Improvements of a Thermal Method for the Determination of Solar Absorptance and Thermal Emittance of Spacecraft Coatings

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I. ABSTRACT

For the determination of the solar absorptance α_s and ε the thermal emittance optical methods are preferred. These optical measuring procedures are relatively exact. They also deliver information about any potential spectral selective behaviour of surfaces. However, special measuring equipment is required. Particularly if space simulation facilities are already available, the method presented in [1] appears as a suitable enrichment of the measurement methods for the determination of the thermooptical properties α_s and ε. It is possible with slight technical expense to expand the usage potential of such facilities.

For this paper the same test rig as in [1] is used. In a common space simulation chamber (vacuum ; cryogenic shroud ; solar simulator) a test item (target) is arranged. In different measuring phases the target is heated up by an integrated electrical heater or by solar irradiation. The arrangement (target / shroud) is regarded as a two node model. Its (integrated) nodal equation describes the behaviour T(t) of the target. A proper Kalman filter-algorithm can estimate the parameters for the heat transfer between target and cryogenic shroud from the transient measured target temperature. Some Improvements compared with [1] are discussed.
The method used for parameter estimation by a Kalman filter is also the first application of a real measured nodal model and is so far the first verification step for a complex correction procedure of incorrect mathematical models of measured nodal temperatures.

II. FUNDAMENTALS OF THE METHOD

The requirements for these measurements are the following. The measuring object must be located in a vacuum chamber and be in contact with its isothermal environment (heat sink via radiation). For the absorption measurements a solar simulator is required, which must be capable of reaching the sun spectrum (Johnson curve) as closely as possible.

As a measuring object a specially prepared plain test sample (measuring target) is used. This sample is rotatable and suspended in a solar simulation facility so that alternatively the comparison side or the measuring side is viewing the "sun". It is important that the target consists of good heat conducting material, and an electrical heater as well as several temperature sensors are integrated in the target. The measuring and comparison foils on the target can be changed and must be so thin that their influence on the thermal mass of the target can be neglected.

The experimental arrangement is presented in figure1. The Alu-bar has it's own electrical heater and is used for the compensation of conducted heat transfer by the cables of the temperature sensors and target heater during the measurements of temperature equilibrium in [1].

Next its transient temperature was measured to estimate if the influence of conducting heat transfer by cables could be neglected.

First let us consider a two node model. Let the target be node 1 and the cryogenic shroud be the second node of a two node model. The thermal behaviour of the target follows from (1).

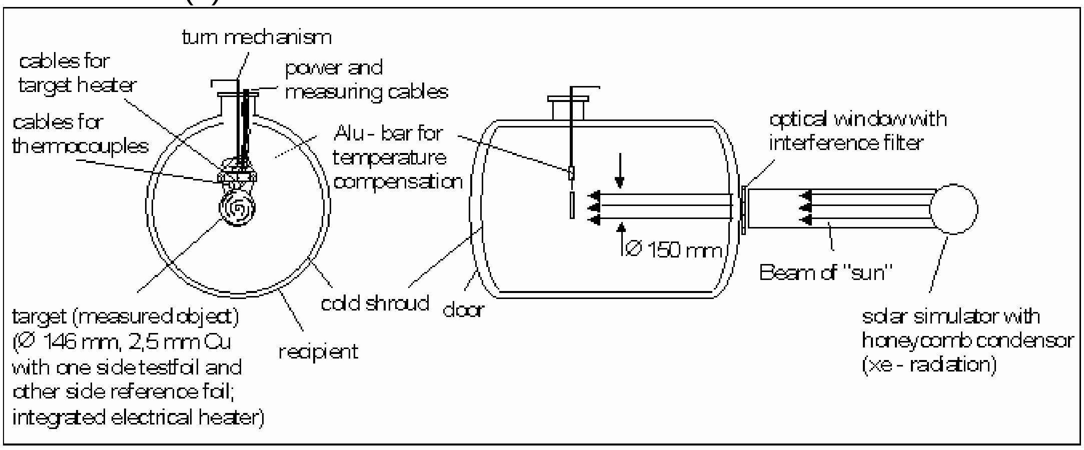

figure 1: solar simulation facility and test rig

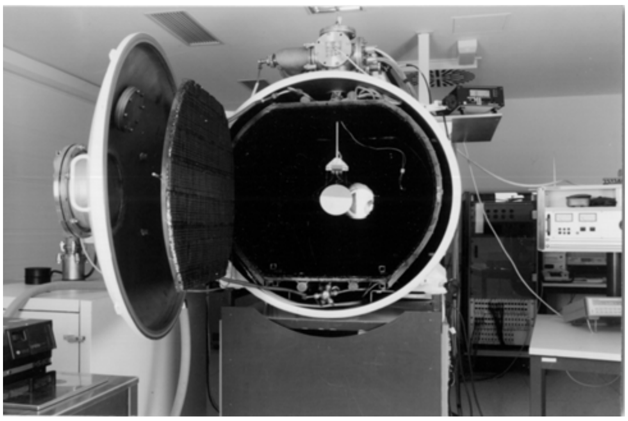

figure 2: target within the solar simulation chamber

(1) $dT_1 / dt = (Q_1 / C_1) (GR(1,2) / C_1) (T_2^4 - T_1^4)$

where C_1 is the heat capacity of the target (C_1=m_1 c_1) and Q_1 is the heat input into the target by electrical heating or solar irradiation. For the heating of the target by solar irradiation one has to consider two cases:

The irradiation of the comparison side, so that Q_1 is:

(2) $Q_{1c} = \alpha_c A_1 E_s$

where E_s is the irradiation intensity of the solar simulator and α_c is the known, e.g.1, absorption of the comparison side.

The irradiation of the measuring side, so that Q_1 is:

(3) $Q_{1m} = \alpha_m A_1 E_s$

The coefficient of radiative heat transfer is

(4) $GR(1,2) = \sigma A_1 F_{1,2} \varepsilon_1 \alpha_2$

where σ is the Boltzmann constant, A_1 the area of the target and ε_1 its emittance. $F_{1,2}$ is the view factor between target and cryogenic shroud. α_2 is the absorptance of the shroud. For the previous arrangement it was possible to set $F_{1,2}$=1 and α_2=1. The emittance ε_1 one has to distinguish in the emittance of the comparison side (ε_c is known) and the emittance of the measuring side ε_m.

So (4) becomes

(4a) $GR(1,2) = \sigma A_1 (\varepsilon_m + \varepsilon_c)$

The equations (1)...(4a) are the base for the calculation of α_m and ε_m.

III. THE KALMAN FILTER ALGORITHM

If the two node model and its differential equation (1) are regarded as a dynamic system then one can formulate a Kalman filter algorithm based on [2].

In a "thermal" formulation of this algorithm the nodal temperature T_1 (or more exactly the temperature difference $T_1^{(t+\Delta t)}$ -$T_1^{(t)}$) and the parameters Q_1 / C_1 and GR(1,2)/ C_1 become components of the state vector.

Before it is possible to start the filter procedure it is necessary to have a priori values of the components of the state vector and of their error variances. Also it is assumed that the measurement noise is a white noise process of known size. Then the Kalman filter uses the transient measured node temperatures in two main steps.

1. In the so called time update (effect of system dynamics) a prediction is made (based on the a priori values of the parameters) of the target temperature for a time t+Δt.
2. In the so called measurement update this prediction is compared with a real measurement of the target temperature at time t+Δt.

The difference between prediction and measurement is used to correct the parameters (in a least square sense) and to formulate a "new" state vector and its associated error covariance matrix.

These steps are repeated until all the measured data have been processed or the error variances of the parameters are smaller than some specified values.

Because the governing nodal model is very simple it is possible to start the Kalman filter with a priori values of the state variables, and their associated error variances, which are very different from their true values. The parameter values are expected to be <<1 and so all a priori values are put as 1.

The result of the Kalman procedure after a number of iterations are especially the terms Q_1 / C_1 and $GR(1,2)/ C_1$.

From the estimated parameter Q_1 / C_1 and the phase of electrical heating one can calculate immediately the heat capacity C_1.

From the estimated parameter Q_1 / C_1 and the phase of solar irradiation of the comparison side of the target one can get the irradiation intensity from equation (2). Putting this into equation (3) one can separate α_m:

(5) $\alpha_m = (Q_{1m} / Q_{1c})\ \alpha_s$

IV. EXPERIMENTAL RESULTS

As a comparison foil Kapton XC was used ($\alpha_s = 0.93$; $\varepsilon = 0.84$). The measurement material was "gold sputtered Al foil" which is used for the inner side of the Cosmic Dust Analyser of the CASSINI mission to minimise radiation losses.

Three cases of target heating were measured according to [1]:

1. Heating the target by electrical power (4.56 W) from a start temperature (160K) up to equilibrium (271.8K).
2. Heating the target by solar irradiation of the measuring side (gold side) from a start temperature (160K) up to nearly equilibrium.
3. Heating the target by solar irradiation of the comparison side from a start temperature (160K) up to equilibrium.

Simultaneously with the wanted parameters the Kalman filter calculates the associated error variances Σ^2, where Σ is the standard deviation of the estimation error. It was assumed that the estimation errors have a normal distribution and the maximum error of estimated parameters is then + - 3Σ.

From the first measuring case the estimated set of parameters is:

$Q_1 / C_1 = 3.863\ 10^{-2}$ + - $1.6\ 10^{-4}$

and

$GR(1,2)/ C_1 = 7.1728\ 10^{-12}$ + - $3\ 10^{-14}$

From the first parameter the heat capacity of the target is separated using the applied electrical power of 4.56 W so that C_1 = 118 + - 0.5 W/K.
The second parameter delivers from (4) ε_m = 0.051 + - 0.008. This is a maximum error of about 16%. This relatively large error range is caused by the use of the already error corrupted heat capacity C_1 to eliminate GR(1,2) from GR(1,2)/ C_1 and the determination of ε_m according to (4a).
The method [1] delivers a value of calculated from the thermal equilibrium between target and cryogenic shroud of 0.047 with a maximum error of (only) 7%. This means that if there is no "better" C_1 available (e.g. C_1 = 117,4 Ws/K was determined from the target mass and the specific heat capacity of copper) method [1] is preferable. But if there is a "better" C_1 than the estimation of GR(1,2)/ C_1 from electrical heating is redundant because the same parameter is available from the heating of the target by solar irradiation.
The measuring cases 2 and 3 yield two sets of parameters and their associated error variances:
From the irradiation of the measuring side we have

GR(2,1)/ C_1 = 7.1724 10^{-12} + - 1 10^{-12}

and

Q1 / C1 = 2.3609 10-2 + - 2 10-3 .

From the irradiation of the comparison side the estimated parameters are:

GR(2,1)/ C1 = 7.1716 10-12 + - 8 10-15

and
Q_1 / C_1 = 9.7862 10^{-2} + - 6 10^{-5} .

For the determination of α_m the heat capacity plays no role and (5) yields α_m = 0.22 + - 0.02.

From the GR(2,1)/ C_1 of the comparison side and an "external" determined C_1 one gets ε_m = 0.047 + - 0.001. This is in very good agreement with [1] without using electrical heating .The table 1 gives a summary of the experimental results as a comparison between the Kalman filter method and the thermal method.

	ESTIMATED BY KALMAN FILTER ALGORITHM	MEASURED BY THERMAL METHOD ACCORDING [1]
α	0.22 + - 0.02	0.23 + - 0.01
ε	0.047 + - 0.001	0.047 + - 0.003

table 1: experimental results

V. CONCLUSIONS

The experimental results show that the application of the parameter estimation method by Kalman filtering is suitable and should be tested in future on more complex nodal models. Compared with the thermal method for the determination of α_s and ε the parameter estimation method brings an improvement because, if the heat capacity of the used target is known, the whole measuring phase of electrical heating can be left out. If in addition the irradiaton intensity (E_s in (2)) is known then the irradiation of the comparison side can be also eliminated. The measurement foil then should be applied on both sides of the target. The measurement procedure to determine α_s and ε is then limited to the irradiation of (one) measuring side.

Nomenclature:

Parameters:

Q = power [W]

α = solar absorption of a surface

ε = thermal emission of a surface

A = surface size [m^2]

E = irradiation intensity [W / m^2]

T = temperature [K]

C = heat capacity of the target [Ws / K]

σ = Boltzmann constant [$W / m^2 K^4$]

t = time [h]

Σ = standard deviation of estimation error

F = view factor

Indices:

1,2 = associated node number

m = measuring side of the target

c = comparison side of the target

s = solar

References:

[1] F. Lura, B. Biering, D. Hagelschuer ; A Thermal Method for the Determination of Solar Absorptance and Thermal Emittance of Spacecraft Coatings, SAE TECHNICAL PAPER SERIES 932122, 23rd ICES Colorado Springs, Colorado, July 12 - 15 1993
[2] R.E.Kalman, A New Approach to Linear Filtering and Prediction Problems. J. Basic Eng. 82 D (1960)