Appendix C

Mercury Retro-Reflection
Modelling and Effects on MPO Solar Array

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Abstract

Mercury's regolith might reflect the incident sun light preferably in the direction of the Sun, causing a retro-reflection effect. In the case of the BepiColombo Mercury Planetary Orbiter solar array this deviation from the bond albedo, which is implemented in most thermal analysis software, may cause significant temperature differences. This causes power losses since the solar array is continuously steered throughout the orbit in order to optimize its sun aspect angle (maximum sun power) without exceeded the design temperatures.

To estimate the influence of this albedo variation the mathCAD sheet Mercury Orbital Heat Fluxes Assessment (Merflux), developed by ESTEC's D. Stramaccioni, was adapted to calculate the heat fluxes that a spacecraft experiences in orbit around Mercury when considering the retro-reflection. Different albedo modelling options were implemented and finally the diffusive reflection modelling was compared with a directional reflection case, where sunlight is reflected back into the direction of the Sun more than into the other directions. The directional reflection modelling was considered the most realistic, based on findings in literature.

The peak albedo flux, impinging on a nadir-pointing cube, calculated with this directional model, was found to be more than twice the flux calculated with the diffusive approach, while the integral remains the same (energy balance of the planet). An extensive parametric study, with different solar panel models and attitudes, concluded that the influence of the albedo modelling has a non-negligible influence on the solar array temperature. For a fixed solar aspect angle throughout the whole orbit, the biggest difference in temperature between the two albedo models was found to be +14°C/ -10°C. A more realistic approach used a steering profile provided by ESOC and found maximum ΔT of +8°C/ -5°C. These worst ΔT are local peaks, not applicable to the whole orbit, nor applicable to the most critical panel wing of the solar array, whose ΔT is only +4°C/ -4°C. Around the sub-solar point the directional albedo provides the highest temperatures, while they are lower at the poles.

This information will permit preparing the best approach for solar array in orbit steering functions definition and calibration.

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Mercury Retro-Reflection:
Modelling and Effects on MPO Solar Array

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03/11/2015

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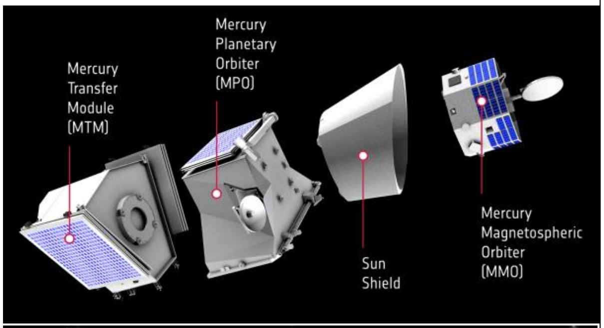
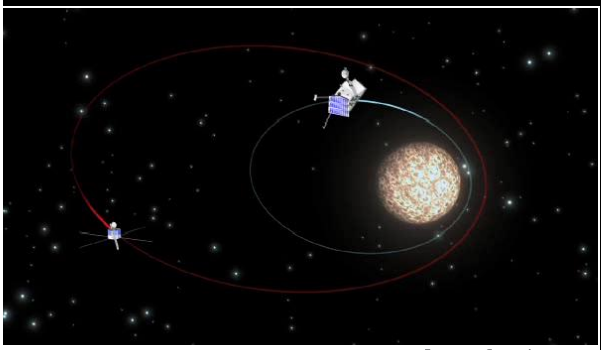
BepiColombo (spacecraft/mission)

- Europe's first mission to the planet Mercury, planned launch 2017
- Three modules:
  - Mercury Planetary Orbiter (MPO, ESA): studies surface and internal composition
  - Mercury Magnetospheric Orbiter (MMO, JAXA) surrounded by the Sunshield (ESA): studies magnetosphere
  - Mercury Transfer Module (MTM, ESA): carries the whole SC to Mercury
- Journey to Mercury takes 7.5 years with eight gravity-assist manovers at Earth, Venus, and Mercury
- Planned mission duration in orbit around Mercury is minimum one year





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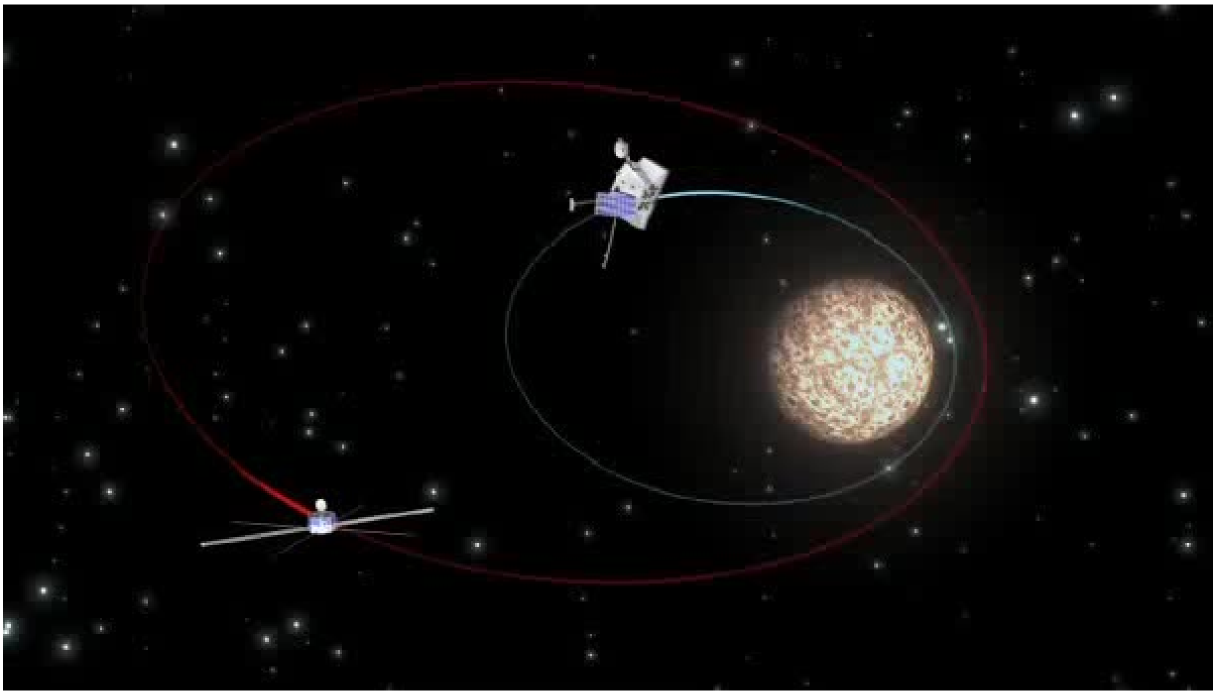

Save the attachment to disk or (double) click on the picture to run the movie.

Scope of the Activity

1. **Modelling of Mercury retro-reflection effects**: this was obtained by adapting the Merflux Worksheet (*) to account for retro-reflection in the albedo calculation
2. **Estimation of retro-reflection effects on MPO Solar Array**: a simplified two nodes model of the SA was analyzed in order to determine the change in the predicted solar panel temperatures

(*) Merflux Worksheet is a MathCAD tool created by D.Stramaccioni for in orbit heat fluxes calculation. This tool was validated against Esatan-TMS by J. Etchells, "MathCAD Heat Flux Calculator Verification Report" [2006, TEC-MCV/2006/3176/ln/JE]

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Environmental Specification: BC-EST-TN-00112

- *Bond albedo:* 0.119
  - Bond albedo is the fraction of incident solar energy that is reflected back to space by a spherical body over all wavelengths. […] Origin of this value and its derivation can be found in reference [3.1] below.
- *Visual geometric albedo:* 0.138
  - Geometric albedo (or head-on reflectance) is the fraction of incident solar energy that is reflected back by a planet into the direction of the Sun (phase angle equal to 0). It can be also thought as the amount of radiation reflected from a planet relative to that from a flat Lambertian surface, which is a diffuse perfect reflector at all wavelength. The reported value is taken from reference [3.1].

[3.1] Vilas F., Chapman C. R. and Matthews M. S. (Eds.), *'Mercury'*, The University of Arizona Press, Tucson, 1988.

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Mercury Albedo

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TABLE III
Estimates of Bond Albedo

	p_v	q_v	A_B
Moon[a]	0.113	0.611	0.123 ± 0.002
Mercury[b]	0.138	0.486	0.119

[a]Values from Lane and Irvine 1973.
[b]This work.

p_v	geometric albedo in the V filter of the UBV system
q_v	phase integral in the V filter of the UBV system
$A_v = p_v q_v$	spherical albedo in the V filter of the UBV system
A_B	bond albedo

$$\left(\frac{A_B}{A_V}\right)_{☿} \simeq \left(\frac{A_B}{A_V}\right)_{☾}$$

UBV:	a wide band photometric system for classifying stars according to their colors.
U:	ultraviolet
B:	blue
V:	visual

Vilas F., Chapman C. R. and Matthews M. S. (Eds.), '*Mercury*', The University of Arizona Press, Tucson, 1988.

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UBV photometric system, also called the Johnson system (or Johnson-Morgan system), is a wide band photometric system for classifying stars according to their colors. It is the first known standardized photoelectric photometric system. The letters U, B, and V stand for ultraviolet, blue, and visual magnitudes.

Lane and Irvine (1973), who determined p and q as a function of wavelength, between 350 and 1000 nm, and used these values to calculate the radiometric Bond albedo shown in Table 111. In the case of Mercury, we lack sufficient information to derive the wavelength dependence of q, and as far as p is concerned, an adequate first approximation is that the wavelength behavior is similar to that of the Moon.

Mercury Orbital Heat Fluxes Assessment (Merflux)

1. Solar flux: $QS_{k,j} = SC \cdot \alpha_k \cdot A_k \cdot F_{ss\,k,j} \left(1 - \delta_{ecl\,j}\right)$
2. Planet IR flux: $QIR_{k,j} = \sum_{grid} \sigma \cdot T^4_{grid} \cdot S_{grid} \cdot \varepsilon_k \cdot A_k \cdot \frac{C1 \cdot C2}{\pi \cdot d^2}$
3. Directional emissivity: $\frac{\varepsilon(\varphi)}{\varepsilon_H} = 0.9(\cos(\varphi))^{\varepsilon n} / \varepsilon_H$
4. Albedo flux: $QA_{k,j} = \sum_{grid,sunlit} SC \cdot a \cdot C3 \cdot S_{grid} \cdot \alpha_k \cdot A_k \cdot \frac{C1 \cdot C2}{\pi \cdot d^2}$

total solar irradiance at the actual distance from the sun *SC*, visible hemispherical absorptance α, and area of the surface *A*, sun illumination factor F_{ss} , shadow terminator function δ_{ecl}

Stefan–Boltzmann constant σ, Area of the facet S_{grid}, infrared hemispherical emittance ε_k of the spacecraft surface, distance of the spacecraft from the grid element *d*, angle between the facet and the location of the spacecraft C1, angle between the spacecraft surface and the location of the facet C2

hemispherical emissivity ε_H, emission angle φ, εn is a number that was found by Mariner 10 to vary between 0.19 ±0.07

angle between the sun incident flux and the grid facets C3, albedo coefficient *a*

J. Etchells, "MathCAD Heat Flux Calculator Verification Report" 2006, TEC-MCV/2006/3176/ln/JE

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Albedo Models alternatives

1. Diffusive Model:
   a. Incident flux is reflected diffusively in all directions
   b. The spatial distribution is even in all directions
2. Retro-reflection Model:
   a. The solar flux is reflected back into the direction of the Sun
   b. The reflection resembles that of a flat mirror
3. Directional Reflection Model:
   a. Compromise between diffusive and retro-reflection
   b. Light is primarily reflected into one direction while some of it is still reflected diffusively

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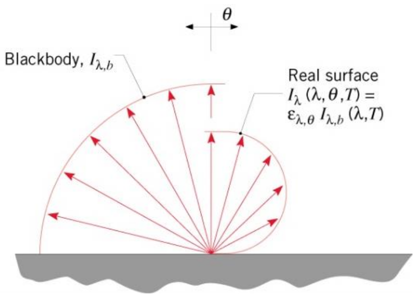
Directional Emissivity

"Radiation: Processes and Properties
Surface Radiative Properties",
http://me.queensu.ca/Courses/346/

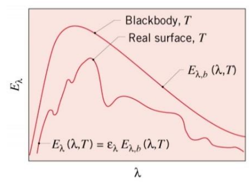
- The spectral, directional emissivity:

$$\varepsilon_{\lambda,\theta}(\lambda,\theta,\phi,T) \equiv \frac{I_{\lambda,e}(\lambda,\theta,\phi,T)}{I_{\lambda,b}(\lambda,T)}$$



- The spectral, hemispherical emissivity (a directional average):

$$\varepsilon_{\lambda}(\lambda,T) \equiv \frac{E_{\lambda}(\lambda,T)}{E_{\lambda,b}(\lambda,T)} = \frac{\int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e}(\lambda,\theta,\phi,T)\cos\theta\sin\theta\, d\theta\, d\phi}{\int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,b}(\lambda,T)\cos\theta\sin\theta\, d\theta\, d\phi}$$



F. P. Incropera, Fundamentals of heat and mass transfer, John Wiley & Sons , 2011.

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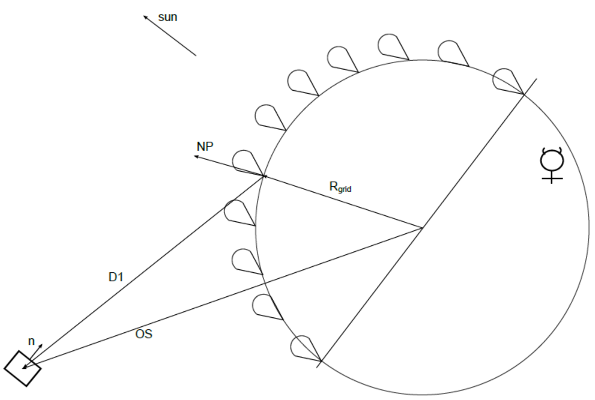
Directional reflection

```
QA_k,j := | qη ← 0·watt
          | C0 ← cos(Δη/2)
          | for η ∈ 1..Nη
          |   | qξ ← 0·watt
          |   | for ξ ∈ 1..Nξ_η
          |   |   | D ← OS_o^<j> − R_p·C0·NP_η,ξ
          |   |   | d ← |D|
          |   |   | D1 ← D/d
          |   |   | C1 ← sun_o·D1  if (sun_o·D1) > 0
          |   |   | C1 ← 0  otherwise
          |   |   | C2 ← n_o_k,j·(−D1)  if [n_o_k,j·(−D1)] > 0
          |   |   | C2 ← 0  otherwise
          |   |   | qξ ← qξ + SC·(sun_o·NP_η,ξ)·a_retro·C1^αn·Sgrid_η·(C1·C2)/(π·d^2)·A_k·α_k
          |   | qη ← qη + qξ
```



C1	angle between reflection direction and spacecraft position
C2	angle between S/C surface and grid point on the planet's surface

Note: tear drop shapes are dimensionless representations of Albedo directional refection

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Directional reflection

8. ALBEDO RADIATION

8.1 Constants and Planet Environment Parameters

Planet Albedo coefficient: $a \equiv 0.12$

Directional reflection described by $a_{retro}(\cos(\phi_{retro}))^{\alpha n}$

Enter values for directional reflection:

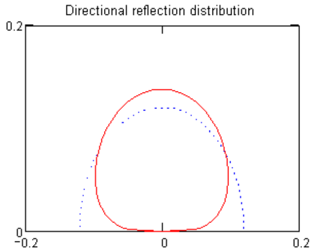
$a_{retro} := 0.138$

$\alpha n := 0.3$

Calculate hemispherical reflection coefficient from directional reflection:

$$a_h := \frac{a_{retro}}{\pi} \cdot \int_0^{2\pi} \int_0^{\frac{\pi}{2}} \cos(\phi_{retro})^{\alpha n} \cdot \cos(\phi_{retro}) \cdot \sin(\phi_{retro})\, d\phi_{retro}\, d\theta_{retro}$$

$a_h = 0.1200$



Reminder: Diffusive Albedo:

$$QA_{k,j} = \sum_{\text{grid,sunlit}} SC \cdot a \cdot C3 \cdot S_{\text{grid}} \cdot \alpha_k \cdot A_k \cdot \frac{C1 \cdot C2}{\pi \cdot d^2}$$

$QA_{k,j} :=$

- $q\eta \leftarrow 0 \cdot watt$
- $C0 \leftarrow \cos\left(\frac{\Delta\eta}{2}\right)$
- for $\eta \in 1 .. N\eta$
  - $q\xi \leftarrow 0 \cdot watt$
  - for $\xi \in 1 .. N\xi_\eta$
    - $D \leftarrow OS_o^{\langle j \rangle} - R_p \cdot C0 \cdot NP_{\eta,\xi}$
    - $d \leftarrow |D|$
    - $D1 \leftarrow \frac{D}{d}$
    - $C1 \leftarrow sun_o \cdot D1$ if $(sun_o \cdot D1) > 0$
    - $C1 \leftarrow 0$ otherwise
    - $C2 \leftarrow n_{o_{k,j}} \cdot (-D1)$ if $\left[n_{o_{k,j}} \cdot (-D1)\right] > 0$
    - $C2 \leftarrow 0$ otherwise
    - $q\xi \leftarrow q\xi + SC \cdot (sun_o \cdot NP_{\eta,\xi}) \cdot a_{retro} \cdot C1^{\alpha n} \cdot Sgrid_\eta \cdot \frac{C1 \cdot C2}{\pi \cdot d^2} \cdot A_k \cdot \alpha_k$
  - $q\eta \leftarrow q\eta + q\xi$

NP	Unit vector normal to planet's surface
a_{retro}	geometric albedo
αn	exponent for directional reflection
Sgrid	Area of the planet's surface grid
α	solar absorptivity

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Reference Orbit Case

Perihelion case:
diffusive Albedo (as considered so far for BepiColombo analyses)

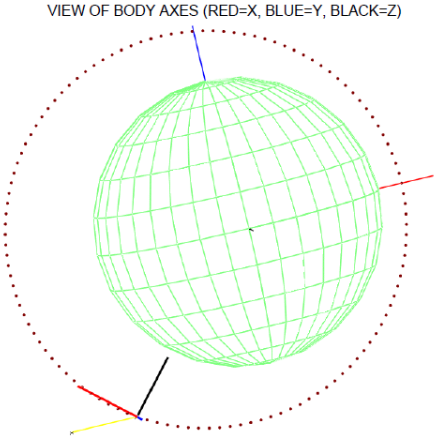
2.1 Input Orbital Parameters

Altitude of periapsis: $h_p := 400 \cdot 10^3 \cdot m$

Altitude of apoapsis: $h_a := 1508 \cdot 10^3 m$

Orbit inclination: $io := 90 \cdot deg$

Nadir pointing



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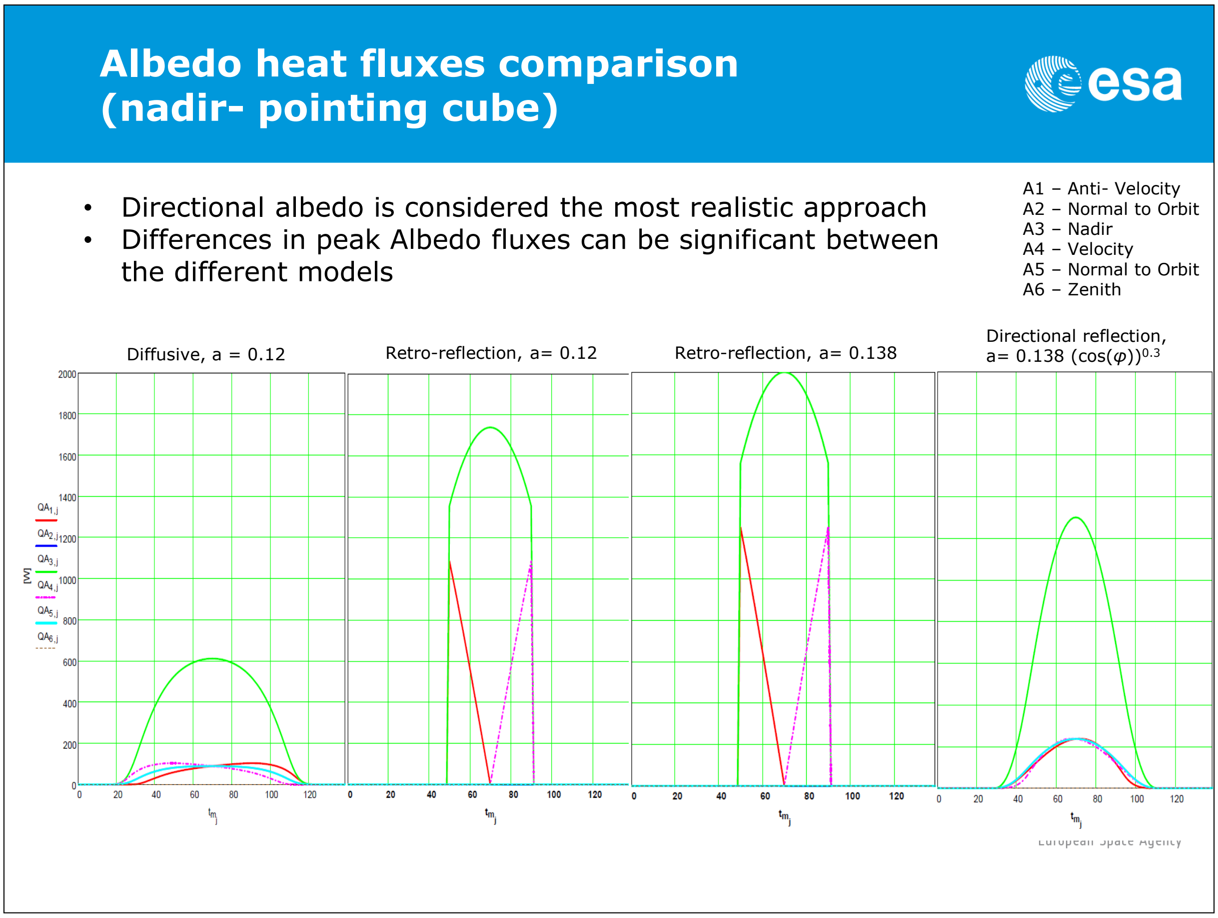
Albedo heat fluxes comparison (nadir- pointing cube)
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• Directional albedo is considered the most realistic approach
• Differences in peak Albedo fluxes can be significant between the different models
A1 – Anti- Velocity
A2 – Normal to Orbit
A3 – Nadir
A4 – Velocity
A5 – Normal to Orbit
A6 – Zenith
Diffusive, a = 0.12
Retro-reflection, a= 0.12
Retro-reflection, a= 0.138
Directional reflection, a= 0.138 (cos(φ))^0.3
[W]
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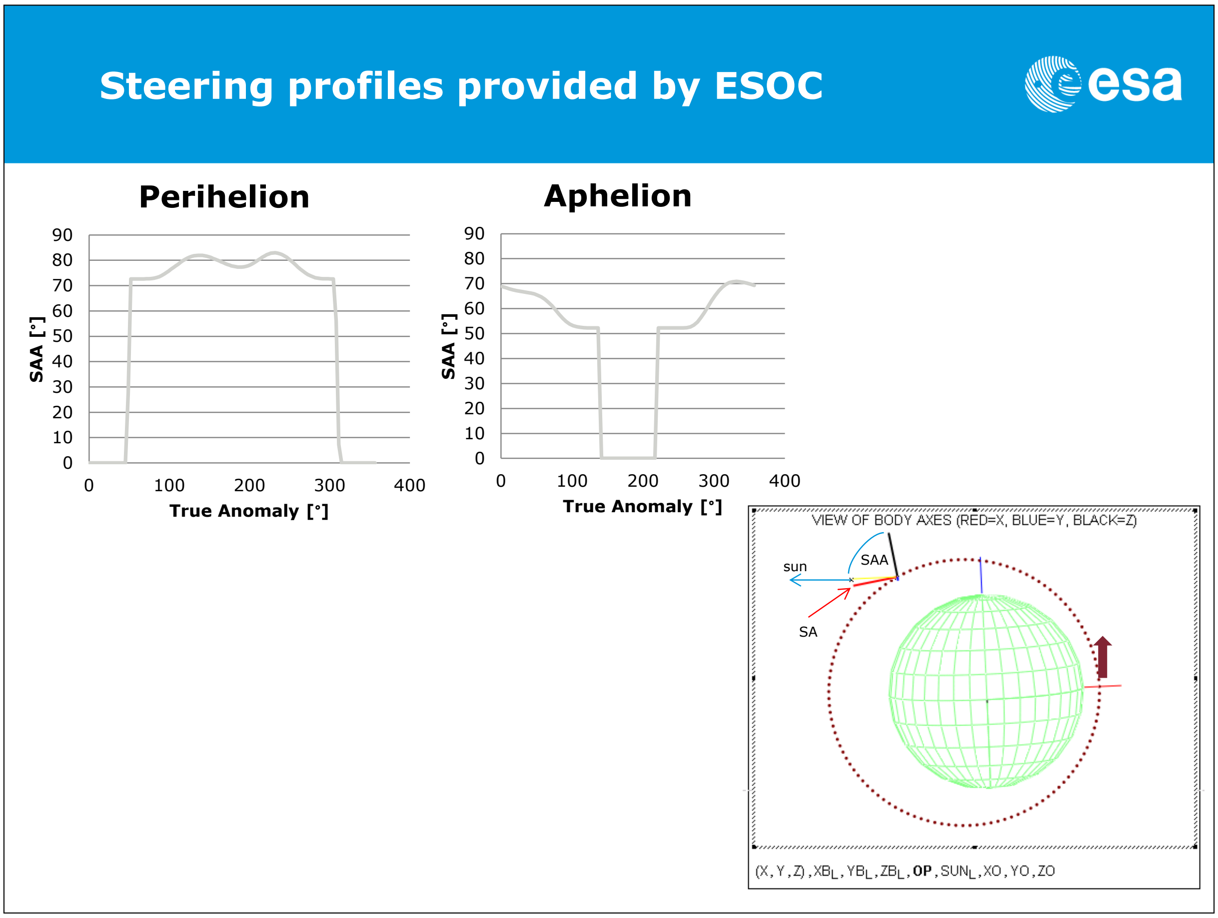
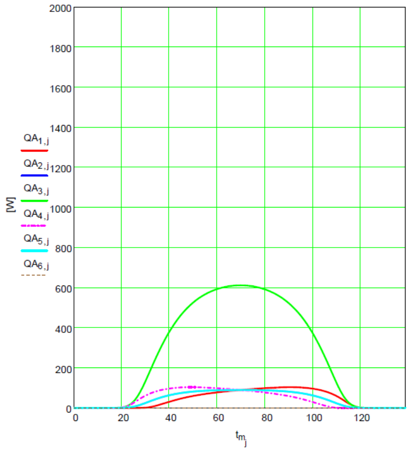

Steering profiles provided by ESOC
esa
Perihelion
Aphelion
SAA [°]
True Anomaly [°]
VIEW OF BODY AXES (RED=X, BLUE=Y, BLACK=Z)
sun
SAA
SA

Albedo heat fluxes comparison (Steering profile)

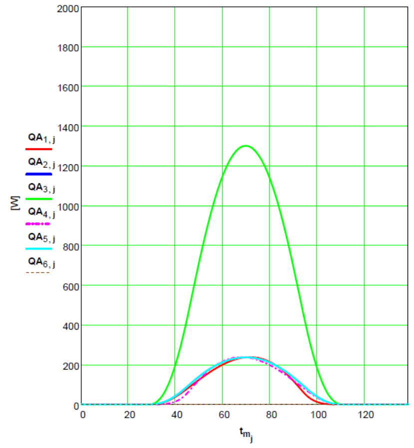
- Directional albedo is considered the most realistic approach
- Differences in peak Albedo fluxes can be significant between the different models

A3 – Front
A6 – Back

diffusive



directional



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Solar Panel Thermal Model

1. 2 Nodes: Front and back
2. Front covered with optical solar reflector (OSR)
3. Back is bare CFC or covered with OSR
4. Solar Panel Area = 1322 mm * 2065 mm, thickness = 22.8 mm
5. Consist of CFC Honeycomb between CFC Sheets
6. Thermal inertia is null

Panel	Front Side	Back Side
Outer Panels	a) OSR 47% EOL: $\alpha/\varepsilon = 0.601/0.827$	1) Bare CFC EOL: $\alpha/\varepsilon = 0.92/0.825$
Inner Panel	b) OSR 82% EOL: $\alpha/\varepsilon = 0.372/0.803$	2) OSR 100% EOL: $\alpha/\varepsilon = 0.25/0.79$

NB1: Case a1 represents Cells/OSR ratio of the outermost panels (2 and 3). Case b2 represent inner panel.
NB2: Null thermal inertia considered: only slightly conservative assumption and closer to real operational mode where SA temperatures are kept close to constant values
[See BC-ASO-AN-116068 Is.3 par.5.1.3 and 5.3 (selected values)]

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Thermal Analysis Cases

Analysis cases are combinations of the following points:

1. 3 SA combinations of optical properties (front/back) have been considered (outer panel, inner panel, and worst case optical properties combination): a1, b2, b1.
2. Solar Panel is at constant angle to the Sun: 90°, 78°, and 65°
3. Perihelion and Aphelion orbits
4. 4 different Albedo modelling approaches:
    a. bond albedo 0.119 (fully diffused)
    b. full retro-reflection 0.12
    c. full retro-reflection 0.138
    d. directional albedo
5. 2 realistic steering profiles (perihelion & aphelion) provided by ESOC

Note: ThermXL and Esatan software (part of Esatan-TMS suite) has been used for SA temperatures calculation

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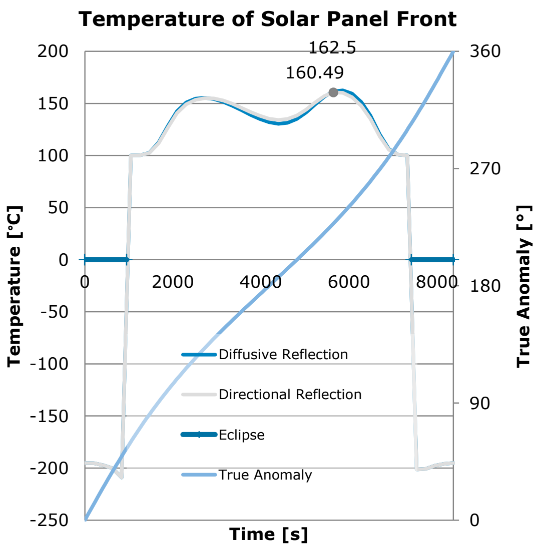
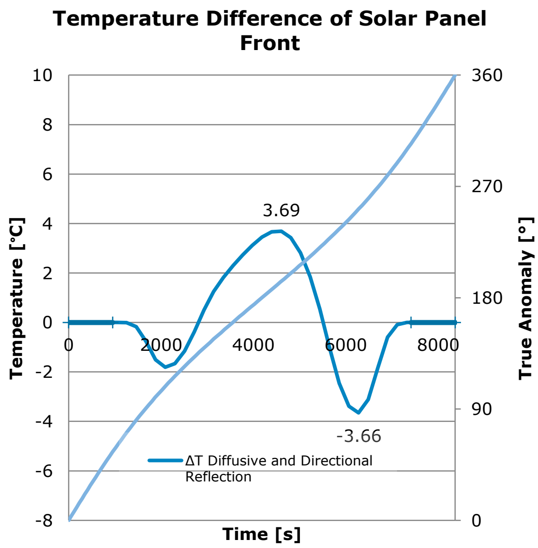
Temperature of inner panel with ESOC SAA profile at Perihelion





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Temperature of outer panel with ESOC SAA profile at Perihelion

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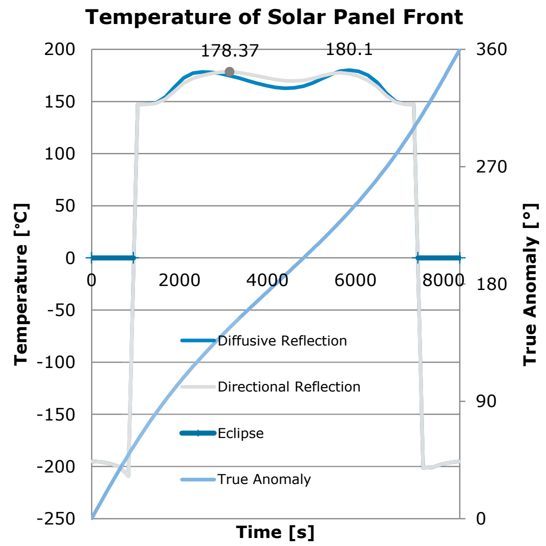

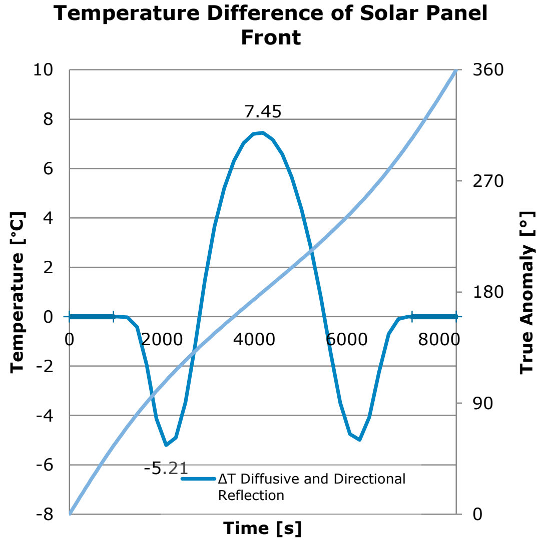

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Temperature of inner panel with ESOC SAA profile at Aphelion

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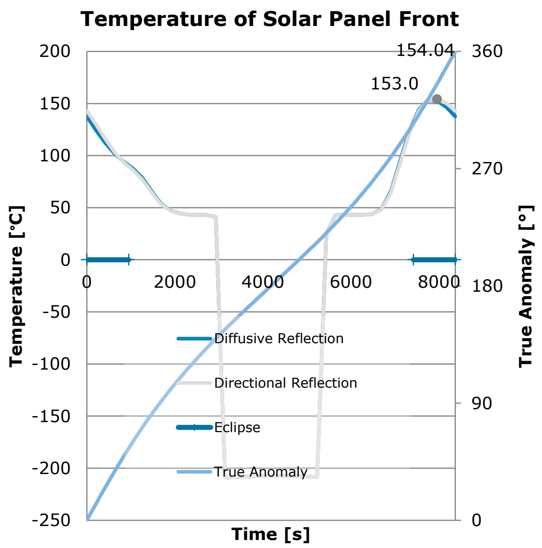

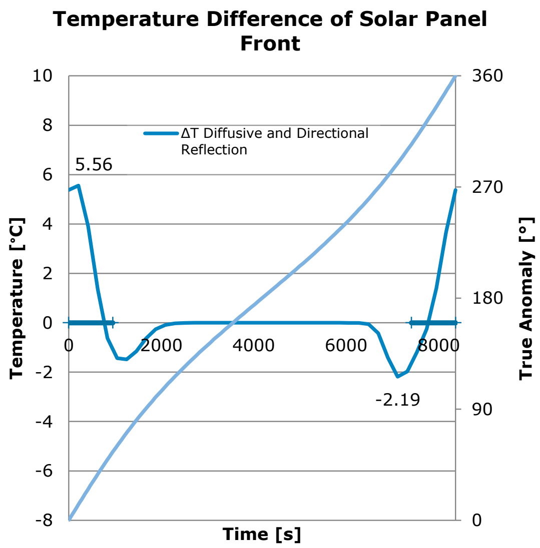

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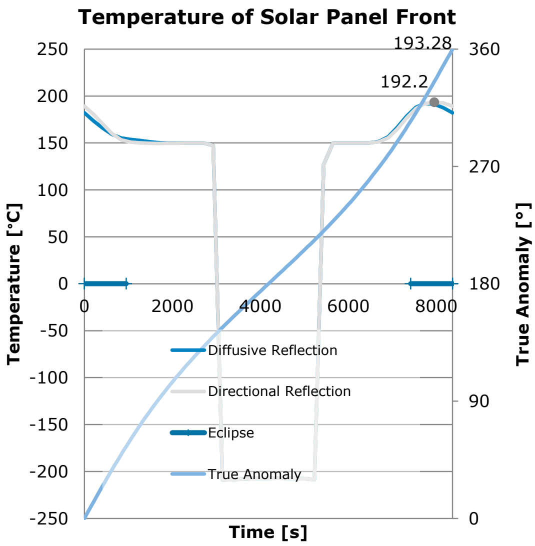
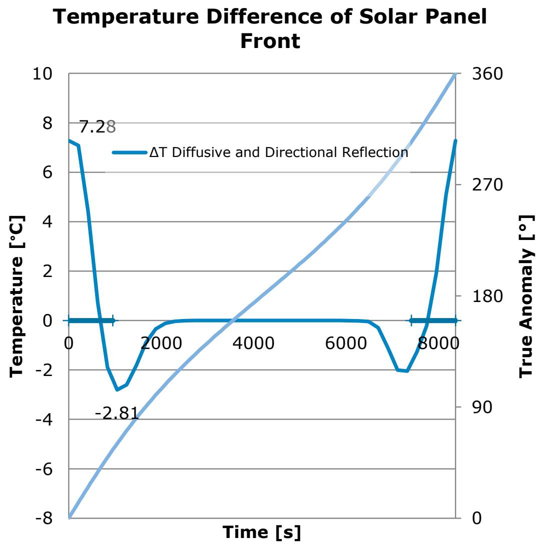
Temperature of outer panel with ESOC SAA profile at Aphelion





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Summary

1. A simplified model of Mercury Albedo has been built
2. Environmental heat fluxes have been calculated
3. The impact on MPO SA temperatures has been studied for:

- Perihelion and Aphelion orbits
- 4 different Albedo modelling approaches (diffusive vs retro-reflection)
- 3 SA combinations of optical front/back properties
- 3 fixed SAA: 90deg, 78deg and 65deg angles
- 2 realistic steering profiles (perihelion & aphelion) provided by ESOC

Note: The most realistic Albedo modelling approach is considered the one with Albedo directional reflection (i.e. diffused reflection with much higher energy concentration around the direction of retro-reflection).

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Conclusions 1/2

1. Albedo modelling has a no negligible influence on SA temperatures
2. Fixed SA SAA (not realistic case): for the directional retro-reflection (considered the best engineering case), the SA front side worst ΔT (directional minus diffusive albedo) during orbit is ~+14/-10degC for outermost panels and ~+10/-5degC for the innermost panel
3. Variable SAA (realistic steering profile case): for the directional retro-reflection, the SA front side worst ΔT during orbit is less than +8degC/-5degC for outermost panels and less then +4/-4degC for the innermost panel
4. Worst ΔT is a peak (limited time duration), not applicable to the whole orbit: around sub-solar point the directional albedo provides the highest temperatures.

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Conclusions 2/2

5. There are parts of the orbit where the diffusive albedo approach is conservative: in those areas Industry models are conservative (safe in temperature), but SAA steering profile might not be optimized at best (reduced power generation).
6. Results are preliminary estimations based on simplified models of planet and SA (e.g. 2 nodes for SA), averaged optical properties for SCA+OSR, albedo modelling approach for Mercury not consolidated.
7. Worst cases occur in SA panels with bare CFC on the backside (outermost panels) and are usually more pronounced in cases with bigger SAA (as visible within analysis cases with fixed SAA).

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Additional Slides

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General comments 1/2

1. Using thermal models for definition of SA steering profile at Mercury is very challenging and was never done before.
2. In this study is estimated the effect that albedo might have on SA. This effect changes based on real environment to be found at Mercury and on modelling assumptions: an improvement of models themselves might help, but will not solve the problem (thermal models limitations, software limitations in retro-reflection modelling, and limited knowledge of Mercury albedo itself).
3. The albedo predictions can be also influenced by Mercury albedo coefficients variations over the planet surface: this is an additional source of uncertainty, partially covered by the Planet IR compensation (higher albedo → lower IR). The overall effect was considered negligible by Industry but never quantified.

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General comments 2/2

4. The SA steering calibration at beginning of MPO orbit phases (after MOI) shall be carefully planned by taking extra margins: i.e. started with a target T lower than nominal and fine tuned once SA simplified model is considered properly validated with flight data.
5. A predefined table of sensitivity to SAA variations at different orbit positions and seasons might help the calibration itself and it is recommended (e.g. sensitivity to 1deg angle variation along mission). Simplified SA thermal model profiles might be corrected based on flight T measurements and these sensitivity tables.
6. Impact on SA thermal control, power budgets and operations should be discussed

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Temperature Differences between Albedo Models (1/2)

Case	Max/min ΔT Diffusive and Directional Reflection [K]	Max/min ΔT Diffusive and Retro- Reflection 0.12 [K]	Max/min ΔT Diffusive and Retro- Reflection 0.138 [K]
Perihelion a1y 90 deg	+13.9/-10.0	0.00/-12.33	0.00/-12.33
Perihelion a1y 88 deg	+7.6/-5.3	+5.37/-8.34	+6.79/-8.34
Perihelion a1y 75 deg	+5.5/-3.4	+9.99/-6.40	+11.82/-6.40
Perihelion a1y SAA profile	+7.6/-5.2		
Perihelion b1y 90 deg	+12.2/-10.1	+0.02/-12.37	+0.00/-12.37
Perihelion b1y 88 deg	+8.4/-6.3	+8.03/-9.62	+9.74/-9.62
Perihelion b1y 75 deg	+6.9/-4.4	+14.32/-7.92	+16.71/-7.92
Perihelion b1y SAA profile	+8.4/-7.0		
Perihelion b2y 90 deg	+6.8/-5.0	+0.00/-6.67	+0.00/-6.67
Perihelion b2y 88 deg	+3.8/-3.5	+1.20/-4.71	+1.72/-4.71
Perihelion b2y 75 deg	+2.4/-2.6	+3.34/-3.28	+4.08/-3.28
Perihelion b2y SAA profile	+3.7/-3.8		

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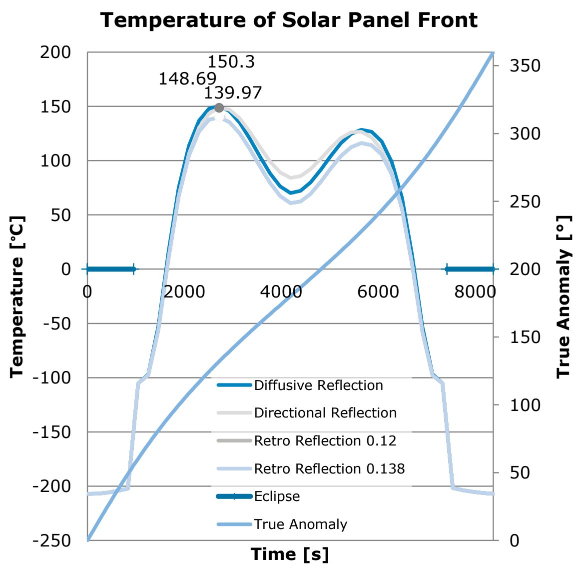
Temperature Differences between Albedo Models (2/2)

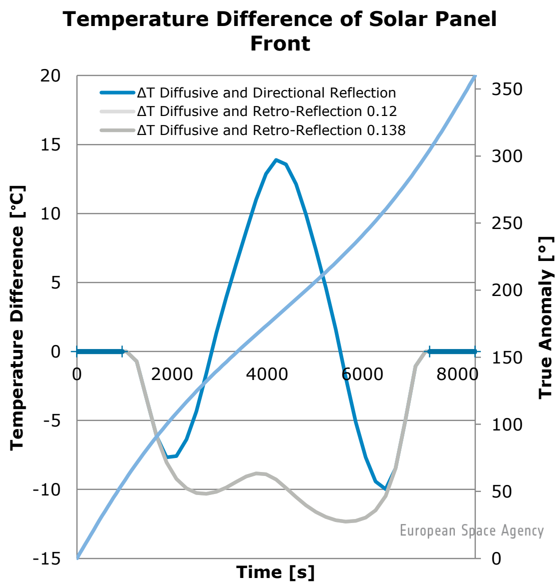
Case	Max/min ΔT Diffusive and Directional Reflection [K]	Max/min ΔT Diffusive and Retro- Reflection 0.12 [K]	Max/min ΔT Diffusive and Retro- Reflection 0.138 [K]
Aphelion a1y 90 deg	+13.4/-8.6	+0.00/-11.81	+0.00/-11.81
Aphelion a1y 88 deg	+9.0/-4.4	+0.00/-6.51	+0.00/-6.51
Aphelion a1y 75 deg	+6.9/-2.9	+2.50/-4.78	+3.52/-4.78
Aphelion a1y SAA profile	+7.3/-2.8		
Aphelion b1y 90 deg	+11.5/-8.6	+0.00/-11.75	+0.00/-11.75
Aphelion b1y 88 deg	+7.2/-4.4	+0.00/-6.51	+0.00/-6.51
Aphelion b1y 75 deg	+5.0/-2.9	+0.00/-4.08	+0.64/-4.08
Aphelion b1y SAA profile	+5.5/-2.7		
Aphelion b2y 90 deg	+6.4/-4.0	+0.00/-6.05	+0.00/-6.05
Aphelion b2y 88 deg	+5.8/-3.1	+0.68/-5.02	+1.21/-5.02
Aphelion b2y 75 deg	+6.2/-4.5	+4.43/-4.47	+5.42/-4.47
Aphelion b2y SAA profile	+5.6/-2.3		

Results (1/24): perihelion/outer panel/ SAA 90deg

Front Side	Back Side
OSR 47% EOL: α/ε = 0.601/0.827	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection





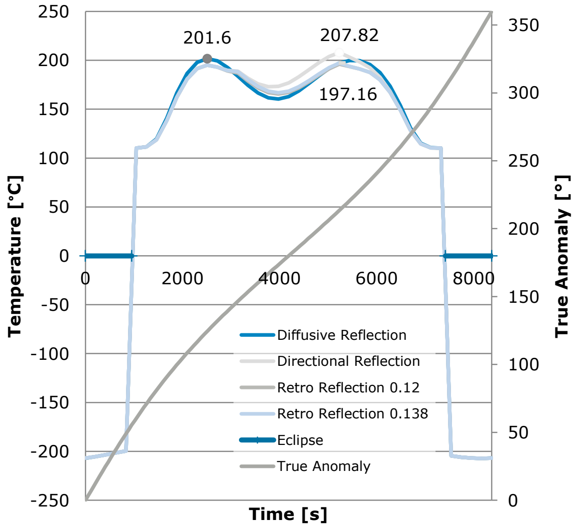
Results (2/24): perihelion/outer panel/ SAA 78deg

esa

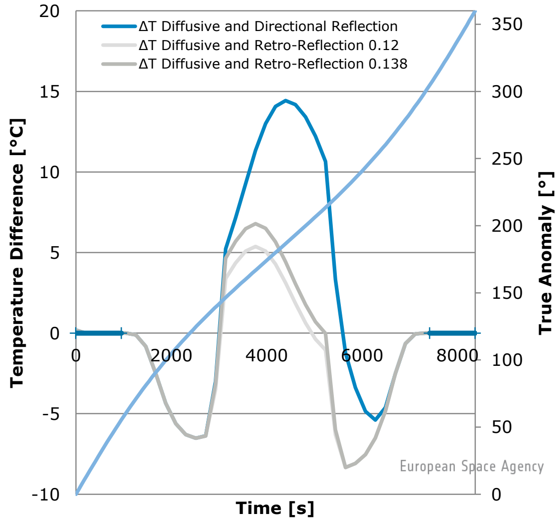
Front Side	Back Side
OSR 47% EOL: α/ε = 0.601/0.827	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front



Temperature Difference of Solar Panel Front



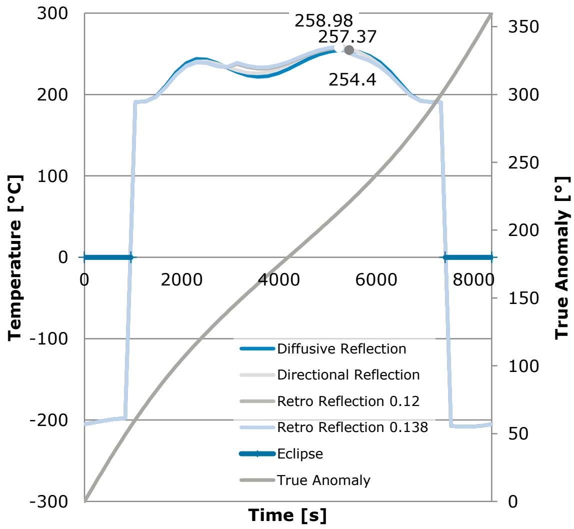
Results (3/24): perihelion/outer panel/ SAA 65deg

esa

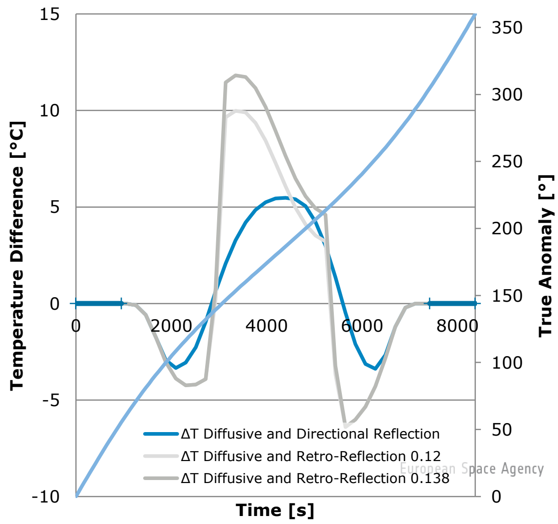
Front Side	Back Side
OSR 47% EOL: α/ε = 0.601/0.827	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front



Temperature Difference of Solar Panel Front



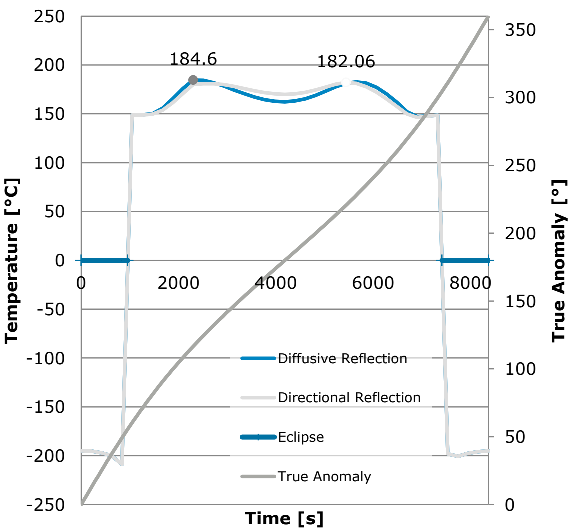
Results (4/24): perihelion/outer panel/ SAA profile

esa

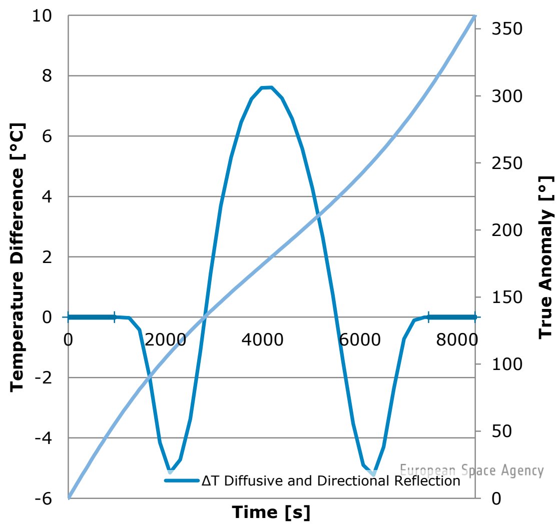
Front Side	Back Side
OSR 47% EOL: α/ε = 0.601/0.827	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front



Temperature Difference of Solar Panel Front



Results (5/24): perihelion/b1/SAA 90deg

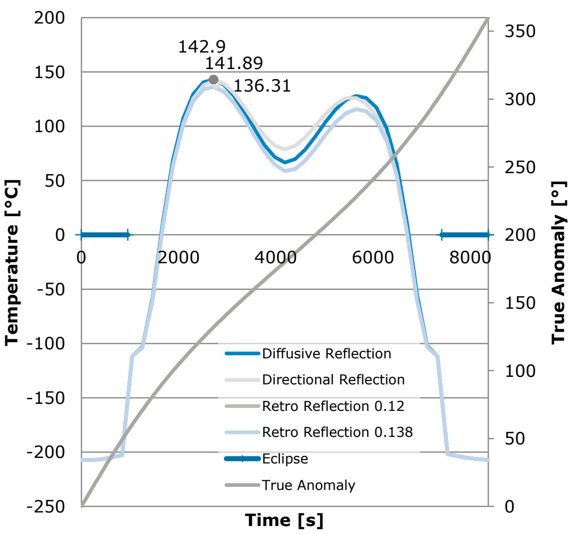
esa

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	Bare CFC EOL: α/ε = 0.92/0.825

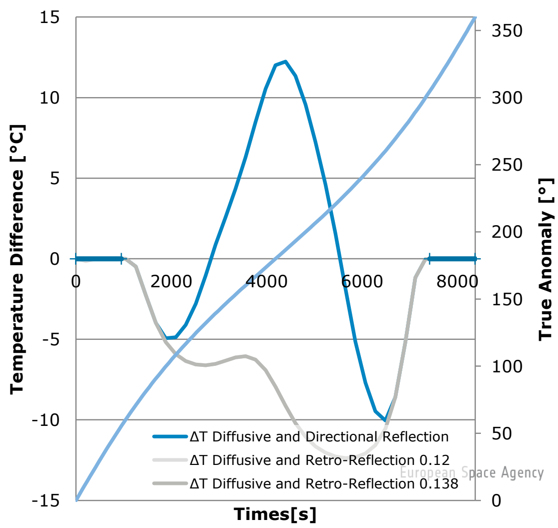
Case a2 is not realistic and not considered. Case b1 might apply to areas of panels 2 and 3 where locally the OSR percentage is higher than the average 47% (TBC if realistic).

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front



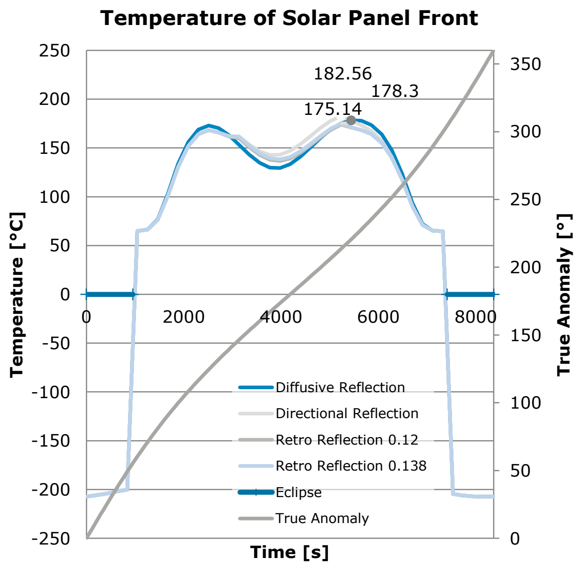
Temperature Difference of Solar Panel Front

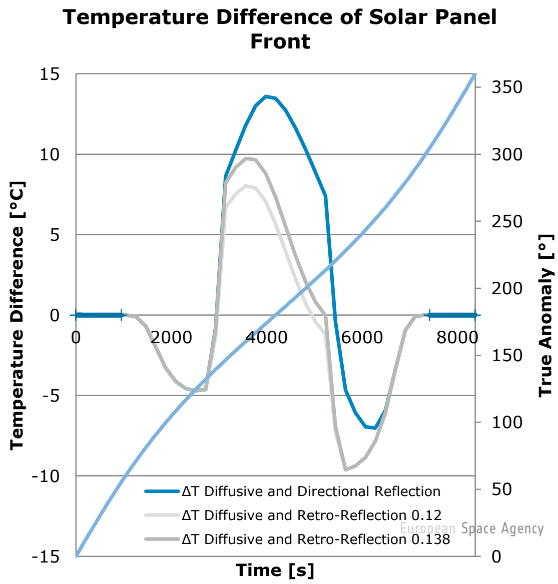


Results (6/24): perihelion/b1/SAA 78deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

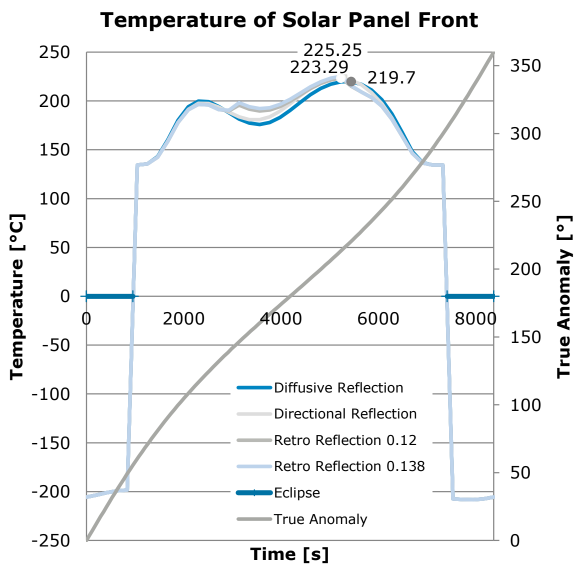


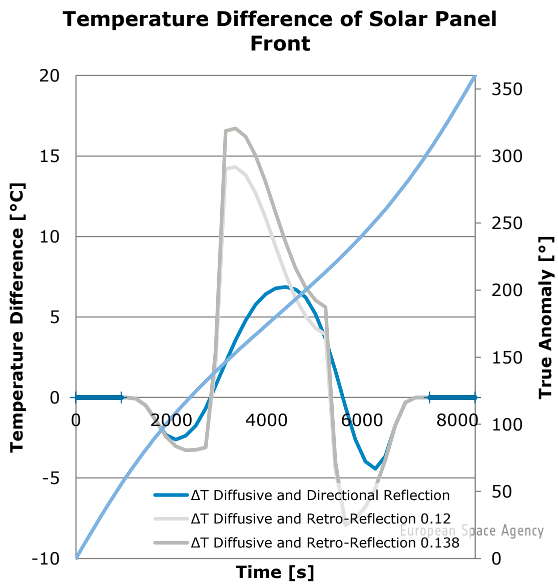


Results (7/24): perihelion/b1/SAA 65deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

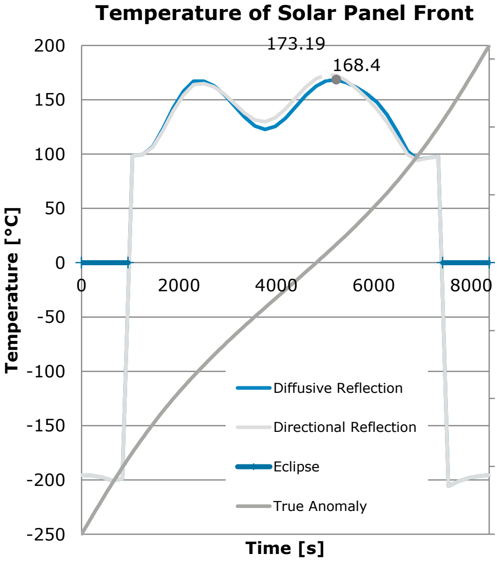


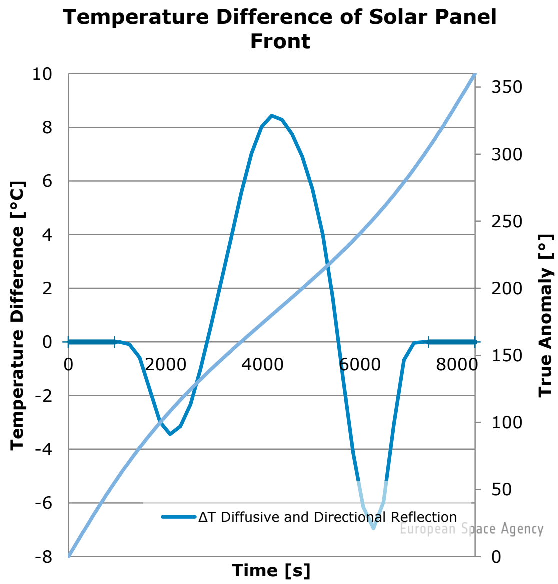


Results (8/24): perihelion/b1/SAA profile

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

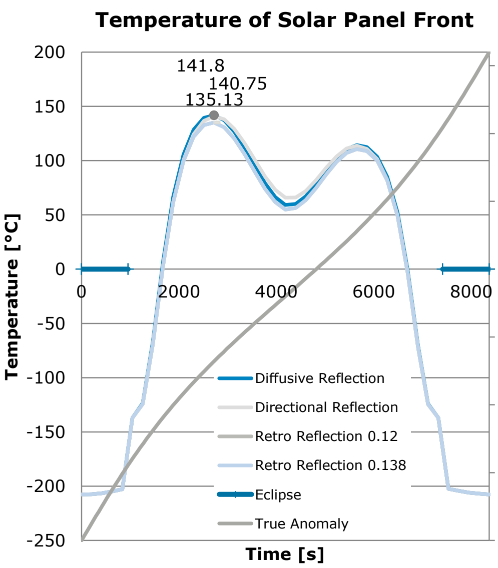


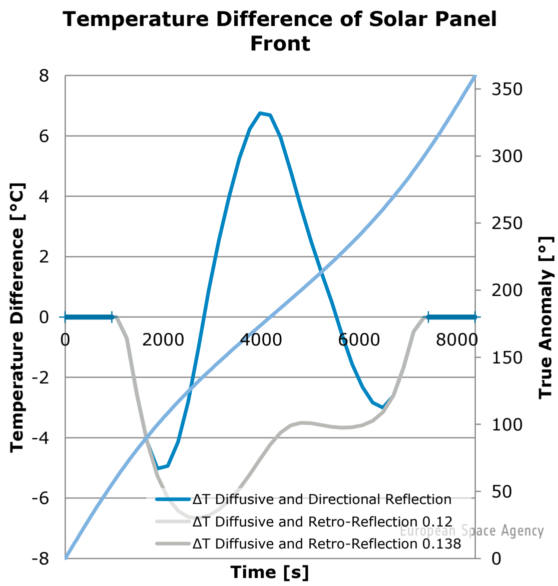


Results (9/24): perihelion/inner panel/ SAA 90deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	OSR 100% EOL: α/ε = 0.25/0.79

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

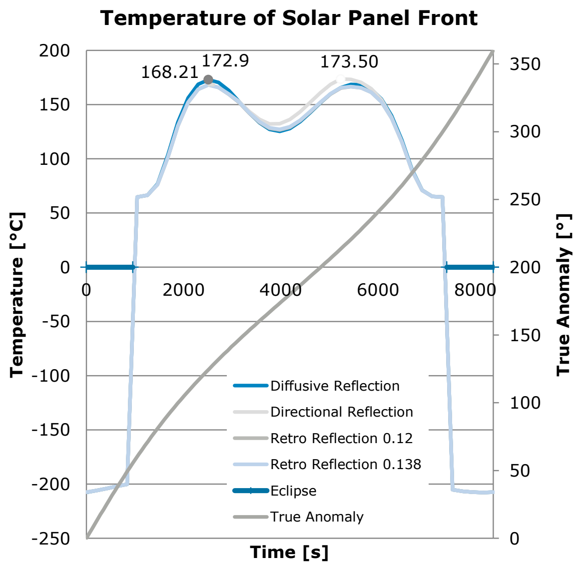


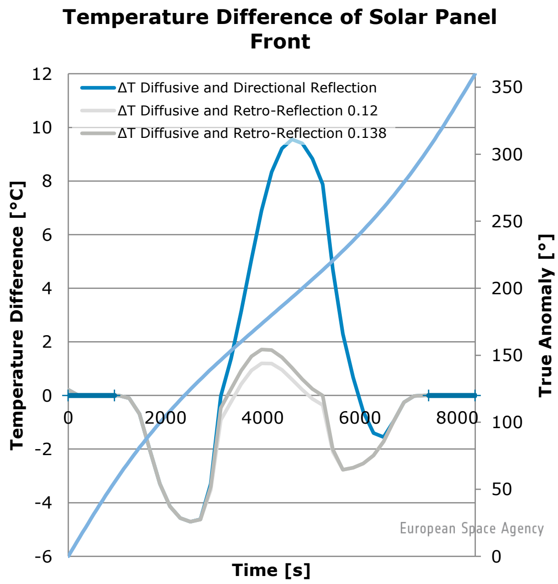


Results (10/24): perihelion/inner panel/ SAA 78deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	OSR 100% EOL: α/ε = 0.25/0.79

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

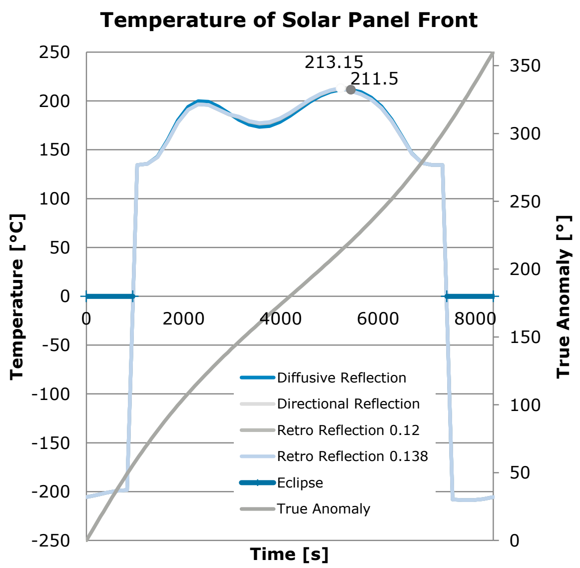


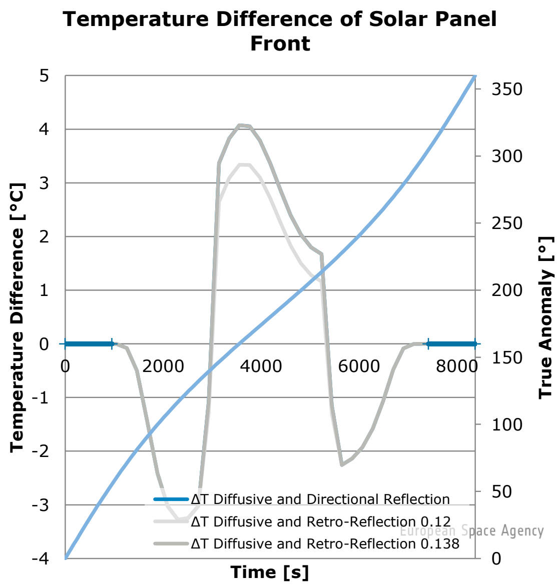


Results (11/24): perihelion/inner panel/ SAA 65deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	OSR 100% EOL: α/ε = 0.25/0.79

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

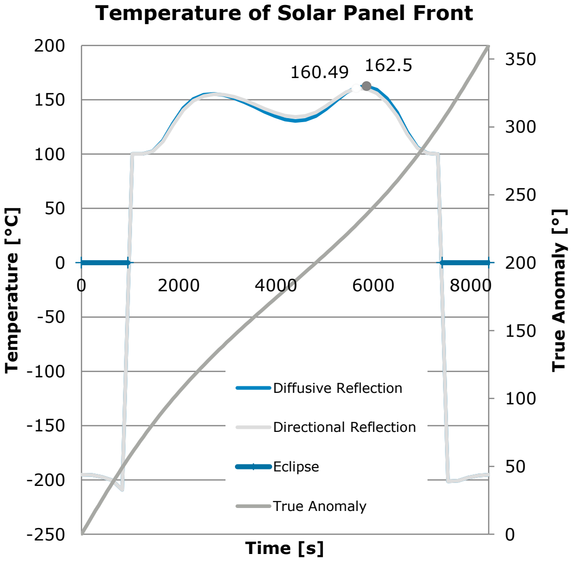


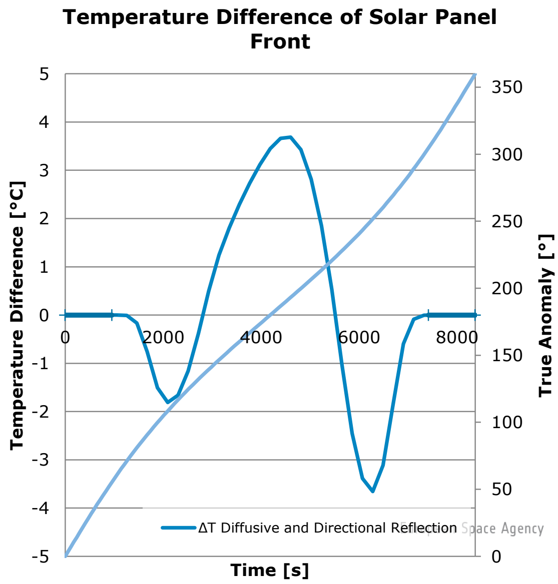


Results (12/24): perihelion/inner panel/ SAA profile

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	OSR 100% EOL: α/ε = 0.25/0.79

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

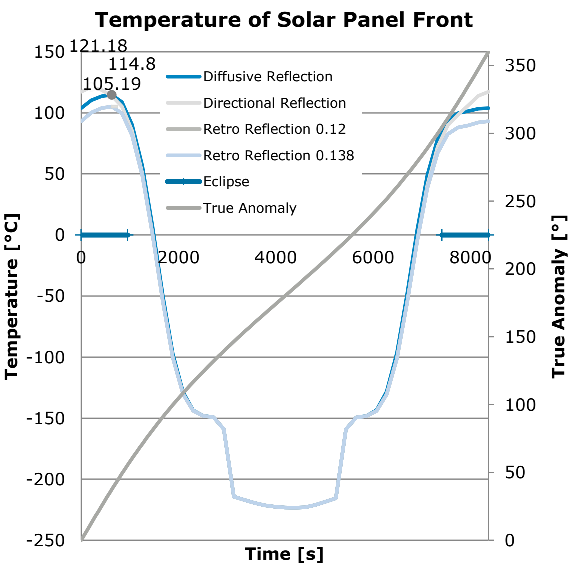


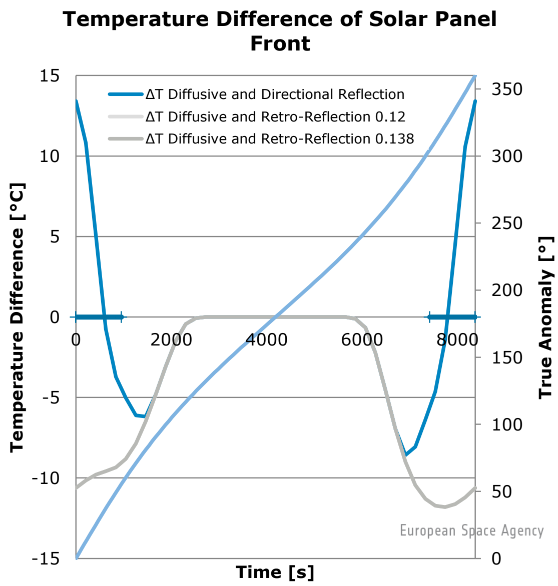


Results (13/24): aphelion/outer panel/ SAA 90deg

Front Side	Back Side
OSR 47% EOL: α/ε = 0.601/0.827	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection



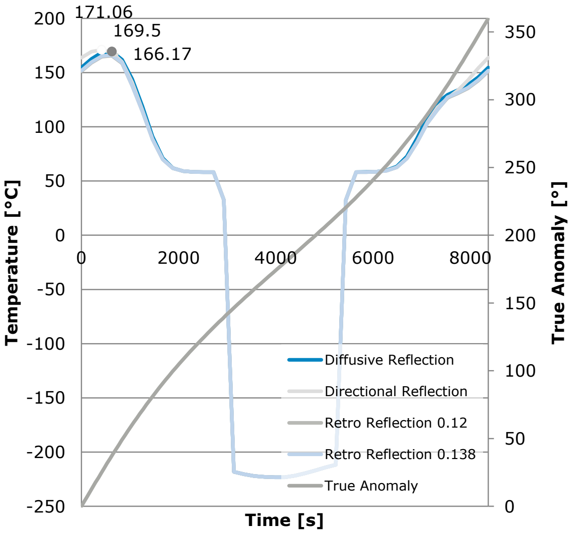


Results (14/24): aphelion/outer panel/ SAA 78deg

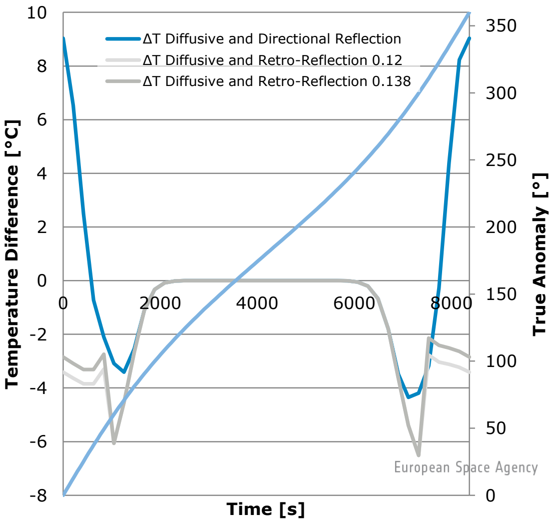
Front Side	Back Side
OSR 47% EOL: α/ε = 0.601/0.827	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front



Temperature Difference of Solar Panel Front

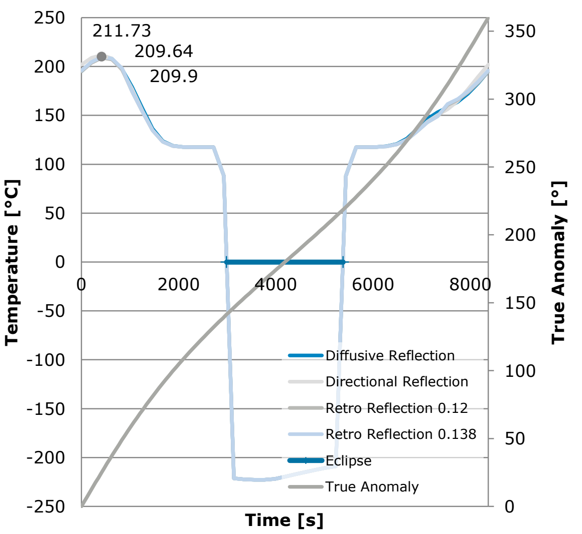


Results (15/24): aphelion/outer panel/ SAA 65deg

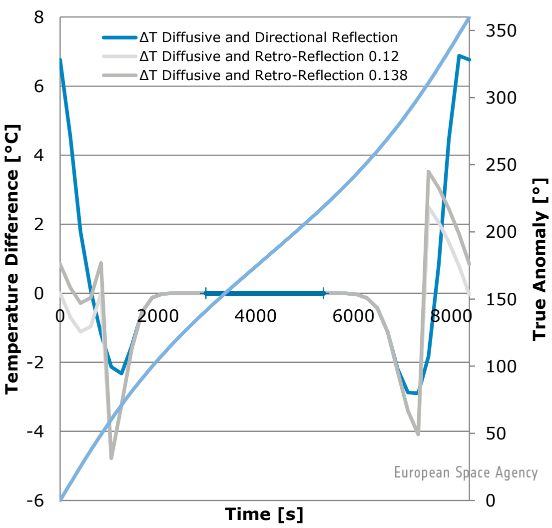
Front Side	Back Side
OSR 47% EOL: α/ε = 0.601/0.827	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front



Temperature Difference of Solar Panel Front



Results (16/24): aphelion/outer panel/ SAA profile

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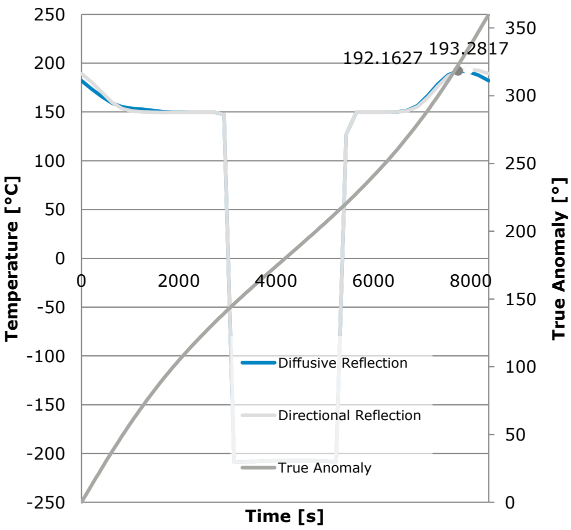
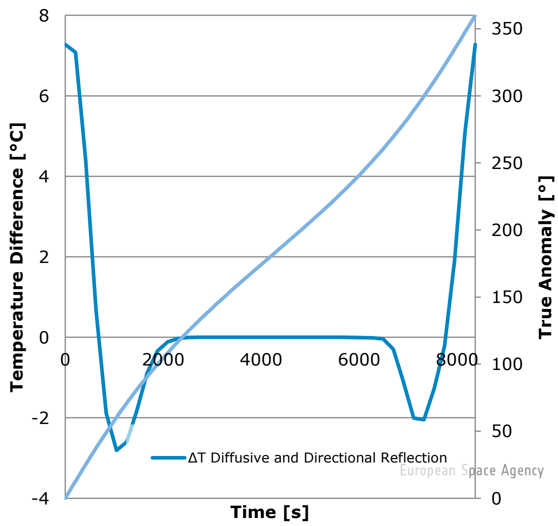
Front Side	Back Side
OSR 47% EOL: α/ε = 0.601/0.827	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front



Temperature Difference of Solar Panel Front



Results (17/24): aphelion/b1/SAA 90deg

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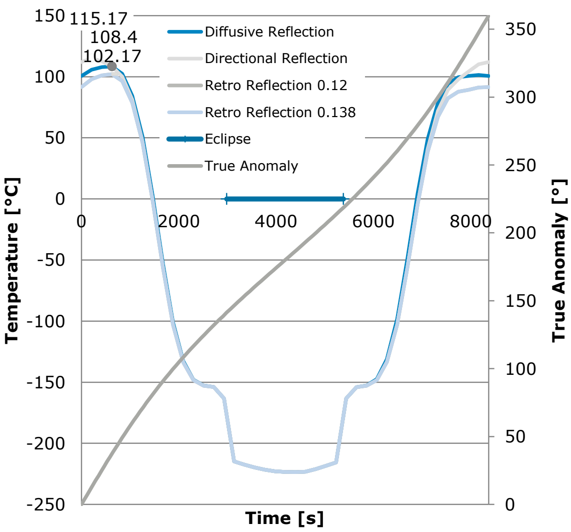
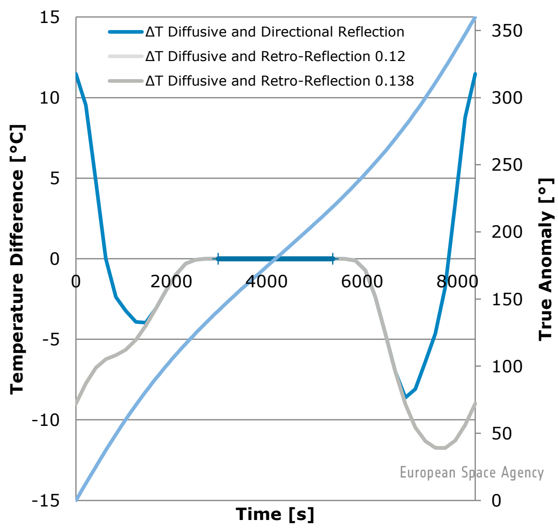
Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

Temperature of Solar Panel Front



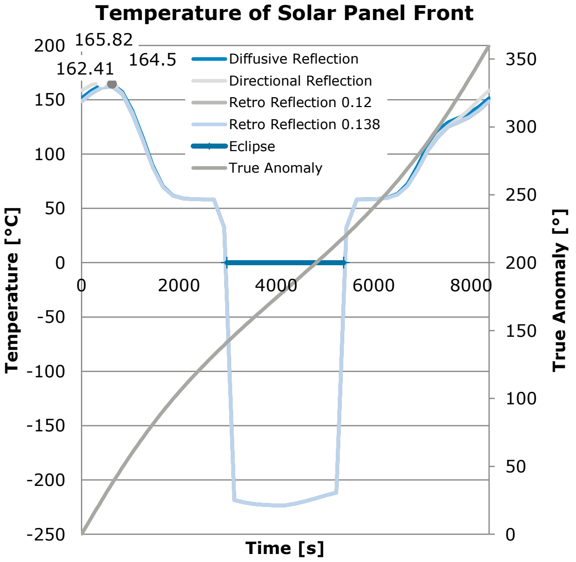
Temperature Difference of Solar Panel Front

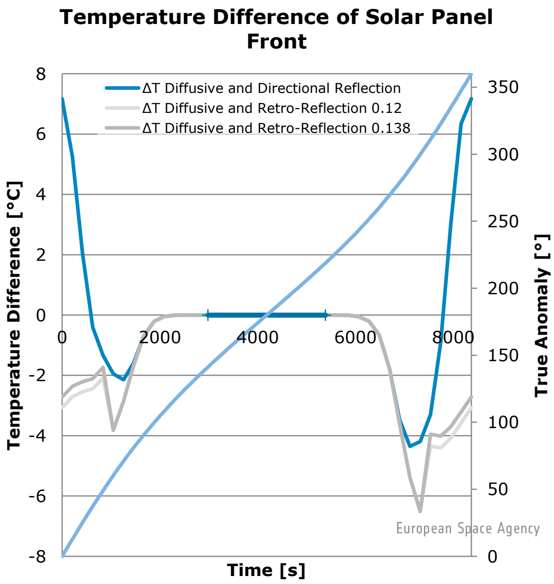


Results (18/24): aphelion/b1/SAA 78deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

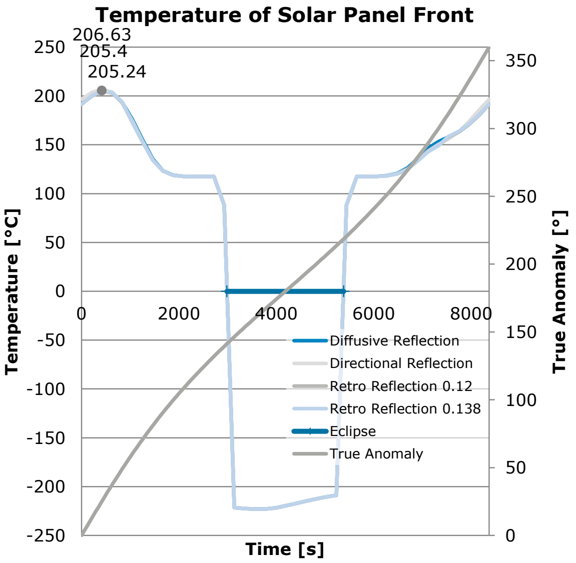


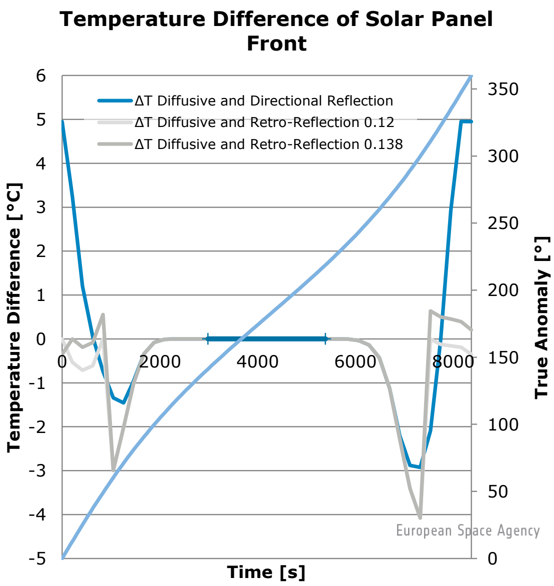


Results (19/24): aphelion/b1/SAA 65deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

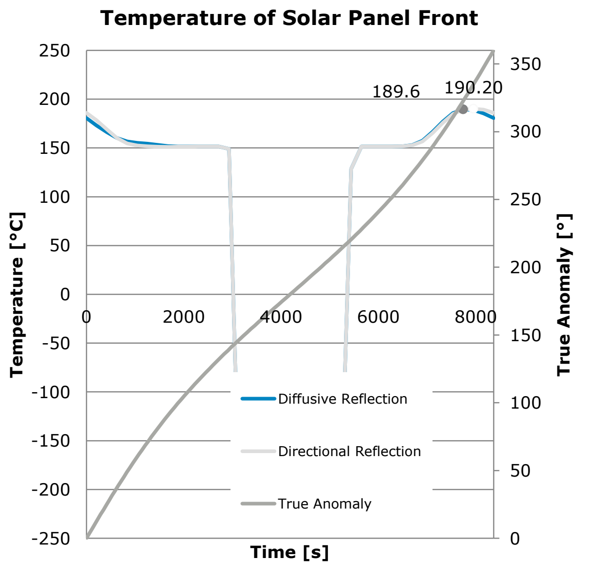


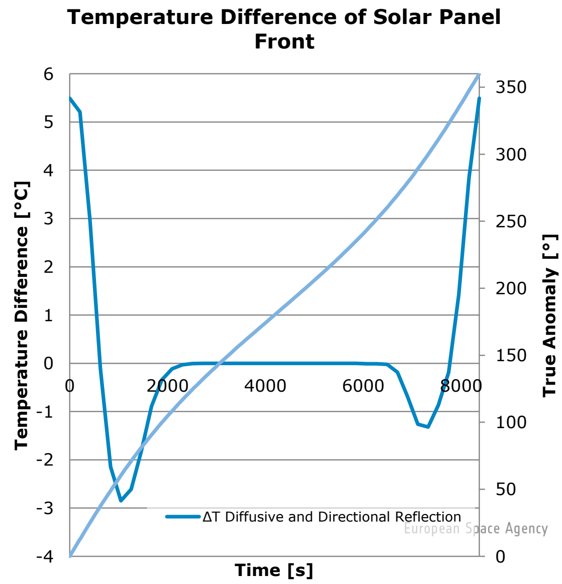


Results (20/24): aphelion/b1/SAA profile

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	Bare CFC EOL: α/ε = 0.92/0.825

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

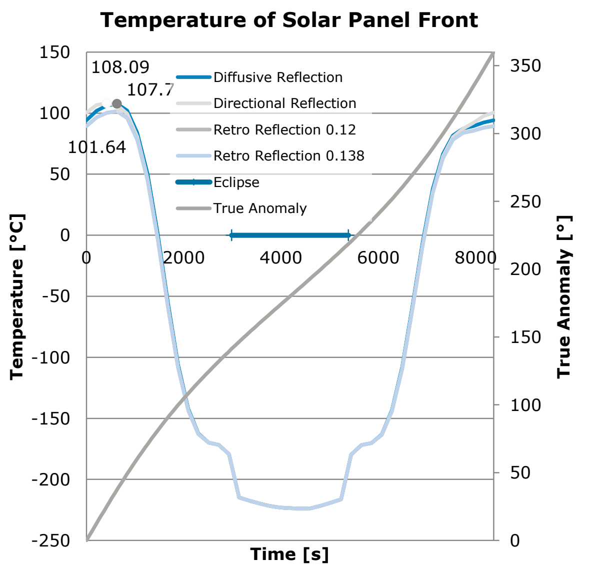


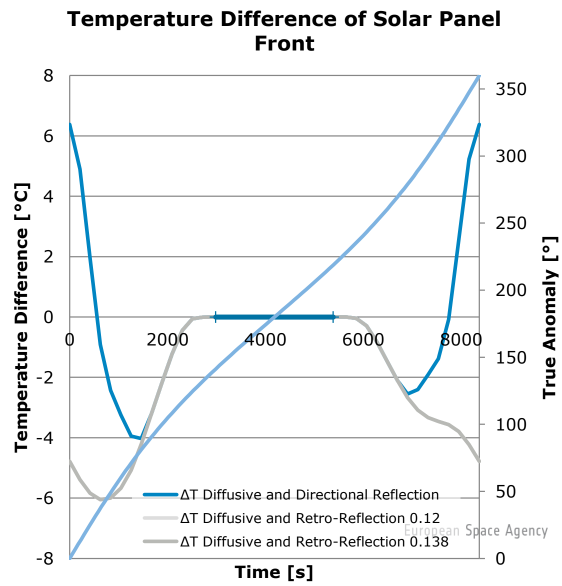


Results (21/24): aphelion/inner panel/ SAA 90deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	OSR 100% EOL: α/ε = 0.25/0.79

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

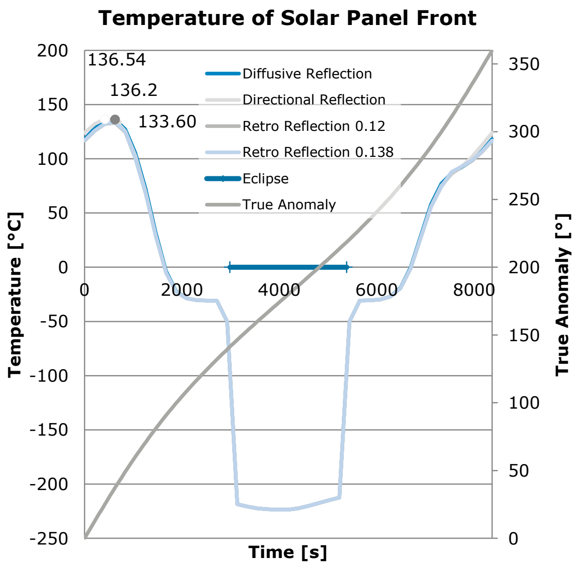


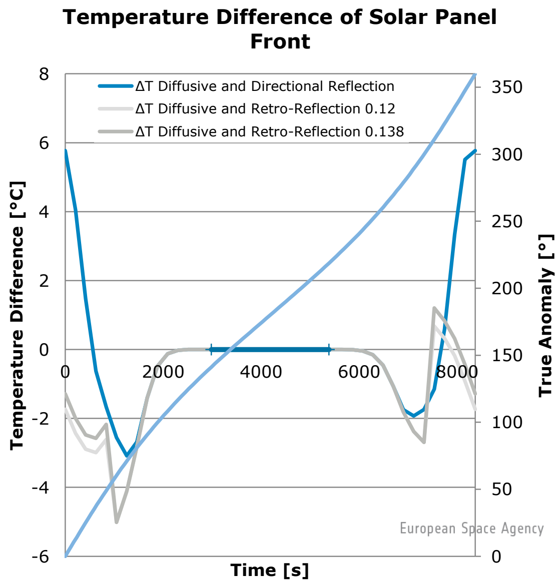


Results (22/24): aphelion/inner panel/ SAA 78deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	OSR 100% EOL: α/ε = 0.25/0.79

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection

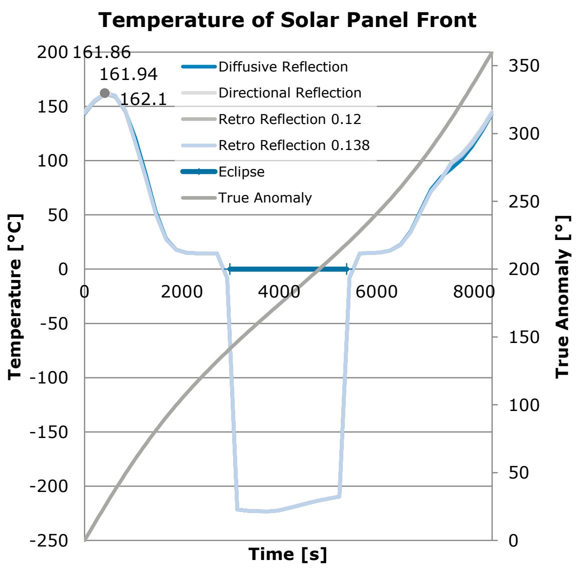


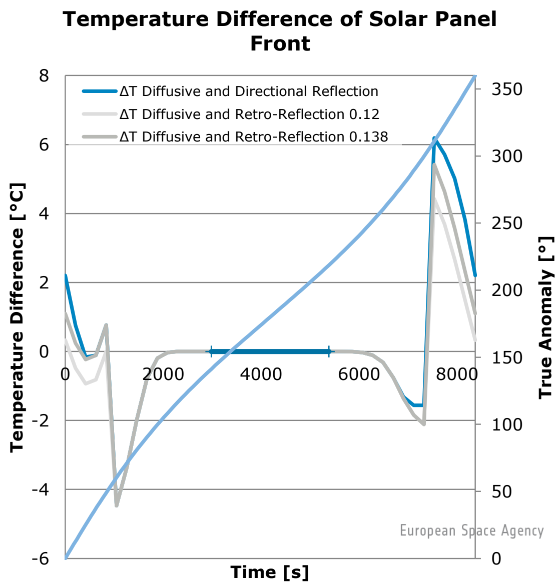


Results (23/24): aphelion/inner panel/ SAA 65deg

Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	OSR 100% EOL: α/ε = 0.25/0.79

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection





Results (24/24): aphelion/inner panel/ SAA profile

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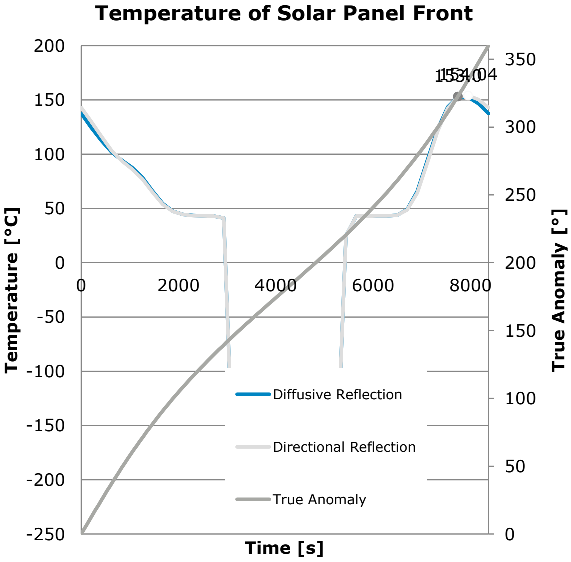
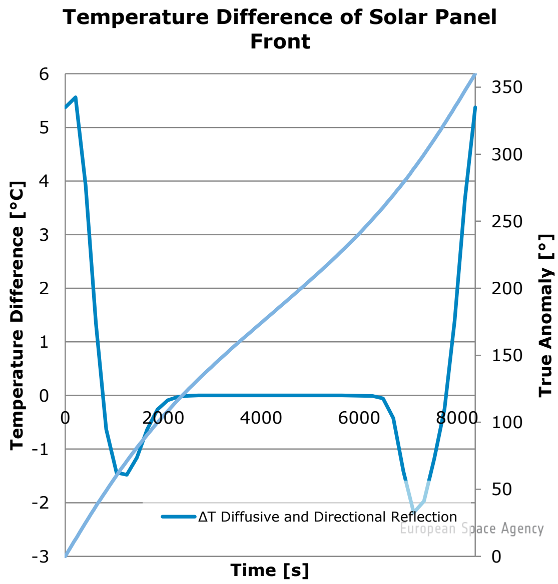
Front Side	Back Side
OSR 82% EOL: α/ε = 0.372/0.803	OSR 100% EOL: α/ε = 0.25/0.79

ΔT logic: ΔT positive means that the retro-reflection approach gives higher T than the diffusive (Lambertian) reflection





European Space Agency

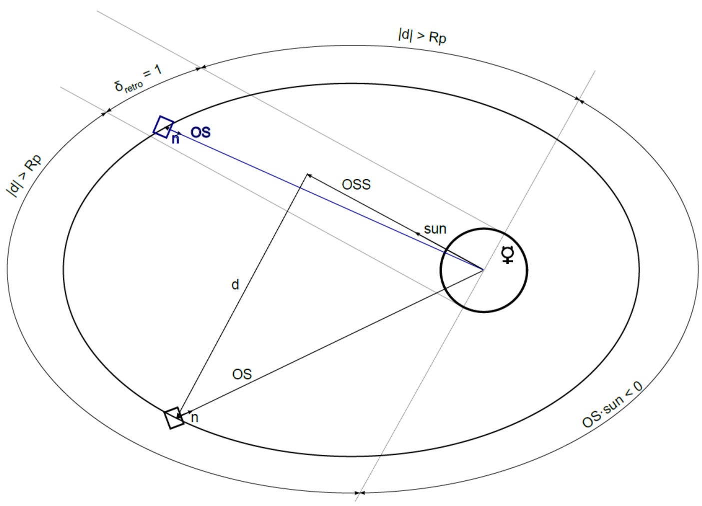
Only retro-reflection

esa

The orbit is divided in three regions with δ_{retro} as the indicator function:

$$\delta_{retro_j} := \begin{cases} 0 & \text{if } \mathbf{OS_o}^{\langle j \rangle} \cdot \mathbf{sun_o} < 0 \\ 0 & \text{if } \left|\mathbf{d}^{\langle j \rangle}\right| > \mathbf{R_p} \\ 1 & \text{otherwise} \end{cases}$$

$$\mathbf{OSS} = (\mathbf{OS} \cdot \mathbf{sun}) \cdot \mathbf{sun}$$
$$\mathbf{d} = \mathbf{OS} - \mathbf{OSS}$$



OS	Position vector
R_p	Planet's mean radius
sun	Solar unit vector (unit vector from the center of the planet pointing to the sun)

European Space Agency

Only retro-reflection

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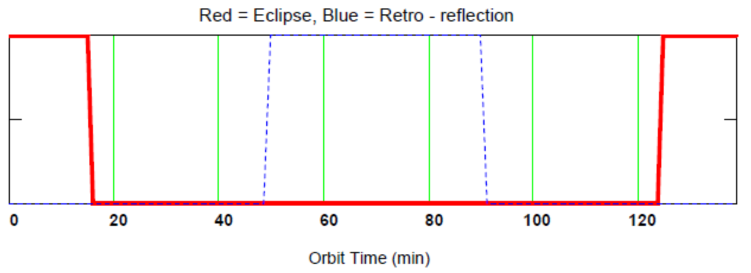
- The orbit is allocated into a number of points along the orbit (different positions).
- The start and end points of the retro-reflection cylinder are found by counting along the orbit until δ_{retro} becomes 1 and then 0, respectively.
- The respective points represent positions along the orbit and therefore specific times.



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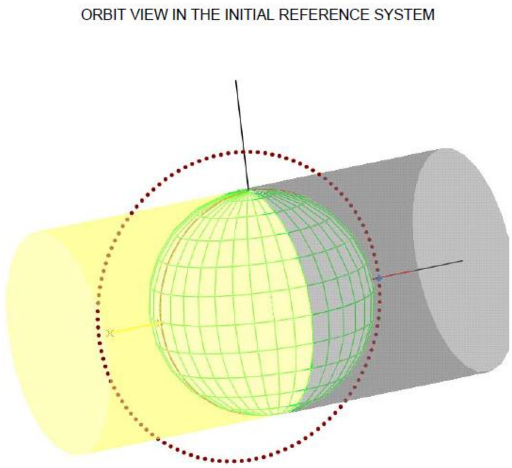
Only retro-reflection

esa

- Albedo is assumed to be reflected back in the direction of the sun
- Like the eclipse, it is assumed as a cylinder



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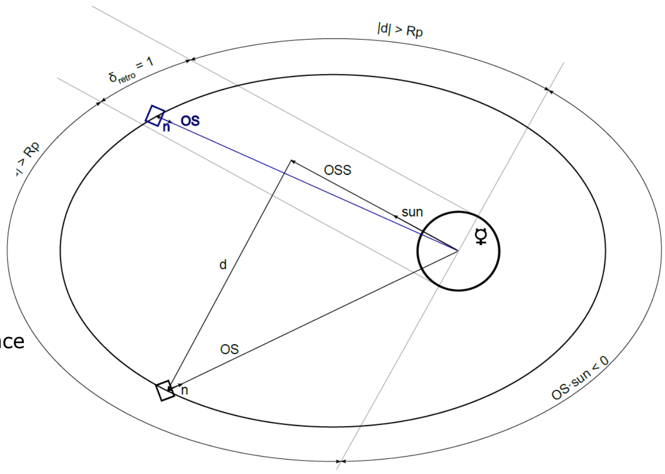
Only retro-reflection

$$C2_{SA_{k,j}} := \begin{cases} F \leftarrow 0 & \text{if } (n_{o_{k,j}} \cdot sun_o) > 0 \\ F \leftarrow -(n_{o_{k,j}} \cdot sun_o) & \text{otherwise} \end{cases}$$

$$QA_{k,j} := SC \cdot a \cdot \alpha_k \cdot A_k \cdot C2_{SA_{k,j}} \cdot \delta_{retro_j}$$

QA	Absorbed Albedo flux
n	Normal to the surfaces
SC	Solar flux
α	Visible, hemispherical absorptance
A	Area
C2	Aspect angle of the surface
a	Planet Albedo coefficient



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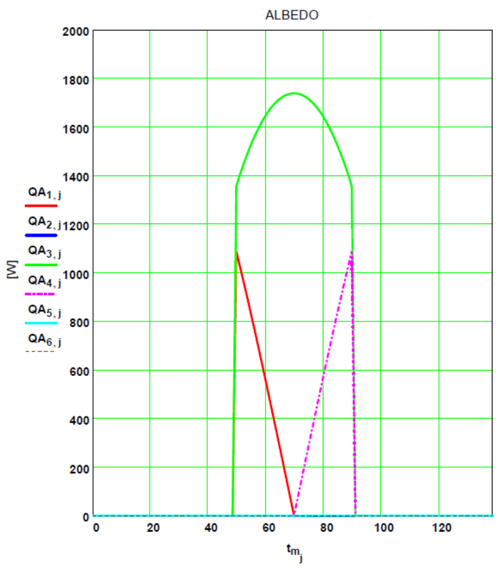
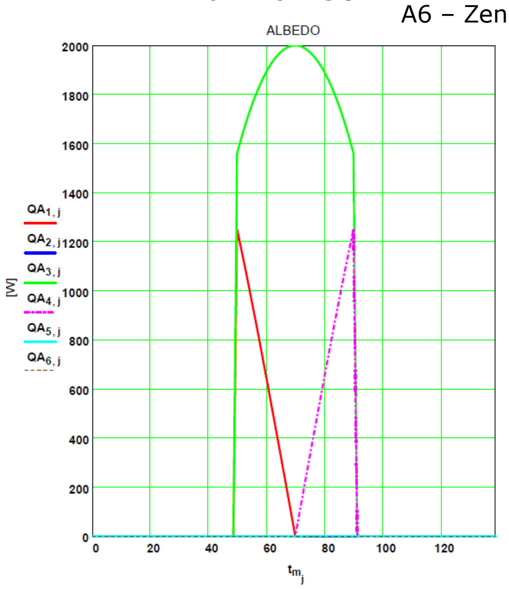
Only retro-reflection – reference case

A1 – Anti- Velocity
A2 – Normal to Orbit
A3 – Nadir
A4 – Velocity
A5 – Normal to Orbit
A6 – Zenith

a = 0.12



a = 0.138



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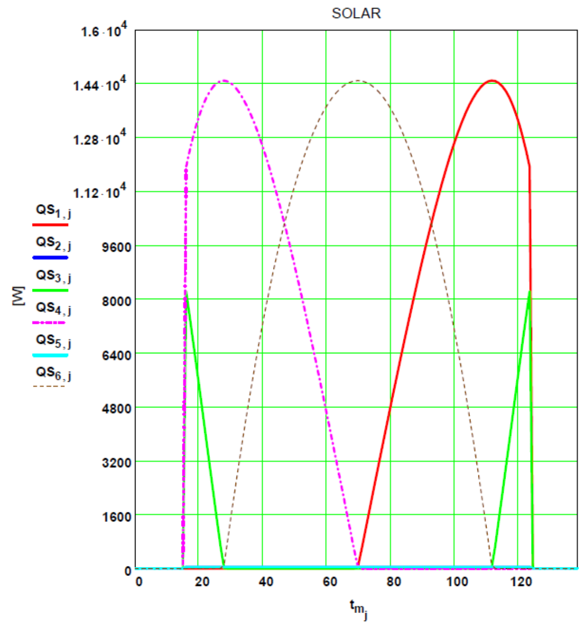
Solar Heat Fluxes – reference case

Perihelion case: incident (*) Solar heat fluxes calculated on a nadir pointing orbiting cube of 1m side



A1 – Anti- Velocity
A2 – Normal to Orbit
A3 – Nadir
A4 – Velocity
A5 – Normal to Orbit
A6 – Zenith

(*) incident → absorbed by 1sqm black body surface

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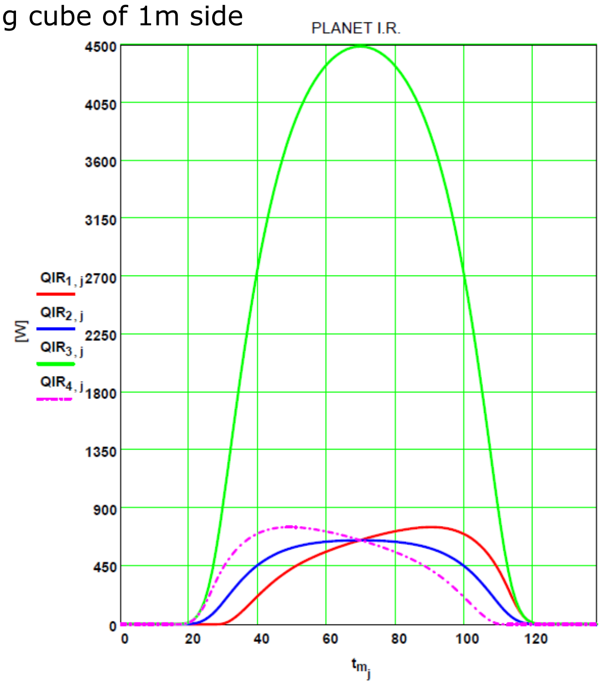
IR Radiation Heat Fluxes – reference case

Perihelion case: incident (*) IR heat fluxes calculated on a nadir pointing orbiting cube of 1m side



A1 – Anti- Velocity
A2 – Normal to Orbit
A3 – Nadir
A4 – Velocity
A5 – Normal to Orbit
A6 – Zenith

(*) incident → absorbed by 1sqm black body surface

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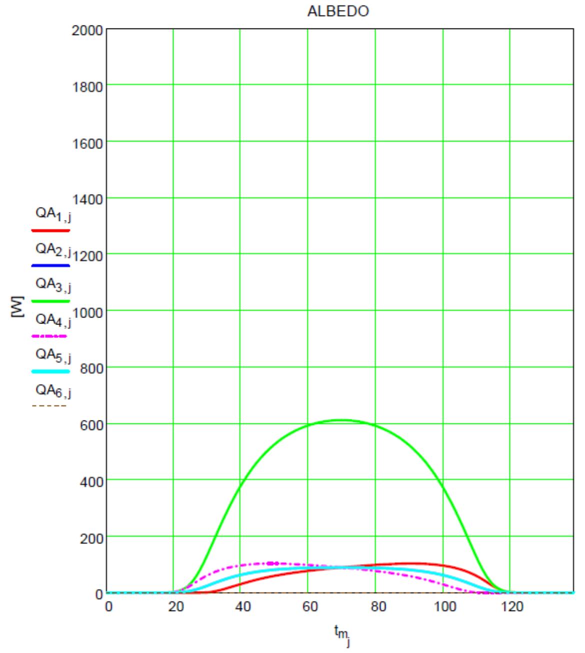
Albedo Heat Fluxes (diffusive model) – reference case

esa

Perihelion case: incident (*) Albedo heat fluxes calculated on a nadir pointing orbiting cube of 1m side



A1 – Anti- Velocity
A2 – Normal to Orbit
A3 – Nadir
A4 – Velocity
A5 – Normal to Orbit
A6 – Zenith

(*) incident → absorbed by 1sqm black body surface

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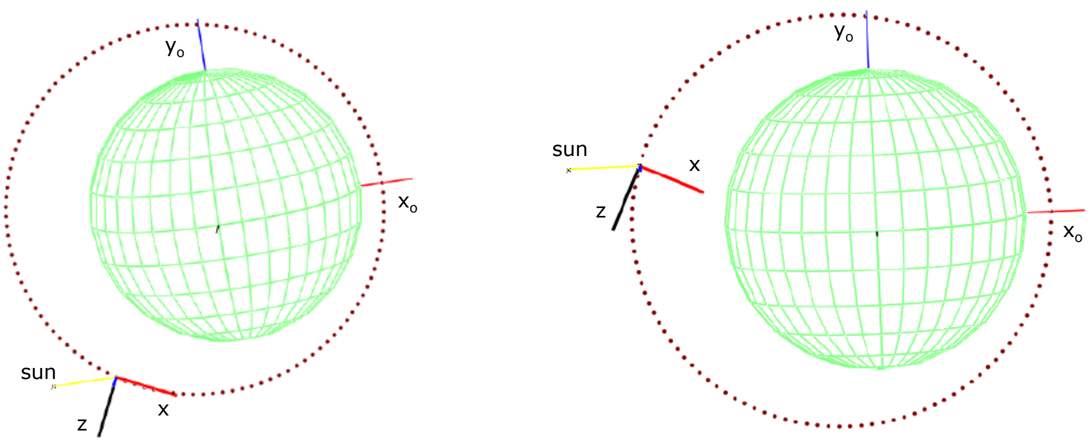
Solar Panel Attitude

esa



SAA (Sun Aspect Angle): angle between solar panel and sun vector
- Solar array plane is represented by the XZ plane
- SAA=90° means Sun lies within the XZ plane (no energy)

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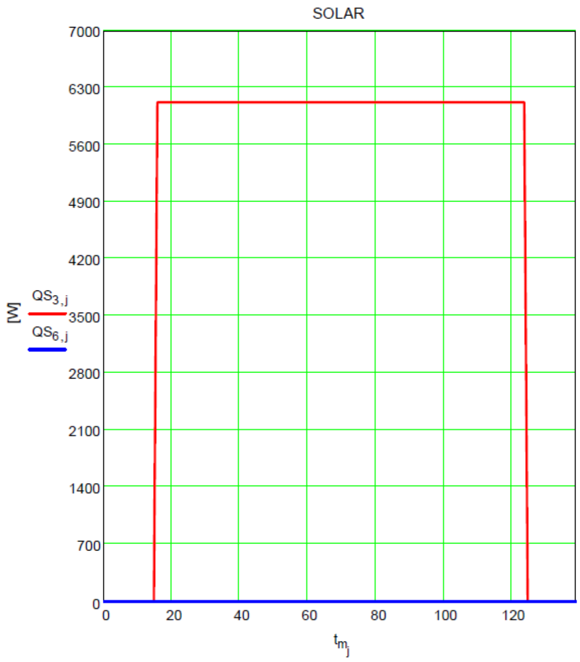
Solar Flux – SAA = 65°



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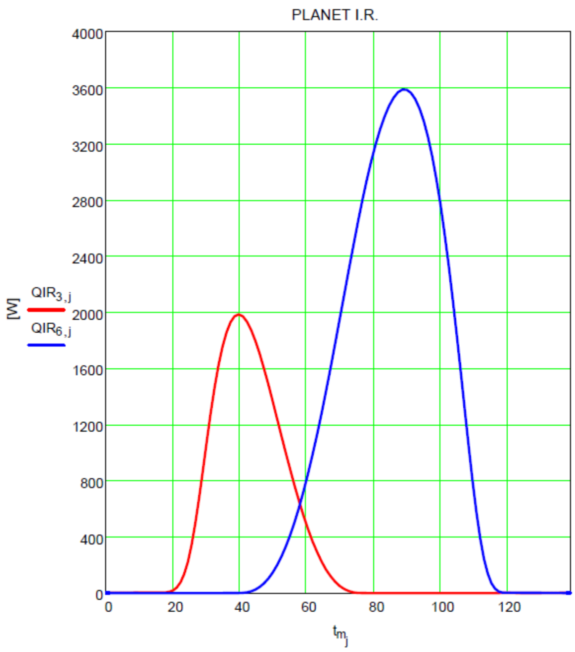
IR Planetary Radiation – SAA = 65°



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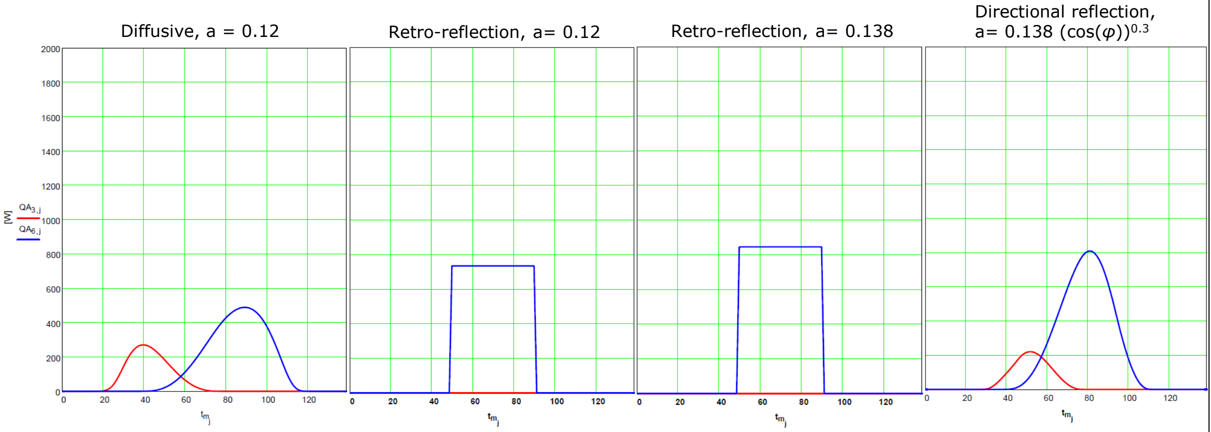
Albedo heat fluxes comparison (SA with SAA=65°)

- Directional albedo is considered the most realistic approach
- Differences in peak Albedo fluxes can be significant between the different models



QA6: Albedo flux incident on SA front side
QA3 : Albedo flux incident on SA back side

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