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In-Flight Aging of Thermal Coatings: THERME Experiment

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Centre National d'Etudes Spatiales has developed a simple and low-cost experiment called THERME to evaluate the in-flight degradation of common space coatings, in which temperature measurements are taken to monitor the evolution of solar absorptivity. The experiment payload is now carried on low-Earth-orbit satellites such as SPOT 5, HELIOS 2A, and DEMETER. In-orbit results provided for some thermal control coatings (white paint, second surface mirror, and Kapton) show the effects of the low-Earth-orbit space environment. Nevertheless, sometimes coatings are more degraded in flight than in ground simulation tests. A possible explanation is that the coatings are contaminated by organic products outgassed when the satellites are placed in orbit. The degradation of the coating would then be due to this early contamination combined with solar radiation, while the flux of atomic oxygen hitting the coating could reduce the degradation by eroding the contamination layer. This hypothesis is consistent with the space environment, the temperature, and the coating chemistry.

Nomenclature

$V+$	=	direction of satellite velocity
$V-$	=	direction opposite to satellite velocity
α_s	=	solar absorptivity
$\Delta\alpha_s$	=	variation of solar absorptivity over time
ε_{IR}	=	infrared emissivity

I. Introduction

THE in-flight evolution of thermooptical properties of thermal control coatings is of great concern, since the aging of these materials has a significant impact on the thermal balance and heating power consumption of instruments and spacecraft. To define spacecraft thermal control, thermal engineers have to take into account both the beginning-of-life (BOL) and end-of-life (EOL) thermo-optical properties of external coatings they intend to use (α_s and ε_{IR}). From experience (in-flight measurements and ground tests in laboratories), the solar absorptivity α_s is known to be the most significant parameter affected by in-orbit aging. It often increases when coatings are subjected to a space environment. An important increase between the BOL value and the EOL value of the solar absorptivity of thermal control coatings has an immediate negative impact, because it significantly increases the hot temperatures reached at EOL. To reduce these temperatures to acceptable values, it is necessary to increase the radiative areas during the design phase, leading to higher heating power consumption at BOL and in safe mode. Improving the knowledge of the EOL solar absorptivity of thermal coatings is thus a good way of optimizing radiators size during the design phase, and then of mastering heating power consumption onboard. More than 1000 materials have been evaluated during several space shuttle flight experiments and from recovered satellites (e.g., LDEF, Solar Maximum Mission, MIR, ISS) [1,2] but there are very few in-flight data available for higher orbits and long exposure. Centre National d'Etudes Spatiales (CNES) has thus developed a very simple, low-cost experiment called THERME, which aims to evaluate the aging of thermal coatings (evolution of α_s) and especially of recent thermal coatings. This experiment is now carried on satellites such as SPOT 5, HELIOS 2A, and DEMETER (all three are on sun-synchronous orbits at an altitude of around 750 kms).

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 are given in this paper for white paints (SG121FD, PCBE, and SCK5 from the MAP company), for silver and aluminum second surface mirrors (SSM, from the Sheldahl company), for Kapton (from Sheldahl), and for Kapton with a protective coating against atomic oxygen (Mapatox K from MAP). The results are compared with those obtained from ground simulation tests and then discussed.

Finally, this paper summarizes 19 years of telemetry data from THERME onboard SPOT 2 confirming the significant impact of contamination and atomic oxygen on coating degradation.

II. Description of the THERME Experiment

The THERME experiment has already been described [3]. Figure 1 shows the principle involved. For SPOT 5 and HELIOS 2A, the experiment consists of 16 calorimeters made from four 100 mm × 400 mm multilayer insulation (MLI) blankets (Figs. 2 and 3). For DEMETER, the experiment consists of eight calorimeters shared in two sets (Fig. 4).

By measuring the evolution of the temperature of the calorimeters during the whole satellite mission, one can simply calculate the variation with time of the solar absorptivity of the coatings.

SPOT 5 was launched on 4 May 2002, and it is on a sun-synchronous orbit at an altitude of 820 km with a 98.7° inclination, a local time of 22 h 30 min at ascending node and Earth pointing. HELIOS 2A was launched on 18 December 2004 in low Earth orbit (LEO, altitude lower than SPOT 5). DEMETER was launched on 29 June 2004 at an altitude of 710 km with a 98.2° inclination, a local time at ascending node of 22 h 25 min and Earth pointing.

III. Description of the Coatings

The thermal control coatings on the three different satellites (see Figs. 2–4.) are SG121FD, PCBE, and SCK5 white paints from MAP, silver (with and without indium thin oxyde, or ITO) and aluminum SSM from Sheldhal, Kapton from Sheldhal, and Mapatox-K from MAP. The coatings are described in Table 1.

IV. Telemetry

A. BOL Solar Absorptivity

On SPOT 5, the aluminum SSM sensor on the side facing away from the Earth did not give an in-flight BOL value due to a wrong

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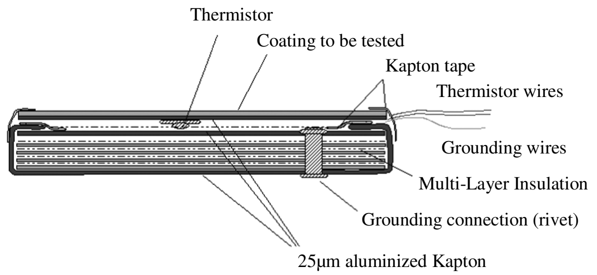


Fig. 1 THERME principle.

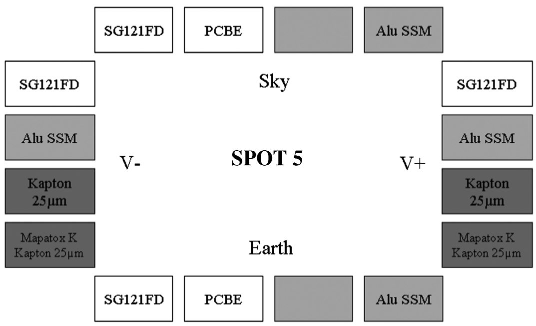


Fig. 2 THERME composition on SPOT 5.

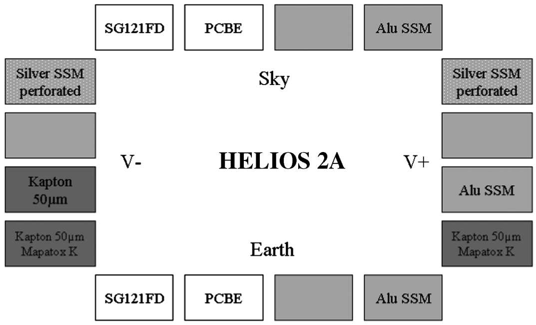


Fig. 3 THERME composition on HELIOS 2A.

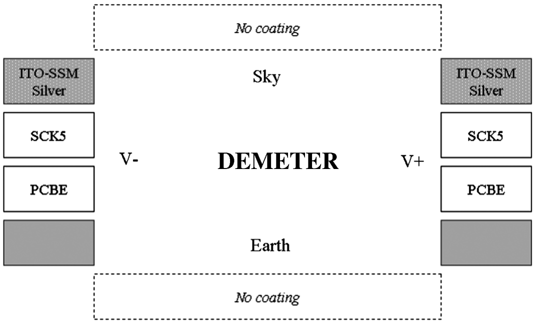


Fig. 4 THERME composition on DEMETER.

choice of the thermistor temperature range. Nevertheless, this problem was resolved naturally through aging and the temperature increase a few months later. Seven years of telemetry data are available from SPOT 5. On HELIOS 2A, the problem was corrected before launch. The telemetry has been recorded for 4.5 years. On DEMETER, the telemetry covers 5 years. Tables 2–4 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 values deduced from temperature measurements. For all coatings, there is a good consistency between the on-ground and the first in-flight values on the three satellites, except for the white paints on the HELIOS 2A Earth–facing side.

B. Variation of Solar Absorptivity

It is very difficult to evaluate precisely the uncertainty component of in-flight values due to the uncertainty of the measured temperatures and in the calculations of the external heat flux rates. This is why the in-flight values are given both in absolute and relative values with regards to initial in-orbit measurements (see Sec. V). The variation of solar absorptivity is given in Tables 5–7 for the three satellites.

The temperatures recorded for all Earth-pointed sensors show important fluctuations with no clear repetition for the different orbits. This is due to the high variation of the local albedo and infrared Earth heat flux rates. The analysis of the telemetry of Earth-facing sides is thus marred by high uncertainty. Consequently, this telemetry data will not be considered in this paper. The BOL solar absorptivity of the aluminum SSM on the space-facing side of SPOT 5 was arbitrarily set at 0.15 (in accordance with the other in-flight values).

V. Analysis and Comparisons

A. First Observations

1. *SPOT 5 (Table 5 and Figs. 5a and 5b)*

The SSM is slightly degraded on the $V+$ and $V-$ sides ($\Delta\alpha_s < 0.10$), but is degraded more on the space-facing wall. The highest solar absorptivity value was 0.28 after seven years. Note that the $V+$ side was less degraded than the $V-$ side for the first five years and that the opposite was true after the first five years. During the first and second years, the increase of α_s was very high for SG121FD and PCBE on the $V+$ and $V-$ sides and especially on the space-facing side. After two years, the degradation slowed down and tended towards an upper value. These values were 0.46 and 0.52, respectively, for SG121FD and PCBE on the space-facing side. It was lower (0.43) on the $V+$ and $V-$ sides for SG121FD. It may be observed that for the first 4 years, the $V+$ side is less degraded than the $V-$ side and after, that the degradation is the same. The

Table 1 Description of the coatings

Coating	Description	External surface	Surface state	Surface energy, mJ/m^2
SG121FD	Nonconductive white paint	Polysiloxane Zinc oxide	Porous	——
PCBE	Conductive white paint	Polysiloxane Zinc oxide	Porous	——
SSM (Al or Ag)	Polymer film with aluminum back surface	Polytétrafluoroéthylène (PTFE)	Smooth	20
Kapton	Polymer film with aluminum back surface	Polyimide	Smooth	47.7
Mapatox K	Polymer varnish on Kapton	Polysiloxane	Smooth	20
ITO-SSM, Ag	ITO deposit on polymer film with silver back surface	Metal oxide	Porous	——
SCK5	Antistatic white paint	Polysiloxane Metal oxide	Porous	——

Table 2 BOL solar absorptivity for SPOT 5

SPOT 5 α_s	On ground	Space-facing side	Earth-facing side	$V+$	$V-$
Al 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 3 BOL solar absorptivity for HELIOS 2A

HELIOS 2A α_s	On ground	Space-facing side	Earth-facing side	$V+$	$V-$
Al SSM	0.11 ± 0.04	0.14	0.09	0.15	
Ag 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 4 BOL solar absorptivity for DEMETER

DEMETER α_s	On ground	Space-facing side	Earth-facing side	$V+$	$V-$
ITO-SSM AG	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

degradation of Kapton and Mapatox K is roughly the same for seven years and remains low ($\Delta\alpha_s < 0.10$). Note that the $V+$ side was less degraded than the $V-$ side for both coatings.

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

The silver SSM is very slightly degraded on the $V+$ and $V-$ sides ($\Delta\alpha_s < 0.05$). The highest value of the solar absorptivity was 0.14 after 4.5 years. The aluminum SSM was slightly degraded on the $V+$ side and more degraded on the space-facing side ($\Delta\alpha_s < 0.10$). The highest value of the solar absorptivity was 0.23 after 4.5 years. As on SPOT 5, during the first and second years, the increase of α_s was very high for SG121FD and PCBE on the space-facing side. After two years, the degradation slowed down and tended towards an upper value. These values were 0.48 and 0.50, respectively, for SG121FD and PCBE. The degradation of Kapton and Mapatox K was practically the same for 4.5 years and remained low ($\Delta\alpha_s < 0.10$). Note that for the whole period of 4.5 years, the $V+$ side remained less degraded than the $V-$ side for Mapatox K.

Table 5 Variation of solar absorptivity on SPOT 5

SPOT 5 7 years $\Delta\alpha_s$	Space-facing	$V+$	$V-$
Al 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 6 Variation of solar absorptivity on HELIOS 2A

HELIOS 2A 4.5 years $\Delta\alpha_s$	Space-facing	$V+$	$V-$
Al SSM	+0.091	+0.035	——
Ag SSM	——	+0.021	+0.040
PCBE	+0.265	——	——
SG121FD	+0.230	——	——
Kapton	——	——	+0.100
Mapatox K	——	+0.070	+0.080

Table 7 Variation of solar absorptivity on DEMETER

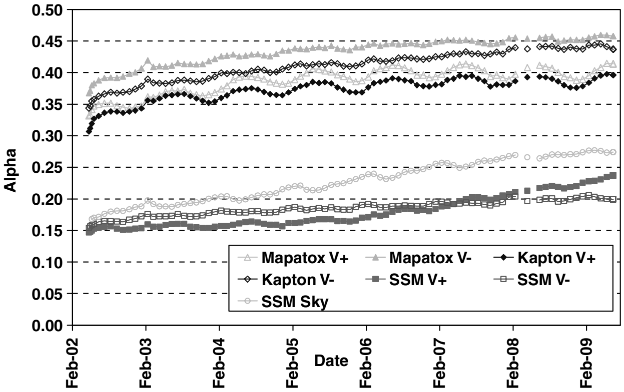
DEMETER 5 years $\Delta\alpha_s$	Space-facing	$V+$	$V-$
ITO-SSM, Ag	——	+0.040	+0.057
SCK5	——	+0.062	+0.097
PCBE	——	+0.235	+0.201

3. DEMETER (Table 7 and Fig. 7)

The silver ITO-SSM was only slightly degraded ($\Delta\alpha_s < 0.06$), with less degradation on the $V+$ side than on the $V-$ side. The highest value of solar absorptivity was 0.21 after five years. During the first and second years, the increase of α_s was very high for PCBE on the $V+$ and $V-$ sides. After two years, the degradation slowed down and tended towards an upper value of 0.48 for both sides. Note that the $V+$ side was less degraded than the $V-$ side although the values remain close. The SCK5 paint was slightly degraded ($\Delta\alpha_s < 0.10$) on the $V+$ and $V-$ sides. The highest value of the solar absorptivity was around 0.45 on the $V-$ side and around 0.38 on the $V+$ side. Once again, the $V+$ side remained less degraded than the $V-$ side.

B. Environment of the Three Satellites

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). Because the three satellites are on sun-synchronous orbits, 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 side of the spacecraft concerned. For SPOT 5 (and typically for HELIOS 2A), the calculated environment is 2000 esh + 3.10^{19} at/cm^2 per year for $V+$, 2000 esh per year for $V-$, and 2600 esh + 2.10^{18} at/cm^2 per year for space-facing sides. For



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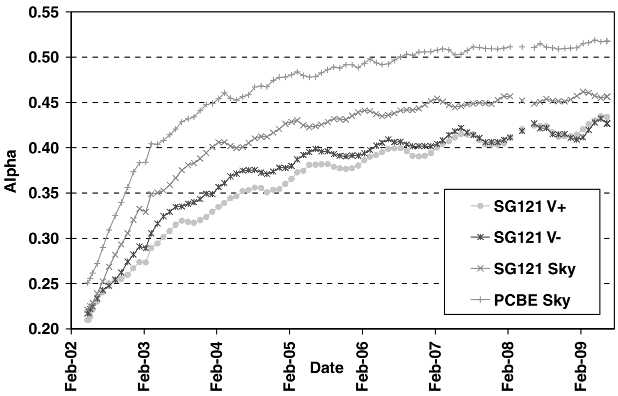


b)

Fig. 5 Graphs of a) evolution of solar absorptivity on SPOT 5, and b) evolution of solar absorptivity on SPOT 5.

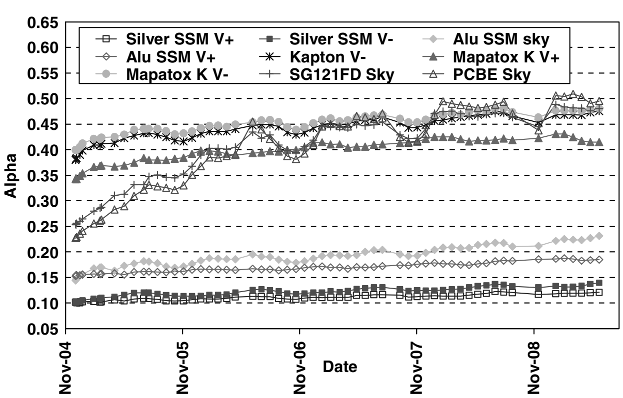


Fig. 6 Evolution of solar absorptivity on HELIOS 2A.

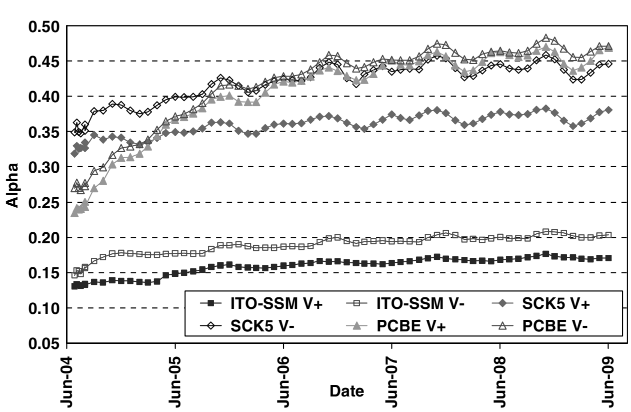


Fig. 7 Evolution of solar absorptivity on DEMETER.

Table 8 Cumulated doses for the three satellites

Spacecraft/Side	AO fluences (atoms/cm^2)	UV, esh
SPOT 5 $V+$	$2.1.10^{20}$	14,000
SPOT 5 $V-$	Insignificant	14,000
SPOT 5 Sky	$1.4.10^{19}$	18,200
HELIOS 2A $V+$	$1.35.10^{20}$	9000
HELIOS 2A $V-$	Insignificant	9000
HELIOS 2A Sky	9.10^{18}	11,700
DEMETER $V+$	$1.6.10^{20}$	10,800
DEMETER $V-$	Insignificant	10,800

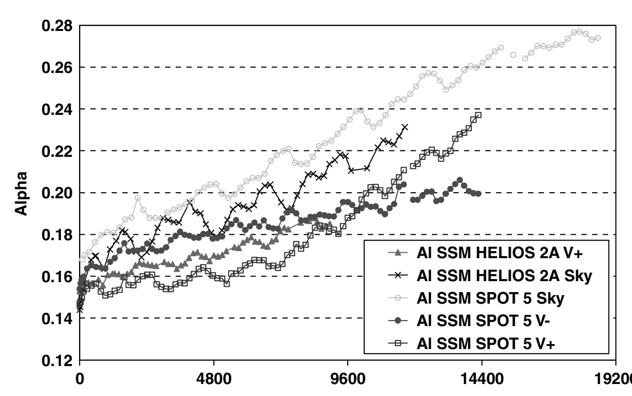
DEMETER, the $V+$, and $V-$ sides receive an average solar flux of $0.25 *$ (solar constant). The total number of esh is calculated by the formula $0.25 *$ (total number of flight hours). For five years, the total is 10,800 esh or 2160 esh per year. At an altitude of around 700 km, the standard AO flux [4] for the $V+$ side is 1.10^{12} at/cm^2/s, namely $3.1.10^{19}$ at/cm^2 per year. Finally, Table 8 gives the cumulated doses for the three satellites.

C. Comparison of Coating Aging on the Different Satellites

The calculations (Sec. V.B.) show that the UV and AO doses received by the sides of the three spacecrafts are comparable for the same duration. It is thus convenient to plot the variation of the solar absorptivity in esh for each coating on the same graph. Figures 8–10 represent these evolutions for SSM, SG121FD, PCBE, Kapton, and Mapatox K. Looking at these graphs and at $\Delta\alpha_s$, it can be seen that the differences between the curves for the three satellites are low.

D. Comparison with Ground Simulation Tests

Ground simulation tests were performed at the ONERA Department of Space Environment in Toulouse. The test scenarios included UV irradiation, AO bombardment, and combined effects.



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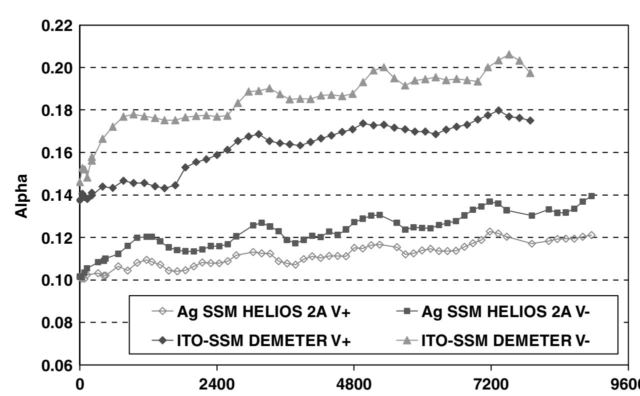

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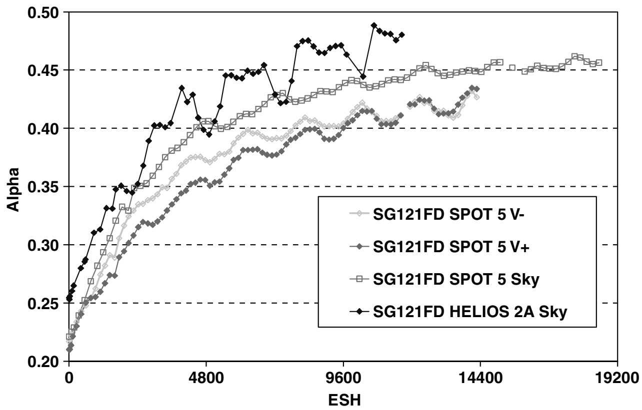
Fig. 8 Graphs of a) evolution of the solar absorptivity of Al SSM, and b) evolution of the solar absorptivity of Ag and ITO-SSM.



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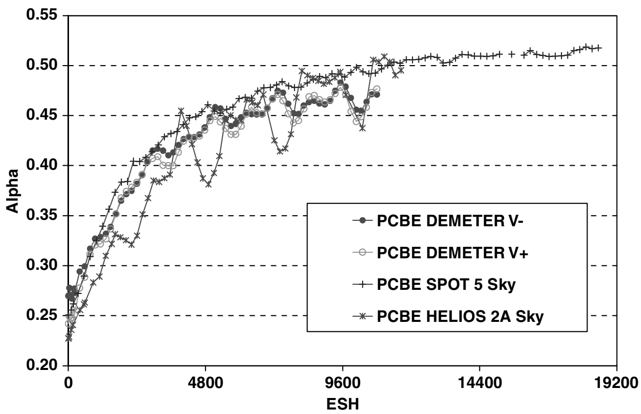

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Fig. 9 Graphs of a) evolution of the solar absorptivity of SG121FD, and b) evolution of the solar absorptivity of PCBE.

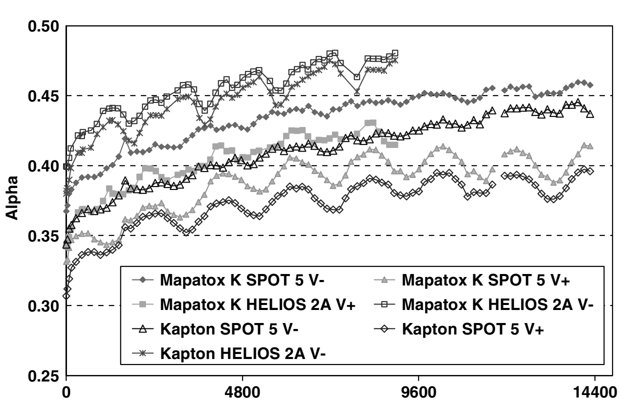

Fig. 10 Evolution of the solar absorptivity of Kapton and Mapatox-K.

Table 10 AO reaction coefficients

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

Table 11 Ground tests results of the combined effects on α_s

Coatings	$\Delta\alpha_s$	$\Delta\alpha_s$	$\Delta\alpha_s$
	after AO 2.10^{20} at/cm^2	after 500 esh AO 2.10^{20} at/cm^2	after AO 2.10^{20} at/cm^2 then UV 500 esh
SG121FD	+0.01	+0.01	+0.03
PCBE	+0.01	+0.01	+0.02
Ag SSM perforated	+0.02	——	——
Mapatox K	0.00	0.00	+0.01

1. *UV Effects*

The UV influence can be estimated only on the $V-$ side of the satellites (no AO). Table 9 compares these results with the in-flight measurements for a given UV dose. For SG121FD and PCBE, in-flight aging is very much higher than ground aging. For Kapton and Mapatox K, the in-flight measurement is higher than the ground one but this difference is less marked than for the white paints. For SSM and SCK5, there is little difference between the in-flight and ground simulated degradation.

2. *AO Effects*

The AO effects have already been discussed in a previous paper [5]. 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 which means erosion.

3. *Combined Effects* (UV + AO)

These results have already been described [5] and are given in Table 11.

It can be seen that the degradation was 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 $V+$ side of an LEO satellite over a period of 6.5 years [4]. These results can be compared with those obtained on the $V+$ and space-facing sides (UV + AO). These ground values are very low in comparison with in-flight measurements.

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

	$\Delta\alpha_s$		$\Delta\alpha_s$ $(V-)$					
	Ground test		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	——	——
Al SSM	3298	+0.017	3260	+0.024	——	——	——	——
Kapton	4054	+0.042	4093	+0.057	——	——	——	——
Mapatox K	4054	+0.040	4093	+0.058	——	——	——	——
SCK5	1500	+0.036	——	——	1572	+0.039	——	——

VI. Discussion

The ground simulation tests show that the studied coatings are slightly sensitive to UV. The $\Delta\alpha_s$ values remain low. The Kapton and SSM materials were very sensitive to AO erosion. The remainder of the materials tested experienced lesser erosion rates. Nevertheless this sensitivity leads to the coating erosion, which does not modify the thermooptical properties. The in-flight measurements, on the other hand, show a high degradation of the paints. Molecular contamination appears to explain this result. Indeed, contamination sources are various in flight, for example, from the outgassing of external materials or from the satellite inside through the outgassing vents. In general, the contaminants are carbon-based or silicones. To demonstrate the nature of a possible contamination of THERME, the experiment has been placed on the satellite walls during the thermal vacuum test. At the end of the test, some chloroform samplings have been performed on the SSM and Kapton coatings. The solutions have been deposited on germanium blade and after evaporation the residues have been analyzed by infrared spectroscopy. This analysis shows aliphatic hydrocarbons absorption bands. Then we can conclude that THERME could be contaminated in flight by carbon-based products from the satellite. Therefore, if there is a molecular contamination layer composed of carbon-based compounds (outgassed when the satellite is first placed on its orbit) on the coating surface, this layer will polymerise under UV rays and will then be eroded by AO. In this case, the coatings on the $V+$ side (AO + UV) will be less degraded than the ones on the $V-$ side (only UV). The total UV irradiation on the space-facing side is higher than on the $V+$ side and the total AO fluence is lower. Consequently, the degradation on the space-facing side is higher than on the $V+$ side.

The SSM surface is composed of a polytetrafluoroethylene film which has a low surface energy. Polysiloxanes such as white paints and the Mapatox K varnish also have low surface energies. Polyimides (Kapton) have much higher surface energies. There is a link between the surface energy and the surface adhesion coefficient (Young equation). The material's surface energy enables an evaluation of its ability to bond with another material. A material with a low surface energy will not bond to contamination products whereas a material with high surface energy will be contaminated more easily. The surface energies of polytetrafluoroethylenes and polysiloxanes were found in the literature [6] and the surface energy of Kapton was determined by a contact angle measurement with a goniometer (Table 1). Polytetrafluoroethylenes and polysiloxanes coatings are less sensitive to molecular contamination. We did indeed observe the SSM coatings are the least degraded in flight. But this is not the case for the polysiloxane paints.

In practice, porosity increases the surface energy, and thus paints are more sensitive to contamination than smooth surfaces (such as SSM). PCBE is more porous than SG121FD, which could explain its higher degradation (for the space-facing side). Moreover, the temperature of the coating is very important: the colder the coating, the more it will be contaminated. SG121FD and PCBE are the coldest coatings (except for SSM) at beginning of life. They behave as traps for the contamination products, which explains the high in-flight degradation. SCK5 is warmer, so it is less contaminated than SG121FD and PCBE. Its in-flight degradation is effectively less marked and closer to the ground test value. Kapton has a higher surface energy than Mapatox K but the extent of their degradation is similar. They are probably not contaminated much because they are warm coatings. Because THERME samples are purely passive and not linked to any dissipative equipment, in-orbit temperatures are much colder than an actual radiator. This is another possible explanation of the contamination which is why it is now envisaged to update the THERME experiment using contaminant absorbers. A new THERME experiment was designed with compressed porous material pellets put in Kapton bags which are fixed between the coatings as described in Fig. 11. These pellets are zeolite-based absorbers with an optimized formulation to trap different types of contamination products in the vicinity of the sensitive thermal control coatings. The experiment was launched on the HELIOS 2B spacecraft at the end of 2009.

The presence of a molecular contamination layer on the coating surface is also consistent with data from the THERME payload on SPOT 2 (LEO orbit) for which there are almost 20 years of telemetry. For SSM (Fig. 12), the solar absorptivity increases on the $V+$ and $V-$ sides when the solar activity is low which means when the AO flux is low (solid line rectangle). On the contrary, when the solar activity increases, i.e., when the AO flux is higher, the solar absorptivity decreases only on the $V+$ side and keeps on increasing on the $V-$ side (dashed line rectangle). This result is fully consistent with the contamination phenomenon. The same result was found for Kapton film (Fig. 13).

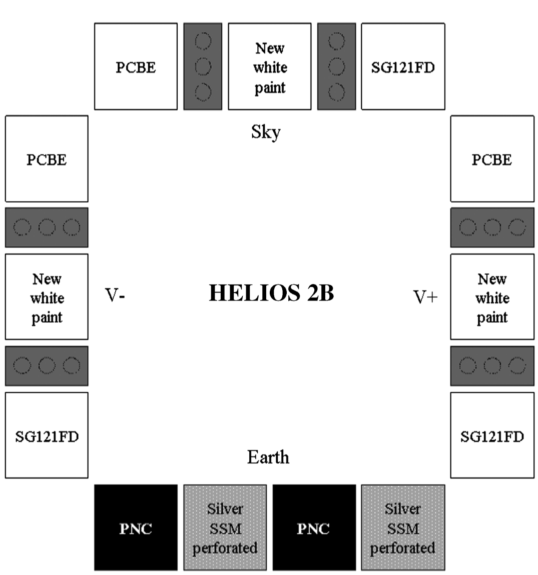

Fig. 11 THERME composition on HELIOS 2B.

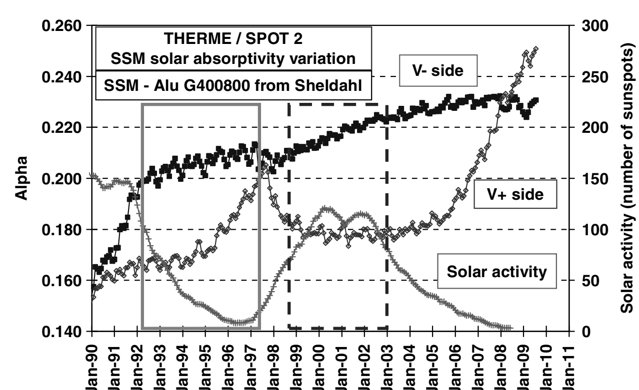

Fig. 12 Data of THERME on SPOT 2 for SSM.

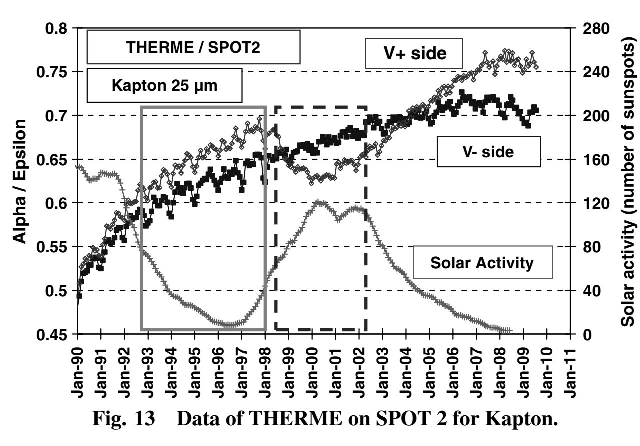

Fig. 13 Data of THERME on SPOT 2 for Kapton.

VII. Conclusions

THERME is a simple, low-cost experiment developed by CNES. Its goal is to measure the degradation of thermooptical properties α_s in an actual space flight environment for different thermal control coatings such as white paints, SSM, and Kapton. THERME is currently carried on several LEO satellites, namely SPOT 5, DEMETER, HELIOS 2A, and HELIOS 2B.

In-flight data acquired from past and present THERME experiments tend to confirm the hypothesis proposed to explain the degradation. It is due to a combination of molecular contamination occurring mainly early in the mission and solar radiation. The flux of atomic oxygen makes a significant contribution to degradation. Indeed, coatings that are subjected to AO flux (on sky or $V+$ satellite sides) systematically show less optical property degradation. The authors believe the AO flux erodes the contamination layer, and as a consequence reduces the degradation. This observation is consistent with the variation of AO flux due to the variation of solar activity. The porosity and temperature of the coating also affect the degree of contamination.

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