**International Conference on Space Optics—ICSO 2018**

Chania, Greece

9–12 October 2018

*Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny*

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International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111804J · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536082

# Wavefront control in the design of narrow- and broad-band optical coatings

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## ABSTRACT

The wavefront distortion induced by some optical coatings has often been underestimated with serious consequences in the performance of optical instruments. The typical approach to face such inconvenience consists in modifying the shape of the coated optics by compensating either the bending induced by stress or the geometrical thickness variations in non-uniform coatings. A relevant contribution to the wavefront distortion can also be given by the interference in the coating layers and a standard approach to overcome such problem is not available. In this work the wavefront deformation that is due to the spatial non-uniformity of thin-film optical coatings is analyzed, with the aim of identifying simple structures in which the influence of thickness non-uniformity on the wavefront shape is minimized. Some examples are reported especially for high-reflectance coatings.

**Keywords:** Optical coatings, thickness non-uniformity, phase profile, wavefront distortion, spectral wavefront

## 1. INTRODUCTION

The requirements on optical coatings are typically given in terms of spectral reflectance and transmittance. However, in some applications it is important to analyze not only the intensity of the reflected and transmitted beams but also the associated phase shift [1,2,3,4]. In particular a non-uniform phase spatial profile (the term phase shift will be shortened to phase in the following) could cause a relevant and somewhat unexpected distortion of the wavefront of a light beam, passing through or reflected by coated optics, with geometrical and chromatic aberrations in the optical system.

The phase spatial variation across the light beam can be caused by several factors, for example stress and consequent bending of the optical element or refractive index inhomogeneities, which require dedicated solutions. The aspect considered here is the effect caused by the coating thickness non-uniformity, which depends on the manufacturing process and in some cases is even intentional.

The problem has been known for many years [5,6,7,8], nevertheless the influence of the interference phenomena, taking place in the coating layered structure, on the beam wavefront is frequently underestimated; while more importance is given to roughness and geometrical shape. The inaccurate evaluation of the wavefront distortion can create problems in the space optical systems, as well as in other applications, when severe requirements are imposed on the optical component figure. For example in mirrors for gravitational wave detection[9], the rms wavefront error should not be greater than $\lambda$ /200 (corresponding to few nanometers) over the whole surface. In some space instruments (e.g. in the Euclid mission) the relevance of this feature has been already pointed out [10].

Therefore an approach to reduce the wavefront deformation in presence of coating non-uniformity should be identified with the aim of minimizing the phase sensitivity to thickness variations. It is worth noting that a change of coating thickness of the order of 1% might have negligible influence on the intensity of reflected and transmitted beams but significant effects on the phase shift[11]. In the design of optical coatings the sensitivity of its reflectance and transmittance, in terms of intensity and spectral behaviour, is often evaluated to prevent detrimental consequences of fabrication errors, while the phase shift associated with the reflected and transmitted beams is usually not of special concern.

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For that reason, methods for the optimization of the phase spatial profile did not get attention in the development of commercial optical thin-film software. More common is the optimization of the phase derivative in the frequency domain (for laser applications) [12,13], which could be used also as a method to improve the wavefront behaviour.

This work is dedicated to the analysis of the wavefront distortion induced by the coating, both in the case of narrowband coatings and in the case of broadband coatings. In the first case only the phase spatial behaviour should be controlled and some acceptable solutions can be found to compensate the wavefront distortion. In the second case it is not sufficient to act on the phase spatial variation at a fixed wavelength but the wavefront shape should be controlled over the entire spectrum of interest, to avoid chromatic aberrations. Several categories of coatings are analyzed, selecting simple coating structures able to minimize the wavefront distortion over non-uniform surfaces, at a reference plane. In general a compromise should be accepted between the required intensity and the phase behaviour, based on the respective relevance for the specific application. Stringent specifications typically require coating structures with a high number of layers (even more than a hundred) and rather complicated fabrication processes, which in some cases cannot be avoided. Here the attention is concentrated on simple structures in which the wavefront deformation is reduced.

## 2. THE WAVEFRONT DISTORTION

The calculation of the wavefront of a radiation beam passing through or reflected by a non-uniform optical coating is quite simple[11,14]. Starting from the transmitted or reflected phase shift at each point of the coating surface, and considering the path of the beam in air with respect to a reference plane (Fig 1), the difference of phase Δph can be calculated between the coating center (higher thickness) and the periphery, and the wavefront profile reconstructed (in terms of waves or degrees):

$$\Delta ph^R (r) = \varphi^R (r) - \varphi^R (0) + 4\pi [t(r)-t(0)]/\lambda \qquad (1)$$

$$\Delta ph^T (r) = \varphi^T (r) - \varphi^T (0) + 2\pi [t(r)-t(0)]/\lambda$$

where $\varphi^{R,T}$ is the reflected or transmitted coating phase, r is the radius, λ is the wavelength, t is the coating thickness.

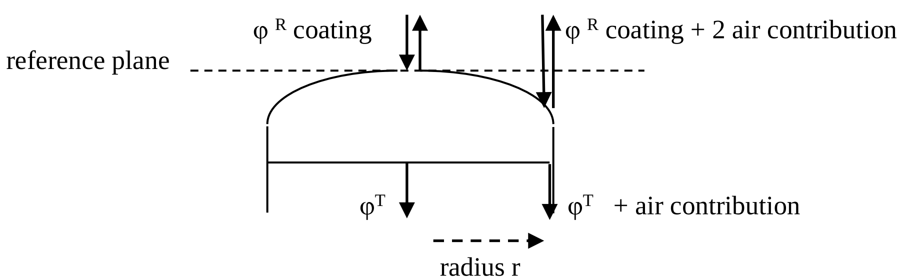



Figure 1. Coating with non-uniform thickness over the surface (radial symmetry).

The wavefront profile can be calculated directly by optical coating software [15,16], or adding to the coating a layer of air with increasing thickness from the center outwards, and calculating the difference of phase over the surface of the complete structure. Here only the reflected wavefront will be considered because is the most critical one, however an example of transmitted wavefront will also be reported.

The wavefront in reflection undergoes a greater distortion than in transmission because the path of the beam in air is doubled. This term (given by the difference of thickness) essentially contributes to the geometrical wavefront, while the contribution due to interference is contained in the phase value φ. An example of wavefront radial profile is shown in Fig 2a for a 19-layer mirror (R= 99.9%) made of quarter-wave (q.w.) layers ($SiO_2$,$Ta_2O_5$) centered at $\lambda_0$= 600 nm with total thickness 1.62 μm and 2% of thickness reduction from the center to the periphery according to a radial parabolic profile. A partial compensation of the geometrical wavefront at λ=600 nm is obtained taking into account also the interference contribution, thus the wavefront error of this coating will be lower than 0.1 waves. At 500 nm it means 50 nm PV (peak-to-valley, typically worse than the rms value), which can be considered an acceptable value for several applications.

When $\lambda_0$ is centered to longer wavelengths the wavefront of this coating remains the same in terms of waves, if the ratio of total thickness to reference wavelength is not varied and the thickness decrease is 2%. This percentage was chosen for illustration purposes, but obviously depends on both the fabrication process and the dimension of the coated optics. The radial parabolic profile is also selected as an example, however all considerations can be extended to different profiles.

The situation becomes worse increasing the number of layers, for example with 25 q.w. layers and the same materials of the previous example, the actual wavefront error becomes 0.15 waves. It has been demonstrated [5,6] that an almost perfect compensation can be reached if the following relation is satisfied:

$$\frac{\partial\varphi}{\partial\sigma} = -4\pi t \qquad (2)$$

where σ is the wavenumber (1/λ) and t the total coating thickness.

In some coating designs the magnitude of the two terms of eq. 2 is comparable, and then the wavefront is less sensitive to coating non uniformities than in other coatings. This value of the phase derivative can be imposed in the optimization procedure of the coating design by software, but at the same time also the reflectance value should be maintained at high level and is not always easy to find a satisfactory solution, unless a lower value of reflectance is accepted. Moreover the same result found for a given wavelength could not be valid over an extended range of wavelengths.

### 2.1 The narrow-band quarter-wave mirror

The quarter-wave structure with alternating high ($n_H$) and low ($n_L$) index layers is a typical solution to make a dielectric mirror with high reflectance at a single wavelength or in a narrow band. It is well know that in such coatings the phase φ of the reflected beam is equal to 180 degrees or zero at the reference wavelength $\lambda_0$ (depending on the index of the last layer), but its behavior at other wavelengths is often ignored. The slope of phase in the reflection band, near the central wavelength $\lambda_0$, is given by the following formula[7] valid for periodic structures (without considering the index dispersion):

last layer H $$\frac{\partial\varphi}{\partial\sigma} = \frac{-\pi\lambda 0}{nH - nL}$$

(3)

last layer L $$\frac{\partial\varphi}{\partial\sigma} = \frac{-\pi\lambda 0\; nHnL}{nH - nL}$$

The slope in the second case is higher and comparing eq. 2 and 3 it appears that the structure ending with a layer L (at the air side) is more favorable, at least for thicknesses of some microns. An example is shown in Fig 2b in which the wavefront of a 18 layer coating with R= 99.5 % (eliminating the last layer from the coating of Fig 2a) is shown. The coatings of Fig 2 have a total thickness higher than 1.5 μm while the reference wavelength is 600 nm.

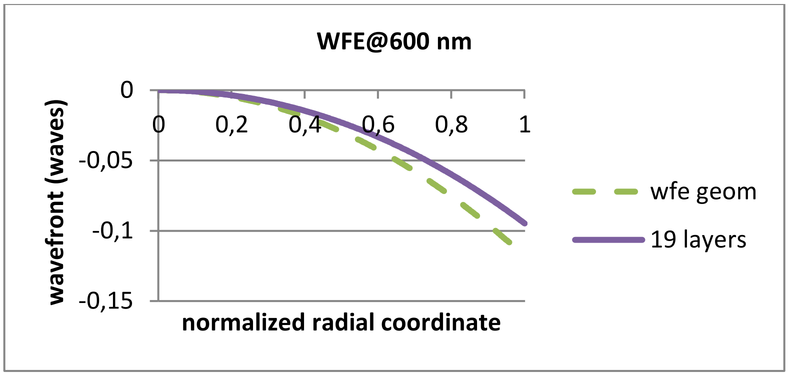
To satisfy eq. 2 and reach an almost perfect compensation in a dielectric mirror, it is possible to act on the number of layers (total thickness) and the refractive indices. Typically high values of $n_H$ and $n_L$ are needed to obtain a flat wavefront together with a high reflectance. An example with 22 q.w. layers, $n_H$=2.35 ($TiO_2$) , $n_L$=1.9 ($Y_2O_3$), and total thickness of 1.57 μm, is shown in Fig 3a; in this case the reflectance will be a bit lower R=95% but the wavefront is significantly improved. The geometrical wavefront in Figs 2 and 3 is similar because the coatings have almost the same thickness.

It is important to underline that this procedure is valid at a single wavelength or in a narrow band around the central wavelength. However, for periodic structures as the quarter-wave coatings, the wavefront spectral profile is almost constant in the reflectance band as shown in Fig 3b.

The situation can become worse for broadband mirrors or in general for non q.w. structures if the phase behavior is ignored

### 2.2 Broad-band mirrors

In several applications it is necessary to extend the reflectance band over a wide spectrum; a typical broad-band mirror covers the whole visible range. In this case a q.w. coating is not sufficient and the combination in the same stack of two or more coatings in series centered at different wavelengths (or a gradual change of thicknesses through the structure) is commonly used.

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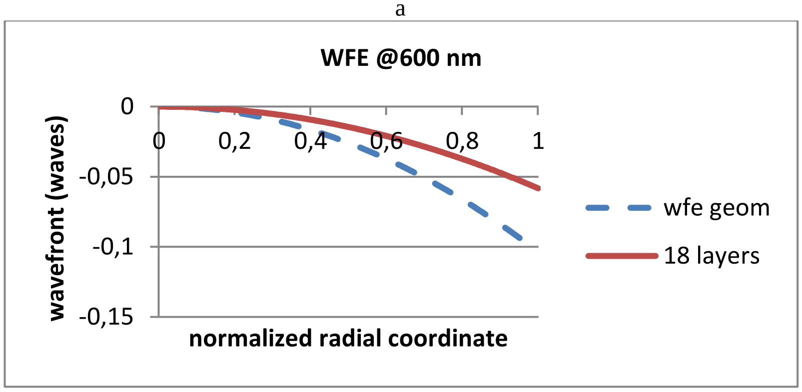


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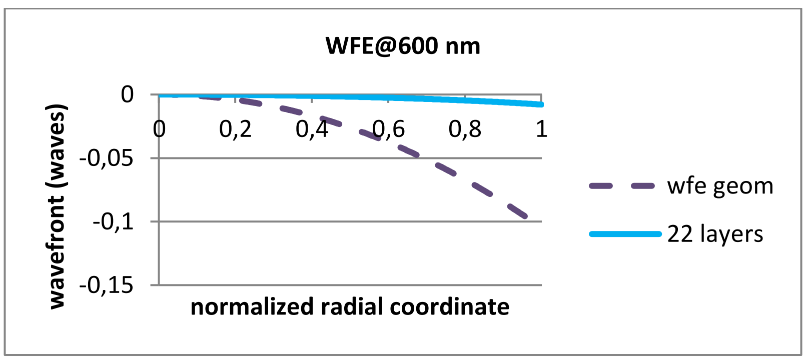
Figure 2. Wavefront of a) 19-layer and b) 18-layer high reflectance coating, compared to the geometrical wavefront (the radial coordinate equal to 1 corresponds to the minimum thickness reduced of 2%).

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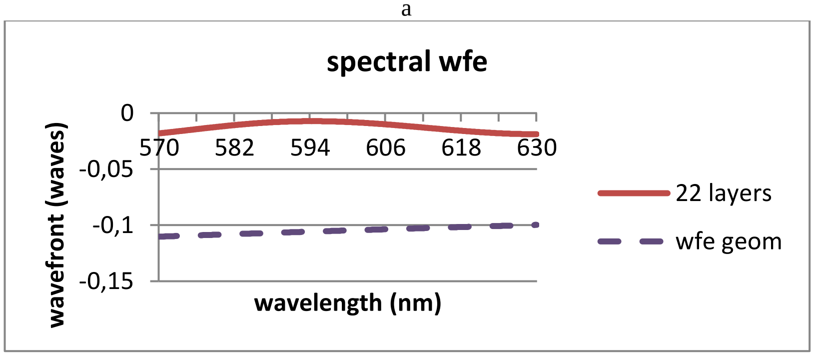


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Figure 3. Wavefront of a 22-layer coating with high indices: a) radial and b) spectral profile with 2% thickness decrease.

The stack with the lower central wavelength is typically the external one on the air side to avoid absorption, thus is the first structure encountered by the beam that will be totally reflected at this short wavelengths. The long wavelengths penetrate into the coating before being returned and that causes a significant phase effect (the situation is reversed if the stack centered at longer wavelengths is positioned on the outer side). The result for a 46-layer broad-band mirror, combining two q.w. coatings, is shown in Fig 4 in which intensity and phase of the reflected beam are reported (index dispersion included). The phase effect is evident and the consequence is that, in case of thickness non-uniformity, the wavefront can change significantly in values and shape with little variations of the wavelength [11,17]. The wavefront for the 46-layer mirror with a thickness non-uniformity of 2% (considered equal for all layers) is shown in Fig 5a at some wavelengths. In few nanometers of wavelength variation, the wavefront is changing from convex to concave passing through other profiles and reaching the value of 0.5 waves at 535 nm (Fig 5b), within the range of high reflectance. An example of the inconvenience of using this kind of mirror in a telescope will be reported in the next section.

Therefore there is a double problem: how to compensate the wavefront distortion for a given thickness non-uniformity and in addition to flatten its spectral profile minimizing the variation with wavelength.

To improve the performance of the coating with respect to the wavefront, the most powerful approach consists of using the classical software programs dedicated to coating design, which include several mathematical methods of optimization. Some conditions on the reflected intensity and on the phase derivative are imposed and in some cases it could be useful to start from an initial coating design. It is a procedure similar to the one used for chirped mirrors [12,13] where the frequency derivative of the phase is considered, instead of the wavenumber derivative needed for the wavefront. There are several approaches to obtain satisfactory results, as for example the robust synthesis [13,18] based on the needle design method, to improve the stability of performance against thickness or refractive index variations. The result generally consists of coating stacks with many layers, each one having a different thickness, and sometimes even more than two materials.

A simple design with only 23 layers, having high reflectance in the range 400-780 nm and a wavefront oscillating between -0.15 and +0.15 waves, over the whole wavelength range, is shown in Fig 6. The materials are $TiO_2$ (n=2.35) and $MgF_2$ (n=1.38), each layer has a different thickness with a total coating thickness of 1.8 μm. This is only a theoretical example with a limited number of layers; it is possible to reach better performance with a higher number of layers, as frequently happens in coating design.

A good analytical way of designing such type of coatings with unperturbed wavefront is not available, but refinement and synthesis methods may provide reasonable results. The main problem will be the stability in the fabrication process because such coatings can be rather sensitive to errors, however with modern deposition processes an accurate control can be obtained. All examples reported here are calculated at normal incidence, but oblique incidence and polarization may be included without changing the general considerations.

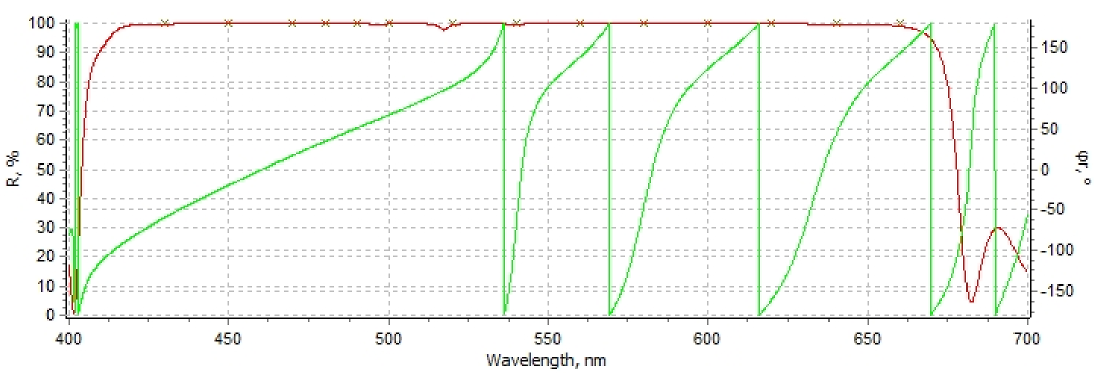
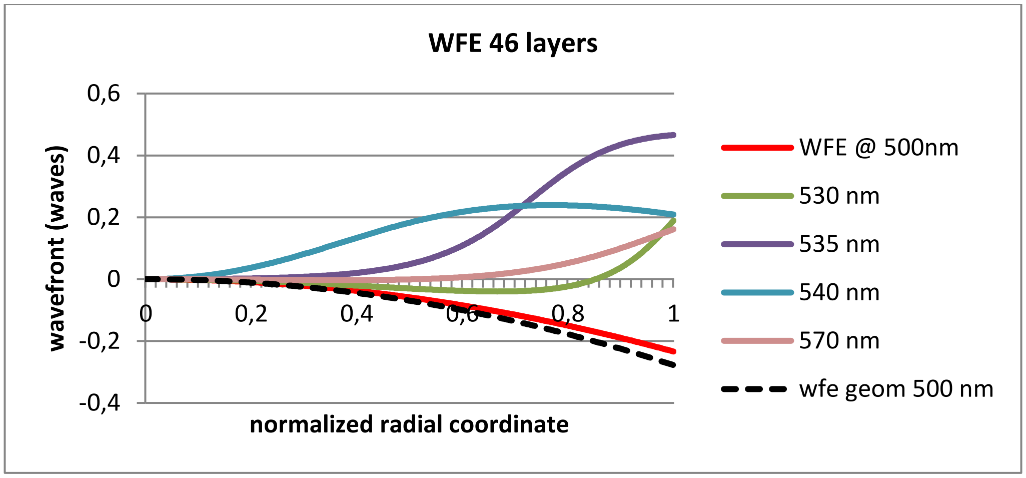



Figure 4. Reflected intensity (red) and phase (green) of a broadband mirror for the visible range, made of 46 layers of $SiO_2$ and $Ta_2O_5$ obtained combining two q.w. stacks, with a total thickness of 3.47 μm.

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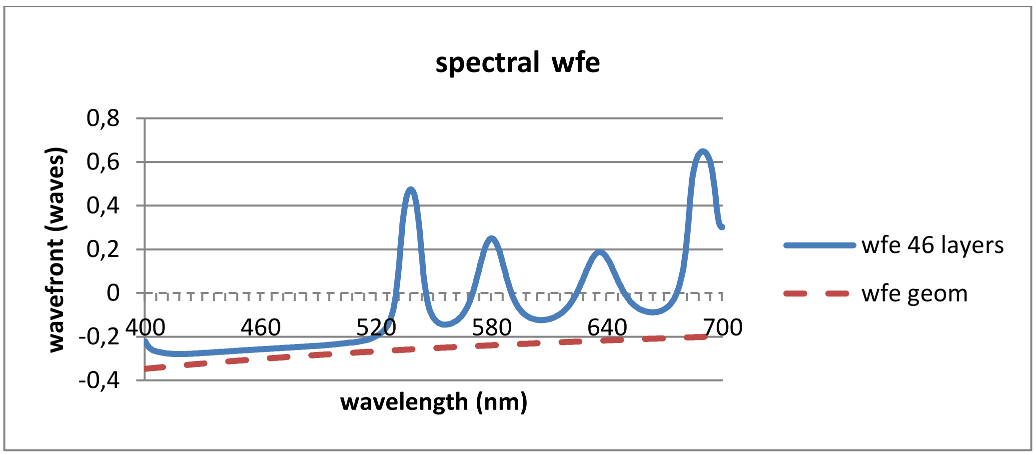


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Figure 5. Variation of the actual wavefront with wavelength, compared to the geometrical wavefront (dashed line): a) radial profile at some wavelengths, assuming 2% thickness decrease along the radius, b) spectral profile in which the correspondence with the upper graph at the maximum radial coordinate can be verified.

Another possible solution for broadband mirrors is the use of metals. In such a case there will be no deformation of the wavefront due to the metal layer non-uniformity, except for the geometrical wavefront. However, if an enhanced reflectance coating is made by adding dielectric layers to the metal, the behavior will be the same shown before for dielectric structures. A silver mirror with four q.w. overlayers of $SiO_2$ and $Ta_2O_5$, having a non-uniformity of 2% on each layer, has a reflectance R> 98% in the range 470-690 nm and the wavefront spectral profile is almost flat in this range with a variation between 0 and - 0.02 waves. Therefore it could be convenient to adopt this solution if the use of metals is compatible with the environment conditions.

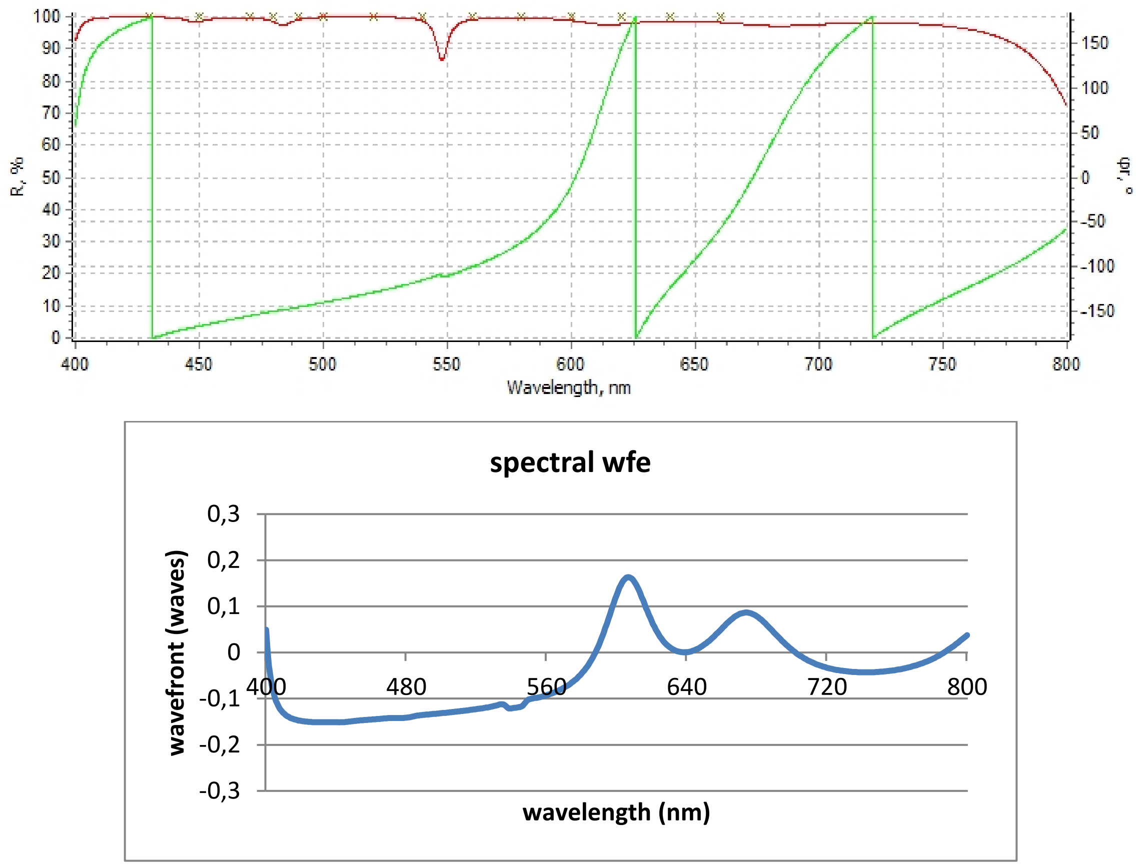
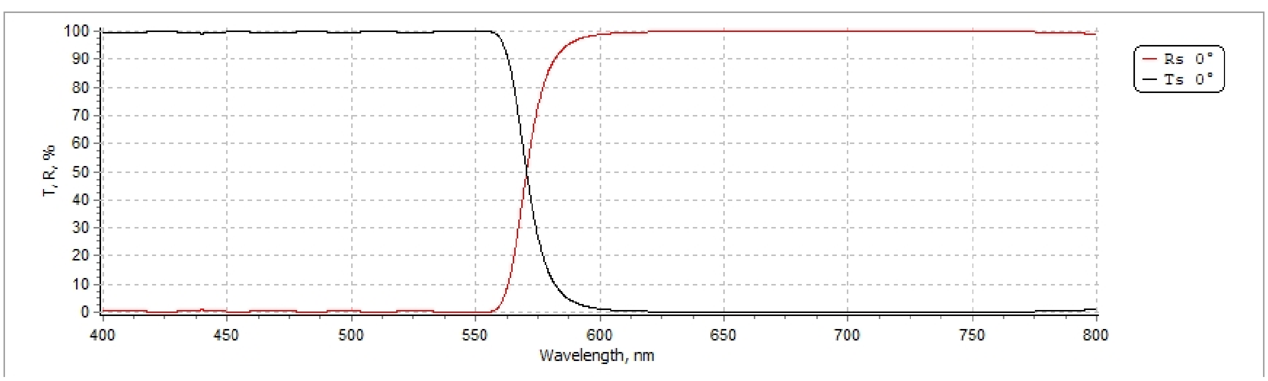



Figure 6. Spectral reflectance (red), phase (green) and wavefront of a 23-layer coating.

### 2.3 Coatings with high transmittance

As already mentioned, the problem of the wavefront distortion in transmittance seems less critical. In a broad-band transmitter the light tends to go straight through and so the phase behaves as expected from a single pass and does not vary as much as it can in a reflector. An example for a 18-layer low-pass filter made of $MgF_2$ and $TiO_2$ is shown in Fig 7. The wavefront deformation in the area of high transmittance (400 – 540 nm) is lower than 0.02 waves, while in the range of high reflectance (580-800 nm) remains below 0.05 waves.

In narrow-band transmittance filters the phase could have significant variations but the effect is limited to a narrow band.

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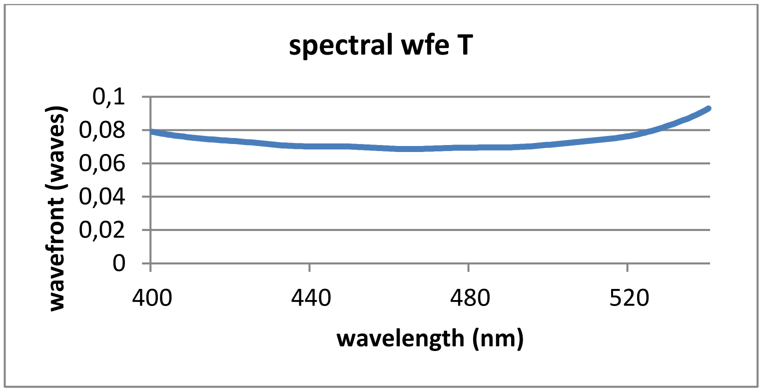


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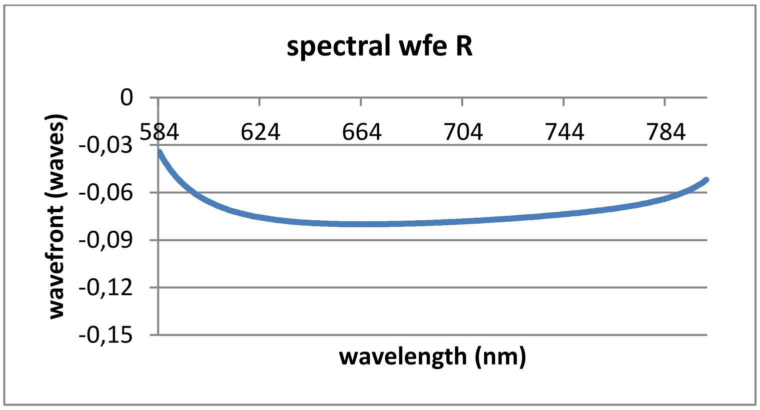


c

Figure 7. Transmittance and reflectance of a 18-layer coating: a) spectral intensity, b) transmitted wavefront, and c) reflected wavefront as function of wavelength with 2% of thickness non-uniformity.

## 3. EXAMPLE OF APPLICATION TO A TELESCOPE

An example of the effect that a broad-band mirror can induce in a telescope (TMA with intermediate focal plane) is analyzed using the 46-layer mirror of Fig 4 for the small folding mirror before the focal plane. This type of telescope is largely used in space instrumentation, as for instance for the IRS and FCI instruments[19] of MTG (Meteosat Third Generation). However, it is important to clarify that the mentioned instruments do not make use of such specific coating that is considered here just as an example.

The clear optical aperture of the folding mirror has a diameter of 30 mm and the mirror is placed in the exit pupil position of the telescope. The layout is shown in Fig 8 and the wavefront maps obtained with a uniform coating and a coating with a non-uniformity of 2% over the radius are shown in Fig 9 (graphics by Zemax[20]).

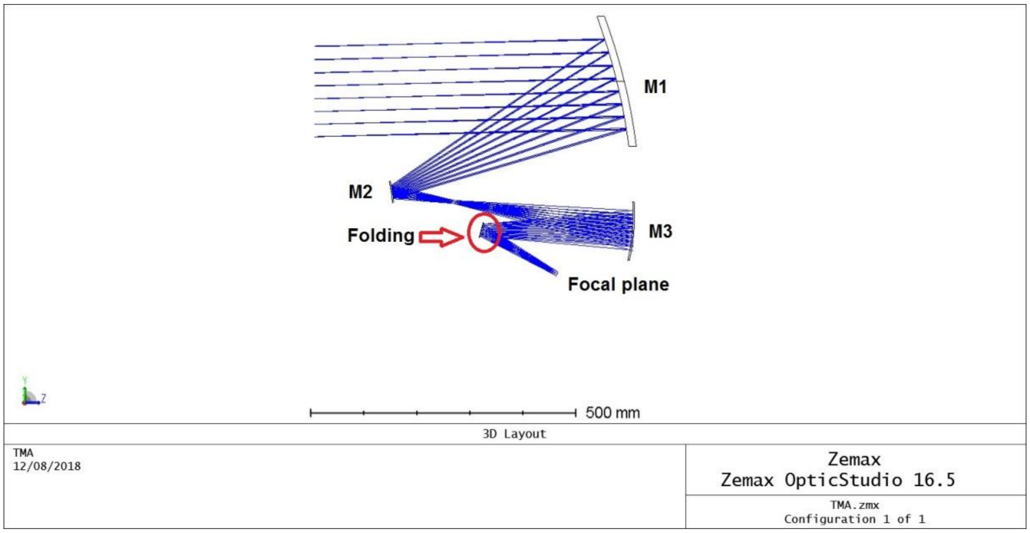


Figure 8. Layout of the TMA telescope

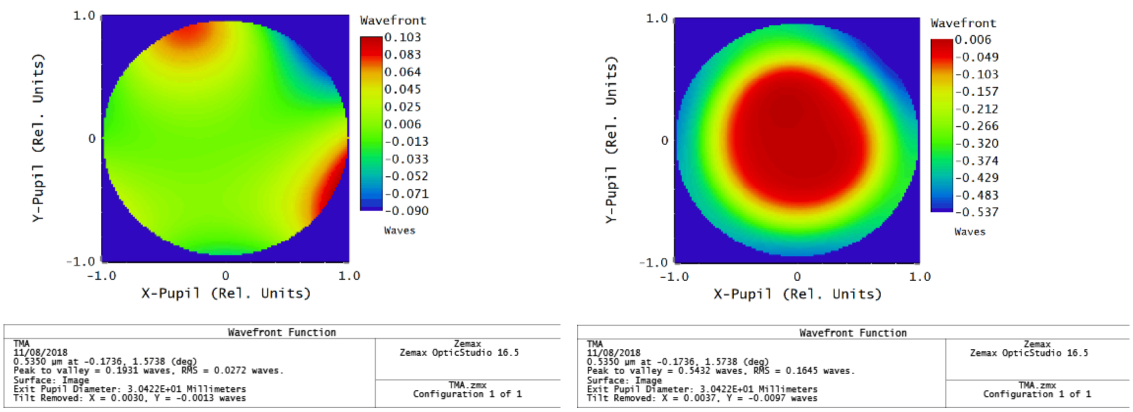


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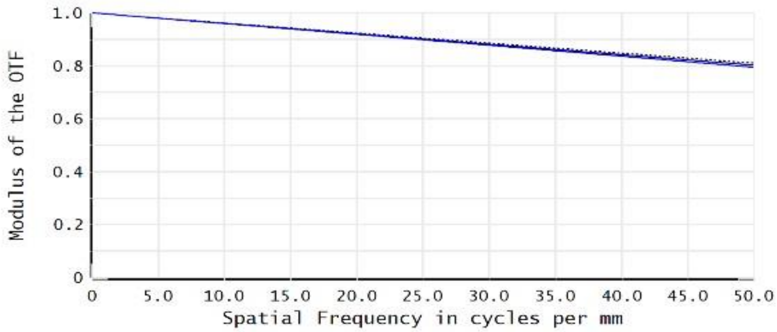
Figure 9. Wavefront map with a) the uniform broadband mirror and b) the non-uniform mirror, at the wavelength of 535 nm. The wavefront error, for the axial field of view, degrades from almost zero (0.03 waves rms) to almost 0.2 waves rms

The nominal image quality of the telescope assuming the ideal coating is diffraction limited, as can be seen from the MTF (Modulation Transfer Function) plot in Fig 10a. A Nyquist frequency of 50 cycles/mm has been considered assuming a typical detector pixel size of 10 µm.

If a non- uniform coating (2% uniformity error) is considered for the folding mirror (Fig 10b) and all the other optical elements are considered as nominal, the drop of MTF is substantial (MTF slightly above 0.4 at Nyquist). The image degradation is most likely not acceptable for typical space applications once all the manufacturing and alignment of the other optical elements are included. In fact the typical system MTF requirement, for a space optical instrument, ask for a value higher than 0.2 at Nyquist. This implies that the MTF of the optics including manufacturing and alignment errors need to be at least 0.5 at Nyquist.

It is important to remark that the mirrors M1, M2 and M3 are aspherical and larger than the “simple” flat folding mirror and therefore at first sight they could be considered as the most critical elements of the telescope. This example shows that even simple elements might hide problems and, if the coating effect is not properly considered, there could be unexpected inconveniences.

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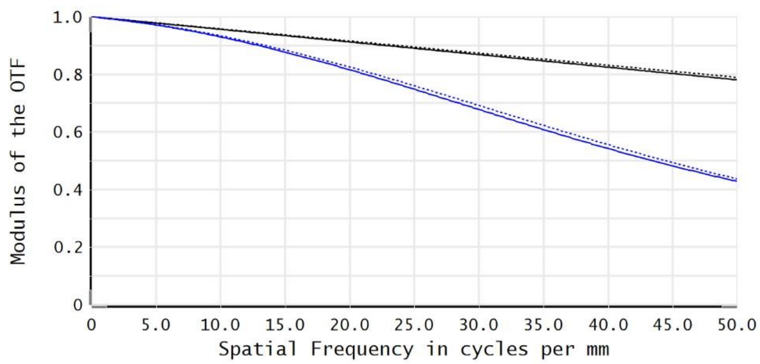


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Figure 10. a) MTF of nominal telescope design. The plot shows that the telescope is diffraction limited (the tangential and sagittal MTF profiles for one telescope field of view are clearly superimposed to the theoretical diffraction limited curve), b) MTF considering only the coating effect for the folding mirror (blue curves). All the other parameters are nominal. The MTF degradation (discrepancy between blue curves representing telescope MTF with respect to black diffraction limited curves) is substantial.

## 4. CONCLUSIONS

In optical coatings based on interference phenomena, the role of the phase of the reflected and transmitted beams is crucial. Nevertheless only a few early works were dedicated to the effects that a variation of phase can induce on the reflected and transmitted wavefront. The compensation of the wavefront distortion caused by non-uniform coating thickness and the procedures to minimize the phase slope as function of wavelength are gaining attention because a detailed analysis helps to prevent negative effects in the optical systems.

The thin-film optical design software available nowadays allows the optimization of the phase behavior using mathematical methods. Methods of synthesis and refining are very efficient but often the result is a coating design with many layers having all different thicknesses, and often rather sensitive to manufacturing errors.

In this work a number of simple examples are reported to illustrate how, in several cases, coatings with a limited number of layers are useful for the wavefront control. Even though some less stringent requirements should be accepted on the reflected or transmitted intensity, the attention to the wavefront behavior could avoid unacceptable distortions by simply acting on few parameters in the classical coating design.

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