IN-FLIGHT THERMAL COATINGS AGEING ON THE THERME EXPERIMENT

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1. INTRODUCTION

The in-flight evolution of thermo-optical properties of thermal control coatings is a great concern, since the ageing of these materials has a significant impact on the thermal balance and heating power consumption of units, instruments and spacecrafts.

To define spacecrafts thermal control, thermal engineers have to take into account both begin (BOL) and end of life (EOL) thermo-optical properties of external coatings they intend to use (α_s and ε_{IR}). We know by experience (in-flight measurements and ground tests in laboratory), that the parameter really affected by the in-orbit ageing is the solar absorptivity α_s, which often increases when coatings are submitted to space environment.

A large increase between BOL and EOL properties is thus directly "paid" through an increase of radiative areas, leading to higher heating power consumption at BOL and in survival mode.

Improve the knowledge of the in-orbit solar absorptivity evolution of thermal coatings is thus a good way to optimize the radiators sizes taken for thermal control, and then to better master the heater power consumption on board.

CNES has developed a very simple and low cost experiment, "THERME", which aims to evaluate the ageing of thermal coatings (evolution of solar absorptivity α_s), especially of recent thermal coatings. This experiment is now flying on spacecrafts such as SPOT 5 and HELIOS 2A and on micro spacecraft such as DEMETER (all three: sun-synchronous orbit).

This paper presents some in-orbit results obtained on SPOT 5 (launched in May 2002), HELIOS 2A (launched in December 2004) and DEMETER (launched in June 2004) platforms for the following thermal control coatings :

- SG121FD, PCBE and SCK5 white paints from MAP.
- Silver and aluminium SSM from SHELDHAL.
- Kapton and Kapton with Mapatox K (MAP), a protective coating against atomic oxygen.

These results are compared with those obtained in ground simulation tests and discussed.

2. DESCRIPTION OF THE THERME EXPERIMENT

The THERME experiment has been already described [1]. Fig. 1. shows the principle of the THERME experiment. For SPOT 5 and HELIOS 2A, the experiment is composed of sixteen calorimeters made from four 100 mm x 100 mm MLI blankets (Fig. 2. and Fig. 3.). For DEMETER, the experiment is composed of eight calorimeters shared in two sets (Fig. 4.).

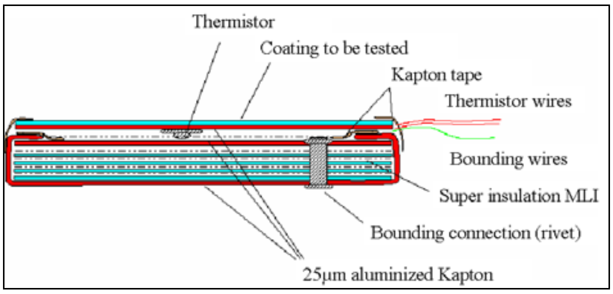

Fig. 1. THERME principle.

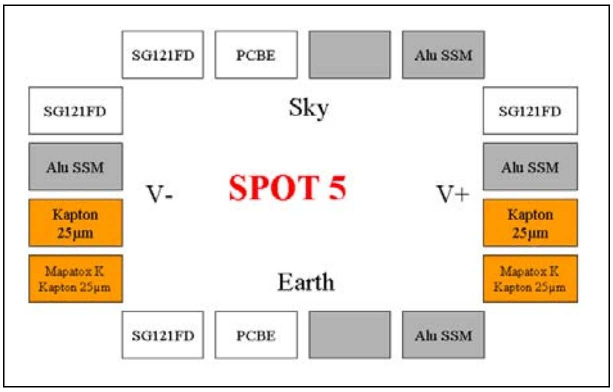

Fig. 2. THERME composition on SPOT 5.

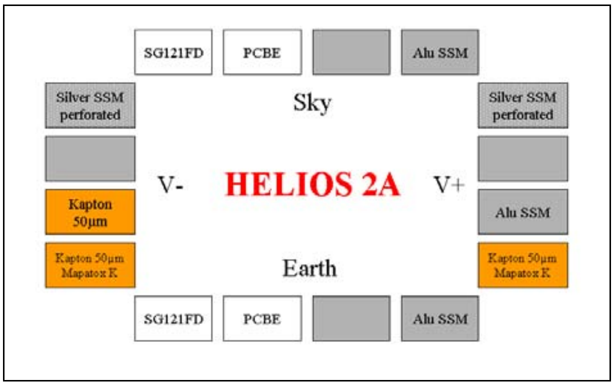

Fig. 3. THERME composition on HELIOS 2A.

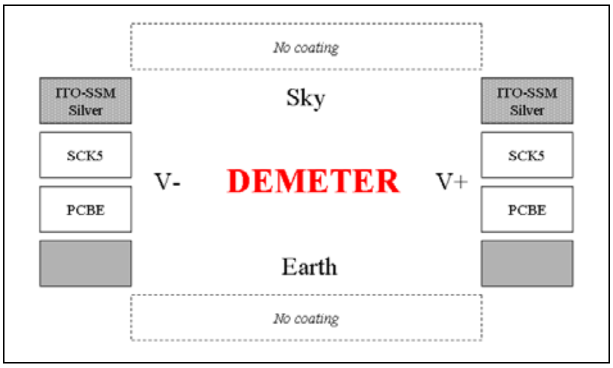

Fig. 4. THERME composition on DEMETER.

SPOT 5 was launched the 4th of May 2002, it is a sun-synchronous orbit at 820 km with a 98.7° inclination, a local time at ascending node at 22h30 and an earth pointing. HELIOS 2A was launched the 18th of December 2004 in LEO (orbit lower than SPOT 5). DEMETER was launched the 29th of June 2004 at 710 km with a 98.2° inclination, a local time at ascending node at 22h25 and an earth pointing.

3. DESCRIPTION OF THE COATINGS

The following thermal control coatings were put on the three different spacecrafts (see Fig 2. to 4.):

- SG121FD, PCBE and SCK5 white paints from MAP.
- Silver (with and without ITO) and aluminium SSM from SHELDHAL.
- Kapton and Kapton with Mapatox-K (MAP), a protective coating against atomic oxygen.

Table 1 gives the description of these coatings.

4. TELEMETRY

4.1. BOL solar absorptivity

On SPOT 5, the sensor aluminium SSM on the sky face did not give a flight BOL value due to a wrong choice of the thermistor temperature range. Nevertheless, this problem has been resolved « naturally » with the ageing and the temperature increase a few months later. 7 years of telemetry are available from SPOT 5.
On HELIOS 2A, this problem was corrected before launch. The telemetry has been registered for 4.5 years.
On DEMETER, the telemetry has 5 years duration.
The following tables (Tables 2 to 4) give the on ground BOL absorptivity (measured with the portable Gier Dunkle reflectometer or with a Perkin Elmer Lambda 9 spectrometer) and the first in-flight measurement.
For all coatings, there is a good consistency between the on ground and the first in-flight values on the three spacecrafts, except for the white paints on the HELIOS 2A earth face.

Coating	**Description**	**External surface**	**Surface state**	**Surface energy (mJ/m^2)**
SG121FD	Non conductive white paint	Polysiloxane Zinc oxide	Porous	-
PCBE	Conductive white paint	Polysiloxane Zinc oxide	Porous	-
SSM (alu or silver)	Polymeric film with aluminium back face	Polytétrafluoroéthylène (PTFE)	Smooth	20
Kapton	Polymeric film with aluminium back face	Polyimide	Smooth	47.7
MapatoxK	Polymeric varnish on Kapton	Polysiloxane	Smooth	20
ITO-SSM (silver)	ITO deposit on polymeric film with silver back face	Metal oxide	Porous	-
SCK5	Antistatic white paint	Polysiloxane Metal oxide	Porous	-

Table 1. Description of the coatings.

SPOT 5 α_s	**On ground**	**Sky**	**Earth**	**V+**	**V-**
Alu SSM	0.11 +/- 0.04	-	0.13	0.15	0.15
PCBE	0.20 +/-0.04	0.25	0.21		
SG121FD	0.19 +/-0.04	0.22	0.22	0.21	0.22
Kapton	0.34 +/-0.04			0.31	0.34
Mapatox K	0.36 +/-0.04			0.33	0.37

Table 2. BOL solar absorptivity for SPOT 5.

HELIOS 2A α_s	On ground	Sky	Earth	V+	V-
Alu SSM	0.11 +/- 0.04	0.14	0.09	0.15	
Silver SSM	0.09 +/- 0.04			0.10	0.10
PCBE	0.22 +/-0.02	0.23	0.13		
SG121FD	0.24 +/-0.02	0.25	0.17		
Kapton	0.36 +/-0.02				0.38
Mapatox K	0.40 +/-0.02			0.34	0.40

Table 3. BOL solar absorptivity for HELIOS 2A.

DEMETER α_s	On ground	Sky	Earth	V+	V-
ITO-SSM (silver)	0.11+/- 0.02			0.14	0.15
SCK5	0.27 +/-0.04			0.33	0.35
PCBE	0.27 +/-0.04			0.24	0.27

Table 4. BOL solar absorptivity for DEMETER

4.2. Variation of the solar absorptivity

The variation of the solar absorptivity is given in Tables 5 to 7 for the three spacecrafts.

It is very difficult to evaluate the uncertainty on the in-flight measurements due to the uncertainty on the measured temperature and on the external heat flux rates calculations. That is why the absorptivity variations will be presented as well as the in-flight value of the solar absorptivity (§5.).

The earth face telemetry for all sensors is observed with a very high range due to albedo and IR earth heat flux rates and it is marred by high uncertainty. Consequently, the earth telemetry will not be considered in this paper.

The BOL solar absorptivity of the aluminium SSM on the sky face of SPOT 5 is arbitrarily chosen at 0.15 (in accordance with the other in-flight values).

SPOT5 7 years $\Delta\alpha_s$	$\Delta\alpha_s$ Sky	$\Delta\alpha_s$ V+	$\Delta\alpha_s$ V-
Alu SSM	+0.124	+0.090	+0.045
PCBE	+0.267		
SG121FD	+0.235	+0.224	+0.210
Kapton		+0.089	+0.094
Mapatox K		+0.083	+0.091

Table 5. Variation of the solar absorptivity on SPOT 5.

HELIOS2A 4.5 years $\Delta\alpha_s$	$\Delta\alpha_s$ Sky	$\Delta\alpha_s$ V+	$\Delta\alpha_s$ V-
Alu SSM	+0.091	+0.035	
Silver SSM		+0.021	+0.040
PCBE	+0.265		
SG121FD	+0.230		
Kapton			+0.100
Mapatox K		+0.070	+0.080

Table 6. Variation of the solar absorptivity on HELIOS 2A.

DEMETER 5 years $\Delta\alpha_s$	$\Delta\alpha_s$ Sky	$\Delta\alpha_s$ V+	$\Delta\alpha_s$ V-
ITO-SSM		+0.040	+0.057
SCK5		+0.062	+0.097
PCBE		+0.235	+0.201

Table 7. Variation of the solar absorptivity on DEMETER.

5. ANALYSIS AND COMPARISONS

5.1. First observations

SPOT 5 (Table 5 and Fig. 5.)

The SSM is slightly degraded on the V+ and V- faces ($\Delta\alpha_s < 0.10$), but it is more degraded on the sky face. The highest value of the solar absorptivity reaches 0.28 after 7 years. It can be noticed that the V+ face is less degraded than the V- face until 5 years and after it is the contrary.

During the 1st and the 2nd years, the α_s increase is very high for SG121FD and PCBE on the V+ and V- faces and especially on the sky face. After 2 years, the degradation slows down and tends to an upper value. This value is 0.46 and 0.52 respectively for SG121FD and PCBE on the sky face. It is lower (0.43) on the V+ and V- faces for SG121FD. It can be noticed that for the first fourth years, the V+ face is less degraded than the V- face and after, the degradation is the same.

The degradation of Kapton and Mapatox K is roughly the same for 7 years and stays low ($\Delta\alpha_s < 0.10$). It can be noticed that the V+ face stays less degraded than the V- face for both coatings.

HELIOS 2A (Table 6 and Fig. 6.)

The silver SSM is very slightly degraded on the V+ and V- faces ($\Delta\alpha_s < 0.05$). The highest value of the solar absorptivity reaches 0.14 after 4.5 years.

The aluminium SSM is slightly degraded on the V+ face and more degraded on the sky face, $\Delta\alpha_s < 0.10$. The highest value of the solar absorptivity reaches 0.23 after 4.5 years.

Like on SPOT 5, during the 1st and the 2nd years, the α_s increase is very high for SG121FD and PCBE on the sky face. After 2 years, the degradation slows down and tends to an upper value. This value is 0.48 and 0.50 respectively for SG121FD and PCBE.

The degradation of Kapton and Mapatox K is nearly the same for 4.5 years and stays low ($\Delta\alpha_s < 0.10$). It can be noticed that for the first fourth years, the V+ face is less degraded than the V- face for Mapatox K.

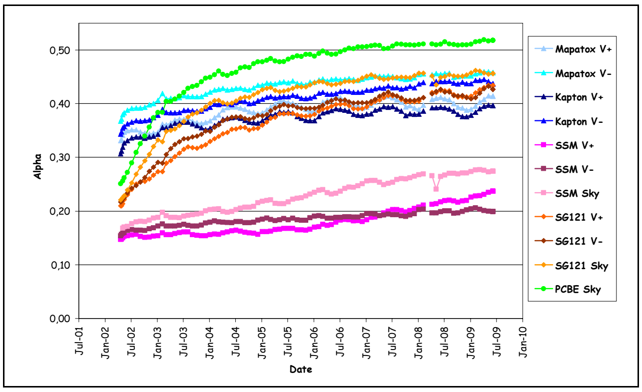

Fig. 5. Evolution of the solar absorptivity on SPOT 5.

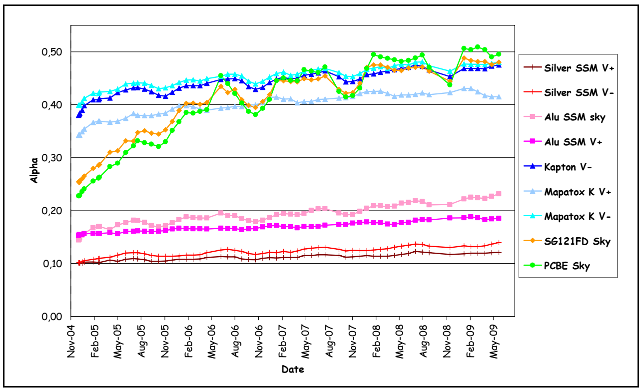

Fig. 6. Evolution of the solar absorptivity on HELIOS 2A.

DEMETER (Table 7 and Fig. 7.)

The silver ITO-SSM is very slightly degraded ($\Delta\alpha_s <$ 0.06), with a lower degradation on the V+ face than on the V- face. The highest value of the solar absorptivity reaches 0.21.

During the 1st and the 2nd years, the α_s increase is very high for PCBE on the V+ and V- faces. After 2 years, the degradation slows down and tends to an upper value, 0.48 for the two faces. It can be noticed that the V+ face is less degraded than the V- face while being very close.

The SCK5 paint is slightly degraded ($\Delta\alpha_s < 0.10$) on the V+ and V- faces. The highest value of the solar absorptivity is around 0.45 on the V- face and around 0.38 on the V+ face. Again, the V+ face is less degraded than the V- face.

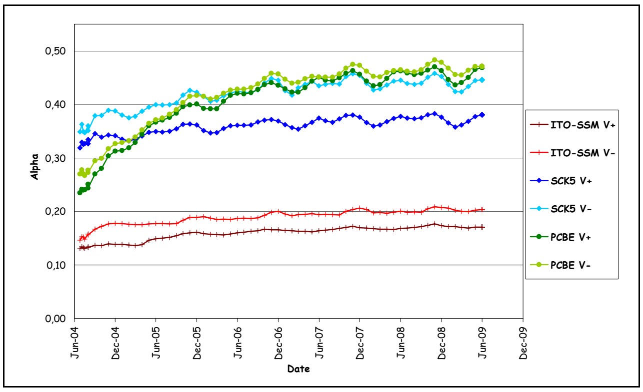

Fig. 7. Evolution of the solar absorptivity on DEMETER.

5.2. Environment of the three spacecrafts

The space environment in LEO is essentially composed of atomic oxygen (AO) expressed in atoms per cm^2 (at/cm^2) and ultraviolet rays expressed in equivalent solar hours (esh). Since the three spacecrafts are sun-synchronous, they have roughly (due to local hour and altitude differences) the same environment.

The dose of each environmental element received by external coatings depends on the spacecraft face.

For SPOT 5 (and typically for HELIOS 2A), the calculated environment is:

- V+ face : 2000 esh + 3.10^{19} at/cm^2 per year
- V- face : 2000 esh per year
- Sky face : 2600 esh + 2.10^{18} at/cm^2 per year

For DEMETER, the V+ and V- faces receive an average solar flux of 0.25*(solar constant). The total number of esh is calculated by the formula : 0.25*(total number of flight hours). For 5 years, it means 10800 esh namely 2160 esh per year. At around 700 km, the standard AO flux [2] for the V+ face is 1.10^{12} at/cm^2/s, namely 3.1.10^{19} at/cm^2 per year. Finally, Table 8 summarizes the cumulated doses for the three spacecrafts.

Spacecraft / Face	AO flux (atoms/cm2)	UV (esh)
SPOT 5 V+	2.1.10^{20}	14000
SPOT 5 V-		14000
SPOT 5 Sky	1.4.10^{19}	18200
HELIOS 2A V+	1.35.10^{20}	9000
HELIOS 2A V-		9000
HELIOS 2A Sky	9.10^{18}	11700
DEMETER V+	1.6.10^{20}	10800
DEMETER V-		10800

Table 8. Cumulated doses for the three spacecrafts.

5.3. Comparison of the coatings ageing on the different spacecrafts

The calculations (§ 5.2.) show that the UV and AO doses received by the faces of the three spacecrafts are comparable for the same durations. It is thus convenient to plot in the same graph the variation of the solar absorptivity in esh for each coatings. Fig. 8. to 10. represent these evolutions for SSMs, SG121FD, PCBE, Kapton and Mapatox K.

Focusing on these graphs and on $\Delta\alpha_S$, it can be seen that the deviation of the curves for the three spacecrafts are low.

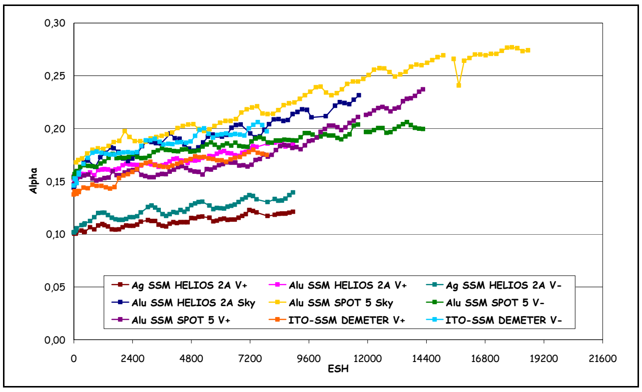

Fig. 8. Evolution of the solar absorptivity of SSMs.

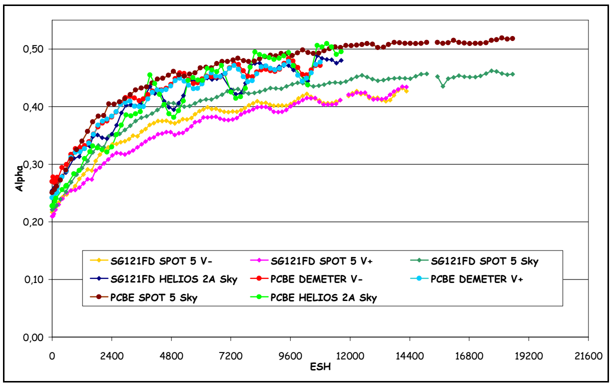

Fig. 9. Evolution of the solar absorptivity of SG121FD and PCBE.

5.4. Comparison with ground simulation tests

Ground simulation tests were performed in the Department of Space Environment (DESP) of ONERA, Toulouse. UV irradiation, AO bombardment and combined effects were carried out.

UV effects

The UV influence can be estimated only on the V- face of the spacecrafts (no AO). Table 9 compares these results with the in- flight measurements at the same UV dose.

For SG121FD and PCBE, the in-flight ageing is very much higher than the ground ageing. For Kapton and Mapatox K, the in-flight measurement is higher than the ground one but it is less pronounced than for the white paints. For SSMs and SCK5, there is a little difference between the in-flight and the ground degradation.

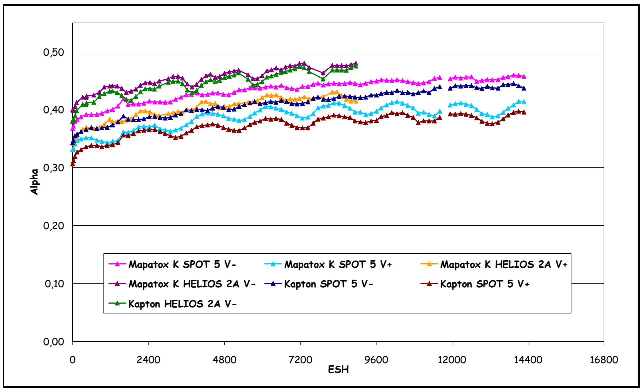

Fig. 10. Evolution of the solar absorptivity of Kapton and Mapatox K.

	$\Delta\alpha_s$ Ground test		$\Delta\alpha_s$ (V-) Telemetry					
	esh	$\Delta\alpha_s$	SPOT 5		DEMETER		HELIOS 2A	
			esh	$\Delta\alpha_s$	esh	$\Delta\alpha_s$	esh	$\Delta\alpha_s$
SG121FD	4054	+0.028	4093	+0.154				
PCBE	3057	+0.024			2952	+0.147		
Silver SSM	1943	+0.024					1849	+0.012
ITO-SSM	1943	+0.031			1917	+0.031		
Alu SSM	3298	+0.017	3260	+0.024				
Kapton	4054	+0.042	4093	+0.057				
MapatoxK	4054	+0.040	4093	+0.058				
SCK5	1500	+0.036			1572	+0.039		

Table 9. Comparison of ground UV irradiation and in-flight measurements.

AO effects

The AO effects were already discussed in a previous paper [3].The AO reaction coefficient was determined for the coatings (Table 10). It represents the coating surface sensitivity to AO. Kapton is the most sensitive coating.

When the coefficient is negative, there is mass gain with formation of a SiO_2 surface layer and when it is positive, there is mass loss that means erosion.

Coatings	AO reaction coefficient*10^{24} cm^3/at
SG121 FD	-0.04
PCBE	-0.04
Silver SSM	1.40
Kapton	3.00
Mapatox K	0.12
SCK5	-0.02

Table 10. AO reaction coefficients.

Combined effects (UV + AO)

These results were already described [3] and the results are given in Table 11.

Coatings	$\Delta\alpha_s$ After AO 2.10^{20} at/cm^2	$\Delta\alpha_s$ After 500 esh + AO 2.10^{20} at/cm^2	$\Delta\alpha_s$ after AO 2.10^{20} at/cm^2 + UV 500 esh
SG121FD	+0.01	+0.01	+0.03
PCBE	+0.01	+0.01	+0.02
Silver SSM	+0.02	-	-
MapatoxK	0.00	0.00	+0.01

Table 11. Ground tests results of the combined effects on α_s.

It can be seen that the degradation is slightly higher for the combined effects than for the AO effects only.

2.10^{20} at/cm^2 simulates the standard AO fluence received by the V+ face of a LEO spacecraft for 6.5 years [2]. These results can be compared to those obtained on the V+ and sky faces (UV + AO). These ground values are very low in comparison with the in-flight measurements.

6. DISCUSSION

The ground simulation tests show that the studied coatings are slightly sensitive to UV. The $\Delta\alpha_S$ values stay low. All the coatings are very few sensitive to AO except Kapton and SSMs. Nevertheless this sensitivity leads to the coating erosion which does not modify the thermo-optical properties.

On the contrary, the in-flight measurements show a high degradation of the paints.

Molecular contamination seems to be an answer to this result.

If there is a molecular contamination layer (composed of organic compounds outgassed at the beginning of flight) on the coating surface, this layer will polymerise under UV and will be eroded by AO. In this case, the coatings on the V+ face (AO + UV) will be less degraded than the ones on the V- face (only UV). The total UV irradiation on the sky face is higher than on the V+ face and the total AO fluence is lower. Consequently, the degradation on the sky face is higher than on the V+ face.

The SSM surface is composed of a polytetrafluoroethylene film which has a low surface energy. Polysiloxanes like the white paints and the Mapatox K varnish have also low surface energies. Polyimides (Kapton) have much more higher surface energies. There is a link between the surface energy and the surface adhesion coefficient (Young equation). The material surface energy allows to evaluate the material ability to develop strong adhesive interactions with another material. A material with a low surface energy will have an “anti-adhesive” behaviour to contamination products whereas a material with high surface energy will be contaminated more easily.

The surface energies of polytetrafluoroethylenes and polysiloxanes were extracted from bibliography [4] and the surface energy of Kapton was determined by a contact angle measurement with a goniometer (Table 1).

Polytetrafluoroethylenes and polysiloxanes will be the less sensitive coatings to molecular contamination. We observe effectively that the SSMs are the in-flight less degraded coatings. But it is not the case for the polysiloxane paints.

In practice, porosity increases the surface energy, thus paints are more sensitive to contamination than smooth surface (like SSM). PCBE is more porous than SG121FD that could explain its higher degradation (in the sky face).

Moreover, the temperature of the coating is very important: the more the coating will be cold, the more it will be contaminated. SG121FD and PCBE are the coldest coatings (after the SSMs) at beginning of life. They act as contamination products traps that explains the high in-flight degradation. SCK5 is warmer, it is thus less contaminated than SG121FD and PCBE. The in-flight degradation is effectively less pronounced and closer to the ground value.

Kapton has a higher surface energy than Mapatox K but their degradations are close. They are probably little contaminated because they are warm coatings.

Since THERME samples are purely passive and not linked to any dissipative equipment, an option to explain contamination is also an in-orbit temperature quite colder than an actual radiator. This is why it is now envisaged to update THERME experiment through “heated samples” and/or use of contaminant absorbers.

The presence of a molecular contamination layer on the coating surface is also consistent with the data of THERME on SPOT 2 for which there are almost 20 years of telemetry. For SSM (Fig. 11.), the solar absorptivity increases on the V+ and V- walls when the solar activity is low that means when the AO flux is low (—). On the contrary, when the solar activity increases that means when the AO flux is higher, the solar absorptivity decreases only on the V+ face and keeps on increasing on the V- face (—). This result is totally coherent with the contamination phenomenon. We have the same result on Kapton film (Fig. 12.).

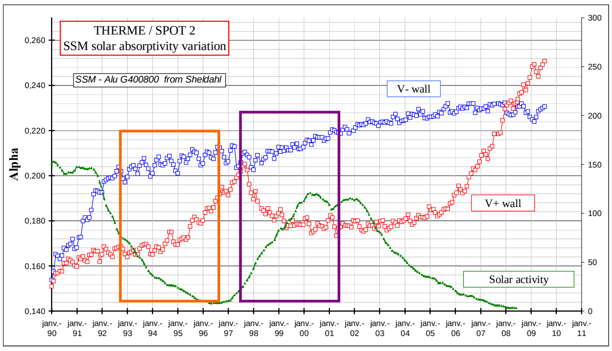

Fig. 11. Data of THERME on SPOT 2 for SSM.

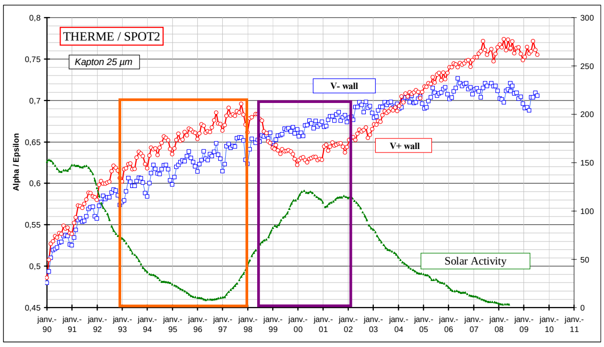

Fig. 12. Data of THERME on SPOT 2 for Kapton.

7. CONCLUSION AND PERSPECTIVES

CNES has developed a very simple and low cost experiment, “THERME”, which aims to evaluate the ageing of thermal coatings by following the solar absorptivity evolution. This experiment is now flying on SPOT 5, HELIOS 2A and DEMETER spacecrafts (sun-synchronous orbit). This paper presents in-orbit results for the following thermal control coatings :

- SG121FD, PCBE and SCK5 white paints from MAP.
- Silver and aluminium SSM from SHELDHAL.
- Kapton and Kapton with Mapatox-K (MAP), a protective coating against atomic oxygen.

These results are compared with the ones obtained in ground simulation tests.

The coatings are very degraded in-flight unlike in ground.

A possible explanation is that all the coatings would be contaminated by organic products outgassed at the beginning of flight. This hypothesis is consistent with the space environment, with the temperature and with the chemical nature of the coatings.

In order to mitigate this phenomenon, a new THERME experiment was designed with pressed porous materials pellets put in Kapton bags which are fixed between the coatings as it is described in Fig. 13. These pellets are zeolite-based adsorbers with an optimized formulation to trap different types of contamination products in the vicinity of the sensitive thermal control coatings.

This experiment is planned to be launched on the HELIOS 2B spacecraft end of 2009.

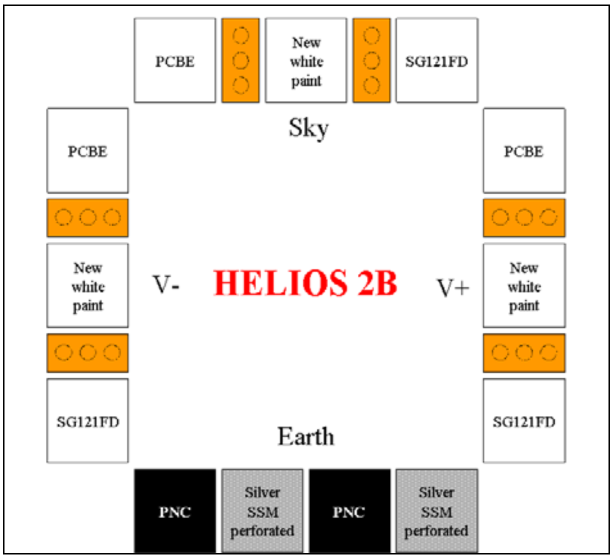

Fig. 13. THERME composition on HELIOS 2B.

Further to this, CNES is currently developing a « GEO-THERME » to evaluate on-site the effects of the geostationary environment. This means an evolution of classical THERME experiment through the use of heated and rigid substrate to typically evaluate OSR coating and get a representative temperature range.

Finally CNES thanks JAXA for selection of a THERME experiment as a mission for JAXA’s small satellite, Small Demonstration Satellite-4 (SDS-4), which is launched tentatively in 2011.

Other flight opportunities are welcome.

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