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OPTICAL ANALYSIS AND PERFORMANCE VERIFICATION ON ALADIN SPECTROMETERS

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ABSTRACT

The Aeolus mission will take an innovative wind lidar called ALADIN (Atmospheric LAser Doppler INstrument) into space to measure wind profiles in the lowermost 30 km of the Earth's atmosphere. ALADIN is a direct detection wind lidar capable of using the backscatter signal from both molecular (Rayleigh-) and aerosol (Mie-) scattering to retrieve independent wind information. To achieve the mission goal, two separate spectrometers have been manufactured. The Rayleigh spectrometer is using a Fabry-Perot etalon with 2 paths and works like 2 narrow band filters. The detector measures the power reflected by the atmosphere for each thin band. The Mie spectrometer core is a Fizeau etalon. A CCD matrix measures directly the spectral response with a very fine resolution.
For both etalons, the critical parameters are the FWHM (Full Width Half Maximum) and the Finesse.
High optical quality and extremely narrow FWHM are needed to achieve mission performance but also request high quality system for the verification of those performances.
The optical performance predictions, the verification philosophy and the test results are presented. The description of the different measurement setups including a system able to do spectral measurement with a resolution of some femtometers, the characteristic of the equipment and mathematical method used for calibration and to optimize the measurement accuracy are described.
For the 2 spectrometers, a numerical model has been developed to analyse and predict the spectral response. The model and the results of the analysis are presented in the documents.
The comparison between analysis and measurement results is discussed.
Keywords: Optical systems, space application, Aeolus, optical modelling, spectrometer

1. INTRODUCTION

The climate became an economical and political subject those last years, but the scientific community has always try to search to explain and predict the weather and the atmospheric behaviours. The Aeolus satellite is a part of the scientific missions dedicated to Earth observation. The goal of Aeolus is to measure the speed of the wind in the atmosphere and for such a purpose it is equipped with a single instrument: the laser doppler lidar named ALADIN. The back reflection of a laser by the air (molecules) is described by the Rayleigh equation and the Mie theory describes the back reflection on particles. Correspondingly, to determine both speeds (molecular and particular) the instrument needs two spectrometers: a Rayleigh Spectrometer (RSP) and a Mie Spectrometer (MSP).
The RSP is based on a double channel Fabry Perot etalon and the MSP uses a Fizeau etalon. Those two high resolution etalons are the core of the instrument and the overall performance is driven by the etalon itself. Their performances are extremely dependent on the quality of the optical surfaces. The modelling of the etalon shall therefore be as far as possible representative to the as built optical surfaces in order to provide the correct information on the behaviour of the system and to be able to link the overall performance to the optical parameters.
In the following sections, we will present the design of the two spectrometers and a detailed description of the etalons including manufacturing aspects. Section 3 presents the optical models developed by Oerlikon Space for both of the etalons. The verification and performance analysis are described in section 4 and section 5 presents a comparison between the model and the verification results.

2. OPTICAL DESIGN

2.1. Etalon design

A Fabry-Perot etalon is an optical system with 2 semi-reflective parallel surfaces in between the interference will appear. For a defined wavelength, depending on the gap between those two surfaces, the interferences will be constructive or destructive and the ideal etalon will be transparent or reflective.
The relative position between the two surfaces is the milestone of the etalon performance. The parallelism of the two surfaces is the main constraint and it has to be stable during all operating conditions. The space between the two surfaces is thermally controlled to adjust the working wavelength while the parallelism has to be maintained.

The RSP uses a two channel Fabry-Perot etalon, in order to measure simultaneously two wavelengths. The main advantage of having one double channel etalon instead of two separated is the capabilities to keep the interval between the 2 wavelengths constant even if the central wavelength is thermally tuned.

The MSP uses a Fizeau etalon. For a monochromatic beam, constructive interference leads to a single fringe on the aperture. In this area of the fringe the etalon is transparent and the other part of the beam is reflected (Fig. 3:). The thickness of the fringe mainly depends on the wedge between the two plates of the etalon.

2.2. Overall design

As the RSP Etalon has to be tunable with temperature, the alignment of all optical elements has to stay stable during temperature tuning. The choice of a baseplate made of glass provides a high stiffness and a very small thermal distortion. All the optical elements are bonded on the baseplate, except the etalon. Due to the weigth of the etalon and to avoid thermal expansion of the glue it is optical contacted to the baseplate. The RSP baseplate is attached to the instrument bench by three bipods.
To allow a high transmission on both paths, the beam is not splitted in two. The beam will first be directed to the path1. The working wavelength is transmitted and all other wavelength are reflected and routed to the path 2. As the peak transmission of the path2 appears for a wavelength reflected by the path1, the transmission is around 80% for both paths.

For the MSP, the baseplate is an Zerodur-Aluminium sandwich structure. This design can withstand the specified loads with a light weight and a great thermal stability. As for the MSP, all the optical parts are bonded on the baseplate which is supported by three bipods.

3. ETALON MODELLING

In order to assess allowable tolerances for manufacturing, a mathematical model has been developed to simulate the performance of the etalons.
For modelling the RSP, the etalon plates are subdivided into a matrix of ideal Fabry-Perot etalons with individual plate separations following the global shape of the etalon plates. Each individual Fabry-Perot etalon (pixel) is treated in an ideal sense. The effects of the limited size of mirrors or diffraction effects are considered to be negligible. With the approach of splitting up the etalon plates into small pixels and treat them as single, ideal Fabry-Perot filters, plate deformations are easy to incorporate into the model such that adequate performance estimation is feasible. The plate deformations which were modelled in this way were surface roughness, spherical bowing and plate parallelism. Instead of parameterized plate deformations, measured surface maps of the etalon plates can be read in the model as well.

Ray divergence is taken into account in the pixelated Fabry-Perot etalon model as an angle distribution. The incoming angular Gaussian intensity distribution is split into a discrete spectrum of plane waves. These plane waves pass through the etalon under their respective angles of incidence and then add up their corresponding transmission values weighted by the original Gaussian distribution.
In order to verify the model, its output was first tested against the results of the analytical formula of the intensity transmission of an ideal etalon. A comparison with test results of the etalon breadboard showed good agreement.
For the MSP, the same model is used. The wedge of the Fizeau etalon is introduced by simply setting the plate parallelism according to the wedge angle. The peak transmission at fringe level is determined by finding the maximum transmission in direction of the Fizeau wedge (orthogonal to the fringe) for each column in the two-dimensional matrix of all Fabry-Perot pixel transmissions. Therefore the result is a vector of local maxima. From this vector the average and the standard deviation is computed.

The result of a model calculation of the RSP taking into account manufacturing tolerances is shown in table 3-1. Figure 3-1 shows the transmission map of the MSP calculated with the model taking into account manufacturing tolerances. Calculated performance is shown in table 3-2.

Table 3-1: Resulting performance of RSP model calculations including manufacturing tolerances.

RSP Performance	Model
FSR	4.6 pm
FWHM	0.73 pm
Finesse F	6.3
Peak Transmission	88.1%
Minimum Transmission	4.4%

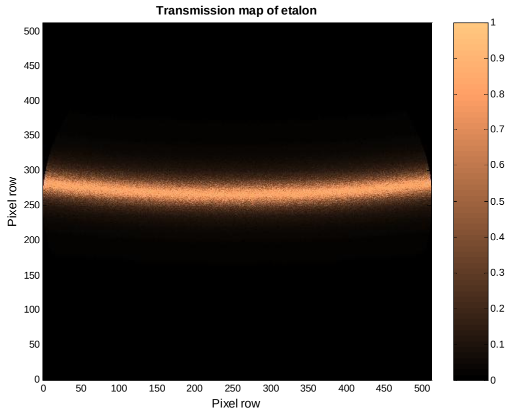

Fig. 1: Transmission map calculated with the MSP Fizeau etalon model including spherical bowing and roughness.

Table 3-2: Resulting performance of MSP model calculations including manufacturing tolerances**.**

MSP performance	Model
FSR	0.92 pm
FWHM	62.6 fm
F	14.7
Peak Transmission (cumulated)	76.4%
Peak Transmission (fringe level)	84.5% ± 0.9%
Min. Transmission	0.6%

4. PERFORMANCE VERIFICATION

The main optical performances were also measured for the RSP as well as for the MSP. The etalon main characteristic is the finesse which is the ratio between the Full Width Half Max (FWHM) and the Free Spectral Range (FSR). The FSR is the gap in wavelength between two transmission peaks.

To perform those tests a dedicated test bench has been setup at Oerlikon Space, including a tunable laser at 355 nm wavelenght. The FWHM of the laser itself is some orders smaller than the parameter to measure. The wavelength of the laser is measured by a wavemeter with a relative accuracy smaller than one fm. By doing a new calibration just before each test, the absolute accuracy achieved was around 10 fm. The expected FWHM is 730 fm for the RSP and 63 fm for the MSP.

The expected FSR is 4.6 pm for the RSP and 0.92 pm for the MSP.

For each measurement, the principle is the same. The powermeter or CCD sensor collects the signal during a scan of the wavelength of the laser. The frequency scan is controlled by software to keep a small slope in order to have enough measurement points in wavelength. The scan is performed over more than 1 FSR. For the Fabry-Perot Etalon (RSP), all the measurements are transmission measurement done with powermeters. For the Fizeau Etalon (MSP), the FSR is measured by transmission with powermeters, and the FWHM of the fringe is measured with a CCD.

4.1. The setup

The working wavelength of the spectrometers is 355 nm. For transmission measurement, the source is a collimated beam obtained with an optical fiber installed at the focal point of a lens. The diameter of the monomode fibre leads to a beam divergence smaller than 0.05 mrad. The source beam is also linear polarised by a polarising beam splitter.

The setup (Fig.2) is as simple as possible: the power of the beam is measure at the output of the collimator during a calibration measurement and after the instrument during the transmission phase.

The tunable laser and the optical fiber at this wavelength are not stable enough to maintain a constant linear polarisation and a continuous power during the frequency scan. The power injected inside the instrument could be different than the power measured during calibration phase. To take into account this unstability two others powermeters are used. The first one collects a part of the input beam before the polarizer and outside of the pupil. This powermeter recorded the instability of the injected power. A second powermeter measured the unwanted polarisation part of the beam (reflected by the polarizing beam splitter). After processing the measured value of those two powermeters during calibration and transmission phase, it’s possible to compute the input power during the transmission phase and then to calculate the transmission of the instrument.

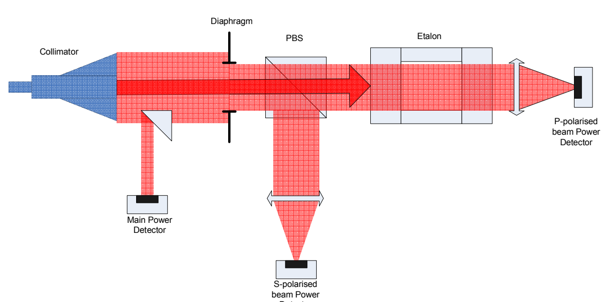

Fig. 2: Setup of transmission measurement

For a monochromatic beam, a fringe will be transmitted by a Fizeau etalon and the other part of the beam is reflected. The overall transmission is then smaller than for a Fabry-Perot and the shape of the fringe define the FWHM of the etalon. A CCD camera is then used to measure the fringe.

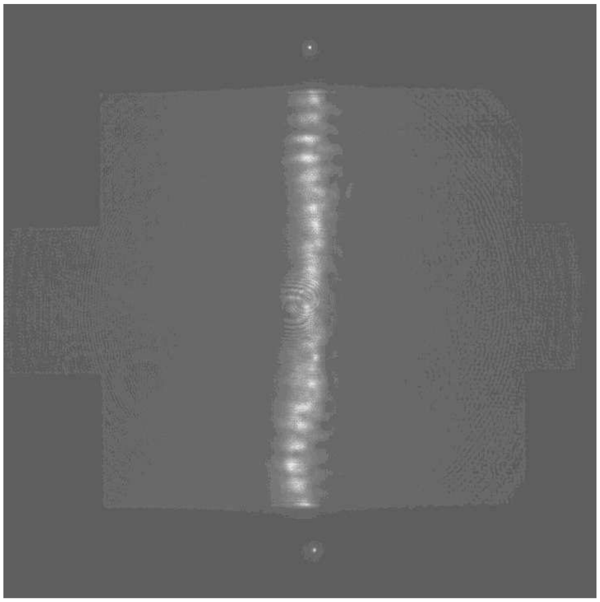

Fig. 3: Fringe image

Images of the fringe are saved and a processing computes the FWHM of the fringe. The FWHM is calculated on the accumulated fringe which is the summation along the theoretical fringe direction of the fringe pattern.

The angle of the fringe with regard to the orientation of the CCD is also recorded.
The image of a dedicated alignment grid was also analysed and the angle between the grid and the CCD computed. Mechanical and theodolite measurement allow the alignment of the grid with regards to the mechanical interface of the instrument. By considering all those measurements, the CCD lines are aligned parallel to the mechanical axis of the instrument before the fringe measurement. The accumulated fringe is then easy to compute as the theoretical fringe direction is parallel to the CCD lines.
On the Fig. 3: , the two small bright spots above and below the fringe are pinholes in the mask used to align the CCD.

4.2. Results

The transmission measurement of the RSP was done twice during the verification campaign. The results are reported in Table 4-1. The discrepancies on the measurement are less than 1% for the transmission and around 10 fm for the FWHM.

Table 4-1: Transmission measurement of RSP

		Intermediate performance	Final performance
Transmission	**Path1**	0.835	0.84
	Path 2	0.735	0.74
FWHM (pm)	**Path1**	0.64	0.64
	Path 2	0.66	0.67
FSR (pm)	**Path1**	4.59	4.59
	Path 2	4.59	4.59

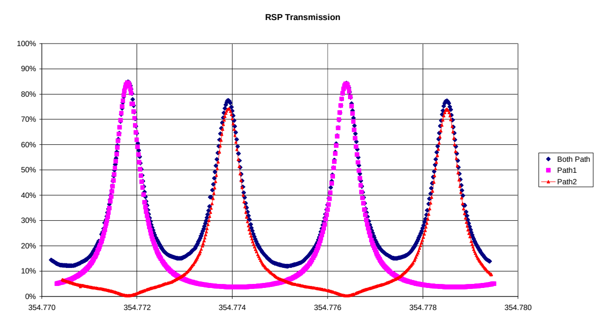

Fig. 4: RSP transmission.

Using the results of the model, the impact of all others components has to be included in the transmission budget to compare the value predicted by the model with the measurement.

Table 4-2: Comparison between model and measurement

	Model	Final performance
RSP		
Transmission p1	84%	84%
Transmission p2	77%	74%
FWHM (pm)	0.73	0.71
FSR (pm)	4.6	4.59
MSP		
Max Transmission	7%	5.2 %
FWHM (fm)	62.6	42.9
FSR (fm)	920	918

The comparison shows that the model fit correctly with the measurement for the RSP. We can then conclude that the measurement itself is reliable and that the model is able to simulate a Fabry-Perot etalon. The differences are just in the order on 1% for the transmission measurement, which is the accuracy of the measurement. The spectral parameters have a discrepancy of 10 fm. This 10 fm are at least one order bigger than the accuracy of the wavemeter but the discrepancy is coming from the uncertainty of the peak positioning which is based on transmission curve.

For the MSP, the measurement is more complex due to the use of a CCD. The dynamic, the linearity and the overall accuracy of the CCD are not as good as for a powermeter. The modelling seems also to be less accurate for the MSP than for the RSP. However, the two models use the same base. The etalon is splitted into a matrix of small etalons. Even for the Fizeau etalon, the small sub-etalons are Fabry-Perot etalon. The wedge is here introduced as a stair; each line of sub-etalon has a different cavity length. This approach did not allow to take completely into account the WFE map of the etalon plates. The maps are here also some steps, but the sub-etalons are still ideal Fabry-Perot, the 2 plates are perfectly parallel. Those maps have bigger influence on the MSP than on the RSP because the quality of the MSP etalon plates was significantly worse. Some rings due to polishing process were visible on the WFE maps of the MSP plates and those rings are also visible in the fringe image. On Fig. 3: , the fringe is centred and the rings produce a “striped” fringe. It is still not clear if the stripes decrease the transmission or just modify the shape of the beam by moving the power from one pixel to the other without any losses. Anyway, as those stripes are not visible in the synthetic fringes, it is obvious that the model did not take all the effect in account.

A new approach for the modelling of the etalon is currently in development using optical design software and direct ray tracing, not to base the model on ideal Fabry-Perot sub-etalon.

5. CONCLUSION

During the manufacturing of those two spectrometers, we acquired a lot of experience in modelling and measuring optical performance at etalon and unit level.

The outcome is that we can achieve good measurement accuracy for the transmission, FWHM and FSR, if the measurements are done with single powermeter but that it is more difficult with a CDD. The model itself is reliable and in good agreement with the measurement if the plates have a high quality wavefront. The new model shall be able to take into account this effects of the low frequency surface structure.