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Modelling of the Transient Environmental Heat Load on the ALADIN Instrument in an Arbitrary ISS-Related Orbit

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ABSTRACT

The described thermal model is part of the Lidar Performance Analysis Simulator (LIPAS), a simulator of the Atmospheric Laser Doppler Instrument ALADIN.

The developed model calculates the transient environmental heat load on ALADIN and gives an overall instrument temperature prediction. The heat load model accounts for the fact that the ISS orbit is a non-fixed one, and is therefore essentially based on the actual position of the spacecraft, rather than on orbit parameters.

In order to verify the validity of the model developed, results are compared with results from other heat load programs.

INTRODUCTION

The Lidar Performance Analysis Simulator (LIPAS) simulates the Doppler Wind Lidar ALADIN accommodated on the International Space Station (ISS) as specified in the Atmospheric Dynamics Mission (ADM) assessment report of the European Space Agency ESA [1],[2]. The National Aerospace Laboratory NLR, together with the Royal Netherlands Meteorological Institute KNMI, developed the simulator under ESA contract. National funding from the Netherlands Agency for Aerospace Programmes (NIVR) was available to cover part of the development cost.

SIMULATION ENVIRONMENT

The LIPAS-simulator [3] is implemented in the modular EuroSim real-time simulator environment [4]. The EuroSim facility is a real-time simulation environment, which is especially well suited if model source code is already available, both in Fortran and C. EuroSim gives a framework where models can be combined in a structured manner (see Figure 1). It takes care of communication between models using an Application Programming Interface (API) [5].
Other interesting features include:

- The dynamic scheduling and scheduling support

- The easy definition and submitting of discrete events using the Mission Definition Language (MDL)
- The easy definition of monitors, and recorders using the MDL
- The test analyser, using the PV-WAVE package.
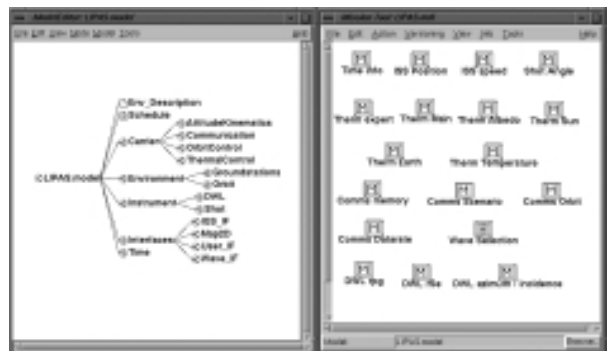
Figure 1: EuroSim Model Editor and Mission Tool with monitors and recorders

LIPAS SIMULATOR

The LIPAS simulator is a mission level simulation tool of the space-based Doppler Wind Lidar ALADIN. The objective is to simulate the performance of the essential elements of the mission in an flexible end-to-end framework. A functional breakdown is given in Figure 2. Scientific, technical and visualisation parts are distinguished.

Figure 2: Functional breakdown of the LIPAS simulator

The scientific issues are directly related to the wind measurements. The technical part concerns the accommodation of the instrument on the ISS. It includes:
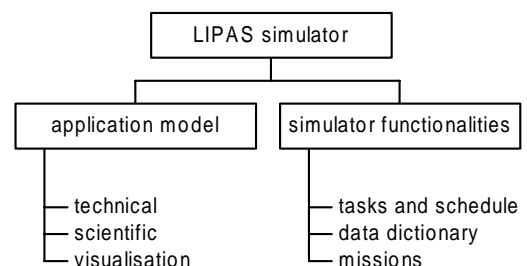
- The Laser schedule
- The ISS orbit, which contains ESOC's Position and Environmental Model (PEM) for orbit determination.
- The ISS attitude, which includes a kinematic attitude model of ISS.
- The shot pattern, which determines the location on the surface of separate laser pulses and cluster centroids.
- Communication
- The thermal model, which gives a first estimate of the thermal loading by radiation and the overall instrument temperature.

The interactions between the important components of the technical part are presented in Figure 3.
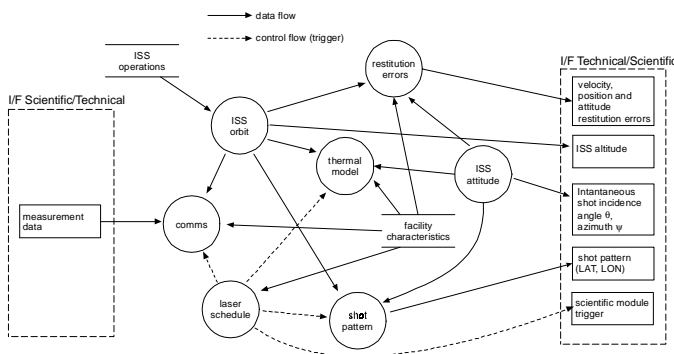

Figure 3: LIPAS Technical modules interaction

The simulator functionalities (Figure 2) take care of the proper timing and running of all modules (tasks and schedule).

THERMAL MODULE

One of the implemented modules is the thermal module. This paper is to describe this model and its possibilities.

OBJECTIVE

The objective of the thermal module is to calculate the heat load on the outside surfaces of the LIDAR instrument and to give an overall instrument temperature prediction. At the same time it had to fit in the cost-effective flexible approach of the LIPAS study, suited to contribute to the phase A study of the ALADIN project.

APPROACH

The major difference between the LIPAS thermal model calculations compared to ordinary heat load calculations is the varying orbit. The ALADIN instrument is attached to the ISS and is therefore subjected to monthly orbit

corrections, which make, commonly used, fixed orbit calculations inappropriate.

Three options are considered to cope with this problem:

1. Adapt and implement an existing thermal solver in the LIPAS-simulator.
2. Create a library of heat fluxes for the whole possible orbit range.
3. Develop a thermal module calculating the incident heat fluxes directly based on instrument position.

Although it fits very well in the LIPAS-philosophy to use existing S/W, option 1 is abandoned because most thermal solvers deal with fixed orbits (fixed orbit parameters) as input for orbital heat load calculations and are not easily adapted to predict heat loads on an instrument in a varying orbit.
Option 2 is only limited applicable and is only used to calculate the variations of the planet heat input in orbit height, earth temperature, ascending node, and solar inclination. These variations are implemented in the model as parameter dependent factors. Application of this approach to calculate complete heat fluxes is not possible without fixing the outside shape and orientation of the ALADIN instrument in order to fix view factors with the earth surface. Fixing shape and orientation is unacceptable and therefore a thermal module was developed (option 3) to calculate the incident heat fluxes directly based on instrument position. The model is developed in the C programming language. The layout of the module and the calculations are described and discussed below.

LAYOUT

In Figure 4 a schematic layout of the thermal module is given showing an overview of the input and output.
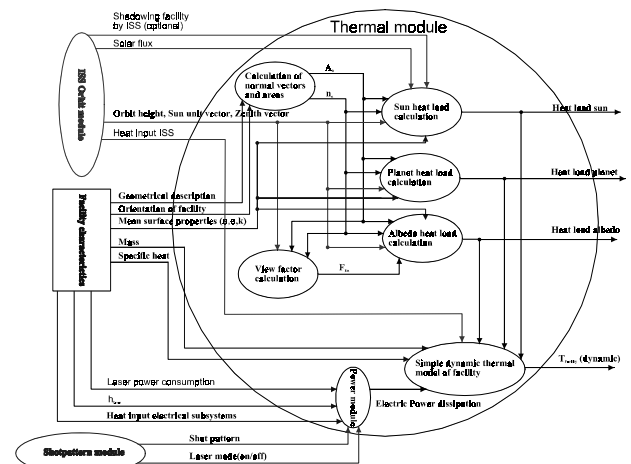

Figure 4: Thermal module lay-out

The input consists of different input variables and parameters of the orbit module, shotpattern module and a user input file describing the facility characteristics, including:

- the outside geometry of the facility
- the orientation of the facility
- the mean surface properties (solar absorption coefficient, IR-emission coefficient)

PROCESSING

The sub-modules shown in Figure 4 represent separate calculations. The interactions between the sub-modules are indicated with arrows. The output of the model is shown on the right side of the module. To come to a clear build-up of the module, the thermal model is divided into six sub-modules:

- Calculation of normal vectors and surface areas of the instrument.
- View factor calculation.
- Sun heat load calculation.
- Planet heat load calculation.
- Albedo heat load calculation.
- Power dissipation calculation
- Simple dynamic thermal model of the instrument.

The normal vectors (n_n) and surface areas (A_n) of the instrument will be calculated at the start of the simulation in the given sub-module. During the simulation only changes in orientation of the instrument can influence the direction of the normal vectors. The surface areas are of course assumed to stay constant.

When the normal vectors are known the sun heat load and the planet heat load can be calculated in the corresponding sub-modules.

Sun heat load calculation

The solar heat load follows straightforward from the orientation of the facility with regard to the sun:

$$Q_{sun} = A_n \cdot \varepsilon_n \cdot \cos(v_{SattoSun}, n_n) \cdot S_{Flux} \tag{1}$$

where:

Q_{sun}	: Sun heat load on facility surfaces [Watt]
A_n	: Surface area of the facility surfaces [m^2]
ε_n	: Solar absorption coefficient [-]
n_n	: Normal vector of the facility surfaces [-]
$v_{sattosun}$	: Vector pointing from facility to sun in IGM [-]
S_{flux}	: Solar flux [Watt/m^2]

Planet heat load calculation

The planet heat load varies only slightly by height, sun inclination, ascending node, or differences in night-day temperature. These variations have been calculated with VWHEAT, fit in equations and implemented in the LIPAS planet heat load sub-module using equation 2.

$$Q_{Planet} = A_n \cdot \alpha_n \cdot F_{Height} \cdot F_{Solarincl} \cdot F_{AscendingNode} \cdot$$
$$(1 + F_{OrbitEarthPhase} \cdot F_{ThermEarthTemp}) \cdot (\frac{VF_{n,Tot}}{C_{VF}}) \cdot Q_{StandardHeatLoad} \tag{2}$$

with:

Q_{Planet}	: Planet heat load on facility surfaces [Watt]
$Q_{Standardxdheatload}$	: Heat load on bottom surface under standard conditions [Watt]
α_n	: IR absorption coefficient [-]
F_{Height}	: Height correction factor [-]
$F_{Solarincl}$	: Correction factor for variation in solar inclination [-]
$F_{AscendingNode}$	: Correction factor for variation in ascending node [-]
$F_{OrbitEarthPhase}$	: Percentage earth surface in sunlight [-]
$F_{ThermEarthTemp}$	: Correction factor for temperature rise of the earth surface in sunshine [-]
$VF_{n,Tot}$	: The overall view factor between facility surface and earth surface [-]
C_{VF}	: Standard overall view factor between bottom surface and earth surface [-]

Before the albedo heat load can be calculated, the view factors have to be known. This view factor (VF_n) calculation between earth and each instrument surface is performed in a special sub-module, discussed below.

View factor calculation

In general the view factor is calculated by solving the following two-dimensional integral [6]:

$$VF_{12} = \int_{A_1} \int_{A_2} \frac{\cos\alpha_1 \cdot \cos\alpha_2}{\pi \cdot r_{12}^2} \cdot dA_1 \cdot dA_2 \tag{3}$$

where:

r_{12}	: is the distance of a point on surface A_1 (the facility's surface) and a point on surface A_2 an earth surface segment.
α_1	: is the angle of r_{12} with the normal on the facility surface
α_2	: is the angle between r_{12} and the normal on the earth surface

In convenient co-ordinates the integral can be re-written as:

$$VF_{12} = \frac{R_E^2}{\pi} \cdot \int_0^{2\pi} \int_0^{\theta_{hor}} \frac{\cos\alpha_1 \cdot \cos\alpha_2}{r_{12}^2} \cdot \sin\theta \cdot d\theta \cdot d\phi \qquad (4)$$

with:

ϕ	: the angle around the line between the earth centre and the facility.
θ	: the angle between the earth centre and the facility and the line form the earth centre to the a place on the earth surface (minimum 0, maximum θ_{hor} the horizon of the facility).

For the LIPAS-calculation this integral is reduced to a one-dimensional integral over θ, therefore the integration over ϕ is replaced by an expression accounting for the view factor variation over ϕ.

This expression is 2π (maximum) when the facility surface is earth looking and $\pi/2$ when the normal of a facility surface makes an angle of 90 degrees with line to the centre of the earth. The expression then becomes:

$$VF_{12} = 2 \cdot \left(\tfrac{1}{4} + \tfrac{3}{4} \cdot \cos^5\gamma \right) \cdot R_E^2 \cdot \int_0^{\theta_{hor}} \frac{\cos\alpha_1 \cdot \cos\alpha_2}{r_{12}^2} \cdot \sin\theta \cdot d\theta \qquad (5)$$

where:

γ	: the angle between the normal on the facility surface and the line form the facility to the earth centre.

This integral is numerically solved by Romberg integration for every facility surface at each time step. To increase the accuracy of the computation the earth surface is divided into 4 circle segments, as shown in Figure 5.
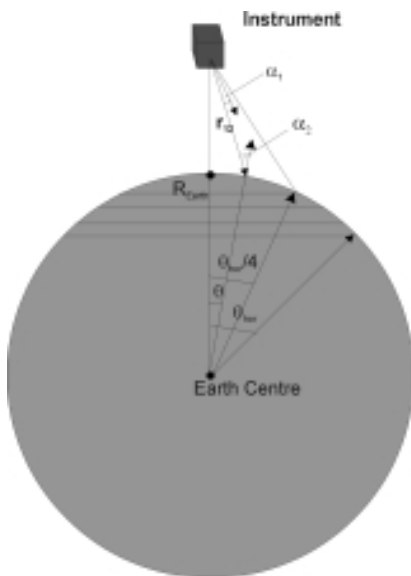

Figure 5: Earth surface subdivision in circle segments

Albedo heat load calculation

The albedo heat inputs of each segment on a separate facility surface are computed and are summed resulting in the albedo heat input on each facility surface. Together with the view factors, the solar flux, the surface reflection coefficient, the surface properties, and the surface area the albedo heat flux at each surface is calculated in expression (6).

$$Q_{Albedo,tot,n} = A_n \cdot \alpha_n \cdot F_{OrbitEarthPhase} \cdot \rho_{Earth} \cdot S_{Flux} \cdot \sum_{n=1}^{n_{max}} \sum_{j=1}^{4} VF_{n,j} \qquad (6)$$

with:

ρ_{Earth}	: the reflection coefficient of the earth surface.
$VF_{n,j}$	: the view factor between the nth surface of the facility and the jth circle segment of the earth surface.

Dynamic instrument temperature calculation

To calculate the temperature of the instrument the power dissipation is needed. This power dissipation is calculated in the power module as function of two parameters:

- The boolean if the laser is off or in standby mode(In off mode the laser dissipation is 0; in standby mode the power dissipation is a given constant value)
- If the laser is active then the power dissipation is equal to:

$$Power_{dissipation} = (1 - \eta_{laser}) \cdot Power_{laser} \qquad (7)$$

with:

$Power_{dissipation}$	: the in the laser dissipated power [Watt]
$Power_{laser}$	: the consumed laser power [Watt]
n_{laser}	: the laser efficiency [-]

The dynamic average instrument temperature is calculated with a simple dynamic thermal model based on the lumped capacitance method and solved by discretisation. For comparison simultaneous calculation of the steady state end temperature is possible and is built in the model.

RESULTS AND EVALUATION

In order to verify the validity of the developed model the results of the model are compared to results from VWHEAT calculations. VWHEAT is a software tool which calculates view factors, radiative exchange factors and solar, albedo and planetary heat inputs.

Test Orbit Specification	
Orbit altitude	350 km
Orbit inclination (I)	51.6 °
Ascending node (Ω)	90.0 °
Solar declination (δ)	0.0 °
Eccentricity	0 (pure circular)
Albedo factor (reflection coefficient)	0.3

Table 1: Test orbit specification

As a test case, a cubic shaped instrument (1x1x1m), is orbited in a fixed ISS-type orbit. One side of the instrument is constantly earth viewing. The orbit is specified in Table 1. Special care had to be taken to synchronise both orbits, because of the difference between the orbit models of VWHEAT (with fixed orbit parameters) and the and the Position and Environmental Model (PEM), used by LIPAS.

HEAT LOAD CALCULATIONS

The results of the VWHEAT calculations are presented in EXCEL figures. The LIPAS thermal model calculations are recorded with the LIPAS mission tool monitor.
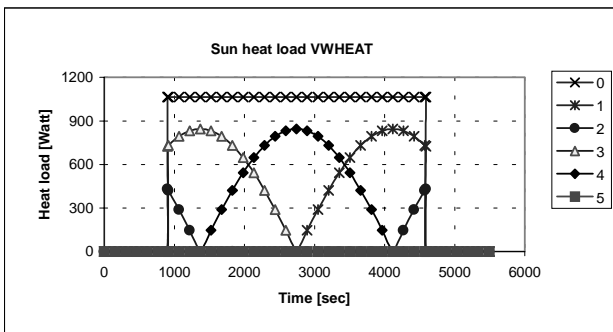
Solar heat load

Figure 6: VWHEAT sun heat load on all 6 sides of a 1m³-cube (ε=α=1) (0=left, 1=back, 2=bottom, 3=front, 4=top, 5=right)

The output of the VWHEAT-modelling for the sun is given in Figure 6. The figure shows that the left side is directed to the sun and the right side is receiving no sun light at all. The bottom side is earth oriented and therefore only receiving sunlight just after sunrise and just before total eclipse. The top side is oriented in the +zenith-direction and has a typically optimum when its directed to the sun. For the front side and the back side of the instrument these optimums occur earlier and later respectively.

The sun heat load results of the LIPAS calculations are shown in Figure 7. It is remarked that the time scale of this figure is a simulation time scale and not real time. In

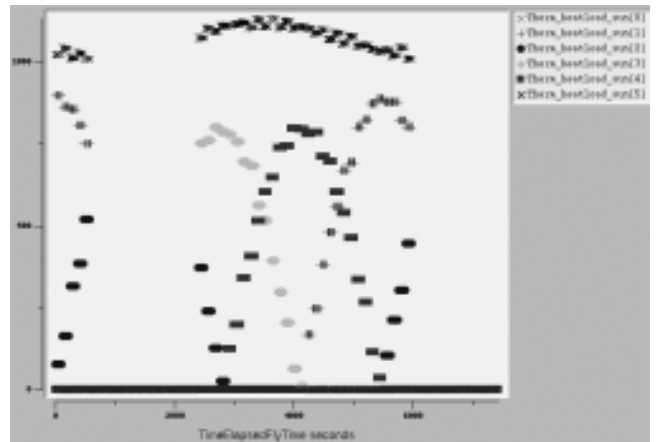spite of this difference, it is easy to make a comparison with Figure 6.

Figure 7: LIPAS sun heat load on all 6 sides of a 1m³-cube (ε=α=1) (0=left, 1=back, 2=bottom, 3=front, 4=top, 5=right)

The VWHEAT-result and the LIPAS-result are matching reasonably well. The only discrepancy, the small optimum in the LIPAS heat load on the sun viewing left side (0), is probably caused by a small rotation introduced by the orbit model of the LIPAS simulator.
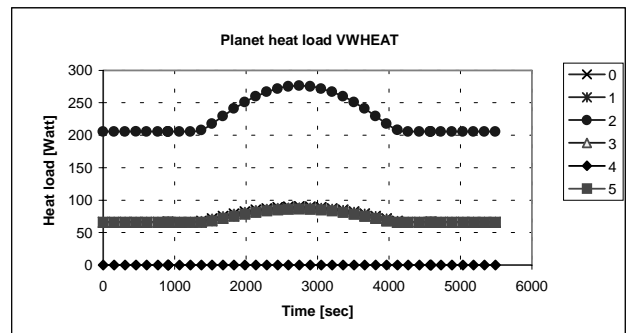
Planetary heat load

Figure 8: VWHEAT planet heat load on all 6 sides of a 1m³-cube (ε=α=1) (0=left, 1=back, 2=bottom, 3=front, 4=top, 5=right)

In Figure 8 the planet heat load of the VWHEAT-modelling is given. It is easily seen that the top side collects no earth heat input. The bottom, earth viewing, side is receiving the most earth heat load, as expected. The other sides are looking with an angle of 90 degrees to the earth and therefore receive a smaller amount of earth heat load. The optimum in all curves in Figure 8 is caused by the higher temperature of the sun receiving side of the earth surface. This trend is also implemented in the LIPAS model. The results of the earth heat load calculations of the LIPAS model are shown in Figure 9.

Despite the huge amount of factors used for the planet heat load calculation (see equation 6), the results of the VWHEAT and LIPAS calculations are of exactly the same magnitude and show the same trends.
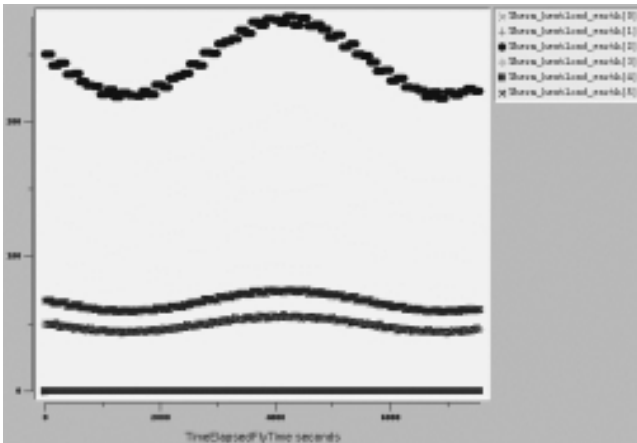
Figure 9: LIPAS planet heat load on all 6 sides of a 1m³-cube (ε=α=1) (0=left, 1=back, 2=bottom, 3=front, 4=top, 5=right).

The difference in heat load on the side surfaces (5,3 vs. 1,0) of the instrument can also be explained by a slightly different orientation of the cube than the orientation in the VWHEAT simulation.
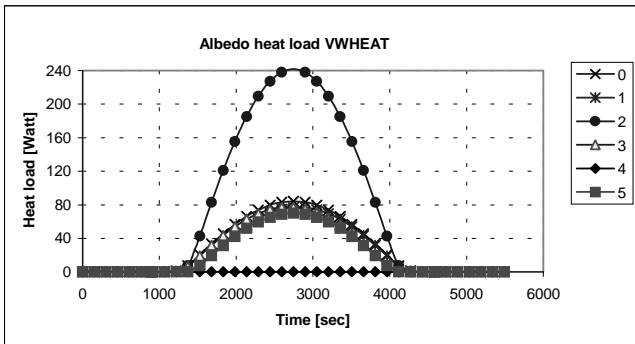
Albedo heat load

Figure 10: VWHEAT albedo heat load on all 6 sides of a 1m³-cube (ε=α=1) (0=left, 1=back, 2=bottom, 3=front, 4=top, 5=right)

Figure 10 shows the albedo heat load of the 6 cube sides. As expected the same trend as for the planet heat input is shown with the difference that in total eclipse no albedo heat input is present.
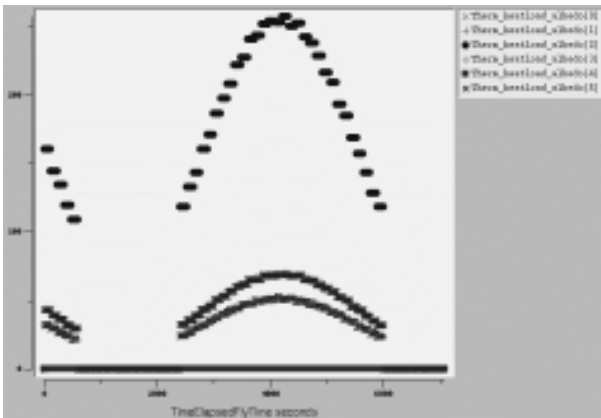

Figure 11: LIPAS planet heat load on all 6 sides of a 1m³-cube ε=α=1 (0=left, 1=back, 2=bottom, 3=front, 4=top, 5=right)

The results of the LIPAS calculations in Figure 11 are similar to the VWHEAT results in Figure 10, with the remark that the side surface heat loads are not exactly matching, which was also the case with the earth heat load in Figure 9.

Transient temperature prediction

The simple dynamic model has been tested by calculating analytically the stationary end temperature of the facility for every time step in LIPAS. The transient temperature of the facility must be in between the two stationary end temperatures of two successive time steps. This is a qualitative test, but sufficiently accurate for an indicative temperature, like the average temperature of the facility. This test is carried out for two facility masses, simulating two different heat capacities.
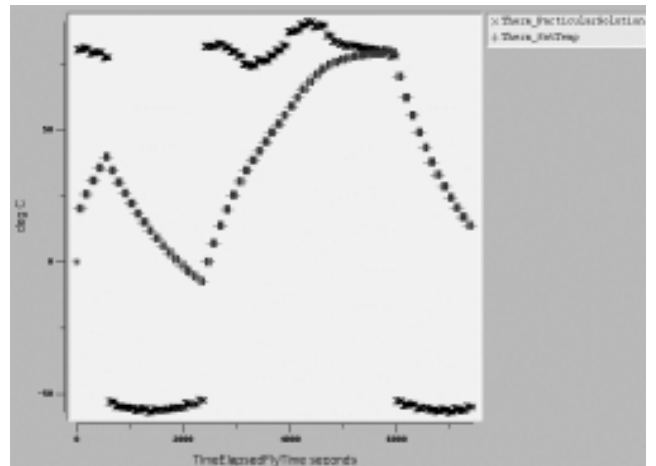

Figure 12: Transient facility temperature compared with transient calculated stationary end temperature (mass=300kg).

In Figure 12 the transient temperature history of the facility is given. A comparison is made with the steady state end temperature of the facility under the given conditions (heat load, power dissipation) at the particular point in orbit. In Figure 12, the mass of the facility is 600 kg, resulting in a slow temperature variation. The figure shows that the modelled facility temperature slowly approaches the steady state end temperature when the environmental conditions are constant for a longer period. This was to be expected.

In Figure 13 the facility mass is 60 kg. The facility temperature reaches the stationary end temperature much faster. This was also to be expected as the lower mass results in a lower heat capacity, which means the response on changes in the heat load are reflected faster in the facility temperature.
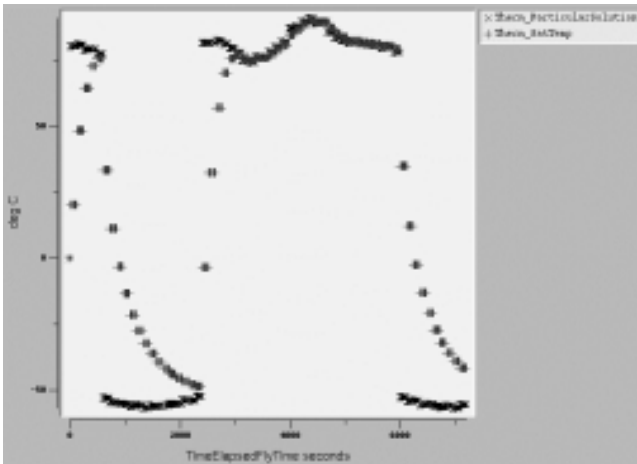
Figure 13: Transient facility temperature compared with transient calculated stationary end temperature (mass=60kg).

RESULTS EVALUATION

In general the LIPAS model is well suited to predict the heat load on a facility with a given geometry. The small discrepancies in the relative magnitude can be caused by:

- a slightly different orientation of the facility compared to the VWHEAT modelling.

- a difference in the number of nodes used for the earth surface (VWHEAT max 132 for VWHEAT and 4 for LIPAS thermal module)

It must also be noted that the model can only be used in low earth orbit because of the assumptions made in the earth heat input module and the view factor calculation used in the albedo and earth heat input module.

The transient temperature gives a good indication of the overall facility temperature under operating conditions.

CONCLUSION

The LIPAS thermal module is able to calculate the environmental heat load based on the instrument position using a relatively simple view factor-calculations.

The LIPAS thermal module is well suited for conceptual trade-off calculations and fits perfectly in the LIPAS simulator objective i.e. to contribute to the phase A studies of the ALADIN-instrument.

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