

MicroCarb Instrument Spectral Transmission Variations: Ice Deposition on Band-Pass Filters and Detector

Matthieu Castelnaud^{*a}, Remi Bellouard^b, Simona Calarco^a, Elodie Cansot^a, Laurent Georges^b, Thomas Gineste^b, Xavier Gnata^b, Hélène Krol^c, Rémi Lhuillier^d, Laurie Pistre^a, Olivier Puig^a, Guillaume Rioland^a

^a Centre National d'Etudes Spatiales, Toulouse, France; ^b Airbus Defence and Space, Toulouse, France; ^c CILAS, Aubagne, France; ^d SAFRAN REOSC, St-Pierre-du-Perray, France
E-mail (corresponding author): matthieu.castelnaud@cnes.fr

ABSTRACT

MicroCarb is a CNES exploratory space mission aimed at measuring the quantity of carbon dioxide in the atmosphere, in order to better understand the fluxes and exchanges of this gas between the atmosphere, oceans, vegetation, and human emissions. The MicroCarb instrument, developed by Airbus Defence and Space, is a passive Short-Wave Infrared Spectrometer. The innovative concept of the spectrometer allows the acquisition of 4 narrow bands (0.76 μm , 1.27 μm , 1.61 μm , 2.04 μm) on the same detector using an echelle grating and a split-pupil telescope. Since its launch in July 2025, some variations in the spectral transmission of the instrument have been observed during calibration measurements. We speak of variations rather than degradation, as certain spectral bands exhibit increased transmission, while others show decreased transmission. The same applies to stray light, whose intensity fluctuates over time. The leading hypothesis to explain these phenomena is ice deposition on the detector, that is operated at 160K, and on the bandpass filters preceding it.

In this paper, we will first briefly review the optical architecture of the MicroCarb instrument and describe the in-flight variations of the spectral transmission. We will then present the simulations we carried out to evaluate the effect of an ice layer on multilayer interference filters such as the MicroCarb bandpass filters, as well as on the Anti-Reflection coating stack of the instrument's detector. We will also present results from experiments conducted at CNES laboratories, aimed at depositing controlled thicknesses of ice on components from the same coating batch as the flight model filters and measuring their spectral transmission as a function of the deposited thickness. Finally, the use of these results to estimate the ice thickness deposited on the various in-flight components of the instrument and to explain its transmission variations will be presented.

Keywords: MicroCarb, spectrometer, ice, multilayer thin-film interferences

1. INTRODUCTION

The monitoring of atmospheric carbon dioxide (CO_2) fluxes is a critical objective for understanding the global exchanges of this greenhouse gas between the atmosphere, oceans, vegetation, and anthropogenic sources. The MicroCarb mission¹, a CNES-led exploratory space mission, is designed to achieve this through high-precision measurements using a compact microsatellite platform. To meet the stringent requirements of CO_2 column quantification, the mission employs a passive Short-Wave Infrared (SWIR) spectrometer characterized by high spectral resolution and compacity.

In spaceborne cryogenic instrumentation, the management of molecular contamination is a challenge for preserving payload performance, including optical, radiometric, and thermal stability². Among volatile species, water is a particularly significant contaminant due to its prevalence in spacecraft materials, such as polymers, adhesives, and multilayer insulation (MLI). Upon exposure to vacuum and thermal transients in orbit, water vapor is released and subsequently migrates toward the coldest elements of the system, where it undergoes condensation.

Since its launch on July 26, 2025, the MicroCarb instrument has exhibited unexpected variations in its spectral transmission and stray light intensity during in-flight calibration and validation phases^{3,4}. These variations are notably

non-monotonic; while certain spectral bands show an increase in transmission, others exhibit a decrease. Furthermore, fluctuations in stray light have been observed. The leading hypothesis to explain these instabilities is the deposition of water-ice on the critical optical surfaces of the instrument, specifically on the Detector Filters (DF) and the Anti-Reflection (ARC) coating of the Next-Generation Panchromatic (NGP) detector.

This paper aims to characterize the interferential effects induced by such ice layers. We present a detailed modeling approach based on multilayer thin-film interference, validate this model through ground-based icing experiments, and demonstrate how these findings explain the in-flight spectral anomalies.

2. OPTICAL ARCHITECTURE AND IN-FLIGHT ANOMALIES

The MicroCarb spectrometer utilizes an innovative, compact optical architecture designed to maximize spectral information while minimizing mass and volume^{5,6}. The system employs a split-pupil telescope combined with an echelle grating and field/pupil splitting to achieve spectral multiplexing.

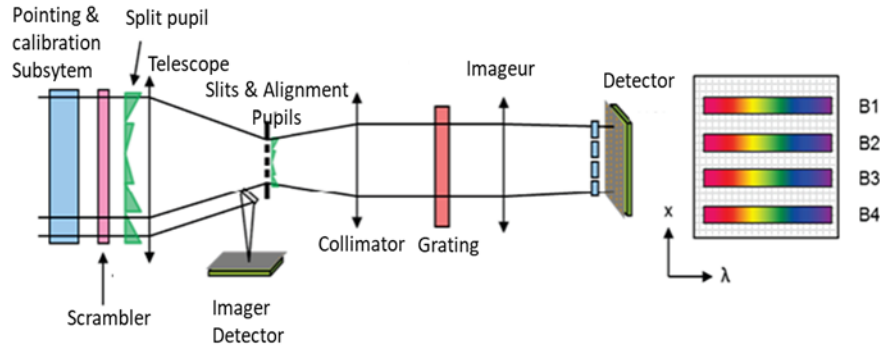


Figure 1: MicroCarb optical principle

This configuration allows the simultaneous acquisition of four narrow spectral bands on a single detector⁷, given in Table 1.

Table 1. MicroCarb spectral bands

	B1	B2	B3	B4
Minimal acquired wavelength $\lambda_{\min}$ (nm)	758.3	1596.8	2023.1	1264.6
Maximal acquired wavelength $\lambda_{\max}$ (nm)	768.8	1618.9	2051.0	1282.1

The final spectral filtering is performed by the Detector Filters (DF), which are positioned a few millimeters in front of the detector. These DFs consist of multilayer interference stacks designed to transmit specific bands while providing high rejection for out-of-band wavelengths.

The MicroCarb instrument is organized into three distinct thermal zones to optimize performance:

- A telescope section, maintained at approximately 290 K.
- A spectrometer section that contains mirrors and the echelle grating, maintained at roughly 240 K.
- A cryostat section that houses the NGP detector, which is passively cooled to approximately 159 K. The detector filters (DF) are located in this section and are maintained at a temperature slightly higher than the detector (approx. 162 K).

The proximity of the cold detector and filters to potentially outgassing components, combined with the confinement within the instrument cavity, creates a high risk for a recurrent outgassing–condensation cycle.

Following an initial three-week decontamination period at 272 K, the instrument was activated one month post-launch. In the entire paper, we refer as the signal the average across rows and columns of a given spectral band, recorded during a dedicated calibration measurement with the internal calibration source.

During first calibration measurements (cycle 1), non-monotonic transmission variations were observed: in the B1 band, the signal initially increased and then decreased (15% variations). Conversely, the B4 band showed a decrease followed by an increase (11% variations). B2 and B3 bands primarily exhibited decreasing trends (11% and 8% respectively). Figure 2 exhibits these data, with a signal normalized by the first in-flight measurement.

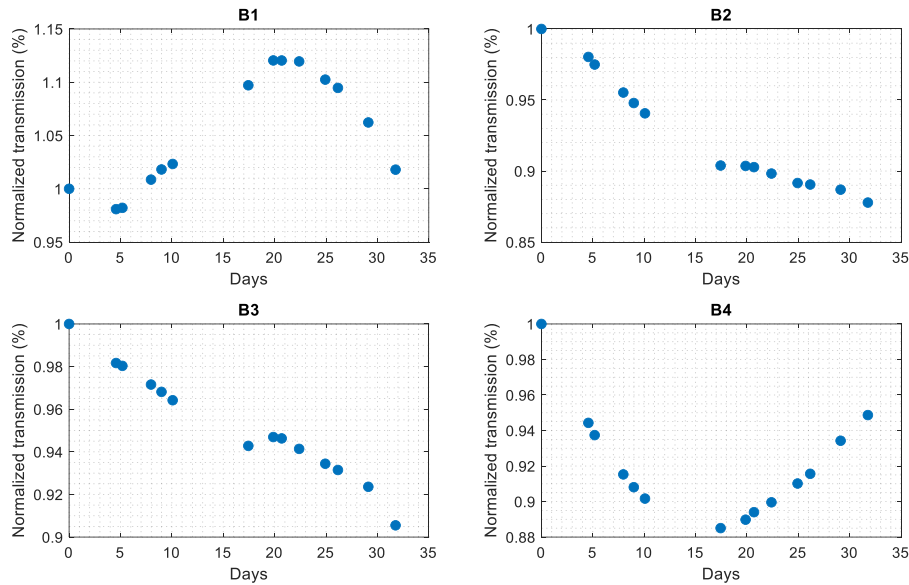


Figure 2. In-flight instrument's response during cycle 1 (lamp measurements, average signal in each band)

It should be noted that lamp ageing is not a valid explanation for these variations, as the same phenomena were observed on direct Sun measurements, enabled by the Sun diffuser built into the instrument.

Three additional decontamination cycles were subsequently performed, beginning with another decontamination cycle at 272 K, but lasting only 3 days. The calibration measurements that follow this decontamination are referred to as cycle 2 in Figure 3.

The next decontamination was performed with the detector turned off but the instrument running, for a shorter 24-hour period, at a temperature of 200 K (cycle 3).

The last one followed the same procedure as the second, lasting 3 days at 272 K (cycle 4).

Figure 3 shows all calibration measurements performed during these 4 cycles, with a signal normalized by the first point of cycle 2.

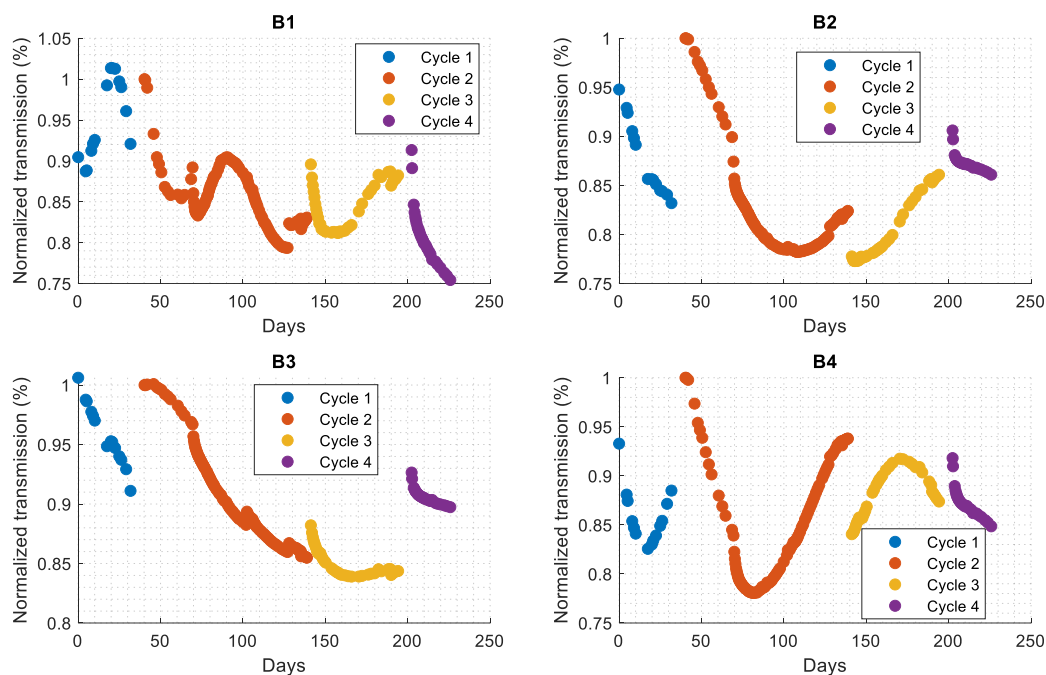


Figure 3. Changes in the instrument's response over the 4 cycles (normalized by the first point of cycle 2) since the launch (lamp measurements, average signal in each band)

The second decontamination allowed us to recover the signal. However, it is changing very rapidly. The discontinuities observed during this cycle are due to other changes in the instrument's configuration (temperature and diffuse optical background level).

As far as the stray light is concerned, this second procedure made possible to significantly reduce it in all spectral bands. Figure 4 shows detector images saturated on purpose to reveal stray light effects. From left to right, the spectral bands are B3, B4, B1 and finally B2. The decrease of straylight is particularly visible at the top of the image (low wavelengths) and around B4.

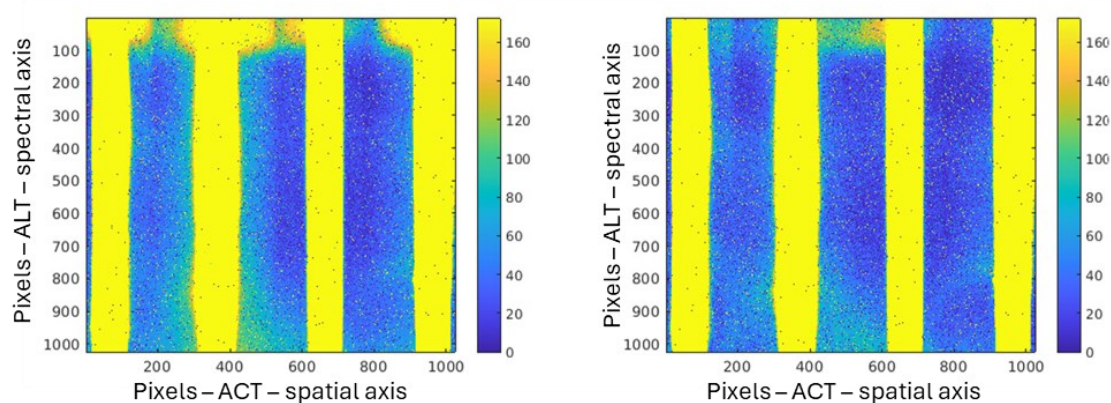


Figure 4. Changes in stray light: measurement before (left) and after (right) the second decontamination

After the third decontamination, the starting point of cycle 3 is not the same as the one of cycle 2. It appears that the system has returned to a state similar to the one it was in 30 days earlier, around the 70th day of cycle 2, but with different kinetics as the slopes are different. This time, an increase of stray light was observed, especially around B4 and in the first 120 lines (see Figure 5).

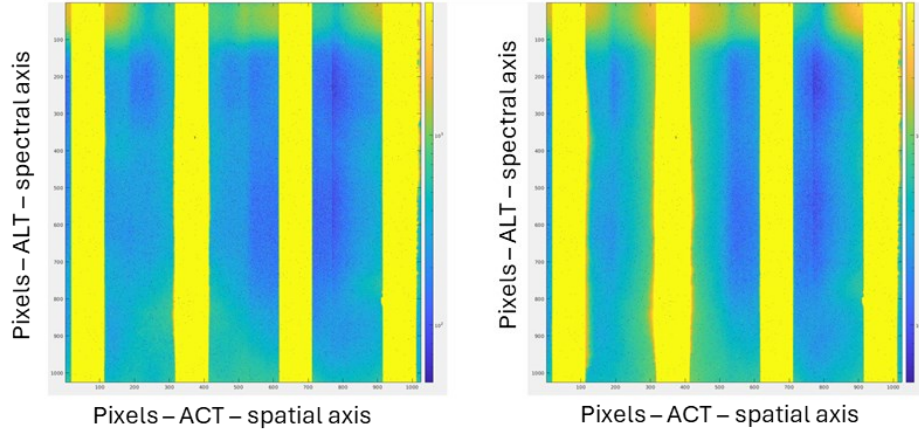


Figure 5. Changes in stray light: measurement before (left) and after (right) the third decontamination

Finally, the signal was restored for all spectral bands compared to cycles 2 and 3, after the fourth decontamination procedure. However, activating the diffuse optical background causes a significant loss of transmission during the first 5 days after the decontamination, that cannot be easily separated from contamination effect.

The variations of transmission (up to 20%) and stray light are of such significance that they compromise the consistency of the radiometric performance of the instrument. These observations suggest that MicroCarb is experiencing a dynamic deposition and sublimation of ice, which modifies the optical response through complex interferential and scattering mechanisms rather than simple broadband attenuation.

3. MODELING OF INTERFERENTIAL EFFECTS

To investigate the non-monotonic transmission variations observed in-flight, a modeling approach was developed based on thin-film interference theory. The core objective was to simulate how a homogeneous layer of water-ice, acting as an additional "first layer" on the existing multilayer stacks, disrupts the optimized spectral response of the MicroCarb components.

The spectral response of the multilayer stacks—both the Detector Filters (DF) and the detector's Anti-Reflection Coating (ARC)—was calculated using two different softwares, CODE V and Matlab. Several validations were conducted, thanks to the use of both computing methods and a cross-check simulation case with the CILAS company.

We used the optical design software CODE V to calculate spectral responses for various angles of incidence and beam apertures, thanks to the MUL module that can perform spectral-response calculations for interferential filters at user-specified angles of incidence. The inputs required for these calculations are the multilayer stack itself (materials and layer thicknesses) and the refractive indices (real and imaginary parts) of those materials over the wavelength range for which the spectral response is to be computed. A CODE V macro was implemented to integrate the multilayer stacks, kindly provided as .seq files by coatings' suppliers, e.g. CILAS for the DFs and Safran REOSC for the ARC.

A custom-developed Matlab model was also used to validate the CODE V results and to perform rapid, high-volume simulations. This model, based on the principles of complex admittance⁸, provided a significant computational speedup while maintaining high accuracy. The complex-admittance formalism is a compact way to compute the reflectance, transmittance, and electric-field distribution of stratified optical media (dielectric or metallic layers) over a broad wavelength range. It treats each layer as an equivalent transmission line with a complex frequency-dependent impedance, enabling a straightforward recursive evaluation of the overall stack response.

The complex refractive index of ice was calibrated to a temperature of 165 K using data from the GATS database—The Refractive Index of Water Ice⁹.

All methods give very close results, with transmission difference greatly lower than 0.1% in the transmitting part of any filter we considered, as illustrated in Figure 6, that shows the theoretical spectral transmittance of one coating (over 2, one on each side, S1 standing for the spectrometer side and S2 for the detector side) deposited on the B1 Detector Filter, computed for an incidence of 7° on one axis, 0° on the other axis, and an aperture of $\pm 5^\circ$. These angular assumptions correspond to the average case for the angle of incidence and the aperture of the incident beams on the filters and the MicroCarb focal plane. This simplified case yields results sufficiently similar to those of actual configurations to be usable ($<0.05\%$ absolute transmission error in the spectral band), allowing for simplified calculations and time savings.

The difference between CODE V and Matlab can be as high as 0.5% in the feet or edges of the curves when we compare the results with angular incidence and aperture. This discrepancy comes from the sensitivity to the angular sampling parameter, that must remain relatively low in CODE V to limit computation time.

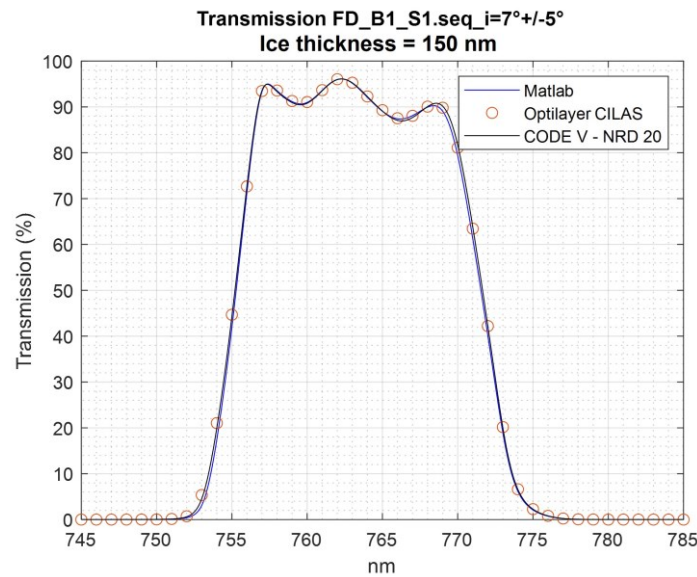


Figure 6. Comparison of the spectral responses of the B1 DF, spectrometer side, with incidence and aperture, obtained with three simulation methods

The Matlab model was validated through cross-comparisons with CODE V and Optilayer in different cases, with and without ice or incidence. This model is used in the performance study, as it performs quick computations and is perfectly adapted to the optimizations we intended to do.

A critical step in the modeling process was ensuring that the simulations reflected the actual "As-Built" state of the flight hardware rather than the theoretical designs.

To bridge this gap, a genetic optimization algorithm was implemented. This algorithm explored the parameter space of layer thicknesses for both faces of the DFs to minimize the quadratic deviation between the simulated spectral curve and the actual measured transmission curves of the manufactured components. This optimization successfully produced "As-Built" models that almost perfectly predicted the measured transmissions, with residual high-frequency errors being attributable to measurement noise (see Figure 7). These optimized stacks were then used as the baseline for all subsequent ice-deposition simulations. It is worth noting that the optimization yielded one stack among many others whose spectral response may correspond to the measured data.

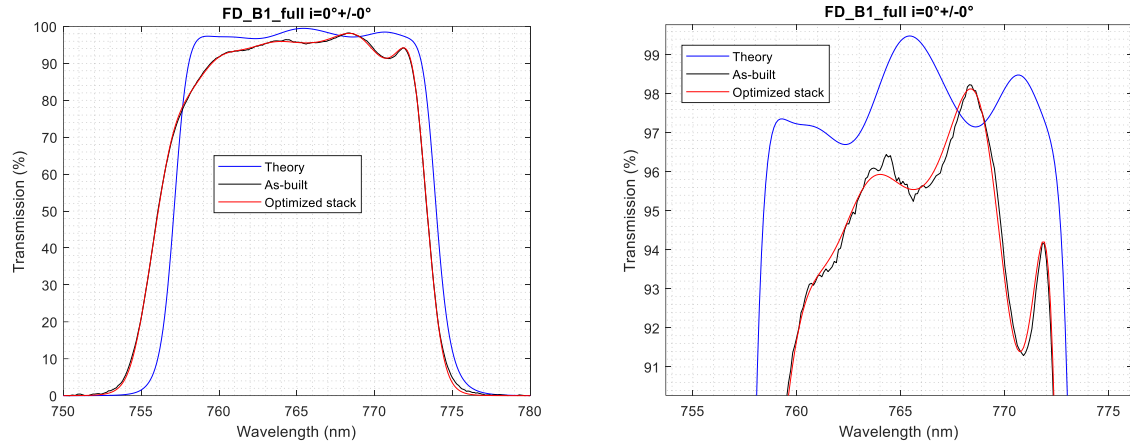


Figure 7. Comparison of the theoretical, as built and optimized spectral responses of the full B1 DF, without incidence and aperture

Effect of ice on the spectral response functions

The simulations revealed that the addition of an ice layer fundamentally alters the phase conditions within the multilayer interference filters. The impact is highly dependent on the relationship between the ice's optical thickness and the target wavelength.

Using the B1 band ($\sim 0.75 \mu\text{m}$) as an example, the modeling allowed to find two well-known distinct physical regimes:

- Quarter-wave layers ($\lambda/4$): for a water-ice layer with a refractive index of approximately 1.312 at 750 nm, a physical thickness of 140 nm corresponds to a quarter-wave layer ($1.312 \times 140 / 750 \approx 0.245$). In this regime, the ice layer induces maximum interference, leading to a significant minimum in the average spectral transmission. This explains why even a thin layer of ice can cause a substantial drop in signal.
- Half-wave layers ($\lambda/2$): conversely, a physical thickness of 290 nm corresponds to a half-wave layer ($1.312 \times 290 / 750 \approx 0.51$). At this thickness, the phase shift introduced by the ice layer is such that it does not alter the transmission or reflection coefficient at the center wavelength, effectively rendering the ice "invisible" to the filter's transmission band.

This is illustrated in Figure 8, that shows the spectral response of one side (S1) of the B1 Detector Filter as a function of ice thickness.

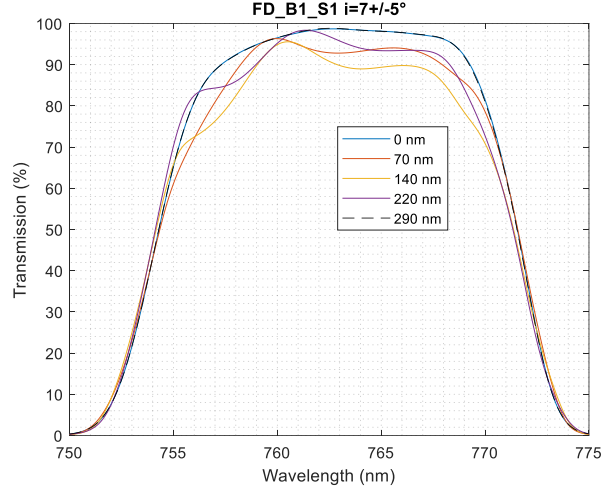


Figure 8. Theoretical transmission curve of S1 B1 DF as a function of ice thickness (green dashed line is superimposed on blue line)

This explains the "up and down" behavior observed in-flight: as ice accumulates, the transmission does not simply decrease; it oscillates as the growing layer transitions through various quarter-wave and half-wave optical thicknesses.

Beyond the main transmission bands, the model was used to evaluate the impact of ice on the rejection capabilities (out-of-band suppression) of the DFs. While the absolute rejection levels remained within the mission specifications, the ice deposition causes significant relative variations in the rejection minima (up to a factor of 2 for the rejection level of B3 in the presence of ice on the B1 DF). This effect contributes to an increase in inter-band stray light, as the "blocking" capability of the filters becomes unstable due to the ice layer.

Similarly, the model addressed the ARC on the NGP detector. The simulations confirmed that ice deposition on the detector surface also contributes to the overall radiometric instability and the observed fluctuations in the signal. The spectral transmission of this multilayer coating is showed in Figure 9 as a function of ice thickness.

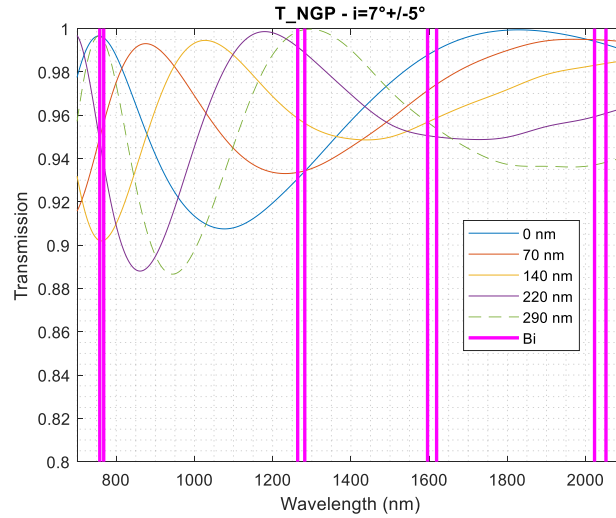


Figure 9. Theoretical transmission curve of the NGP's ARC as a function of ice thickness

For each spectral band, the average transmittance is calculated within the band, between the limits defined in Table 1, for increasing ice thicknesses and for the three surfaces on which ice deposition is simulated: the NGP detector and the two faces of the detector filters.

The resulting curves are shown in Figure 10.

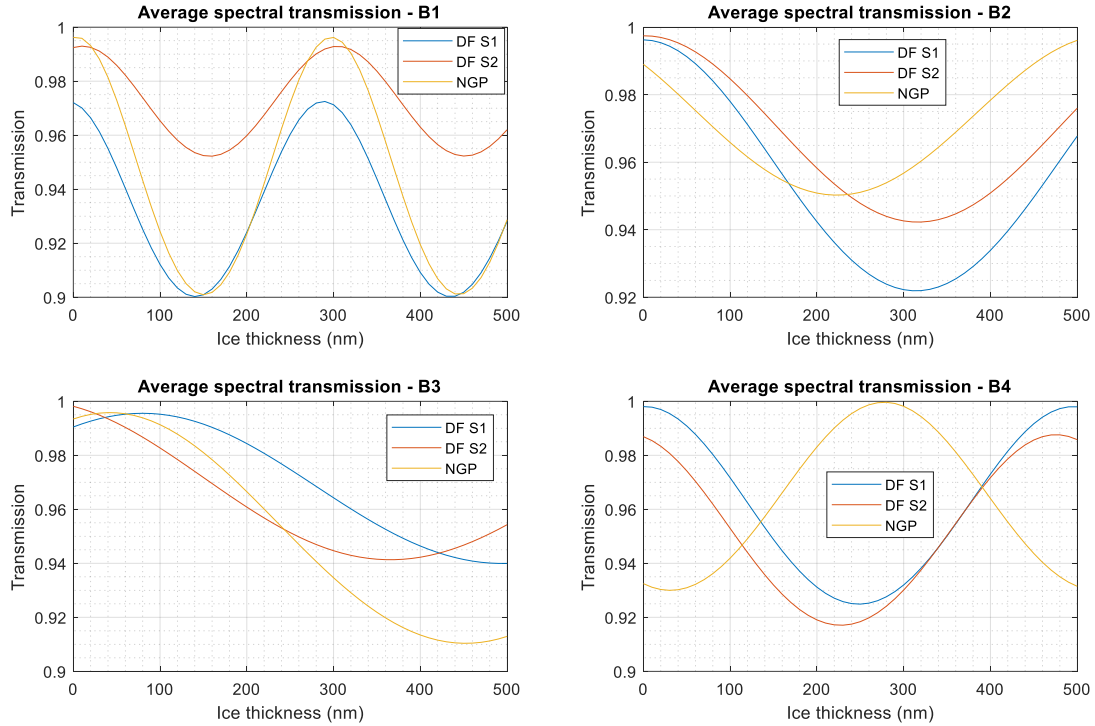


Figure 10. Changes in average transmittance across the spectral bands as a function of ice thickness on the three surfaces studied: DF Side 1, DF Side 2, and the NGP detector

Changes in transmittance across the different surfaces exhibit different behaviors depending on the spectral band, with either in-phase (B1) or out-of-phase (B4) behavior for the same variations in thickness between the NGP and the surfaces of the DFs. The magnitude of the drops in transmittance is consistent with those observed in flight, less than 10% per surface, and the ice thicknesses considered also appear realistic.

Impact of other contaminants

Optical index measurements of contaminants outgassed from two adhesives commonly used in space optical component assemblies were used to study the impact of these contaminants depositing on the detector and the MicroCarb FDs. The adhesives in question are EC-2216 epoxy adhesive and RTVS691 silicone adhesive.

Higher transmission loss values were observed with these contaminants compared to ice. The transmission drop observed in flight is consistent with an adhesive contamination deposition model only if a single surface is contaminated, and not the others. Otherwise, the transmission drop observed in flight would be greater.

However, the thicknesses involved here do not seem realistic, given the numerous bake-out cycles the components underwent on the ground. The estimated amounts of residue that were not degassed on the ground would not be sufficient to deposit several hundred nanometers of contaminants on the surfaces of the FDs or the detector.

Nevertheless, the presence of contaminant residues a few nanometers thick on these surfaces cannot be entirely ruled out. The impact would then be a change in transmission of a few percent, which cannot be separated from the change associated with the presence of ice.

4. EXPERIMENTAL VALIDATION

To corroborate the interferential mechanisms identified through numerical modeling, a series of ground-based experiments were conducted at CNES laboratories³. The primary objective was to replicate the in-flight phenomenon by depositing controlled thicknesses of water-ice on representative optical components and measuring the resulting spectral transmittance variations.

The experimental configuration was designed to provide a stable, cryogenic environment conducive to controlled ice growth. The setup consisted of a rotating copper sample holder, which was temperature-controlled by coupling it to a cold plate maintained at 77 K using liquid nitrogen. To ensure high precision in thickness monitoring, two Quartz Crystal Microbalances (QCMs) were mounted on the sample holder alongside a sample detector filter (referred to as the LAT DF).

The deposition process was driven by the outgassing of 1.2 g of molecular sieves (LTA-type zeolite) placed in an effusion cell. To achieve a reliable and repeatable linear deposition rate over several hours, the outgassing temperature of the sieves was optimized at 333 K. The sample holder was programmed to rotate to face the effusion cell, allowing for controlled exposure.

The deposition temperature of the sample was stabilized at 148 K. To ensure thermal accuracy and minimize radiative coupling with the 293 K chamber walls, several precautions were taken:

- An aluminum foil sheet was placed in front of the furnace to prevent temperature disturbances.
- The coupling between the optical sample and the copper holder was enhanced using Cho-therm® on both sides of the optics.
- An aluminum shield with a central aperture was positioned in front of the sample to reduce radiative heat transfer.

Spectral measurements were performed using an SR6500 spectrophotometer, providing luminance measurements sampled every 1 nm with a spectral resolution of 1.5 nm. A broadband white light source was used for illumination, and measurements were taken at 20-nm thickness intervals ranging from 0 to 600 nm. To account for any instrumental drifts during the long deposition process, unfiltered spectrum measurements were taken periodically, allowing for precise correction of the filtered spectra.

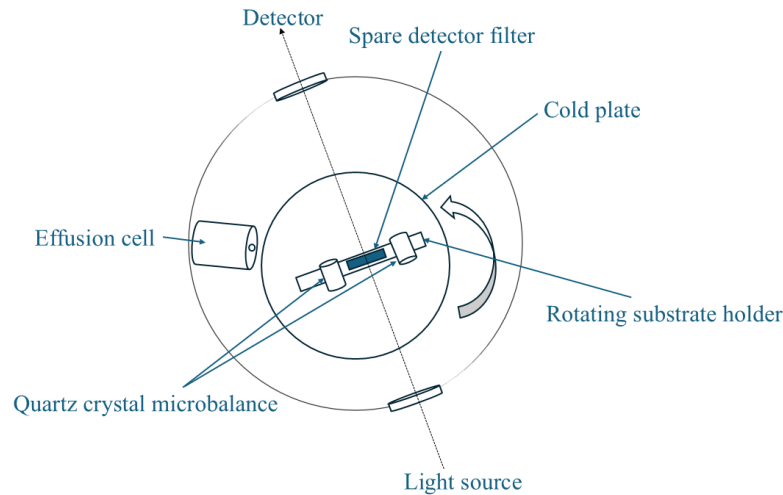


Figure 11. Drawing of the test setup

The experimental results confirmed the prediction of the model: the spectral response of the filter undergoes significant shape modifications and exhibits an oscillatory behavior in average transmittance as the ice thickness increases. Figure 12 and Figure 13 illustrate these spectral transmittance measurements and the resulting evolution of the average transmittance, compared to the simulation of the expected transmission of this filter in these experimental conditions.

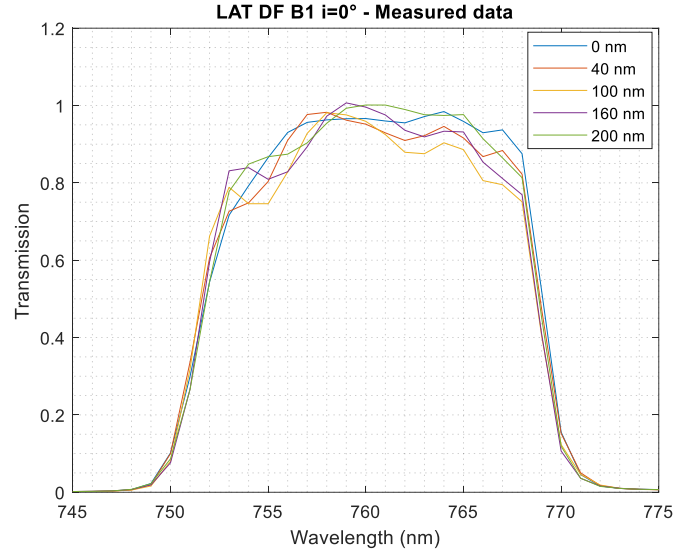


Figure 12. Spectral transmittance measured for various ice thicknesses on the sample

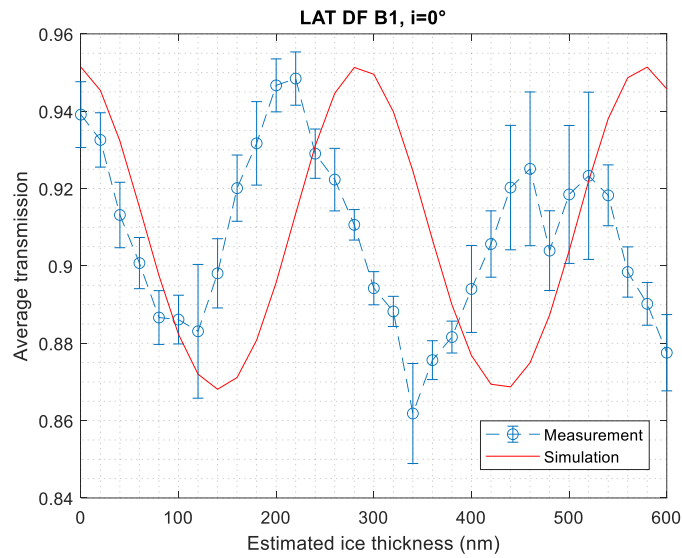


Figure 13. Average measured transmittance as a function of the estimated ice thickness deposited on the sample

The model, when using the initial assumed ice density of 0.93, provided a satisfactory reproduction of the overall oscillatory behavior in both amplitude and period. However, notable discrepancies remained:

- The simulated period and the starting point of the transmission did not perfectly match the measurements.
- The measured transmittance exhibited a continuous decrease as ice thickness increased, a phenomenon not captured by the pure interference model. This drop is attributed to signal scattering by the frost, which is directly linked to the ice thickness.

A critical finding of the experimental phase involved the calculation of physical thickness from the QCM resonance frequency. The initial thickness estimation relied on a density of 0.93. However, ice density and porosity are highly sensitive to various parameters, including the deposition rate, surface temperature, angle of incidence, and substrate nature.

By applying a revised ice density of 0.77, the consistency between the measured average transmittance and the simulated spectral response was significantly enhanced. This adjustment corrected the estimated physical thickness, bringing the simulated oscillations and the spectral shape into much closer alignment with the experimental data (see Figure 14 and Figure 15).

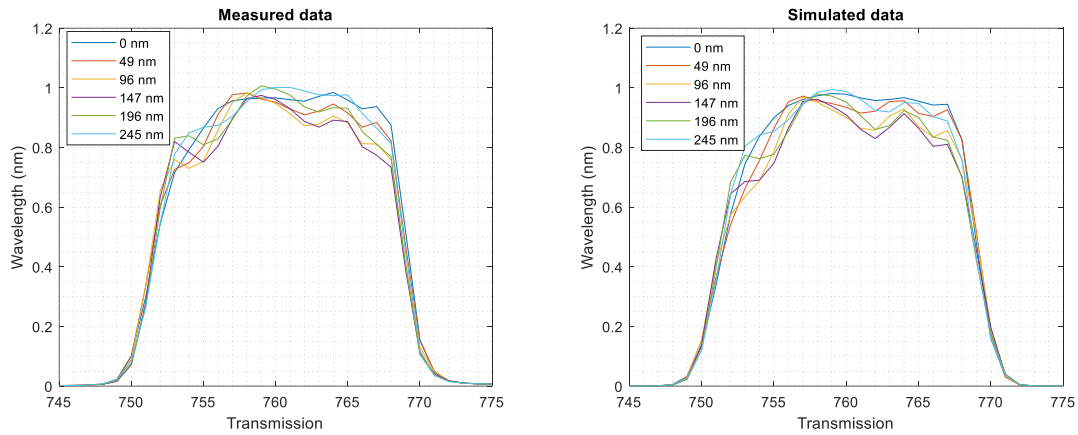


Figure 14. Measured (left) and simulated with convolution and resampling (right) spectral transmittances for various ice thicknesses, with modified ice density

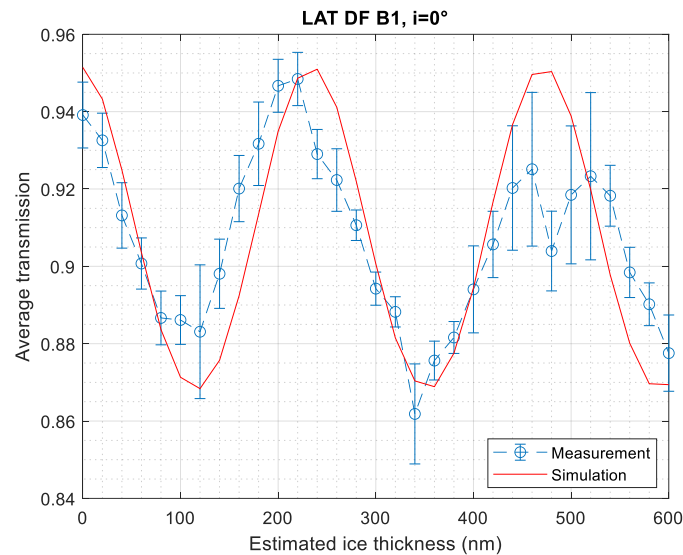


Figure 15. Average measured and simulated transmittances as a function of the estimated ice thickness deposited on the sample, with modified ice density

In conclusion, the ground-based observations demonstrate that the DF transmission curve becomes oscillatory as the ice layer thickens. This evolution of the spectral shape aligns with the anticipated optical effects of a progressively growing thin-film ice coating. Nonetheless, some uncertainties persist: the spectral data are limited by coarse wavelength sampling, and the precise control of the ice-film thickness remains imperfect. Moreover, the assumed ice density is a critical factor—it directly links the deposited mass to the actual film thickness and thus influences the evaluation of performance loss.

5. ESTIMATION OF IN-FLIGHT CONTAMINATION

Following the validation of the interferential model and the successful correlation of ground-based icing experiments, the final stage of the study involved applying these tools to the in-flight data. The objective was to reconstruct the evolution of ice thickness on the various critical surfaces of the MicroCarb instrument to explain the observed transmission anomalies.

To link the measured transmission variations to physical ice thicknesses, several temporal deposition models were tested within an optimization loop. This loop utilized an algorithm to minimize the quadratic error between the observed in-flight average transmission and the predicted transmission (calculated as the product of the transmissions of the DF faces and the NGP detector).

The following ice deposition temporal models were evaluated:

- A linear model where the variables are a constant deposition rate k , in nm/day, and the initial ice thickness T_0 , in nm, for each surface:

$$T_{ice}(t) = k * t + T_0$$

As we consider 3 surfaces, there are 6 variables in this model.

- An exponential model that assumes a deposition rate following a charging-capacitor-like curve with a time constant τ , in days, reaching an asymptotic thickness $T_I + T_0$, in nm:

$$T_{ice}(t) = T_I * \left(1 - \exp\left(\frac{-t}{\tau}\right)\right) + T_0$$

There are 9 variables in this model.

- A non-constrained point-to-point model where the ice thickness for each surface is optimized independently for every single in-flight measurement point. The ice deposition law is therefore no longer imposed and becomes an output of the optimization. We initially imposed the constraint that ice deposition must increase over time, before removing this constraint as well. The optimization also seeks the initial ice value that yields the best match between measurements and simulation.

The limitations of the constrained models (linear and exponential) became evident during the optimization of the in-flight cycles. Linear or exponential laws impose constraints on optimization, since they cannot account for multiple decelerations or accelerations in deposition rate over time. Both models of ice accumulation do not accurately reproduce the behavior observed in flight, as seen in Figure 16 and Figure 17 that show the results of the best optimizations for cycle 2 with both models.

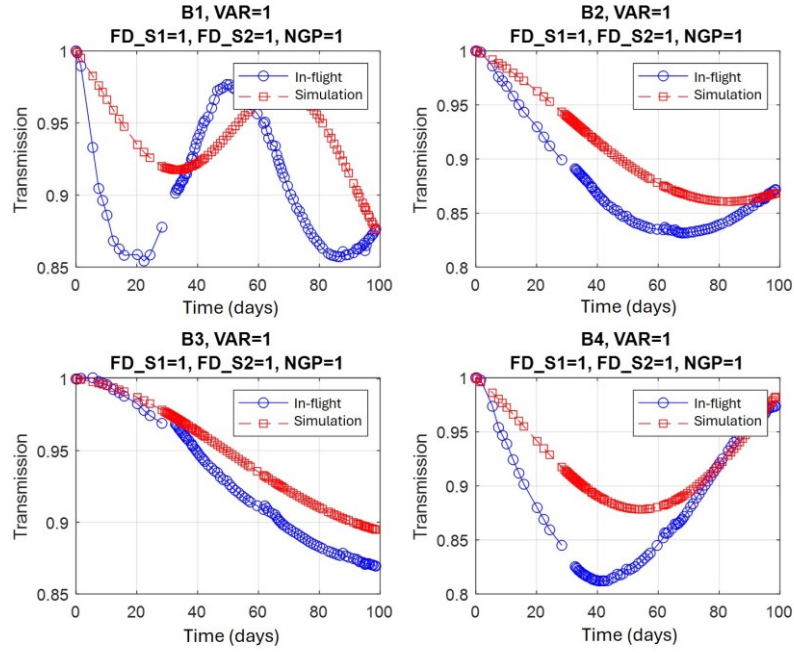


Figure 16. Measured (in-flight) and simulated average transmission curves, linear model, cycle 2

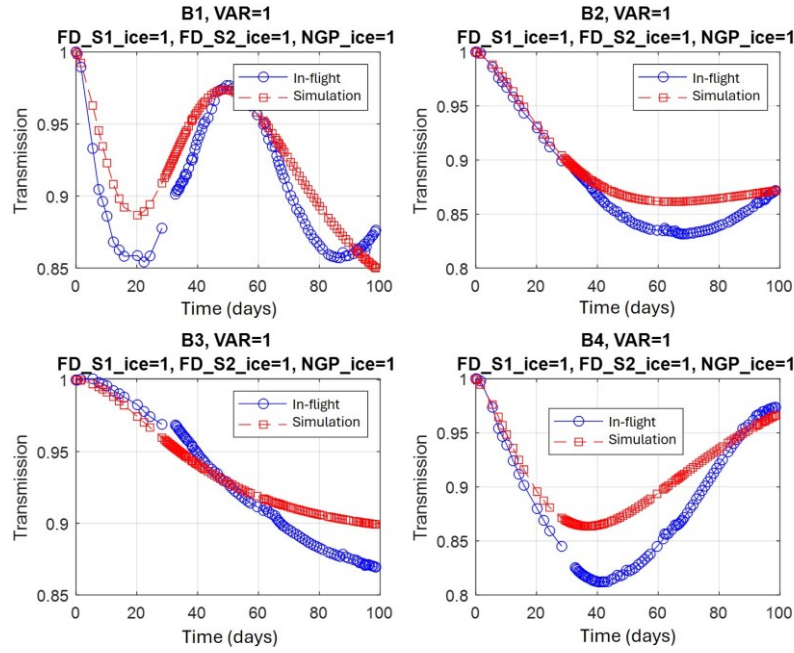


Figure 17. Measured (in-flight) and simulated average transmission curves, exponential model, cycle 2

One can see that the linear model does not reproduce the oscillations observed in the B1 band and leads to discrepancies between 5% and 8% for the other spectral bands.

The exponential model is closer to the in-flight measured data in every spectral band, but the rebound in B1 at the end of the cycle isn't accurately depicted and neither is the dip in B4.

The outputs of the optimization process are also the temporal evolution of the ice thickness on the 3 surfaces (Figure 18), and the associated parameters (Table 2 and Table 3).

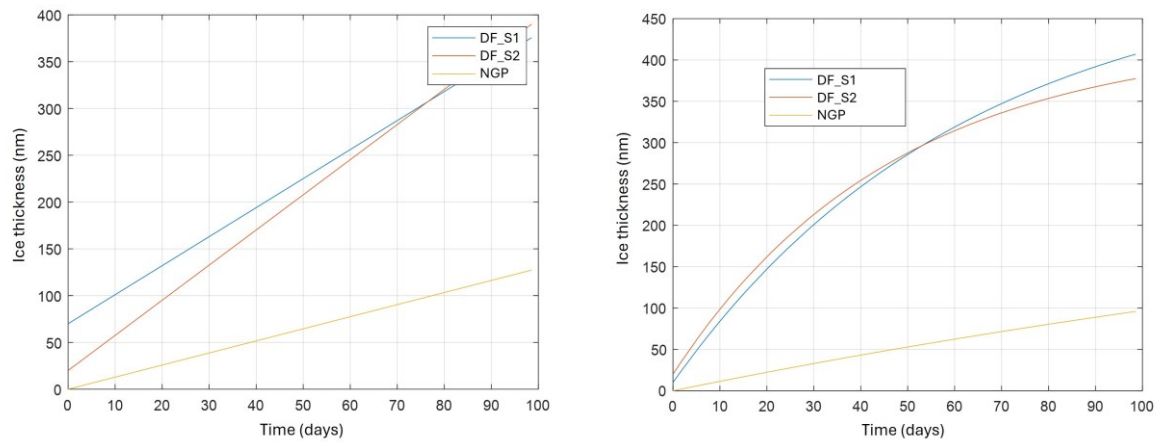


Figure 18. Changes in ice thickness, linear model (left) and exponential model (right), cycle 2

It is worth noting that the models indicate a greater amount of ice on the filters than on the detector. Both models find that the initial ice thicknesses are low, and final thicknesses on DF are around 400 nm.

Table 2. Optimized parameters of the ice deposition model, linear model, cycle 2

Surface	Initial ice thickness (nm)	Deposition rate (nm/day)	Merit function value	0.353
DF S1	70	3.1		
DF S2	20	3.75		
NGP	0	1.3		

Table 3. Optimized parameters of the ice deposition model, exponential model, cycle 2

Surface	Initial ice thickness (nm)	Asymptotic thickness (nm)	Time constant (days)	Merit function value	0.112
DF S1	10	510	62.4		
DF S2	20	426	46.5		
NGP	0	320	276.5		

The point-to-point model proved to be the most robust and accurate tool. By removing the constraints of a fixed functional form, the optimization could account for sudden changes in deposition or sublimation rates. This model was particularly effective when allowing the thickness to decrease over time. This "free" version yielded the best global correspondence with the in-flight measurements (see Figure 19).

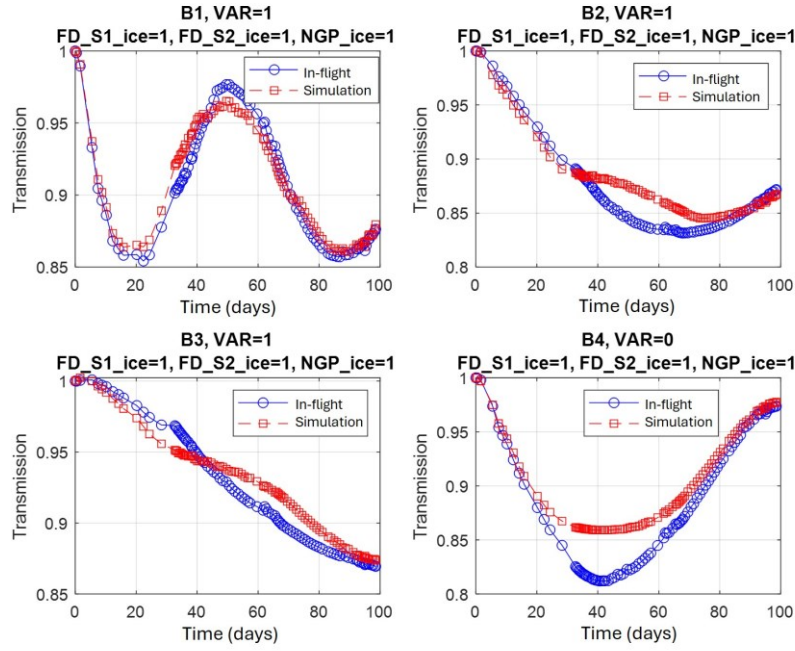


Figure 19. Measured (in-flight) and simulated average transmission curves, point-to-point model, cycle 2

The ability of the model to show a decrease in thickness (e.g., around day 30 of Cycle 2, see Figure 20) likely reflects the impact of instrument configuration changes, such as thermal transients or the activation of the diffuse optical background, which affect the local condensation/sublimation equilibrium. The best merit function has a value of 0.079 and all initial ice thicknesses are null.

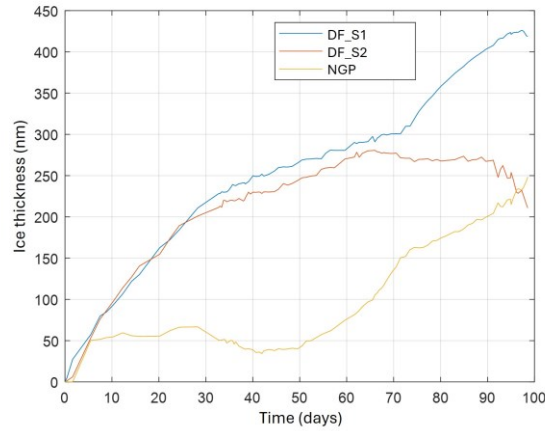


Figure 20. Changes in ice thickness, point-to-point model, cycle 2

A key challenge in the optimization was determining which surfaces (DF S1, DF S2, or the NGP detector) were the primary sites of ice accumulation.

Optimization results for cycle 1 indicated that the deposition occurs essentially on the faces of the Detector Filters, with significantly less impact on the NGP detector. This was corroborated by the point-to-point optimization for cycle 2, which demonstrated that the most accurate reconstruction of the spectral bands was achieved by focusing on the contamination of the DF surfaces.

Furthermore, the optimization revealed that the in-flight contamination levels are highly sensitive to the chosen band. Optimizing for different spectral bands can lead to variations in the estimated optimal ice thickness of several hundred nanometers, highlighting the complexity of the contamination environment.

The successful application of the point-to-point model confirms that the observed non-monotonic transmission variations are directly linked to the thickness of a water-ice layer acting as an interferential filter. The model demonstrates that a thin layer of ice, on the order of a few hundred nanometers, is sufficient to significantly modify the spectral response and the average transmission of the MicroCarb instrument. This concludes the characterization of the icing anomaly, providing a validated method for estimating contamination levels in future measurement cycles.

6. CONCLUSION

The investigation into the MicroCarb instrument's spectral instabilities has provided a comprehensive understanding of how water-ice deposition affects transmission performance. Through a combination of numerical modeling, ground-based experimental validation, and in-flight data reconstruction, we have demonstrated that ice formation significantly contributes to the radiometric performance instabilities observed during flight.

The core of this study demonstrated that a water-ice layer, acting as an additional thin-film component on the Detector Filters and the detector's Anti-Reflection coating, disrupts the optimized multilayer interference response. The modeling and ground tests confirmed that the spectral response oscillates as the ice thickness grows. This model will be used to make further estimates of ice deposition during future measurement cycles of the MicroCarb instrument. It could also be adapted for use in other projects that plan to place multilayer filters near a cooled detector. Finally, the effect of any contaminant for which the refractive index and optical absorption properties are known can also be evaluated using this model.

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