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Cubesat in-situ degradation detector (CIDD)☆

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ABSTRACT

The design of the thermal control and management system (TCS) is a central task in satellite design. In order to evaluate and dimensionize the properties of the TCS, material parameters specifying the conductive and radiative properties of the different TCS components have to be known including their respective variations within the mission lifetime. In particular the thermo-optical properties of the outer surfaces including critical TCS components such as radiators and thermal insulation are subject to degradation caused by interaction with the space environment. The evaluation of these material parameters by means of ground testing is a time-consuming and expensive endeavor. Long-term in-situ measurements on board the ISS or large satellites not only realize a better implementation of the influence of the space environment but also imply high costs. Motivated by this we propose the utilization of low-cost nano-satellite systems to realize material tests within space at a considerably reduced cost. We present a nanosat-scale degradation sensor concept which realizes low power consumption and data rates compatible with nanosat boundaries at UHF radio. By means of a predefined measurement and messaging cycle temperature curves are measured and evaluated on ground to extract the change of absorptivity and emissivity over mission lifetime.

1. Introduction

The development and the qualification of the thermal control and management system (TCS) is one of the most critical steps in satellite design. The TCS has to meet thermal requirements throughout a satellite mission and to operate safely within the specified performance throughout the designed mission lifetime. Typically thermal coatings, multi-layer insulations, heaters and radiators are used for the design of the TCS. Among these, those components exposed to the space environment are subject to a degradation of their thermo-optical surface properties [1,2]. The magnitude of surface degradation effects varies greatly with different materials and depends on the mission profile, the mission duration, the orientation of the respective surfaces and the solar activity. The dominant environmental causes for degradation are photon radiation, interaction with charged particles, micro-meteoroid and debris impacts, low earth atomic oxygen [3] and cyclic variations of surface temperatures caused by absorbed solar radiation. In this respect, satellites operating in low earth orbits are most vulnerable to optical degradation effects [4]. Efforts can be taken to mitigate degradation effects for commonly used spacecraft materials such as Kapton or MLI, which show severe degradation for long-time space exposure [5–7]. However, different materials are affected in different ways by exposure to the space environment and the magnitude of the effect depends on mission and spacecraft specific parameters. Consequently, any material used in the TCS has to be tested before it can be used within the spacecraft design process.

With respect to the performance of the TCS, the coefficients of absorptivity α and emissivity ε are the critical parameters subjected to surface degradation effects. In the

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following we only consider mean values and do not include any wavelength-dependencies in the approach. Since both parameters determine the efficiency of radiating surfaces used as a heat sink, any change in α or ε effectively changes the equilibrium temperatures and the resulting heat fluxes in or out of the satellite system. With regard to the equilibrium temperature the heat balance for an external flat plate with surface A illuminated by the sun with solar intensity $P_{\odot}$ at illumination angle $\phi_{\odot}$ and heated by internal heat sources with Q_{SAT} shows

$$P_{in} = P_{out} \tag{1}$$

$$\cos(\phi_{\odot})A\alpha P_{\odot} + Q_{SAT} = \varepsilon A\sigma T_e^4, \tag{2}$$

where σ is the Stefan–Boltzmann number. If e.g. for the case of a radiator the internal heat flow Q_{SAT} is used as an indicator for its efficiency then it is obvious that any change of α or ε reduces or increases the radiator performance. Since internal payloads have to be kept within a specified temperature range by the TCS, such changes in optical properties have to be mitigated to guarantee that the TCS operates within specifications for the mission lifetime.

As a consequence, data on the degradation properties of each material used for external components of the TCS is needed for the design of satellite missions and the development of the involved thermal control concepts. Typically the best results are achieved, when ground laboratory tests, in-situ tests in the space environment and numerical modelling are performed in unison. Ground experiments enable access to the experiment at any time. However, they are limited in the feasible level of space environmental modelling and also imply high costs for personal and equipment, in particular for long-duration degradation experiments [8]. Numerical models [9] can back experimental results and enable a much faster parameter analysis than experimental testing but always need tests as a confirmation of simulated results [10]. Long-term in-situ exposure onboard the ISS such as the Materials International Space Station Experiment (MISSE) [11,12], or by means of a full scale dedicated missions such as the Long Duration Exposure Facility (LDEF) [13]) not only enables an improved quality of test data, since the tests are performed directly within the space environment but also implies a considerable cost and planning effort.

In order to obtain the advantages of in-situ testing but at the same time reduce the costs drastically, dedicated cubesat missions with degradation sensors seem to be a feasible option. A typical[1] cubesat [14] mission can be realized within a much lower timeframe and at much lower costs than experiments aboard the ISS or a full scale satellite. The technology is Commercial-Of-The-Shelf (COTS), available and starting options at reduced costs are becoming increasingly available. Hence, a degradation sensor concept has been developed at ZARM, which allows the conduction of degradation experiments on a 1U cubesat for 16 different material specimen. The measured degradation data is directly available via downlink and experiment evaluation does not require the return of specimen to earth. The design of the sensor, first results from qualification tests, details on the methods used and an outlook on the dedicated cubesat mission which will enable a space qualification of the hardware will be given in the following sections.

2. CIDD basic concept

The degradation sensor concept introduced here uses the dynamic evolution of a heated plate which cools off while emitting heat radiation into space. A typical temperature profile used for emissivity evaluation is shown in Fig. 1. After a heating time (1.), in general any starting temperature (2.) can be realized by an equilibrium of ingoing and outgoing heat fluxes P_{in} and P_{out}. If the sensor is shaded from direct solar influence and the thermal interface between sensor and mounting can be considered as perfectly isolated, Eq. (1) can be employed to calculate an equilibrium temperature T_e with

$$T_e = \left(\frac{Q_H}{\sigma\varepsilon A}\right)^{1/4}, \tag{3}$$

where Q_H is the power of the applied heating, A is the area of the surface facing space and ε is the coefficient of emissivity of the outward surface. If the heater is turned off, the plate will cool down (3.), depending on the total heat energy stored within its heat capacity. The emerging evolution of surface temperature T can then be employed as a direct measure for the surface emissivity following the heat flow equation:

$$\rho c\frac{\partial T}{\partial t} - \lambda\Delta T = -\dot{q}_{e,V} = -\frac{1}{V}\varepsilon A\sigma T_e^4, \tag{4}$$

where $\Delta T = \delta T^2/\delta x^2 + \delta T^2/\delta y^2 + \delta T^2/\delta z^2$ is the temperature gradient, c is the specific heat capacity of the emitting body, V is the body volume, d is the body thickness and ρ is the density of the respective material, λ is the heat conductivity and $\dot{q}_{e,V}$ is the volume-specific emitted heat flux.

A comparable approach can be taken for the determination of the plate absorptivity α. Here, the plate is pointed towards the sun and the heating of the plate is purely conducted by absorption of solar radiation. In this case the equilibrium temperature can be expressed as

$$T_e = \left(\frac{\alpha P_{\odot}\cos\phi}{\sigma\varepsilon A}\right)^{1/4}. \tag{5}$$

If the surface emissivity is known (e.g. from a previous emissivity measurements), the equilibrium temperature is a measure for the surface absorptivity. In addition the temperature evolution during heating can be employed to determine α. Details on ε/α determination are shown in the following section.

3. CIDD layout

The basic CIDD layout for a single sensor element is shown in Fig. 2. The sensor consists of three different layers, which are pinched by clip mountings of low thermal conductivity. The first layer is the material specimen for which the optical parameters have to be determined. In order to realize a good

[1] 10 cm × 10 cm × 10 cm standard cube.