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## *Microcarb polarization scrambler*

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# MICROCARB POLARIZATION SCRAMBLER

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## I. MICROCARB MISSION

Monitoring the concentration of greenhouse gases from space is an important need. It can be achieved via a precise analysis of the chemical gaseous species (CO2, CH4, CO, etc.) signature in the spectrum of the reflected sunlight. The MICROCARB project aims to reach a very high quality measurement from on board a small volume Microsat platform, in 4 different spectral bands (O2 spectral band, 2 CO2 spectral bands and a CH4 spectral band), in order to locate and characterize the CO2 sinks and sources and to have a better understanding of the carbon cycle. But this is a very tricky measurement especially for the CO2 monitoring as its concentration in the atmosphere is about 380ppm and we need to measure it with accuracy better than +/- 1ppm. Another presentation is fully dedicated to the MICROCARB instrument design (see [1]). In this presentation, we will focus on one of the most challenging aspect of the instrument: The polarization

Aerosols clouds can polarize the transmitted light. When this is the case, if the instrument is also polarized, a small variation of the entrance beam polarization will lead to a radiometric error. MICROCARB specification is designed to limit this radiometric error under 1/1000, which allows to neglect it. The goal is to reach a polarization hardened instrument. **Doing that requires an instrument which polarization is lower than 0.1%**.

## II. SOLUTIONS FOR THE POLARIZATION REQUIREMENTS

### *A. Polarization measurement*

This is the chosen solution on GOSAT mission. It is a really interesting option because it can improve the measurement quality but it has the drawback of an important cost: It needs to either double the number of detectors, with an impact on mass, volume, and consumption incompatible with a flight on a Microsat platform, either have a more complex optical design and half the optical field because one half of the detector will be used for S polarization and the other half for P polarization. This second solution also requires more calibrations. This is why it is not the chosen solution for Microcarb Mission. But nevertheless it is an interesting option.

### *B. Use of a polarizer inside the instrument*

This is the chosen solution for OCO mission. With a polarizer inside the instrument, a variation of the entrance beam polarization angle results in a flux variation at the detector level, but induces no radiometric error. But there is a strong drawback: an optical flux loss in cos² of the difference between entrance beam polarization angle and instrument polarization angle. The consequence is an SNR loss. We must also consider that the entrance beam polarization mainly depends on the angle between Earth, Sun and the satellite. Thus, for a polar orbit, the SNR depends directly on the observed area on Earth. Some large areas cannot be covered because of a too low SNR. The solution is a quarter wave plate with its axes oriented at 45° compared to the polarizer axes. In that configuration, after the quarter wave plate and the polarizer, the flux is half the entrance flux, whatever the entrance beam polarization angle, which allows covering every area on Earth. This solution allows observing anywhere on Earth, but with requires to increase the pupil size of to $\sqrt{2}$ compensate the losses. The consequence is a scale factor on the instrument size that would be incompatible of a launch on a Microsat platform. This solution also suffers from high thermal sensitivity on the quarter wave plate. This solution was rejected for MICROCARB.

### *C. Use of an electro-optic polarization scrambler*

An electro-optic polarization scrambler consists of a liquid crystal plate driven by a dedicated electronics that allows controlling the rotation of a beam polarization angle. This rotation can be quick enough to make an integer number of revolutions during the integration time. The instrument thus receives the same flux for S and P polarization whatever the entrance beam polarization angle. Such a polarization scrambler exists and is commercialized by Ball Aerospace, with a maximum diameter of 40 mm, compatible with MICROCARB's pupil. But the space qualification of a liquid crystal component seems to be tricky, and it is an American component, potentially under ITAR license, not compatible with ITAR free requirements. It was thus rejected.

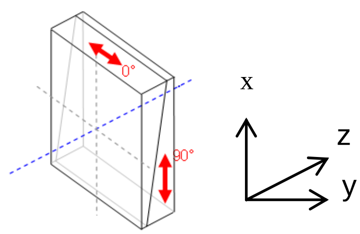
*D. Use of a Dual Babinet polarization scrambler*

A Dual-Babinet polarization scrambler is an optical component composed of 4 birefringent prisms. This component allows scrambling the polarization state when placed before the entrance slit of a spectrometer, ideally in the pupil or close to. Indeed, the polarization state of a ray is modified when crossing the dual-Babinet and this modification is variable as a function of the ray position on the component. The resulting beam polarization state is the average of the polarization state of all the different rays. The resulting polarization is then scrambled. This component can reduce a polarization ratio of a factor 100 and even more. The main advantages of this type of scrambler are the good scrambling performances, the absence of flux loss, and the small volume of the component. The drawback is that the entrance beam no more comes from one direction, but from 4 directions. The result is a ground PSF (Point Spread Function) composed of 4 different spots. The spatial separation between these 4 spots on ground is typically around 100 m. The flux proportion of these 4 spots in the entrance beam is variable as a function of the polarization, which results in a variation of the spots barycenter and thus the line of sight. But this effect is sufficiently weak compared to the 25Km² corresponding to the area of 1 sounding point. It is thus suitable for use in the MICROCARB instrument. That's the solution we chose for the MICROCARB mission. We will thus focus on it in the following part of this paper.

## III. THE DUAL BABINET POLARIZATION SCRAMBLER

*A. Babinet plate*

A Dual Babinet polarization scrambler design is based on the Babinet plate concept. A Babinet plate is a set of 2 birefringent prisms, assembled by silicate bounding, which angles are opposed to form a plate with the entrance surface parallel to the exit surface. The principal axes of each prism are perpendicular to the propagation axis, and the principal axes of the 1rst prism are perpendicular to those of the second prism.




This configuration allows having a delay between 2 principal axes of polarization, which is variable as a function of the position along the direction for which the prism thickness is variable. In other words, it is phase plate with a variable delay along one axis. Indeed, the entrance polarization is first decomposed on the 2 principal axes of the Babinet. The first component propagates through the fast axis and then through the slow axis, while the second component propagates through the slow axis and then through the fast axis. This results in a phase different between the 2 components of the beam, which can be expressed as follows:

$$\Delta\varphi = \frac{2\pi}{\lambda}\Delta n(e1 - e2) \tag{1}$$

With $\Delta\varphi$ the phase difference introduces by the Babinet plate, $\lambda$ the wavelength, e1 the thickness of the 1rst prism, and e2 the thickness of the 2nd prism.

Considering that ox is the axis of variation of prism thickness, and with $\alpha$ the prism angle, we can write:

$$e1 - e2 = 2.x.\tan(\alpha) \tag{2}$$

$$\Delta\boldsymbol{\varphi}(\boldsymbol{x}) = \frac{4\pi}{\lambda}\Delta\boldsymbol{n}.\boldsymbol{x}.\tan(\boldsymbol{\alpha}) \tag{3}$$

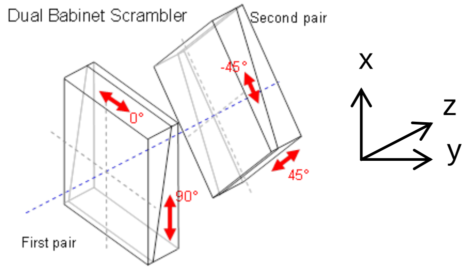
We can note that:

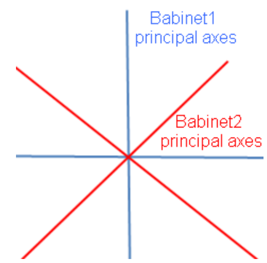
- The phase difference is variable along the axis of thickness variation of the prism, the ox axis.
- The phase difference depends on the wavelength, the birefringence and the prism angle.

But even with a variable phase difference along the x direction, a Babinet plate is not suitable to efficiently scramble polarization. To understand it, it must be noticed that the Babinet phase plate decompose the entrance beam polarization on the principal axes of the Babinet and then applies a phase difference on one component compared to the other. The consequence is that an entrance beam which polarization is oriented along one of the principal axis of the Babinet plate is not modified while crossing the Babinet plate, while en entrance beam which polarization would have 2 components once decomposed on the Babinet principal axes will be modified. Thus, in that configuration, the scrambling efficiency strongly depends on the entrance beam polarization. That's why it is not an efficient polarization scrambler.

*B.* *Dual Babinet polarization scrambler*

A dual Babinet is composed of 2 Babinet plates, rotated of 45° one from each other, around the propagation axis.




This configuration allows to successively applying 2 phase shifts. To fully understand of these 2 phase shifts, we must notice that each Babinet plate is characterized by 2 systems of axes: First, the system of the birefringent material principal axes, and then the axis of prisms thickness variation. These 2 systems of axes are not necessarily collinear.

*C.* *Orientation of principal axes*

The second phase shift occurs after polarization decomposition on principal axes that are different from the ones of the first phase shift. Thus, whatever the entrance beam polarization angle, it is never collinear to both Babinet principal axes at the same time. The entrance polarization is thus modified by the dual Babinet whatever its orientation. A 45° between the 2 Babinet principal axes is optimal. Indeed, in such a configuration, an entrance beam which polarization is collinear to one of the first Babinet principal axis won't be modified by the first Babinet, but will be decomposed on 2 equal components while crossing the second Babinet. Thus this absence of scrambling efficiency by the 1rst Babinet is compensated by a high scrambling efficiency while crossing the 2$^{nd}$ Babinet. This leads to a high efficiency of the scrambling whatever the entrance polarization angle.

*D.* *Orientation of the prism thickness variation axis*

The phase shift introduced by Babinet2 is also variable along an axis which is different from the one of Babinet1. This allows to have a global phase shift which is variable as a function of both x and y axes. This 2 dimensional phase shift variation is a key for a good polarization scrambling: the polarization scrambler should be place on the instrument pupil, and the resulting polarization seen by the detector is thus the average polarization state over the pupil surface.

It is logical that the prism thickness variation axis of the second Babinet should be perpendicular to the one of Babinet1, because in that configuration, the polarization variation over the pupil area is maximum. But in practice, the gain of such a configuration compared to a configuration with 45° between the 2 Babinet prism thickness variation axes is not so evident. The choice is toward the 45° because it allows dealing with 2 identical Babinets and thus fabricating it at the same time, reducing the risks of assembling and orientation errors.

*E.* *An example of the polarization state modification by the Dual Babinet scrambler.*

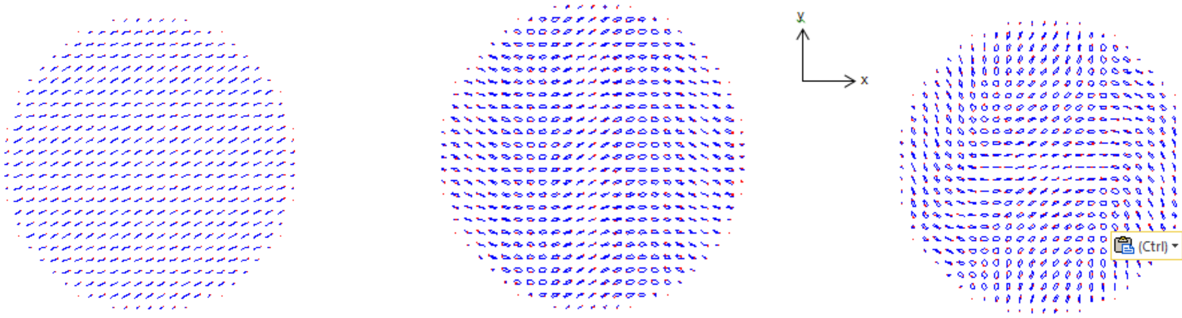
The series of figures here-under shows the polarization state as a function of ray positions over the pupil area, at different steps while crossing the dual Babinet polarization scrambler.

For this example, we choose an entrance beam polarization at 45° of the 1rst Babinet principal axes. The principal axes of the 1rst Babinet are ox and oy, and the axis of prism thickness variation is ox. The second Babinet is similar to the first one, but turn of 45° around the propagation axis.

The first figure, here under show the entrance beam polarization state. Its orientation is uniform over the pupil.

The second figure shows the polarization state after the propagation through the 1rst Babinet. We can see that the polarization state varies as a function of x, which is the prism thickness variation axis.

The last figure shows the polarization state after propagation through the second Babinet. We can see that now the polarization state varies as a function of both x and y. Looking more closely, the symmetry of the polarization state let intuitively understand that the resulting polarization must be scrambled. It is possible to have an idea of the pupil size impact. Indeed, with a 3 times smaller pupil, we can imagine that the performance must be really worse because the resulting polarization state would have a clear horizontal component. This point will be detailed in the following paragraph.



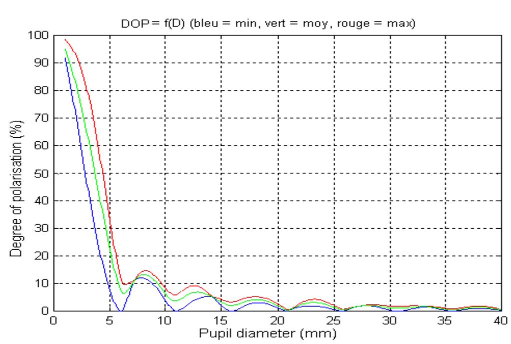

*F.* *Impact of the pupil size*

To clearly understand how the pupil size can impact, it is important to see that the **key parameter for the scrambling performance is the <u>encircled phase shift variation</u>**. That's to say the phase variation inside the pupil size. In other words, a pupil 2 times bigger is strictly equivalent to:

- A prism angle 2 times bigger
- A birefringence 2 times higher
- A wavelength 2 times smaller (if the birefringence wouldn't vary with wavelength)

For a given polarization scrambler (given prism angle, birefringence, wavelength), the encircled phase shift variation over the pupil area is directly proportional to the pupil size. Let's imagine a polarization scrambler with an infinitely small pupil. We easily understand that there would be no scrambling because the encircled phase shift variation would be infinitely small. The dual Babinet would only work as a classical phase plate, but without any scrambling. We can also understand that the larger the pupil size, the better will be the scrambling performance. This is true, but with a subtlety because it is possible to reach a perfect scrambling only when the encircled phase shift variation is exactly $2K\pi$, with K a non-zero positive integer. To give a 1 dimension analogy, we could say that it is equivalent to average a cosine type function between –x and +x. The average value is 0 for $x = 2K\pi$, with K a non-zero positive integer.

The figure here under shows an example of the typical scrambling performance as a function of the pupil size. The Degree Of Polarization (DOP) is calculated with a 100% polarized entrance beam, and a 100% polarized instrument. The red curve shows the degree of polarization for the worst orientation of the scrambler compared to the instrument. The blue one shows the degree of polarization for the best orientation of the scrambler compared to the instrument and the green one is the average degree of polarization over the orientations between the dual Babinet scrambler and the instrument.




We can see that the DOP curves have several minimums. These minimums occur when the encircled phase shift variation is $2K\pi$. We can also see that the DOP curves envelope is an exponential function decreasing with the pupil diameter. This is logical because the encircled phase shift variation is all the more high than the pupil diameter is large. We can thus conclude that the larger the pupil, the better is the tolerance on the polarization scrambler orientation relative to the instrument. Indeed, with a large pupil diameter, the difference between the min DOP and the max DOP are small, and thus the error on polarization scrambler orientation is small. And the larger the pupil diameter, the better the fabrication tolerances and the thermal tolerance.

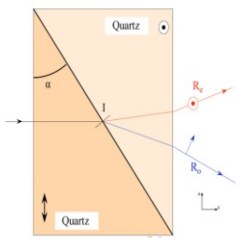
*G. Geometrical effects*

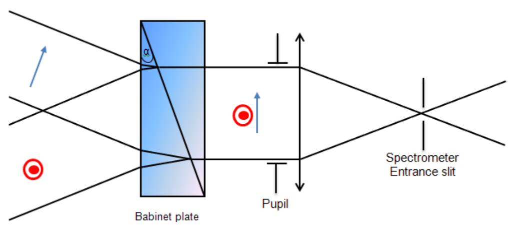
If we remember that the Babinet plate is usually used to separate the polarizations, we understand that we expect some geometrical effects with which we have to deal. The 1rst fig here under is a section of a Babinet plate. Because of the prism angle α, the beam has an incidence which is not zero on the surface between the 2 prisms. And because of the birefringent material used, each polarization component (decomposed on the principal axes of the birefringent material) see a different optical index. Snell's law implies that S and P polarization are diffracted in 2 different directions. This is why this component is used to separate polarizations. We can calculate the angular deviation between those 2 components with the equation below:

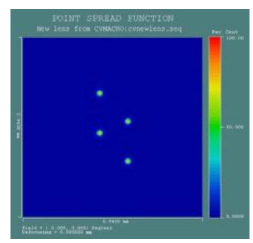
$$\emptyset = 2(ne - no).\tan(\alpha) \tag{4}$$

With Φ the angular deviation between S and P polarization, ne the fast axis optical index, no the slow axis optical index, and α the prism angle.

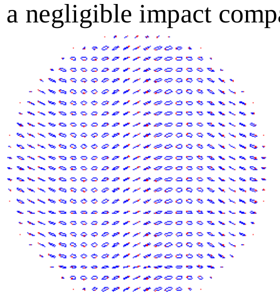
To understand the impact of this angular separation, it is important to remember that the scrambler is placed on the pupil, as we can see in the second fig here-under. Note that this figure is simplified. It only shows one of the 2 Babinet plates of a polarization scrambler, and only the part of the instrument up to the spectrometer entrance slit. The spectrometer entrance slit is placed after the polarization scrambler. There is no double image in the spectrometer, because the spectrometer part of the instrument makes the image of the slit on the detector, after spectral dispersion. But the beam crossing the slit comes from 2 different directions if we use a single Babinet plate, and from 4 different directions if we use a dual Babinet polarization scrambler. The result is a ground PSF (Point Spread Function) composed of 4 spots as we can see in the 3rd figure below.




The required image quality for MICROCARB fixes a limit to the extent of these 4 spots. This gives a limit on the coupled parameters "material birefringence / prisms angle". But fortunately, given the large field of view of one sounding point (around 25 km²), it is not a strong constraint on the polarization scrambler. This limit fixed by the image quality applies to both Babinet plates of the polarization scrambler. But there is another geometrical effect which has a stronger impact on performances. The optics power coming from each of the 4 ground spots of the PSF depends on the beam polarization angle. The spots barycenter evolves as a function of the scene polarization state. And while no polarization measurement is done, this cannot be corrected and results in a geolocation error. The geolocation error budget allocated to the polarization scrambler fixes also a limit on the coupled parameters "material birefringence / prisms angle". But this time, this limit only applies to the 1rst Babinet plate. Indeed, after crossing the 1rst Babinet plate, the polarization state is already variable as a function of ray positions over the pupil area. In first approximation we can consider that the polarization state repartition after the 1rst Babinet is uniform as we can see on the figure here-under. This approximation is not strictly exact but in practice the second Babinet plate has a negligible impact compared to the 1rst Babinet one.



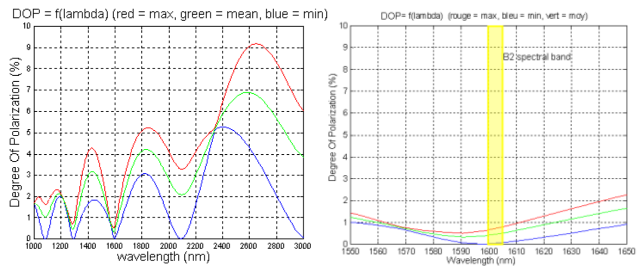
So it is possible to choose a configuration for which the prism angle of Babinet1 is different from the prism angle of Babinet2. In this configuration, the limit on the 1rst Babinet is given by the geolocation requirement, while the limit on the second Babinet is given by the image quality requirement.

It is also possible to turn the polarization scrambler compared to satellite trajectory so that the 4 spots barycenter variation with the polarization states will be along the ALT axis (ALong Track). This reduces the geolocation errors. But there is a compromise between the better orientation of the polarization scrambler compared to the instrument which gives the best scrambling performances, and the better orientation of the polarization scrambler compared to the satellite trajectory which gives the least geolocation error.

### *H. No spectral fringes*

One fundamental question: Will the polarization scrambler generate ghost fringes, either in the spectrum, or in the field? If it was the case, it could be unsuitable, or implies calibrations and stabilization to avoid bias. But this is not the case. To understand, let's come back to the key parameter: the encircled phase shift variation. We saw that multiplying by 2 the wavelength is strictly equivalent to divide by 2 the pupil diameter. In MICROCARB case, the wavelength varies of around 3/1000 over each spectral band. This is equivalent to a pupil diameter variation of 3/1000. The optimal configurations are those for which the encircled phase shift variation are 2Kπ, with K a non-zero positive integer. In practice, the geolocation requirements and the accessible pupil diameters on MICROCARB limit K to a value under 10. That means that, with K = 10, a variation of 1/10 of the pupil size, or 1/10 of the wavelength results in a complete oscillation of the degree of polarization. The spectral width MICROCARB spectral bands are thus negligible compared to a 1/10 variation corresponding to a complete oscillation on the scrambling performance. Spectral performance variation is only a very low amplitude and very low frequency error.

The here-under figures shows the typical DOP variations as a function of the wavelength for a scrambler configuration with K = 4, for a 100% polarized beam and a 100% polarized instrument. The $2^{nd}$ fig is a zoom with MICROCARB B2 spectral band. Performances variations along the spectral axis are extremely small.



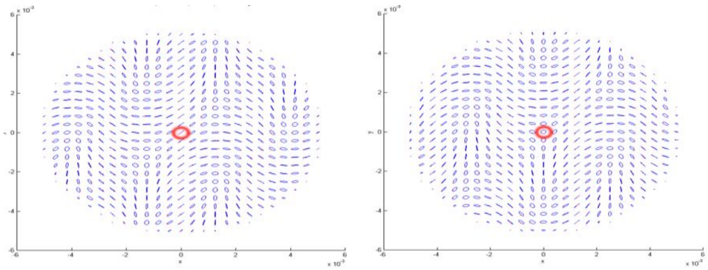

### *I. Decenter impact*

Unlike what it seems, a dual Babinet has a center. This center is defined by the point for which the phase difference introduced between S and P polarization is zero for both Babinet plates. This is thus the point for which the 1rst prism thickness is equal to the $2^{nd}$ prism thickness and this for each Babinet plates. The polarization state of a ray crossing the scrambler at this point is unchanged. It is a singular point around which is organized the polarization state symmetry as a function of pupil position.

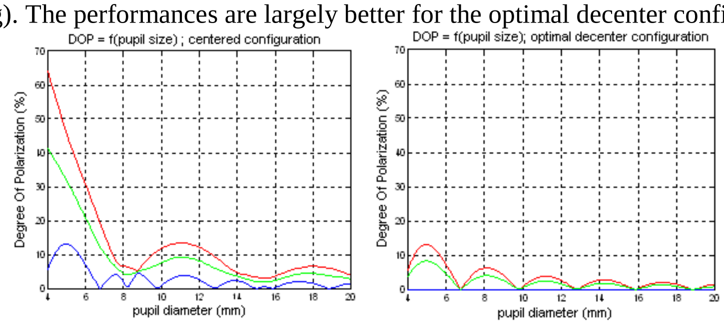
Decenters of the scrambler compared to the pupil center has a strong impact on the scrambling performances. As the phase shift is a linear function of the pupil position (x, y), the polarization state at the exit of the scrambler varies in a cosine like function of the pupil position. In other words, its average (the encircled phase shift variation) is zero only for pupil diameter D = 2Kπ, with K a non-zero positive integer. This explains the behavior of the DOP curves as a function of the pupil diameter. This is in fact the worst configuration, because except for a few pupil diameters, the resulting polarization is not perfectly scrambled.

A configuration allows better performances: The one for which the dual Babinet introduces a λ/4 phase shift in the pupil center. This can be created by adding a λ/4 phase plate in front of the dual-Babinet, or with a suitable decenter of the scrambler compared to the pupil. These 2 solutions are stricly equivalent. The interest is to transform a cosine type phase shift, in a sine type phase shift. Because of the odd symetry in such a configuration, the resultant of the polarization states averaged over the pupil size is unpolarized, whatever the pupil size. The result is a perfect polarization scrambler.

The here-under figures shows the polarization state as a function of the pupil position, for a linear entrance polarization at 45°, for a centered configuration (left fig) and for an optimal decenter with a λ/4 phase shift at the pupil center (right fig). We can see that the pupil center polarization state (circled in red) is unchanged for the centered configuration, but is transformed in a circular polarization state for the optimaly decentered configuration (λ/4 center phase shift ). Looking closely, the odd symetry is visible.



It is thus possible to reach a perfect polarization scrambling, whatever the pupil size, as we can see in the here-under example. The figures represent the Degree Of Polarization (DOP) as a function of the pupil size (curves described in the "impact of the pupil size" chapter). Both figures show the performances of the same polarization scrambler, in a centered configuration (left fig), and for the optimal decenter (λ/4 phase shift in the pupil center) (right fig). The performances are largely better for the optimal decenter configuration.




But there is a drawback: the optimal decenter is wavelength dependend. The width of Micarb spectral bands, around 3/1000 of the bands center wavelength, is sufficiently small, so there is no associated problem. But with 3 different spectral bands at the same time it is much more diffuclt to find a good configuration. It is theoretically possible to have a phase plate with a λ/4 phase shift for each of the spectral bands, but this requires a very thick phase plate resulting in a high thermal sensitivity. This solution is not directly suitable. But it is possible to find a configuration with a thin phase plate (and thus thermically tolerant), not optimal but better than the centered configuration. It is interesting to calculate the decenter that allows to reach a λ/4 phase shift at the pupil center, because it gives an idea of the mechanical and thermal tolerances. This decenter corresponds to the change between the worst configuration (centered configuration) to the best configuration (optimal decenter configuration). The centering must be stable at a precision which must stay under a small fraction of this optimal decenter. With (3), we can see that reaching a λ/4 phase shift in the pupil center requires a decenter of :

$$x = \frac{\lambda}{8.\Delta n.\tan(\alpha)} \tag{5}$$

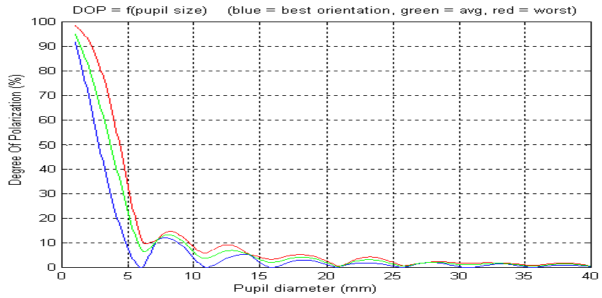
The decenter tolerance is all the more weak that: the wavelength λ is small, the birefringence Δn is large, and that the prisms angle α is large. For MICROCARB, this optimal decenter value is between 0.3mm and 1.6mm depending on the spectral band. The thermal impact will be negligible because $dn/dT = 6.10^{-5}$ for quartz and the birefringence variation is of the same magnitude. Even with a temperature change from 320K to 250K, the decenter corresponding to a λ/4 phase shift should no vary more than 4.5/1000.

### *J. Field effect*

With a scrambler placed in the pupil, the optical field only changes the ray incidences on the scrambler, thus the optical paths inside the scrambler, and thus the phase shift induced by the polarization scrambler. A field angle θ changes the optical paths with a factor 1/cos(θ). MICROCARB field of view is < to +/-1°, which corresponds to a relative change of $1.5.10^{-4}$ on optical paths and thus to a relative change of $1.5.10^{-4}$ on the encircled phase shift variation, whatever the configuration, centered or decentered. This relative change with the optical field is really weak and has a negligible impact on scrambling performances, as we can see on the DOP curve as a function of the pupil size, which is an equivalent to the DOP curve as a function of the encircled phase shift variation (see the "impact of the pupil size" chapter).

In the case for which the scrambler is at the distance d of the pupil, the optical field not only changes the ray incidences, but also the beam decenter on the scrambler. For an optical field θ, it will corresponds a decenter d.tan(θ). This impact is not negligible. For example, for a configuration like MICROCARB, but with the scramble at 30mm away from the pupil position, from the field center to the field edge, the scrambling performances would change from the best to the worst configuration. In this configuration, it is not possible to optimize its performances with a phase shift at the center of the pupil.

*K. Tolerances*




Looking at the typical DOP curve as a function of the pupil diameter, we see that 2 choices are possible:

- Choosing a small pupil such that we have a minimum DOP, for the example here-over, a 6mm diameter pupil allows to perfectly scramble the polarization.
- Choosing the largest possible pupil diameter, while being in a minimum of the DOP curve. For the here-over example, a 40mm pupil diameter also allows to perfectly scramble the polarization.

In both cases, theoretical scrambling performances are the same but the toloerances differs. We see it by comparing the DOP curve for the best orientation (in blue) to the DOP curve for the worst orientation (in red).

Tolerance on the scrambler orientation as respect to the instrument:

With a small pupil, it is possible to reach a DOP close to 0, but the maximum DOP stay high. This is not the case with the large pupil diameter because the maximum DOP stay weak, even for the worst orientation.

Tolerance on the pupil size:

The figure with the DOP curves as a function of the pupil size shows that the pics amplitude dicrease with the pupil size. Local DOP variations with pupil size variations are all the more weak that the pupil size is large.

Tolerances on thermal variations:

At first order, the thermal variation consequence is a modification of the encircled phase shift variation. But a variation of the encircled phase shift variation is stricly equivalent to a variation, in the same proportions, of the pupil size. The conclusion is thus the same: the configuration is all the more tolerant that the pupil is large. Mechanical tolerances of the scrambler center as respect to the pupil center: The centering tolerance is all the more small that the wavelength $\lambda$ is small, the birefringence $\Delta n$ is large, the prism angle $\alpha$ is large.

## X. MODEL VALIDATIONS

The theoretical model results were compared to real measurements done on MICROCARB bread board, with a real polarization scrambler, on a real spectrometer, especially on:

- The minimum DOP as a function of the pupil size
- The maximum DOP as a function of the pupil size
- The best orientation of the polarization scrambler, as a function of the pupil size.
- Decentered configurations

The agreement between the model and the measurements is perfect. The model is considered as fully validated.

## XI. CONCLUSION

MICROCARB mission aims to monitor the $CO_2$ concentration with a very high measurement quality. This implies, especially in the case of aerosols clouds, reducing the Degree Of Polarisation under 1/1000 in order to limit the polarization induced radiometric errors at a negligible level. To reach this performance, we made the choice of a Dual Babinet Polarization Scrambler. This type of polarization scrambler was exetensively modeled, tested, and its design rules were understood with all their side effects, their limitations, and their tolerances. These design rules were described in this paper. And we are now completely confident in reaching a degree of polarization under 1/1000 for MICROCARB instrument, compliying with a very high measurement quality.

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