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Herschel optical performances-transmission budgets

Product Code: 100000

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TITRE

Herschel optical performances transmission budgets

AUTEUR (S) (Personne physique) Ph. MARTIN

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RESUME D'AUTEUR

Cette note technique présente les budgets de transmission. Elle est basée sur le statut actuel de l'analyse contamination

Réf. disquette ou fichier
NA

Catégorie de diffusion

2		D	
3	x	I	x

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ENREGISTREMENT DES EVOLUTIONS / *CHANGE RECORDS*

ISSUE	DATE	§ : DESCRIPTION DES EVOLUTIONS *§ : CHANGE RECORD*	REDACTEUR *AUTHOR*
1	06/06/2002	First draft issue	Ph. MARTIN
2	17/03/2004	Second issue Now concerns both LOU windows and telescope	Ph. MARTIN
3	23/07/2004	The cleanliness budgets are set in line with cleanliness analysis 4.0 The sensitivity of LOU transmission to contamination is explained	Ph. MARTIN
3.1	28/02/2005	Revision to include the improvement on the LOU windows due to the passive baffle. This leads to a margin of a factor 100 in terms of water ice thickness	Ph. MARTIN

TABLE OF CONTAINTS

1. SCOPE

The goal of this TN is to present and justify the transmission budgets of the Herschel Telescope and LOU windows. This justifies the compliance status to the following customer requirements:
SGEN-200 H and SGEN-202 H from [AD1]
Transmission need for the LOU windows in the HIFI IID-B
current optical performances degradation budgets induced by system activities contamination on Herschel mirrors. Both particulate and molecular contamination are covered. Optical performances are transmission and self-emission. Straylight is out of the scope of this TN.

It firstly describes the inputs, expressed in terms of contamination levels at End of Life on Herschel mirrors and LOU windows. These inputs represent the current status of contamination analysis and contamination control plan, and are completely justified in these documents.
The second step is the description of the contamination model, and the justification of all the hypotheses.
Afterwards, and based on the two preceding sections, the impact of the contamination is assessed.

2. APPLICABLE/REFERENCE DOCUMENTS

2.1 Applicable document:

[AD1] "System Requirement Specification"
SCI-PT-RS-059111 Is/Rev 3/2
[AD2] "HIFI Instrument Interface Document"
SCI-PT/IID-B/HIFI-02125 Is/Rev 3/2
[AD3] "Herschel Telescope requirement specification"
SCI-PT-RS-04671 Issue 7/0

2.2 Reference documents:

[RD1] "Cleanliness requirement specification"
H-P-1-ASPI-SP-0035
[RD2] "ISO cleanliness Policy"
ISO-AS-1300-TN-0429 Is 1-Rev B
[RD3] "Principles of Optics"
Born and Wolf - 7th (expanded) edition
[RD4] "Optical properties of NH_3 ice from the far infrared to the near ultraviolet"
Applied Optics/ Vol. 23 No. 4
[RD5] "Optical constants of ice from the ultraviolet to the microwave"
Applied Optics/ Vol. 23 No. 8
[RD6] "Photochemically deposited contaminants Film Effects"
SPIE Vol 2864 - pp269
[RD7] EOL cleanliness analysis
H-P-1-ASPI-TN-269 issue 4/0
[RD8] "Scattering in the (sub)mm-wave range by dust on reflectors and its consequences in the case of the Planck Telescope
070500/EEA/PDM
[RD9] HIFI contamination degradation analysis
SRON-U/HIFI/TN/2000-002 issue 02
[RD10] molecular contamination – sensitivity to optical index hypothesis
H-P-1-ASP-TN-430 issue 2 dated 18 dec 2002
[RD11] Herschel optical windows assembly test report
HP-2-QMC-TR-0001 issue 2 rev 1 dated 05 dec 2003
HP-2-QMC-TR-0001
[RD12] ESA blue book
PT-TN-05967

3. ABBREVIATION/ACRONYMS

BRDF	**B**i-**D**irectional **R**eflectance **D**istribution **F**unction
CVV	**C**ryo **V**acuum **V**essel
EOL	**E**nd **o**f **L**ife
IR	**I**nfra**r**ed
PA	**P**roduct **A**ssurance
PLM	**P**ay**l**oad **M**odule
Ppm	**p**art **p**er **m**illion (10^{-6})
RMS	**R**oot **M**ean **S**quare
S/C	**S**pace**c**raft
Spec	**spec**ification
SRS	**S**ystem **R**equirement **S**pecification ([AD1])
TBC	**t**o **b**e **c**onfirmed
TBD	**t**o **b**e **d**efined
TIS	**T**otal **I**ntegrated **S**catter

4. TELESCOPE MIRRORS

4.1 Contamination impact

4.1.1 End of life contamination levels

This section presents the contamination budgets on Herschel mirrors. It is based on the current status of contamination analysis and contamination control plan.

4.1.1.1 Particulate contamination

the current particulate contamination budget is the following (on each mirror)

Phase		M1		M2	
		Contribution	Total	Contribution	Total
Telescope at delivery	[AD3]	300ppm	300ppm	300ppm	300ppm
Spacecraft AIT till encapsulation	From AsED cleanliness Plan	1900 ppm	2200 ppm	95	400 ppm
Spacecraft launch campaign	8 days in class 10 000	480 ppm	2680 ppm	24	420 ppm
Ascent	[AD1]	2300	4980	2300	2720ppm
Micrometeorite and redistribution	[RD7]	Neg(*)	4980 ppm	Neg(*)	2720 ppm
Total		4980			2720ppm

4.1.1.2 Molecular contamination

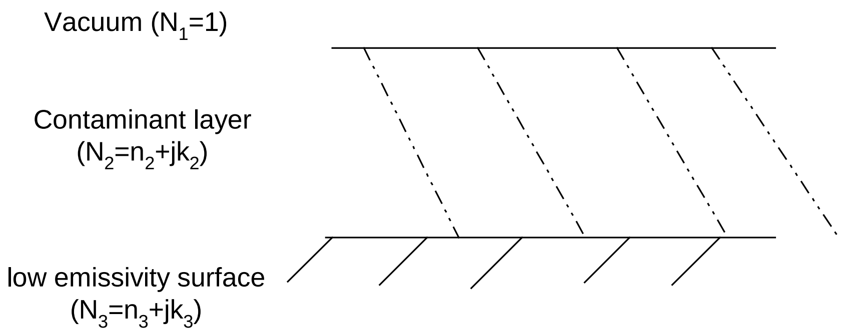
Three kind of contaminants have been considered: on ground contaminants, water and ammonia. For each one of these contaminants, the contamination budget in the following subsections

g/cm2	Ref	Ground contaminants		H2O		NH3		TOTAL	
		M1	M2	M1	M2	M1	M2	M1	M2
Delivery	[AD3]	2 10-7	2 10-7	-	-	-	-	2 10-7	2 10-7
AIT	ASED cleanliness budgets	4 10-7	4 10-7	-	-	-	-	4 10-7	4 10-7
Launch preparation	8 days in class 10 000	2.4 10-8	2.4 10-8	-	-	-	-	2.4 10-8	2.4 10-8
Outgassing	[RD7]	-	-	1.1 10-5	9.5 10-8	-	-	1.1 10-5	9.5 10-8
Thruster plume	[RD7]	-	-	-	-	0	7 10-10	0	7 10-10
TOTAL								1.2 10-5	7.2 10-7

4.1.2 Contamination models

4.1.2.1 Molecular contamination model

geometry:



hypotheses

contaminant layer index will be considered at the useful wavelength range for transmission losses assessment: 80μm up to 670μm

Mirror index is considered to be $n_3+jk_3=0.001-1500j$. This is a good assumption to represent a perfectly reflecting mirror.

Prediction law

$$|\Delta a| = |\Delta\varepsilon| = 1 - |r|^2 = 1 - \left| \frac{r_{12} + r_{23} e^{2i\alpha t}}{1 + r_{12} r_{23} e^{2i\alpha t}} \right|^2$$

Equation 4-1 emissivity and absorption change calculation

where :
- r is the reflection loss on the low emissivity surface
- r_{12} is the amplitude reflection loss on the air-contaminant interface
- r_{23} is the amplitude reflection loss on the contaminant-mirror interface
- α $\alpha = \frac{2\pi}{\lambda} * N_2$
- t is the thickness of the (contaminant) layer
- N_2 is the complex index of the (contaminant) layer
- λ is the wavelength

As the contaminant thickness and nature are given as inputs, the preceding relation directly give the transmission.

4.1.2.2 Particulate contamination model

To assess the impact of particulate contamination transmission losses, Mie theory is issued. This is an approximation which is perfectly valid of spherical particles, which are small with regards to the wavelength. However, it has been shown to be conservative if this is not perfectly verified.
To use Mie theory, hypotheses on dust nature and particle size distribution have to be made. They are presented and justified in the next two sub-sections.

4.1.2.2.1 Particle size distribution

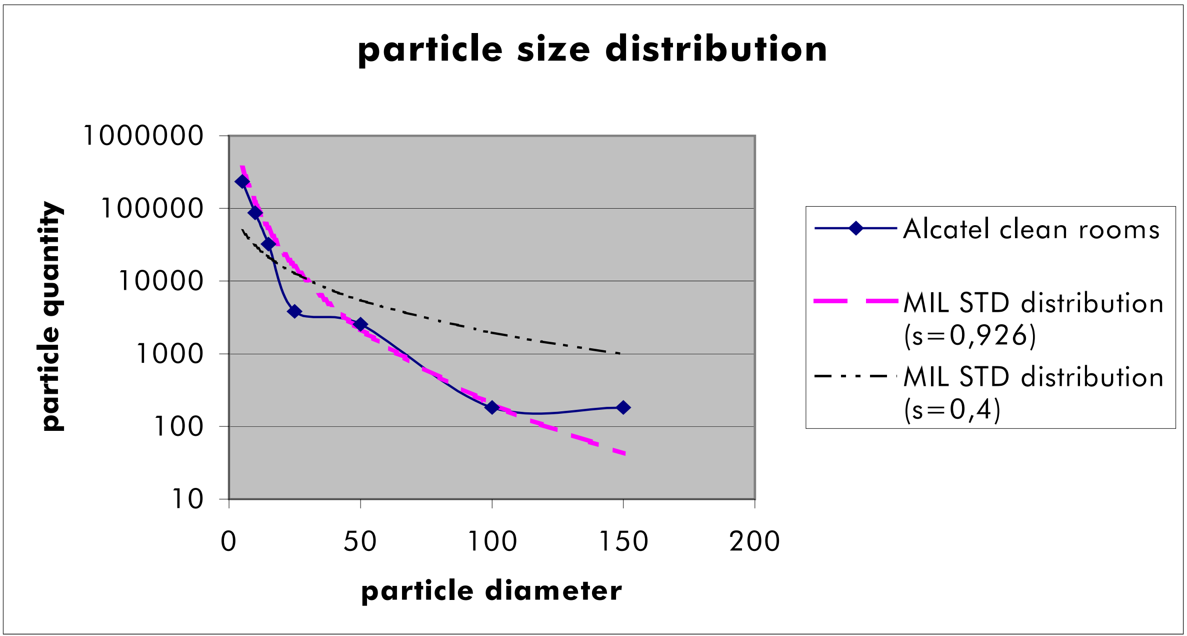
The particle size distribution as been supposed to follow the MIL-1246C law, where, for a given cleanliness level Xc, the quantity n(D) of particles having a diameter above D is given by:

$$\log_{10}[n(D)] = s \cdot (\log_{10}^2[Xc] - \log_{10}^2[D])$$

the slope s depends on the environment i.e. the clean room. For our study, we consider s=0.926. This is the slope proposed in MIL-STD-1246C, and it has been cross-checked via distribution measurements made in the frame of a previous program.

The following graph shows

-the measurements performed on sample in a previous program
-the MIL-1246C law with a 0.926 slope
-the MIL-1246C law with a 0.4 slope (for information only)



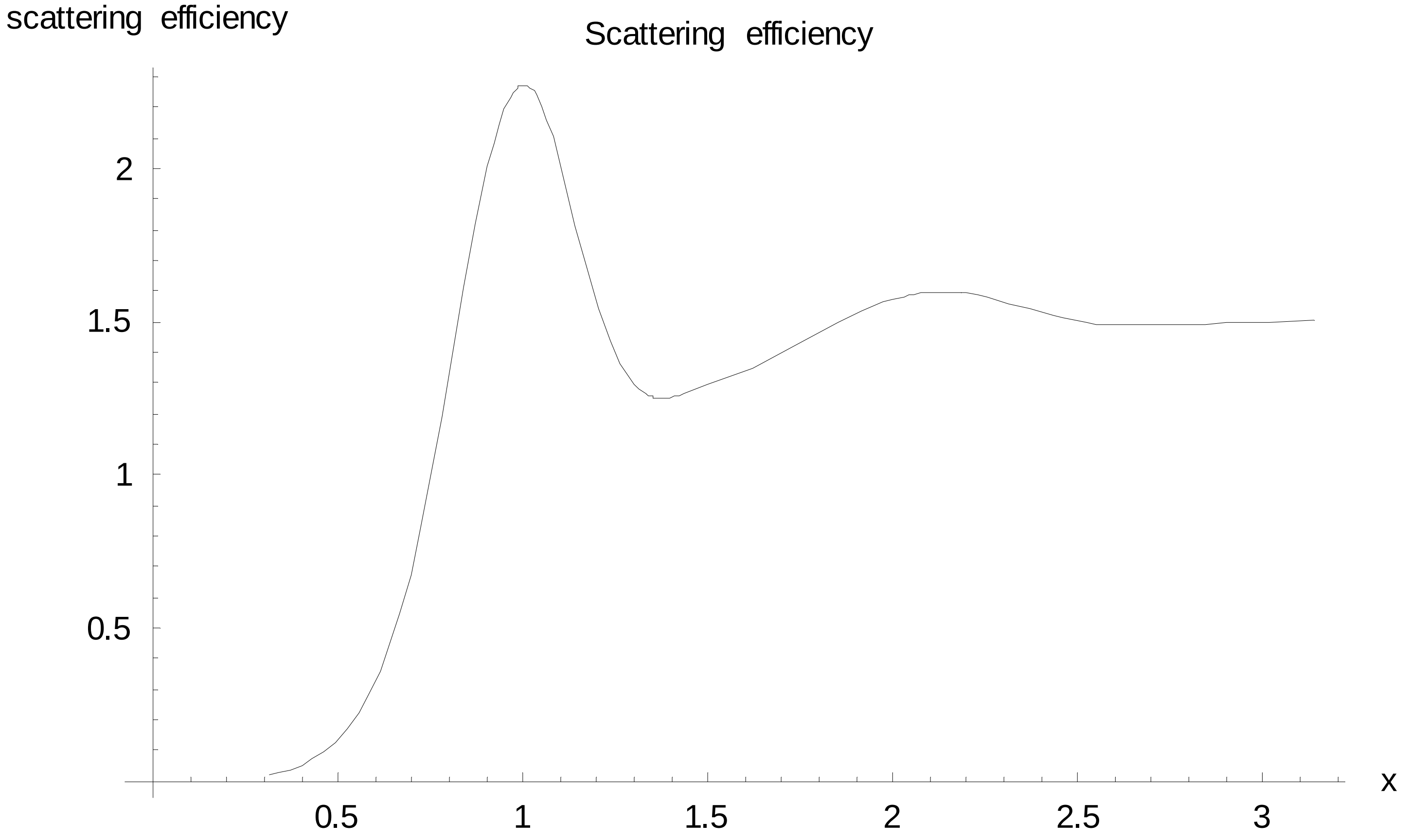
This graph shows the good accordance between Alcatel clean rooms and the MIL-STD-1246C distribution, with a slope at 0.926, and justifies the hypothesis taken in this study.

4.1.2.2.2 Dust nature

The diffusion of light, as described by Mie theory, highly depends on dust optical properties. Sensitivities have shown that Al_2O_3, with the following properties at several wavelengths, can be considered as a worst case:

Wavelength (µm)	Al_2O_3 Optical index
70	3.557-0.64i
350	3.31-0.454i
500	3.399-0.335i

The next graph shows the scattering efficiency Qscat, as defined in Mie theory, as a function of $x=\pi D/\lambda$, for Al_2O_3 .


scattering efficiency
Scattering efficiency
2
1.5
1
0.5
0.5
1
1.5
2
2.5
3
x

For comparison, the next graph shows for a given Cleanliness level of Xc=558 (i.e. 5000ppm), depending on the particle size, the product of

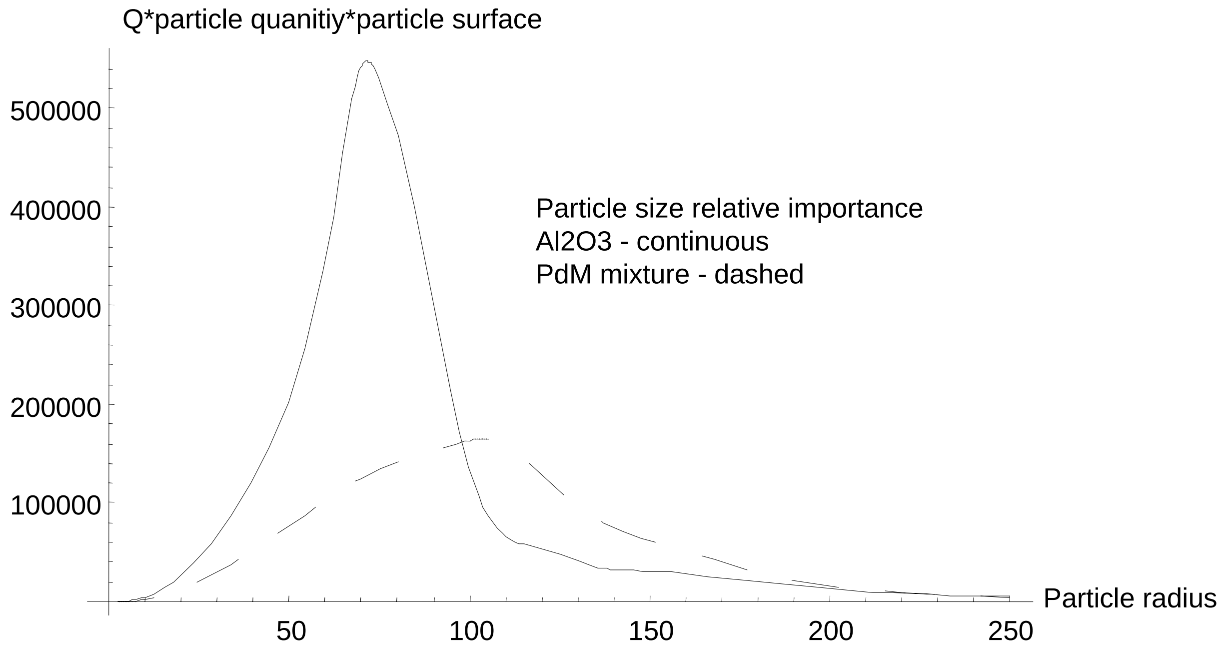
-particle quantity as defined by MIL-STD-1246C, with a 0.926 slope

-particle surface

-Qscat at 500µm wavelength

this product is gives a tool to compare several dusts, and to know which particle sizes are important.

The continuous curve represents Al_2O_3, the dashed curve represent the mixture proposed by ESA in [RD8].



This shows that Al_2O_3 diffuse more light than other contaminant, and justifies the fact that we consider it as a worst case. Of course, a more systematic approach considering the optical properties of each possible dust nature would be preferable, but we are facing the lack of knowledge in this domain.

4.1.3 EOL transmission budget degradation assessment

This section will present the impact of particulate and molecular contamination on the Herschel Telescope transmission. A global transmission loss budget is finally built.

4.1.3.1 Molecular contamination

4.1.3.1.1 H_20

H_2O maximum absorption near the [80-670]μm spectral band occurs at $\lambda=65\mu m$. At this wavelength (see [RD5] and Annex 2), H_2O has the following optical properties:

Wavelength λ (μm)	Refractive index n	Absorptive index k
65	1.737	0.7

These data are taken out of [RD5], and can be found in the annex.

Applying Equation 4-1, a 0.12μm water ice thickness (corresponding to 1.2 10^{-5} g/cm^2 contamination) induces a 1.6 10^{-5} transmission loss on M1 ->completely negligible

Note: on M2, the contamination being 15 times lower, the transmission loss will be around 10-6

4.1.3.1.2 NH_3

NH_3 maximum absorption near the [80-670]μm spectral band occurs around $\lambda=85\mu m$. At this wavelength (see [RD4] and Annex 1), NH_3 has the following optical properties:

Wavelength λ (μm)	Refractive index n	Absorptive index k
80	2	0.4

These data are taken out of [RD4], and can be found in the annex.

Applying Equation 4-1, a 7 10^{-6} μm ammonia ice thickness (corresponding to 7 10^{-10} g/cm^2 contamination) leads to a negligible loss

4.1.3.1.3 On-Ground contaminants

Following Annex 3, on ground contaminants are considered to have the same optical properties whatever the wavelength. In this condition, the worst case is the shortest wavelength, i.e. 80µm .

Wavelength λ (µm)	Refractive index n	Absorptive index k
80	1.6	0.003

These data are taken out of [RD6] , and can be found in the annex.

Applying Equation 4-1, a 0.004µm contaminant thickness (corresponding to 4 10^{-7} g/cm^2 contamination) induces a 3 10^{-8} transmission loss per mirror

4.1.3.2 Particulate contamination

The following table gives the transmission loss du to scattering and absorption computed by the Mie Model in the range of Herschel wavelengths for different levels of contamination

λ (µm)	**300ppm**	**1000 ppm**	**5000 ppm**	**10 000 ppm**
80	0.033%	0.107%	0.540%	1.107%
350	0.007%	0.023%	0.115%	0.235%
500	0.004%	0.012%	0.06%	0.123%

Table 4-1 transmission losses due to particles at Herschel wavelengths

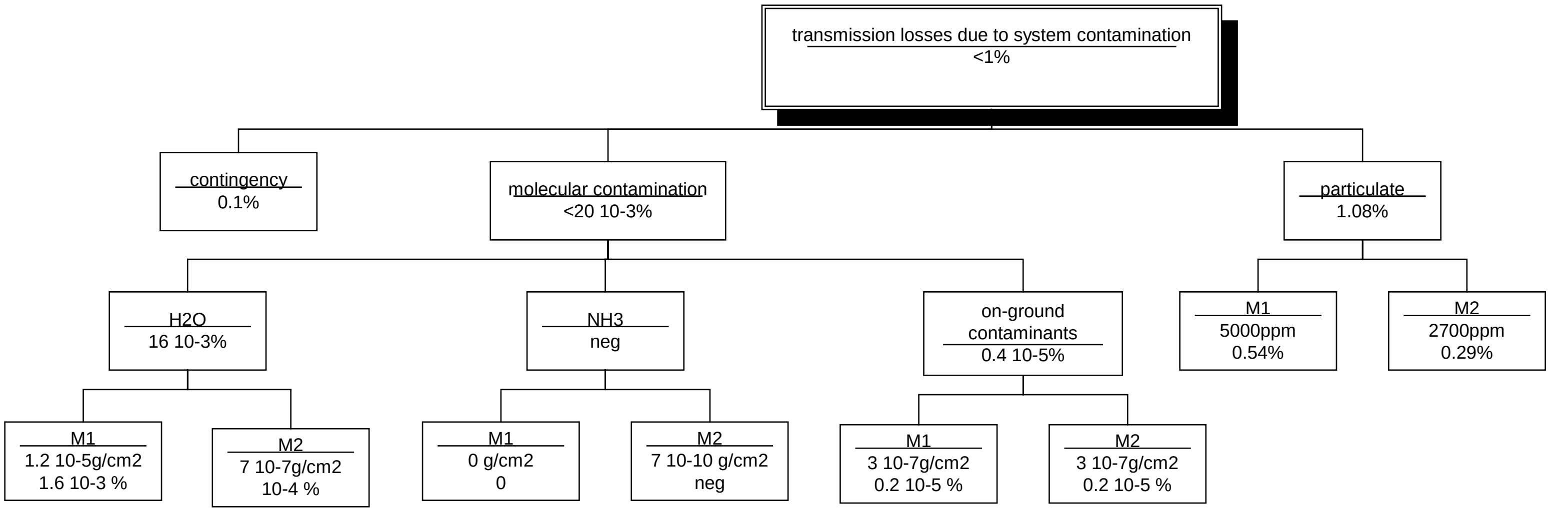
At 80µm, the transmission loss is 0.54% on M1, and 0.3% on M2

4.1.3.2.1 Contingency

An allocation of 0.1% transmission loss is made to absorb some variations, essentially for the particulate contamination levels

4.1.3.2.2 Conclusion

The transmission losses due to system contamination are represented in the following tree:



4.2 Overall transmission loss budget

	Transmission loss
Telescope delivery	2.5%
Telescope ageing	0.5%
Telescope contamination	1.0%
total	4.0%
Requirement	<4.2%

At cryostat opening, the telescope transmission will be between 3.5% and 4.0% depending on the value to be taken for telescope ageing which is not mastered by ASP. This is above the required 3.5 % of SGEN-200 H (see also request for deviation HP-220000-ASPI-RD004)

5. CVV WINDOWS

In HIFI IID-B ([AD-2] §5.8.2.3), the EOL window transmission is required to be better than 80% (including window absorption, coating efficiency and contamination impact)

5.1 clean window transmission

In the frame of the optical window CDR, it has been shown that the transmission of clean window is better than 97% (see [RD11])

5.2 contamination levels

HIFI LOU EOL cleanliness budget is the following:

	LOU external	LOU internal	Total	Reference
Particulate	448ppm	300ppm	748ppm	[RD7]+new baffle
molecular	32 10-7 g/cm2	38 10 –7 g/cm2	70 10-7g/cm2	[RD7]+new baffle

5.3 HIFI windows sensitivity to contamination

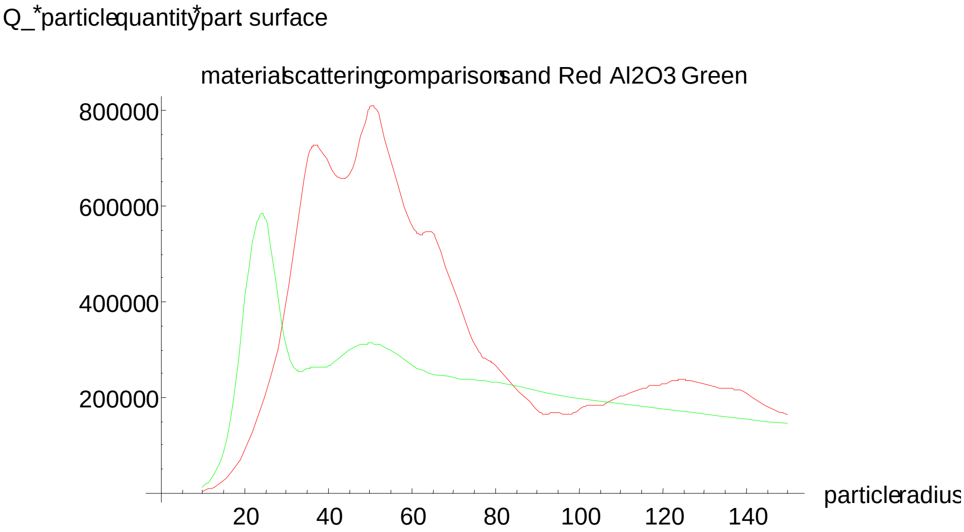
Only the shortest band, centered at 150μm wavelength (band 6-H) will be considered because it is the more sensitive.

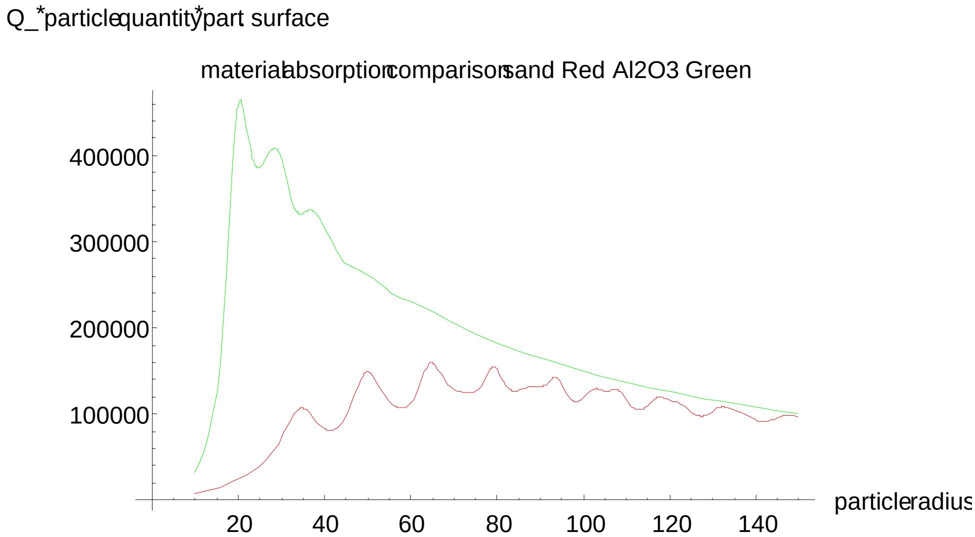
5.3.1 Sensitivity to particulate contamination

Agreed with HIFI, the dust size distribution is as per MIL-STD-1246C, with a slope of 0.4

The proper theory is Mie, which only considers spherical spheres. Another model, named Videen, accounts for non-spherical particles. It has been shown in a dedicated ESA study that the Mie model is a worst case approach as the non-spherical particles demonstrates scattering below the one in the spherical case (for a given obscuration factor (see [RD12] fig 5.45 on p 5-69)

For the dust nature, we compared sand (HIFI hypotheses) and alumina (Al2O3): the two following graph shows, for the chosen distribution, the scattering and absorbing efficiency of the two materials:





Note that the intergal of the curve is the interesting parameter to compare. In that sense, both material are quite identical:

- the sand scatters slightly more (~+30%)
- the Alumina absorbs significantly more (+60%)

Finally alumina is a slightly worst case

Combining both absorption and scattering of alumina on both sides of the windows, the Mie theory gives

- 0.094% scattering
- 0.083% absorption
- giving 0.18% in total

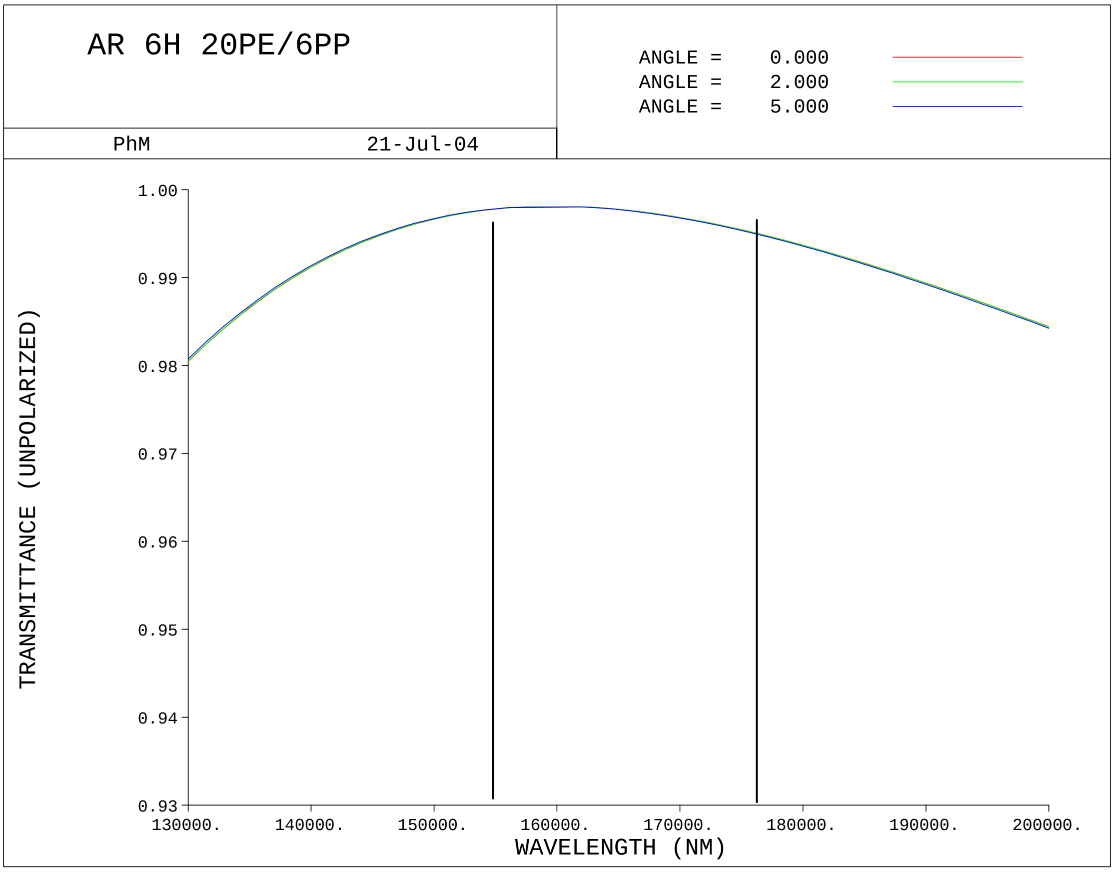
5.3.2 Sensitivity to molecular contamination

The AR coating on the windows has the following characteristics (band 6-H):

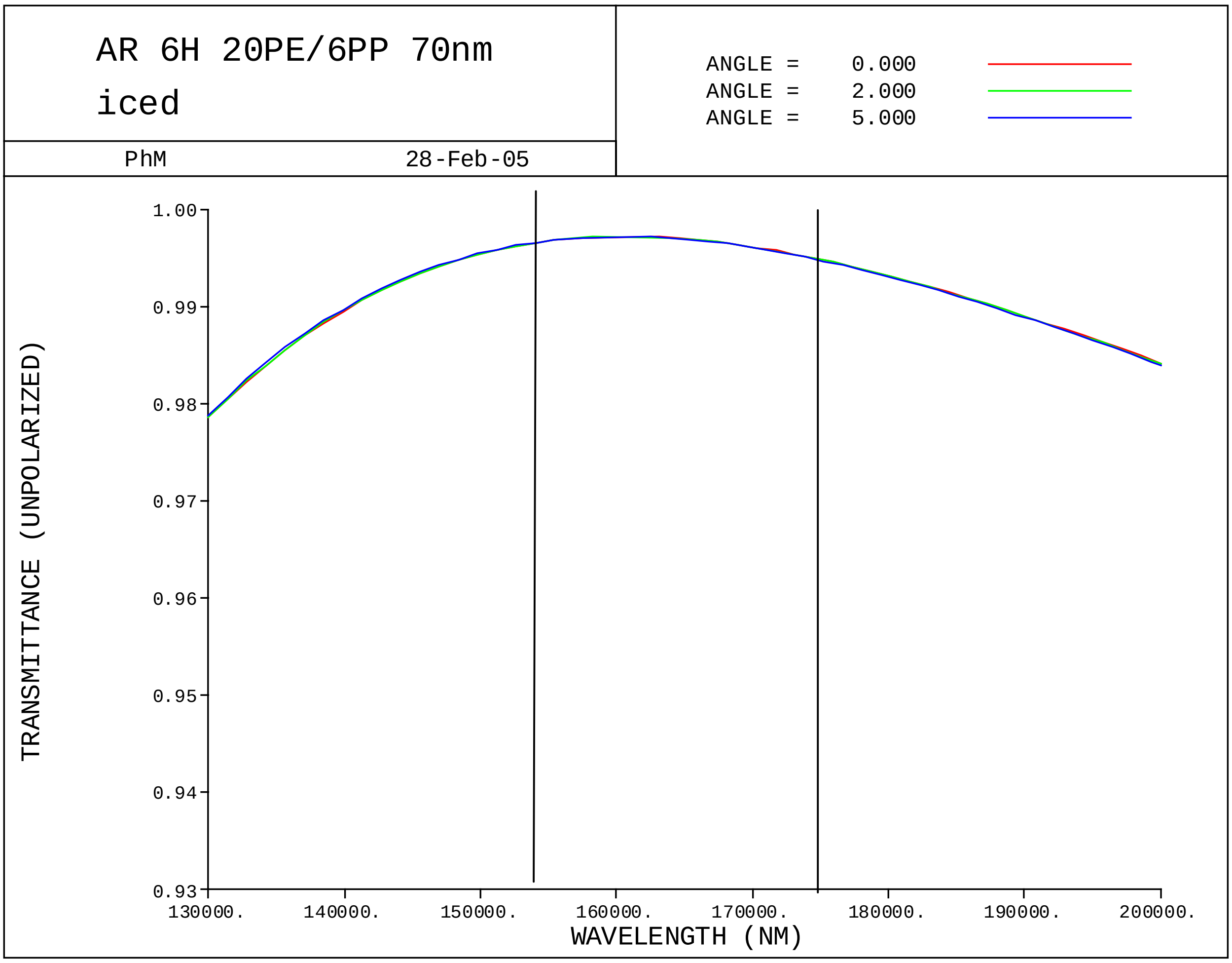
Nature	Optical index	thickness
Air	1	
Polyethylene	1.52	6µm
Polypropene	1.48	20µm
Quartz	2.105	5mm

The performance of this coating (one side) has been modeled: it is the following:

It is well centered on the band 6-H, and the thoeretical transmission is around 99.5%, well in line with QMC measurements (see [RD11]).



With 0.07µm ice on top of the coating (corresponding to 0.7 10-5 g/cm2), we have the following performance (one side)



we see almost no effect. The water thickness is indeed much smaller than the wavelength (lambda/2000)

This results of a loss of less 0.1% integrated on the HIFI band 6-H

5.3.3 synthesis

The sensitivity of HIFI to contamination leads to the following transmission losses:

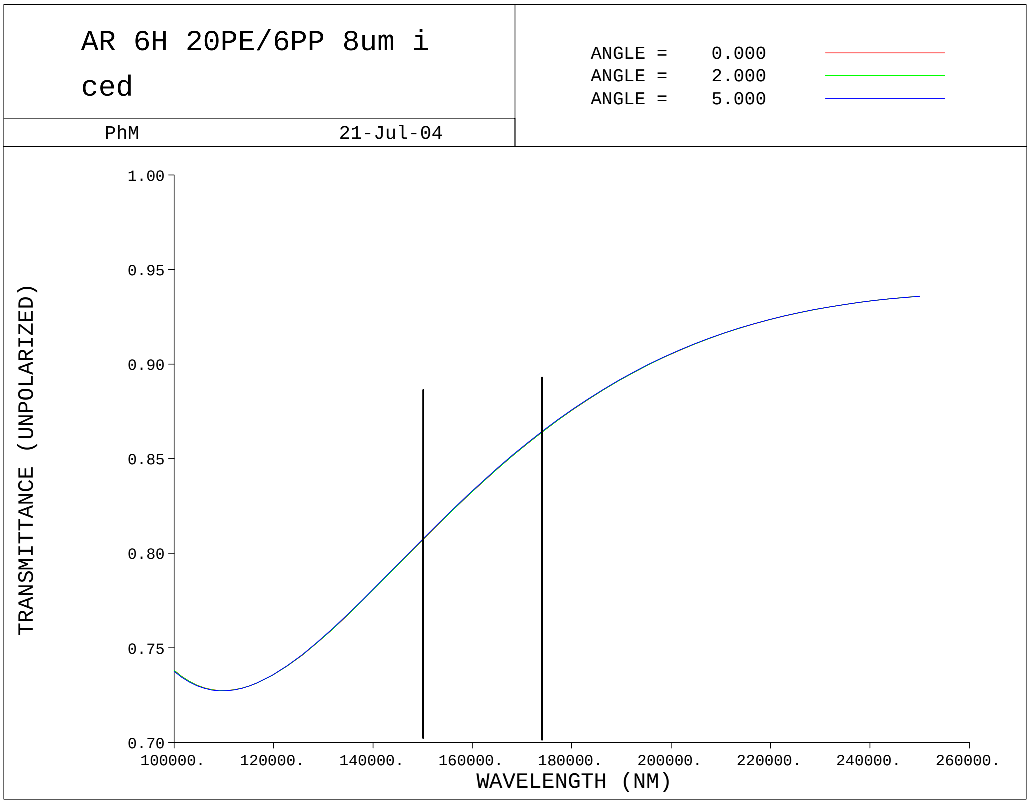
	Budget	**Transmission impact**
Particulate	748ppm	-0.2%
molecular	70 10-7g/cm2	-0.1%
Total		-0.3%

5.4 transmission budget

	Transmission
Clean window	97%
Contamination	-0.3%
Total	96.7%
IID-B requirement	>80%

The LOU window transmission budget is compliant with large margin with the instrument requirement.

The most uncertain contributor is the molecular contamination. Although worst case hypotheses have been considered in the model, it is interesting to assess the margin we have in terms of water ice thickness on the windows.
We have increased the ice thickness in the model until we reach around 0.16 transmission loss (this would lead, together with particulate contamination and intrinsic coating properties to be just above the required 80%)
This leads to a water ice thickness of 8μm, and to the following transmission curve (with the molecular contamination only):



In other words, the current worst case level of contamination (0.07μm water ice thickness) leads to a margin of 16.7% transmission. A thickness of 8μm(100 times more) would reduce this margin to almost zero.

Annex 1 Thermo-optical properties of on-ground contaminants (except water)

Based on SPIE paper "photochemically Deposited Contaminant Film Effects (cf. [RD6]), the following hypotheses are made in the frame of Herschel and Planck programs contamination analyses:

- Refractive index n and absorptive index k of molecular contaminants tend to decrease with increasing wavelength.
- So, data at $\lambda=1\mu m$ are conservative for all Herschel and Planck wavelengths.

⇒n=1.6 and k=0.003 are considered to be conservative values for on-ground contaminants (except water)

n=1.6 corresponds to squalene (Silicone)
k=0.003 correponds to Zeiner's model, developed by a prime contractor's contamination analyst.

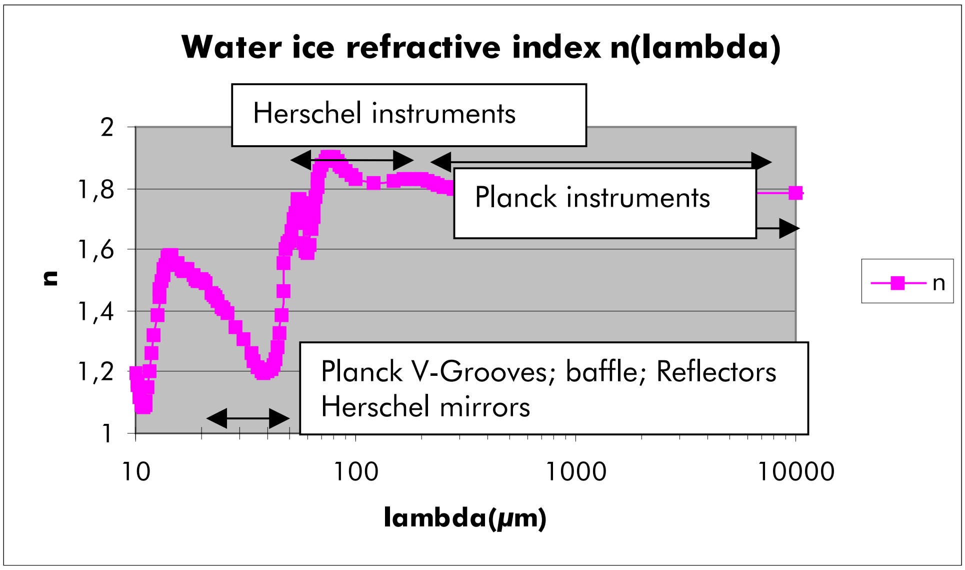
Remark:
Depending on the nature of contaminants which will actually be present on Herschel and Planck spacecraft, one can imagine that absorption bands at high wavelengths could unfortunately be present. However, the following points have to be considered:

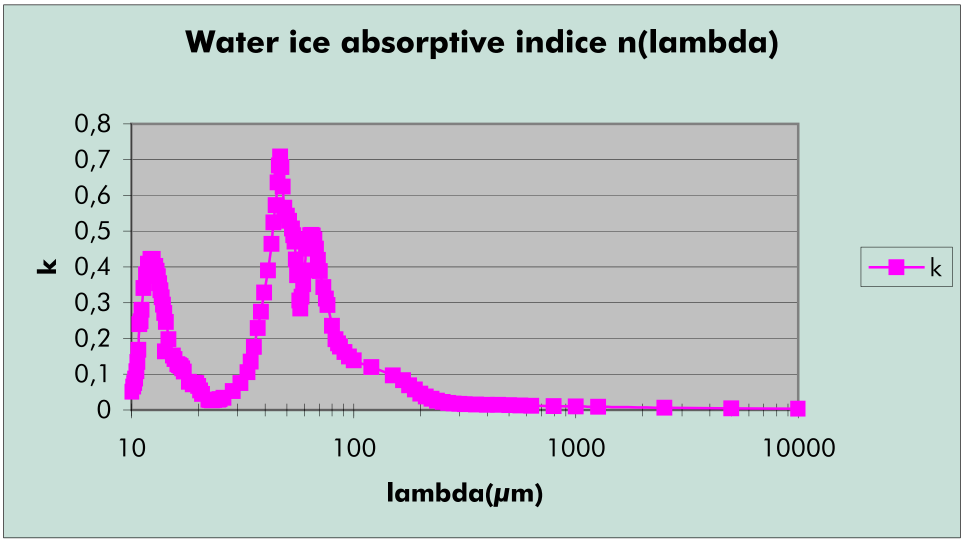
- n=1.6 and k=0.003 have been measured at $\lambda=1\mu m$, and Herschel and Planck wavelengths are much higher than $1\mu m$

-The possible absorption bands would anyway be very thin with regards to Herschel and Planck useful bandwidths, and the absorbed energy would be completely negligible with regards to the total flux received by each detector over it's whole spectral domain.

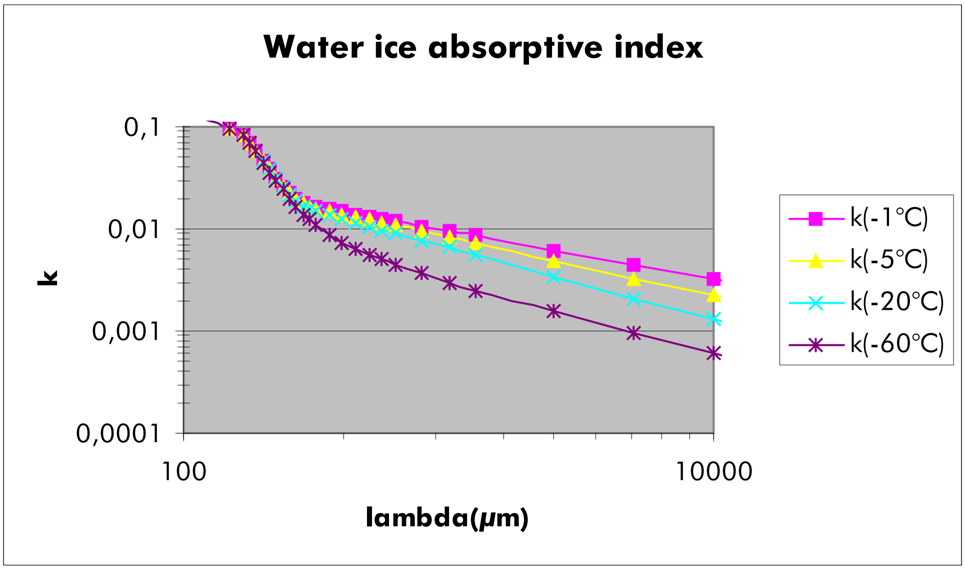
ANNEX 2 Thermo-optical properties of Water-ice at Herschel and Planck wavelengths

The following data are extracted from Applied Optics paper "Optical constants of ice from the ultraviolet to the microwaves" (cf. [RD5])
The refractive index n and the absorptive index k values for the [10µm-10mm] spectral band are presented hereafter:





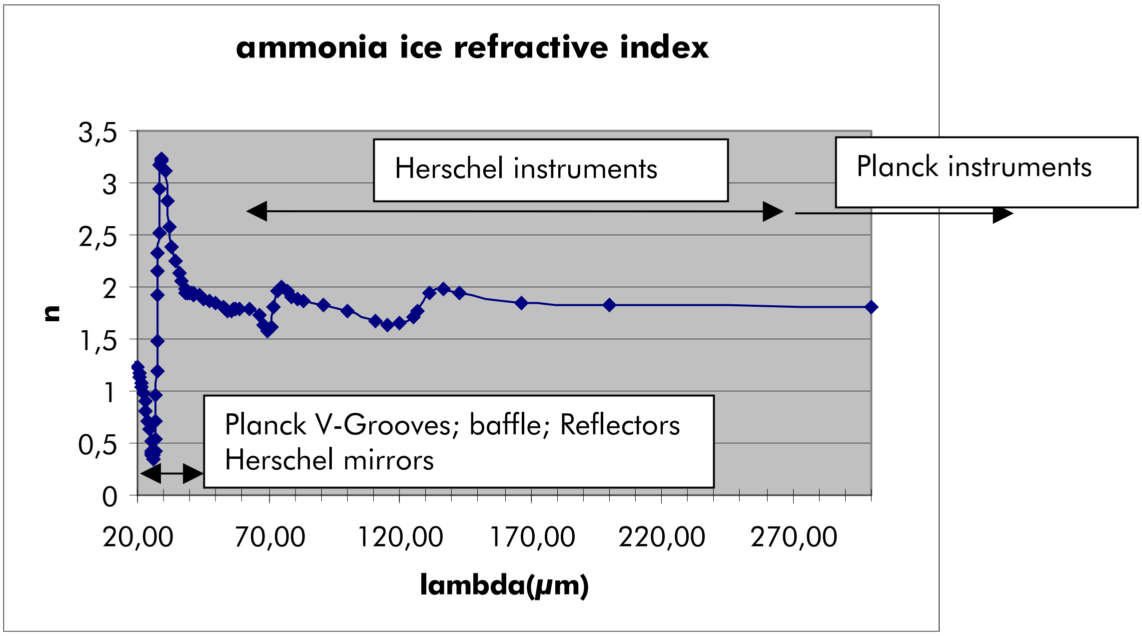
Between 200μm and 10mm, k depends on water ice temperature. As k decreases with temperature, -60°C corresponds are conservative values for Planck (Herschel is not considered by such high wavelengths)

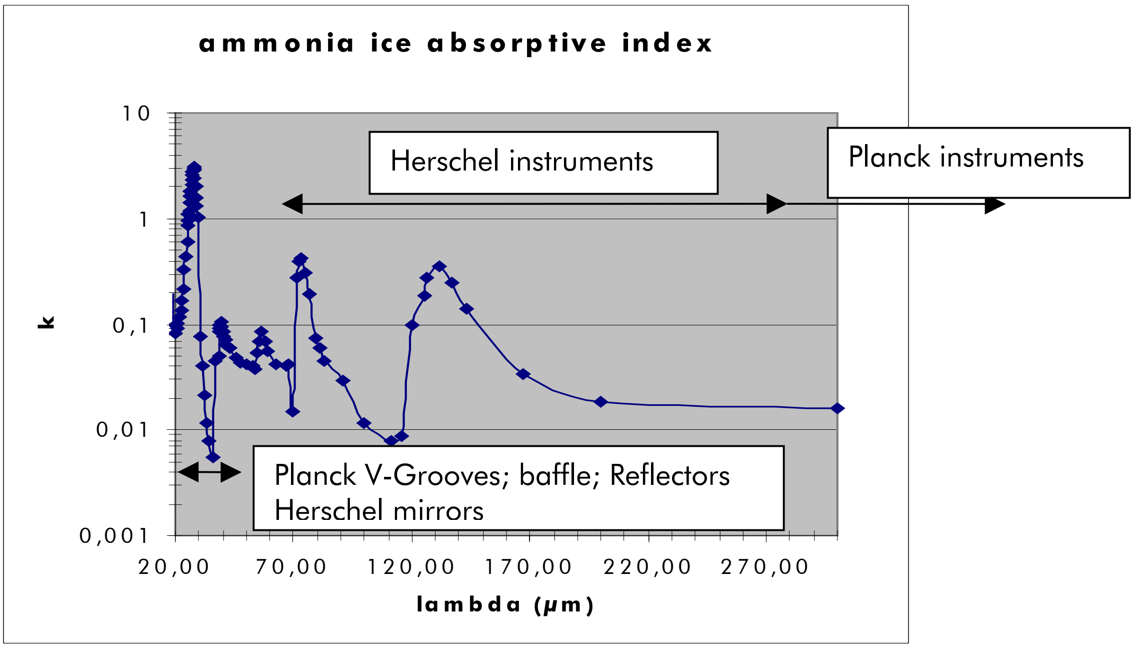


ANNEX 3 Thermo-optical properties of ammonia-ice at Herschel and Planck wavelengths

The following data are extracted from Applied Optics paper "Optical properties of NH_3 from the far infrared to the near ultraviolet" ([RD4])

The refractive index n and the absorptive index k values for the [20µm-300µm] spectral band are presented hereafter:





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