# Thermal Radiation Effects on Deep-Space Satellites Part 2


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**Fundamental Physics in Space, Bremen**

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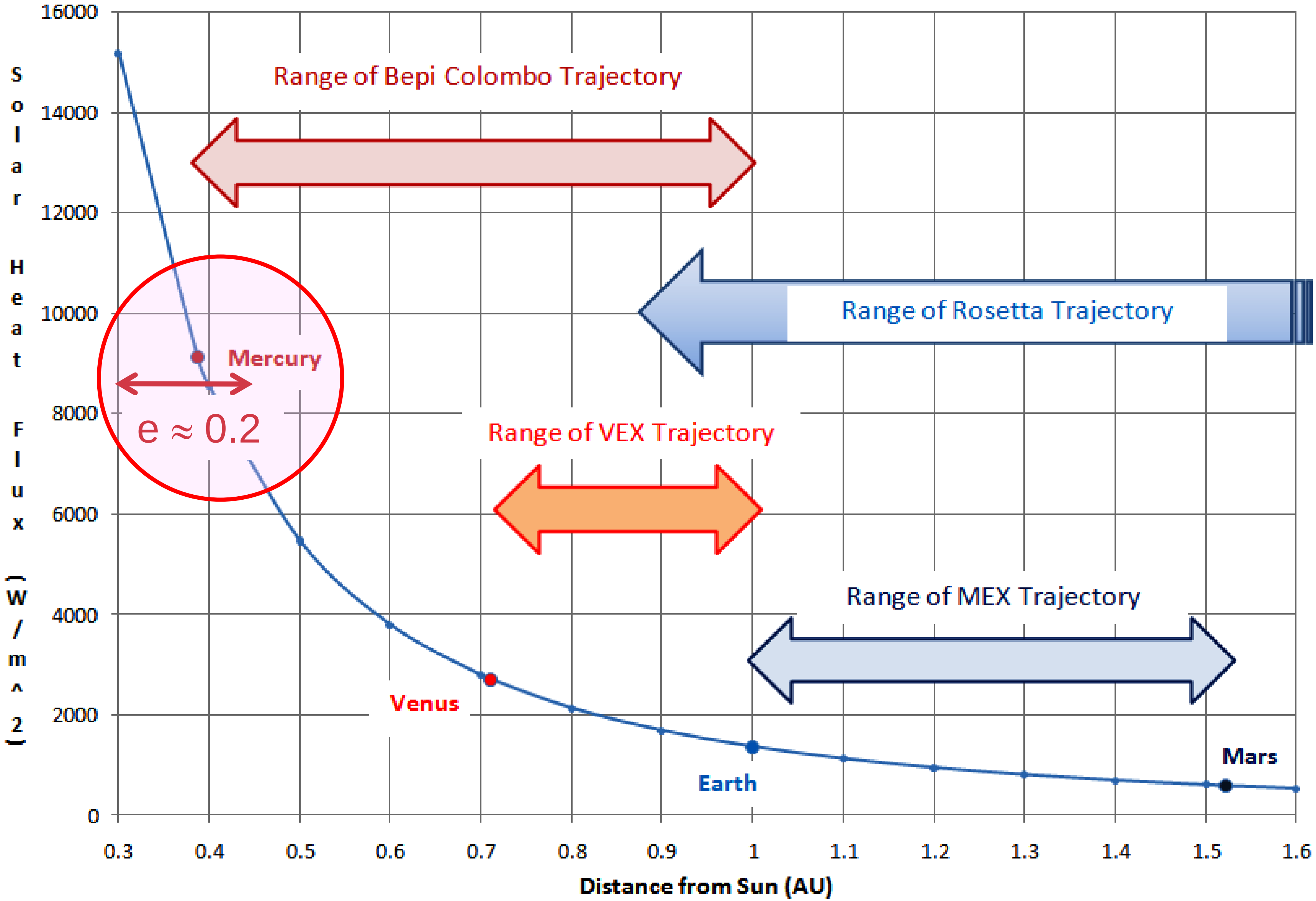
# Mercury Orbital & Thermal Characteristics

- ✓ **Mercury's Orbit** has High **Eccentricity** and **Inclination**:

$$e_M \approx 0.2; \quad i_M \approx 7°$$

- ✓ **Mercury** has High Daytime Surface **Temperatures** (2nd after Venus!): up to 720 °K = 450 °C but only ≈ 100 °K at Night
- ✓ **Mercury's Rotation Rate** is 1.5 Times its **Mean Orbital Rate** (i.e., **3 : 2 Resonance** between Rotation and Orbit Motion)
- ✓ **Mercury's 'Day'** (i.e., Time between two Sun Passages over the Same Meridian) is Extremely Long: ≈ **176 Earth Days**
- ✓ As a Result, Variations in Local **Solar Elevation** and **Surface Thermal** Characteristics Occur only very Gradually
- ✓ **Mercury's Rotation Axis** is Close (≈ 0.01°) to Orbit Plane Normal ➔ **Subsolar Points** are Practically on Equator
- ✓ At **Perihelia** (Aphelia) They are Called: **Hot** (Warm) **Poles**

# Variation of Solar Radiation Energy

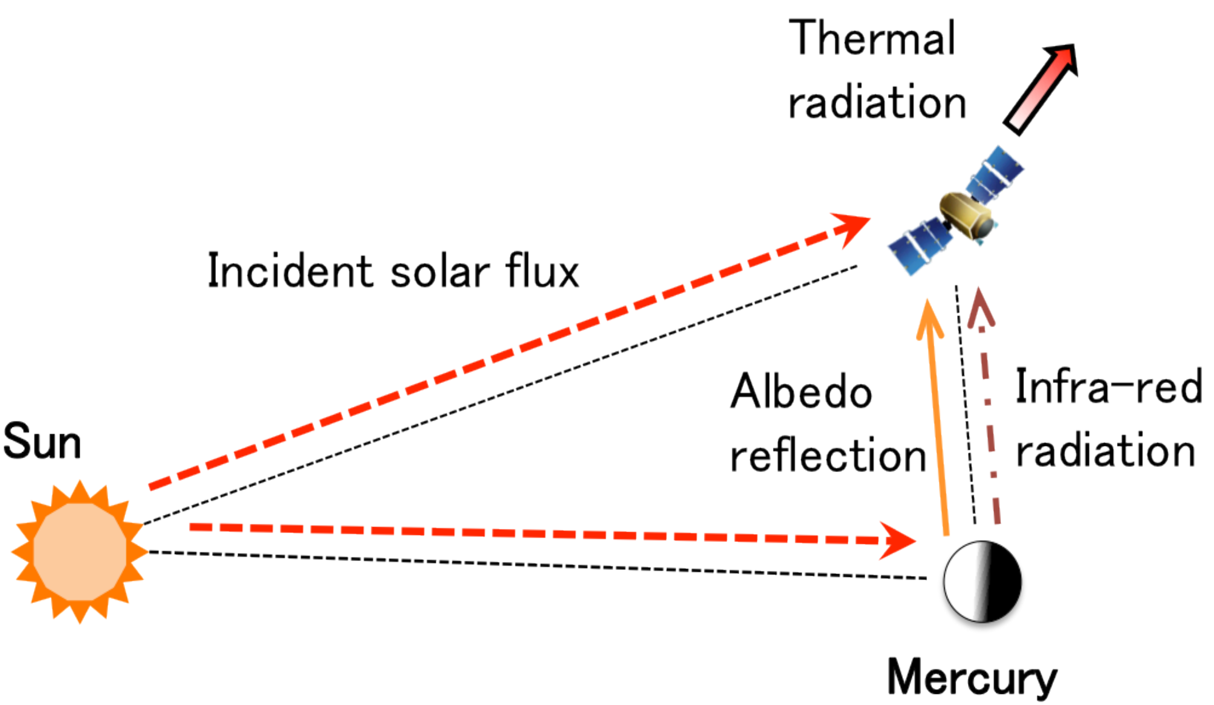


# Mercury's Orbital & Thermal Input Parameters

| | | |
|---|---|---|
| $a$ : | Mercury's orbital semi-major axis in [AU] | 0.3871 |
| $e$ : | Mercury's orbital eccentricity | 0.2056 |
| $i$ : | Mercury's orbital inclination | 7.00° |
| $\Omega$ : | Mercury's longitude of ascending node | 48.33° |
| $\omega$ : | Mercury's longitude of perihelion | 77.46° |
| $M$ : | Mercury's mean longitude | 252.25° |
| $\mu_M$ : | Mercury's gravitational parameter (GM) in [$km^3\ s^{-2}$] | 22030 |
| $R_M$ : | Mercury's equatorial (and polar) radius in [km] | 2439.7 |
| $o_M$ : | Mercury's obliquity of rotation axis to orbit plane | ~ 0° |
| $P_{rot}$ : | Mercury's sidereal rotational period in [days] | 58.65 |
| $P_{orb}$ : | Mercury's sidereal orbital period in [days] | 87.969 |
| $P_{syn}$ : | Mercury's synodic orbital period in [days] | 115.88 |
| $d_M$ : | Mercurian 'day' in [days] | 175.94 |
| $A_b$ : | Mercury's Bond albedo coefficient | ~ 0.12 |
| $\alpha_M$ : | Mercury's surface thermal absorption coefficient | ~ 0.88 |
| $\varepsilon_M$ : | Mercury's surface thermal emissivity coefficient | ~ 0.82 |

# Mercury's Unique Thermal Environment

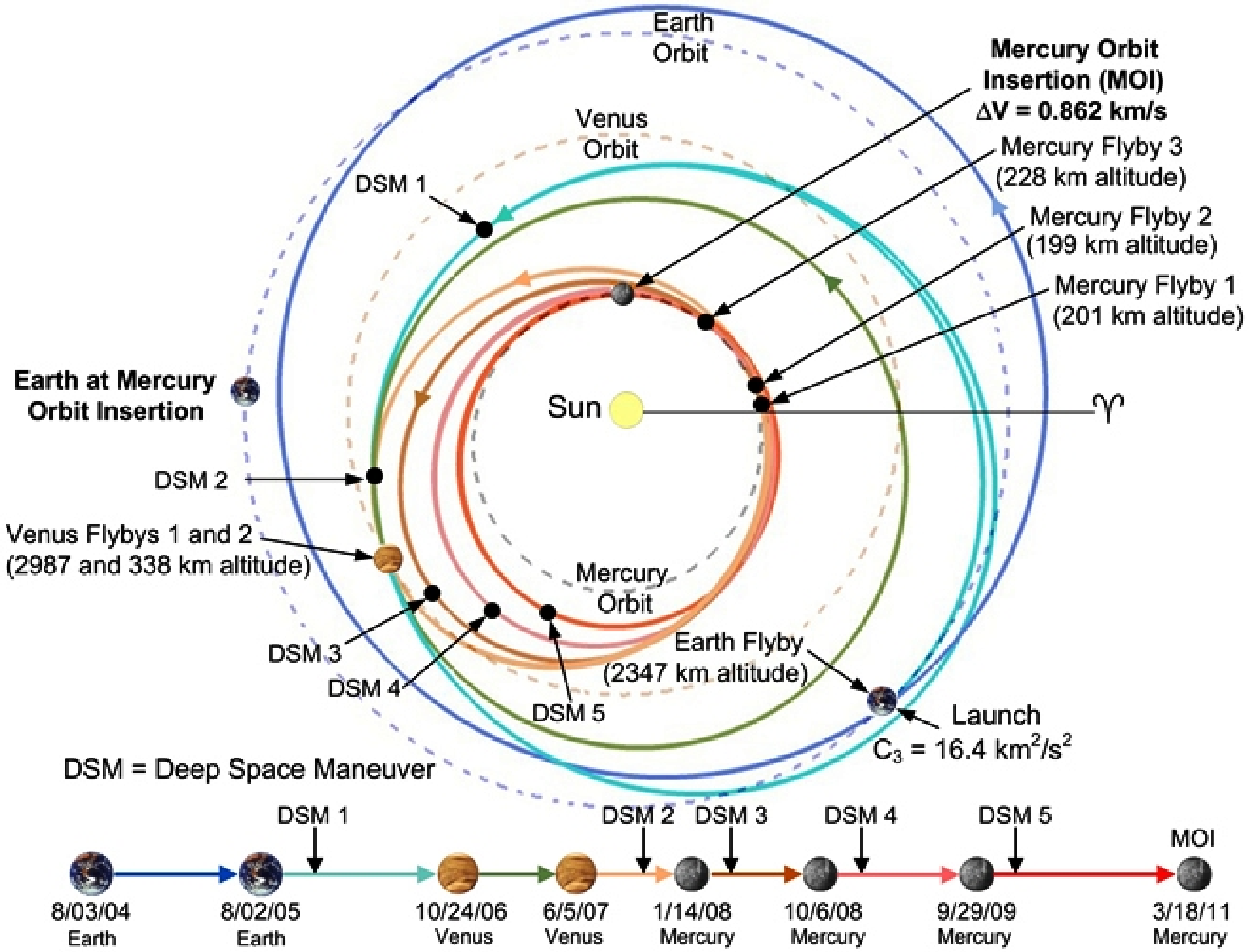
## Mercury's Incident Solar Flux is much Higher than Earth's




**Non-Gravitational Effects on Satellite**

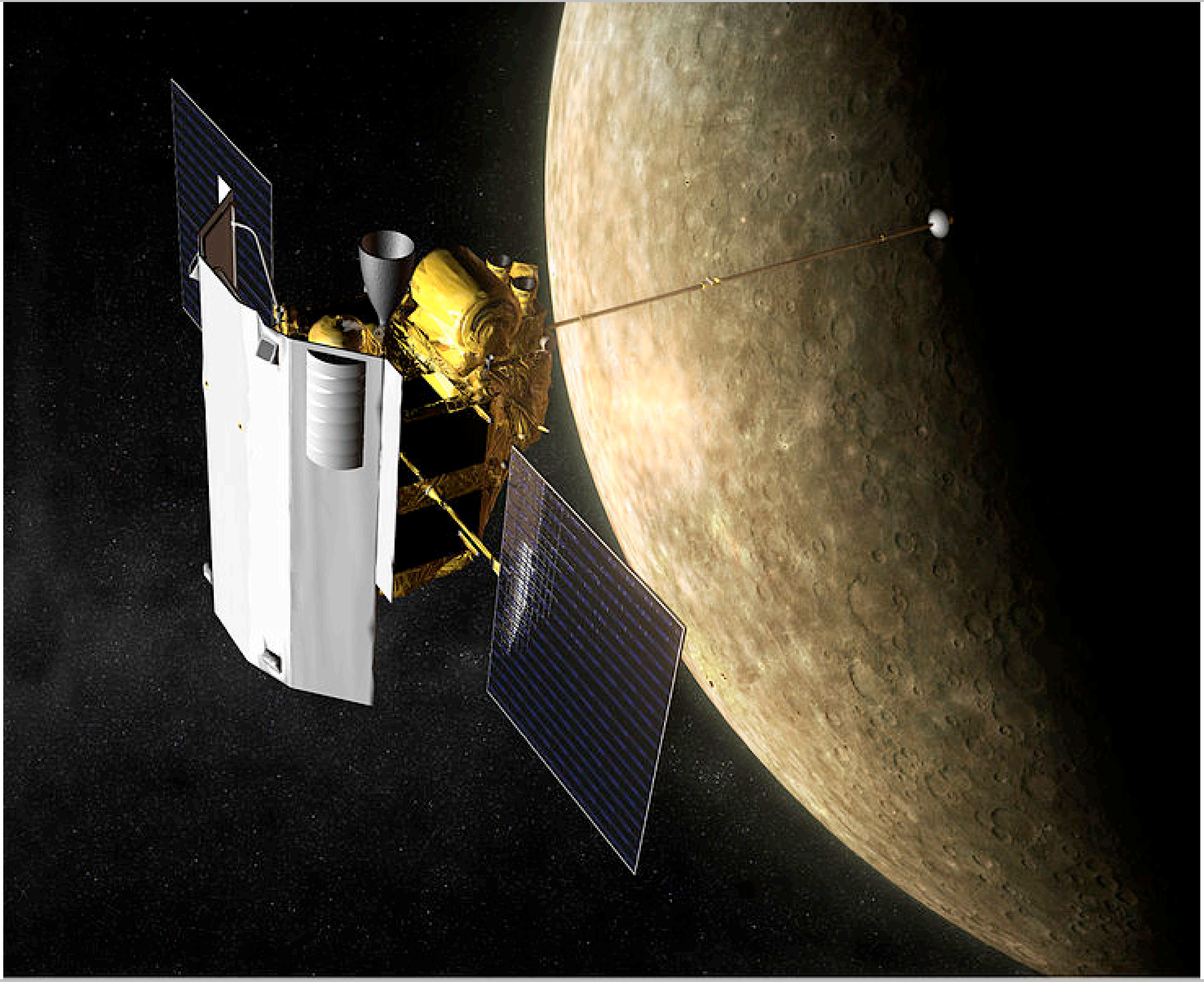
- Solar Radiation (SR)
- Satellite's Thermal Radiation (TR)
- Mercury's Infra-Red Radiation (IR)
- Mercury's Albedo Reflection (AL)

# Messenger Unique Trajectory Design

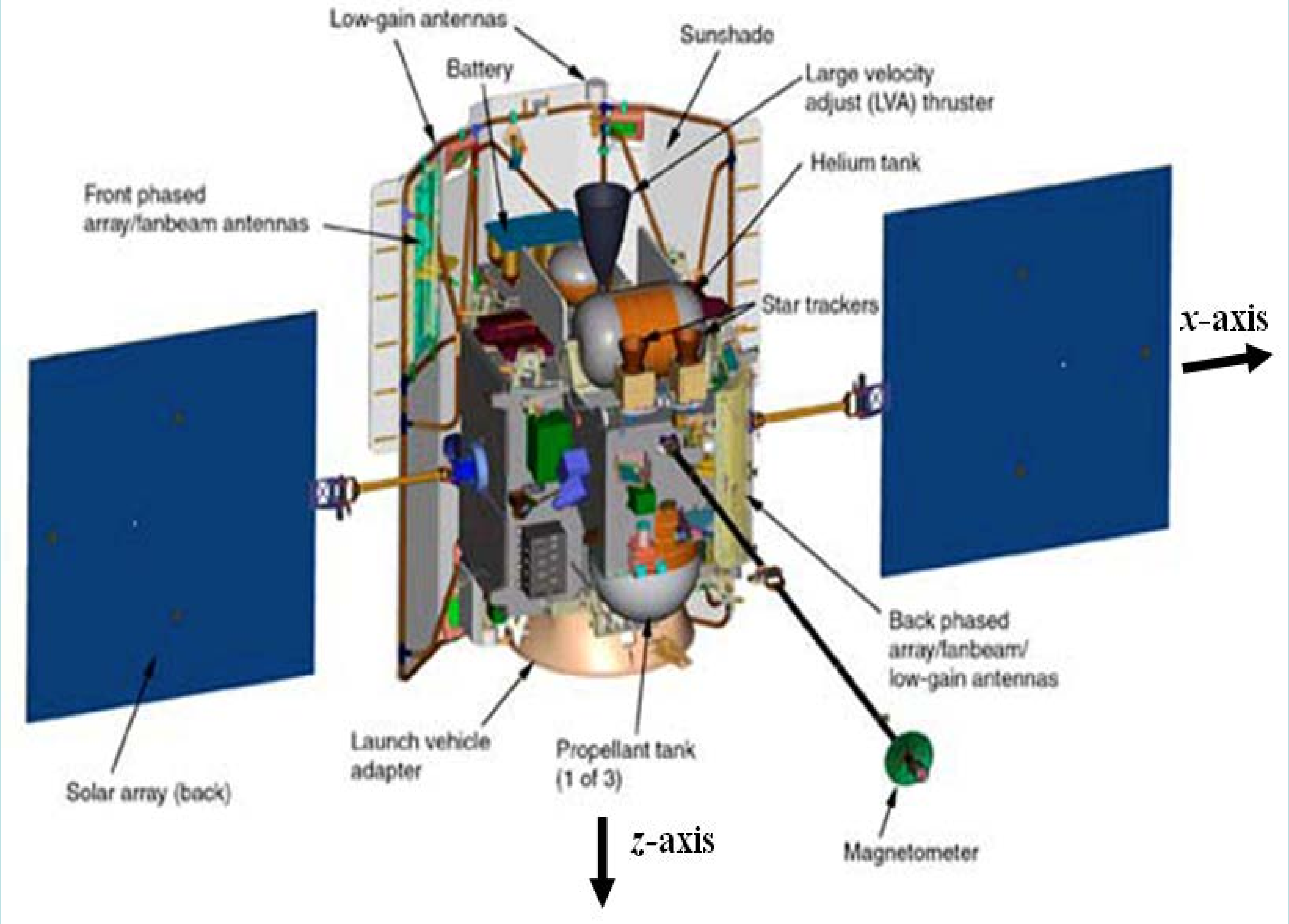



End of Life: **April 2015**

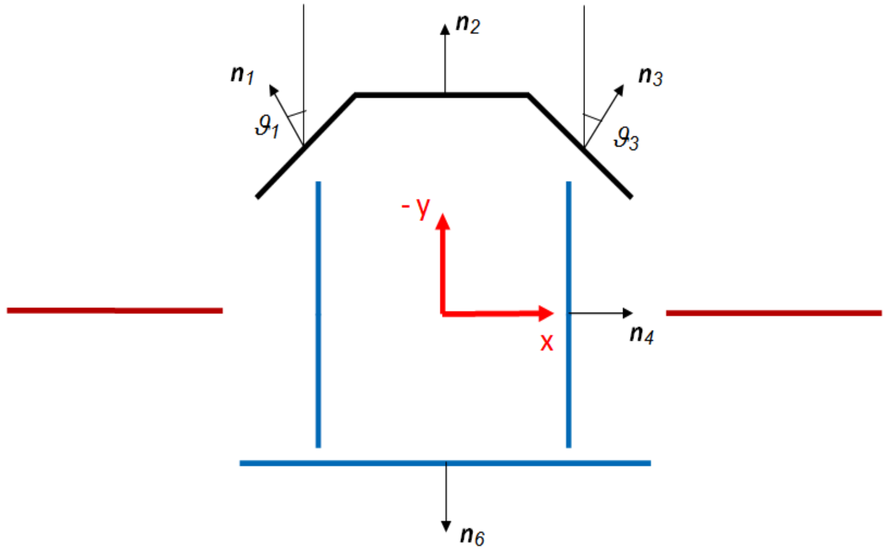
# Messenger Orbiting Mercury



# Messenger In-Flight Spacecraft Configuration



# SRP Input Parameters for 10-Plates Configuration




| ID | Component | Area | RA | DE | $\rho$ s | $\rho$ d |
|---|---|---|---|---|---|---|
| 1 | X- Sunshield wing | 2.121 | -127.2 | 0 | 0.138 | 0.219 |
| 2 | Center Sunshield | 1.668 | -90.0 | 0 | 0.138 | 0.225 |
| 3 | X+ Sunshield wing | 2.121 | -52.8 | 0 | 0.138 | 0.231 |
| 4 | X facing (2-way) | 5.000 | 0.0 | 0 | 0.040 | 0.240 |
| 5 | Z facing (2-way) | 2.200 | 0.0 | 90 | 0.040 | 0.240 |
| 6 | Y+ facing (backside) | 5.046 | 90.0 | 0 | 0.040 | 0.240 |
| 7 | X+ Solar panel, front | 2.724 | 0.0 | 90 | 0.244 | 0.006 |
| 8 | X- Solar panel, front | 2.724 | 0.0 | 90 | 0.244 | 0.006 |
| 9 | X+ Solar panel, back | 2.724 | 0.0 | -90 | 0.040 | 0.240 |
| 10 | X- Solar panel, back | 2.724 | 0.0 | -90 | 0.040 | 0.240 |

# Total Acceleration Induced by SRP on Satellite with *n* Surfaces $A_j$

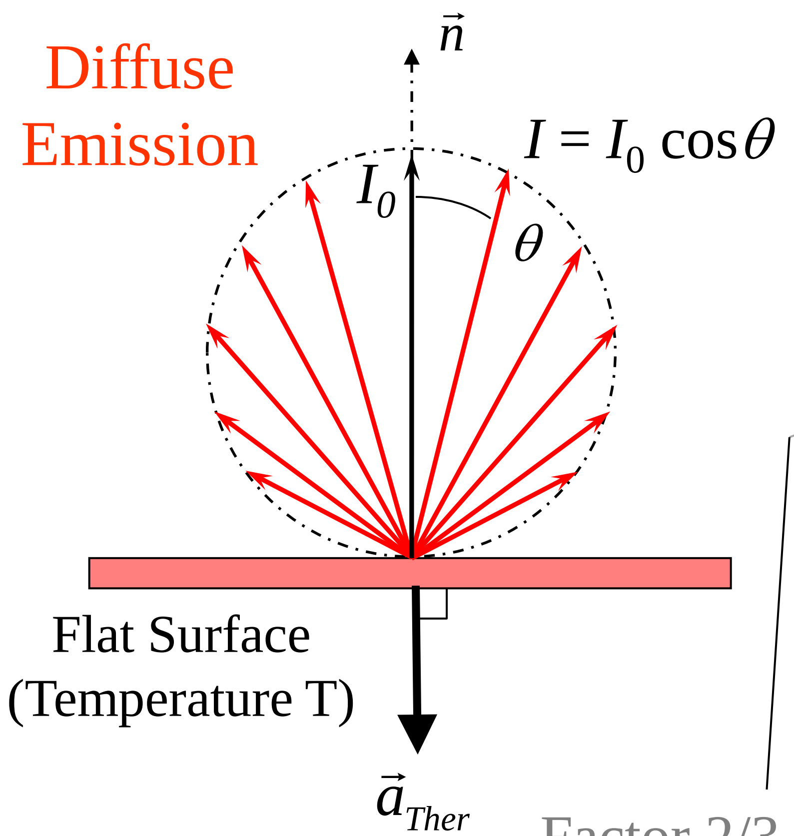
$$\mathbf{a}_{SRP,j} = \mathbf{a}_{absorbed,j} + \mathbf{a}_{specular,j} + \mathbf{a}_{diffuse,j}$$

$$\mathbf{a}_{SRP} = -c_{SRP} \sum_{j=1}^{n} A_j \cos\vartheta_j \left\{ \left(1-\rho_{s,j}\right)\mathbf{s} + 2\left(\rho_d/3 + \rho_s \cos\vartheta\right)_j \mathbf{n}_j \right\}$$

$$\mathbf{a}_{SRP} = -c_{SRP} \sum_{j=1}^{n} A_j \left\{ f_j\,\mathbf{s} + g_j\,\mathbf{n}_j \right\} \quad [\mathrm{m/s^2}]$$

# Accelerations due to Thermal Heat Flux

## Recoil Acceleration due to Thermal Radiation




Emitted Heat Flux: $q_{Ther} = \varepsilon \sigma T^4$

$$\vec{a}_{Ther} = -\frac{2}{3} C_{Ther}\, \vec{n} \; [m/s^2]$$

with:

$$C_{Ther} = \frac{q_{Ther}}{c}\frac{A}{m} = \frac{\varepsilon \sigma T^4}{c}\frac{A}{m} \; [m/s^2]$$

Factor 2/3 is due to Lambert's Law

*A: Area*

*m: Satellite Mass*

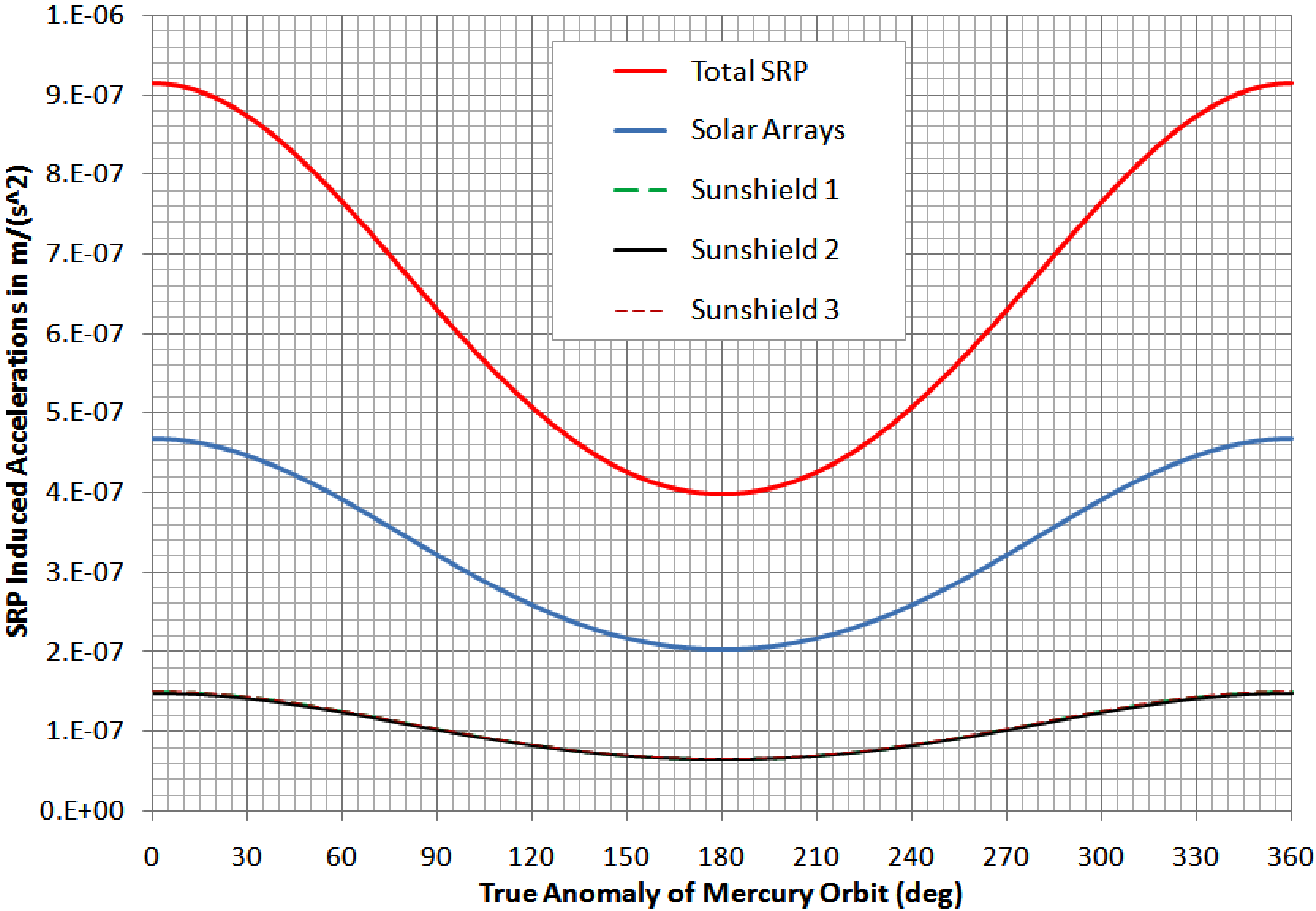
*c: Speed of Light*

# SRP Inputs & Acceleration Results (at Perihelion)

## For 'Ideal' Attitude, Symmetry Assures that SRP Force is Along y-Axis

| Parameters | Arrays | Sunshields # 1, 2, 3 | | |
|---|---|---|---|---|
| area ($m^2$): | 5.448 | 2.121 | 1.668 | 2.121 |
| projected area ($m^2$): | - | 1.689 | - | 1.689 |
| C-SRP ($m/s^2$): | 3.751 E-07 | 1.163 E-07 | 1.148 E-07 | 1.163 E-07 |
| $\alpha$ : | 0.75 | 0.643 | 0.637 | 0.631 |
| $\rho$ : | 0.25 | 0.357 | 0.363 | 0.369 |
| $\rho_s$: | 0.244 | 0.138 | 0.138 | 0.138 |
| $\rho_d$: | 0.006 | 0.219 | 0.225 | 0.231 |
| mass (kg): | 700 | | | |
| **Accelerations** ($m/s^2$): | **4.681 E-07** | **1.493 E-07** | **1.479 E-07** | **1.503 E-07** |
| **Total Acceleration** ($m/s^2$): | **9.156 E-07** | | | |

# SRP Induced Acceleration Results over Orbit

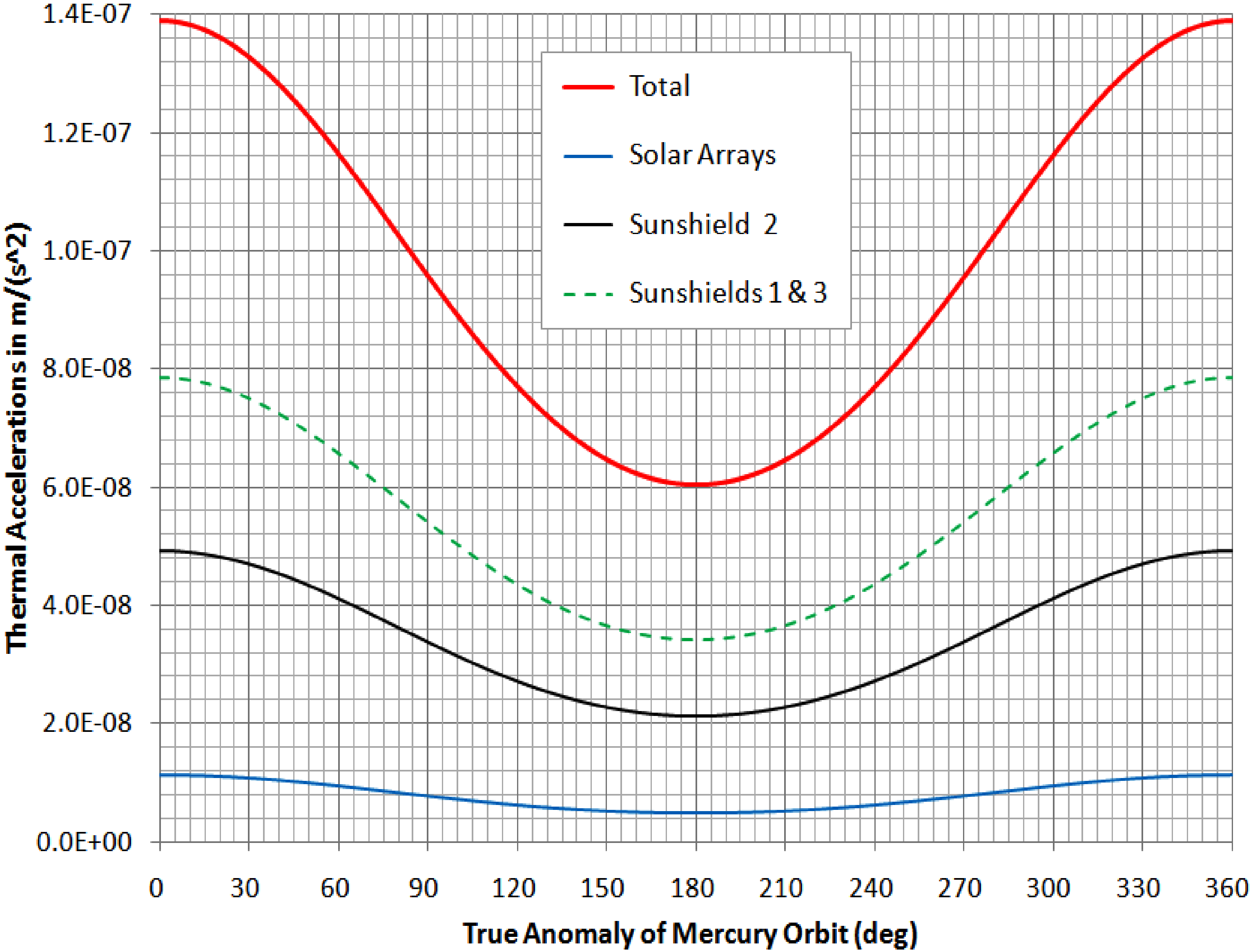


# TRP Inputs & Acceleration Results (at Perihelion)

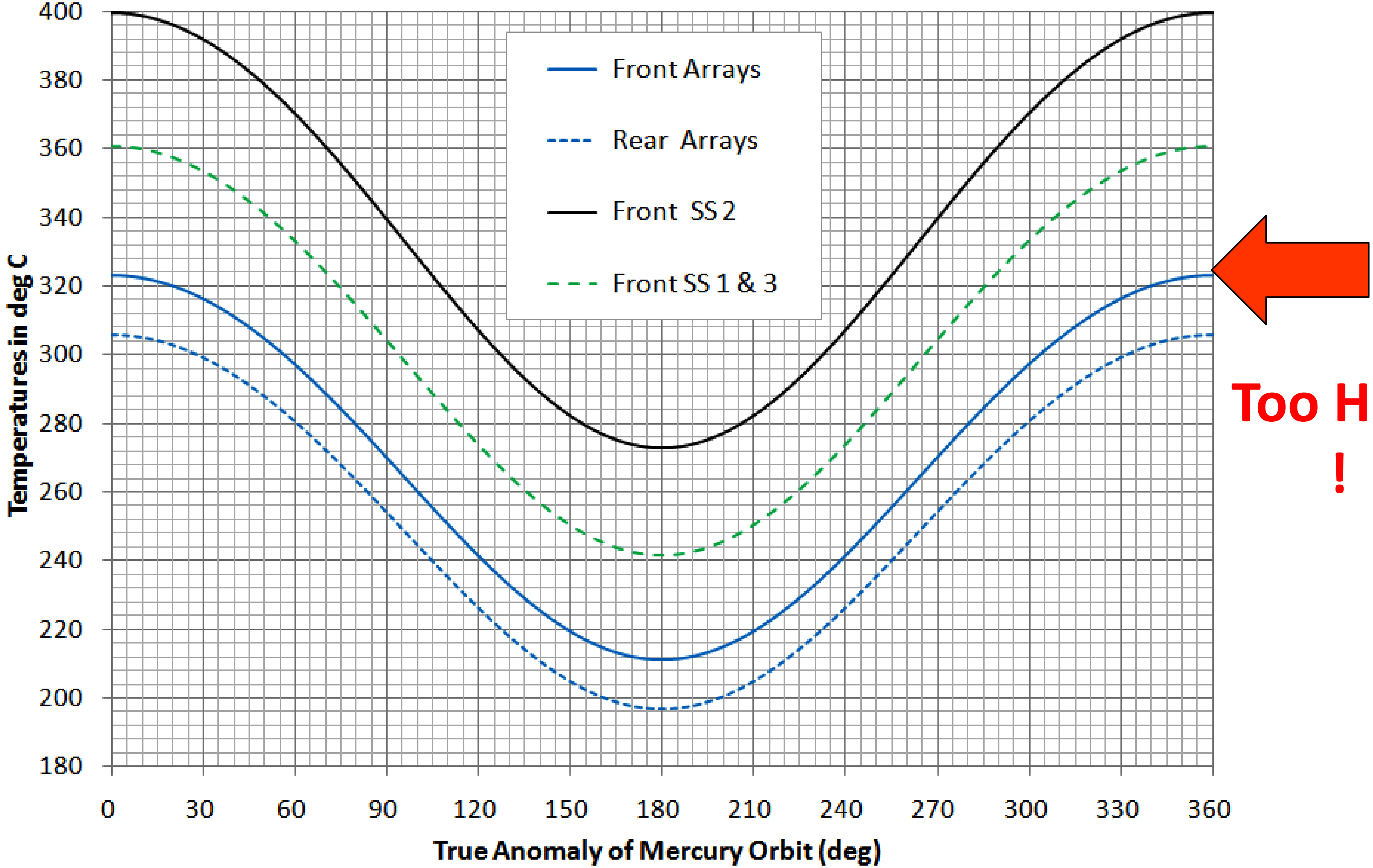
## 'Ideal' Attitude Assures that also TRP-Induced Force is Along y-Axis

| Parameters | Arrays | Sunshields # 1, 2, 3 | | |
|---|---|---|---|---|
| area ($m^2$): | 5.448 | 2.121 | 1.668 | 2.121 |
| C-TRP($m/s^2$): | 1.472E-18 | 5.731E-19 | 4.507E-19 | 5.731E-19 |
| alpha: | 0.75 | 0.643 | 0.637 | 0.631 |
| epsilon: | 0.80 | 0.80 | 0.80 | 0.80 |
| mass (kg): | 700 | | | |
| **Accelerations** ($m/s^2$): | **1.125 E-08** | **3.932 E-08** | **4.929 E-08** | **3.932 E-08** |
| **Percentages** (%): | 8.1 | 28.3 | 35.4 | 28.3 |
| **Total Acceleration** ($m/s^2$): | **1.391 E-07** (= **15.2** % of SRP) | | | |

# TRP Induced Acceleration Results over Orbit



# Variation of Temperature over Orbit - 1

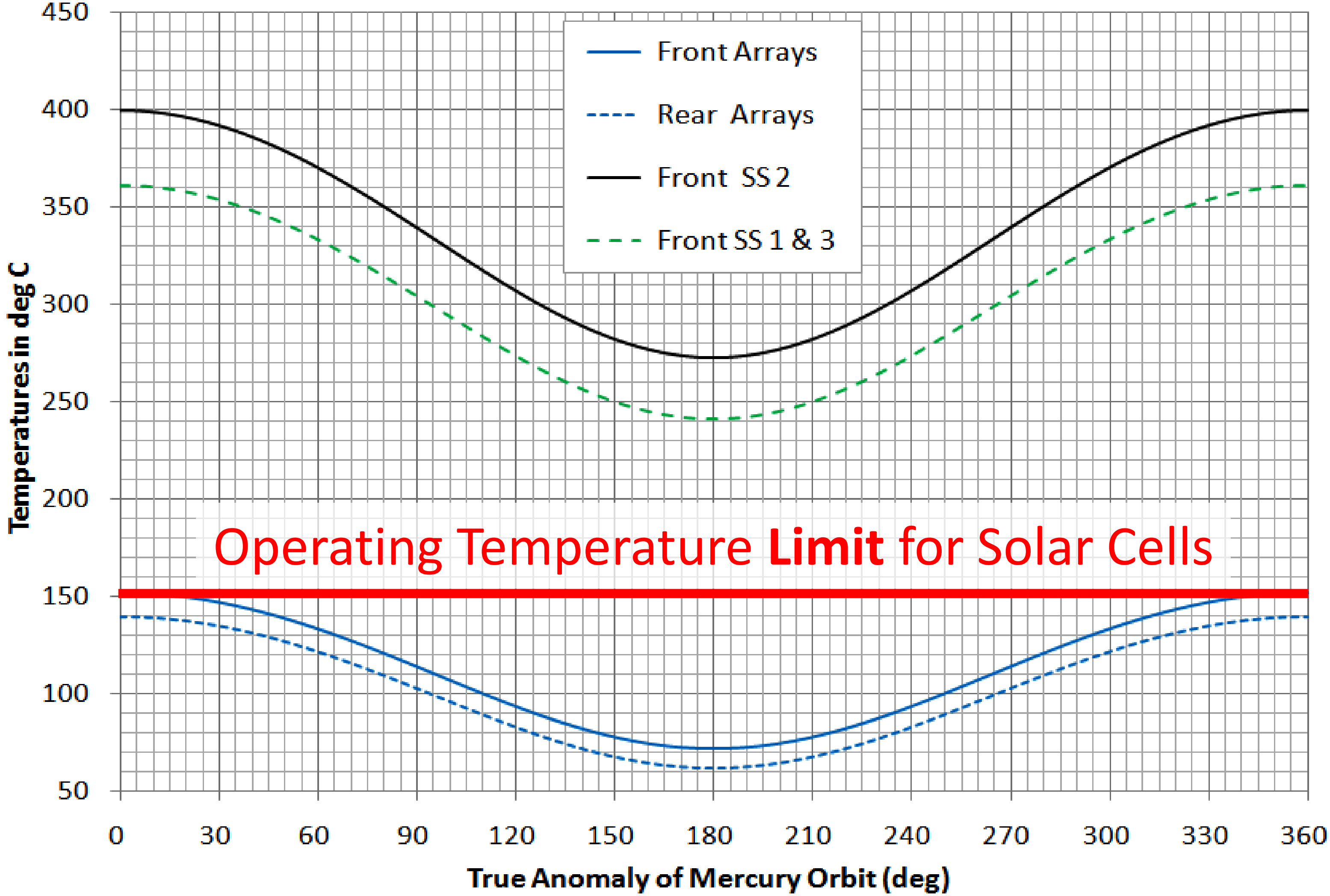



**Too High !**

**Operating Temperatures of Solar Cells Should be < 150 C …**

# Variation of Temperatures over Orbit - 2

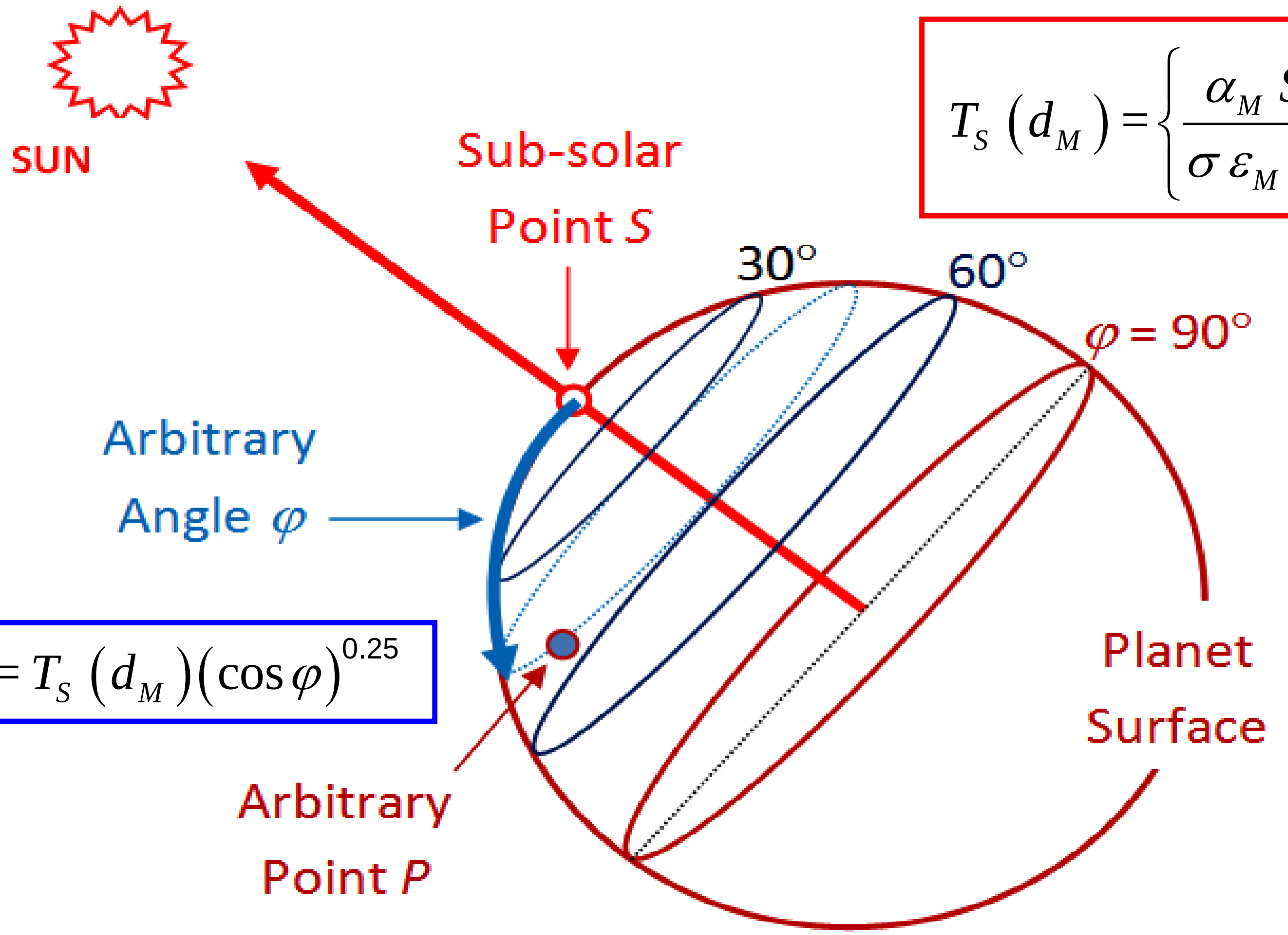
## Therefore, Solar Arrays Must be Off-Pointed by Angle of 25°



# Mercury Sub-Solar Latitudinal Temperature Model

## Heat Balance Conditions for Infinitesimal Latitude Bands

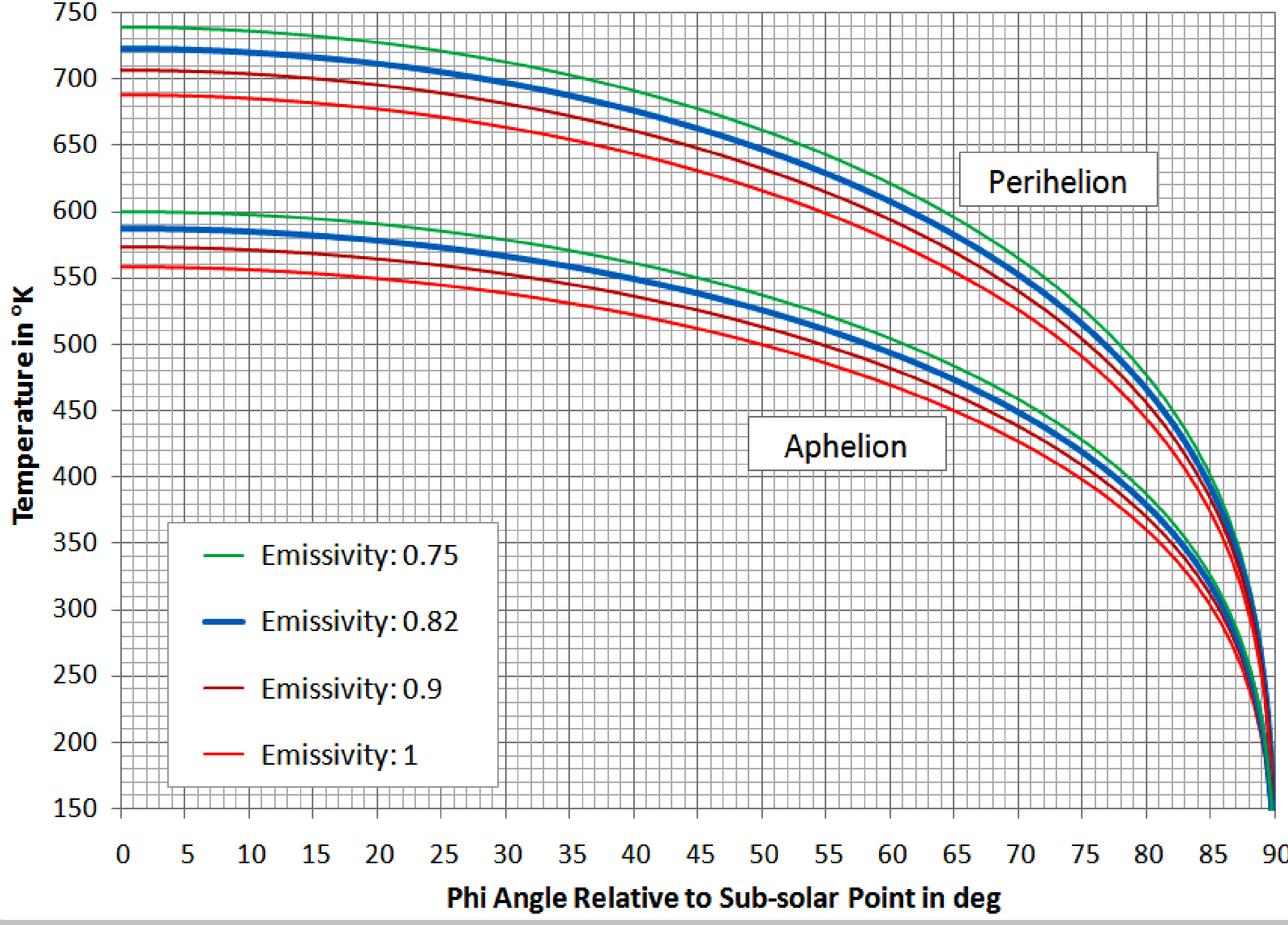
$$T_S\left(d_M\right) = \left\{ \frac{\alpha_M S_{\odot}}{\sigma \varepsilon_M d_M^2} \right\}^{0.25}$$




$$T_P\left(d_M, \varphi\right) = T_S\left(d_M\right)\left(\cos\varphi\right)^{0.25}$$

$$T_S = 723\,^{o}K\ (Perihelium)$$

# Mercury Surface Temperature as Function of Phi Angle



# Mercury Hemispherical Temperature Model

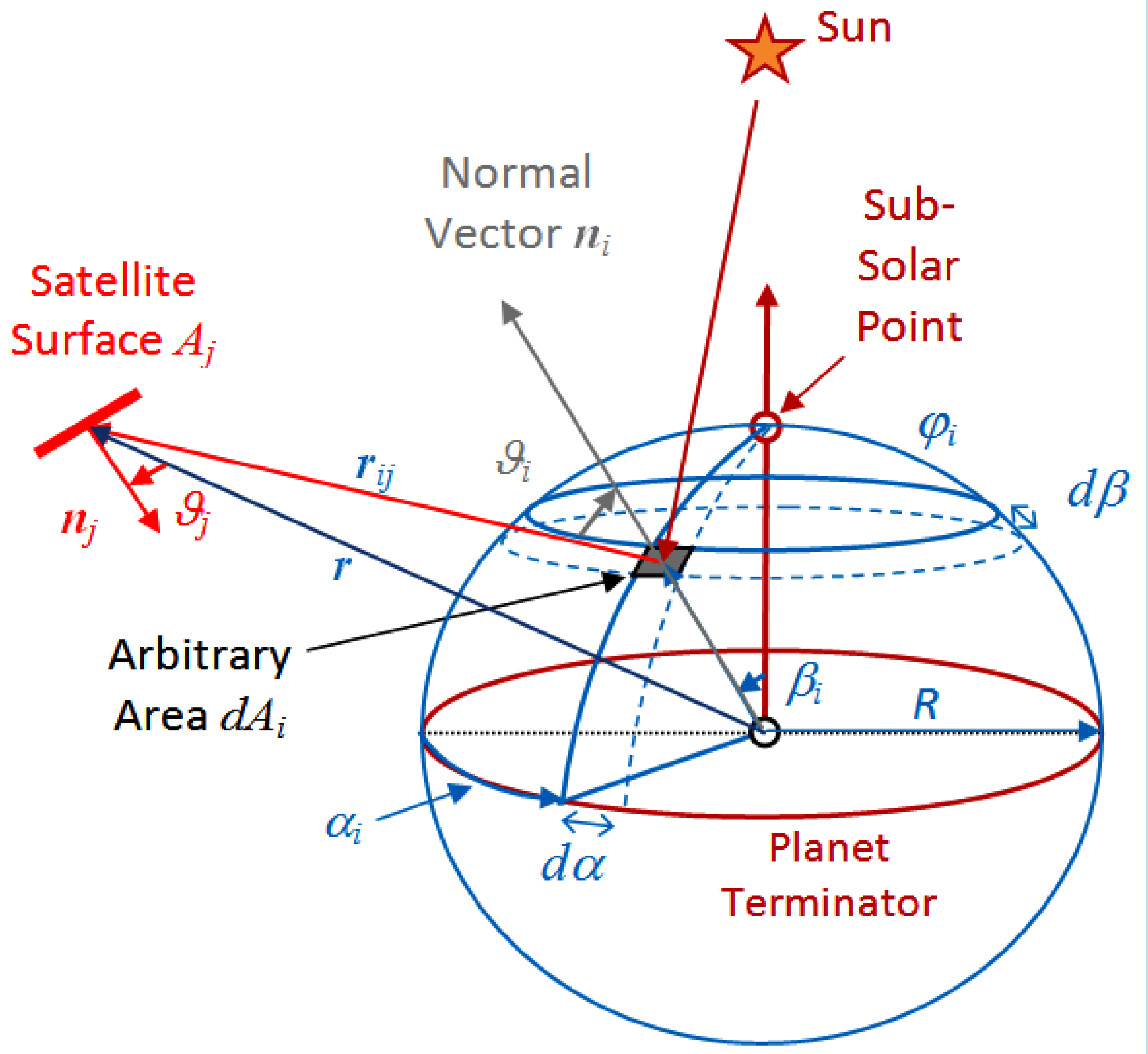
## Heat Balance Condition over Entire Daylight Hemisphere

$$\frac{\alpha_M S_{\odot}}{d_M^2}\left(\pi R_M^2\right) = \sigma\,\varepsilon_M\,T_M^4(d_M)\left(2\pi R_M^2\right)$$

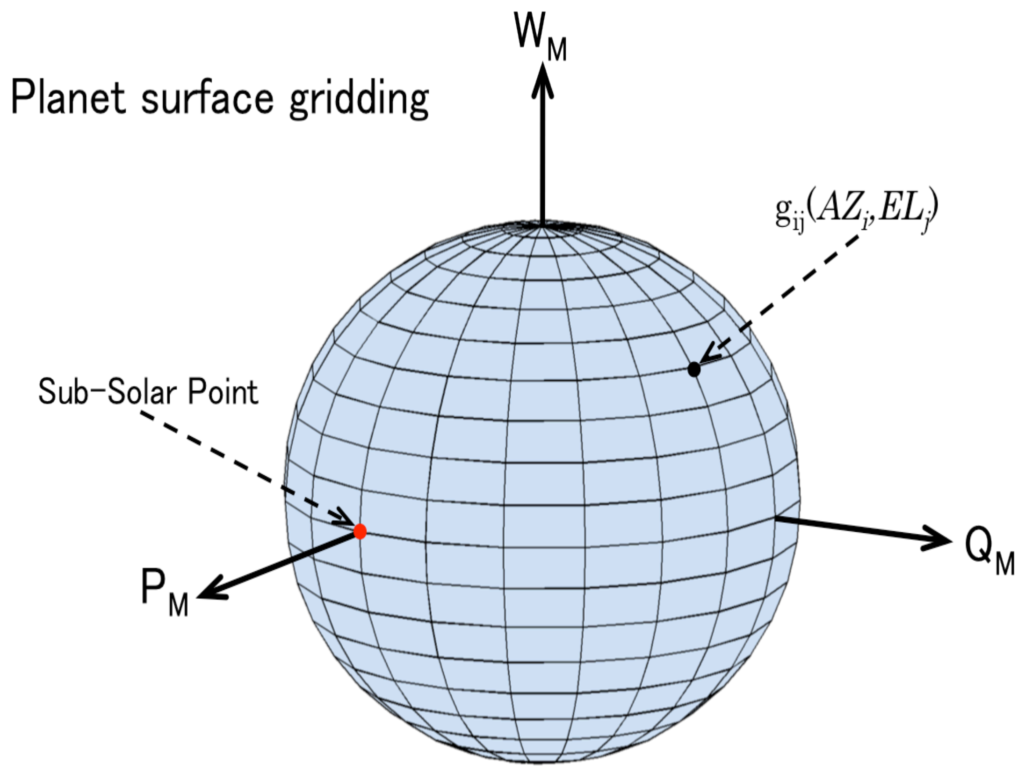
$$\Rightarrow T_M(d_M) = \left\{\frac{\alpha_M S_{\odot}}{2\sigma\,\varepsilon_M\,d_M^2}\right\}^{0.25}$$

- This Hemispherical Temperature is $(0.5)^{0.25}$ = 84.1 % of Subsolar $T_S$
- When Using Baseline Values $\alpha_M$ **= 0.88** and $\varepsilon_M$ **= 0.82**, We Find Equilibrium Temperatures over Mercury's Daylight Hemisphere:
  - 608 °K at Mercury's **perihelion**
  - 494 °K at Mercury's **aphelion**

# Geometry of Mercury Albedo Reflection on Satellite



# Grid Configuration over Mercury's Surface




$$AZ_i = -\pi + \frac{2\pi}{az}(i-1) \quad (\, for\ i = 1,2,\ldots,az)$$

$$EL_j = -\frac{\pi}{2} + \frac{\pi}{el}(j-0.5) \quad (\, for\ j = 1,2,\ldots,el)$$

Number of grids:

Azimuth : *az* = 100

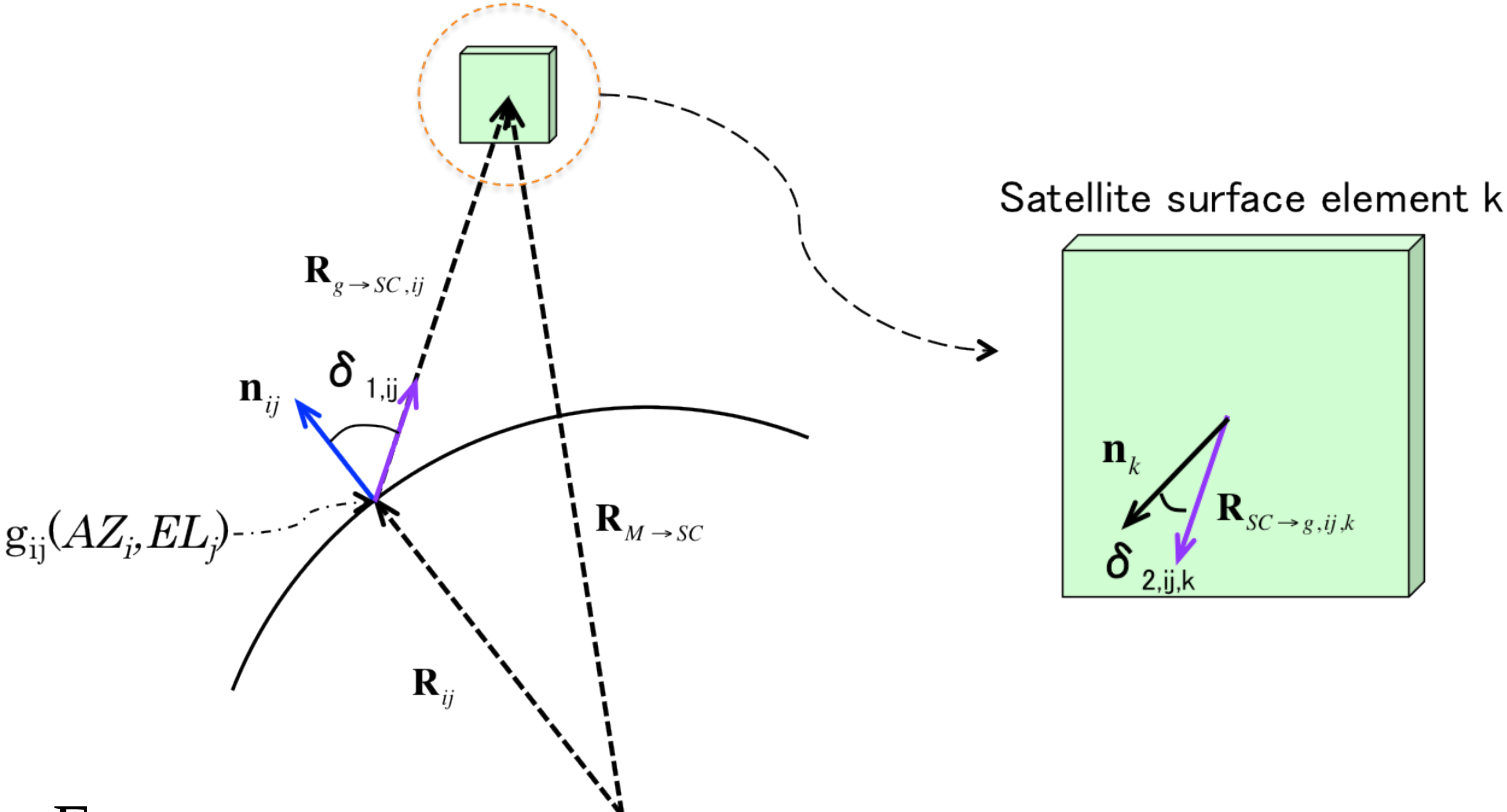
Elevation : *el* = 50

Grid point position vector:

$$\mathbf{R}_{ij} = R_M \begin{bmatrix} \cos EL_j \cos AZ_i \\ \cos EL_j \sin AZ_i \\ \sin EL_j \end{bmatrix} = R_M \mathbf{n}_{ij}$$

$\mathbf{n}_{ij}$ : unit surface normal at $g_{ij}$

# Geometrical View-Factor Modeling for IR & AL

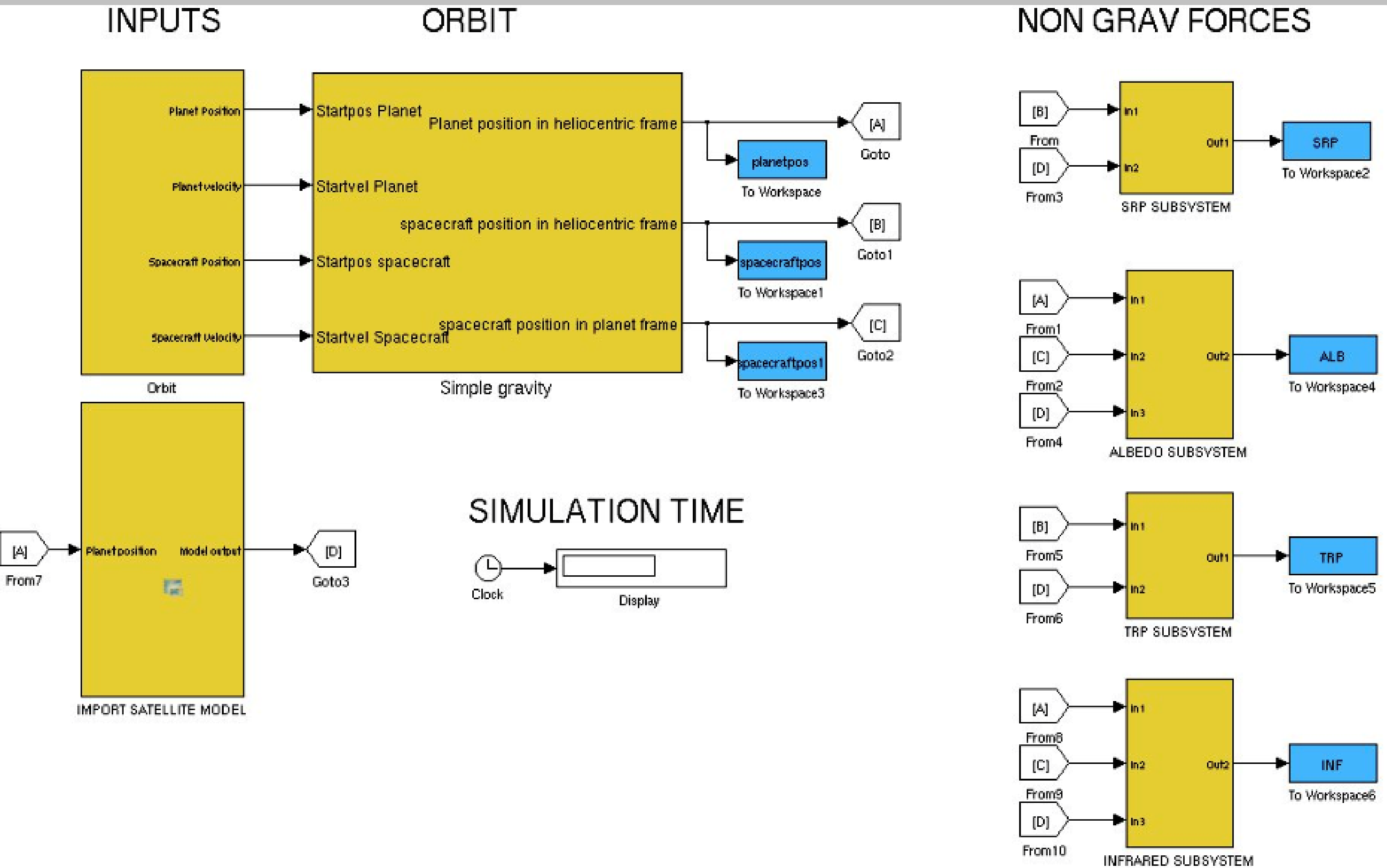



View Factor:

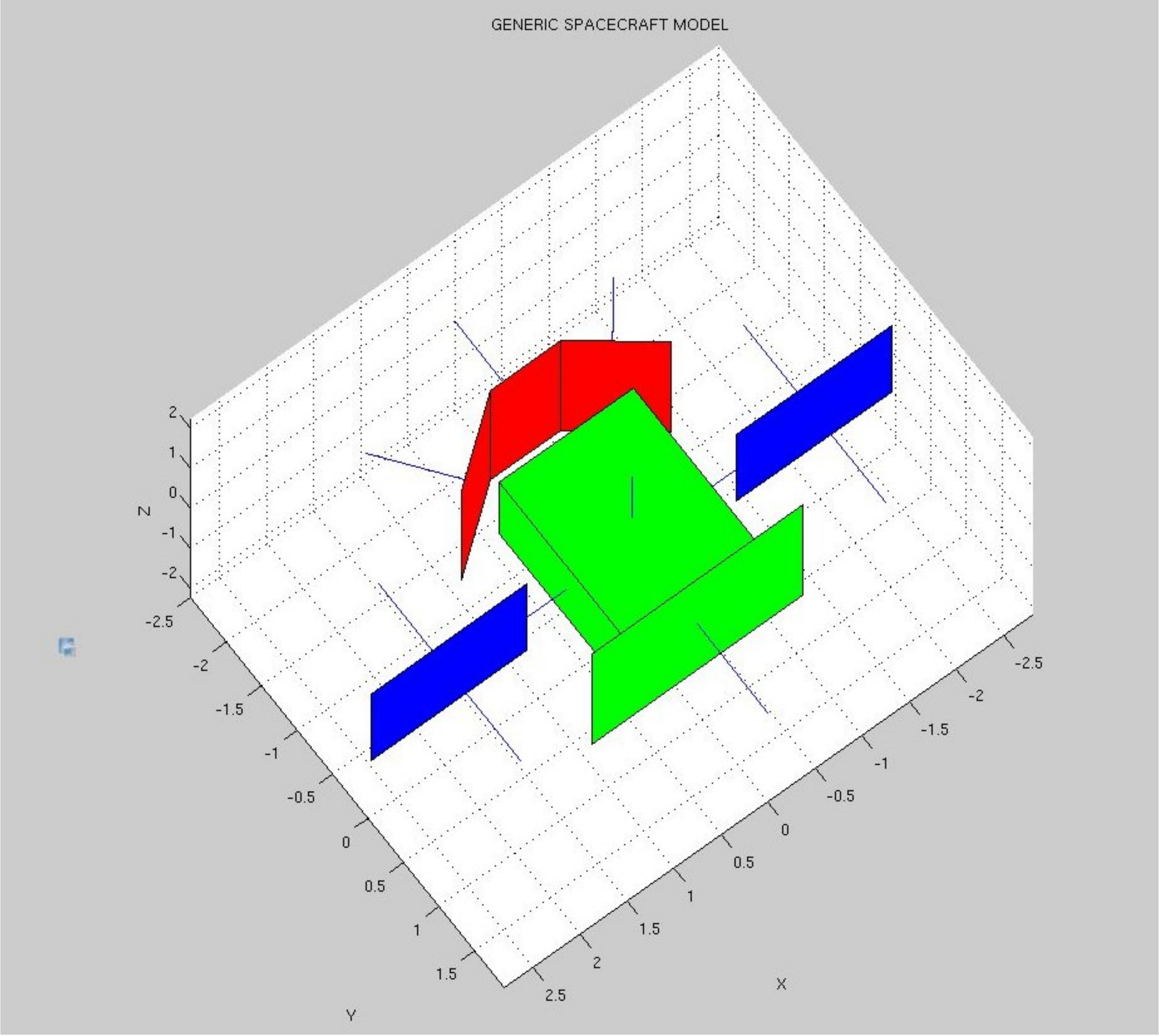
$$f_{ij,k} = \frac{\cos\delta_{1,ij}\cos\delta_{2,ij,k}}{\pi r_{ij}^2} A_k$$

If $\delta_{1,ij} \geq \pi/2$ or $\delta_{2,ij,k} \geq \pi/2$:
$f_{ij,k} = 0$

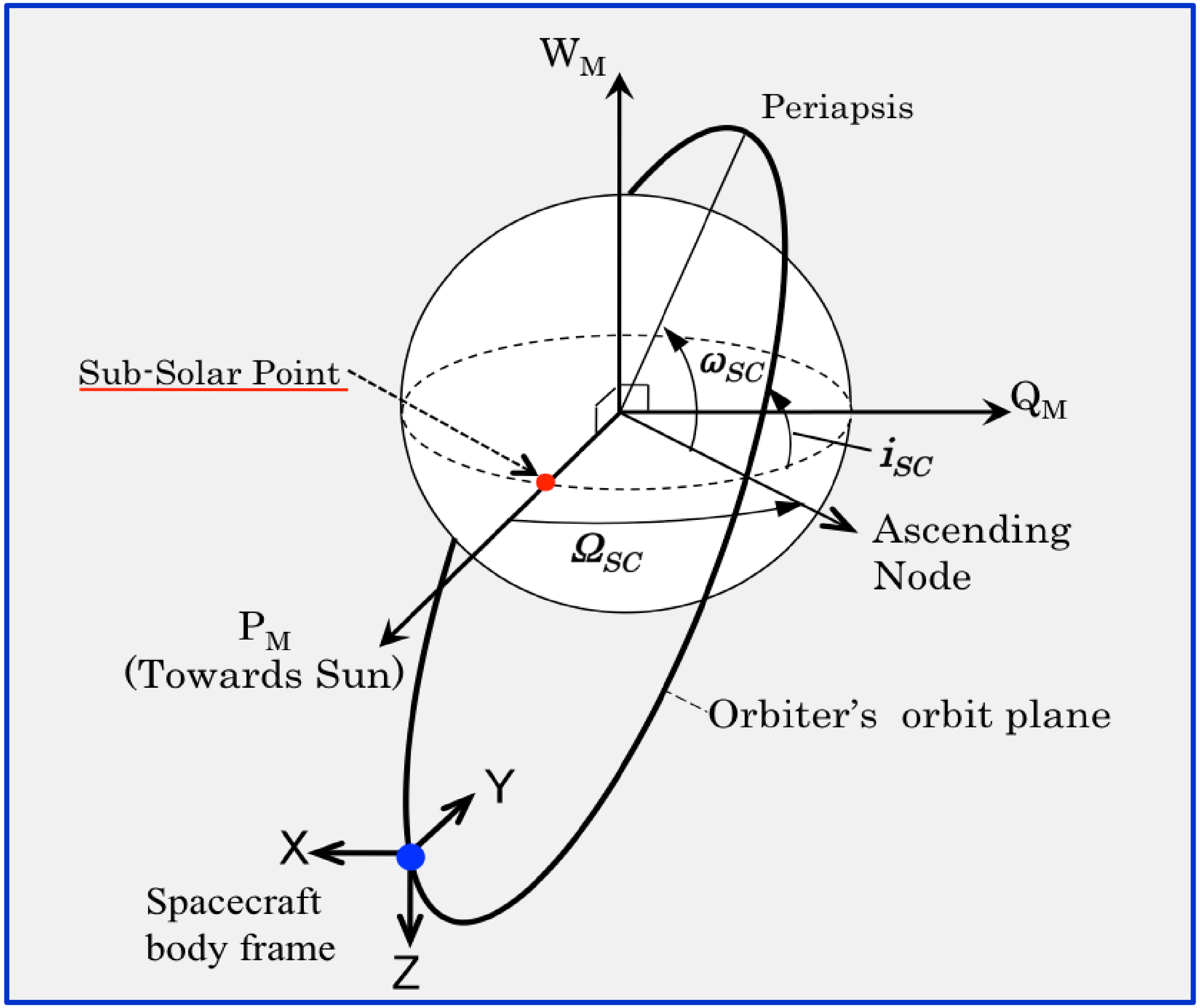
# Modular Simulink Model for Mercury Orbiter



# SIMULINK SPACECRAFT MODEL



# Messenger Orbit about Mercury




**MESSENGER ORBIT:**

$a$ = 10175.39 km

*Period* = 12 h

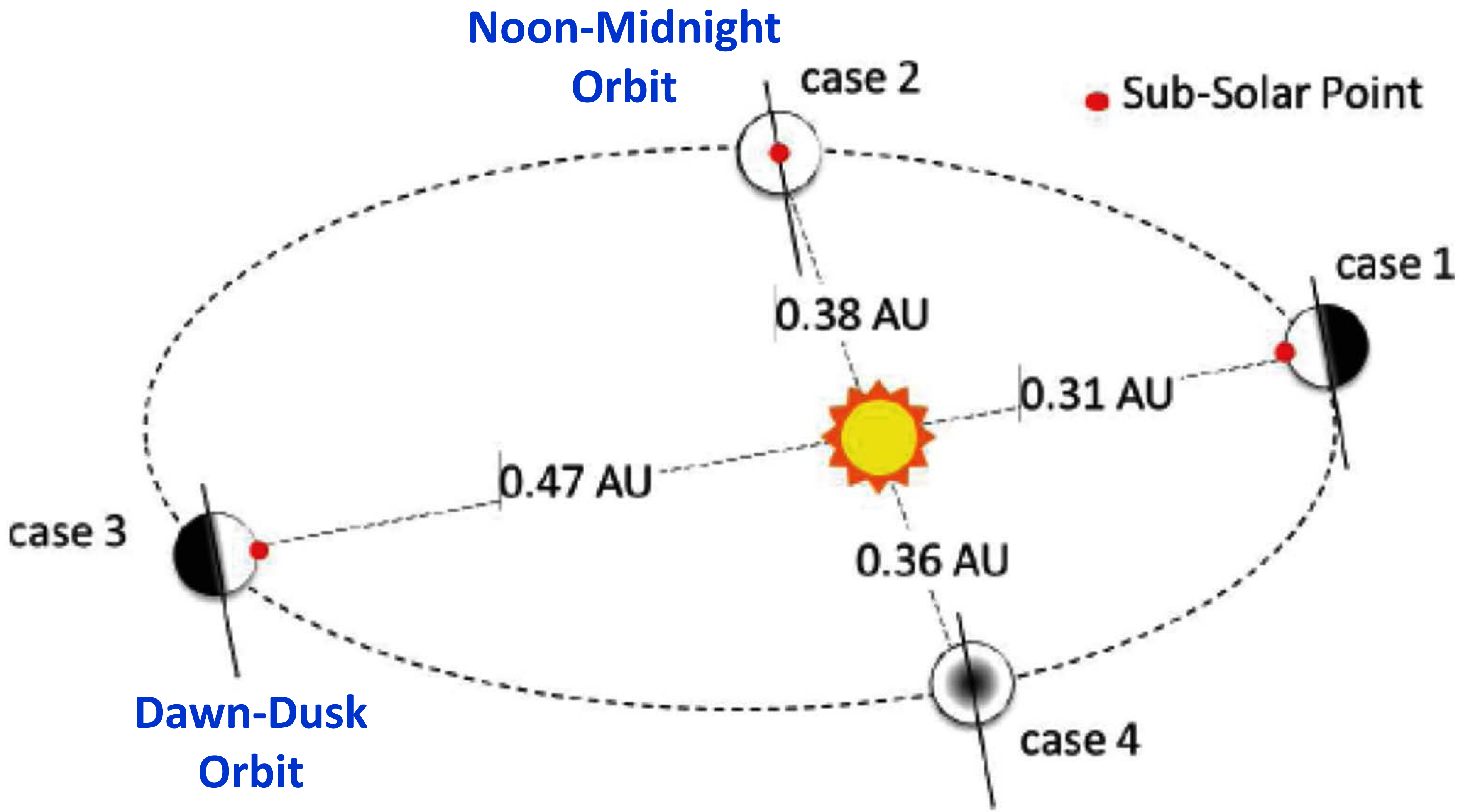
$e$ = 0.74

$i$ = 82.52°

$\omega$ = 119.16°

**Mercury-Sun Coordinate System $P_M$, $Q_M$, $W_M$**

# Visualization of Messenger Test Orbits



# Analytical & Numerical Results

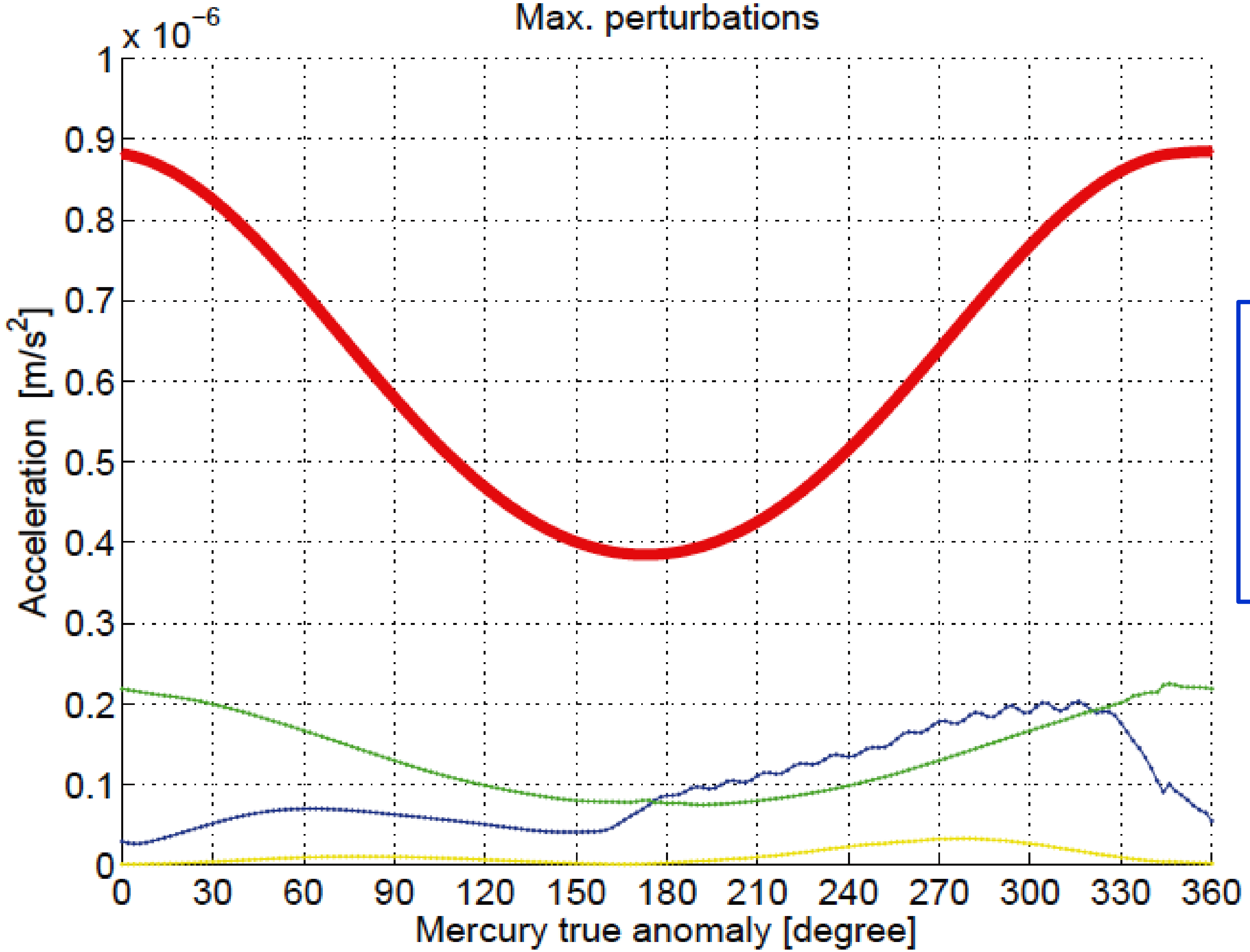
Table 7. Analytical Results of Acceleration in [%] of SRP Magnitude

| | | ALB [% of SRP] | | INF [% of SRP] | | TRP [% of SRP] | |
|---|---|---|---|---|---|---|---|
| Case | SRP [$10^{-7}$m/s$^2$] | max | min | max | min | max | min |
| 1 | 8.45 | 0.32 | 0.02 | 6.68 | 0.18 | 25.60 | 23.44 |
| 2 | 5.51 | 2.37 | 0.00 | 14.10 | 0.01 | 23.24 | 18.80 |
| 3 | 3.71 | 0.95 | 0.01 | 19.24 | 0.14 | 19.99 | 18.81 |
| 4 | 6.22 | 6.45 | 0.00 | 26.79 | 0.00 | 24.05 | 17.93 |

Table 8. Numerical Results of Acceleration in [%] of SRP magnitude

| Case | SRP [$10^{-7}$m/s$^2$] | | ALB [% of SRP] | | INF [% of SRP] | | TRP [% of SRP] | |
|---|---|---|---|---|---|---|---|---|
| | max | min | max | min | max | min | max | min |
| 1 | 8.45 | 8.42 | 0.20 | 0.00 | 3.66 | 0.17 | 23.78 | 23.31 |
| 2 | 5.51 | (eclipse) | 4.40 | 0.00 | 25.22 | 0.02 | 20.43 | 18.46 |
| 3 | 3.72 | 3.71 | 0.77 | 0.01 | 17.56 | 0.08 | 18.97 | 16.89 |
| 4 | 6.33 | (eclipse) | 6.11 | 0.00 | 25.70 | 0.00 | 21.33 | 17.74 |

# Accelerations over Mercury Year (Simulink)




Red: SR

Green: TR

Blue: IR

Yellow: AL

# Conclusions

- ✓ Solar **Radiation Intensity** at Mercury is up to 10 x Larger than at Earth Location
- ✓ We Present **Analyses & Results** of **SR, TR, IR, & AL Radiation** Effects on the Mercury Orbiter **MESSENGER** by Means of Analytical & Numerical Approaches
- ✓ **TR & IR Effects** Introduce **Appreciable Accelerations** on Messenger Trajectory with Both **up to 25 %** of SRP
- ✓ **AL Effect** is Appreciable only over a **Small Interval** and is Significantly Smaller than TR & IR : ~ 5 % of SRP
- ✓ High-Fidelity Thermal Models are Essential for Robust Satellite **Thermal Subsystem Design**
- ✓ Also they Improve Deep-Space Navigation by **Enhancing Trajectory Prediction Models**

# Our Publications on Thermal Radiation - 1


1. Van der Ha, J.C., 'Lessons Learned from the Dynamical Behaviour of Orbiting Satellites', 20th John V. Breakwell Memorial Keynote Lecture (65th IAC, Toronto, Canada, October 1, 2014), *Acta Astronautica*, Vol. 115, October-November 2015, pp. 121-137.
2. Van der Ha, J. C., Mimasu, Y. , Tsuda, Y., and Mori, O., 'Solar and Thermal Radiation Pressure Models and Flight Evaluation for IKAROS Solar Sail', *Journal of Spacecraft & Rockets*, Vol. 52, Nr. 3, May 2015, pp. 958-967.
3. Kato, T., Theil, S., and Van der Ha, J.C., 'External Torques affecting the Attitude Motion of a Mercury Orbiter', *Advances in the Astronautical Sciences*, Vol. 152, pp. 3475-3493, 2014.
4. Van der Ha, J. C. 'Comparison of Solar and Thermal Radiation Accelerations of Deep-Space Satellites', *Advances in the Astronautical Sciences*, Vol. 152, pp. 2727-2746, 2014.
5. Rievers, B., Kato, T., Van der Ha, J.C., and Laemmerzahl, C., 'Numerical Analysis of Thermal Radiation Perturbations for a Mercury Orbiter', *Advances in the Astronautical Sciences*, Vol. 148, pp. 2639-2658, 2013.
6. Shoemaker, M., Van der Ha, J.C., and Morley, T., 'Modeling and Validation of Thermal Radiation Acceleration on Interplanetary Spacecraft', *Journal of Spacecraft and Rockets*, Vol. 49, Nr. 2, March-April 2012, pp. 212-219.
7. Kato, T. and Van der Ha, J.C., 'Precise Modeling of Solar and Thermal Accelerations on Rosetta,' *Acta Astronautica*, Vol. 72, March 2012, pp. 165 - 177.
8. Rievers, B., Kato, T., Van der Ha, J.C., and Laemmerzahl, C., 'Numerical Prediction of Satellite Surface Forces with Application to Rosetta,' *Advances in the Astronautical Sciences*, Vol. 143, pp. 1123-1142, 2012.

# Our Publications on Thermal Radiation - 2


9. Kato, T., Rievers, B., Van der Ha, J.C., and Laemmerzahl, C., 'Sensitivity Analysis of the Non-Gravitational Perturbations on Mercury Orbiter', *Advances in the Astronautical Sciences*, Vol. 143, pp. 1579-1595, 2012.
10. Kato, T., Rievers, B., Van der Ha, J.C. and Laemmerzahl, C., 'Detailed Analysis of Solar and Thermal Accelerations on Deep-Space Satellites', *Advances in the Astronautical Sciences*, Vol. 143, pp. 1761-1776, 2012.
11. Van der Ha, J.C., 'Model for Thermal Radiation Recoil Accelerations of Inter-planetary Satellites', *28-th International Symposium on Space Technology and Science*, Okinawa, Japan, June 5-12, 2011, Paper ISTS-2011-d-55.
12. Sugimoto, Y., and Van der Ha, J.C., 'Thermal Radiation Modeling for Interplanetary Spacecraft Orbit Propagation', *28-th International Symposium on Space Technology and Science*, Okinawa, Japan, June 5-12, 2011, Paper ISTS-2011-d-57.
13. Sugimoto, Y., Van der Ha, J.C., and Rievers, B., 'Thermal Model for the Rosetta Spacecraft', *AIAA / AAS Guidance, Navigation, and Control Conference*, Toronto, Canada, August 2-5, 2010, Paper AIAA-10-7659.
14. Shoemaker, M.A., Van der Ha, J.C., and Morley, T. 'Reconstruction of Rosetta Thermal Effects Using Orbit Determination Results', *AIAA/AAS Guidance, Navigation, & Control Conference*, Toronto, Canada, August 2-5, 2010, Paper AIAA-10-8263.
15. Van der Ha, J.C., and Stramaccioni, D., 'Thermal Radiation Effects on Deep-Space Trajectories', *Advances in the Astronautical Sciences*, Vol. 136, pp. 1861-1880, 2010.
16. Terauchi, M., Kim, I., Hanada, T., and Van der Ha, J.C., 'Effect of Thermal Radiation Force for Trajectory during Swing-by', *26-th International Symposium on Space Technology and Science*, Hamamatsu, Japan, June 2-6, 2008, Paper 2008-d-60.