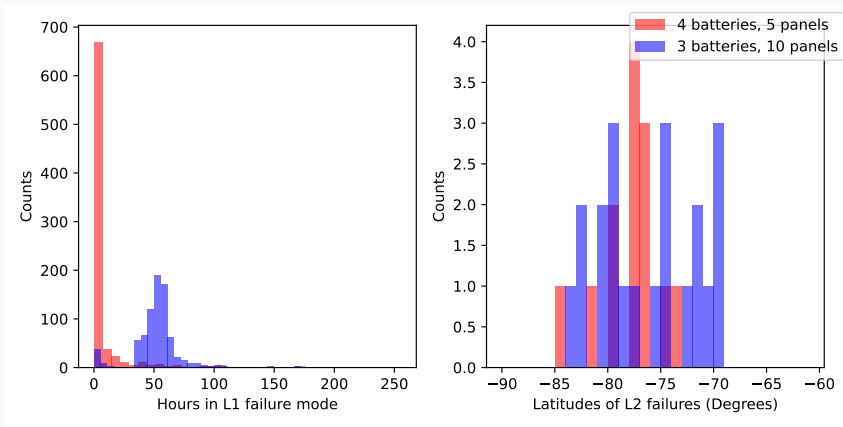


Figure 9: Comparison of two configurations where we increase the number of batteries vs a number of solar panels.

Summary:

- BI-PASS estimates power generation and consumption based on given system configuration
- BI-PASS can estimate the performance of a power system on a given flight trajectory
- BI-PASS provides statistical design arguments based on simulated flight trajectories generated from MERRA-2 data

Future developments:

- Finalize and publish the current state of the software
- Design a Graphical User Interface
- Develop in flight software
 - Based on predicted flight trajectory KML
 - Predict power system performance
- Optimize performance
- Automatic inclusion of environmental constraints like temperature effects on battery and solar panel performance

Comments, feedback, and collaboration are more than welcome to julia_burton@mines.edu!!

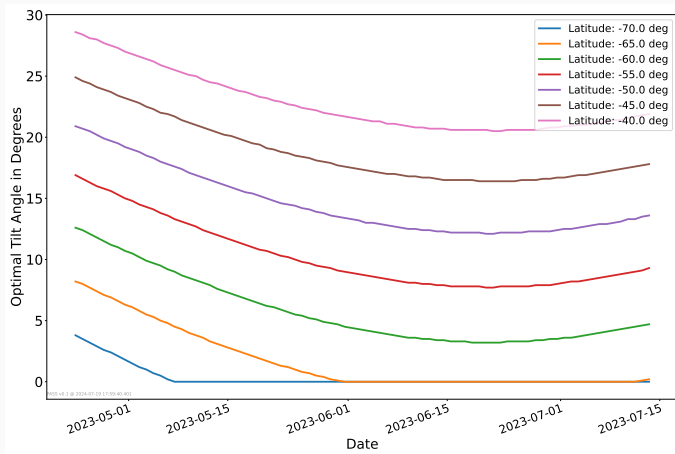
Backup Slides

Solar Power Production Implementation

Track the solar elevation angle throughout the day

- If the sun is above the horizon, the charging mode is active
- Relative angle between sun and detector panels define efficiency
- Optimization is possible, but depends on latitude of the balloon

Optimal tilt angle relative to vertical panels in counterclockwise direction





National Aeronautics and Space Administration
Goddard Space Flight Center

Earth Sciences Division | Sciences and Exploration

Global Modeling and Assimilation Office

GMAO

WEATHER ANALYSIS & PREDICTION

SEASONAL-DECADAL ANALYSIS & PREDICTION

REANALYSIS

GLOBAL MESOSCALE MODELING

OBSERVING SYSTEM SCIENCE

MERRA-2 Project

Data Access

Citing MERRA-2 Data

Documentation

WMO Climate Reanalysis

MERRA-2 AMIP

Highlights

Images

Videos

FAQ

Publications

Mailing List

User Metrics

Dagnostic Feedback

GMAO Reanalysis Page

Modern-Era Retrospective analysis for Research and Applications, Version 2

Project Overview

The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) provides data beginning in 1980. It was introduced to replace the original MERRA dataset because of the advances made in the assimilation system that enable assimilation of modern hyperspectral radiance and microwave observations, along with GPS-Radio Occultation datasets. It also uses NASA's ozone profile observations that began in late 2004. Additional advances in both the GEOS model and the GSI assimilation system are included in MERRA-2. Spatial resolution remains about the same (about 50 km in the latitudinal direction) as in MERRA.

Along with the enhancements in the meteorological assimilation, MERRA-2 takes some significant steps towards GMAO's target of an Earth System reanalysis. MERRA-2 is the first long-term global reanalysis to assimilate space-based observations of aerosols and represent their interactions with other physical processes in the climate system. MERRA-2 includes a representation of ice sheets over (say) Greenland and Antarctica.



Global Modeling and Assimilation Office (GMAO):
inst3_3d_asm_Cp: MERRA-2 3D IAU State, 443
Meteorology Instantaneous 3-hourly (p-coord,
0.625x0.5L42), version 5.12.4.

Simulated Trajectory Dataset

