Thermal Radiation Effects on Deep-Space Satellites Part 1

Jozef C. Van der Ha

www.vanderha.com

Fundamental Physics in Space, Bremen

October 26, 2017

Table of Contents

Summary of Objectives

- ✓ We Study **Thermal Radiation** Effects on **Deep-Space Trajectories** during Cruise & Mission Operations Phases:
  - **Modeling** Accelerations due to Solar & Thermal Radiation
  - **Comparing** Predicted Effects with In-Orbit Observations
- ✓ Our Models are Based on Detailed Knowledge of Satellite's **Thermal-Optical, Geometrical, Attitude & Orbit Properties**
- ✓ We Make Careful Distinctions between Effects Induced by:
  - **Solar Radiation Pressure (SRP)**
  - **Thermal Radiation Pressure (TRP)**
- ✓ We Aim at Constructing **Thermal Acceleration** Models that **Improve Trajectory Predictions** from SRP-only Models
- ✓ We Studied ESA's **Rosetta**, **Mars & Venus Express**, **Bepi Colombo**, NASA's **Messenger**, & JAXA's **IKAROS** (Solar Sail)

Observed in-Orbit Anomalies

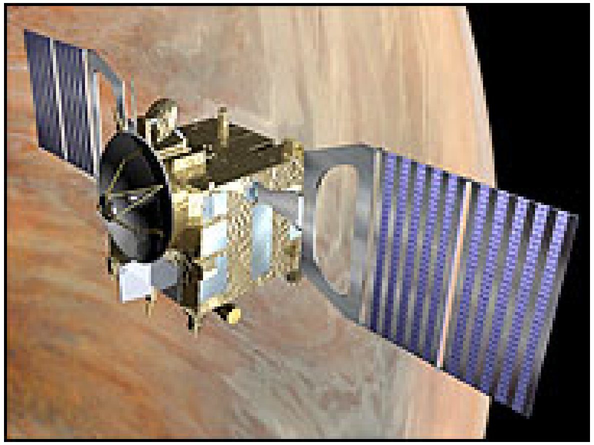
ESA / ESOC has Observed Significant Anomalous Accelerations during ***Deep-Space Cruise Phases***:

- Rosetta: between **5 - 10 % higher**
- Mars Express & Venus Express: between **10 - 30 % higher**

These Anomalies were 'Mis-Modeled' by Introducing Scale Factors for the Baseline SRP Model

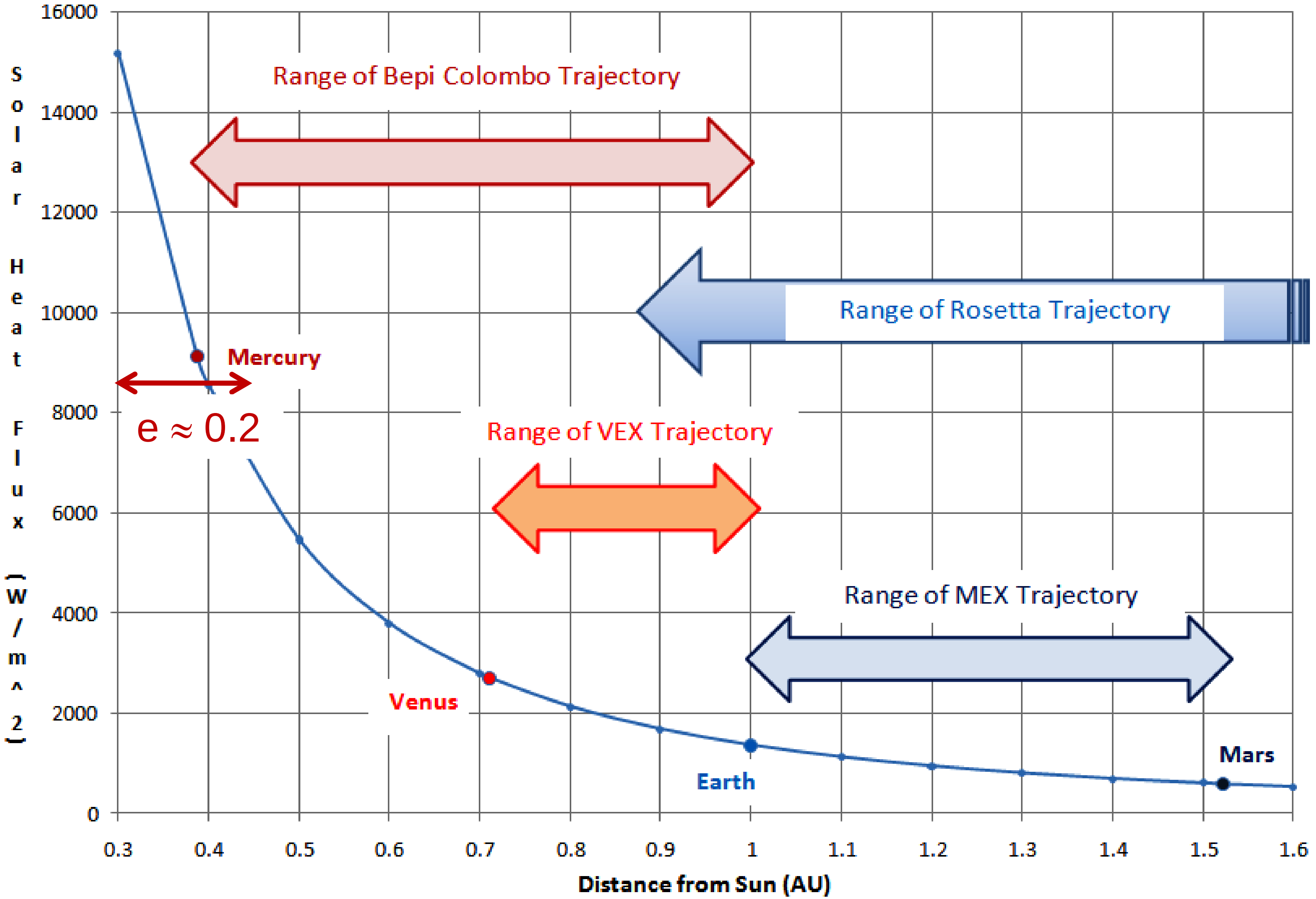
Rosetta: 0.9 – 5.4 AU

MEX: 1.0 – 1.5 AU

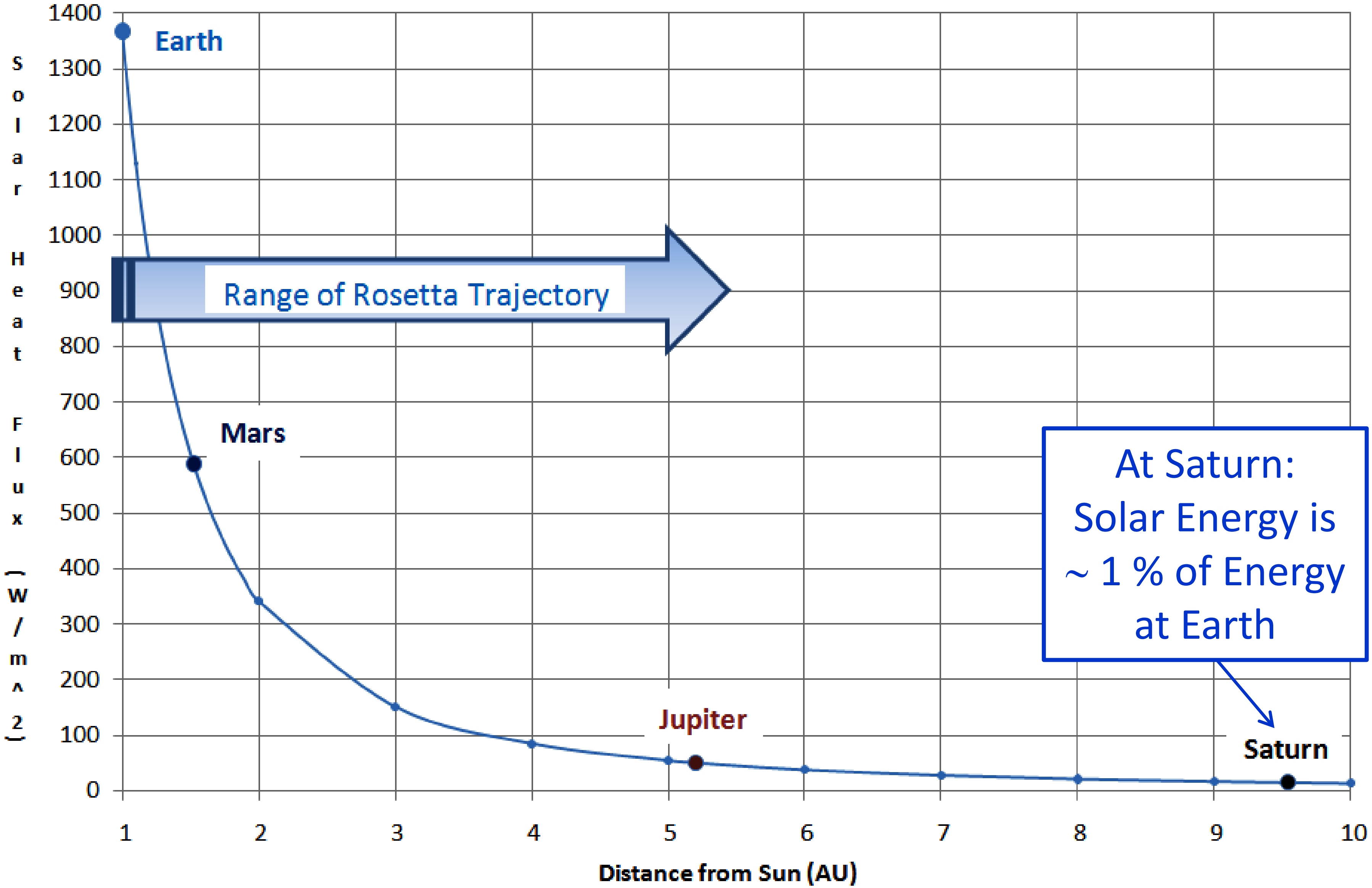


VEX: 0.7 – 1.0 AU

Variation of Solar Radiation Energy - 1



Variation of Solar Radiation Energy - 2



Accelerations due to Solar Radiation Pressure - 1

Accelerations Induced by Solar Radiation Pressure (SRP)

✓ Solar Flux: Energy ΔE Incident on Area A over Time Δt :

$$q_{Sun} = \frac{\Delta E}{A \Delta t} \approx 1366 \; [\mathrm{W/m^2}] \quad \text{(at 1 AU)}$$

✓ Recoil Impulse Δp of Energy Incident on Area A ($\perp$ Radiation) :

$$\Delta p = \frac{\Delta E}{c} = \frac{q_{Sun}}{c} A \Delta t \quad [\mathrm{kg\,m/s}]$$

c: Velocity of light

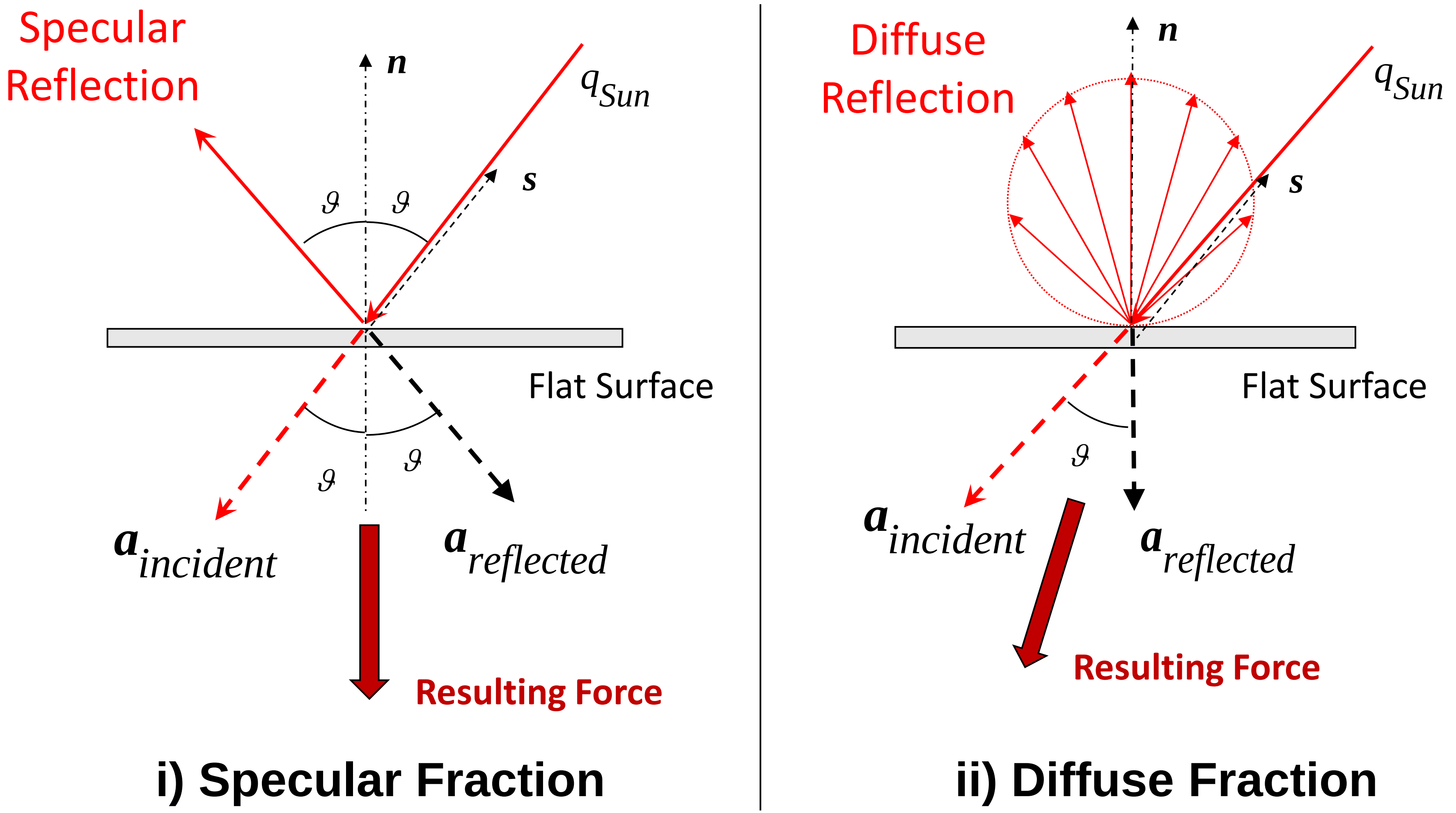
✓ **SRP Acceleration Coefficient** C_{SRP} is Defined by :

$$C_{SRP} = \frac{1}{m}\frac{\Delta p}{\Delta t} = \frac{q_{Sun}}{c}\frac{A}{m} \quad [\mathrm{m/s^2}]$$

m: Satellite mass

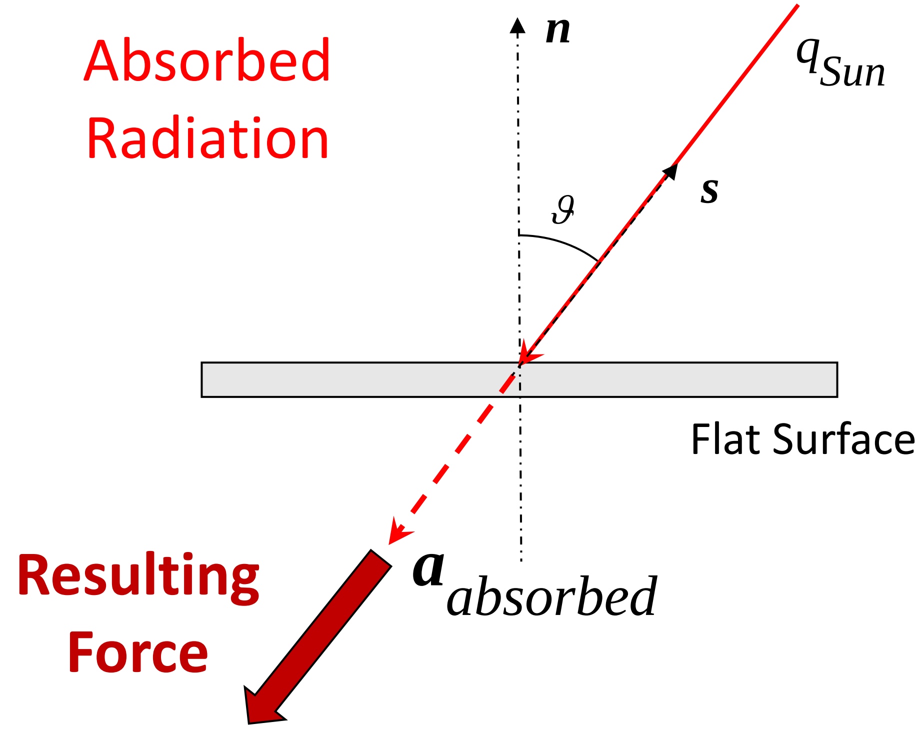
Accelerations due to Solar Radiation Pressure - 2

SRP Accelerations Depend on Surface Properties



Accelerations due to Solar Radiation Pressure - 3

SRP Accelerations Depend on **Surface Properties**

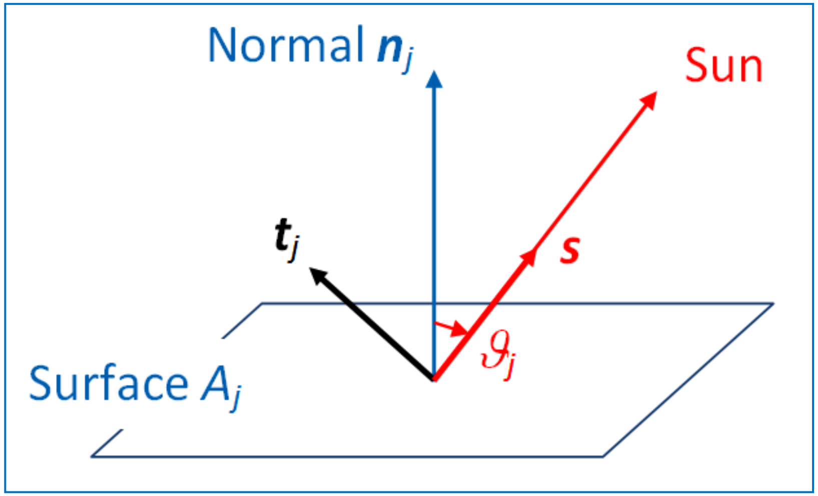


iii) Absorbed Fraction

Accelerations due to Solar Radiation Pressure - 4

SRP Acceleration Induced by Spacecraft Surface A_j:

$$\boldsymbol{a}_{SRP,j} = C_{SRP,j}\left\{ f_j\, \boldsymbol{s} + g_j\, \boldsymbol{n}_j \right\}$$



with:

$$\begin{pmatrix} f \\ g \end{pmatrix}_j = \cos\vartheta_j \begin{pmatrix} 1-\rho_s \\ 2\rho_d/3 + 2\rho_s\cos\vartheta \end{pmatrix}_j$$

and:

$$C_{SRP,j} = \frac{1}{d^2}\frac{S_o}{c}\frac{A_j}{m} = c_{SRP}A_j \quad with: \; c_{SRP} = \frac{1}{d^2}\frac{S_o}{mc}$$

Solar Constant: 1366.1 [W/m^2]

d: Solar Distance (AU)

c: Velocity of Light

m: Satellite Mass

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

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

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

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

Accelerations due to Thermal Heat Flux - 1

Heat Flux from 'Isotropic' Surface at Temperature T

Stefan - Boltzmann Law:

$$q_{Ther} = \varepsilon \sigma T^4 \; [\mathrm{W/m^2}]$$

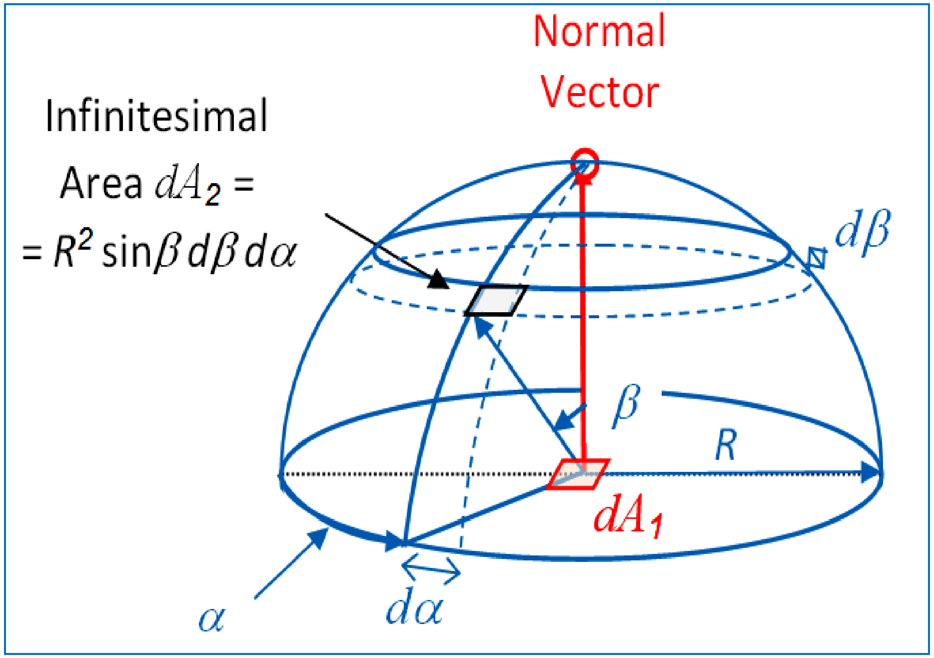
q_{Ther}: *Emitted Heat Flux*

ε: *Emissivity of Surface*

σ: *Stefan-Bolzmann Constant,*

$5.67 \times 10^{-8} \; [\mathrm{W/(m^2 K^4)}]$

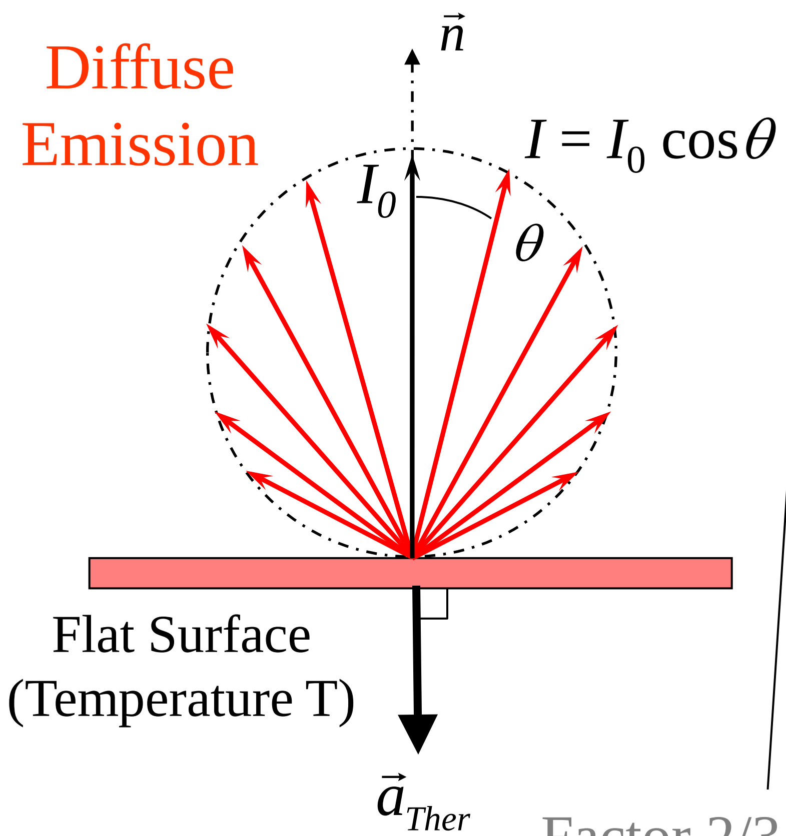
T: *Temperature of Surface*



Thermal Flux from 'Isotropic' Surface dA_1 through Hemisphere

Accelerations due to Thermal Heat Flux - 2

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

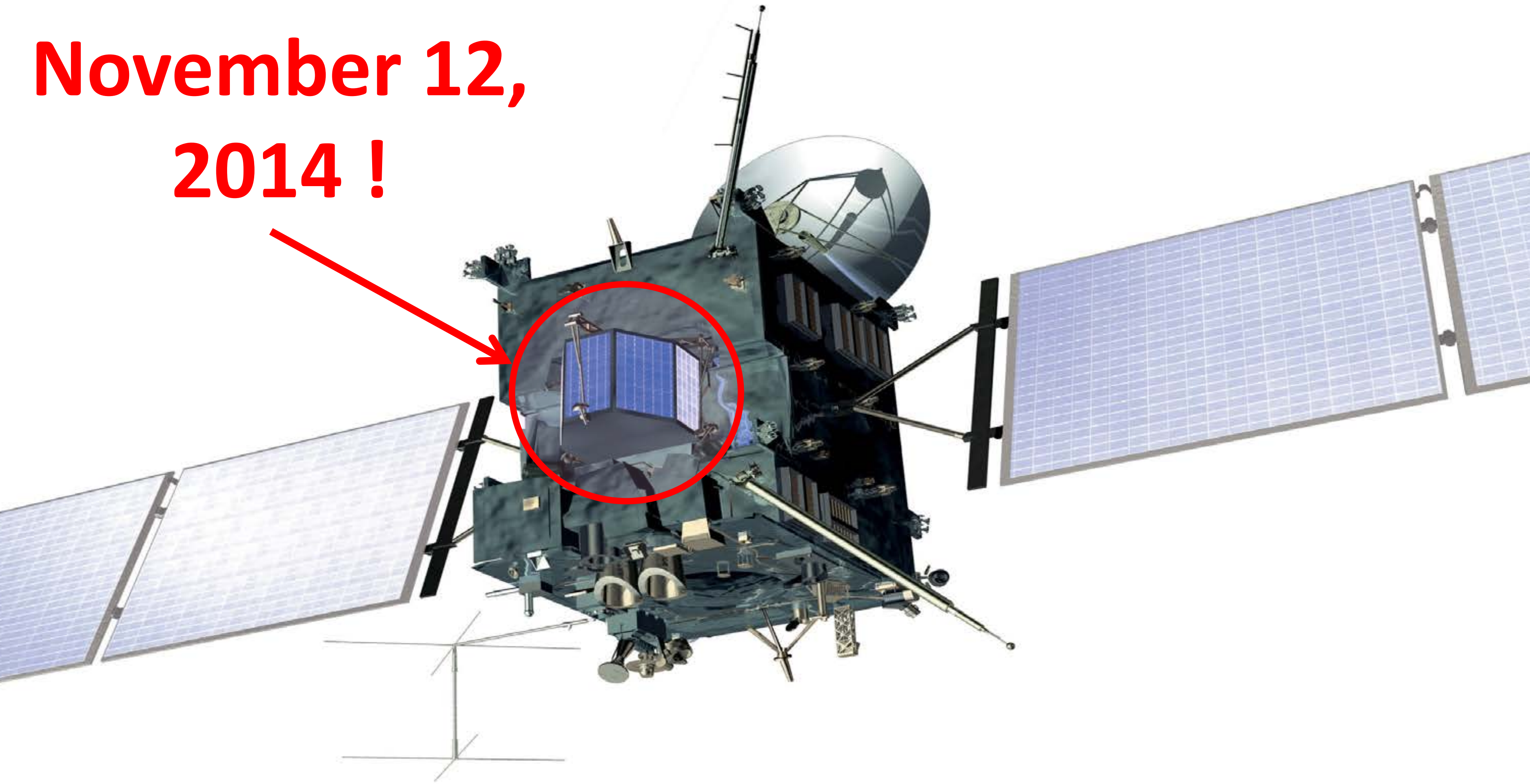
A: Area

m: Satellite Mass

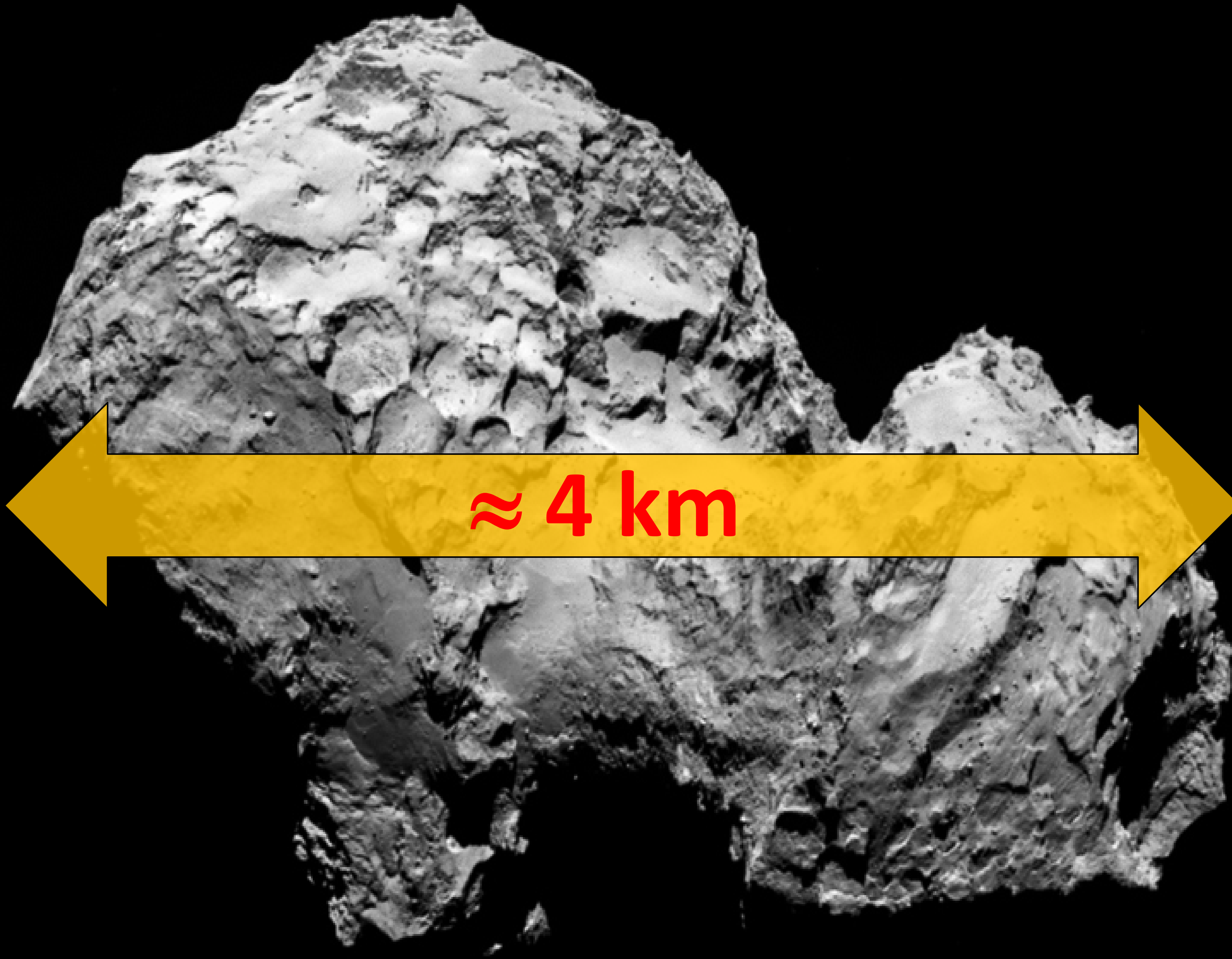
c: Speed of Light

Rosetta and its Landing Craft Philae

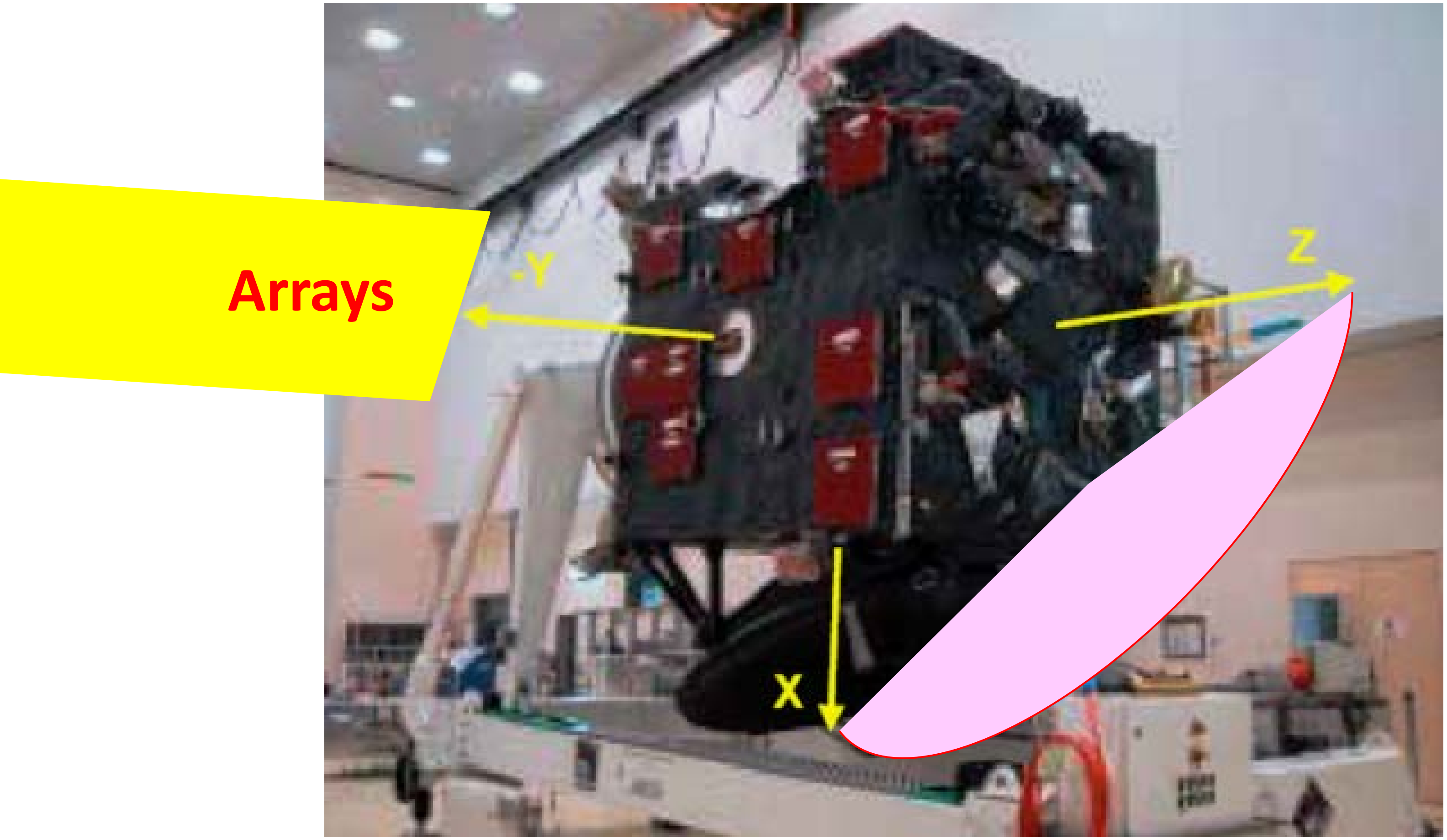
Released on November 12, 2014 !



ROSETTA NEEDS VERY PRECISE NAVIGATION !

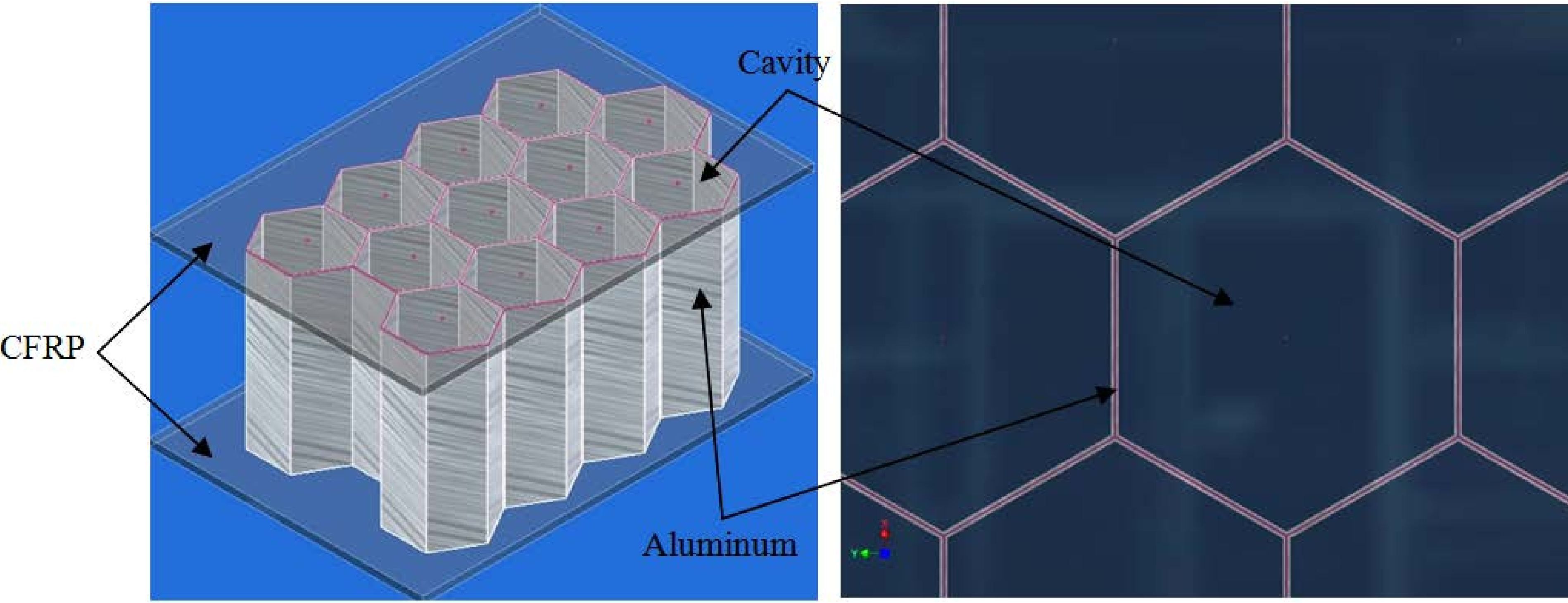


Rosetta Geometry & Reference Frame



- Sun Vector is Always **Kept within +X, +Z Quadrant** of X, Z Plane
- Solar Arrays are Mounted on ±Y Axes and are **Kept pointing to Sun**
- The -X, -Z Sides are **Kept Shadowed**; ±Y Sides ‘Barely’ see the Sun

Aluminum - Honeycomb Structure of Arrays



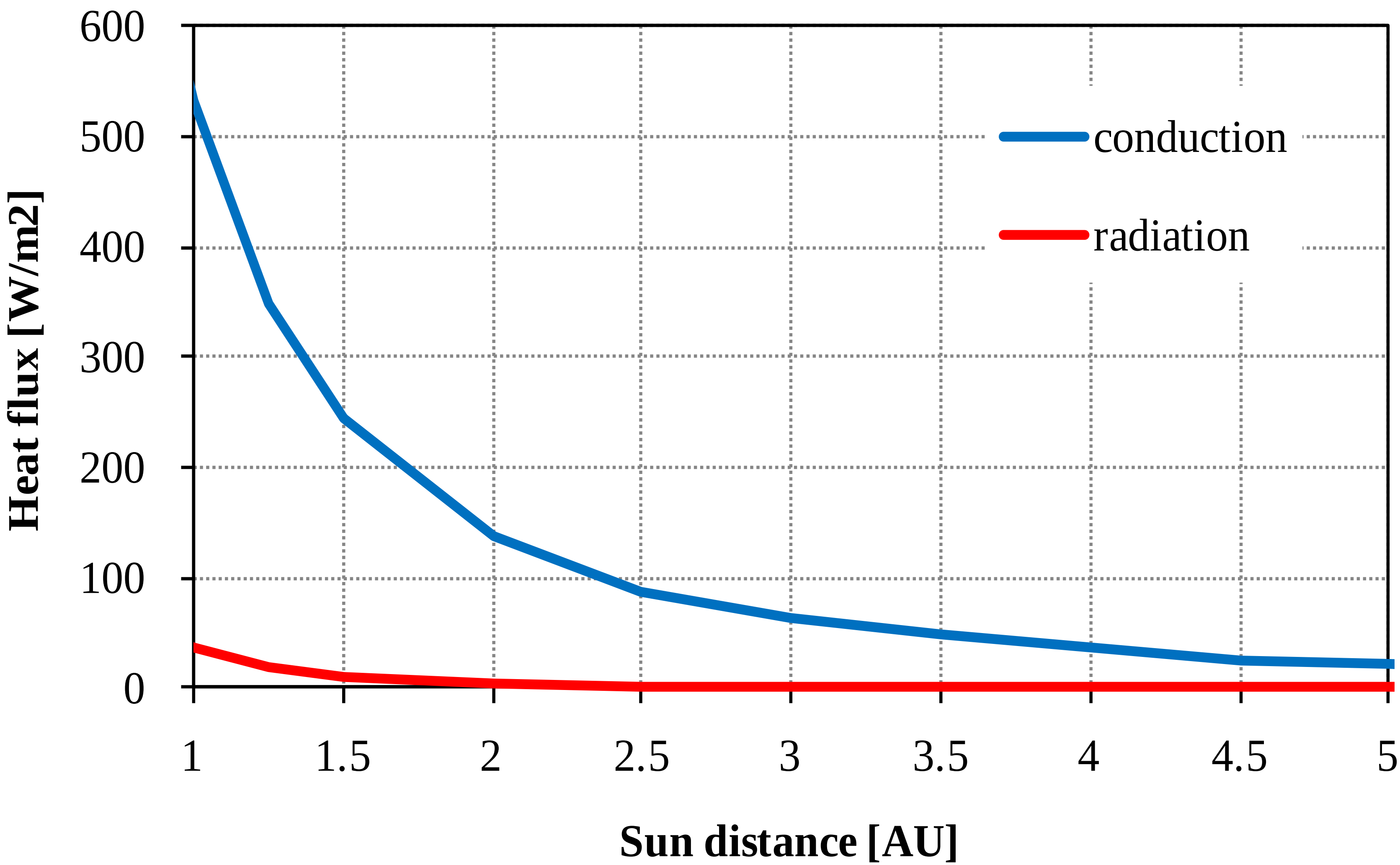
(a) See-through Image (b) Image from Above

Linear Heat Conductance (per m²) of Core: $G_L(T) = k(T)\{0.95 A_{Al} / h\}$

Radiative Heat Transfer through Core: $G_R = \sigma \varepsilon_i (1 - A_{Al}) / (2 - \varepsilon_i)$

$(A_{Al} = \rho_{hon} / \rho_{Al} \approx 0.00578)$

Conducted & Radiated Heat Transfer thru Arrays

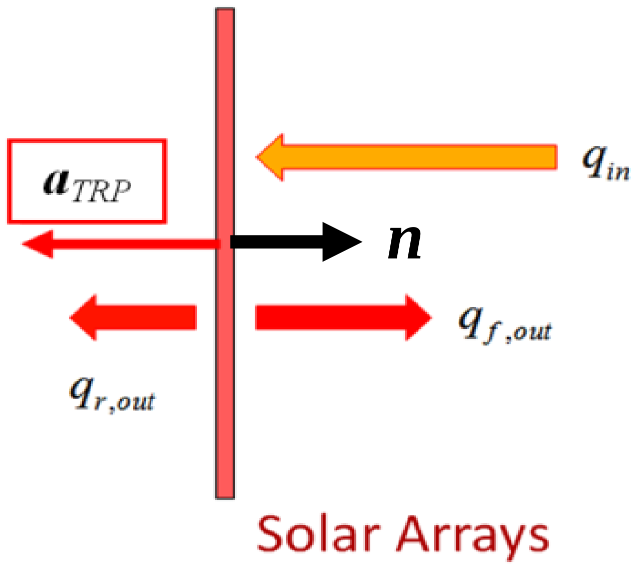


Conducted Heat through Core of Arrays Dominates **Radiated** Heat!

Thermal-Optical Parameters - Rosetta Arrays

Parameter	Notation	Surface Type	Value
Front Surface (Solar Cells)			
Cell conversion efficiency	η_{cell}	-	0 (up to ~ 0.15)
Absorptivity of cells (for $\eta_{cell} = 0$)	α_{cell}	specular (glass)	0.84
Absorptivity of gaps between cells	α_{gap}	diffuse	0.9
Emissivity of cells (IR, hemisphere)	ε_{cell}	diffuse	0.78 (normal: 0.825)
Emissivity of gaps between cells	ε_{gap}	diffuse	0.85
Cell packing factor	f_p	-	0.958
Core of Solar Array (Aluminum-Honeycomb)			
Thickness [mm]	h	-	22
Honeycomb core density [kg/m³]	ρ_h	isolating	16
Aluminum (Al) density [kg/m³]	ρ_{Al}	} conducting	2770
Aluminum (Al) conductivity [W/mK]	$k(T)$		109 + 0.245 (T-273.15)
Emissivity of inner surfaces of arrays	ε_i	diffuse (T)	0.6
Rear Surface (CFRP)			
Emissivity of rear surfaces	$\varepsilon_r(T)$	CFRP	0.312 + 0.003288 T - 0.00000533 T^2

TRP Accelerations on Rosetta Solar Arrays



- ✓ Heat Balance Condition in [W/m^2]:

$$q_{in} = q_{f,out} + q_{r,out} \quad \Rightarrow$$

$$\alpha_f \frac{S_{\odot}}{d^2} \cos\vartheta = \sigma \left\{ \varepsilon_f T_f^4 + \varepsilon_r T_r^4 \right\}$$

- ✓ TRP-Induced Acceleration in [m/s^2]:

$$\boldsymbol{a}_{TRP,SA} = -\frac{2}{3}\frac{A_{SA}}{mc}\left(q_{f,out} - q_{r,out}\right)\boldsymbol{n} = -\frac{2}{3}\frac{A_{SA}}{m}\frac{\sigma}{c}\left(\varepsilon_f T_f^4 - \varepsilon_r T_r^4\right)\boldsymbol{n}$$

or:

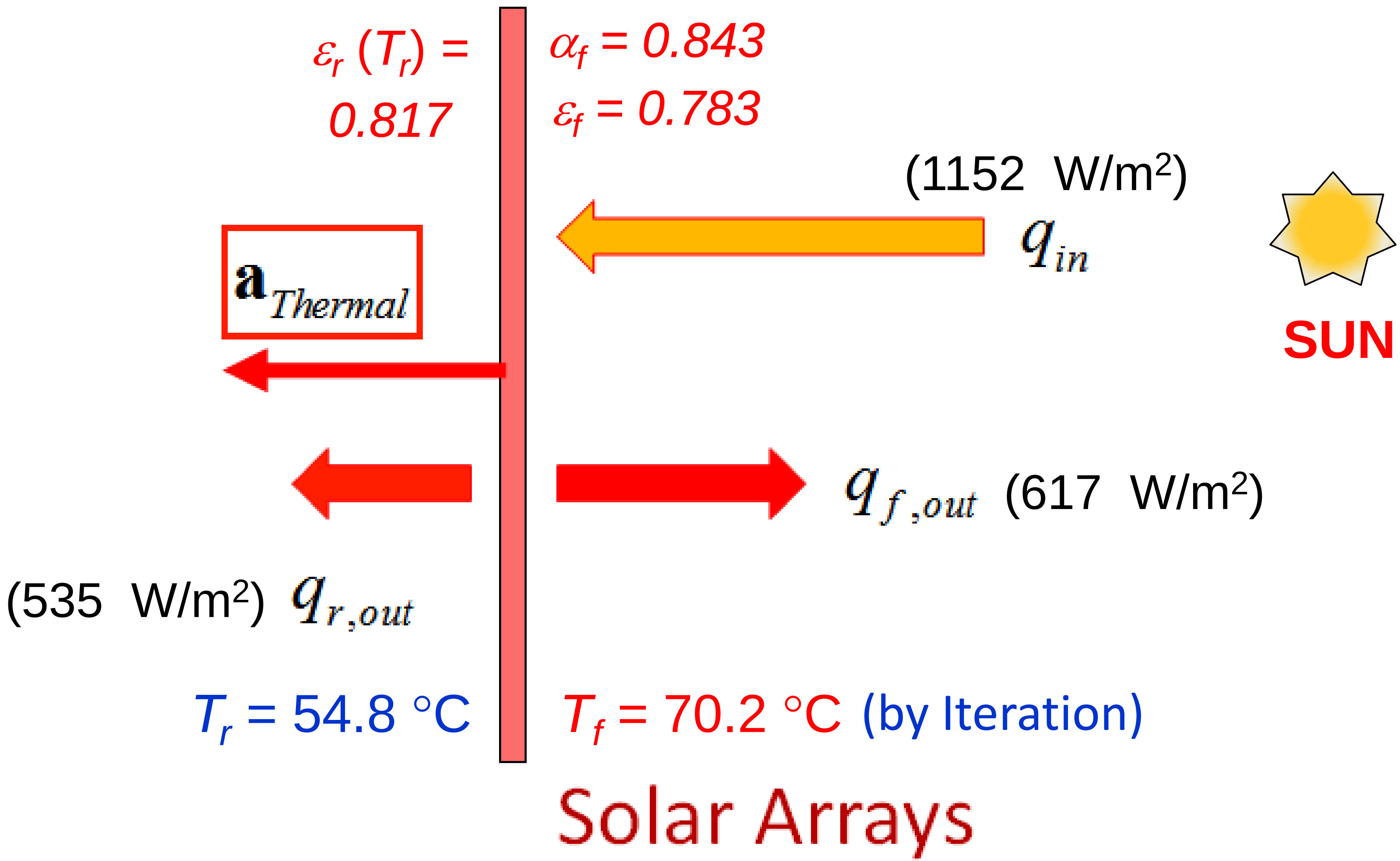
$$\boldsymbol{a}_{TRP,SA} = -\frac{2}{3} C_{SRP}\left(\kappa\,\alpha_f A\cos\vartheta\right)_{SA}\boldsymbol{n}$$

with:

$$\kappa = \left(\frac{\varepsilon_f T_f^4 - \varepsilon_r T_r^4}{\varepsilon_f T_f^4 + \varepsilon_r T_r^4} \right)$$

Results for Rosetta’s Solar Arrays

Steady - State Values at 1 AU from Sun



Rosetta Thermal Heat Balance Calculation

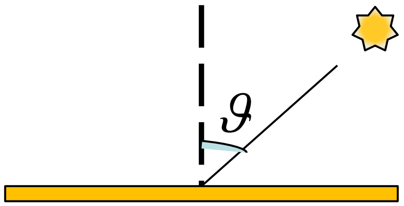
- ✓ Heat Flux Emitted by a Satellite MLI Surface at Temperature *T*:

$$q_{out} = \varepsilon \sigma T^4$$

with:

ε	is the emissivity of the satellite surface.
T	is the temperature [K]

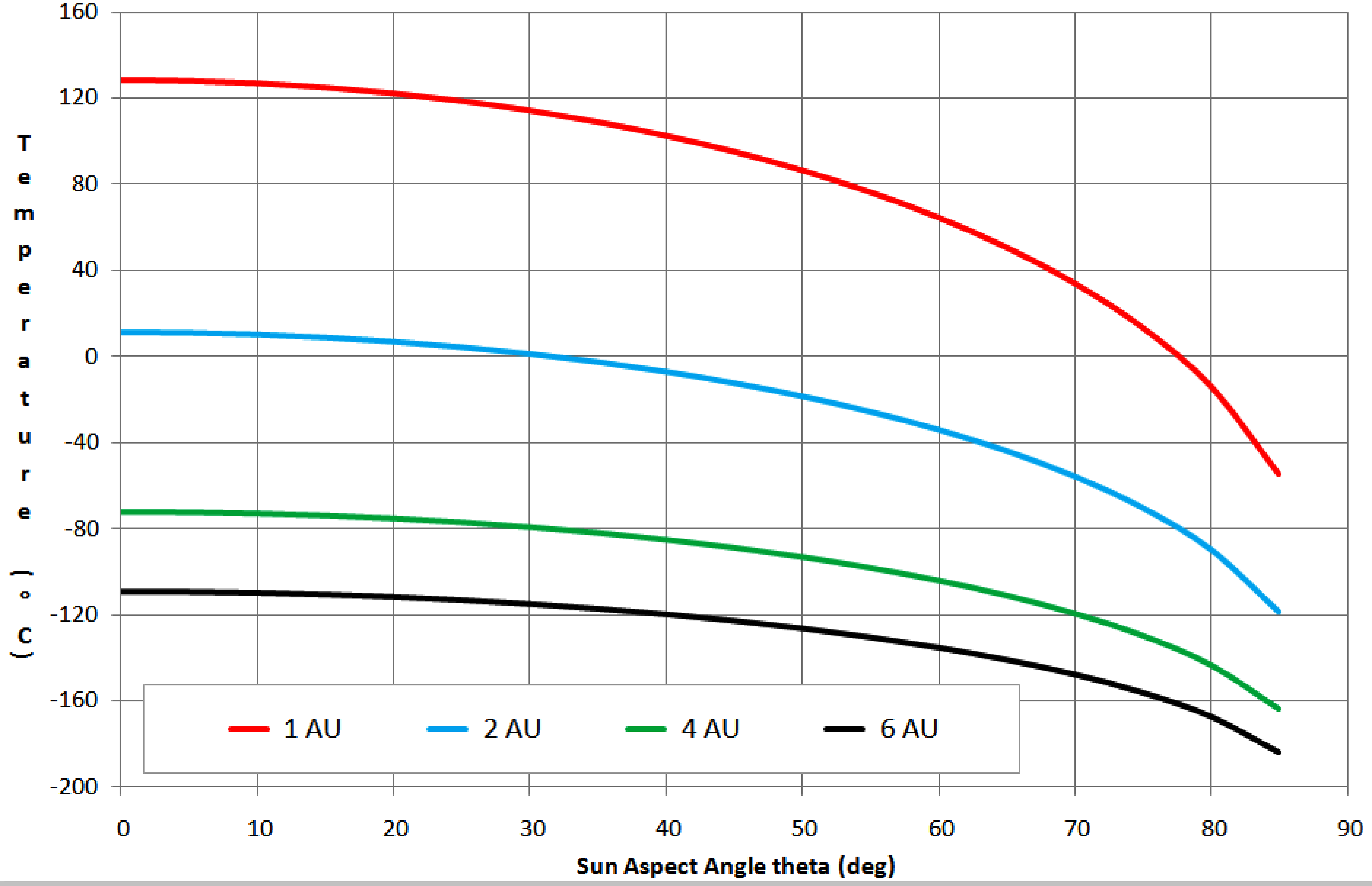
- ✓ It is Realistic to Assume that MLI is **Close-to-Perfect Insulator**
- ✓ Satellite Surface **Temperatures** Follow from **Heat Balance**:



$$q_{out} \approx q_{in} \quad \Rightarrow \quad T \approx \left\{ \left(\frac{\alpha}{\varepsilon \sigma} \right) \frac{q_{Sun}}{d^2} \cos \vartheta \right\}^{1/4}$$

- ✓ The Model Looses Validity for $\theta \rightarrow 90°$

MLI Temperature versus Sun Incidence Angle



Energy Balance for Body Surfaces - 1

- ✓ Now We Present a Model for Heat Exchanges through the MLI Blankets (from Warm Satellite Interior to Cold Space)
- ✓ Rosetta MLI's *"Effective Conductance Coefficient"* is Known:

$$c_{MLI} = \frac{q_{MLI}}{T_i - T_o} \approx 0.026 \quad [\mathrm{W/m^2/°K}]$$

- ✓ Heat Balance Conditions in [W/m^2] for +X and -X Surfaces:

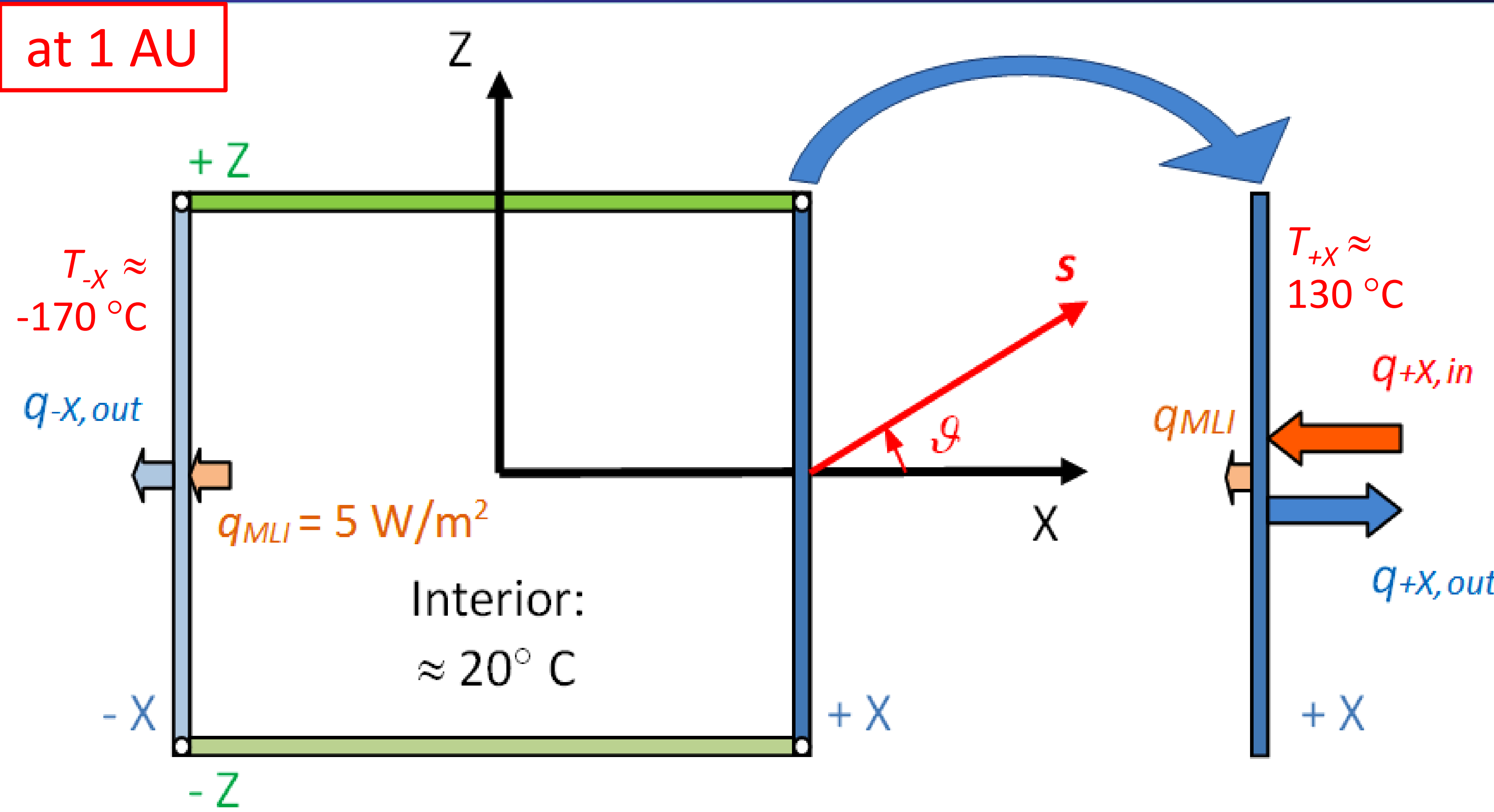
$$q_{+X,in} = \alpha_{MLI} \frac{S}{d^2} \cos\vartheta$$

$$q_{+X,out} = \sigma\, \varepsilon_{MLI} T_{+X}^4 \approx q_{+X,in}$$

$$q_{-X,out} = \sigma\, \varepsilon_{MLI} T_{-X}^4 \approx 5$$

$\Rightarrow$ Temperatures T_{+X} and T_{-X}

Energy Balance for Body Surfaces - 2



Energy Balance for **Satellite Body** is VERY Different from SA's !

TRP Accelerations on Body Surfaces

- ✓ Accelerations for Body Surfaces in 2 Directions X and Z :

$$\boldsymbol{a}_{TRP,X} = -\frac{2}{3}\frac{A_X}{mc}\left(q_{+X,out} - q_{-X,out}\right)\boldsymbol{n}_X =$$

$$= -\frac{2}{3}\frac{A_X}{mc}\sigma\,\varepsilon_{MLI}\left(T_{+X}^4 - T_{-X}^4\right)\boldsymbol{n}_X$$

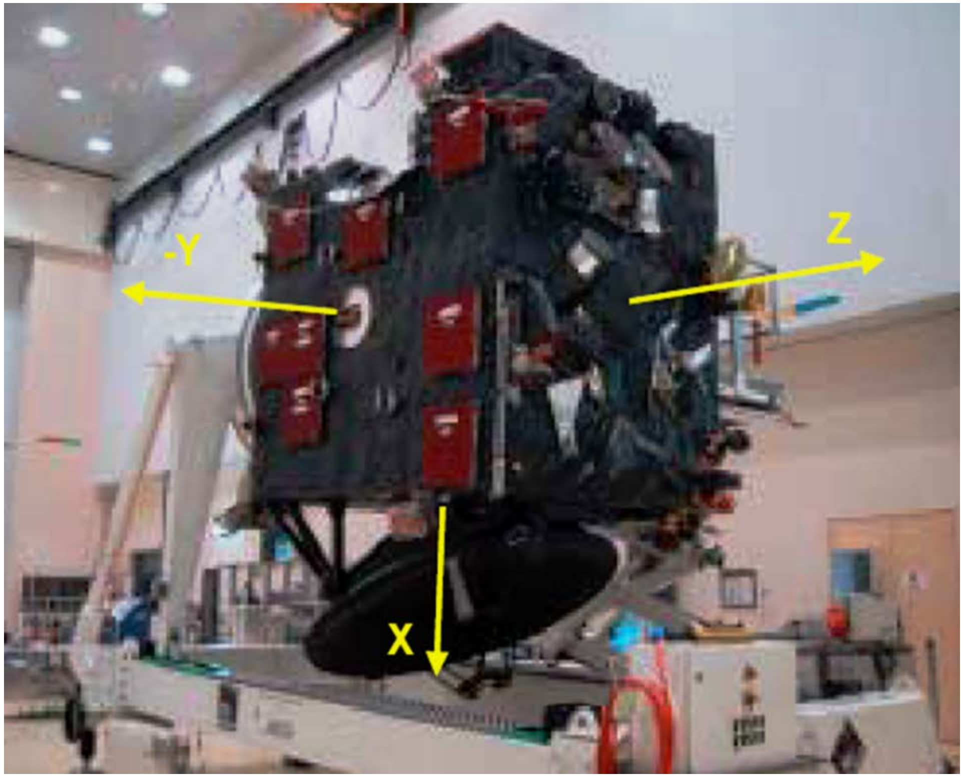
$$\Rightarrow \quad \boldsymbol{a}_{TRP,X} = -\frac{2}{3}c_{SRP}\left(\kappa\,\alpha_{MLI}\,A\right)_X \cos\vartheta\,\boldsymbol{n}_X$$

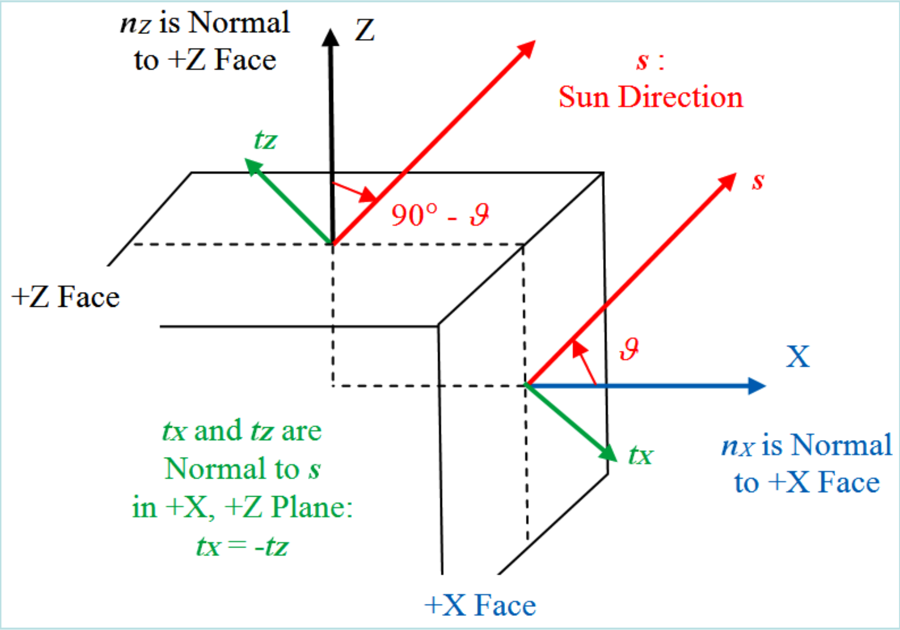
with:

$$\kappa_X = 1 - \left(\frac{T_{-X}}{T_{+X}}\right)^4$$

For Rosetta: $T_{-X} \approx 100$ °K; $T_{+X} \approx 200$ to 500 °K $\Rightarrow$ $\kappa \geq 0.96$

TRP Accelerations on Satellite Body





✓ TRP Acceleration on Satellite Body (for Sun in X,Z Plane):

$$\boldsymbol{a}_{TRP} = -\frac{2}{3} c_{SRP} \left\{ (\kappa \alpha A)_X \cos\vartheta \, \boldsymbol{n}_X + (\kappa \alpha A)_Z \sin\vartheta \, \boldsymbol{n}_Z \right\}$$

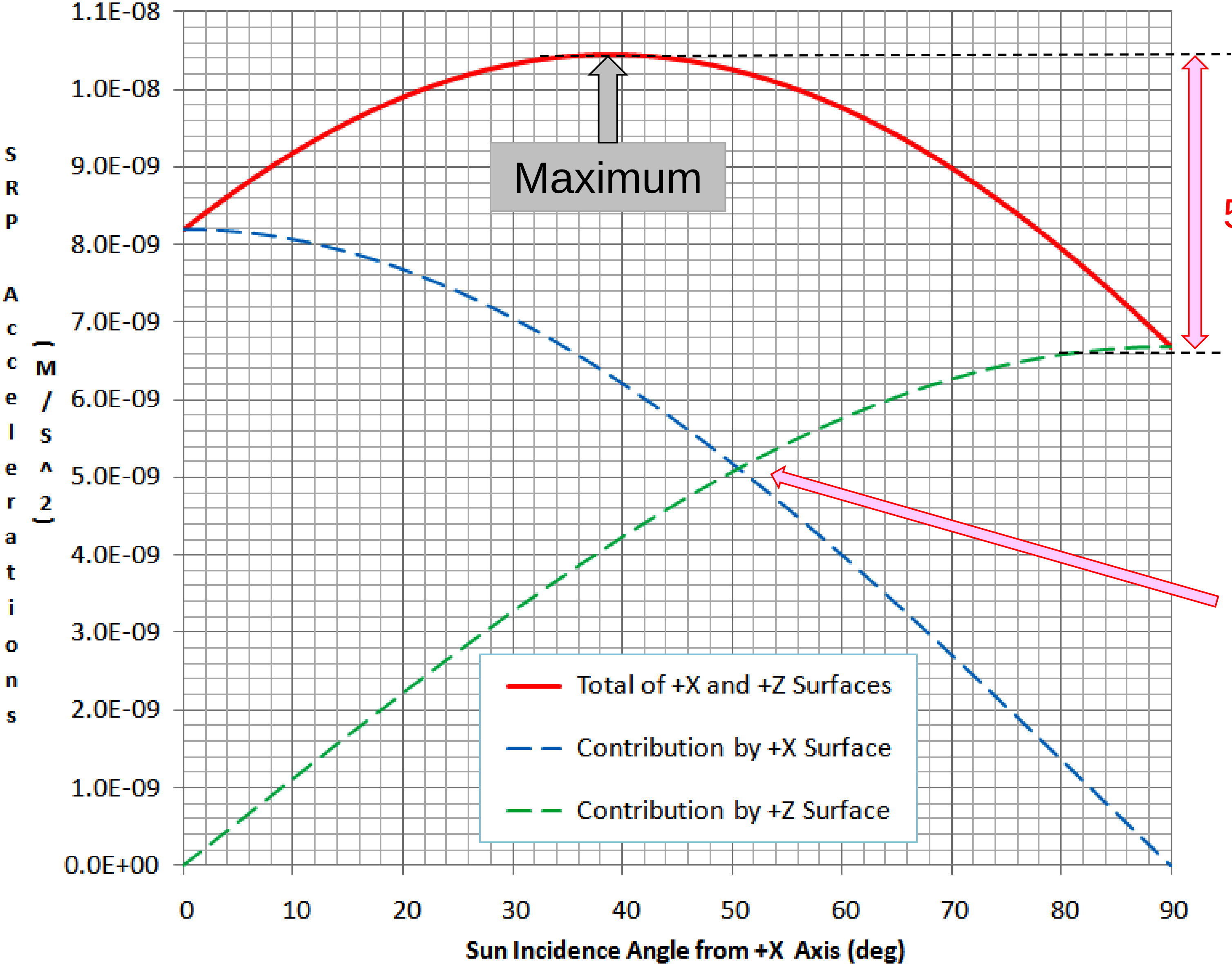
Summary of Thermal Accelerations on Satellite (1 AU)

Parameters	Front	Rear	Difference
Solar Arrays			
Emissivities	0.783	0.817	-
Temperatures (°C)	70.2	54.8	15.4
Acceleration (m/s^2)	-2.93×10^{-8}	2.54×10^{-8}	-3.89×10^{-9}
Body Surfaces (MLI)			
Emissivities	0.86	0.86	-
Temperatures (°C)	128.7	-172.5	301.2
Acceleration +/- X Faces (m/s^2)	-4.85×10^{-9}	1.95×10^{-11}	-4.83×10^{-9}
Acceleration +/- Z Faces (m/s^2)	-3.96×10^{-9}	1.59×10^{-11}	-3.94×10^{-9}
Average Acceleration (m/s^2)	-4.41×10^{-9}	1.77×10^{-11}	-4.39×10^{-9}

Note:

1. Thermal Acceleration Due to Body > that due to Solar Arrays !
2. Total Thermal Radiation is ~ 8.3×10^{-9} ≈ 7 % of Total SRP Effect

SRP Accelerations from +X and +Z Body Faces

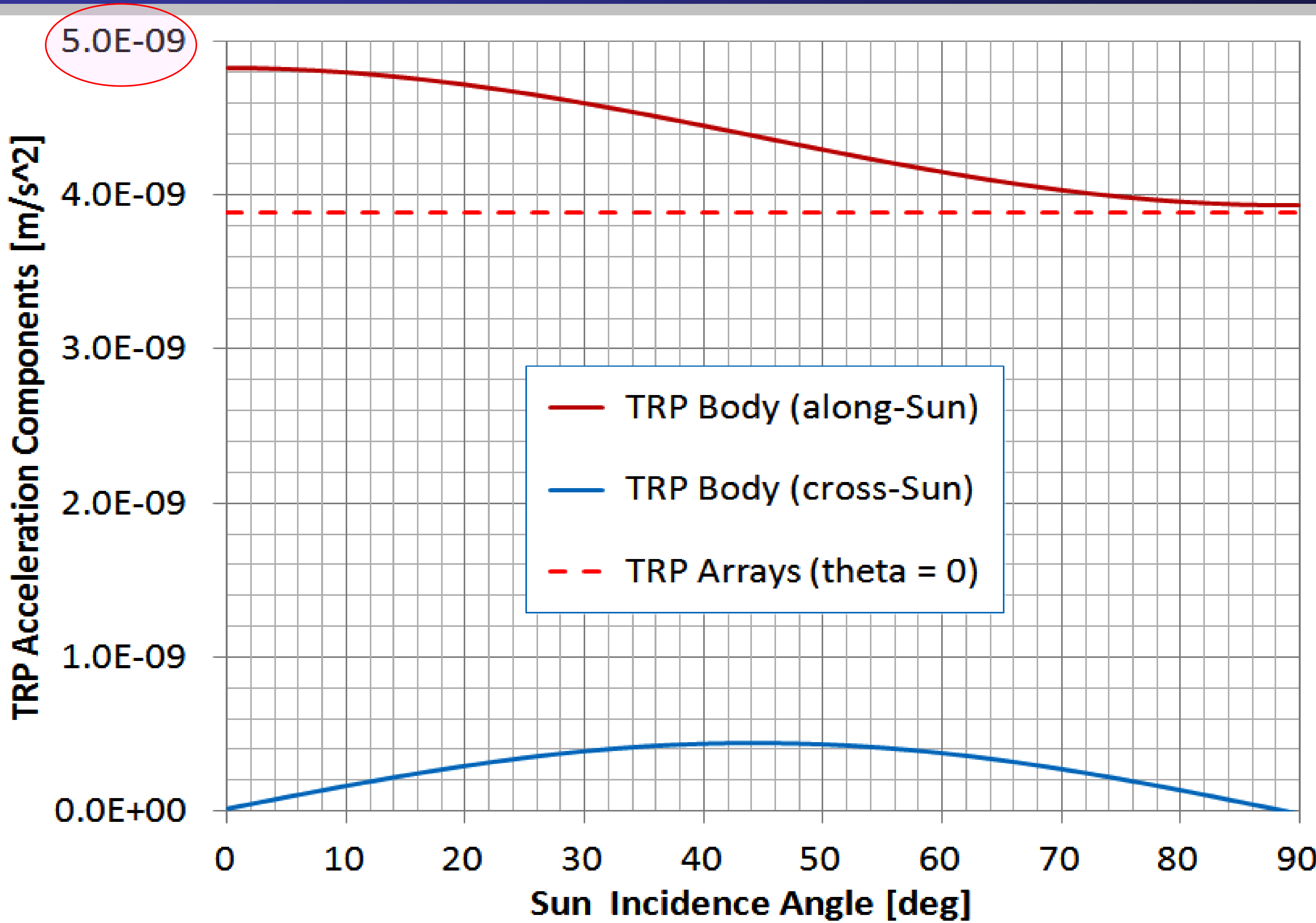


+X Area is 5.15 m^2 > +Z Area of 4.2 m^2

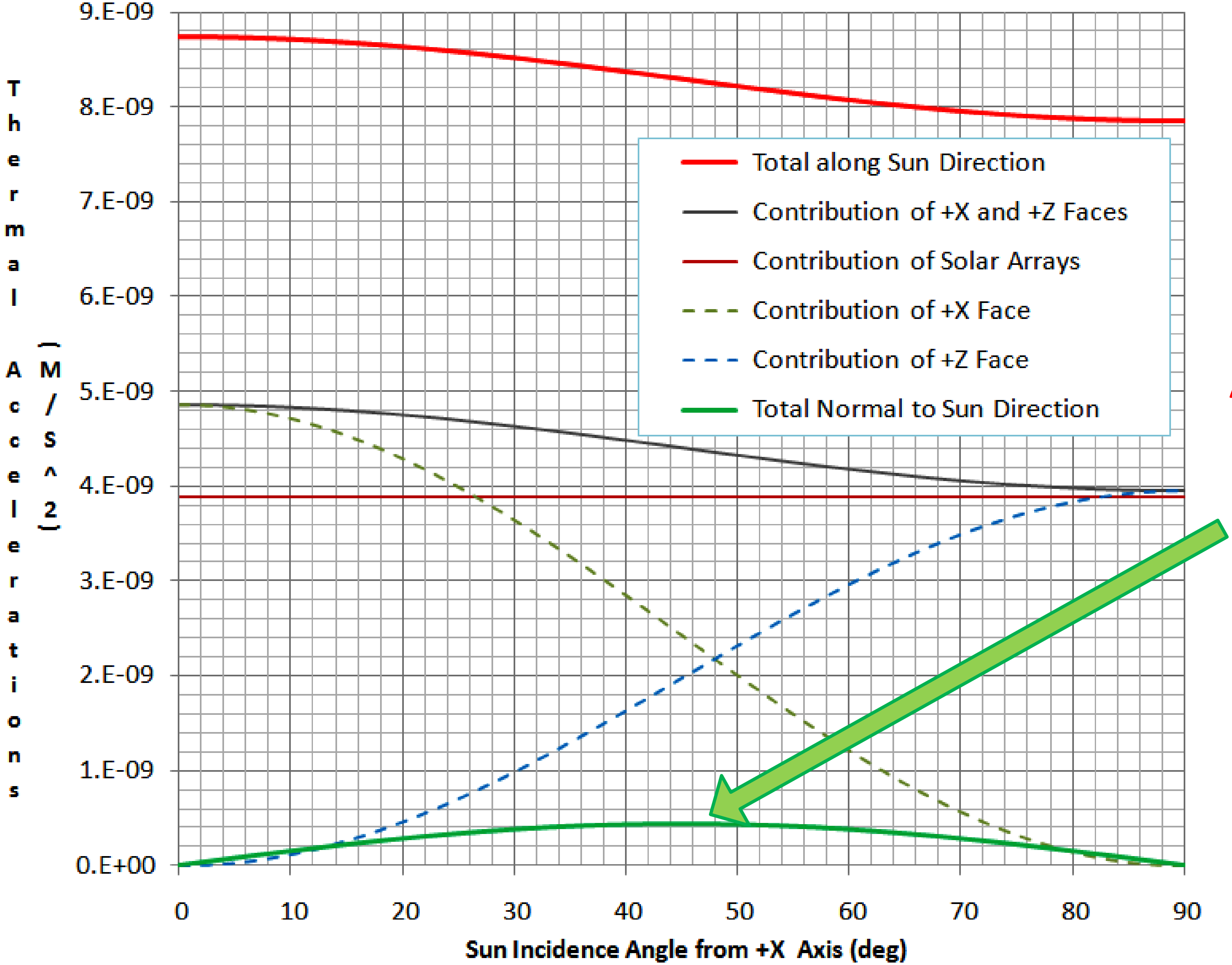
➔

Cross-Over at $\vartheta = 50.6°$

TRP Accelerations from +X and +Z Body Faces

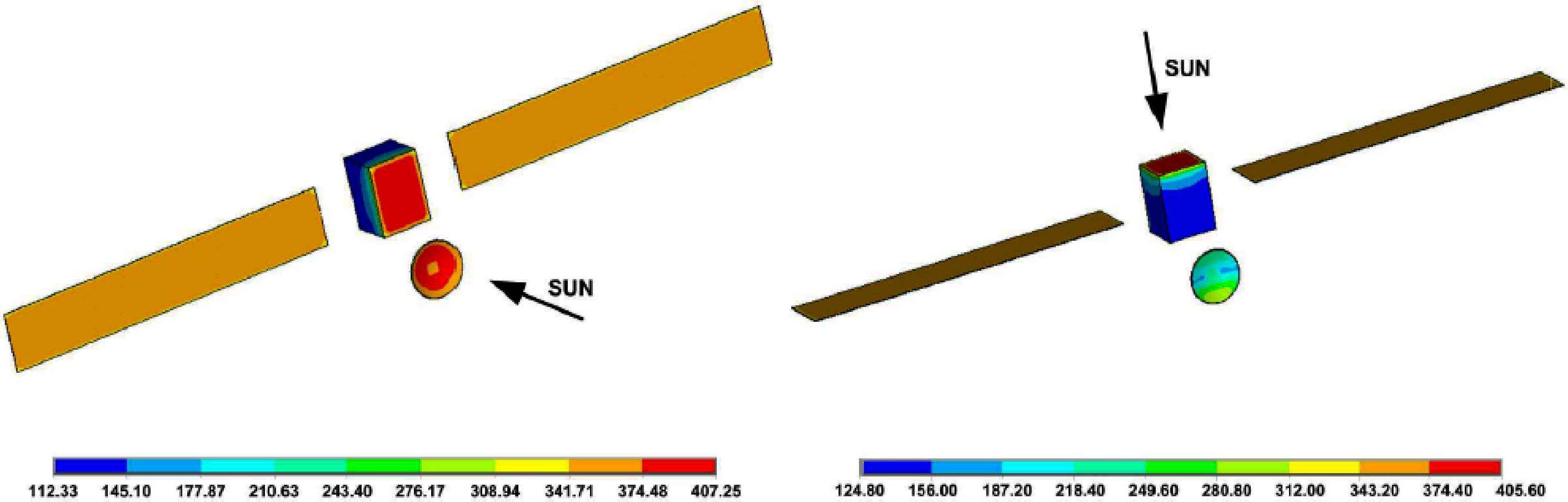


Summary of Thermal Accelerations Results (1 AU)



Thermal Effects Induce an Appreciable Acceleration in Direction Normal to Sun Direction: ~ 5.4 % of Total

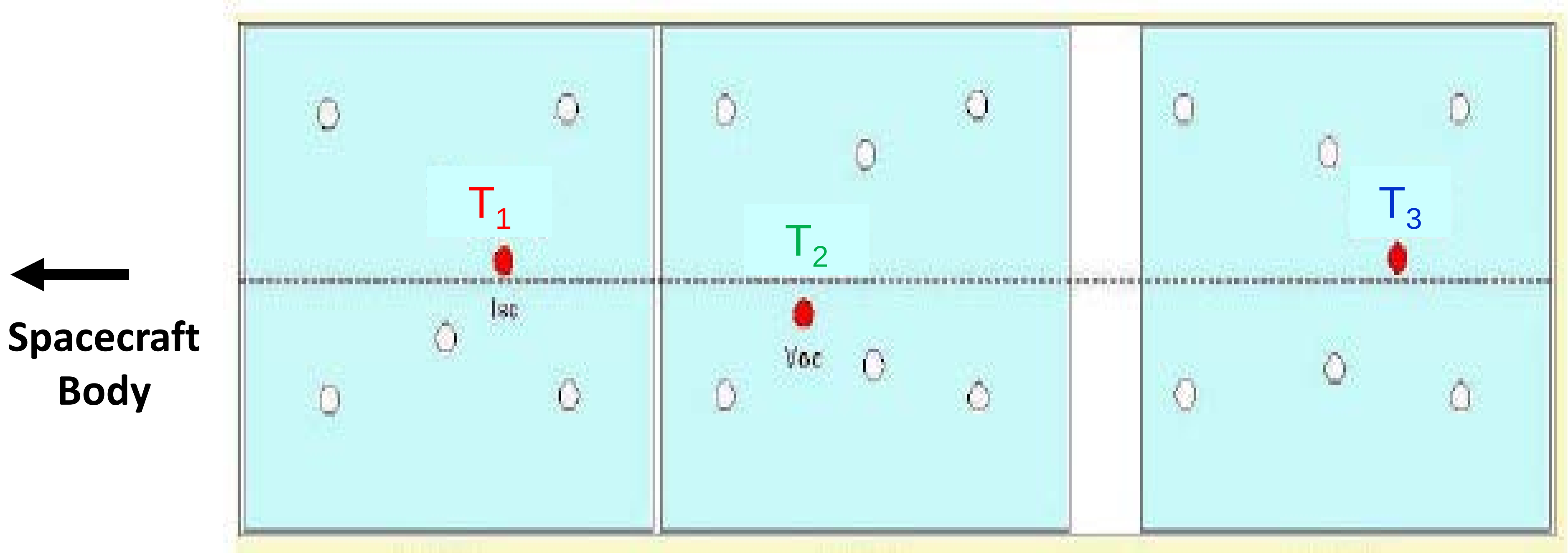
Numerical Results from Finite Element Method



Equilibrium Surface Temperatures of Rosetta's External Surfaces for $\vartheta = 0$ (left) and $\vartheta = 90^\circ$ (right)

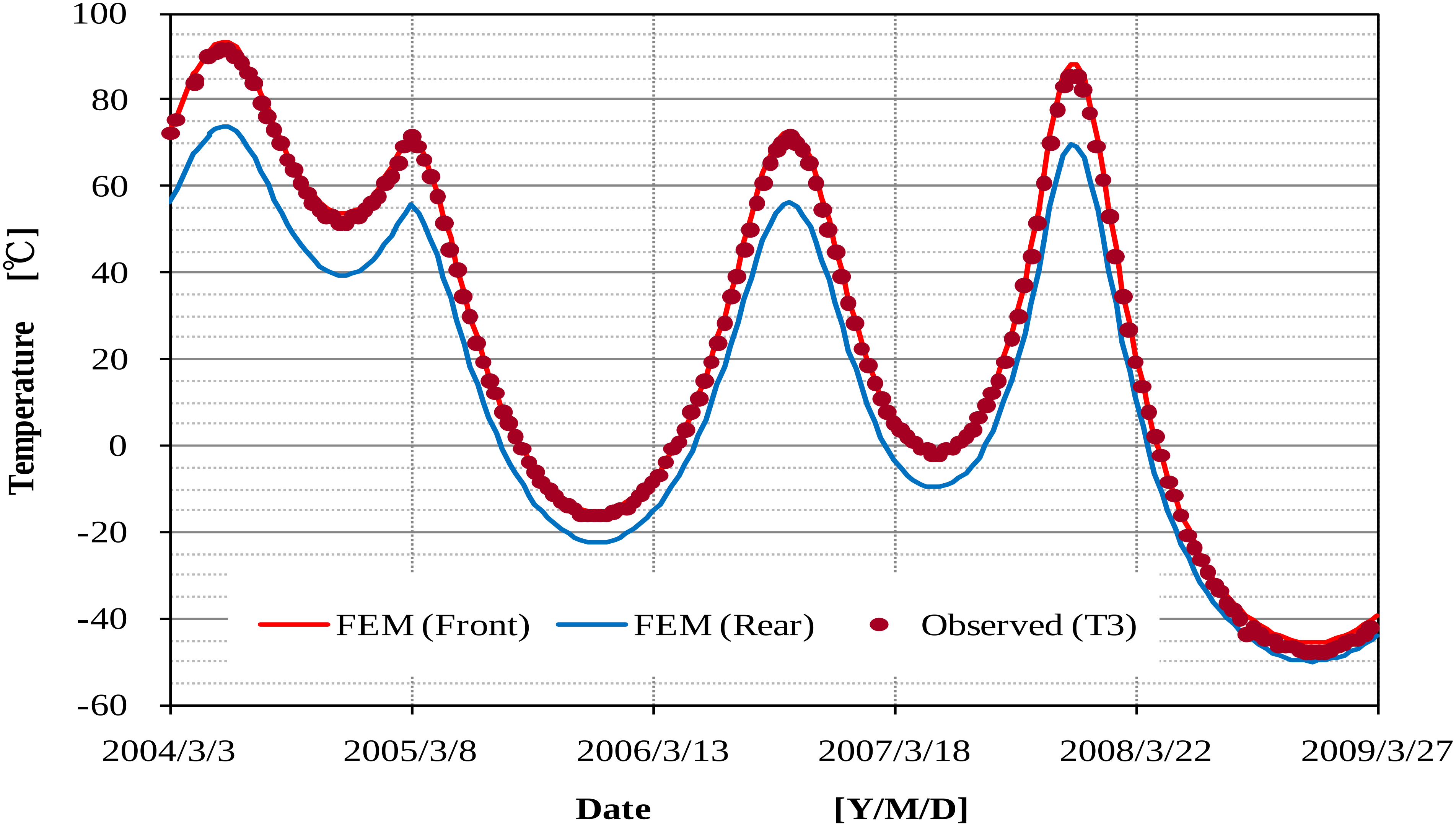
Analytical & Numerical Approaches are Compatible!

Locations of Thermistors on Rosetta Solar Arrays



- ✓ Rosetta has **3 Thermistors** on Each of its Solar Arrays
- ✓ They Measure Temperatures on **Rear of Solar Cells** Attached to the **Front** Surface Panel of the Solar Arrays
- ✓ The 3 Solar Cells, to which the Thermistors are Attached, are **Different** in Power Generation Properties

Temperature Comparisons for Rosetta (5 Years)



Observed Temperature = Average of both T3 Thermistors

Comparison of Predicted & Measured Temperatures

Mission Phase	Absolute Temperature Differences [°C]	
	Average	Maximum
Cruise 1	1.4	2.2
Cruise 2	0.7	2.5
Cruise 3	0.5	1.7
Cruise 4-1	0.8	1.8

This Looks Preddy Goodddd …

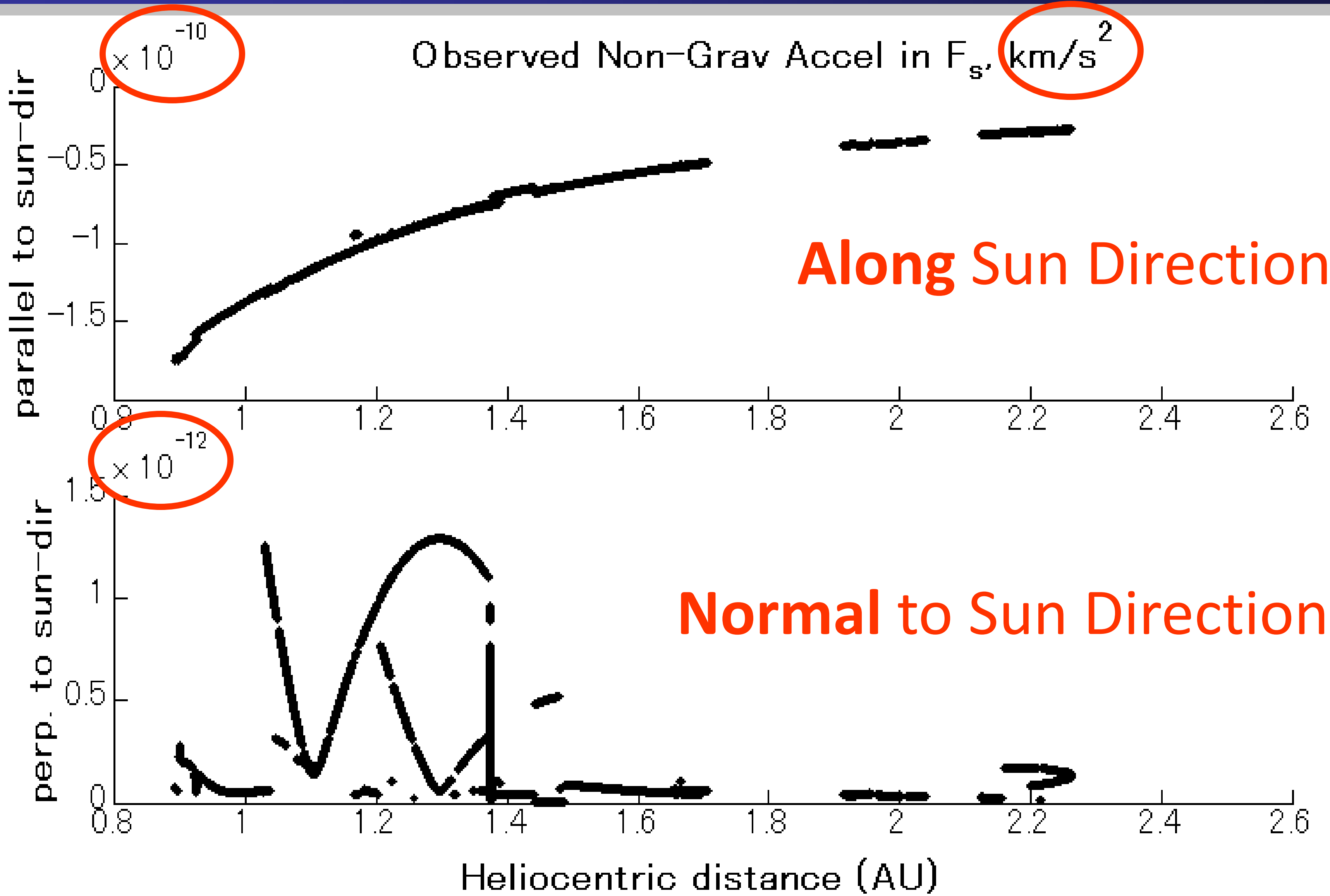
Summary of Analysis Concept

1. Extract Orbit and Attitude ASCII files from ESOC TASC Website
2. Collect **Maneuver** History, **SRP** Predictions, **Solar Array Pointing** Data
3. Identify Suitable **Cruise Phase Intervals** for Analysis (Timestep 300 s)
4. Convert Files to Binary and Interpolate Data (Using Fortran Routines)
5. Select Sub-intervals for Numerical Differentiation of Velocity Data
6. This Produces **Approximate Inertial Accelerations** of Satellite in SSB
7. Calculate **Positions of Planets** by Matlab Scripts and JPL SPICE Toolkit
8. S**ubtract Gravitational** Accelerations from Approximate Results in # 6
9. This Establishes **Non-Gravitational** Accelerations of Satellite in SSB
10. **Subtract** ESOC's Predicted **SRP Accelerations** from the Results in # 9
11. Remaining Accelerations are **Largely Caused by Thermal** Radiation
12. This Hypothesis is **Checked** by Means of Analytical Thermal Models
13. Results **Confirm** that Thermal Radiation Essentially Fill the Gap!

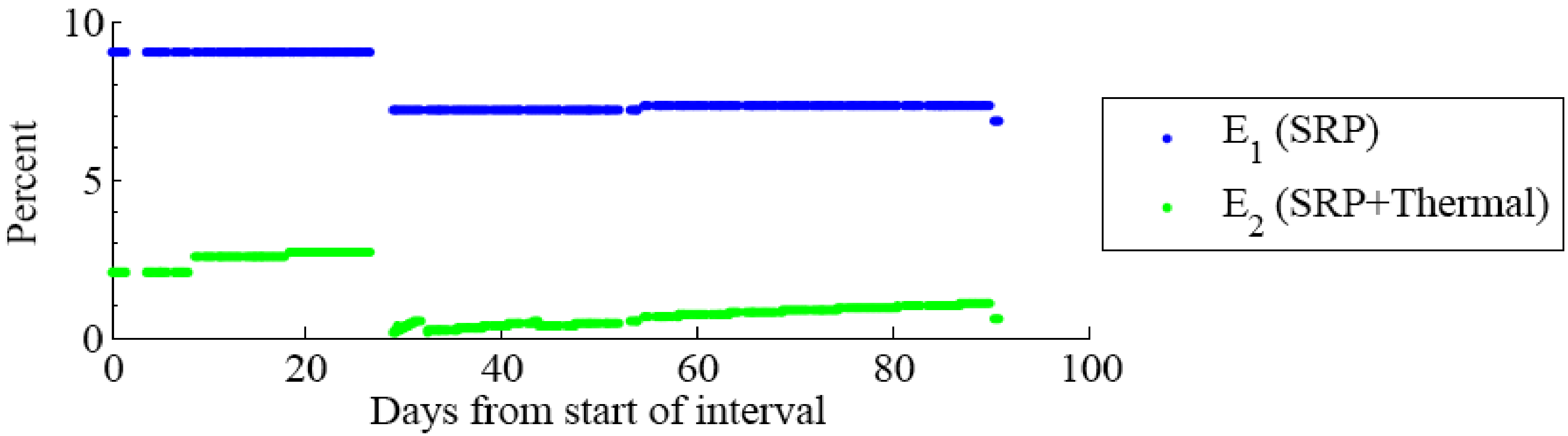
Gravitational Sources & Parameters Considered

Body or System	Gravitational Parameter (km^3/s^2)
Sun	132712440040.944000
Mercury	22032.080
Venus	324858.599
Earth	398600.436233
Moon	4902.800076
Mars Barycenter	42828.314
Jupiter Barycenter	126712767.863
Saturn Barycenter	37940626.063
Uranus Barycenter	5794559.128
Neptune Barycenter	6836534.064
Pluto Barycenter	983.055

Non - Gravitational Acceleration Components



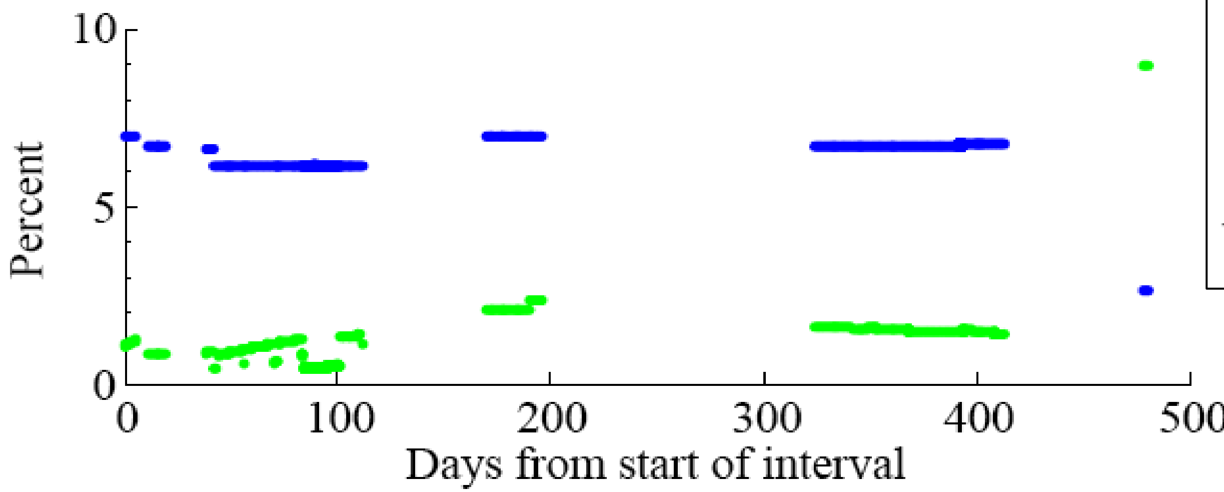
Errors in Rosetta Non-Gravitational Force Models



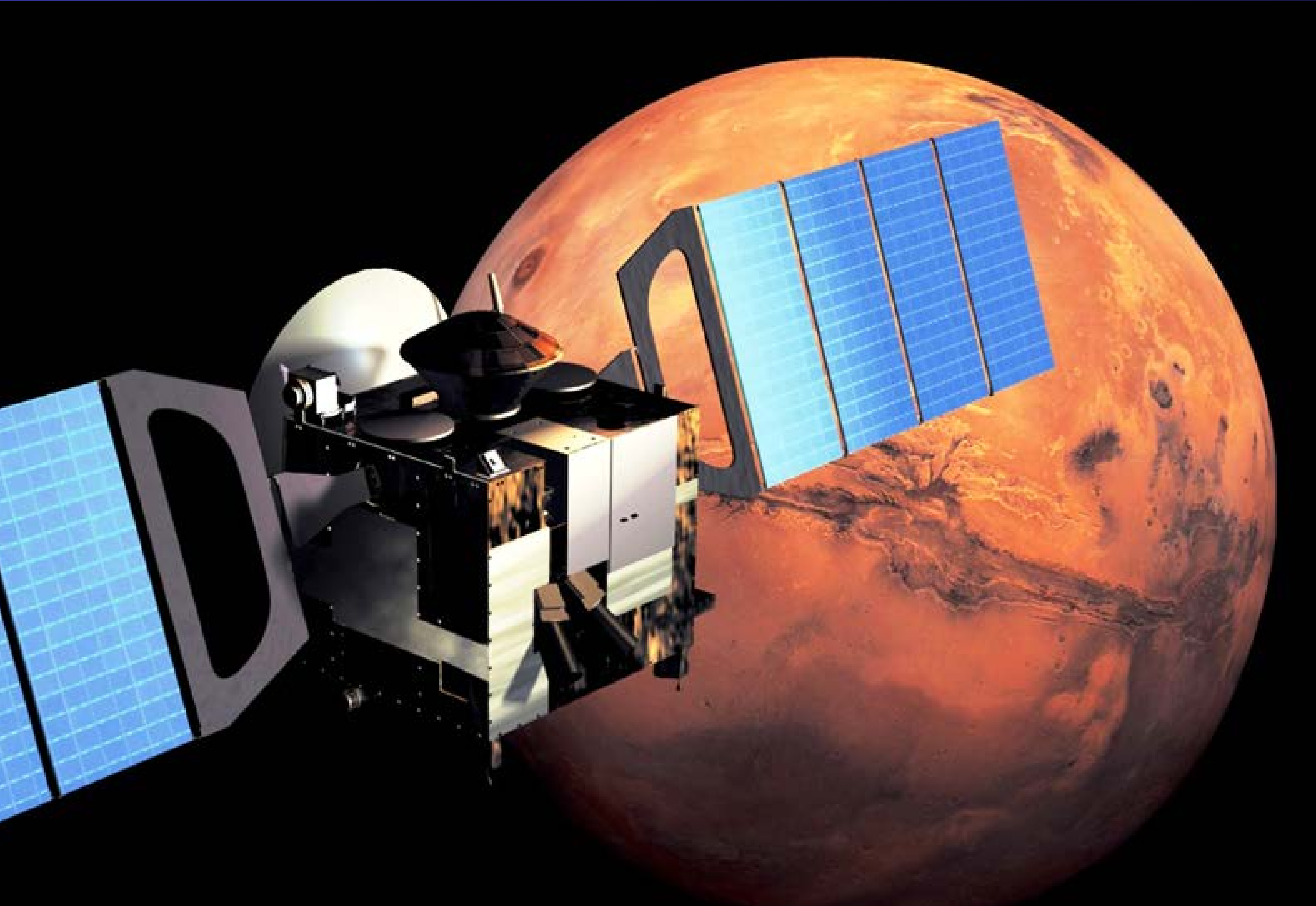
(a) Cruise 1

$$E_1 \equiv 100 \times \frac{|\mathbf{a}_{\text{obsNG}} - \mathbf{a}_{\text{srp}}|}{|\mathbf{a}_{\text{obsNG}}|}$$

$$E_2 \equiv 100 \times \frac{|\mathbf{a}_{\text{obsNG}} - \mathbf{a}_{\text{srp}} - \mathbf{a}_{\text{ther}}|}{|\mathbf{a}_{\text{obsNG}}|}$$

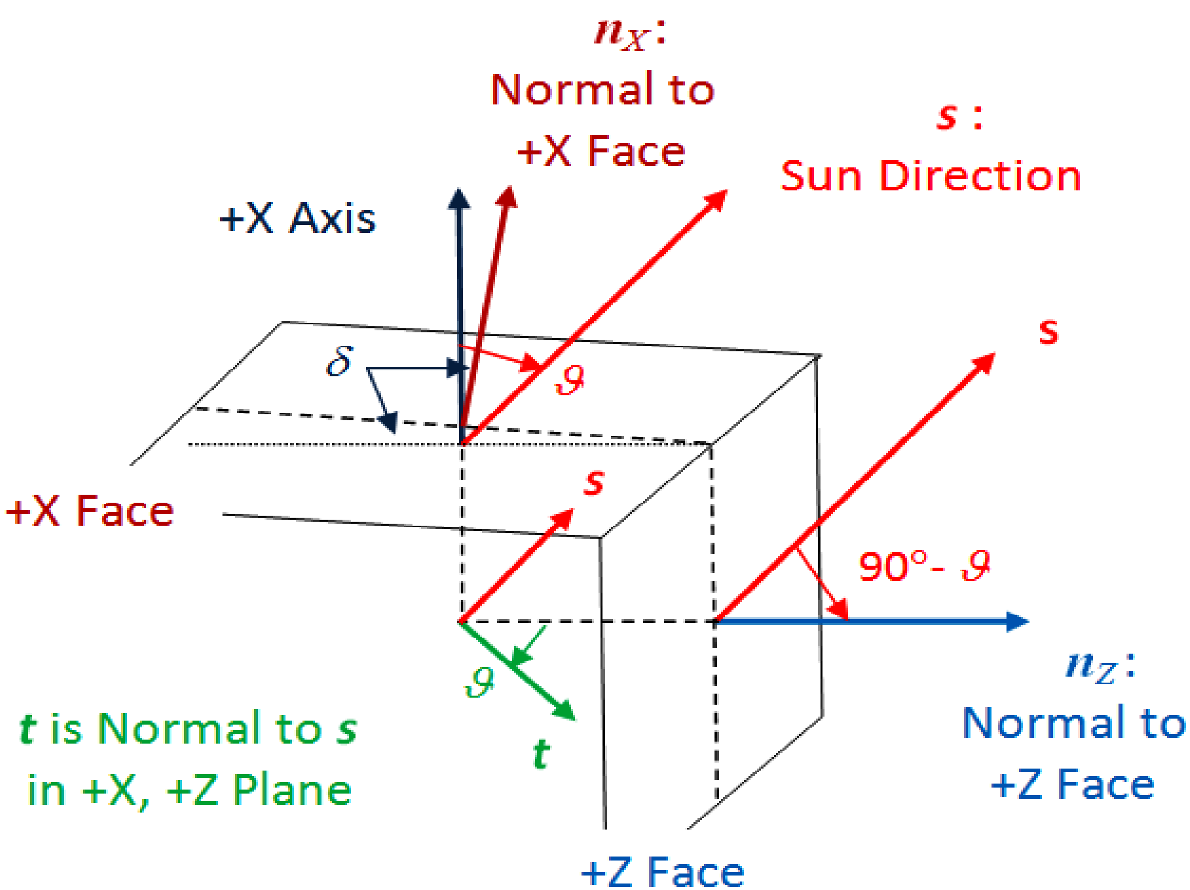


(b) Cruise 2



MARS EXPRESS (MEX)

MARS EXPRESS Spacecraft Model

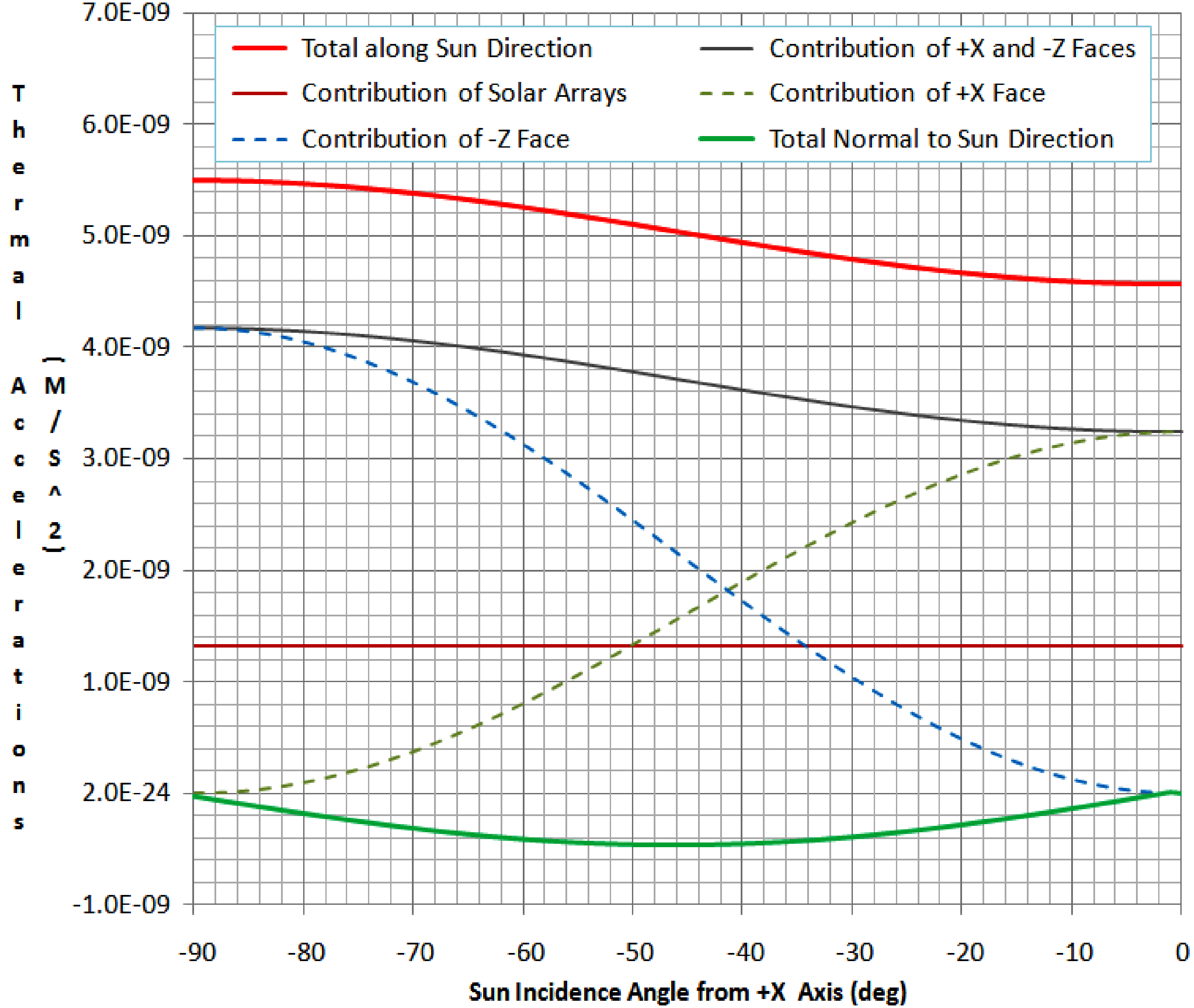


Specific Issues:

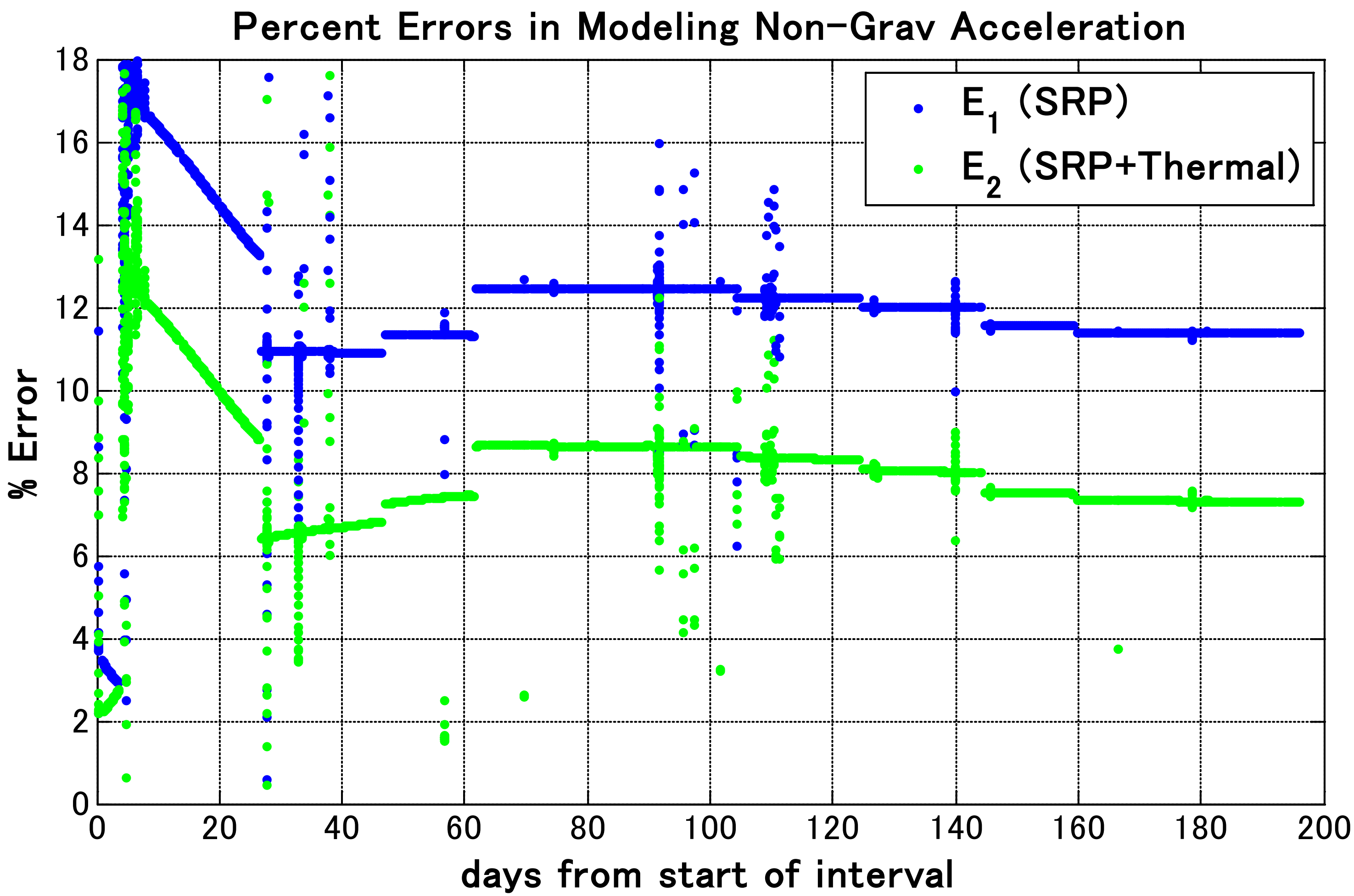
1) Inclination Angle of about 5° between Spacecraft X, Z Sides

2) Sun is Always Kept within +X, -Z Quadrant

Thermal Accelerations for Varying Sun Angle

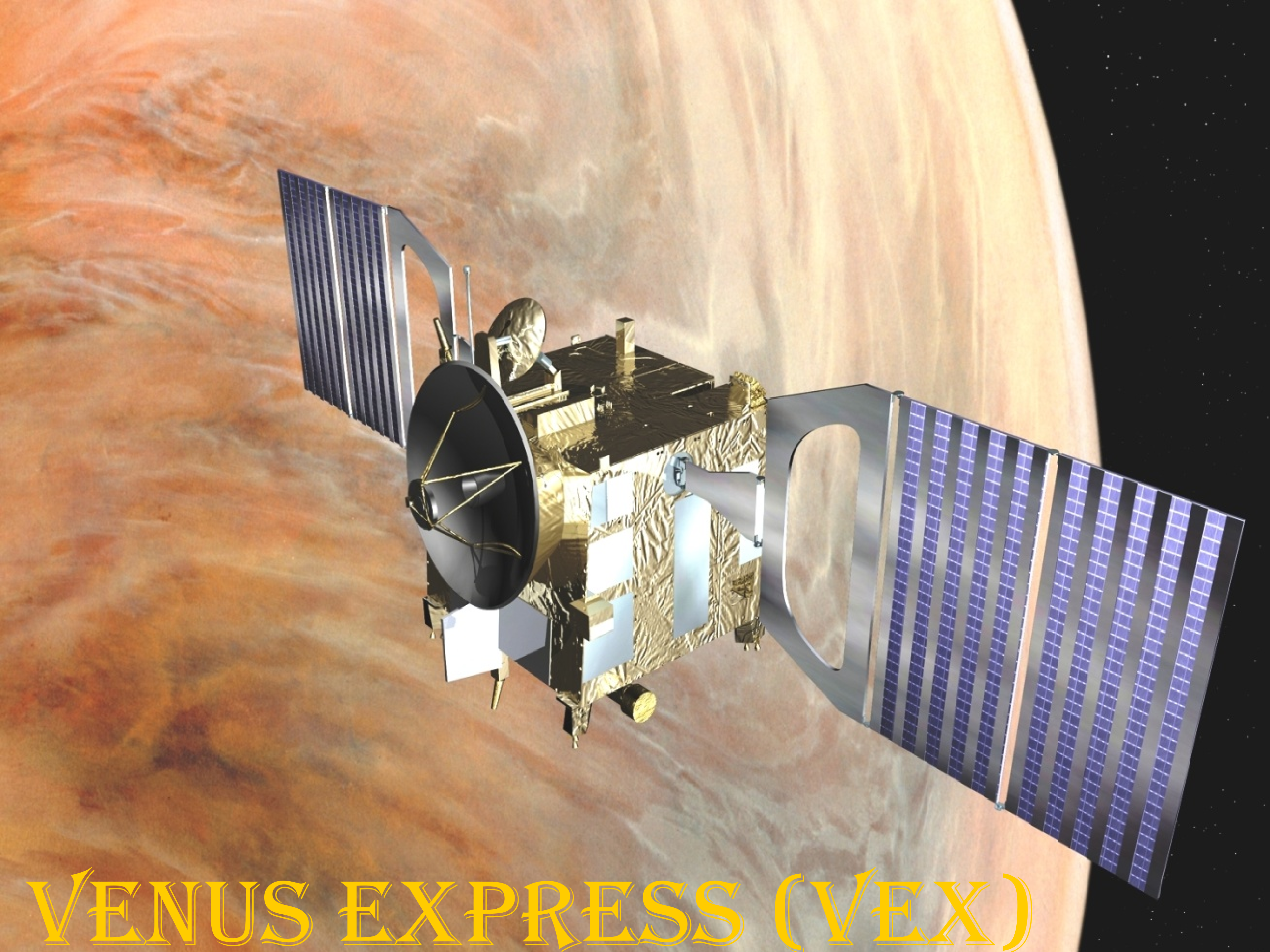


Non - Gravitational Acceleration Errors for MEX

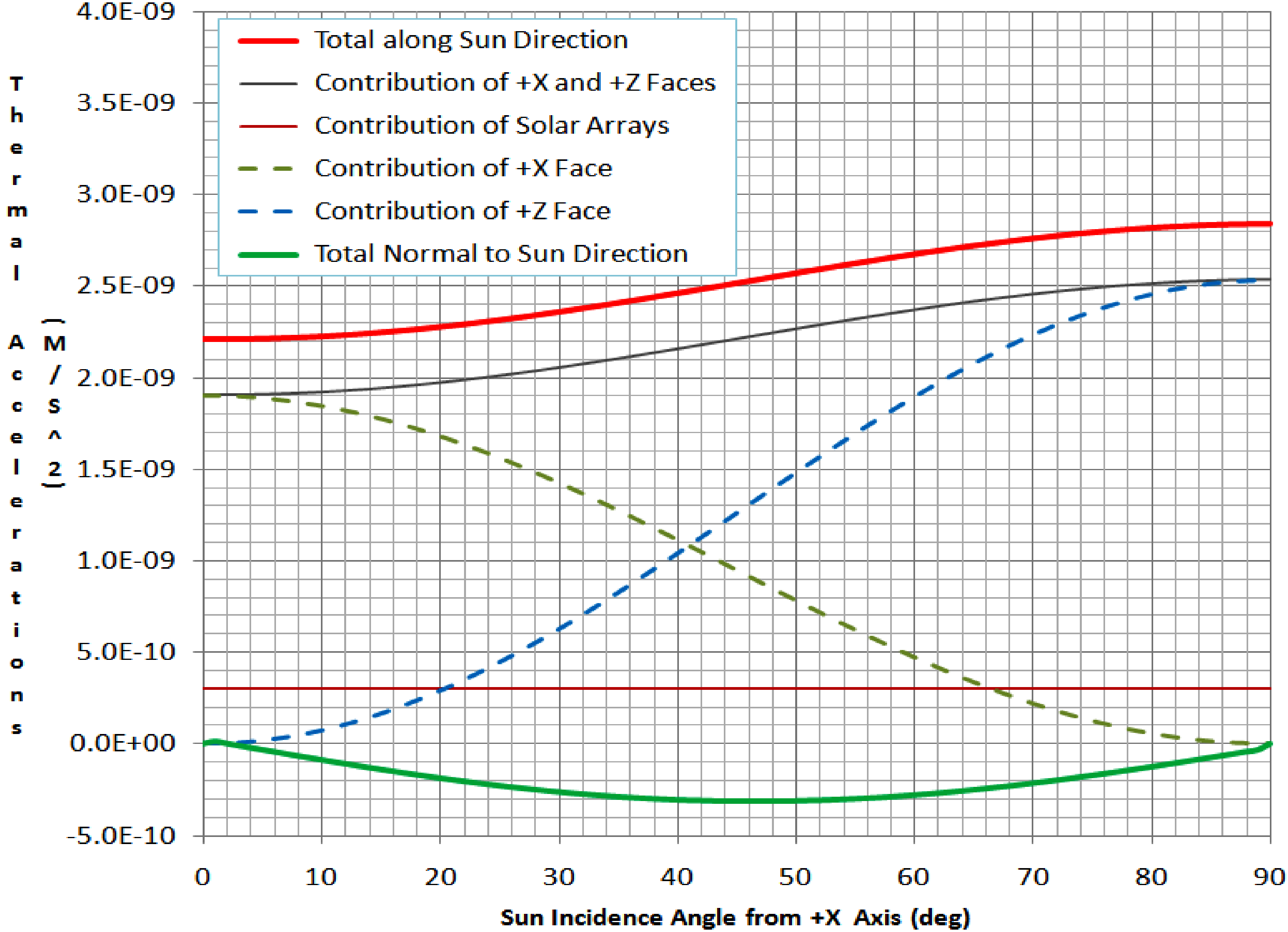


Thermal Model Improves Predictions by ~ 4 % .....

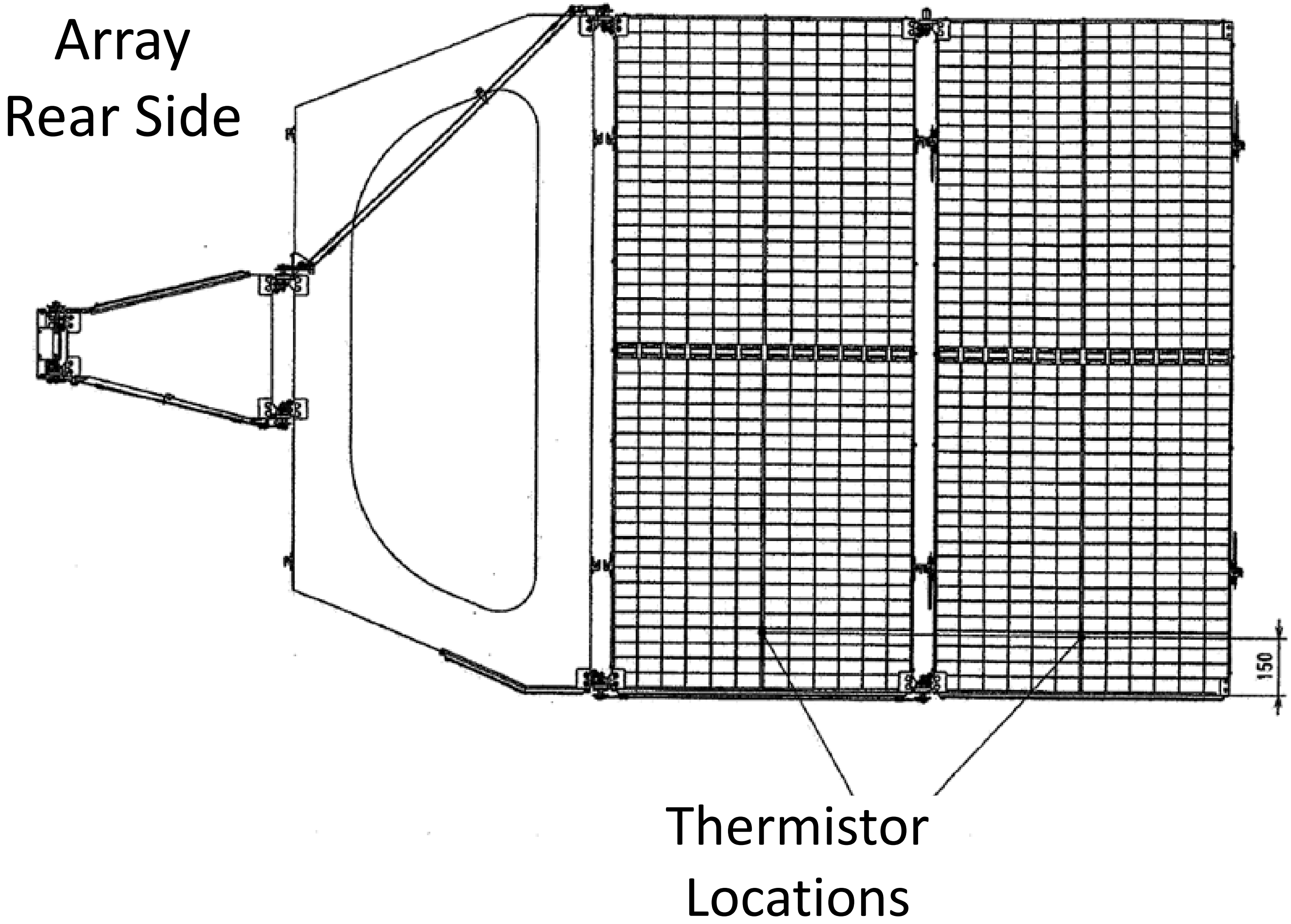
but still leaves ~ 8 % Unexplained!


Venus Express (VEX)

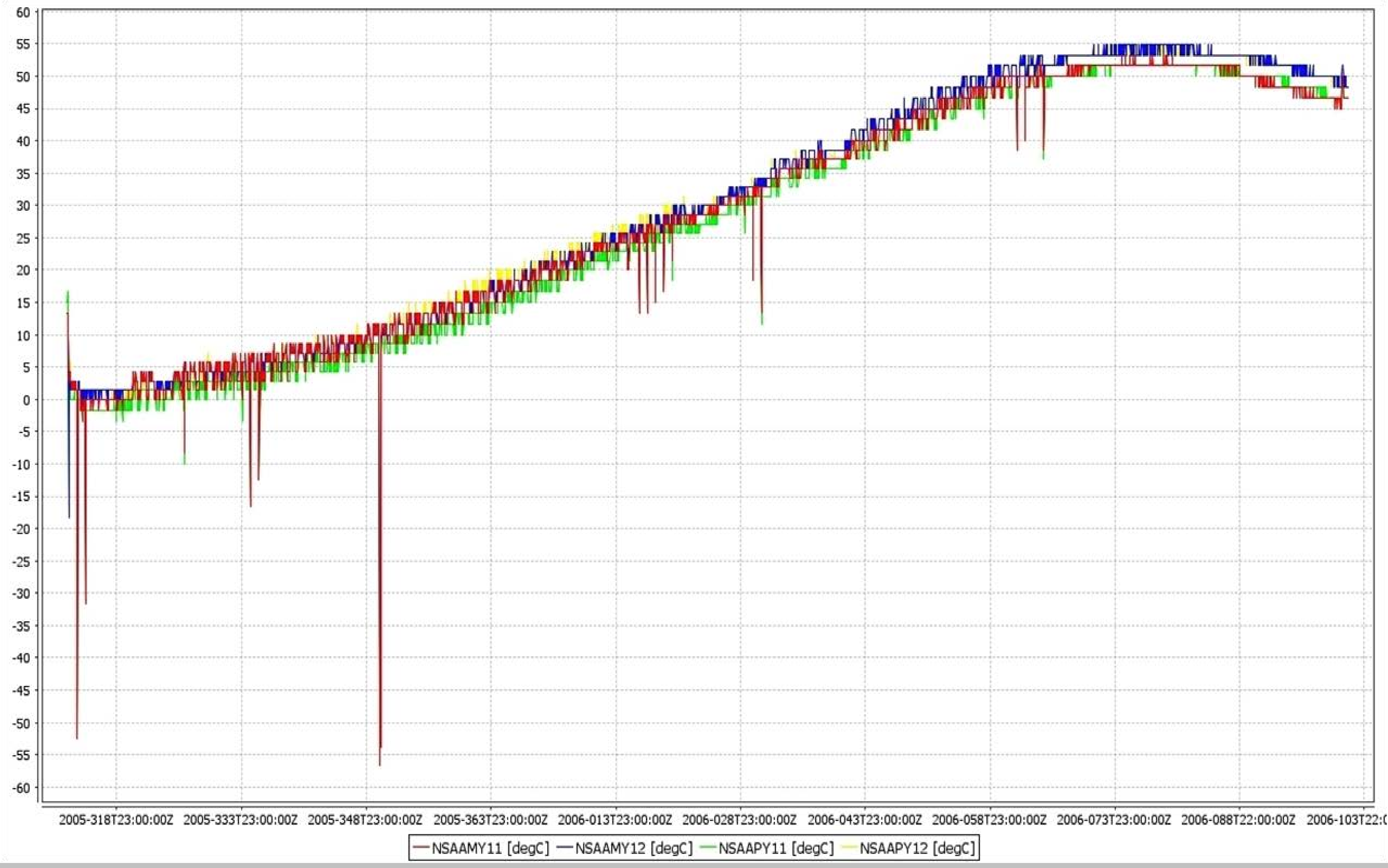
Thermal Accelerations for Varying Sun Angle



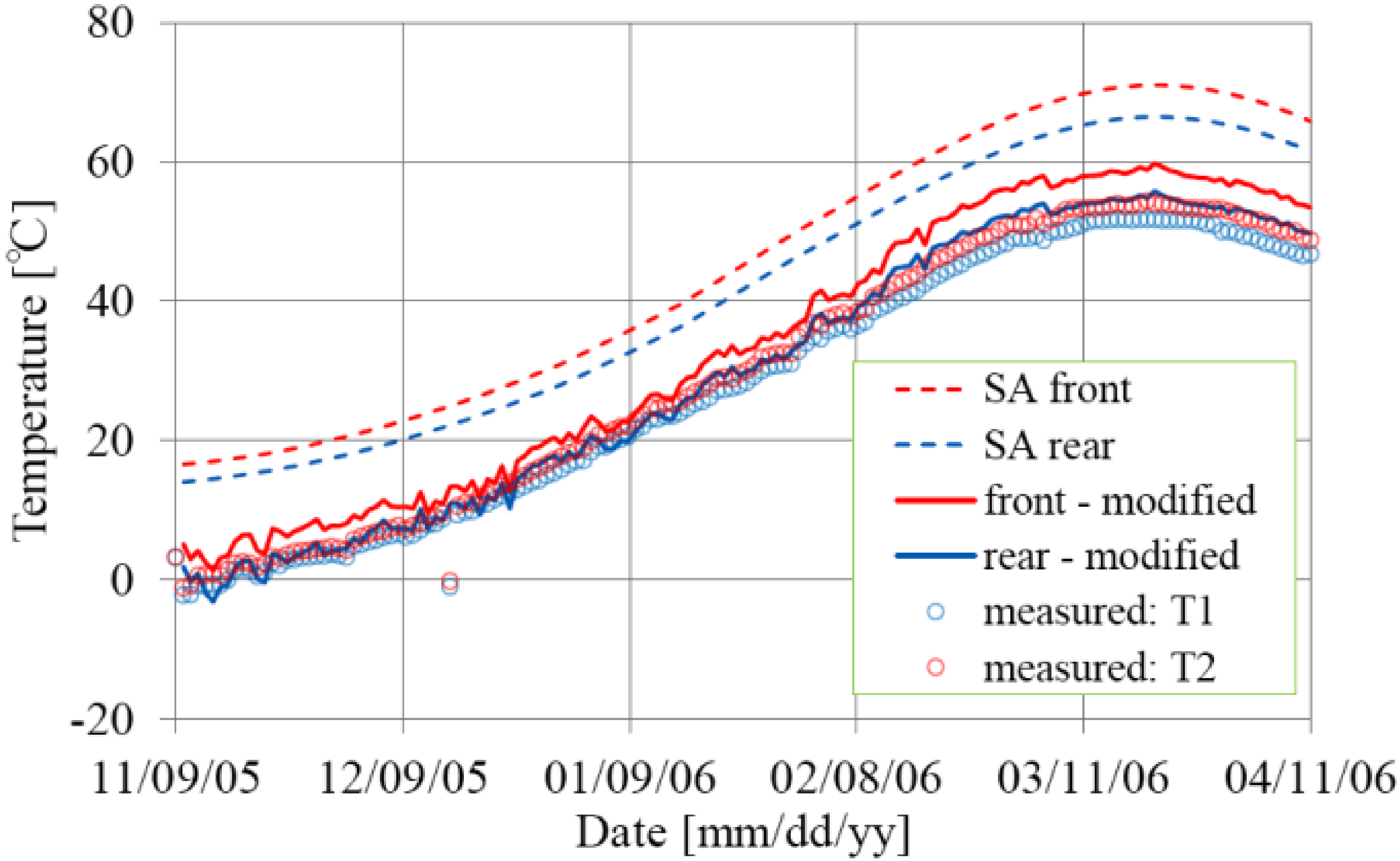
Thermistor Locations on VEX Solar Arrays



VEX Thermistor Measurements (Solar Arrays)



VENUS Express Solar-Array Temperatures



'Modified': Includes Actual **Power Conversion** (from Telemetry Data) plus Solar **Cell Efficiency Degradation** at Higher Temperatures

Reconciliation of Temperature Discrepancies

Potential Causes:	Cell Conversion Factor	Absorptivity	Emissivity
Nominal Values	< 0.15	0.439	0.770
Modified Values	0.12	0.388	0.886

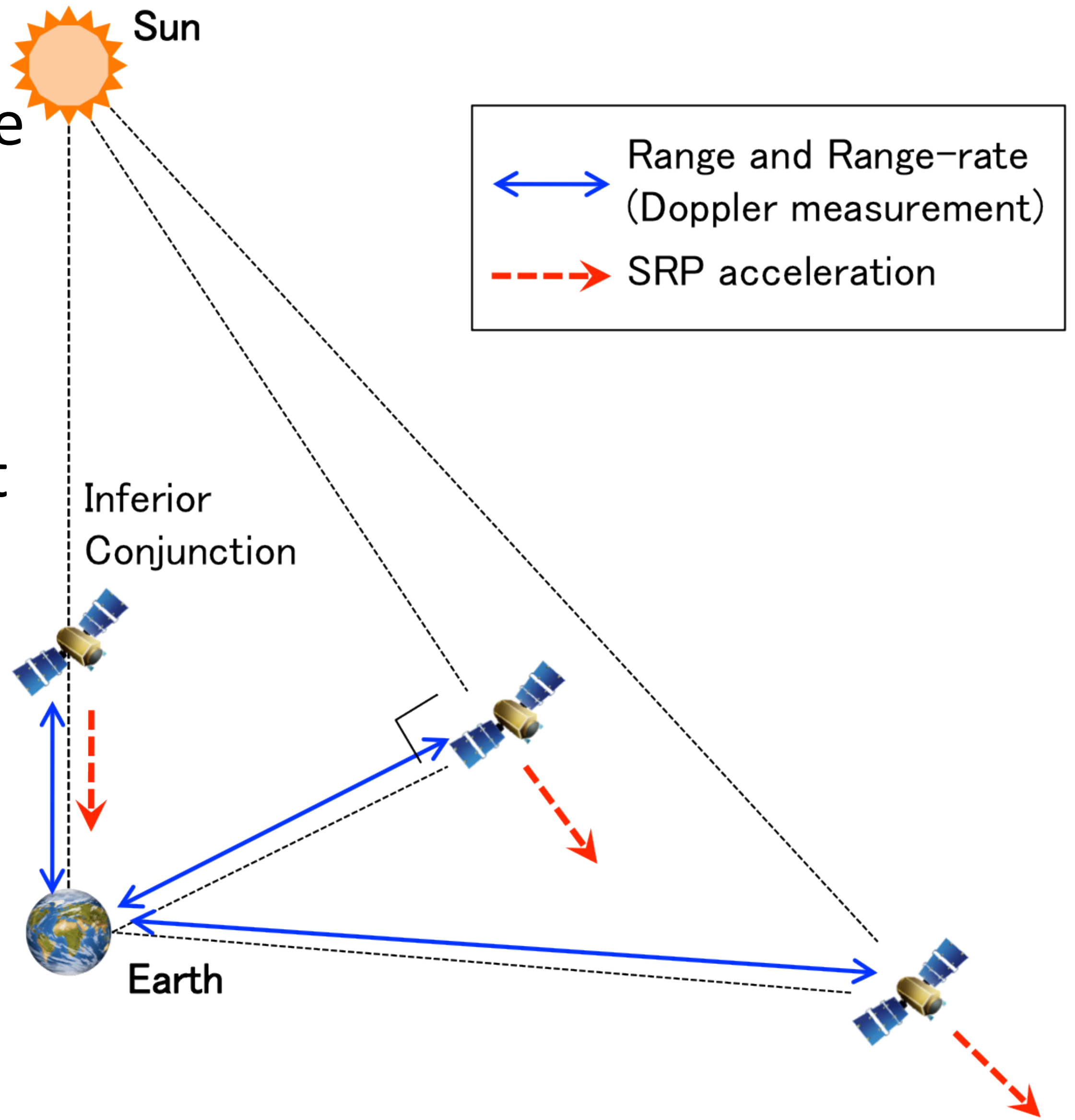
Conclusions:

1) Fairly Large Discrepancies Observed between Predicted & Measured Temperatures
2) Most Likely Reason is the Power Decrease due to high Solar Cell Conversion Factor
3) Perhaps too low Emissivity Parameters may play a Role as well

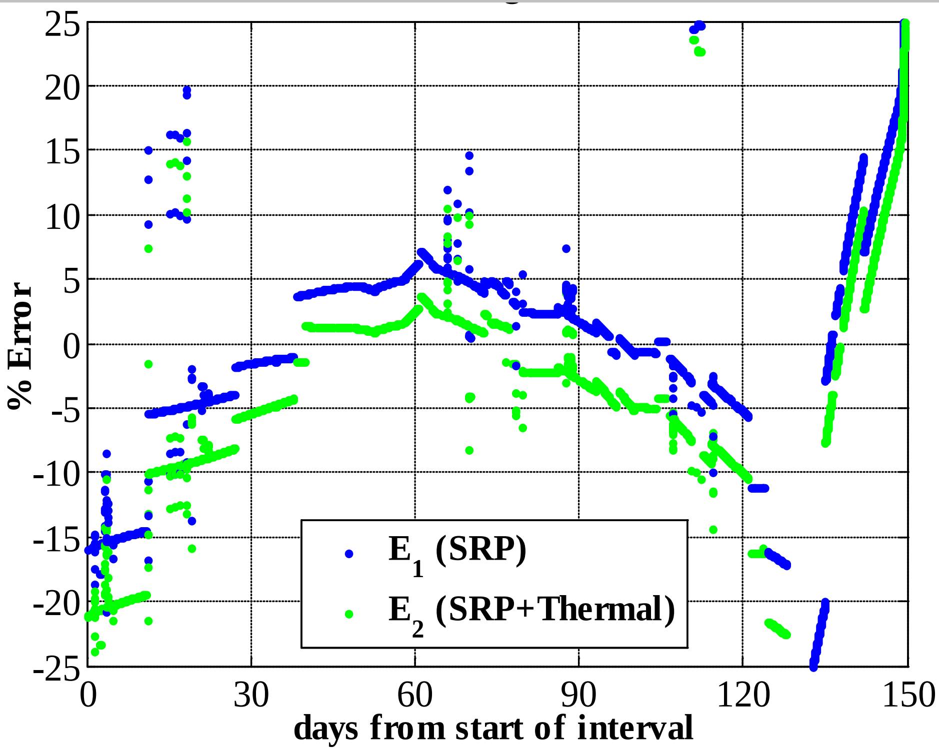
Fundamental Orbit Determination Principles

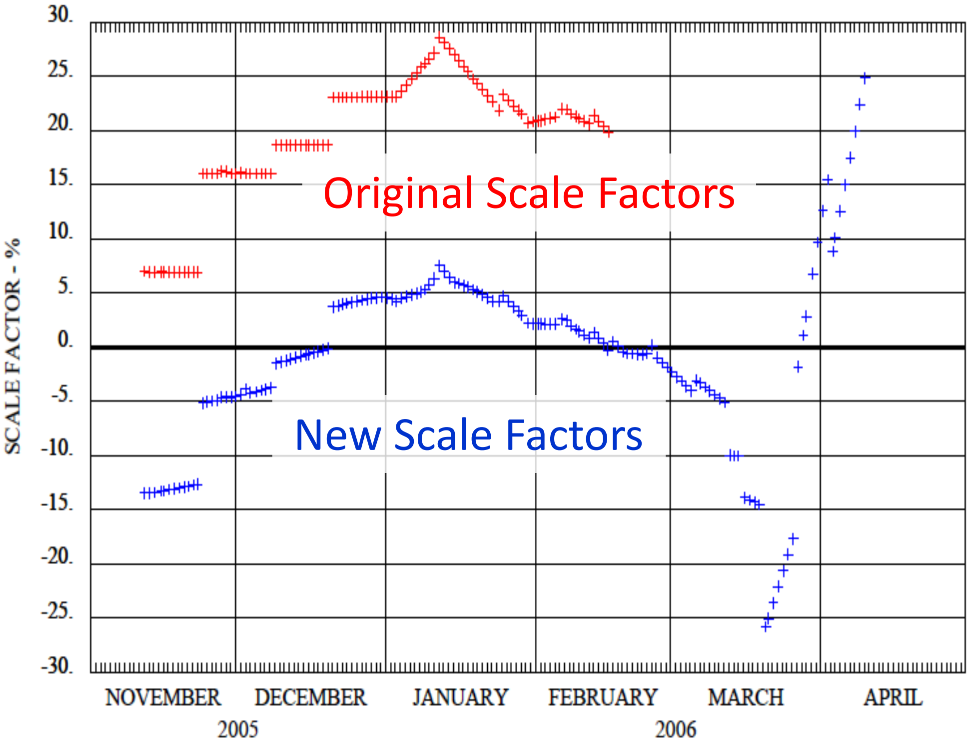
- Accuracy Depends on Satellite Position Relative to Earth & Sun
- Doppler has Sensitivity in Radial Direction only
- Thermal Radiation Effect was ***not*** Included
- Solar Radiation Pressure 'Tuned' by Scale Factors

Scale Factors are *not* Always ***Observable !***



Non - Gravitational Acceleration Errors for VEX





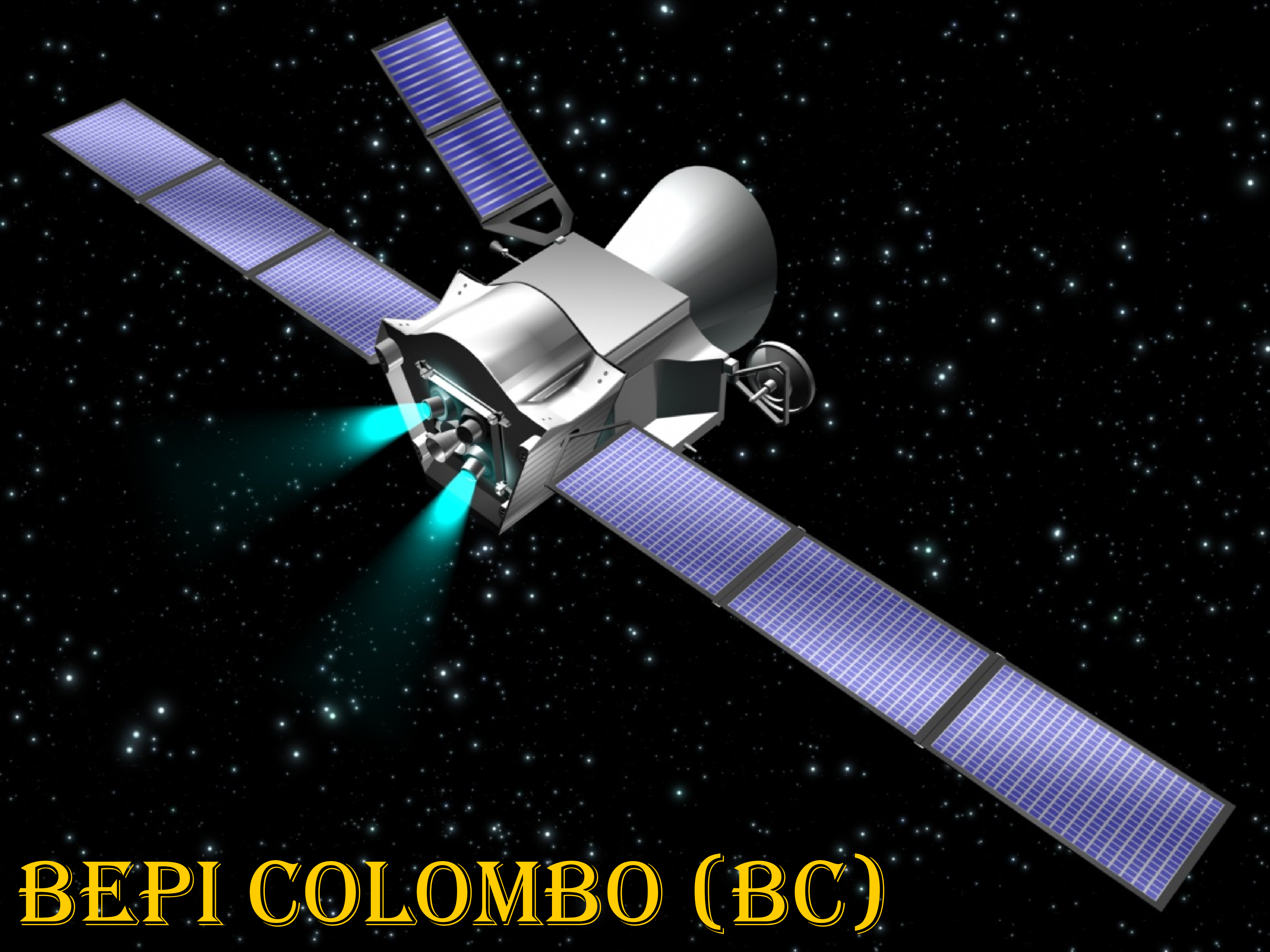
Conclusions:

1) Similarities between E_1 , E_2 and Scale Factors Evolutions are very Convincing !

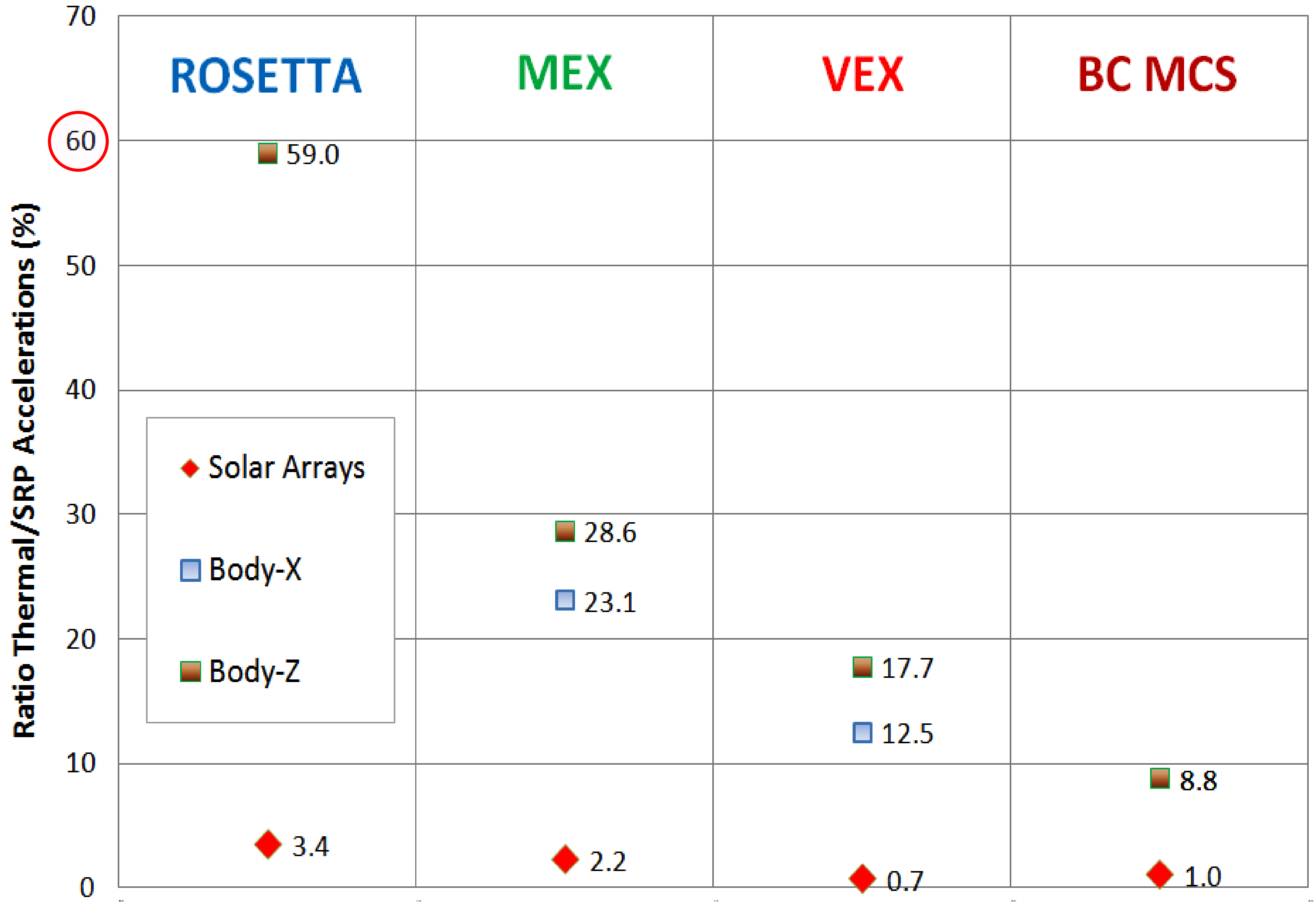
2) Thermal Contributions are ‘Helpful’ over Interval between 40 and 70 days

3) Sun-Satellite-Earth Angles are ~ **90° at Start and End** of Cruise Phase ➔

➔ **Deterioration of Observability** for Orbit Determination and SRP Scale Factors


BEPI COLOMBO (BC)

TRP / SRP Along-Sun Accelerations (All at 1 AU)



Conclusions

- ✓ We Study **Thermal Radiation** Effects on ESA Deep-Space Satellites by Analytical & Numerical Methods
- ✓ **Predicted** Temperatures on Rosetta's Solar Arrays are Consistent with **In-Flight Measured** Temperatures
- ✓ We Show that Thermal Radiation Induces **Appreciable Accelerations** on Rosetta's Trajectory, i.e. ~ 7 % of SRP
- ✓ Unlike SRP, Thermal Effects may Induce Relatively Large Accelerations **Normal to Sun Direction** of up to about 6 %
- ✓ Similar Results Obtained for **MEX** and **VEX** Spacecraft
- ✓ Predictions for **Bepi Colombo** SRP & Thermal during Cruise
- ✓ Reliable Thermal Models **Improve Trajectory Predictions** of ESA's Interplanetary Satellites and Benefit Navigation

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.