Numerical Method to Calculate Spacecraft Environmental Heating From Celestial Bodies With Non-uniform Surface Properties and Temperatures

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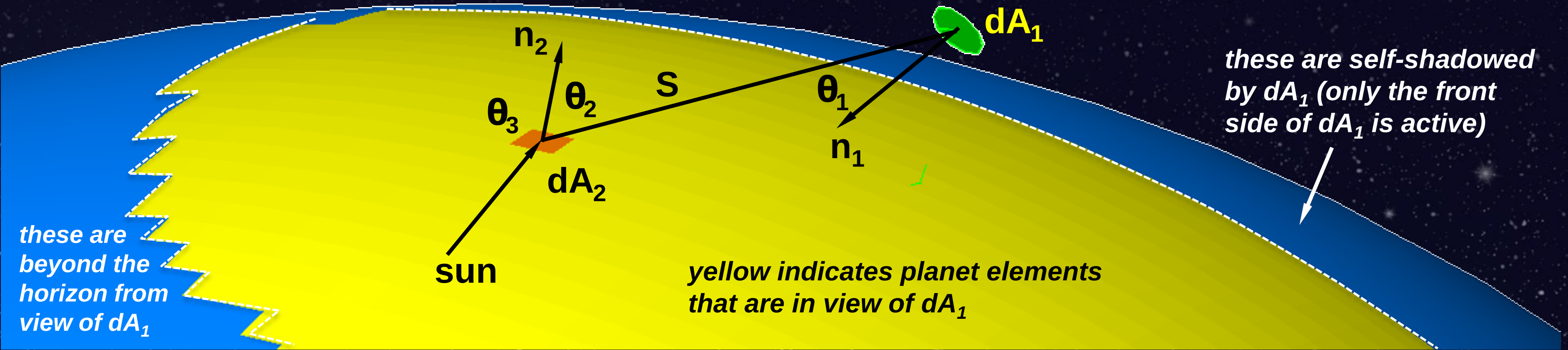
Description

- Algorithm calculates environmental heating for a S/C near a celestial body
- Approach is to discretize the body into small enough elements as to consider each flat, then the heating from the celestial body to the S/C is the sum of the individual contributions
  - **Any element for which θ_1 or $\theta_2 > 90°$ is discarded (planet IR and reflected solar)**
  - **Any element for which θ_3 is $> 90°$ is discarded (only relevant for reflected solar)**
- $dF_{1\text{-}2}=[\cos\theta_1\cos\theta_2/(\pi S^2)]dA_2$
- Planetary infrared heating is sum of $q_{planet}\cdot dF$
- Solar reflected heating is the sum of $Gs\cdot\cos\theta_3\cdot albedo\cdot dF$



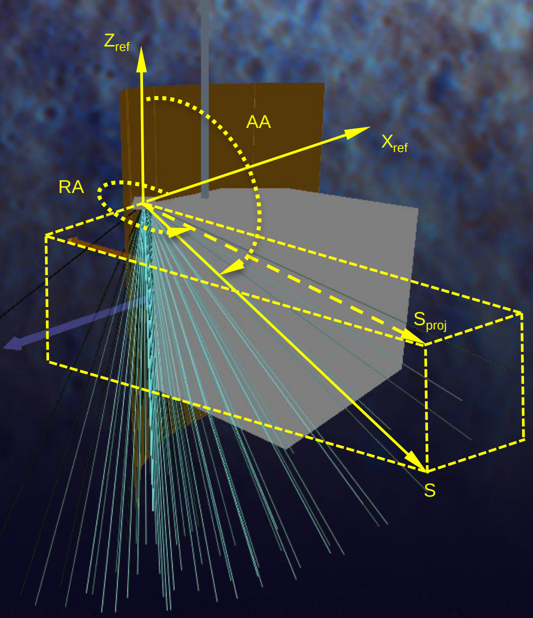
these are self-shadowed by dA_1 (only the front side of dA_1 is active)

these are beyond the horizon from view of dA_1

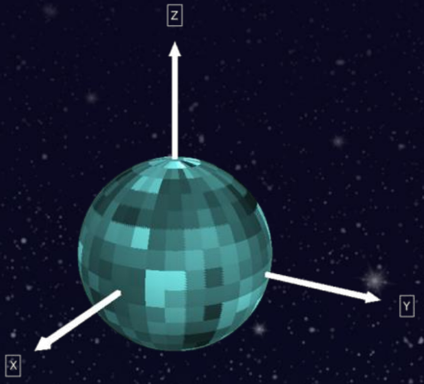
yellow indicates planet elements that are in view of dA_1

Extensions

- S/C self-shadowing effects
  - Ray tracing codes, such as NVIDIA's OptiX, can be used to efficiently characterize the S/C geometry
  - Blockage array for each S/C surface created separately by ray-tracing program (only needs to be run once, unless S/C surfaces articulate)
  - Heating algorithm applies percent blockage from this array given the direction of vector S for each element of the celestial body
  - Example shown to the right is for the bottom FPAA surface on the MESSENGER spacecraft (unblocked rays shown)
- Can be modified for the geometry of any celestial body
  - Ray tracing for concave bodies (similar implementation to the self-shadowing example)
- Varying surface properties and temperature
  - Moon, Mercury, asteroids have extreme temperatures



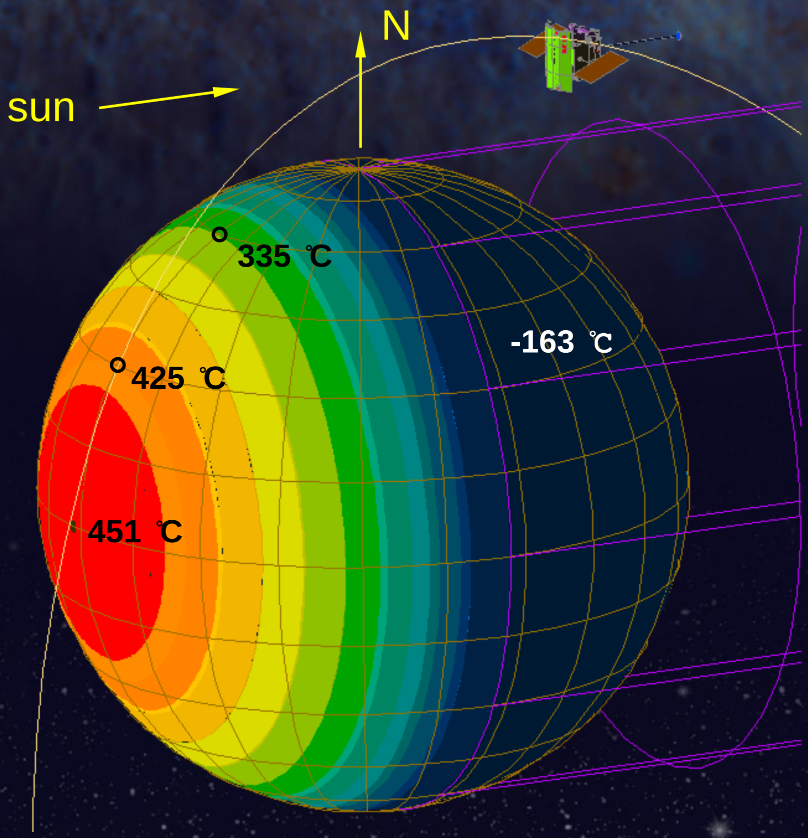
S/C self-shadowing



Planet albedo variation

Mercury Thermal Environment

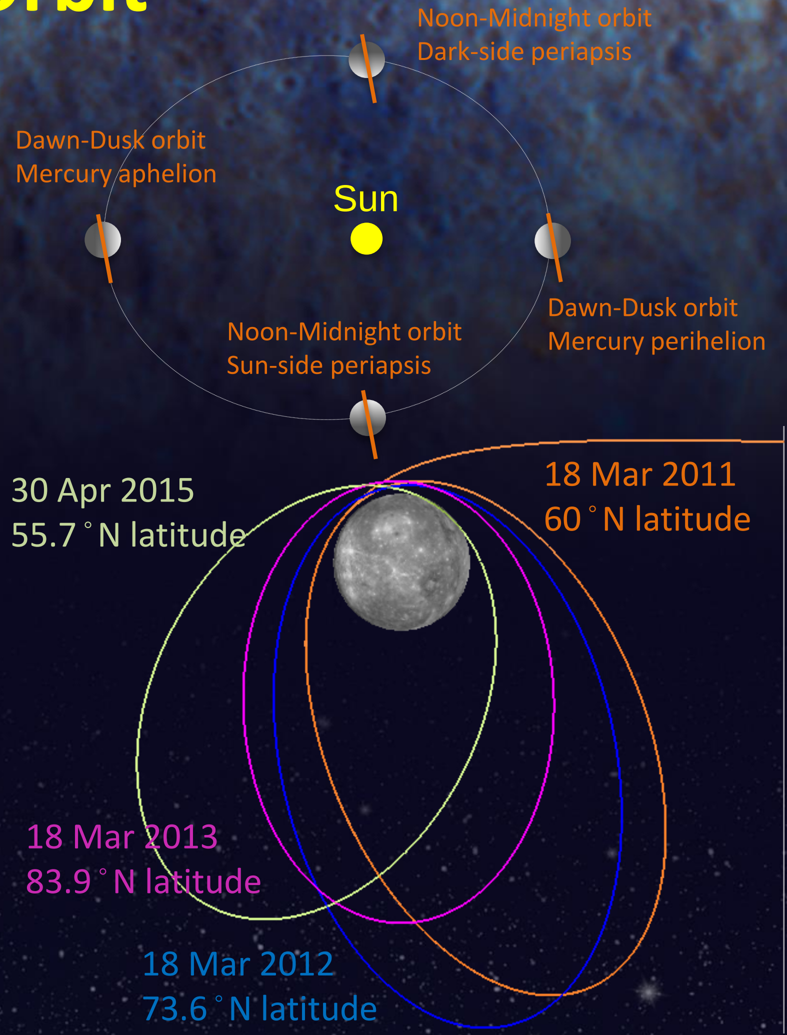
- High solar heating
  - **4.7 to 11 ESC (Earth Solar Constant)**
- Extreme and highly variable planetary heating
  - **Surface emissivity 0.93**
  - **Virtually no atmosphere**
  - **Rotation once per 59 days**
  - **Temperatures range from -163 to 451 °C (at perihelion)**



MESSENGER thermal environment was extreme, with an orbit that changed constantly, and S/C planning was executed on a fast schedule

MESSENGER Orbit

- Orbit details chosen by comprehensive thermal analysis
  - **Planned for one Earth year (lasted more than four)**
  - **Orbit relatively inertial**
  - **Dawn-dusk at Mercury perihelion**
  - **Results in two hot seasons, at Mercury True Anomaly (MTA) 100° and 280°**
- Orbit period changed from 12 to 8 hours after the primary mission
  - **Less time for components to cool off**
- Periapsis altitude changed frequently
  - **Managed with Orbit Correction Maneuvers (OCMs)**
  - **Was not of great impact thermally (until it became zero)**
- Orbital line of apsides rotated about Mercury throughout the mission
  - **Was 60° N at MOI, to 84° in 2013, back down to 55.7° at the end of mission**
  - **Caused one season to become hotter, and the other to be less hot**



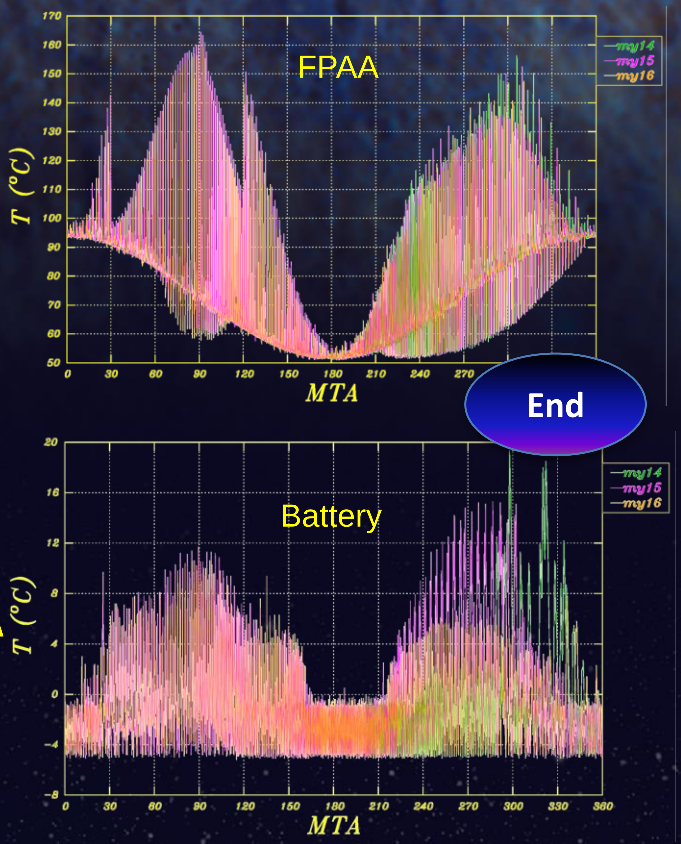
Rotation of the MESSENGER orbital line of apsides is what made the seasons at the end of the mission so thermally challenging.

MESSENGER Thermal Analysis Process

Start

Vector input (mission design, GNC, or SciBox)

MESSENGER thermal analysis process*



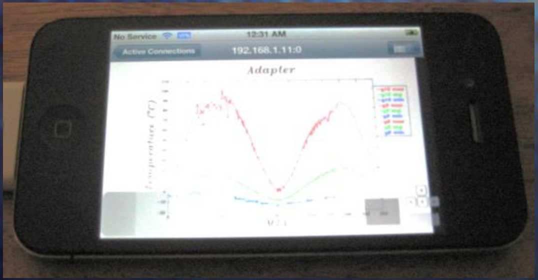
End

Thermal analysis process has environmental heating calculations as presented here, as well as internal heating and integration of the total heating to get temperatures

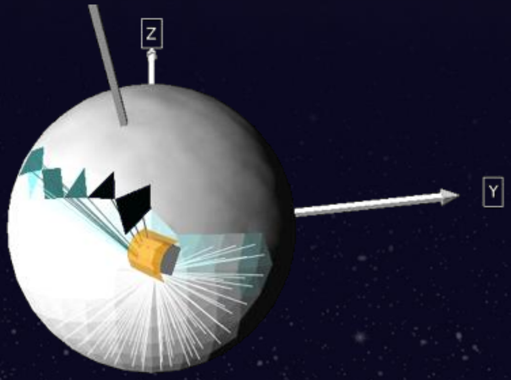
Thermal process used to evaluate the S/C position and attitude plan only looks at critical components, but runs with very little setup and can evaluate full-mission time scales.

Benefits

- Thermal analysis process can be streamlined to take input directly from mission design/GNC and generate temperature plots in one step
  - **Remote command line execution, even from an iPhone**
- Heating calculations run on a GPU for enhanced performance
  - **Since each time step is independent, heat rate calculations are “ridiculously parallelizable”, and a 500X speed improvement was achieved for MESSENGER over serial versions of the code**
  - **Full-mission time scales are possible, allowing optimization studies**
- Customized graphics to help diagnose S/C issues
- Increased science return from MESSENGER
  - **Authorized out-of-the-ordinary tasks, like comet observations**
  - **Pushed some S/C components to survival limits near end of mission**
- Technique could be adapted and used for other missions
  - **Lunar orbiters and sample return missions**
  - **Comet proximity operations**
  - **Europa solar array eclipse predictions, from any solar system body**



Minimal client side requirements



Mercury surface visible to FPAA for a given time step