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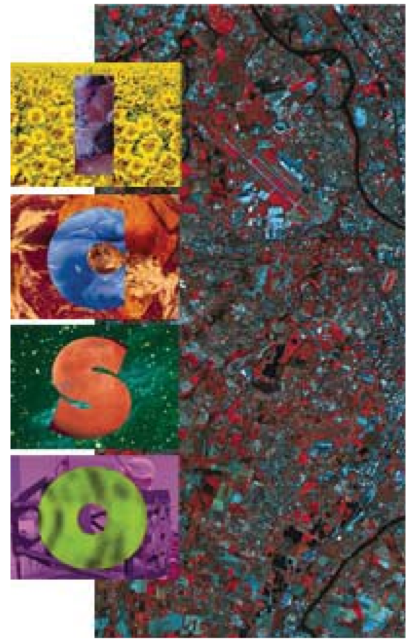

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ACHROMATIC PHASE SHIFTERS FOR NULLING INTERFEROMETRY

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ABSTRACT *- In the search for extra-solar Earth-like planets, nulling interferometry is required. This technique provides the extinction of the light from the parent star so as to "see" objects in its immediate vicinity. This nulling process is based on appropriate phase shifts applied to the collected waves made to destructively interfere. These phase shifts must be performed in the thermal infrared domain and must be achromatic so as to enable working on a large bandwidth.*
After briefly recalling the principle of nulling interferometry, we state what should mean "achromatic" in the context and we present various techniques potentially able to meet the stated requirements. Critical points and interesting features of the presented techniques are outlined.

1 - INTRODUCTION

Numerous exoplanets have been detected by indirect methods (that is from the light of the parent star) but these methods are not convenient for Earth-like exoplanets and do not allow their spectroscopic study. Space-based Nulling Interferometry has been identified as a promising tool able to directly detect and spectrocopically analyse the radiation of Earth-like planets. Projects like DARWIN (ESA) and TPF(NASA) include in their scope this topic and the search for life as well (see ESA and NASA web sites : http://sci.esa.int/home/darwin/ and http://tpf.jpl.nasa.gov/)
The major problem for direct detection is the tremendous flux ratio between the parent star and the planet. Working in the thermal infrared makes it possible to record the planet's radiation itself and so to take advantage of a comparatively lowered flux ratio (typically 10^6 in the infrared instead of 10^9 in the visible domain). Working in the large spectral bandwidth 6 μm to 18 μm allows detection of possible atmospheric constituents (such as water vapour, carbon dioxyde, nitrogen and ozone), thus revealing possible signatures of life (Léger et al., 1996).

Nulling techniques provide the suppression of starlight and interferometry enables to reach the resolution required to deal with the very tiny angular separation between planet and parent star. Nulling interferometry has been introduced by Bracewell (1978) in order to meet the two requirements and has been demonstrated on the sky (Hinz et al., 1998).
This technique is based on destructive interference applying to the light of the on-axis star whilst the light

from the planet escapes the destructive process and remains detectable. The destructive process is performed by reversing the phase (shift by π) of one of the interfering waves before they are coherently added (recombination step).

A more general scheme uses more than two apertures. In that case, a phase shift equal to a fraction of π must be applied on each arm, this fraction depends on the recombining set-up and can be different for each interfering wave.

In any case, the phase shift to perform must be achromatic so as to preserve the full efficiency of the interference process over the whole spectral bandwidth. If not like this, the destructive interference is not complete and some light from the parent star is not suppressed (leakage), what prevents the light from the planet from being detectable. Therefore an approach based on simply inserting an extra optical path between waves is not relevant, and dedicated systems must be used.

In this paper we recall briefly the basics of the nulling interference process, we identify some evaluation criteria for Achromatic Phase Shifters (APS in the following) in the context of a Space-based infrared nulling interferometry mission. We then present the principle of various APS's. Critical points in each approach are outlined.

2 - REMINDERS ON NULLING INTERFEROMETRY

This technique, introduced by Bracewell (1978) works by collecting coherent lightwaves from an on-axis source at two separate apertures, and by making them interfere destructively. Regular use of a stellar interferometer virtually projects a transmission map on the sky (also named fringe grid or antenna pattern), with a full transmission area along the optical axis.

With nulling interferometry this map is reversed so that light from an on-axis source is theoretically not transmitted whilst the light from the planet, located off-axis, is fully transmitted when the infererometer is properly "tuned" (see figure 1). This means that the transmission map can be given an angular frequency high enough to match the separation planet-star (known from astrophysical considerations, like the angular size of the "habitable" zone). This is achieved by proper setting of the separation between apertures (or baseline length).

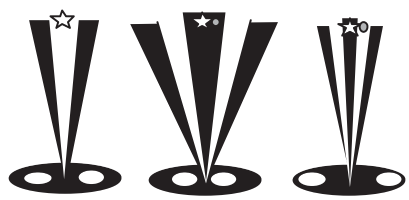


Figure 1. Synoptic illustration of the nulling processes B and C as compared to the non-nulled process A. Signal from star at A, no signal at B, signal from planet at C thanks to "tuned" baseline.

The algebra of the process is the one of coherent addition of complex amplitudes.

A wave from a point-like on-axis source, collected by the aperture number k and arriving on the detector has a complex amplitude expressed by

$$U_k = A_k . \exp(i.\frac{2\pi}{\lambda}.d_k + i.\phi_k) \quad (2.1)$$

where "A" is the energy-amplitude (giving A^2 = Intensity), "d" is the optical path from aperture to detector and ϕ a phase shift experienced by the wave on his way, for example by inserting a phase shifter. For a 2-aperture interferometer, with $A_1 = A_2 = A$ and $A^2 = I_0$, the recorded intensity is :

$$I = 2.I_0.[1 + \cos(\frac{2.\pi}{\lambda}.(d_2 - d_1) + (\phi_1 - \phi_2))] \quad (2.2)$$

The zero-OPD condition ($d_2 - d_1 = 0$) must be satisfied by set-up adjustment.

Normal stellar interferometry works with $\phi_2 - \phi_1 = 0$ and give $I = I_{Max} = 4.I_0$

Nulling interferometry ideally would work with $\phi_2 - \phi_1 = \pi$ so that $I = I_{min} = 0$, giving a total suppression of starlight. Actually, at least for some wavelengths, we have $\phi_2 - \phi_1 = \pi + \varepsilon$, where ε is a residual error in the phase shift. Therefore we have : $I = I_{min} \cong I_0.\varepsilon^2$

A planet located off-axis by a small angle α, gives an additional intensity, which expression bears an extra phase term $\phi_{planet} \approx 2\pi.\alpha.B/\lambda$, with B for the baseline. Thanks to this term the intensity is not nulled and the planet escapes the destructive process.

With this 2-aperture scheme the transmission map around the axis, varies as α^2 along the baseline direction and if the star is not utterly point-like some starlight reaches the detector. The use of a configuration with N apertures leads to a transmission map keeping flat near origin and having a stiffer profile at edges of the "hole". This benefits to the suppression of starlight (and relaxes the requirement for point-like source) without lowering the light from the planet. With such a configuration, the recorded intensity (multi-axial recombination) will be canceled when the sum of the N complex amplitudes is a null vector, which implies that the ϕ_k's take fractional values of π.

3 - ACHROMATICITY CRITERION AND OTHER CRITERIA

Several APS systems are existing or in development. Their adequation to a space-based infrared nulling interferometric mission, must be evaluated and some criteria or guidelines are needed.

The prime criterion is the ability to remove starlight. We refer to the basic 2-aperture interferometer to introduce the extinction tracer. Actually, even for a N-aperture interferometer, the problem of achromatic phase shifting basically remains to combine two phase shifts ϕ_1 and ϕ_2 on separate arms so as to end up with a π-phase shift in the coherent addition (what must take into account the phase shifts inserted by the set-up itself, which overall value is ϕ_{inst}).

This means that we must end up at a target value $\phi_0 = \phi_2 - \phi_1$ (see figure 2)

Some systems, that we may call "direct" or "absolute", provide ϕ_0 on one arm, so that $\phi_1 = 0$. Other systems, that we may call "differential", deal with both ϕ_1 and ϕ_2 what offers more parameters to play with, in the making of the target value. In any case the zero-OPD condition must be taken care of .

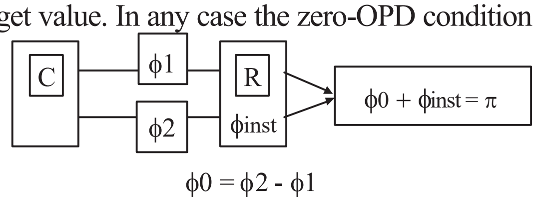


Figure 2. Managing with phase shifts in a 2-arm nulling interferometer. C and R for collection step and recombination step respectively. Depending on the collection and recombination set-up, an instrumental phase shift ϕ_{inst} is inserted in the phase balance ending with π. The target value is ϕ_0.

3.1 - Achromaticity criterion

The efficiency of extinction is traced by the rejection rate $R = I_{max}/I_{min}$, with I_{max} and I_{min}, like given in equations (2.1) with the difference that here they represent intensities integrated over the spectral bandwidth $\Delta\lambda$ of work. So, we have (at zero-OPD and with $A(\lambda) = A$ and $I_0 = A^2$) :

$$I = \int_{\Delta\lambda} I(\lambda).d\lambda = 2.I_0.\int_{\Delta\lambda} (1 + \cos(\pi + \varepsilon(\lambda)).d\lambda \tag{3.1}$$

In these conditions we have : $I_{max} \approx 4.I_0.\Delta\lambda$ and $I_{min} \approx I_0 .\int_{\Delta\lambda} [\varepsilon(\lambda)]^2.d\lambda$ and the rejection rate is then: $R = (4.\Delta\lambda)/(\int_{\Delta\lambda} [\varepsilon(\lambda)]^2.d\lambda)$.

As done in (Mieremet et al., 2000) a criterion can be defined by $<\varepsilon^2> = (1/\Delta\lambda).\int_{\Delta\lambda} [\varepsilon(\lambda)]^2.d\lambda = \Gamma^2$

and the connection is given by : $R = 4 / \Gamma^2$. A more severe tracer would use the upper value of the reisuals $\varepsilon = \sup_{\Delta\lambda}(\varepsilon(\lambda))$ and so we would have $I_{min} = I_0.\varepsilon^2.\Delta\lambda$. In that case the connection between the residual phase shifts and the rejection R is given by the two conditions :

$$R = \frac{4}{\varepsilon^2} \text{ and } \varepsilon = \sup_{\Delta\lambda}(\varepsilon(\lambda)) \tag{3.2}$$

So, being given the behaviour of the phase residual it is possible to exhibit a reachable rejection and conversely, from a given target rejection R_0 it is possible to specify the tolerable residual.
For example, the target rejection of 10^6 leads to a ceiling value of $\varepsilon = 2.10^{-3}$ radian over the whole bandwidth. Let us note that these two criteria do not show which bandwidth is concerned, therefore this latter must be taken into account in parallel.

3.2 - Other criteria

Besides achromaticity, some criteria must be considered since any departure from the ideal situation may lower the available rejection, as for example unequal intensities or unmatched directions of polarisation (not appearing in our algebra so far).

Disregarding other effects, *unequal intensities* such as $I_1/I_2 = q$, result in a lowered rejection R(q), which is expressed as :

$$R(q,\varepsilon) = \frac{(1+\sqrt{q})^2}{(1+q-2.\sqrt{q})+\varepsilon.\sqrt{q}} \tag{3.3}$$

For example, with an ε of 2.10^{-3}, giving $R=10^6$ the ratio R(q)/R is 0.945 as soon as q = 0.999 (an intensity mismatch of 0.1 %). Assuming ε is zero, and a target rejection $R=10^6$ the tolerable ratio q must be larger than 0.996.

Unmatched polarisations (in terms of alignment) also tend to lower the rejection. Being given an angle θ between linear polarisation vectors, the same formulae, quoted (3.3) , applies but here with $q = [\cos(\theta)]^2$. Specifying q > 0.999 means that θ must be smaller than $\theta_{max} = 0.032$ radian.

Other criteria regarding the effective implementation or the use of the system must be considered too. Thus, beyond the principle of the phase shift itself, we have to consider such features as the technical feasability, the luminosity (overall throughput), the sensitivity to departures from nominal conditions, the volume and the weight to embark. Also the folding of the output beam can make the phase shifter prohibitively bulky. This list is not limitative.

4 - PRINCIPLES AND FEATURES OF VARIOUS PHASE SHIFTERS

From APS systems appearing in the literature or in handbooks few families of approaches are found. They respectively rely on i) use of dispersive materials, ii) use of birefringence, iii) focus-crossing phase shift property, iv) reversal of electric field vector and v) phase change at total reflexion (rhomb). Some of them provide any wanted value of phase shift, some are shifting only by π or $\pi/2$. For every system both the zero-OPD constraint, the intensity matching and the polarisation-matching constraints must be satisfied (see previous section).
Given bibliographic references are for illustration and do not pretend to be exhaustive.

4.1 - Use of dispersive material

This approach uses plane parallel elements distributed over the two arms and having different refractive indexes so as to make the various dispersion gradients mutually neutralize.This gives an OPD varying as much as possible linearly with wavelength over a given spectral range, this results in an achromatic phase shift (Mieremet et al., 2000; Morgan & Burge, 1998 and 1999).

Playing with the number of elements, their thickness and their refractive index leads to minimize the residuals. Fine tuning towards minimum residuals is obtained by slightly tilting some elements (this reacts on their effective thickness).
Modeling this approach (Mieremet et al.,2000) starts with the expression of OPD for a set of K elements indexed by k

$$OPD(\lambda) = d_0 + \sum_1^K (n_k(\lambda) - 1).d_k \qquad (4.1)$$

where d_0 is the OPD when no plate is inserted, d_k and n_k respectively are the thickness and the refractive index of the element number k.
Being given a target value ϕ for the phase shift, the residual shift $\varepsilon(\lambda)$ is expressed by :

$$\varepsilon(\lambda) = \frac{2\pi}{\lambda}.OPD(\lambda) - \phi = \frac{2\pi}{\lambda}.[d_0 + \sum_1^K (n_k(\lambda) - 1).d_k] - \phi \qquad (4.2)$$

For a given arm, after selecting the spectral range (λ_1, λ_2), the target value ϕ, the number of plates K, and the materials (giving the n_k), it is possible to find the deeper residual dwell, by the least square method applied on the d_k's. Actually the parameter to minimize is expressed by :

$$\Gamma = \left[< \varepsilon^2 > \right]^{1/2} \text{ where } < \varepsilon^2 > = \frac{1}{\lambda_2 - \lambda_1} . \int_{\lambda_1}^{\lambda_2} \varepsilon(\lambda)^2 . d\lambda \qquad (4.3)$$

and the process works by getting the condition : $\partial\Gamma / \partial d_k = 0$ to be satisfied for every k.
Let us note that negative values of thickness may occur, this just means that the plate is to be inserted in the opposite arm. Note that with this approach, the zero-OPD condition is inherent.

The efficiency of this approach has been shown by numerical simulations in the visible spectral range (Mieremet et al., 2000) for a π target value with a rejection of 7.10^4 for a spectral range (400,1000 nm). An experimental demonstrator is under way. In the infrared, Morgan & Burge (1998 and 1999) forecast through simulations a rejection of 10^5 over the interval (7,17 µm).
A numerical simulation (E.Bascou) pertaining to the range (8,20 µm) shows that the specification $\varepsilon < 2.10^{-3}$ radian ($R > 10^6$) is met for a target value of $\pi/5$ by using 5 plates (3+2) made of KrS5, CsBr, CdTe, ZnS and CdSe (see figure 3).
A critical point with this technique is the sensitivity of rejection to thickness errors. This should be overcome by tilting the plates by a very small angle in the range of undredth to tenth of radian in the visible (constraint relaxed in the infrared domain) .
Another critical point (only partially ruled out by tilting the plate) is the occurence of spurious light from multiple reflections both at front end and within each plate.

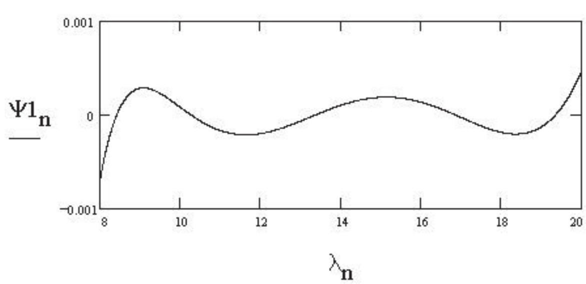


Figure 3. Numerical simulation of the residual phase shift obtained for a π/5

target value with the dispersive elements method, using 5 plates. Limits of vertical axe are – 0.001 and + 0.001 radian. Spectral interval is (8µm, 20 µm)

4.2 - Use of birefringence.

This approach uses a set of plane parallel plates (also named retardation plates), made of birefringent crystal and cascaded along the propagation axis, and oriented perpendicular to it. Achromatic phase shifters using this approach have been effectively built and provided λ/4 retarders and circular polarisers (Destriau & Prouteau, 1949; Pancharatman, 1955).

The principle is to perform a sequence of polarisation changes, each providing a chromatic phase shift but each being different from the other. The net result, from competing opposite effects, is a constructed quasi-achromatic phase shift. The formalism of Jones' matrixes provides the algebra of the process (MacIntyre & Harris, 1968; Kucherov,1997).

Each plate, that we refer to by index j, is made of a "linear" anisotropic material without loss, and allows propagation without deformation of linear polarisation vectors oriented parallel to the "axis" of the crystal (eigen vectors of polarisation). In the cascade, each plate is rotated in its plane by an angle φ_j and so are the "axis" (as shown in figure 4). The two axis, named fast and slow have different refractive indexes that we respectively note n_j' and n_j''. Thickness is noted l_j.

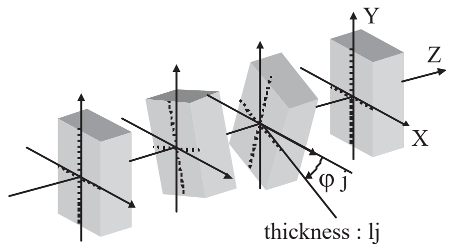


Figure 4. Schematic description of the APS using birefringing plates.
Axis labelled X and Y (dotted lines) feature the referential of the laboratory, the φ_j's (only one shown) are the rotation angles around the propagation direction, labelled Z, to which the plates are perpendicular.

The Jones matrix of a single plate, tracing the change from incident to emerging polarization, is far from being achromatic:

$$Mj = e^{i\psi j}.\begin{pmatrix} \cos(\frac{\phi j}{2}) + i.\cos(2.\varphi j).\sin(\frac{\phi j}{2}) & i.\sin(2.\varphi j)\sin(\frac{\phi j}{2}) \\ i.\sin(2.\varphi j)\sin(\frac{\phi j}{2}) & \cos(\frac{\phi j}{2}) - i.\sin(2.\varphi j).\sin(\frac{\phi j}{2}) \end{pmatrix} \quad (4.4)$$

In this expression, $\Psi_j = (\pi/\lambda).(n_j' + n_j'').l_j$ reflects the propagation with average index $(n_j'+n_j'')/2$ while $\varphi_j = (2\pi/\lambda).(n_j'-n_j'').l_j$ is the differential phase shift between the two polarization vectors.

The effect of cascaded plates is modeled by a product of Mj-like matrixes. Playing with the quantities $(n_j'-n_j'')$, φ_j, and l_j, in the resulting matrix, leads to make it diagonal. This allows shaping the set-up so as to make it achromatic over a chosen spectral bandwidth, as proven on both theoretical and experimental grounds (Pancharatnam, 1955; McIntyre & Harris, 1968; Kucherov, 1997; Hariharan & Ciddor, 1995; Hariharan, 1996; Title & Rosenberg, 1981).

Yet, quality wise, the results from such APS's are not, at the moment, suitable for the required achromaticity performance (see sect.3). Fitting it, would certainly increase the number of components and therefore the difficulty of adjustment and the energy losses as well.

4.3 - Focus-crossing phase shift property

A beam crossing a focus is achromatically dephased by π, with respect to a parallel beam following an equal optical path (Gouy, 1890; Boyd, 1980; Born & Wolf, 1970; Baudoz et al., 1998). This property allows for extinction when recombining two such beams (with an additional effect of a centro-symmetric rotation around optical axis for the focused beam).

The Achromatic Interfero Coronagraph (Gay & Rabbia, 1996; Baudoz et al., 2000a) for a single aperture is based on this property. The nulling effect has been demonstrated in laboratory and on the sky as well (Baudoz et al., 2000b).

Nulling can be achieved with a 2-aperture interferometer using this dephasing property in one arm as shown in figure 5 (and maintaining OPD at zero). The π-dephasing is obtained by means of a cat's eye device (also performing the pupil 180° rotation). Since this set-up uses only mirrors, no dispersion occurs and the produced phase shift is intrinsically achromatic.

In figure 5, the upper set of mirrors depicts the cat's eye, the lower set, made of flat mirrors is there to preserve OPD balance and total similarity of the beam folding. At recombination, coherent wavefronts from the star experience destructive interference while wavefronts for the planet (which are symmetrically tilted) do not interfere. Another way to perform this nulling would be to use a combination of a Cassegrain-type and a Gregory-type telescopes at the collecting step, what would provide a built-in focus-crossing.

If the recombination is made by means of a beamsplitter, the target phase shift is $\pi/2$. In that case the focus-crossing approach is made suitable by using cylindrical components instead of spherical ones in the cat's eye (Rabbia & Gay, submitted). The key point is that the π shift occuring at the focus is actually made of two superimposed $\pi/2$ shifts, at a common focus (Boyd, 1980). Splitting the focus in two sub-foci (intra and extra focus) makes the π shift appearing in two steps, each contributing for $\pi/2$. This happens for example, with a lens suffering from astigmatism .

Using cylindrical surfaces is like rejecting at infinite the second step, so that only a $\pi/2$ achromatic phase shift happens.

Algebraïc derivation using the formalism of Fourier Optics validates the focus-crossing approach (for both π and $\pi/2$) on the theoretical ground and in the scalar approximation. A demonstration in laboratory remains to be made for the $\pi/2$ case (cylindrical) . For the π case, an early laboratory set-up with "on the shelves" components provided a rejection of 300, with the whole K-band (Baudoz, 1999).

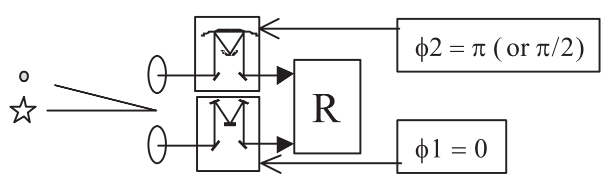


Figure 5. Schematic description of the focus-crossing approach for a two-aperture interferometer. R is for Recombination.

4.4 - Reversal of electric field vector at reflexion

This method (Serabyn et al, 1999) provides a phase shift by π, based on the achromatic reversal of the electric field vector on one of two interfering waves. This reversal is performed in a rotational shear interferometer with a fixed shear of 180°, by means of rooftop mirrors with summit lines are orthogonal (hence perpendicular planes of incidence) as seen by waves. For each collected wave, A and B, a 50/50 beamsplitter gives both a transmitted and a reflected part, which are recombined at two outputs. They respectively drive the transmitted A along with the reflected B and the complementary arrangement reflected A along with transmitted B. Since the s-polarisation (perpendicular to plane of incidence) experiences an achromatic reversal at reflection, the set-up (see figure 6) provides at each output, the fields A and B as opposed vectors. This results in a null signal as soon as the OPD is zero.

The set of mirrors is arranged so that the geometry of beams is identical on the two arms created by the beamsplitter (same number of s and p reflections for interfering beams and same folding sequence). The beamsplitter induces dispersion on one arm, which is corrected by using a compensation plate on the opposite arm. The beamsplitter being traversed twice by each beam, departures from the 50/50 regime have no effect on the nulling. However, use of a non-symmetrical beamsplitter could induces a spurious phase shift (Phillips and Hickey, 1995)
Wavefront distorsions tend to reduce the nulling efficiency. Care is taken, by means of optical monomode fibers, to clean the wavefronts prior to let them interfere.
This method initially used only one polarisation of the incoming waves but works are in progress towards using both polarisations (Serabyn, 2000) so as to work with the whole collected energy.
The efficiency of the process has been demonstrated and have exhibited deep nulling, which is progressively improving, both regarding nulling depth, stability and spectral bandwidth. Nulling depth of about 7.10^{-5} (rejection R better than 10^{4}) has been demonstrated with a 18% bandwidth centered at 660 nm (Serabyn, 2000).

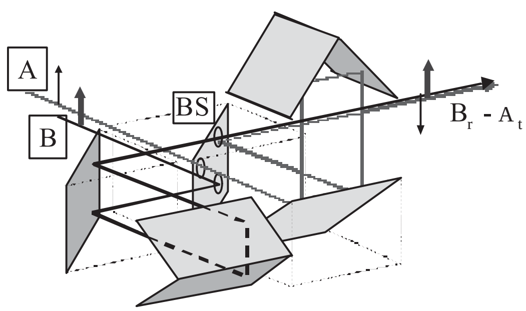
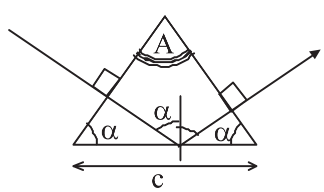


Figure 6. Schematic of the set-up and (partially) the process providing nulling for waves collected on apertures noted A and B. Only one output (A tramsmitted and B reflected) is shown. Also the compensation plate on the reflection side of the beamsplitter (BS) is not featured.

4.5 - Dephasing properties at total reflexion

This approach (Gay et al.,submitted) is based on dephasing properties of total reflexion. It uses, on each intrerferometric arm, a couple of isoscele prisms having unequal refractive indexes and being assembled in such way that the lightwave meets successively two planes of incidence each perpendicular to the other. Such a "composite rhomb" makes this approach somewhat departing from the Fresnel rhomb phase shifters (Born & Wolf, 1970; Title & Rosenberg, 1981).
When traveling through the prism (see figure 7) the lightwave experiences a chromatic phase shift resulting from propagation in a dispersive material to which is added an achromatic phase shift induced by total reflexion. This latter depends on the polarisation of the incident wave and we have to deal with p-type and s-type reflections (electric field vectors respectively parallel and perpendicular to the plane of incidence).



$A = \pi - 2.\alpha$
$d = c.\sin(\alpha)$

Figure 7. Geometry of one prism and optical path "d"

Let us consider the couple of prisms, having respectively angles α and β, refractive indexes n_1 and n_2 and bases c_1 and c_2, what we call the (α,β,n_1,n_2) configuration.

We note ϕ_{p1} and ϕ_{p2} the achromatic phase shifts for the p-reflection respectively with indexes 1 and 2, and similarly ϕ_{s1} and ϕ_{s2}. The incident wave is of p-type, but at the second reflexion it is seen as a s-type wave. For this "rhomb1" the phase difference $\phi 1$ (outcoming – incoming) is given by :

$$\phi 1 = \frac{2.\pi}{\lambda}.(n_1.d_1 + n_2.d_2) + \phi_{p1} + \phi_{s2} \tag{4.4}$$

We now consider the couple prisms in the (α,β,n_2,n_1) configuration (refractive indexes have been permuted). Similarly, for this second assembly the achromatic phase shifts to consider now are ϕ_{s1} and ϕ_{p2} and the resulting phase shift is :

$$\phi 2 = \frac{2.\pi}{\lambda}.(n_2.d_1 + n_1.d_2) + \phi_{s1} + \phi_{p2} \tag{4.5}$$

Thus, the phase difference between waves on the two interferometric arms is :

$$\phi 0 = \phi 1 - \phi 2 = \frac{2.\pi}{\lambda}.[(n_1 - n_2).(d_1 - d_2)] + (\phi_{p1} + \phi_{s2} - \phi_{s1} - \phi_{p2}) \tag{4.6}$$

As soon as we have the same geometry for the two "rhombs" (d_1=d_2), the chromatic term correlatively cancels. The remaining terms are achromatic and their values are governed by the angles of incidence (α and β) and by the refractive indexes (n_1 and n_2) (Born & Wolf, 1970). So that, it is possible (for each couple of refractive indexes selected) to manage with α and β (or equivalently with summit angles A and B) so as to make $\phi 0$ reaching the target value ϕ_0,

Figure 8 shows a schematic of the two composite rhombs. Each beam is folded twice. Neither for prisms nor in the folding of the beams are there right angles, their appearance in the figure is just for drawing convenience). Outcoming beams are parallel and so are electric field vectors as well.

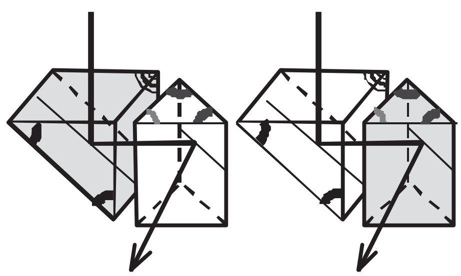


Figure 8. Couple of composite "twisted" rhombs, each made of two prisms having different refractive indexes and shapes). The geometry is identical for the two rhombs, but materials are permuted one to the other. Appearance of right angles is just for drawing convenience.

5 - DISCUSSION

In this section we try to compare the capabilities of the APS systems presented in section 4, Actually our basis is not homogeneous : performances of these APS either are demonstrated experimentally or are assessed on a theoretical ground. Some of them are designed or devised purposedly for nulling interferometry, others are not. Moreover, targeted shifts are not the same for all. So that, a straight comparison would not make much sense. Nevertheless we can identify what could be promising approaches, as suggested either by results or by expected performance and taking into account foreseeable critical issues. An attempt to put APS's into classes could rely on discrete targeting (fixed values π ou $\pi/2$) versus open targeting (any fraction of π) but we find it more relevant to consider APS's with "intrinsic achromatism" versus APS's with "compensated chromatism", by reference to the process providing achromatism. The former class pertains to reflection properties and focus properties, the second pertains to processes which mix competing effects from dispersion or from birefringence. Since phase shifts at total reflection are achromatic we put composite rhombs into "intrinsic" eventhough residual dispersion occurs within the material (but at high order level).

Compensated APSs exhibit rejection performances with a clear advantage for the dispersive scheme which goes closer to the required range (R > 10^6) over the desired bandwidth when the number of element increases. However, this makes more difficult the set-up adjustment and greater the energy losses due to spurious multiple reflections at front end and within the plates.

They induce energy losses and degradation of the nulling by sending light escaping the destructive interference. Moreover the compensation efficiency is very sensitive to thickness errors.

Let us note also that, as compared to what is found in the visible, the choice of materials for infrared is not as rich, refractive indexes are not as precisely known and machining the surfaces is not as well mastered. This feasibility issue also affects the composite rhombs, which in addition suffer from inhomogenities while plates do not.

Also it appears from simulations that higher target values makes achromatisation more difficult to achieve. An advantage for APS's using plates is the open-targeting ability coupled to relative simplicity of the set-up, this making implementation and insertion in beams easier.

Intrinsic APS's are limited to discrete shifts π or $\pi/2$ (excepted for composite rhomb) but "by nature" they operate on large spectral bandwidths. A drawback is that these APS are comparatively bulky and are less easy to accomodate because of the folding of beams. However, the example of the compact Achromatic Interfero Coronagraph (Rabbia et al., 1998) shows a way to reduce the bulk (with the advantage of a stable zero-OPD), but the help of an appropriate technology which includes assembling under interferometric control is required. Spurious phase shifts might occur in case of absorption by dielectric coating.

With respect to *rejection*, experimental demonstration of deep nulling have been made in the visible with both intrinsic APS (vector-flip, Wallace et al., 2000) and compensated APS (dispersive plates, Morgan & Burge, 1998). With the vector-flip, a stable null of 7.10^{-5} (R greater than 10^4) has been obtained with 18% bandwidth on thermal light. With dispersive plates, null of 10^{-4} is achieved over the (400nm-700nm) bandwidth. Numerical simulations for the visible (400nm-1000nm) show a 7.10^4 rejection, 3 plates being used (Mieremet et al., 2000) and for the infrared (8µm -20µm) a rejection of 10^6 is found achievable, 5 plates being uses (Bascou, this paper). Besides the rejection capability, some other aspects must be taken into account.

Regarding *feasibility* some comments are given above and mainly concerns suitable manufacturing of elements and bulk considerations.

Energy losses occur in APS's using reflection properties, mainly because one polarisation is discarded in the nulling process, until the use of two polarisations is made available (work under way; Serabyn, 2000). They occur in APS's using plates because of spurious multiple reflections, as already mentioned. Let us note that tilting the plates does not completely rule out the problem, because of double reflections within the material.

Unmatched intensities rather concerns compensated APS's, for which symmetry is not easy to achieve, and originates again in spurious reflections.*Unmatched polarisation* directions can be transformed into unmatched intensities by using linear polarisers.

The *large bandwidth requirement*, is at first sight in favor of intrinsic APS's, regarding rejection. However, since monomode optic fibers are likely to be used at the recombination step, this advantage could be reduced if the lack of appropriate fibers makes it necessary to split the spectral bandwidth. Anyhow, in such conditions, the complexity (and weight) of the set-up would be increased and achromatisation over a large bandwidth should remain looked for.

6 - CONCLUSION

After recalling evaluation criteria for APS's, we have briefly described the principle of various approaches, either found in the literature or not yet published, in order to build a panel of instrumental schemes providing achromatic phase shifts. Then, we have briefly examined what could be the interesting features and the drawbacks as well, in the context of such missions as DARWIN and TPF.

A straight comparison, sticking to a list a criteria, would not really make sense since the panel includes approaches having much different levels of advancement and being not necessarily designed for the present purpose. Nevertheless, the various approaches can be distributed into few families. From them, essentially two types of achromatisation processes can be extracted, that we have respectively named "intrinsic" and "compensated" (see section 5). Hence, two types of critical issues have been outlined.

From published results to date, two approaches are emerging as much promising, namely the use of dispersive elements (compensated APS's) and the vector-flip achieved at reflexion (intrinsic APS's) respectively conducted by Mieremet et al. (2000) and Morgan & Burge (1998, 1999) on one side and by the JPL group (Serabyn et al.,1999, Serabyn, 2000; Wallace et al.,2000) on the other side.

Briefly, rejection of about 10^4 relative to bandwidths covering the visible are experimentally demonstrated (Wallace et al.,2000, Morgan & Burge, 1998) whilst numerical simulations show even larger rejections to expect, both in visible 0.4µm -1µm (Mieremet et al., 2000) and in infrared 7µm-17µm (Morgan & Burge, 1999) or 8µm -20µm (Bascou, this paper).

Other intrinsic APS's (composite rhombs and focus-crossing) are not advanced enough yet to provide numerical figures but should be payed attention to, since they tend to relax some problems. Experimental demonstration is lacking and progresses in this direction are needed.

Compensated APS's using birefringence (devised in another context) do not appear as fitting the achromatic rejection requirement (short by roughly two orders of magnitude).

Another point of view regarding the panel of APS's may prove interesting, which consists in mixing approaches rather than in making them compete, for example in devising an hybrid APS's. This would combine advantages of intrinsic and compensated systems. This view is encouraged by the fact that compensated APS have better performance for small target values (regarding both rejection and spectral bandwidth). Therefore large fractional target values can be thought of as the sum (π or $\pi/2$ shift + a small fractional shift). In doing such, large rejection, large bandwidth and open targeting could be obtained simultaneously.

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