# Scientific Ballooning Technologies Workshop

## Balloon Thermal Model Design Parameters and Sensitivities

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# Balloon Thermal Model Design Parameters and Sensitivities
## Outline

- Recent process improvements regarding environmental parameters
  - Spreadsheet tool
  - Conservative modeling approach
- Recent process improvements w.r.t. convection
  - Comparison of PMC-Turbo solar array temperatures
  - Iridium Pilot antenna (and other) back-correlation efforts
- Future Plans for thermal models
  - Ascent
  - Convection

# Balloon Thermal Model Design Parameters and Sensitivities
## Introduction
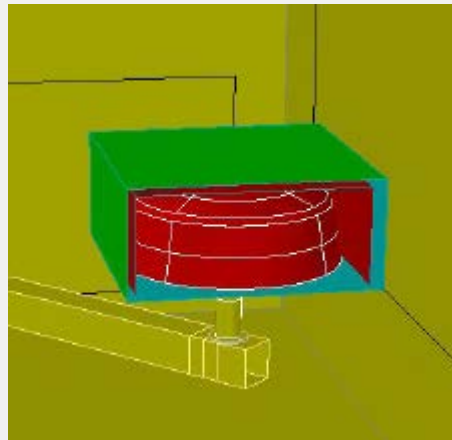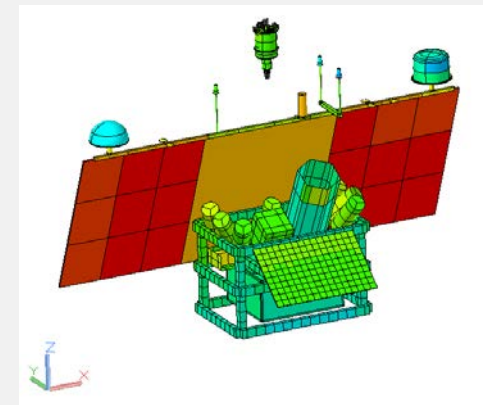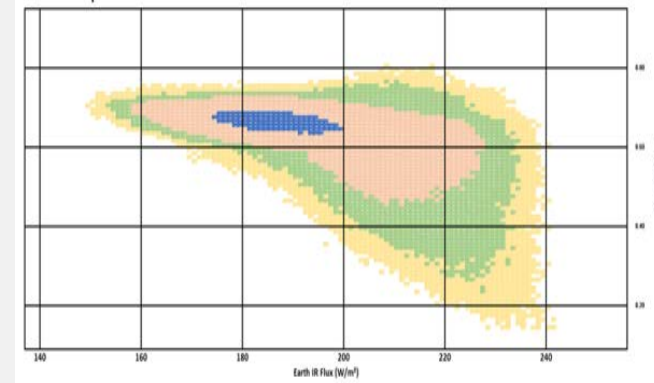
- As many as three regions of a balloon experiment are analyzed, each typically with its own model.
  - Gondola and components
  - Flight train
  - Apex Plate
- Three mission phases
  - Ground
  - Ascent
  - Float
- Three methods of heat flow
  - Conduction – relatively simple
    - $Q = kA(\Delta T)/L$ or $Q = h^{*}A(\Delta T)$
  - Radiation – harder
    - $Q = \sigma \varepsilon A F(T_1^4 - T_2^4)$
  - Convection – harder still
    - $Q = hA(\Delta T)$; the proper "h" is highly situation-dependent
    - Often neglected; expanded effort is planned

# Balloon Thermal Model Design Parameters and Sensitivities
## Environmental Parameters (Radiation)

- Radiation heat transfer in a thermal model refers to three processes:
  - Heat absorbed by the balloon model's exterior surfaces from:
    - Direct solar (UV)
    - Indirect solar, mainly albedo (UV)
    - Earth emission (IR)
  - Heat radiated by external model surfaces to deep space (IR)
  - Radiation between surfaces in a model (IR)
    - Often minor
- Two key parameters for each surface treatment are the coefficients of radiation heat transfer, $\alpha$ (solar absorptance) and $\varepsilon$ (infrared emittance)
  - $\varepsilon$ is the coefficient of IR radiation heat transfer, including *absorbed* IR radiation
  - $\alpha$ and $\varepsilon$ are always greater than zero, and no more than unity.

# Balloon Thermal Model Design Parameters and Sensitivities

## Environmental Parameters (Radiation)
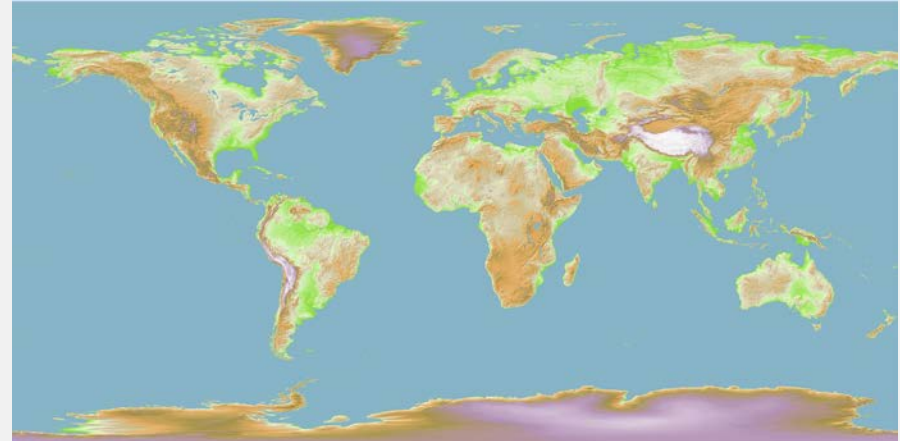
**Orbital ATK**

- NASA's CERES database of Top-of-Atmosphere (TOA) properties enables thermal modelers to determine appropriate, conservative albedo factor and Earth IR flux values for specific balloon missions.

  - The database contains specific values for each calendar day over decades.
  - The data is discretized by 2.5° latitude and longitude increments ("bins") over most of the Earth.

- We have recently converted an existing MATLAB-based TOA search tool to Excel, using Visual Basic logic to scan the database.

  - Close-up review of the data
  - Enables quick turnaround of "what if" questions



World map with TOA albedo factor data mapped onto it
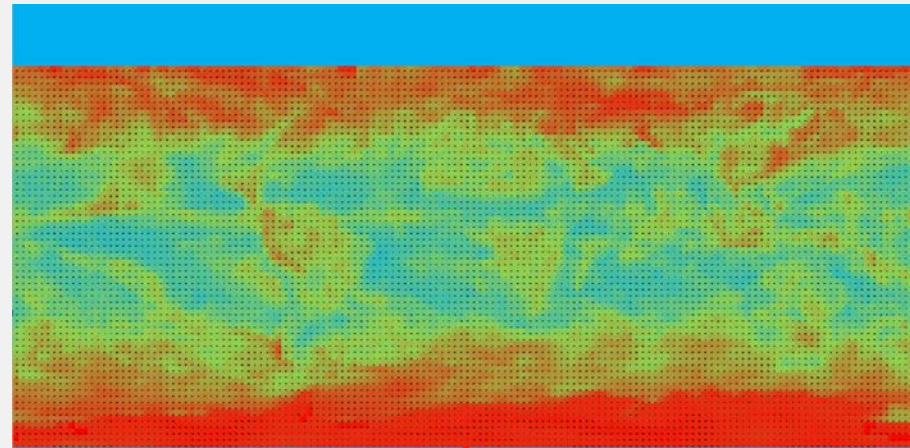


Red = ice or clouds, high (~0.6) albedo factor
Green = land, moderate (~0.4) albedo factor
Light blue = ocean water, low (~0.15) albedo factor
N.B. albedo factors vary with weather and time of year also!

- User inputs to the search tool include:
  - The possible range of flight dates
  - The considered range of possible latitude (at float)
  - Longitude range (can be "all")
- The search tool narrows the TOA data from the 50 million-plus values in the database to those relevant to the search inputs.
- Probabilistic results are assembled in tables like those to the right for the GUSTO mission.
  - 98% data is highlighted, but the correct percentage of data to consider varies with the program's risk appetite.
  - 98% is essentially a position on a "knob" we can "turn."

|  | ocean case | ice case | all GUSTO |
|---|---|---|---|
|  | 12/10-3/24 | 12/10-3/24 | 12/10-3/24 |
|  | 50 to 60°S | 75 to 90°S | 50 to 90°S |
| 99% of albedo data is <= | 0.67 | 0.75 | 0.74 |
| 98% of albedo data is <= | 0.65 | 0.74 | 0.73 |
| 95% of albedo data is <= | 0.61 | 0.72 | 0.71 |
| 90% of albedo data is <= | 0.58 | 0.71 | 0.69 |
| 84% of albedo data is <= | 0.55 | 0.7 | 0.68 |
| 67% of albedo data is <= | 0.48 | 0.68 | 0.65 |
| 50% of albedo data is <= | 0.42 | 0.66 | 0.62 |
| 51% of albedo data is >= | 0.42 | 0.66 | 0.62 |
| 67% of albedo data is >= | 0.35 | 0.65 | 0.51 |
| 84% of albedo data is >= | 0.26 | 0.63 | 0.39 |
| 90% of albedo data is >= | 0.22 | 0.62 | 0.33 |
| 95% of albedo data is >= | 0.18 | 0.61 | 0.26 |
| 98% of albedo data is >= | 0.15 | 0.58 | 0.2 |
| 99% of albedo data is >= | 0.13 | 0.5 | 0.17 |
|  |  |  |  |
| 99% of Earth IR flux data is <= | 247 | 221 | 240 |
| 98% of Earth IR flux data is <= | 243 | 214 | 236 |
| 95% of Earth IR flux data is <= | 237 | 205 | 229 |
| 90% of Earth IR flux data is <= | 233 | 199 | 224 |
| 84% of Earth IR flux data is <= | 229 | 194 | 219 |
| 67% of Earth IR flux data is <= | 222 | 186 | 209 |
| 51% of Earth IR flux data is <= | 216 | 179 | 199 |
| 50% of Earth IR flux data is >= | 216 | 179 | 198 |
| 67% of Earth IR flux data is >= | 210 | 168 | 187 |
| 84% of Earth IR flux data is >= | 203 | 152 | 172 |
| 90% of Earth IR flux data is >= | 199 | 145 | 161 |
| 95% of Earth IR flux data is >= | 193 | 139 | 150 |
| 98% of Earth IR flux data is >= | 186 | 132 | 140 |
| 99% of Earth IR flux data is >= | 181 | 128 | 134 |

# Balloon Thermal Model Design Parameters and Sensitivities
## Environmental Parameters (Radiation)

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- The new Excel tool can plot a design mission's most likely albedo factor and earth IR flux data values in a color density grid.
- Each circle or star below represents one of four possible modeling approaches for a given design case set.
  - ➢ Circles represent cold-biased analysis cases.
  - ➢ Stars represent hot-biased analysis cases.

**Orbital ATK**
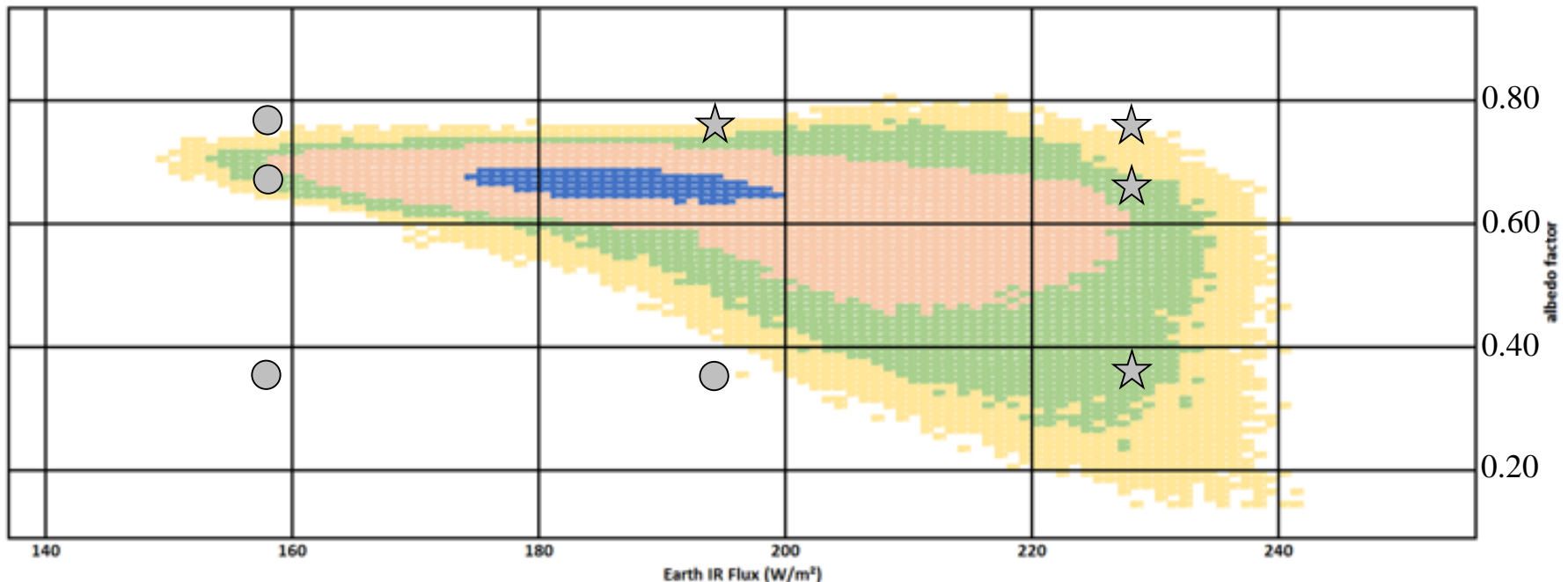
- Previous practice was to vary the two parameters inversely.
  - ➢ A low-biased albedo factor and high-biased Earth IR flux value in one case (hot)
  - ➢ A low-biased Earth IR flux value and low-biased albedo factor in the other case (cold)
- This approach employs the fact that the two parameters in reality tend to vary inversely.
- Current practice does not use this method, to achieve adequate conservatism.
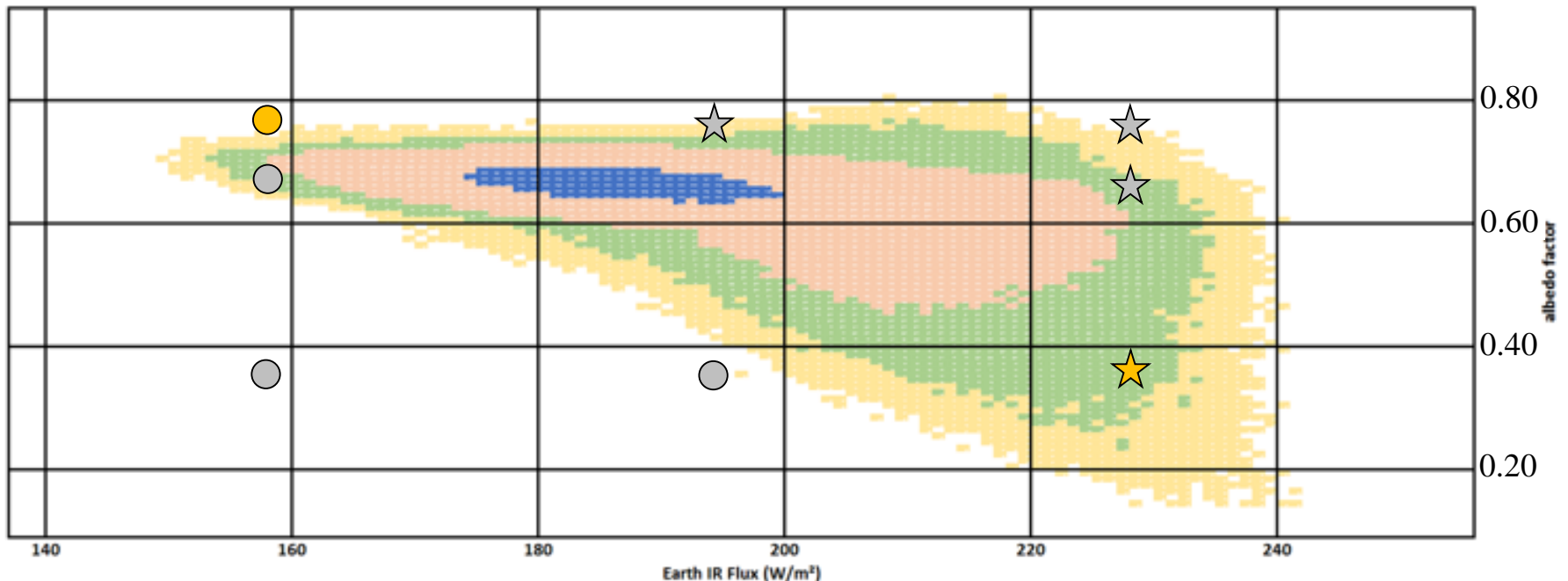
- A more conservative approach would be to select design parameter values varied in tandem.
  - This is not realistic; at least one of the design points will be far removed from the cloud of likely possibilities and produce unreasonably severe temperature (and perhaps heater power) predictions.
  - This approach is not used for balloon thermal modeling.

# Balloon Thermal Model Design Parameters and Sensitivities
## Environmental Parameters (Radiation)
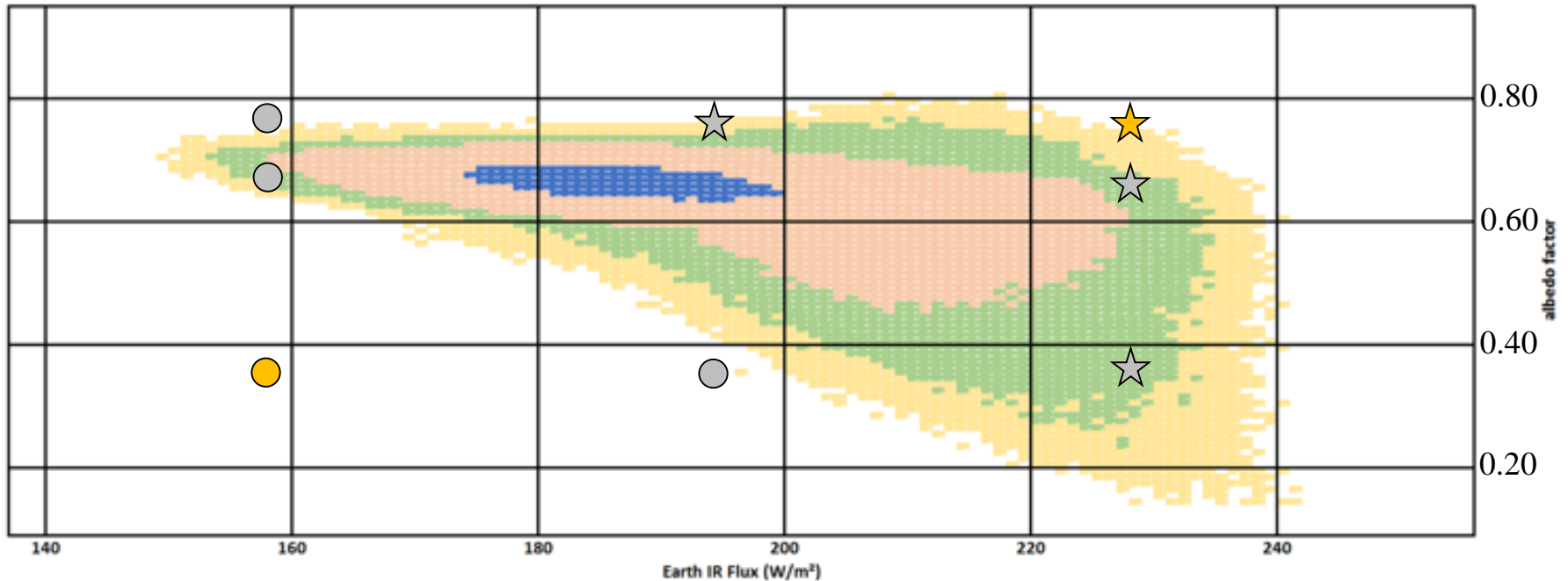
- A more realistic, yet conservative approach is as follows.
  - ➢ For the cold case: A low-biased Earth IR flux value and median albedo factor
  - ➢ For the hot case: A high-biased Earth IR flux value and median albedo factor
- Model temperatures are typically much more sensitive to the Earth IR flux value.
- No parameter is biased inversely with the design case this way, and the data modeled is inside the extreme ranges of the data "cloud."

# Balloon Thermal Model Design Parameters and Sensitivities
## Environmental Parameters (Radiation)
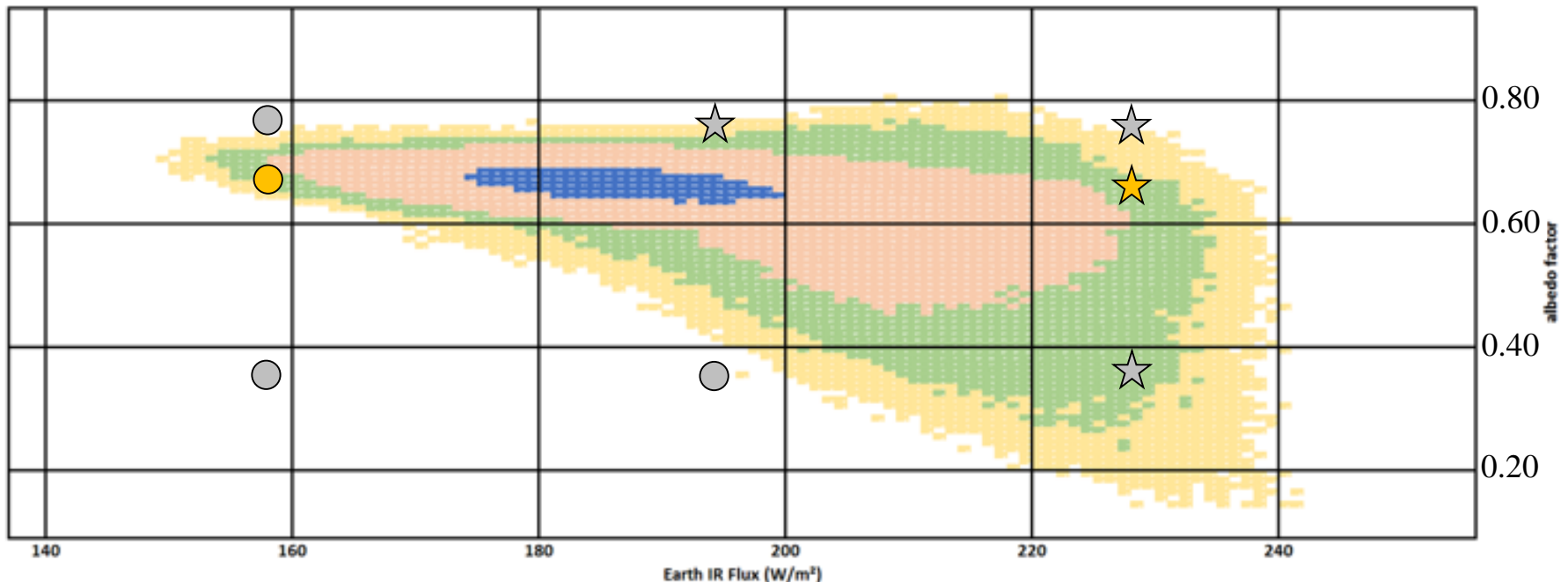
- An alternate approach is used in special circumstances to check the sensitivity to albedo.
  - For the cold case: A low-biased *albedo factor* and median Earth IR flux value
  - For the hot case: A high-biased albedo factor and median Earth IR flux value
- This approach is used occasionally, as test cases, during the design cycle to verify albedo sensitivity is minimal.
- An external, high-$\alpha$, temperature-sensitive component might respond to this approach with an extreme (and genuine) temperature prediction, but for the vast majority of components this approach is benign.
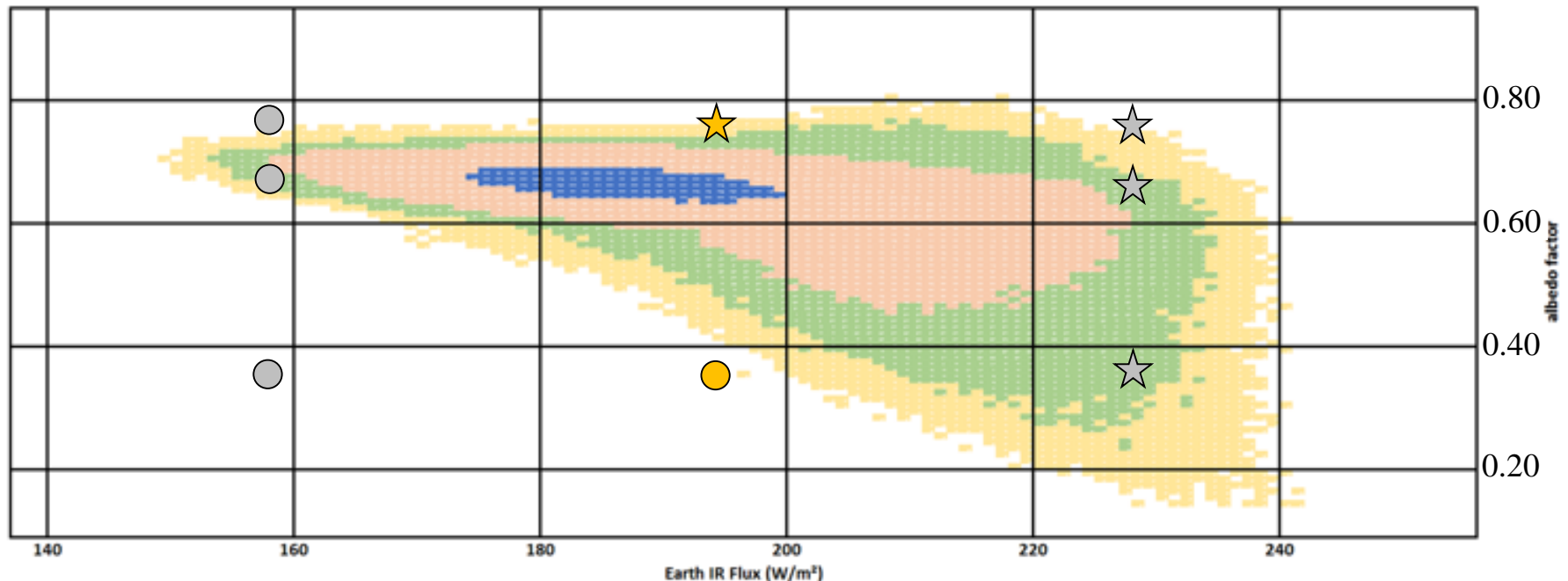
# Balloon Thermal Model Design Parameters and Sensitivities
## Convection

- Convection effects on a balloon thermal model are complex.
  - The main equation is $Q = hA(\Delta T)$; with h as the "film coefficient" or "convection coefficient".
  - The convection coefficient varies with wind speed
    - Different correlations for laminar or turbulent flow
    - At near zero velocity, natural vs. forced convection – different h relationships
    - Laminar flow and forced convection is the most relevant situation
  - Fluid property variations add complexity.
    - Conductivity, density, and viscosity vary with temperature and altitude.
    - Temperature varies with altitude (see the 1976 Standard Atmosphere below).
    - Other sources of variation exist.
    - Observations as low as -85°C
    - Standard tropopause: -56°C
  - Direction of wind speed matters.
    - Characteristic length
  - Air pressure matters.
    - ~0.1 atm at tropopause
    - ~0.01 atm at float



Earth Atmospheric Temperature
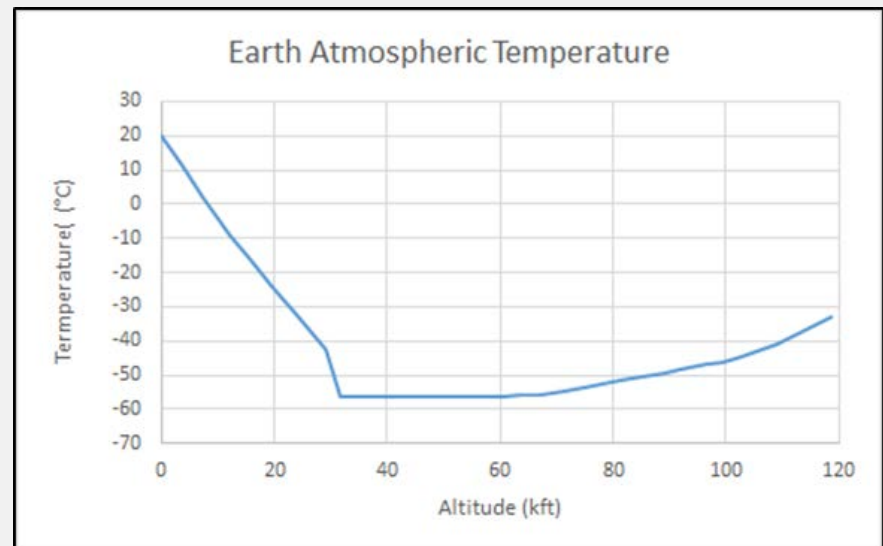
- Because convection heat transfer coefficients are themselves functions of temperature, convection heat transfer is thus nonlinear.
  - ➢ Coefficients vary from surface to surface within a model, and also vary with time.
  - ➢ Heat transfer coefficients are derived mostly from empirically-derived relationships.
    - − These relationships use dimensionless parameters e.g. Re, Pr, and Nu.

- Some notes from a CSBF intern's work are to the right, showing the complex variability of the convection coefficient determination.
- Textbook Nusselt number correlations like these all have an applicable range of conditions or stipulations e.g. Reynolds number range, laminar flow, horizontal plate, etc.

Ivan Huerta
10/19/17
Test Model Report

### Nusselt Numbers

$$Nu_1 := .0296 \cdot (Re_1)^{\frac{4}{5}} \cdot (Pr)^{\frac{1}{3}} = 828.701$$

$$Nu_3 := .0296 \cdot (Re_3)^{\frac{4}{5}} \cdot (Pr)^{\frac{1}{3}} = 2.464 \cdot 10^3$$

$$Nu_2 := .683 \cdot Re_2^{.466} \cdot Pr^{\frac{1}{3}} = 70.084$$

### Heat Transfer Coefficients

$$h_1 := \frac{Nu_1 \cdot k}{l_b} = 33.607 \ \frac{kg}{s^3 \cdot K}$$

$$h_2 := \frac{Nu_2 \cdot k}{d_c} = 29.918 \ \frac{kg}{s^3 \cdot K}$$

$$h_3 := \frac{Nu_3 \cdot k}{l_{bo}} = 10.237 \ \frac{kg}{s^3 \cdot K}$$

# Balloon Thermal Model Design Parameters and Sensitivities
## Convection

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- Referring to Christopher Geach's presentation, the PMC-Turbo solar array flight temperatures were somewhat colder than predicted in a convection-free model.
- Simple spreadsheet estimates of convection (at float) for a hypothetical unit solar array area calculated a temperature difference of 13 degrees Celsius.

| zero convection | realistic convection | extreme convection | |
|---|---|---|---|
| 1 | 1 | 1 | in², panel area |
| 0.9 | 0.9 | 0.9 | panel α |
| 0.8 | 0.8 | 0.8 | panel ε |
| | | | |
| 0.9 | 0.9 | 0.9 | W/in², solar constant |
| | | | |
| 350 | 337 | 302.5 | K, panel T (user input) |
| 243 | 243 | 243 | K, air T |
| 3 | 3 | 3 | K, space T |
| 268 | 268 | 268 | K, experiment T |
| | | | |
| 1.5 | 1.5 | 1.5 | view factor to space, 2= perfect 2-sided view |
| 0.5 | 0.5 | 0.5 | view factor to experiment |
| | | | |
| 1.2 | 1.2 | 1.2 | in², radk to space |
| 0.4 | 0.4 | 0.4 | in², radk to experiment |
| | | | |
| 3.66E-11 | 3.66E-11 | 3.66E-11 | W/in²-K^4, S-B constant |
| | | | |
| 0 | 2 | 10 | W/m²-K, user-input convection coefficient |
| 0 | 0.001 | 0.006 | W/in²-K, assumed convection coefficient |
| | | | |
| 0.80 | 0.80 | 0.80 | W, solar input |
| 0.66 | 0.57 | 0.37 | W, radiation to space |
| 0.14 | 0.11 | 0.05 | W, radiation to experiment |
| 0.00 | 0.12 | 0.38 | W, convection to air |
| | | | |
| 0.00 | 0.00 | 0.00 | W, heat balance, net input, ideally zero |

CSBF PMC-Turbo Model



- Other factors may have played a role in the discrepancy.

# Balloon Thermal Model Design Parameters and Sensitivities
## Convection
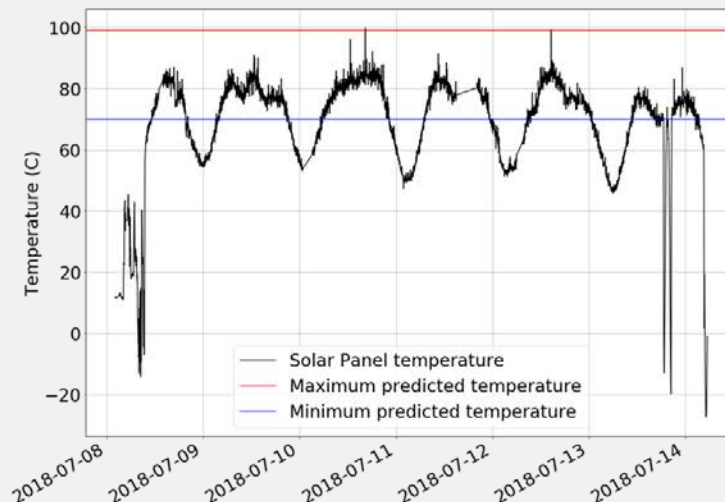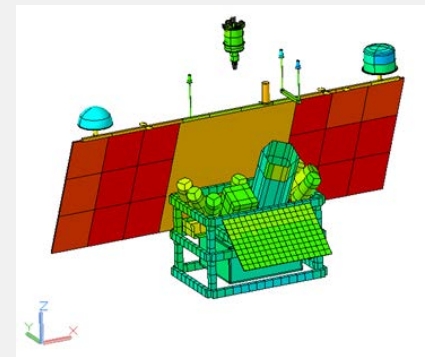
- An intern research project is in work to assess the effect of convection on a SIP heat shield during a typical mission.

- Our intern developed a Thermal Desktop-based set of symbols, useful for automating convection calculations in future models.

- Results of the heat shield test model are preliminary at this point.

  - Early returns show ascent phase convection effects on the order of 10°C on the SIP heat shield.

  - At float, convection effects are much reduced, on the order of 2°C.

  - SIP components, residing inside a heat shield, are affected less, especially if well-isolated from the SIP shield.

- A 13°C difference for a solar array at float seems large…but may be consistent with the heat shield finding. An <u>illuminated</u> solar array has a large ΔT to the ambient air, even at float.

# Balloon Thermal Model Design Parameters and Sensitivities
## Convection

- An Iridium Pilot antenna has been the subject of recent testing and analysis, partially for the purpose of assessing convection.
- Temperature data has been collected for the antenna operating in different conditions.
  - Palestine launch pad
  - Internal CSBF building
  - Several BEMCO test chamber conditions
    - With and without foam insulation
    - With and without active chamber fans
    - With and without active LN2 panels
    - At ambient or float air pressure
    - At different test control heater settings
- CSBF interns have correlated a model to the above data collected in different environments and configurations.
  - Convection calculations were part of the task.
- The next step is to adjust the back-correlated model to a future flight model.
  - A different set of convection calculations is required.

# Balloon Thermal Model Design Parameters and Sensitivities
## Conclusions and Path Forward
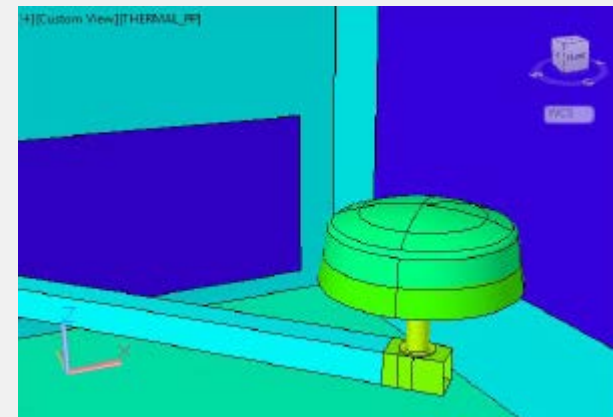
- The following actions are planned for future CSBF thermal models.
- Convection will be modeled in specific circumstances.
  - External components that can't survive tropopause conditions are a key focus.
  - Large, external, and solar-illuminated surfaces like solar arrays and radiator panels are good places to start.
    - They tend to have the highest "h" values, which lend themselves to conservative hand calculations for other surfaces/components.
  - External components that can't survive tropopause conditions are a key focus.
  - We may consider convection only in cold-biased cases, and perhaps only during ascent.
- Balloon film will be modeled at air temperature, even at float.
- Automation is a goal; creating convection couplings manually is time-consuming but can complicate proceeding model adjustments.
- We will consider modeling the ascent phase separately.
  - Separate, i.e. less extreme, TOA values will apply.
- Ongoing research objectives include:
  - CERES and other NASA data – update TOA database and search tool as needed
    - New data
    - Context of existing data
    - Similar databases, especially covering at intermediate altitudes
  - Conservative and realistic