Lithium Niobate Fabry-Perot etalons in double-pass configuration for spectral filtering in the visible imager magnetograph IMaX for the SUNRISE mission.

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ABSTRACT

The Imaging MAgnetograph eXperiment, IMaX, is one of the three postfocal instruments of the Sunrise mission. The Sunrise project consists of a stratospheric balloon with a 1 m aperture telescope, which will fly from the Antarctica within the NASA Long Duration Balloon Program.

IMaX should work as a diffraction limited imager and it should be capable to carry out polarization measurements and spectroscopic analysis with high resolution (50,000-100,000 range).

The spectral resolution required will be achieved by using a LiNbO$_3$ (z-cut) Fabry-Perot etalon in double pass configuration as spectral filter.

Up to our knowledge, few works in the literature describe the associated problems of using these devices in an imager instrument (roughness, off-normal incidence, polarization sensitivity...). Because of that, an extensive and detailed analysis of etalon has been carried out. Special attention has been taken in order to determine the wavefront transmission error produced by the imperfections of a real etalon in double pass configuration working in collimated beam. Different theoretical models, numeric simulations and experimental data are analysed and compared obtaining a complete description of the etalon response.

KEYWORDS

Polarimetry, Fabry-Perot etalons, Lithium Niobate, magnetographs, balloon borne telescopes, Sun

1. INTRODUCCION

IMaX (Imaging Magnetograph eXperiment) is part of the payload of the SUNRISE balloon project [1] to study solar magnetic fields at high spatial resolution (100 km on the solar surface). The SUNRISE project consists of the launch from Antarctica of a stratospheric balloon within the NASA Long Duration Balloon Program that uses a 1-meter aperture solar telescope and post-focus instrumentation. IMaX makes images of the solar surface magnetic field by measuring the state of polarization of the light within a selected spectral line. In this sense IMaX is a polarimeter. The spectral line is sensitive to the solar magnetic fields through the Zeeman effect, which induces various polarization states of the emitted light. To meet this goal IMaX should work as a:

- High sensitivity polarimeter.
- High resolution spectrometer.
- Near diffraction limited imager.

The central aim of SUNRISE is to understand the structure and dynamics of the magnetic field in the solar atmosphere. Interacting with the convective flow field, the magnetic field in the solar photosphere develops intense field concentrations on scales near 100 km, which are crucial for the dynamics and energetics of the whole solar atmosphere. To achieve this spatial resolution is the central motivation of the SUNRISE project that requires special care on image
quality and stability. In addition, SUNRISE aims to provide information on the structure and dynamics of the solar chromosphere and on the physics of solar irradiance changes.

The project is leaded by the Max Plank für Aeronomie (MPAe, Lindau). MPAe contributes with the telescope structure, Instruments Control Unit (ICU) and the post focus instruments SUPOS (SUNRISE Polarimetric Spectrograph) and SUFI (SUNRISE Filtergraph). The Kiepenheuer Institut für Sonnenphysik (KIS, Freiburg) contributes with the wavefront sensor and tip-tilt mirror. The German funding for the project comes through DLR. The USA participates in the project through the institutions High Altitude Observatory (HAO/NCAR, Boulder) and Lockheed Martin Solar and Astrophysics Laboratory (LMSAL, Palo Alto). HAO is the PI institution of the NASA Long Duration Balloon (LDB) proposal and contributes with the gondola and the camera system of SUPOS. LMSAL contributes with the primary mirror of the telescope and the guiding participation in this project comes through IMaX.

A consortium of four Spanish research institutes is building IMaX. The PI institution is the IAC (Tenerife). IAC is responsible (other than leading institute and project managing) for the user interface of the ground segment and the communication protocol with the SUNRISE ground segment. As PI institution is responsible of the delivery on time of IMaX to MPAe (SUNRISE PI institution). IAA (Granada) is responsible for all the IMaX electronics including the detectors and control computers. INTA (Madrid) is responsible for the optical design, opto-mechanical design, thermal analysis and the characterization of the IMaX polarization modulator based on Liquid Crystal Variable Retarders (LCVRs). IMaX AIV phases will take place at INTA facilities under IAC responsibility. GACE (Valencia) is responsible of all the structural elements of the instrument. The SUNRISE telescope is fully in phases C/D and has a delivering date of mid 2006. This is also the scheduled date for the final AIV phase of IMaX in the INTA facilities in Madrid, which will be sent to Lindau for integration at the mid of 2006.

The SUNRISE project has a key milestone in mid 2007 when it has to successfully pass a test flight at the NSBF (National Science Balloon Facility) in the USA. This test would constitute part of the Mission Readiness Review and only after its successful completion can the project consider the Antarctica flight, most likely by the end of 2009, early 2010. During the test flight only the gondola and part of the pointing system will actually fly. The rest (telescope and payload including IMaX) will be dummy elements.

IMaX uses a lithium niobate etalon in double pass configuration and a band-pass filter to select the wavelength of interest with a FWHW of 100 mÅ. The knowledge of the IMaX’s etalon performance is crucial to understand and to control the overall instrument performance. The theoretical models found in the literature, justify properly the etalon’s spectral response (Airy function) but, up to our knowledge, the etalon’s behaviour as an image former has not been considered and described enough yet [2][3][4]. For such a reason, several simulations based on thickness maps and ASAP™ software been carried out in order to analyze the influence of a real etalon in an optical system.

2. ETALONS GENERAL THEORY

2.A) Ideal etalons

The equations describing the performance of a single pass through an etalon are well-known. The Airy formula describing the intensity distribution of the light passing through the etalon is:

\[ I_r = \frac{\tau}{1 + F \sin^2 \frac{\delta}{2}} I_i \]

where \( I_i \) and \( I_r \) represent the incident and transmitted light intensity respectively, \( \tau \) is the etalon peak transmission related to the fraction of light absorbed, \( A \), by the combined effect of the etalon and the coatings [5].

\[ \tau = \left(1 - \frac{A}{1 - R}\right) \]

The parameter \( F \) is related to the etalon surfaces reflectivity \( R \) through the usual equation:

\[ F = \frac{4R}{(1-R)^2} \]

The phase difference is given by:

\[ \delta = \frac{4\pi}{\lambda} n'h \cos \theta' \]
with \( \lambda \) representing the wavelength, \( n' \) the refractive index of the etalon, \( h \) is the thickness of the etalon (with a nominal value of \( h_0 \) for the reference wavelength \( \lambda_0 \)) and \( \theta' \) is the propagation angle inside the etalon.

For LiNbO\(_3\) the refractive index changes with wavelength (dispersion). These changes have been included in the results presented in this work by taking into account the dependence of the refractive index with wavelength and temperature \([6]\).

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The absolute phase of the wavefront, \( \phi \), after passing through the filter for the case of a single etalon equation:

\[
\phi = \arctan \left( \frac{9R \sin \delta}{1 - 9R \cos \delta} \right) + \frac{2\pi n' h}{\lambda} \tag{5}
\]

where all the factors have previously been introduced.

The parameters \( F \) and \( \Re' \) are related to the so-called reflective finesse, \( \Im' \), by:

\[
\Im' = \frac{\pi \sqrt{\Re'}}{(1 - \Re')} = \frac{\pi \sqrt{F}}{2} \tag{6}
\]

The separation between two successive etalon peaks is called the free spectral range (FSR) and is given by:

\[
FSR = \frac{\lambda^2}{2n'h} \tag{7}
\]

It is necessary to emphasize that for an accurate use of these equations, the dispersion effects mentioned above of LiNbO\(_3\) etalons must be taken into account.

The transmitted wavelength of etalon can be tuned by varying the thickness of the etalon, \( h \), and/or its refractive index \( n' \). Since the lithium niobate is a piezoelectric and electro-optic material, by applying an electrical field across the etalon, the thickness and the refractive index will change.

Lithium niobate is a birefringent material. Nevertheless, the crystal used in this application is a Z-cut type (considering Z axis perpendicular to the faces of the etalon) and, therefore, the propagation of light is independent of the polarization for normal incidence and the refractive index of the material corresponds to the ordinary ray.

The tuning relationship is \([6]\):

\[
\Delta \lambda(V) = \left( d_{33} - \frac{n'^2 r_{13}}{2} \right) \frac{\lambda V}{h} \tag{8}
\]

where \( r_{13} \) is the unclamped electro-optic coefficient due to the Pockel’s effect, the constant \( d_{33} \) is related to the converse piezoelectric effect in the crystal and \( n' \) and \( h \) are the unperturbed refractive index and etalon thickness, respectively. The constants \( r_{13} \) and \( d_{33} \) depend on the specific sample.

Etalon tuning is also possible by tilting. An etalon that transmits at normal incidence the wavelength \( \lambda \), will transmit a different wavelength at another incidence angle. If we denote this angle by \( \theta \), the transmitted wavelength at this incidence angle is:

\[
\lambda(\theta) = \lambda_0 \sqrt{1 - \frac{\sin^2 \theta}{n'^2}} \tag{9}
\]

For small angles this equation can be written as:

\[
\lambda(\theta) \approx \lambda_0 \left( 1 - \frac{\theta^2}{2 n'^2} \right) \tag{10}
\]

Note that the performance of the etalon is optimum at normal incidence, and when extended sources are utilized the central pass band is not symmetric across the field of view at non-normal incidence. Therefore, it is desirable operate the etalon as close as possible to normal incidence. For IMaX, the etalon will place at an incidence angle of 0.12º (vertically) in order to avoid ghost images in the detector. This value was obtained from the straylight analysis of the instrument using ASAP\textsuperscript{TM} software \([7]\) and it takes into account the wavelength shift produced over the field of view shall be less than 50 mÅ in order to fulfil the scientific requirements.
2.B) Actual etalons

The etalon effective finesse, $\mathcal{I}_e$, which is usually measured empirically, contains information about all the parameters that produce broadening of the wavelength peak tuned by the etalon. $\mathcal{I}_e$ can be written as follows [8]:

$$\frac{1}{\mathcal{I}_e} = \sum \frac{1}{\mathcal{I}_j} \approx \frac{1}{\mathcal{I}_r} + \frac{1}{\mathcal{I}_d} + \frac{1}{\mathcal{I}_a} + \frac{1}{\mathcal{I}_{tilt}} + \frac{1}{\mathcal{I}_{dif}}$$

(11)

Where

- $\mathcal{I}_r$ is the reflection finesse: defined in equation (6).
- $\mathcal{I}_d$ is the defect finesse: it includes the effect of departure from parallelism of the reflecting surfaces, spherically bowed plates and surface irregularities.
- $\mathcal{I}_a$ is the aperture finesse: it considers the effect of the aperture when the incoming beam is convergent or divergent. Even if the beam is collimated, it is advisable to analyze the consequences of departure from collimation in means of the effective finesse.
- $\mathcal{I}_{tilt}$ is the tilting finesse: off-normal incident angles produce a diminution of the effective finesse and a blue wavelength shift.
- $\mathcal{I}_{dif}$ is the diffraction finesse: it takes into account the diameter of the beam entering the etalon and the telescope diameter.

It is important to note that instead of the defect finesse $\mathcal{I}_d$, the term fabrication finesse $\mathcal{F}$ is usually utilized [6]. This last one is only related to the rms thickness deviations from $h_0$, $\varepsilon_{rms}$ ($\varepsilon$ is the local fluctuation of the etalon thickness at a point in the etalon surface so that $h = \varepsilon + h_0$), by the equation:

$$\mathcal{F} \approx \frac{\lambda_{laser}}{8 \lambda \varepsilon_{rms}}$$

(12)

where $\lambda_{laser}$ is 633 nm.

The only terms that have been considered that they contribute to the effective finesse are $\mathcal{I}_d$ and $\mathcal{F}$. The rest were here neglected. Then, it can be seen that the demanding fabrication finesse of 30 corresponds to errors with an rms value of 1.1 nm. For IMaX it was specified over any 25 mm size subaperture.

Once the fabrication and the reflective finesse are known, the effective finesse can be computed using equation (11). This effective finesse provides an effective reflectivity that should be used (instead of the nominal reflectivity) in order to derive the correct spectral profile with Airy’s equation.

The real Full Width at Half Maximum (FWHM) is given by:

$$FWHM = \frac{FSR}{\mathcal{I}_e}$$

(13)

Actual etalons have fluctuations of the etalon thickness that deviate from the nominal value that give raise, when illuminated by monochromatic light, to the so-called “orange peel” effect in transmitted intensity pattern (Figure 6). These fluctuations in the etalon thickness produce phase variations described by equation (5) for an ideal etalon. Nevertheless, a satisfactory theory that can be used to accurately reproduce wavefront distortion has not been provided yet, up to knowledge. This is the main aim of this work, where some theoretical simulations have been compared to experimental results over the IMaX etalons (Section 4 and 5).

3. ETALONS in IMaX

For the selection of a spectral band of interest, IMaX uses a LiNbO3 etalon (z-cut) in double pass configuration that allows reaching a spectral resolution of around 60 mÅ. This type of etalons is available from ACPO/CSIRO (Australian Center for Precision Optics, CSIRO). Multiple pass configurations with non-ideal etalons need careful considerations of their performance, as their implications are not trivial. In order to achieve a spectral resolution of a FWHM of 50 mÅ, which is a top level scientist requirement, a configuration of one etalon in double pass was considered. This option was selected against a tandem of two different etalons.
The major drawbacks of the etalons tandem option were first the use of two different etalons, and second the implications that the simultaneous tuning of the two etalons could have. Two different etalon require two identical etalon as spares, which would have been impossible to accommodate within the IMaX budget. The simultaneous tuning of the two etalons and the calibration for use in tandem has non-trivial implications for the AIV phase. An efficient use of the two etalons suggested the design of a chamber that contained both etalons using very different voltages and creating voltage differences between the two etalons that could be a source of arcing problems. As a strategy to simplify all these problems and to provide a realistic spare strategy, it was decided by the project to use only one etalon in double pass.

The intensity modulation is the result of combining two etalons, including the incoherent reflections between them, that is:

\[ I^{\text{total}} = \frac{x \Gamma_1 \Gamma_2}{(1-x^2(1-\Gamma_1)(1-\Gamma_2))} I^{(i)} \]

where \( x = \tau^2 T_m \), with \( T_m \) the transmittance of the media in between the two etalons and \( \tau \) the absorption of the etalon. Both, \( \Gamma_1 \) and \( \Gamma_2 \) are the Airy functions describing a single pass through the etalon.

The beam goes through the etalon twice so that the final spectral resolution is improved by a \( \sqrt{2} \) factor over the single pass case. But the secondary peaks that are located exactly at the same place for both passes are not reduced at all. In this strategy, the only factor that reduces the strength of the secondary peaks is a prefilter located at Liquid Crystal Variable Retarders (LCVRs) support. The optical quality of this prefilter is \( \lambda/10 \). The location of this filter corresponds to a telecentric beam to assure that its final influence in the optical quality of the IMaX instrument could be considered small. To make this more effective a FWHM of 1 Å with a double cavity prefilter is specified.

After considering the dispersion effects mentioned in Section 2, it was clear that to force a 1.93 Å FSR the thickness of the etalon should be 275 µm. This is an acceptable thickness for a LiNbO$_3$ etalon but is closed to the lower limit recommended by CSIRO of 200 µm. Thinner etalons are possible but they are more prone to voltage breakdown and piezoelectric deformation as one tunes the voltage. In a way our value, 275 µm, is also near the upper limit where the homogeneity of the original material of the wafer may become a problem (according to CSIRO). So, both, the clean continuum windows at 2 Å near our spectral line and the fact that the etalon thickness falls in a nice value for the typical ranges used by CSIRO, have made the single etalon in double pass solution a valid one for IMaX. Needless to say, one of the most attractive properties of this solution is the fact that we can buy a flying device and a fully compatible spare unit. This has been the adopted philosophy for IMaX.

It is necessary to highlight that in double pass configuration the distance between the folder mirrors and the etalon shall be enough large in order to avoid coherent reflections. Note that the folder mirrors and the etalon form an additional etalon cavity, so it shall be higher than the spatial coherence of the beam to eliminate undesirable interference effects.

The tuning strategy of the IMaX etalon will be by applying ± 3500 Volts. It turned out that this etalons are relatively slow (maximum rates applied by ACPO are 1500 V/s). Typically one spectral step of 50 mÅ would take 135 ms. The decision was taken to investigate the possibility of faster tuning with an unpolished (but otherwise identical) etalon. This has also been the driver for the decision to modulate the LCVRs (polarization modulation) faster than the etalon (wavelength modulation) to shorten the total time needed by the observing modes.

4. SIMULATIONS

4.A) Simulations from optical thickness maps

One of the top-level requirements of IMaX is that the Strehl ratio in the focal plane should be larger than 0.8 when a perfect wavefront enters the instrument. While the optical concept achieves a nominal Strehl ratio of 0.96, it is to be confirmed that the tolerances in the system and the degradation introduced by the etalon provide a total contribution to the Strehl ratio that is above 0.8. In this section, the effect of a double pass system in the final Strehl ratio is studied when phase and amplitude fluctuations due to imperfect polishing (but still good polishing!) are included. IMaX LiNbO$_3$ etalon is near a pupil image so diffraction theory of image formation is applied to the pupil complex function to investigate these image distortion effects.

As input for the polishing performance of the etalons, two optical thickness maps of actually finished etalons are available (thanks to CSIRO). The first one will be referred to as Z6-09 and it corresponds to a Z-cut etalon. It has an rms...
thickness fluctuation of 0.9 nm over the aperture (excluding some 10% near the edges). This corresponds to $\lambda_{\text{laser}} / 703$ (for $\lambda_{\text{laser}}$ of 633 nm) or to a fabrication finesse of 43. The second will be referred to as Y2-24 and has rms fluctuations of 1.42 nm over the same central region ($\lambda_{\text{laser}} / 446$, or fabrication finesse of 28). The fabrication finesse of the IMaX etalons (flying and spare units) should be larger than 30 (on a best effort basis from CSIRO).

Depending exactly on the area being used of the etalon, the effective thickness will vary and thus the Airy functions will be slightly different. The most important change being the central wavelength being transmitted at the peak of the Airy function. The transmission fluctuations at our pupil plane arise from the fact that, at a given wavelength, Equation (14) provides a different value depending on the exact locations selected over the etalon for the two passes. Thus, before simulating exactly the magnitude of this effect, two subapertures within the etalon must be defined.

It is also necessary to know the phase of the wave after exiting the double pass set up. Using Equation (5) it can be deduced that for a perfect etalon and at the reference wavelength $\lambda_o$ results that $\delta = \delta_o = \frac{4\pi}{\lambda_o} n' h_o = 2m\pi$ providing a null contribution to the phase from the first term of Equation (5). The output wavefront has then a uniform value equal to $\phi_o = \frac{2\pi}{\lambda_o} n' h_o$. This term represents the phase term of a plane parallel plate with the same thickness and refractive index.

Real etalons behave differently. In principle, Equation (5) can be used to estimate the amount of wavefront distortion of a real etalon. But measurements made by us and by CSIRO show that Equation (5) predicts deviations in the wavefront that are a factor 2-3 larger than what is measured. So the situation can be slightly better than predicted here.

Equation (5) provides the net phase of one etalon pass. If the first pass occurs at a location with a thickness of $h_1 = h_o + \varepsilon_1$, introducing a phase $\phi_1$ and the second pass takes place at a location with $h_2 = h_o + \varepsilon_2$ inducing a phase of $\phi_2$, the total phase after the double pass would be simply:

$$\phi = \phi_1 + \phi_2$$

To carry out the simulations, we must select two portions used by our beam in the double pass mode. The diameter of the thickness map corresponds to about 64 mm, while the pupil image of IMaX has a size of 21 mm (the beam is slightly diverging so this number changes depending on the exact location of the etalon in the optical path, but this effect is ignored here). In Figure 1 one example used for the selection of the sub-apertures is shown. Other choices are given by rotating the etalon by different amounts and by changing the centring of the sub-apertures.

Figure 1. Example of choice of sub-apertures for the double pass configuration in the Z6-09 etalon. The white areas represent the IMaX light beam.

Once the sub-apertures are selected, computation of the intensity and phase fluctuations is made by simply using Equations (5) and (14) at a given wavelength within the typical bandpass of IMaX (60 mÅ FWHM). Note that in these equations it is irrelevant which one of the sub-apertures is selected for the first pass and which for the second pass, as they are symmetric with respect to one another. In this work, the intensity and phase changes for three wavelengths have been evaluated: the central wavelength $\lambda_o$, the wavelength at half the FWHM to the blue $\lambda_o - \lambda_{FL} / 2$, and the wavelength at half the FWHM to the red $\lambda_o + \lambda_{FL} / 2$. For completeness and after doing the computations, a secondary mirror central obscuration is also introduced.

In Table 1, we provide the rms thickness fluctuations within the selected subapertures and their degree of correlation (in parenthesis for subaperture #2) for the various cases studied. Several cases are presented in Table 1. The case ‘Rotation 0’ corresponds to Figure 1. The other rotations are for the same configuration but rotated the corresponding angle. ‘Same passes’ refers to the left subaperture of Figure 1 and going twice through it. The ‘one third’ case is the same
as Figure 1 for the first subaperture, but the second subaperture is one third of the radius apart (near the center of the etalon), instead of half a radius (as in Figure 1). ‘Single pass cases’ correspond to the two subapertures of Figure 1 but going only once through it (given here for reference). The ‘centered and closer’ configurations are like the one-third case but with both subapertures moved closer to the center of the etalon. All these cases turned out to have a positive correlation between the subapertures. The fact that the phase dependence in equation (5) goes with the $\sin \delta$, introduces a dependence on the sign of the correlation (see Figure 4 below). Positive correlations have phase fluctuations of the same sing and introduce a larger wavefront error. Negative correlations show a phase term with different sings for each of the two passes and allow for some cancellation of the wavefront errors. The fact that most of the cases had a positive correlation is most likely due to the way in which the polishing process is carried out and the way in which our double pass is configured (where points near the outer [central] part of the etalon in the double pass go through the outer [central] part also in the second pass). Thus it is necessary to search manually for configurations where an anticorrelation was obtained. In both cases, the Z6-09 and Y2-24 etalons, such a configuration was found by placing the two subapertures in particular orientations. These configurations correspond to the last row of Table 1. Also the same configuration as in the same pass but with an artificially changed sign for the polishing error has been included in order to see the effect of a perfect anticorrelation. Note that this last option does not have a practical application.

<table>
<thead>
<tr>
<th>Case</th>
<th>$\varepsilon_{\text{rms}}$ (nm) Z6-09</th>
<th>$\varepsilon_{\text{rms}}$ (nm) Y2-24</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>aperture #1</td>
<td>aperture #2</td>
</tr>
<tr>
<td>Rotation 0</td>
<td>0.76</td>
<td>0.68 (0.63)</td>
</tr>
<tr>
<td>Rotation 90</td>
<td>0.68</td>
<td>0.87 (0.23)</td>
</tr>
<tr>
<td>Rotation 45</td>
<td>0.66</td>
<td>0.64 (0.31)</td>
</tr>
<tr>
<td>Rotation 135</td>
<td>0.73</td>
<td>0.81 (0.42)</td>
</tr>
<tr>
<td>Same passes</td>
<td>0.76</td>
<td>0.76 (1.0)</td>
</tr>
<tr>
<td>1/3 separation</td>
<td>0.76</td>
<td>0.66 (0.49)</td>
</tr>
<tr>
<td>Single pass 1</td>
<td>0.76</td>
<td>N/A</td>
</tr>
<tr>
<td>Single pass 2</td>
<td>N/A</td>
<td>0.68</td>
</tr>
<tr>
<td>Centered, closer</td>
<td>0.83</td>
<td>0.72 (0.57)</td>
</tr>
<tr>
<td>Centered, closer, Rotation 90</td>
<td>0.78</td>
<td>0.92 (0.53)</td>
</tr>
<tr>
<td>Anticorrelated</td>
<td>0.82</td>
<td>0.97 (-0.55)</td>
</tr>
<tr>
<td>Same passes, Anticorrelated</td>
<td>0.76</td>
<td>0.76 (-1.0)</td>
</tr>
</tbody>
</table>

Table 1. Rms thickness fluctuations over selected subapertures of the two etalons studied. For the second aperture we also provide the degree of correlation between them.

As an example of the magnitude of intensity and phase fluctuations obtained with these simulations, it is shown in Figure 2 the results obtained for the Z6-09 etalon in the ‘Rotation 0’ configuration of Figure 1. The left image shows the monochromatic normalized intensity fluctuations (at $\lambda_0$) of the pupil image after the double pass. The mean intensity over the pupil is 0.797. The right image shows the phase fluctuations (in nm) at the pupil. The rms fluctuation of this pupil case is 50.96 nm, which corresponds to about $\lambda/10$ (including tip-tilt or wavefront gradients).

![Figure 2](image_url) Left: ‘Rotation 0’ case intensity fluctuations after double pass for the Z6-09 etalon. Right: Phase fluctuations (nm) for the same case.
The amplitude and phases at the pupil plane of IMaX derived in the previous section can be used to study the degradation of the image produced by the etalon. For that, the complex pupil function:

\[ P(r, \theta) = A(r, \theta) \exp(i \phi(r, \theta)) \]  

(16)

is formed by the amplitude images \( A \) (square root of left image in of Figure 2) and phase images (right of Figure 2) as mentioned above. \((r, \theta)\) are coordinates in the pupil plane.

Note that from equation (14), \( A \) has been computed as the square root of the ratio \([I_{\text{total}}]/[I^{(i)}]\). Diffraction theory of image formation is then used to compute the OTF by calculating the autocorrelation of the pupil function (16). The modulus of the OTF provides the MTF that characterizes the performance of an optical system by providing the attenuation factor of the frequencies in the transformed space. However, providing the bidimensional MTF for each one of the cases proposed above makes it difficult to grasp the overall image quality of each case and their comparison. To this end, we proceed a step further and take the inverse Fourier transform of the OTF to yield the system PSF, the response of the optical device to an impulse input signal. The Strehl ratio, \( S \), is then defined as the ratio between the peak of the system PSF and the peak of the PSF of an ideal instrument with the same aperture and central obscuration. It is important to stress here that our Strehl ratios will be computed wherever the peak of the PSF is found, no matter how shifted from the origin it might be. This in practice means that image shifting by terms like tip-tilt aberration introduced by the etalon are ignored, only other aberration terms that provide image degradation are considered. The IMaX image quality requirement is specifically set to \( S \geq 0.8 \). The computations of the Strehl ratio are carried out for all the cases in Table 2, for the wavelength set \((\lambda_0, \lambda, \lambda_+^-)\) and for the cases where \( P = A \), where \( P = \exp(i \phi) \) and where \( P \) follows equation (16). The last two cases are useful in order to understand which of the effects, amplitude or phase fluctuations, is more important in the image quality balance.

<table>
<thead>
<tr>
<th>Case</th>
<th>Z6-09</th>
<th>Y2-24</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_0 )</td>
<td>( S )</td>
<td>( S )</td>
</tr>
<tr>
<td>Rotation 0</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Rotation 90</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Rotation 45</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Rotation 135</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Same passes</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>1/3 separation</td>
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<td>0.98</td>
</tr>
<tr>
<td>Single pass 1</td>
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<td>0.99</td>
</tr>
<tr>
<td>Single pass 2</td>
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<td>1.00</td>
</tr>
<tr>
<td>Centered, closer</td>
<td>0.97</td>
<td>0.97</td>
</tr>
<tr>
<td>Anticorrelated</td>
<td>0.98</td>
<td>0.98</td>
</tr>
<tr>
<td>Same passes</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>

Table 2. Strehl ratios for the cases in Table 1 and different wavelengths within the bandpass. Amplitude, phases and the combined effect of both are presented separately.
Several points can be seen from the results in Table 2. First of all, it is clear that the amplitude fluctuations alone (columns $P = A$) have a minor effect at the central wavelength $\lambda_0$, and become more important in the side wavelengths, $\lambda_-$ and $\lambda_+$. Still, the Strehl ratios generated by the amplitude fluctuations are almost always above 0.9. The opposite is true for the case of phase fluctuations alone (columns $P = \exp(i\phi)$). These phase changes are the dominant factor at $\lambda_0$ but are less important (still noticeable) in the wings of the spectral profile. This performance can be traced back to the dependence with wavelength of the functions $A$ and $\phi$ (see Figure 4). Polishing errors translate into wavelength shifts of these functions and they produce a larger effect where they are steeper. Amplitude fluctuations are more important on the sides of the spectral profile while phase errors are more important at the central wavelength. It is clear from Table 2, that image quality is clearly controlled by the phase, not amplitude, fluctuations.

The two effects compensate to some degree, with image quality (when all the effects are included $P = A \exp(i\phi)$) slightly better in the wings of the spectral profile than at the central wavelength. The overall image quality has to be considered as some linear average of the Strehl ratios at the three wavelengths. The two etalons perform similarly. One would have expected that the Z6-09 etalon would perform better due to the, on average, better polishing compared to the Y2-24 etalon. While this tendency was clearly seen when the tip-tilt effects were not removed (Strehl ratios computed at the origin), when tip-tilt effects are ignored (excluding global gradients in the phase maps) this becomes less evident. It is interesting that the best Y2-24 case is very similar to the best Z6-09 case. This is due to the performance of the individual subapertures and seems to indicate that a similar case will be easily found for the IMaX etalons (with Strehls in the range of 0.9). It is clear that as soon as the thickness maps of the IMaX etalons are available, subapertures with small values of $\varepsilon_{\text{rms}}$ and the highest degree of anticorrelation (after the large scale gradients are removed) should be looked for. While using anticorrelated pupils clearly helps in the case of the Z6-09 etalon, this is not the case for the Y2-24 etalon. In particular, this last case shows one of the worse performances. The reason for that is, again, that the anticorrelation in this case can be clearly traced back to an anticorrelation in the global gradients of the two subapertures. When these global trends are removed the two pupils are indeed correlated, not anticorrelated.

Table 2 corresponds to a reflectivity of $\Re = 0.9$. It could be expected that the higher the reflectivity, the larger the number of internal reflections and the larger the degradation of the image (smaller Strehls ratios). To see how the results above change for other reflectivities it is shown in Table 3 the $\Re = 0.85, 0.90$ and 0.94 cases for the ‘Rotation 0’ case.

<table>
<thead>
<tr>
<th>Case</th>
<th>$\lambda_0$</th>
<th>$\lambda_-$</th>
<th>$\lambda_+$</th>
<th>$\lambda_0$</th>
<th>$\lambda_-$</th>
<th>$\lambda_+$</th>
<th>$\lambda_0$</th>
<th>$\lambda_-$</th>
<th>$\lambda_+$</th>
<th>$\lambda_0$</th>
<th>$\lambda_-$</th>
<th>$\lambda_+$</th>
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<th>$\lambda_+$</th>
<th>$\lambda_0$</th>
<th>$\lambda_-$</th>
<th>$\lambda_+$</th>
<th>$\lambda_0$</th>
<th>$\lambda_-$</th>
<th>$\lambda_+$</th>
<th>$\lambda_0$</th>
<th>$\lambda_-$</th>
<th>$\lambda_+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Re = 0.9$</td>
<td>0.99</td>
<td>0.92</td>
<td>0.92</td>
<td>0.89</td>
<td>0.95</td>
<td>0.94</td>
<td>0.89</td>
<td>0.87</td>
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<td>0.95</td>
<td>0.94</td>
<td>0.85</td>
<td>0.90</td>
<td>0.95</td>
<td>0.94</td>
<td>0.85</td>
<td>0.93</td>
<td>0.89</td>
<td>0.80</td>
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<tr>
<td>$\Re = 0.94$</td>
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<td>0.81</td>
<td>0.77</td>
<td>0.77</td>
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<td>0.91</td>
<td>0.75</td>
<td>0.74</td>
<td>0.67</td>
<td>0.88</td>
<td>0.86</td>
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<tr>
<td>$\Re = 0.85$</td>
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<td>0.97</td>
<td>0.94</td>
<td>0.96</td>
<td>0.96</td>
<td>0.94</td>
<td>0.93</td>
<td>0.93</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Strehl ratios for different reflectivities
From Table 3 the improvement for smaller reflectivities is clear, but the degradation of image quality suffered for the high reflectivity case is quantitatively more important. For $\Re = 0.85$ the Strehl ratios for the Z6-09 etalon are at or above 0.93. Note how for the high reflectivity case, the amplitude effects become more important than the phase effects outside on the wings of the profile.

Results on tables 2 and 3 refer to the nominal value of the IMaX pupil used so far (early 2004) of 21 mm. Over such small subapertures the polishing errors have a much smaller value than over the whole etalon aperture. Some of the rms values that appear in Table 1 provide fabrication finesses higher than 45! This, of course, helps to improve the resulting Strehl ratio. The above results clearly demonstrated that a Strehl ratio in the range of 0.9 is a realistic estimate for the double pass etalon contribution. Together with an optical design for IMaX (excluding the etalon but with tolerances) providing an additional contribution of 0.9, the required Strehl ratio for IMaX of 0.8 can be safely achieved.

The stray light analysis carried out at INTA has shown that to avoid ghost images, one needs to tilt the etalon by as much as 0.2°. As this shifts the bandpass over the image plane and as there is a requirement for this shift to be smaller than 50 mÅ, a better collimation of the pupil image (involving smaller angles was needed). This produces in turn a larger pupil size that, of course, impacts the above results of the Strehl ratio contribution from the etalon double pass. To study this effect the above simulations has been run for two other pupil sizes: 25 mm and 26.7 mm.

<table>
<thead>
<tr>
<th>S</th>
<th>Z6-09</th>
<th>Y2-24</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation 0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case</td>
<td>$\lambda_0$</td>
<td>$\lambda_1$</td>
</tr>
<tr>
<td>21 mm</td>
<td>0.99</td>
<td>0.92</td>
</tr>
<tr>
<td>25 mm</td>
<td>0.98</td>
<td>0.91</td>
</tr>
<tr>
<td>26.7 mm</td>
<td>0.98</td>
<td>0.90</td>
</tr>
</tbody>
</table>

Table 4. Strehl ratios for different pupil sizes

Table 4 considers 3 polishing conditions, the ‘Rotation 0 Z6-09 and Y2-24 cases and the ‘anticorrelated’ Z6-09 case (the ‘anticorrelated’ Y2-24 case could not be studied because pupils of 25 mm size were extending outside of the etalon aperture). Only the most representative case including amplitude and phase fluctuations are discussed: $P = A \exp(i\phi)$. Pupils with 25 mm aperture have Strehl ratios that are 3-5 % smaller, whereas 26.7 mm pupils reduce the Strehl by 5-6 %. For the 25 mm case, thus it is expected a Strehl ratio of 0.87-0.88 and for 26.7 mm 0.84-0.85. To ensure that the final IMaX Strehl ratio stays above 0.8, the optical design including tolerances should provide a Strehl ratio of 0.93 for a 25 mm pupil and of 0.95 for a 26.7 mm pupil.

<table>
<thead>
<tr>
<th>S</th>
<th>Z6-09</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anticorrelated</td>
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<tr>
<td>Case</td>
<td>$\lambda_0$</td>
</tr>
<tr>
<td>21 mm</td>
<td>0.98</td>
</tr>
<tr>
<td>25 mm</td>
<td>0.98</td>
</tr>
<tr>
<td>26.7 mm</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Table 5. Strehl ratios for different pupil sizes

4.B) ASAP™ simulations

The ASAP™ software, developed by Breault Research Organization, is a well-known optical tooling to design and characterize complex optical system. The ability of this software to be combined with CAD programs permit to the user to have a complete understanding of the optomechanical system under design. The process followed in our simulation was to consider the etalon in a single pass but with a realistic behaviour in each component. The number allowed of times a ray may be split into specular components was assigned to be 10 (SPLIT 10), all the rays was considered as coherently added and the ROUGHNESS RANDOM command was considered for each surface in the etalon. This enables to control the both the RMS random height variation and the RMS normal deviations. It has been considered both the refractive index change of the Lithium Niobate as a function of the wavelength (etalon) and the reflectivity change as a function of the wavelength for the prefilter influence in the waveband of interest.
The main drive in our simulations with ASAP was to understand the following behaviour of the etalon which could affect the imaging performances of the IMaX instrument following:

- Intensity fluctuations due to roughness of the surfaces
- Spectral behaviour of a real etalon including manufacturing defects
- Influence of the Reflectivity in the wave front aberrations.
- Influence of the piezo-electric effect produced during high voltage tuning of the etalon in the optical quality

In relation with the first effect; intensity fluctuations produced by micro-roughness of surfaces, the simulation was performed by creating a random deformation which follows a Gaussian profile (4nm rms) in each face and with a 0.9 of reflectivity between faces for a 275 microns of thickness. All this values were considered typical of our Etalon.

The results are collected on Figure 5, in which each image represents the transmitted light intensity when all the wavelengths of the transmission band are considered. Last image in Figure 5 corresponds to the peak wavelength of the etalon.

![Figure 5. ASAP™ simulation of the effect evolution produced over the transmitted intensity through the etalon by the faces rms roughness.](image)

As it can be observed in the Figure 5, the final aspect is quite similar to the experimentally observed (see Figure 6)

![Figure 6. Experimental observed effect of the micro-roughness of an etalon in single pass.](image)

The spectral response at the peak wavelength is showed in Figure 7, the width at half maximum (FWHM) deduced from the ASAP™ simulation is 115mA at 525.01nm which should be compared with the 95 mA obtained in the theoretical simulations performed for an Etalon with defects (effective finesse of 30).

![Figure 7. Spectral response of the etalon with roughness faces: a) without prefilter to see the aspect of the maximum; b) with prefilter showing the secondary transmitted peaks.](image)
Wavefront error as a function of the roughness.

One of the most important parameters that must be known in order to evaluate the effect on the optical quality of an etalon in an imaging system is the wave front aberration. Once such an aberration is known, the system is completely characterized. Hence, it is crucial to know the relationship between the real parameters of an etalon (i.e., reflectivity, thickness and polishing of the surfaces) and the resultant optical quality. This is difficult to do through the theoretical analysis of the Airy function because it provides only information about a point to point scheme. The statistical process of the polishing should be translated to the mathematical model, and this is not so trivial as it could be considered at a first glance. When the roughness of the polishing process is not very small, one cannot substitute \( \arctan \frac{x}{\lambda} \approx \frac{x}{\lambda} \). For the \( \lambda/400 \) case we are considering, this substitution would be justified. But in general, it is clear that the statistics of the polishing errors is transmitted to the wavefront errors in non-trivial ways. In particular, even if the polishing errors are gaussian distributed, the wavefront errors will, in general, not be gaussian distributed, so the theoretical relations between the roughness and phase error is when the approach is valid:

\[
\Delta \phi = \arctan \left( \frac{9\sqrt{\pi \eta \Delta}}{(1-\eta)} \frac{4\pi n^2 \Delta}{\lambda} \right)
\]

(17)

To perform our study in ASAP\textsuperscript{TM}, various simulations were carried out in order to obtain the wave front error evolution as a function of the wave length for different surface roughness values and for the etalon’s nominal aperture (20mm). A single pass etalon was simulated in order to reduce the computational time, the wave front aberration of a grid source (GRID command) have been used and the phase variation have been calculated as an average of all the light beams located in the detector surface (with the same size than the pupil of the etalon). In Figure 7 it can be observed that the phase derived from the Airy function is being averaged and that the lower the roughness the more similar to the theoretically expected.

![Figure 8: Phase variation simulated with ASAP\textsuperscript{TM} for different rms roughness](image)

It could be concluded that the roughness affect locally to he beam path of the incident beam (producing the orange peel before commented, for example) but when all the aperture is analyzed and the wave front error is averaged in the clear aperture the roughness has lower impact in the global optical quality. To further comprehension of such a situation, a nominal etalon (thickness = 275microns, reflectivity = 0.9, \( \lambda_\text{p} = 525.01 \) nm) response has been analyzed when the roughness of the plates are varied. This magnitude has been taken into account in terms of waves (units commonly employed), in order to estimate the response. Thus, the rms roughness value considered for the simulation is the inverse of the roughness factor (FA) used in each case.

The wave front aberration, \( W(p,q) \), was calculated employing the well known expression:

\[
U(p,q) = A(p,q)e^{-2i\phi(p,q)\lambda}
\]

(18)

The results deduced from ASAP\textsuperscript{TM} shows that when a relatively high polish quality is achieved (\( n\lambda/100 \)), the wave front aberration obtained in the entire aperture is better than \( \lambda/60 \).
Wavefront error as a function of the reflectivity.

The behaviour of the etalon in terms of spectral resolution versus reflectivity of the surfaces is extensively reported in the literature. However, when the objective is to study such an effect on the wave front error, the results are not so clear and in general more difficult to understand. The finesse is said to be statistically related to the number of times that a ray goes back and forth before the ray gets out from the element. Therefore, the higher the finesse (i.e., the higher the internal number of reflections), the larger the wave front aberration obtained. Such an aspect has been simulated in order to clarify this effect. As it was said before, a nominal etalon has been considered. The surface reflectivity was varied from 0.1 to 0.98 but without considering the roughness effect in the plates in order to decouple both effects.

As it can be observed in Figure 10, the wave front aberration dependence increases as the etalon’s reflectivity increases (i.e., as the finesse increases) although it does not seem to follow the expected theoretical dependence with the finesse. Nevertheless, with high reflectivity in each face it is possible to have a wave front error that can be better than $\lambda/37$.

Wavefront error as a function of the deformation (piezo-electric effect).

It is well known that the etalons based on Lithium Niobate present an additional problem: when the high electric fields required to tune the wavelength is applied, a spatial deformation is induced. Such a deformation produces that the faces of the etalon, plane before applying the voltage, became similar to an optical meniscus. Therefore, the application of a voltage produces a certain deformation of the surfaces which could be critical and should be considered.

Fortunately, we have some radial deformation maps measured in similar etalons by our manufacturer (CSIRO) that allow us to fit the final surface obtained to a well-known optical surface. With these experimental values it was carried out a simulation by fitting the CSIRO’s supplied surface to a Zernike’s polynomials and considering that both faces suffer the same deformation in a first approach (meniscus effect). It is worthy to note that the supplied profile does not
permit to create a well-defined revolution surface. For such a reason, the Zernike’s approach was made by taking into account the maximum radial deformation.

Data were obtained by considering a reflectivity of 0.9, a thickness of 275 microns and a band width equivalent to the prefILTER’s width.

![Gold etalon surface deformations](image)

**Figure 11.** Transmittance of a nominal etalon in a single pass configuration when the faces surfaces follow a deformation based on Zernike’s polynomials.

The weights of Zernike’s polynomial obtained are mainly related with piston, astigmatism, coma, spherical, and very few of higher orders.

![Zernike data](image)

**Table 6.** Zernike data

In the spectral response analysis (Figure 11), it can be observed that if both faces suffer the same deformation (meniscus effect), the performance losses of the real etalon are neglected. The obtained FWHM is 72 mÅ for the λ, a slightly wider profile than those associated to a perfect etalon of the same characteristic (65 mÅ) (see). Therefore, it has been showed that if the Zernike’s polynomial weights that define the faces of an etalon are low enough and if both faces suffer the same deformation (meniscus), then the influence over the wave front deformation or the spectral response is low.

Following our ASAP™ simulations it can be concluded that with a proper control of the roughness and reflectivity of both faces (according to Figures 4 and 5) the behaviour of a real etalon can be similar to the theoretical etalon.

In addition, it is clear that if the deformation of the faces is the same and the weights of the resultant Zernike’s polynomial are low, the performance of the etalon is not relevantly altered.

**5. EXPERIMENTAL RESULTS**

Some interferometric tests of the real etalon supplied by CSIRO have been compared with the simulation described. In a first case, a single pass interferometric set-up using a Zygo has been considered to measure the wavefront error of the real system (Figure 12).

It is worth to mention that in the real etalon there are two entrance windows that protect the LiNbO3 and avoid the occurrence of electrical arcs inside the cavity. Considering this extra parallel plates it have been obtained in single pass
values as high as $\lambda/39$ at 525nm for the wave front error of the element (see Figure 13b). This value is worst than the corresponding value simulated by ASAP™ $\lambda/60$ but in our simulation the two parallel windows have not been included.

The etalon was tested too in the real configuration in which the etalon will work in IMaX; i.e. in double pass and with a beam size close to 20mm. In order to do it, the light coming from the visible phase-sifting Fizeau ZYGO (GPI model) interferometer (FZI) passed twice through the etalon, thanks to the employment of two folding mirrors (M1 and M2). After that, the light was directed through one more mirror (M3) to the plane-parallel plate (PPP) employed to close the interferometric cavity. In addition, some measurements in a single pass configuration were also carried out just by locating the PPP in the M1 position, normal to the incident light. In order to measure the wavefront error of the etalon working Figure 12 shows the optical set up employed to implement the thermally controlled etalons (TCEs) interferometric measurements in double pass. After considering the measurements performed the values obtained is $\lambda/23$ at 525nm which correspond approximately with the rss sum of an etalon in single pass (see Figure 13a).

![Optical set up employed for the thermally controlled etalons (TCEs) for the interferometric measurements in double pass.](image)

Figure 12: Optical set up employed for the thermally controlled etalons (TCEs) for the interferometric measurements in double pass.

**Figure 13:** Wave Front error measured for a real etalon.

(a) Single pass

(b) Double pass
6. CONCLUSIONS

Lithium Niobate etalons in double pass configuration will be utilized in the IMaX instrument. The assessment of the wavefront distortion produced by the etalon is a critical issue in order to fulfil the scientist top level requirement of IMaX as diffraction limited imager. It will permit to resolve the required 100 km spatial resolution.

Up to knowledge, a satisfactory theory that can be used to accurately reproduce wavefront distortion has not been provided yet. In this sense, theoretical simulations using the optical thickness data of the etalons provided by CSIRO have been carried out and compared to experimental results over the IMaX etalons.

Additionally, intensity fluctuations due to roughness of the surfaces, the spectral behaviour of a real etalon including manufacturing defects, the influence of the reflectivity in the wave front aberrations and influence of the piezo-electric effect produced during high voltage tuning of the etalon in the optical quality have been analyzed.

The theoretical and experimental results obtained are in concordance and it can be envisaged that the image quality requirement will be fulfilled.

ACKNOWLEDGMENTS

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REFERENCES


