Thermo Lab 3 - Design Lab

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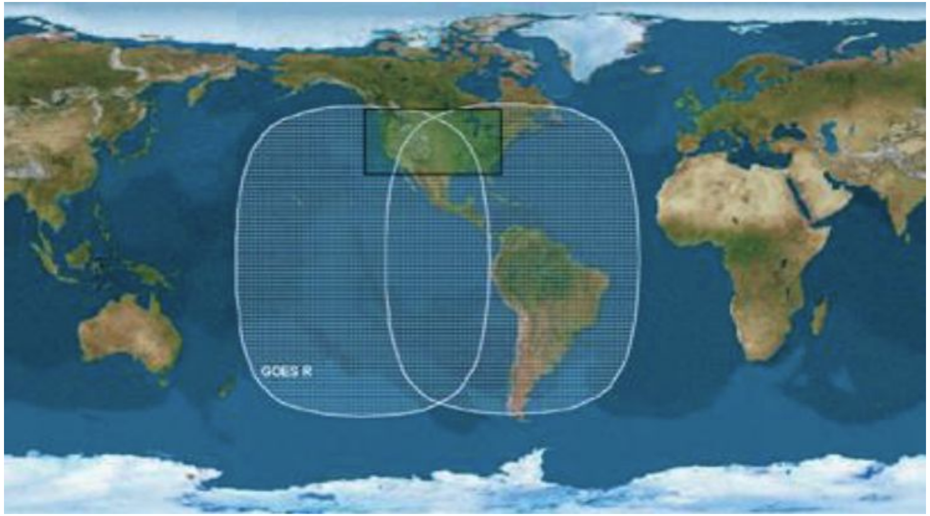
Introduction

Our task was to design a thermodynamic system capable of keeping a spacecraft in geosynchronous orbit within operating conditions for its flight time of ten years. This consists of several design requirements needed to maintain other systems on the spacecraft.



Images taken from Design.Lab-2022.pdf

Design Requirements

- The scientific device will draw 20 W of power when in operation
- The spacecraft on which the instrument resides shall be located in a geostationary orbit
- The spacecraft shall have one surface continually nadir pointing.
- The device must be maintained between 20°C and 30°C while in operation
- When the instrument is powered off, the device shall be maintained above -40°C
- The device must be able to operate during summer solstice, winter solstice, and equinox
    - Infrared heat load will vary as operational environment varies. IR values are as follows:
        - Winter solstice - 88 W/m^2
        - Summer solstice - 63 W/m^2
        - During eclipse - 11 W/m^2

Research

- Material Coating
  - Thermal Coating Research is often done by NASA's Goddard Space Flight Center
  - Temperature Control Parameters
    - Thickness
    - Surface Preparation
    - Coating Formulation
    - Manufacturing Techniques
  - Lower absorptivity and higher emissivity results in small required area
- Pivoting Radiator
  - Allows for sunlight heating therefore less dependent on electrical power
  - Mechanically more complex
  - Increase in Weight
  - Increase in Cost
- Multiple Radiators
  - Multiple smaller radiators gives flexibility when using area efficiently
  - The mechanical and overall thermodynamic system rises in complexity

Surface Treatment Flight Heritage

Ideal Emissivity: High Value

Ideal Absorptivity: Low Value

Material Options:

Material	Emissivity	Absorptivity
Dow Corning White Paint	0.88	0.19
Clear Anodized Aluminum	0.76 - 0.84	0.27 - 0.35
GSFC SiOx-Al_2 O_3-Ag	0.68	0.07
Helios Second Surface Mirror/Silver Backing	0.79-0.80	0.07 - 0.08

*Data from shuttle era research

Thermal coating is critical for heat management of a spacecraft. Thermal coatings have been used to regulate thermal conditions on spacecraft for many years and as a result of this there is extensive research into coatings that have high emissivity and low absorptivity values.

A variety of kinds of coatings are used for spacecraft depending on what other requirements influence the needs of the outside of the spacecraft. These coatings include black and white paints, conductive paints, anodized aluminum, metals and conversion coatings, vapor-deposited coatings, composite coatings and films and tapes. Things that cannot be coated like solar cells are also analyzed for their absorptivity and emissivity values.

Radiator Area

- The maximum heating case was used to determine the Area of the radiator required to always maintain a temperature of 30˚C or below
  - Equinox at about 6 hours after noon (when the radiator is completely perpendicular to the direction of solar radiation) was chosen for this
- The Area of the radiator was determined to be 0.2830 m^2
- The values of IR emissivity and absorptivity were 0.85 and the solar absorptivity was 0.2 for these calculations

$$A_s = \frac{20}{(\epsilon_{IR} * \sigma * T_s^4) - (IR_{backload} * \alpha_{IR}) - (\alpha_{solar} * sin(\theta) * G)}$$

Governing Heat Transfer Equation of Radiator

$$20 + (\alpha_{solar} * A_s * sin(\theta) * cos(\phi) * G) + (IR_{backload} * A_s * \alpha_{IR}) + HeaterPower = (\epsilon_{IR} * \sigma * A_s * T_s^4)$$

- In Operational Mode:
  - The 20 W instrument power is included, and heater power must be maintained at a level that allows surface temperature of radiator to remain between 20˚C-30˚C
- In Survival Mode:
  - 20 W instrument power is not included, and heater power is increased to maintain temperatures above -40˚C
- General Note:
  - For equinox, the cos(phi) in the solar radiation term was not needed because the relative inclination angle of the Earth here is 0˚
- Assumptions:
  - Ignore Earth IR loading
  - Ignore differences in solar irradiance between the Earth and spacecraft (used values from Sun to Earth instead of from Sun to spacecraft at its exact location in orbit)
  - Unlimited Heater Power
- Given Information:
  - Values of IR Backload at different points in orbit
  - Operational Instrument power

Design Software

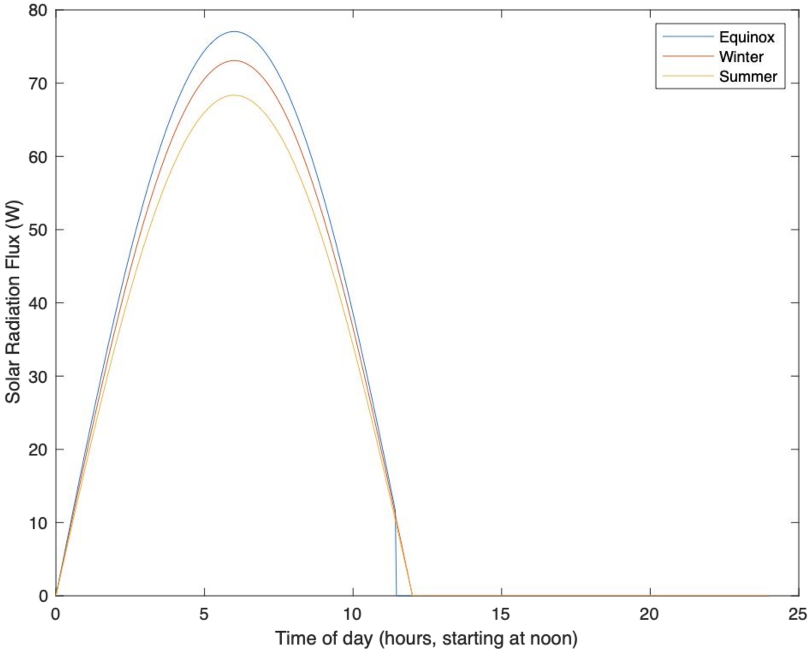
General Notes:

- Software was written in MATLAB
- General Processes
  - Instrument heat absorbed and heat emitted by radiator were same for all operational cases, but solar flux and IR backload radiation changed depending on case
- Determination of Eclipse

Checking Software:

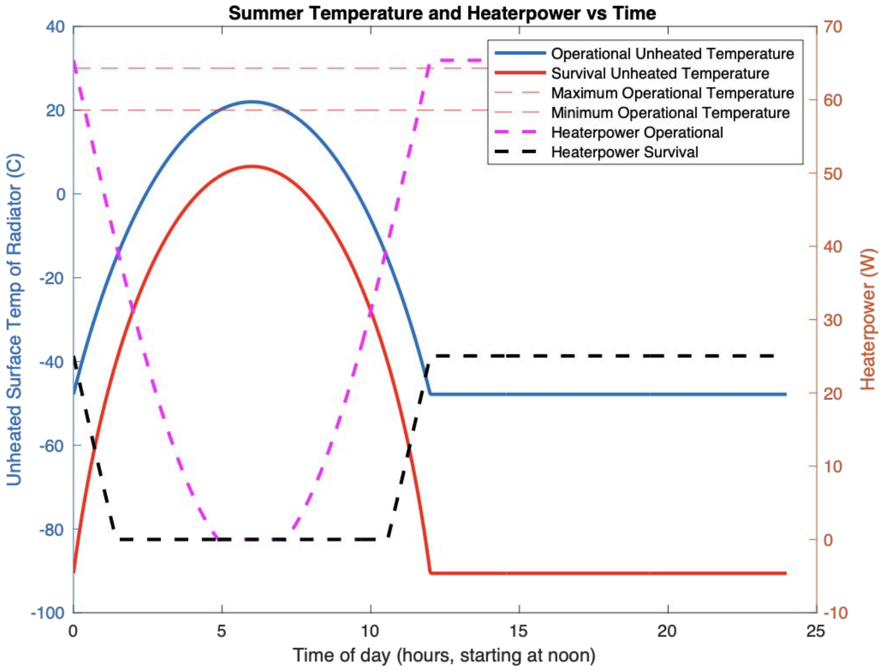
- The software was checked by ensuring that the relative values of solar radiation flux at each of the points in Earth's orbit made sense
- Checked relative heater-powers for operational and survival modes, in addition to the range that the unheated temperature of the radiator surface remained at throughout each orbit

Solar Flux Absorbed by Radiator



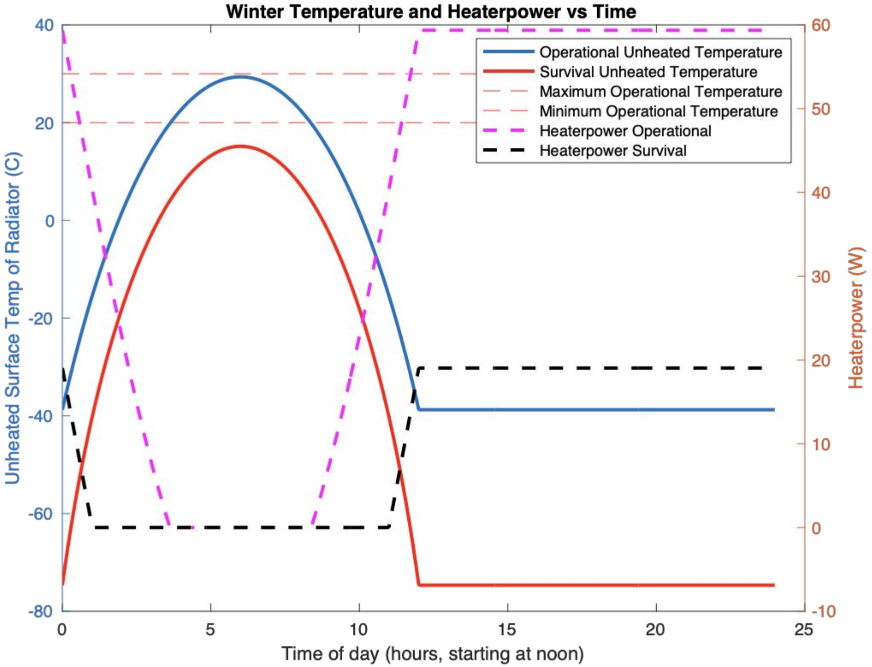
- The spacecraft will be exposed to the highest amounts of solar radiation during Earth's Fall and Spring equinoxes
  - There will be short eclipses at these equinox positions, during which the Earth will block some of the Sun's radiation
- The lowest amount of solar radiation will be observed during the Summer Solstice
  - Highest required heater power of the solar orbit to maintain both operational and survival conditions

Results: Summer Solstice



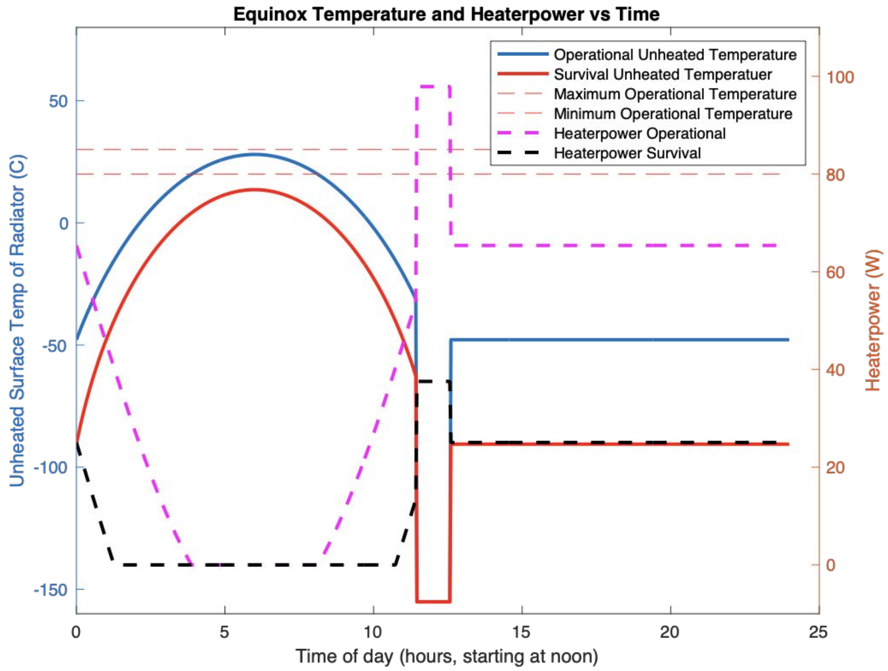
- Earth is at aphelion, Northern Hemisphere is at maximum tilt towards the Sun
  - IR Backload 63 W/m^2
    - Lowest value in entire solar orbit (Earth farthest from Sun)
    - Operational unheated radiator temperature max 21.9909℃, min -47.8355℃
- Maximum required operational heater power of 65.38 W for 12 hrs during furthest section of orbit
  - Off for 2.1391 hrs (hottest period)
- When in survival mode, instrument is powered off with minimum -40℃ allowed
  - Max heater power at 25.0479 W for 12 hrs during same portion of orbit as operational conditions
  - Off for 9.0909 hrs

Results: Winter Solstice



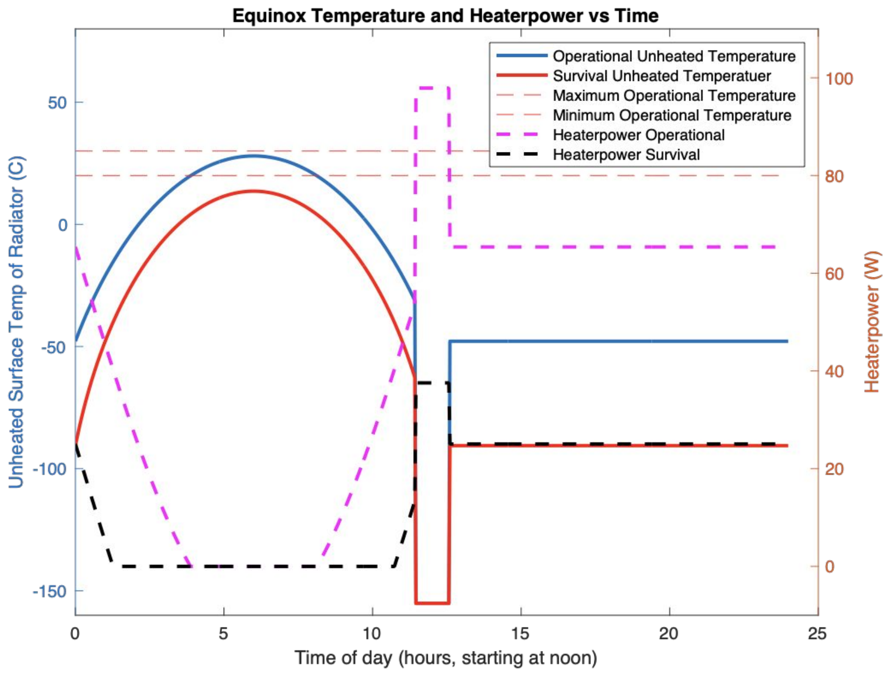
- Earth is at perihelion, Northern Hemisphere is at maximum tilt away from the Sun
  - IR Backload 88 W/m^2
    - Highest value in entire solar orbit (Earth closest to Sun)
    - Operational unheated temperature max 29.3660℃ min -38.7618℃
- Maximum required operational heater power of 59.3653 W for 12 hrs during furthest section of orbit
  - Off for 4.6601 hrs
- Instrument is again powered off in survival mode with a minimum allowable temperature of -40℃
  - Max heater power at 19.0332 W for 12 hrs, off for 9.9313 hrs

Results: Equinox



- Axial tilt of Earth with respect to the Sun is 0°, radius of the Earth from the Sun is midway between aphelion and perihelion
  - IR Backload 75.5 W/m^2
    - Average of max and min values over entire solar orbit
    - Unheated radiator temperature max 28.002℃, min -47.8355℃ (no eclipse)
- Required operational heater power of 65.38 W for 12 hrs during majority of furthest section of orbit
  - Off for 4.2017 hrs
- In survival mode, instrument is powered off with a minimum allowable temperature of -40℃
  - Heater power 25.0479 W for 12 hrs, off for 9.3965 hrs

Results: Equinox Eclipse Conditions



- A satellite in a geostationary orbit will experience an eclipse while passing through Earth's shadow
  - IR Backload 11 W/m^2
  - Unheated satellite temperature of -155.131°C
  - Heater power for the operational mode must increase by 32.5105 W, while the survival mode will only increase by 12.5105 W
    - Increase operational heater power to 97.8905 W
    - Survival heater power increased to 37.5584 W
- Duration of eclipse approximated using the Earth's diameter projected onto the orbital path of the satellite
  - 0.1513 radians

Conclusions

- Surface treatment
  - Low absorptivity and high emissivity ideal for this project, best option:
    - Helios Second Surface Mirror/Silver Backing (absorptivity 0.07–0.08, emissivity 0.79–0.80)
- Radiator area
  - In order to maintain a temperature of 30℃ or lower during the hottest period of use, the area of the radiator must be 0.2830 m^2
  - Radiator perpendicular to solar radiation during equinox 6 hrs after noon

- Summer Solstice
  - Unheated temp -47.8355℃ – 21.9909℃
  - Operational power 65.38 W maximum
  - Survival power 25.0479 W maximum
- Winter Solstice
  - Unheated temp -38.7618℃ – 29.3660℃
  - Operational power 59.3653 W maximum
  - Survival power 19.0332 W maximum
- Equinox
  - Max total flux absorbed
  - Unheated temp
    - -47.8355℃ – 28.002℃ (no eclipse)
    - -155.131℃ (eclipse)
  - Operational power 65.38 W maximum
    - 97.8905 W during eclipse
  - Survival power 25.0479 W maximum
    - 37.5584 W during eclipse

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Sources

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