DEVELOPMENT, SIMULATION AND TESTING OF TEMPERATURE SENSORS FOR THE ATTITUDE DETERMINATION OF THE MASCOT ASTEROID LANDER

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Abstract: *This paper discusses one of the sensor concepts that have been considered for the attitude determination system of the mobile asteroid surface scout (Mascot), flying aboard the Hayabusa2 spacecraft. Newly developed orientation temperature sensor (OTS) are used to acquire temperature readings from multiple sides of Mascot, and determine the orientation of the lander relative to the asteroid surface based on these readings. We describe the modelling and hardware testing of the OTS using different optical surfaces with high and low absorptance and emittance. OTS performance is then evaluated under actual mission conditions to determine which sensor type or combination of sensor types can be used for attitude determination. The results show that both single and multiple sensor type concepts can be used to determine the attitude relative to the asteroid surface. A single type low α, high ε sensor provides information on which side of the lander is facing the surface, while a combination of two sensors with identical ε and very distinct α makes it possible to determine the direction of the Sun with an error of 5°. While not used as part of Mascot's attitude determination system due to a response time of 5–10 min, opposed to other available, instant sensor types (optical, photovoltaic), the OTS have been added to the Mascot baseline design as a proof of concept, and to collect additional science data during Mascot's mission on the surface of 1999 JU3. This provides the opportunity to validate the OTS hardware and concepts as a lightweight, low cost alternative for future missions, and directly compare their performance with Mascot's other sensor types.*

Keywords: *Attitude Determination, Sensor Hardware, Landers, Small-Body Exploration*

1. Introduction

On December 3. 2014, the asteroid explorer Hayabusa2 began its journey to the C-type asteroid 1999 JU3. On board is the mobile asteroid surface scout (Mascot), a 10 kg lander developed by the German Aerospace Center DLR in cooperation with the French National Centre of Space Research CNES. After being deployed from Hayabusa2, Mascot will autonomously conduct in-situ science experiments at multiple locations on the asteroid surface. The maximum expected surface time of the battery powered lander is approximately 16 h (2 asteroid days).

Mascot is equipped with an ex-center mass, allowing it to jump on the asteroid surface. This allows the lander to position itself correctly after the initial landing and during planned relocation manoeuvres This ability is a critical part of the mission, as the lander's advanced payloads require correct oriented to the asteroid surface.

Determining if and when these up-righting manoeuvres need to be performed is the task of Mascot's guidance navigation and control (GNC) system. Due to the fast development time of Mascot and the need for a reliable system, a number of sensor types have been considered and studied in parallel. Next to photo-electric cell sensors (PECS) and optical proximity sensors (OPS), the use of temperature sensors for has been investigated as well.

2. OTS Overview

2.1. OTS Hardware

The developed orientation temperature sensors (OTS) make use of a surface with well defined optical properties (emittance ε, absorptance α), to determine the orientation of Mascot based on temperature readings from multiple sides of the Mascot lander. Figure 1 shows a schematic of the OTS.

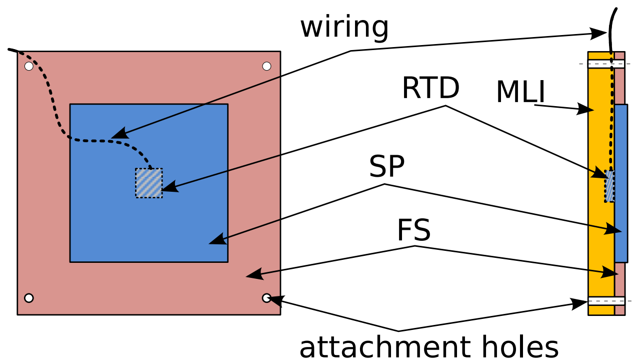

Figure 1. Schematic showing the OTS set-up.

To prevent the readings from being influenced by the temperature of Mascot T_{MSC}, a multi layer insulation (MLI) is added to the back of the sensors for insulation. A face-sheet (FS) is also placed around the specially coated sensor-plate (SP) to provide additional insulation and allow attaching the OTS to Mascot. The SP has a high conductance to equalize the temperature over its entire surface, and provides low emittance towards the MLI side of the OTS. The resistance temperature device (RTD) used to measure the SP temperature, is connected using wires with low conductance to further improve thermal insulation between the OTS and Mascot.

The following three types of optical coatings have been considered:

sun-type: High α, low ε coating that reacts strongly to sunlight, but remains unaffected by IR radiation from Space or the asteroid surface.

soil-type: Low α, high ε coating that has the opposite behaviour of the Sun-type; strong reaction to asteroid and space IR radiation, weak reaction to sunlight.

black-type: High α, high ε, similar to a black body; reacts strongly to both sunlight and IR radiation sources. This type also has the most stable optical properties.

Table 1 shows the material selection, based on the previously mentioned properties of the different sensor types. Values for the sun-type sensor had to be adjusted using a second type of coating, to prevent exceeding OTS temperature limits under worst-case conditions (direct illumination with $\varphi_{\text{sun}} = 0°$). The coating is applied to the aluminium SP which provides an even temperature distribution over its entire surface area.

Table 1. Materials chosen for the three OTS types.

type	SP coating	α	ε
sun	alanod miroterm + FEP-Al	0.68	0.36
soil	FEP-Al	0.15	0.85
black	black PI	0.90	0.82

The main role of the FS is to provide an attachment option for the OTS. The FS hereby provides additional isolation between the attachment points and SP. FS materials are selected to fit the α/ε ratio of the SP coating, however, the selection is limited to thin polyimide (PI) films to keep thermal conductance in the FS low. Throughout the OTS development, slight changes to the SP and FS materials have been made to improve sensor performance and eliminate construction problems.

2.2. OTS Simulation Model

OTS behaviour is analysed using a simple thermal simulation model. The model consists of two nodes; one for the sensor plate temperature T_{SP}, and one for the face sheet temperature T_{FS}. The SP temperature T_{SP} is hereby of interest, as it is the one measured by the RTD in the OTS. It is also referred to as T_{OTS} External influences on the OTS from both Mascot and the space/asteroid environment are modelled.

The external influences on T_{OTS} can be divided into those coming from Mascot:

- radiative transfer through MLI
- 2D heat transfer through FS
- heat transfer through RTD wires
- radiation from Mascot elements

and influences from the space environment:

- direct illumination from Sun
- reflected illumination (albedo)
- space background IR radiation
- IR radiation from asteroid surface
- direct contact with asteroid

Analytical heat transfer equations are available for most of the conductive and radiative heat transfers [1]. An approximation is available for the two-dimensional transfer that occurs in the FS [2]. View factors needed to determine the radiative heat transfer with the space background and asteroid are determined from the lander's orientation with respect to the asteroid surface, modelled as a infinite, flat plane. The radiative transfer through the MLI can be determined analytically [1]. Due to the small dimensions of the sensor's MLI, some adjustments are required, based on that data collected during thermal-vacuum testing (Section 4.). Heat-exchange with the asteroid surface is modelled using a multi layer model of the asteroid surface and soil as described by [3, 4], using currently known properties of 1999 JU3 [5, 6].

Figure 2 shows an overview of the OTS model with all external and internal influences. Section 6. uses this model to simulate OTS behaviour during the Mascot mission.

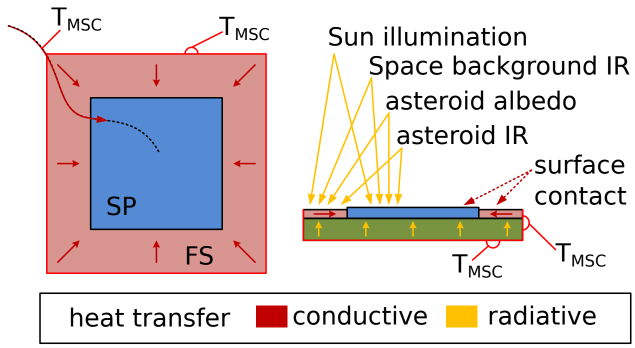

Figure 2. Schematic of the OTS thermal model.

3. Attitude Determination Concepts

Two approaches for attitude determination using the OTS are investigated, one using a single sensor on each side of Mascot, and a second option that utilizes a set of two different OTS types on each side.

3.1. Single-Sensor Concept

This concept is based on finding out if one of the sensor types shows a temperature reading that can be uniquely linked to a specific orientation of that sensor to the asteroid surface. Readings between sensors, located on all six sides of Mascot need to be compared, to see if one of the sides shows a distinctive temperature. Tests are performed to investigate if and how well the different sensor types perform for use in this concept. The influence of the asteroid surface on the OTS temperature plays an important role in this concept.

3.2. Two-Sensor Concept

The two sensor concept uses both a soil and black type sensor on each side of Mascot to determine the Sun angles φ_{sun} on the illuminated sides, from the temperature difference ΔT between the two sensors. The large difference in α between the soil and black type OTS causes a large ΔT when illuminated Their nearly identical ε_{OTS} means that they have the same reaction to sources of IR radiation such as the space environment and asteroid surface. This allows eliminating influences caused by different asteroid temperatures and orientations.

This concept allows identifying the illuminated sides of the lander, as well as measuring the Sun angle φ_{sun} (Eq. 1).

$$\cos\varphi_{\text{sun}} = \frac{\varepsilon_{\text{OTS}}\,\sigma\,\left(T_{\text{black}}^4 - T_{\text{soil}}^4\right)\left[F_{\rightarrow\,\text{space}} + (1-\rho)\,F_{\rightarrow\,\text{ast}}\right]}{\dot{q}_{\text{sun}}\left(\alpha_{\text{black}} - \alpha_{\text{soil}}\right)} \tag{1}$$

ε_{OTS} is the nearly identical emittance of the soil and black type OTS, α_{black} and α_{soil} are the distinct absorptance of the respective sensor type resulting in different sensor temperatures T_{black} and T_{soil} (in Kelvin). $\dot{q}_{\text{sun}}$ is the local solar power flux density in W m^{-2}, and σ is the Stefan-Boltzmann constant (5.670×10^{-8} W m^{-2} K^{-4}). $F_{\rightarrow \text{ast}}$ and Space $F_{\rightarrow \text{space}}$ are the view factors of the OTS towards Space and the asteroid surface respectively, the sum of the two being equal to 1. ρ is the albedo of the asteroid surface.

Due to the low asteroid albedo ρ (0.06 [6]) $F_{\rightarrow \text{space}} + (1-\rho)\, F_{\rightarrow \text{ast}}$ in Eq. 1 can be reduced to $\sim$1, resulting in Eq. 2. This eliminates the need to consider individual view factors of the OTS towards the asteroid $F_{\rightarrow \text{ast}}$ and Space $F_{\rightarrow \text{space}}$.

$$\cos\varphi_{\text{sun}} = \frac{\varepsilon_{\text{OTS}}\,\sigma\,(T_{\text{black}}^4 - T_{\text{soil}}^4)}{\dot{q}_{\text{sun}}(\alpha_{\text{black}} - \alpha_{\text{soil}})} \tag{2}$$

The Sun angles on the illuminated sides of the lander can be used to determined the direction of the Sun vector $\vec{v}_{\text{sun}}^{\text{MSC}}$ in the lander reference frame Comparing the direction of this vector to the direction of the local sun vector on the asteroid surface $\vec{v}_{\text{sun}}^{\text{ast}}$ makes it possible to determine the orientation of the lander with respect to the asteroid surface.

4. OTS Testing

4.1. Test Facility

Multiple thermal-vacuum tests have been conducted to determine the performance of the OTS hardware. These tests were performed using the SSC (Solar Simulation Chamber) at the DLR Institute of Space Systems in Bremen. Next to an LN2-cooled shroud to simulate deeps space conditions, the SSC is equipped with a Sun imitator (SI), allowing tests under illuminated conditions. PT100 RTDs have been used during thermal vacuum testing due to the SSC measuring equipment. The OTS flight models are equipped with PT1000 RTDs with identical properties. Because of time constraints, only a limited number of dedicated OTS tests, using the SSC's SI could be conducted. Most tests have been performed alongside the Mascot test campaigns, under shadowed conditions.

4.2. Test Set-up

To simulate the temperature influence from Mascot, the OTS are attached to a temperature controlled plate (MSC imitator) at the backside (Fig. 3). T_{MSC} is set to the expected operational temperatures of Mascot (-20 to 70 °C), including lower temperatures down to -70 °C. The sensors are attached to the MSC imitator with Kapton tape along the entire edge of the FS, as a worst case scenario. The sensor wiring coming out of the OTS is directly attached to the MSC imitator plate.

4.3. Test results

Figure 4 shows a plot of the data recorded during one of the dedicated OTS tests. Steady-state temperatures T_{SS} for all sensor types, with different Mascot temperatures T_{MSC} and under illuminated and shadowed conditions are measured. Variations of the SI power flux density $\dot{q}_{\text{SI}}$ are tested by

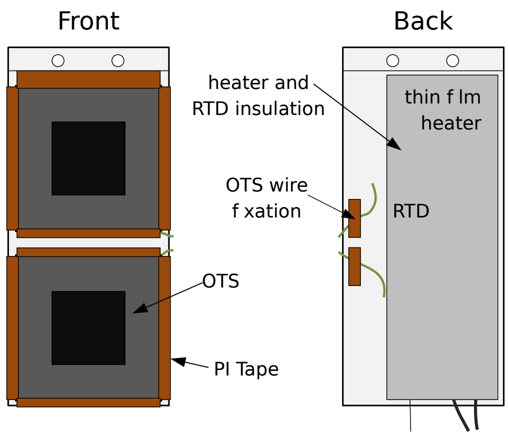

Figure 3. Set-up used for OTS testing inside SSC.

varying the Sun angle φ_{sun}. Both recorded steady-state temperatures (illuminated and shadowed), an the required stabilization time of the OTS are important for the evaluation of OTS performance.

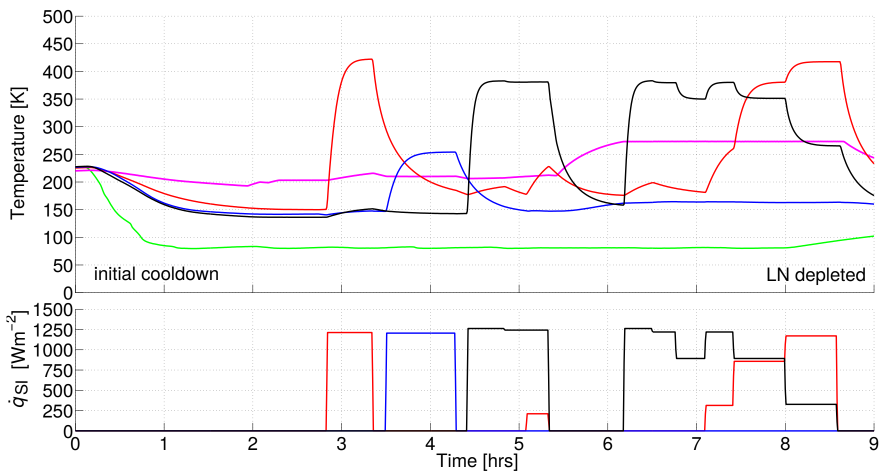

Figure 4. Data recorded during one of the OTS tests, including shroud temperature (green), MSC temperature (magenta) and the OTS temperatures for sun (red), soil (blue), and black (black) type sensors. Solar power flux density based on φ_{sun} is also recorded.

5. Hardware and Model Performance

OTS performance is evaluated based on the thermal resistance R_{th} between Mascot and the sensors during steady-state conditions; in particular the non-illuminated (shadowed) cases. The transition speed from shadowed to illuminated states is also important in evaluating OTS performance for use in Mascots GNC system. The values acquired from the thermal-vacuum tests (Section 4.) are hereby compared to the simulation model (Section 2.2.). Adaptations to the model parameters have been made to improve model accuracy based on the results of the thermal-vacuum tests. The two adaptations are:

2D transfer in MLI: The 2D transfer takes place in the MLI as well, not just the FS. Mascot temperature influence in the model is slightly increased to adapt steady-state temperature.

increased SP capacity: The MLI capacity has a noticeable effect on the reaction speed of the OTS. Thermal capacity is increased to adjust OTS reaction time.

Figure 5 compares recorded and simulated OTS temperatures, using both initial and adapted model parameters. The adapted model shows improved accuracy, especially during the transition between steady-states.

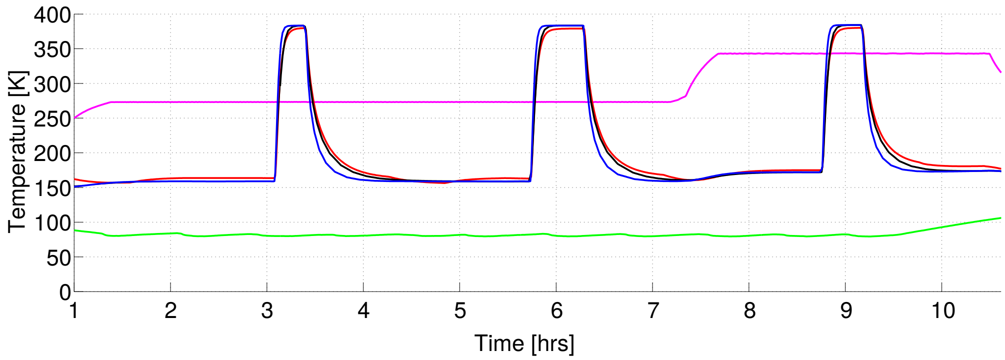

Figure 5. Comparison of recorded (red) and simulated OTS temperatures using the initial (blue) and adapted (black) model for the black-type OTS. The error ΔT_{error} of the adapted model is reduced, especially during the transition between shadowed and illuminated state. Shroud (magenta) and MSC temperature green) are plotted as well.

5.1. Steady-State Accuracy

Temperature difference between model and the tested OTS engineering models generally remains within ±10 °C, as seen in Fig. 5, for operational temperature ranges of over 200 °C. One exception are the sun-type OTS (Ta 2). The reason for this is the two component construction of the sun-type SP, which causes an additional temperature drop between the two coatings (Section 2.1.).

Table 2. OTS steady state temperatures; measured T_{test} and simulated T_{sim}.

OTS type	T_{MSC} [°C]	$\dot{q}_{\text{SI}}$ [W m^{-2}]	T_{sim} [°C]	T_{test} [°C]	ΔT_{error} [°C]
sun	0	0	-97.6	-105.0	7.4
	70	1212	163.8	150.4	13.4
soil	0	0	-123.8	-118.6	-5.2
	70	0	-111.5	-102.6	-8.9
	0	1205	-5.3	-12.8	7.5
black	0	0	-126.3	-129.7	3.4
	70	0	-114.1	-110.2	-3.9
	0	1262	110.2	110.0	0.2

The steady state temperatures of Mascot T_{MSC} and the OTS T_{OTS} during the shadowed case allow calculating the thermal resistance R_{th} between Mascot and the OTS (Eq. 3, based on heat exchange of the OTS (both SP and FS) with the cooled shroud $\dot{Q}_{sh}$.

$$R_{th}^{-1}\left(T_{MSC} - T_{OTS}\right) = \dot{Q}_{sh} \tag{3}$$

with

$$\dot{Q}_{sh} = \sigma\, \varepsilon_{SP} A_{SP} \left(T_{OTS}^4 - T_{sh}^4\right) + \sigma\, \varepsilon_{FS} A_{FS} \left(T_{FS}^4 - T_{sh}^4\right) \tag{4}$$

using the respective emittance and surface area for the SP and FS. The shroud temperature lies at ~79 K.

For the shadowed conditions, R_{th} of the newest OTS iteration (v3) lies between 2000 and 5000 K W^{-1} (Fig. 6), depending on the adapted temperature T_{ad} (Eq. 5).

$$4\,T_{ad}^3 = \frac{T_{hot}^4 - T_{cold}^4}{T_{hot} - T_{cold}} \tag{5}$$

The hot and cold temperatures are either T_{OTS} or T_{MSC}, depending on the test conditions.

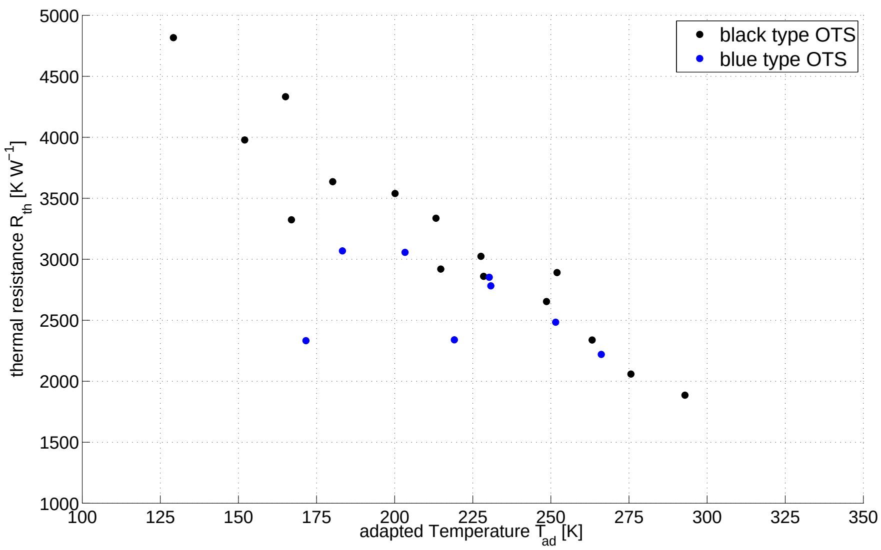

Figure 6. Thermal resistance between OTS and Mascot during shadowed steady state conditions.

5.2. Transition Times

Next to steady state temperatures, transition times between different illuminated and shadowed conditions are of interest for evaluating OTS performance. During the initial touchdown and relocation phases, abrupt changes of the external influences on the OTS can occur. The Sensors should have a fast response time, to not require a waiting period after every relocation/up-righting manoeuvre. Figure 7 shows the transition time for all three OTS types from shadowed to illuminated steady state, under different test conditions (T_{MSC}, φ_{sun}). The maximum transition times until the OTS reaches a temperature within ±2 °C of T_{SS} have been marked for all three sensor types.

This transition from shadowed to fully illuminated steady-state represents an absolute worst-case scenario, as such an extreme change in the illuminated condition is unlikely to occur during Mascot's

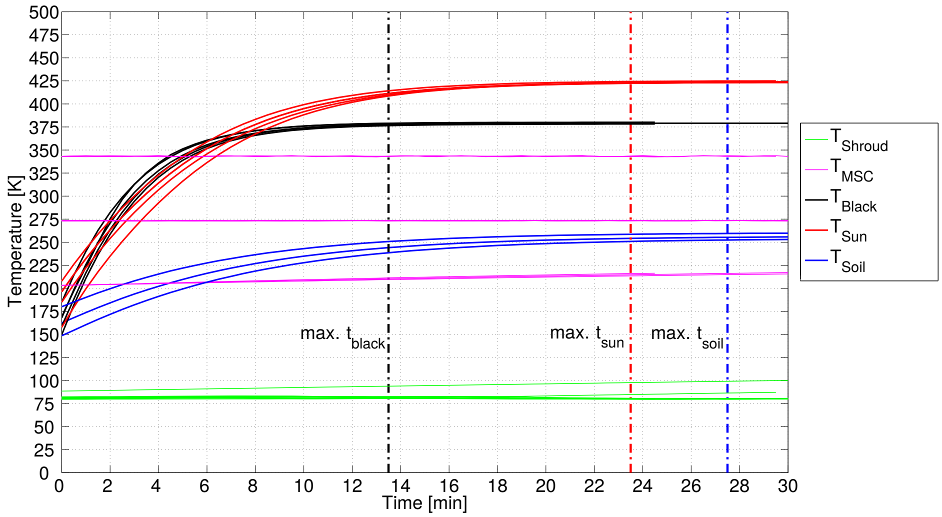

Figure 7. Transition times between shadowed and illuminated state for all OTS types under different conditions. Transition time and illuminated T_{SS} are not affected much by variations of T_{MSC}. The soil type OTS are hereby affected the strongest ($T_{soil} = \pm 5\,^{\circ}$C for $T_{MSC} = \pm 70\,^{\circ}$C).

mission. However, these values provide a conservative choice for the evaluation of OTS performance during attitude determination.

6. On-Mission Scenario

Using the adapted OTS model, sensor behaviour during actual mission scenarios is simulated and evaluated.

6.1. Scenario Overview

The mission scenarios used for the OTS simulation are based on the expected environment at the landing site on the asteroid surface. Due to still uncertain asteroid properties both a hot and cold case landing scenario are considered. A thermal inertia Γ of 250 J $m^{-2}K^{-1}s^{-1/2}$ is used, based on the expected ranges [6, 5]. The rotation axis is chosen according to [5]. Two landing sites are chosen (Tab. 3) to provide a hot and cold case scenario.

Table 3. Local solar power flux $\dot{q}_{sun}$, landing site latitude Φ, and maximum solar angle on the surface φ_{sun} for the cold and hot case scenarios at 1999 JU3.

case	$\dot{q}_{sun}$ [Wm^{-2}]	Φ [deg]	max φ_{sun} [deg]
hot	1458	N10.49	16.5
cold	1320	S66.84	61.5

A total of 252 cases have simulated, based on variation of the parameters listed in Tab. 4. Mascot temperatures are kept constant during the simulation at either minimum (0°C) or maximum (70°C) expected values. As the attitude of Mascot during the initial decent is not known, the initial OTS temperature are chosen based on the illuminated and shadowed worst case conditions. Mascot is

Table 4. Parameters and values, used in the on-mission simulation of OTS temperatures. The initial OTS temperatures depend on the chosen sensor type.

parameter	value
case	hot/cold
sensor type	sun, black, soil
Mascot temperature T_{MSC} [°C]	0, 70
initial OTS temperature $T_{\text{OTS-init}}$	$T_{\text{init-max}}$, $T_{\text{init-mix}}$
Mascot in-plane orientation η	0–90°

expected to rest flat on the asteroid surface after touchdown, with an unknown in-plane rotation angle η. The +z side of Mascot is hereby facing the asteroid. Soil interaction is simulated using a multi-layer soil model (Section 2.2.). The local Sun angle $\vec{v}_{\text{sun}}^{\text{ast}}$ progresses based on the local time and latitude of the landing site. Simulation starts from local noon, with a total duration of 2 asteroid days. Figure 8 shows OTS temperature progression during one of the simulated cases.

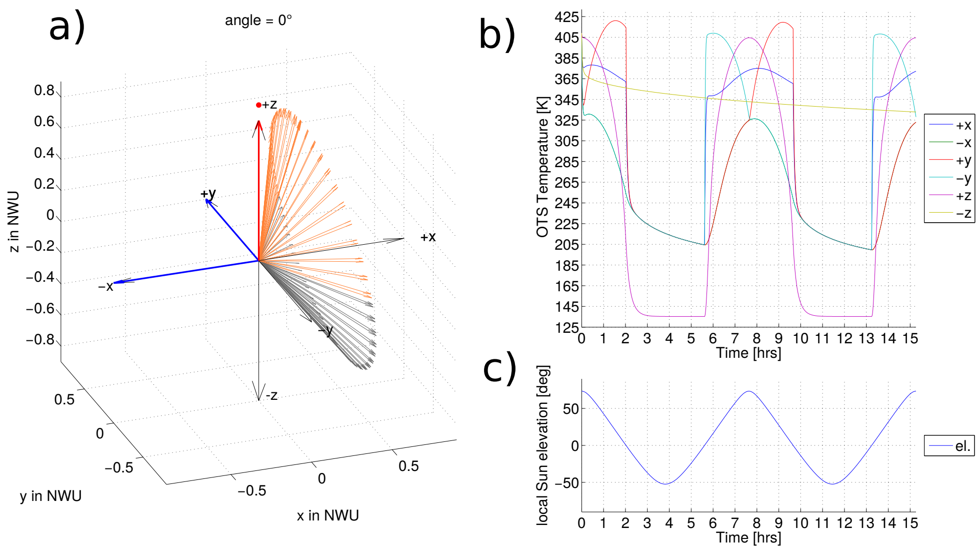

Figure 8. Simulation of OTS temperatures on all six sides of Mascot. The orientation of the Mascot coordinate system in the asteroid's local North-West-Up (NWU) frame is shown in a), including the progression of the local Sun vector during the mission duration of two asteroid days, starting from local noon. Temperatures of the OTS are shown in b) for all six sides of Mascot. The local elevation of the Sun during this time is shown in c).

6.2. Single-Sensor Performance

Figures 9–11 show an overlay of all 126 simulated cold cases, sorted by sensor-type. Results for the hot cases have identical temperature profiles, only with increased temperatures on all sensors during daytime and a sharper rise/fall during dusk/dawn. While the sun and black type sensors do not display a unique temperature that could be linked to a specific orientation, the soil type OTS on the +z side of Mascot consistently has the lowest temperature reading of all six sensors.

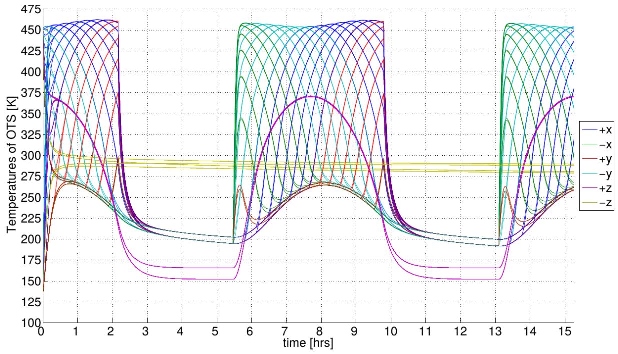

Figure 9. Simulated sun type OTS.

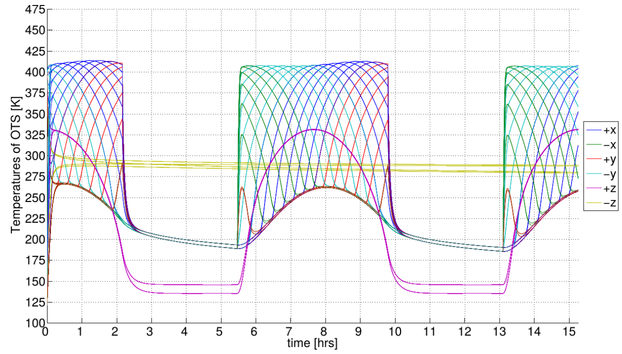

Figure 10. Simulated black type OTS.

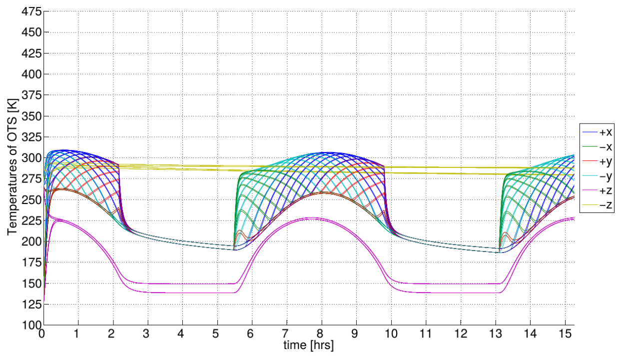

Figure 11. Simulated soil type OTS.

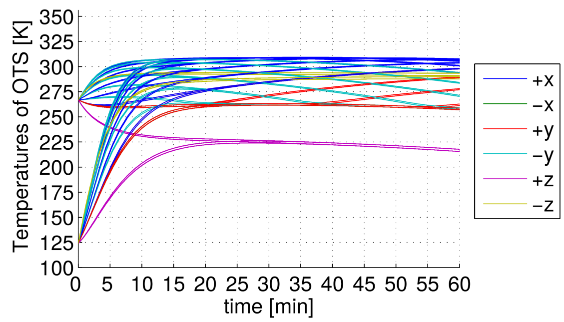

Figure 12. Stabilization phase of soil type OTS.

Due to the high emittance of the soil type sensor it is impacted strongly by the asteroid surface temperature, which varies between -200 and 110 °C, depending on the time and landing site. The low absorptance of the soil type sensor further ensures that the +z side OTS has the lowest temperature, even under illuminated conditions.

According to Fig. 11 the +z side OTS has a temperature that is at least 10 °C below that of any other, with exception of the initial stabilization phase (Fig. 12). Under the simulated worst-case conditions, it takes around 20–30 min to reach full stabilization. This has been confirmed during the thermal-vacuum tests (Section 4., Fig. 7). The time during which false readings, can occur is actually shorter (5–10 min). False readings refer to cases where the minimum OTS temperature is measured on a side other than the one facing towards space.

6.3. Two-Sensor Performance

The two sensors concept, described in Section 3. allows greater accuracy by proving information about the direction of the Sun vector relative to the reference frame of the lander $\vec{v}_{\text{sun}}^{\text{MSC}}$. The maximum deviation between actual and measured direction does not exceed 7°, based on a ±5° measurement error of the Sun angle on the illuminated sides of the lander. Figure 13 shows the error between simulated and actual Sun angle $\Delta\varphi_{\text{sun}}$ measured on the up to three simultaneously illuminated sides, used to calculate the sun vector $\Delta\vec{v}_{\text{sun}}^{\text{MSC}}$.

As with the single sensor concept, an initial stabilization period of 5–10 min is required until the sensors provide reliable measurements. The error peaks in Fig. 13 during the transition between day and night are also caused by the reaction time of the sensors. The origin of the 5° error during daytime is a 3% difference in emittance ε between soil and black type OTS (Tab. 1), and the asteroid's albedo.

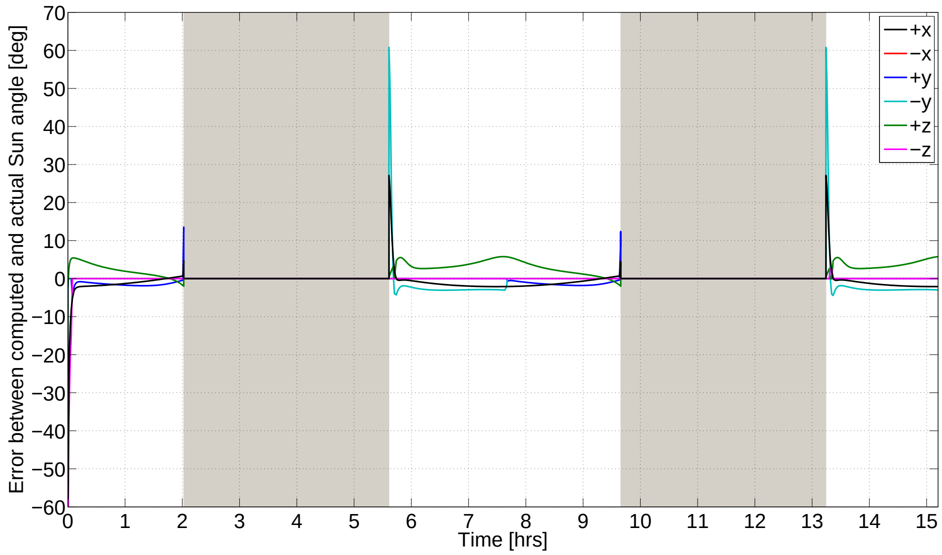

Figure 13. Error between simulated and actual sun angles on the illuminated sides of the lander. For the simulated case the -z (surface facing) and -x (south facing) sides are always shadowed, and -y (east facing) and +y (west facing) switch between illuminated and shadowed state during one asteroid day.

7. Conclusion – OTS Concept Performance and Current Status

In conclusion, both the single and two sensor concepts provide sufficient accuracy for the attitude determination of Mascot during its mission on the surface of 1999 JU3. The single sensor concept hereby allows determining which side of the lander is facing the surface, without any additional knowledge of the asteroid, such as its specific surface properties, spin-axis orientation, and the Sun-vector at the landing site. The use of two sensors can provide more accurate attitude determination by comparing the measured sun vector $\vec{v}_{\mathrm{sun}}^{\mathrm{MSC}}$ with the local sun vector $\vec{v}_{\mathrm{sun}}^{\mathrm{ast}}$ on the asteroid surface. However, this requires prior knowledge of the asteroid spin axis and landing site. This concept also only works during daytime.

One limitation of both concepts is the initial stabilization time during the initial landing and after each jump, which can take between 5-10 minutes. Especially when multiple up-righting manoeuvres are required to complete the up-righting, a waiting period of 5–10 min after every jump can significantly reduce the time that Mascot has available for conducting its primary mission. While this waiting period represents a worst case scenario, the time critical operation of Mascot, due to its limited battery life, and the successful development and testing of alternative sensors with faster response time (PECS, OPS) lead to the decision to not use the OTS in Mascot's GNC concept.

Although the OTS are omitted from the GNC concept due to the availability of better suited options, one pair of black and soil type OTS has been included in the baseline design as a proof of concept and to collect scientific data on surface temperatures during Mascot's mission at 1999 JU3 (Fig. 14).

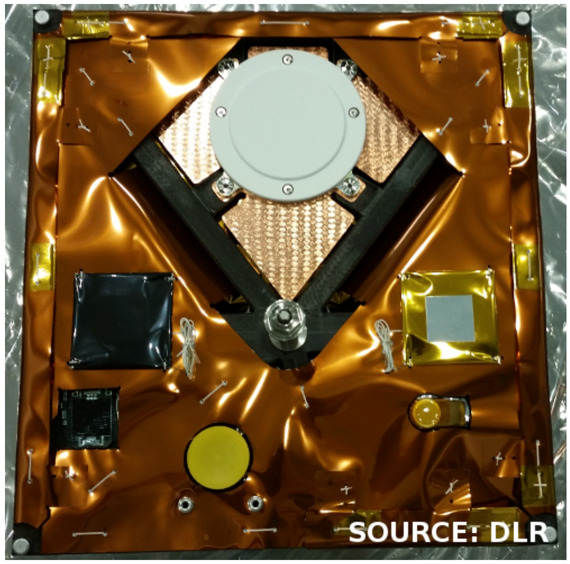

Figure 14. Picture of the black (left) and soil (right) OTS on the -z side of the Mascot FM.

Having the OTS on board of Mascot will allow on-mission testing and validation of the developed hardware and attitude determination concepts for use in future, less time-critical missions, as a lightweight and inexpensive alternative to similar sensors such as the PECS.

8. References

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