

International Conference on Space Optics—ICSO 2014

La Caleta, Tenerife, Canary Islands

7–10 October 2014

Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas



Retrieval of physical properties of interference filters integrated in radiometer instruments by using reverse engineering process

F. Javier Álvarez-Ríos

Juan José Jiménez

Miguel Gonzalez-Guerrero

Israel Martin



International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105634Q · © 2014 ESA and CNES
CCC code: 0277-786X/17/\$18 · doi: 10.1117/12.2304064

RETRIEVAL OF PHYSICAL PROPERTIES OF INTERFERENCE FILTERS INTEGRATED IN RADIOMETER INSTRUMENTS BY USING REVERSE ENGINEERING PROCESS

(F. Javier ÁLVAREZ-RÍOS¹, Juan José JIMENEZ¹, Miguel GONZALEZ-GUERRERO¹,
Israel MARTIN¹)

¹ Space Sciences and Payloads Department, National Institute of Aerospace Technology (INTA)
Madrid, Spain

I. INTRODUCTION

The Solar Irradiance flux experiment a spectral filtering process as the irradiance flux propagates from the source to the sensor. When using radiometer sensors for optical measurement both the atmospheric transmittance, sensor's filter and the responsivity of the detector produces a spectral filtering, see Fig. 1

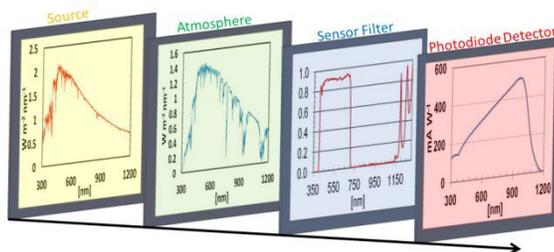


Fig. 1. Irradiance flux filtering throughput from the source to the sensor

The total response of the radiometer is the integral of the convolution from the spectral Irradiance source reaching to the sensor with the Optical Transfer Function (OTF) that is composed by the sensor filter and detector responsivity. For MetSiS and DREAM SIS radiometers the sensor filter are composed by Schott filter and an interference filter. Schott filters were added to the optical system to improve the behavior of interference filters.

The OTF is dependent on the next parameters: temperature, angle of incidence of the incoming radiation and the incoming light distribution (diffusive or collimated). Any element of the optical system contributes uncertainty to the measurement, being the interference filter the most affecting in the optoelectronic chain by these parameters.

Due the characterization of interference filter under different conditions of temperature and angular orientation is difficult, so modelling the behavior of the interference filters is helpful in order to assess how much uncertainty this optical element introduces into the final OTF of the radiometer instrument [1], [2].

We describe a method to find an equivalent interference filter based in the characteristic matrix approach, the theoretical model calculate filter properties as a function of the number of layers, the layers thickness and the type of material every layer is made of. Combining experimental measurement of optical transmittance with the theoretical model is possible to get an equivalent filter using inverse methods.

II. EXPERIMENTAL SETUP

This part describes the experimental setup to perform the optical transmittance measurement with different orientation of the filter respect to the incident light. The setup is divided in four parts; see Fig.2:

- Xenon Lamp (lamp housing E7536 of Hamamatsu) with condenser lens, it emits a quasi-collimated beam.
- A pinhole to reduce the beam width.
- Filter mounted on a gonio-meter (Model GB-GD SN G1008 of Gigahertz-Optik) to perform angular measurements for filters.
- Sensor connected to Spectrometer and computer to acquire data (Model X4 light analyzer of Gigahertz-Optik).

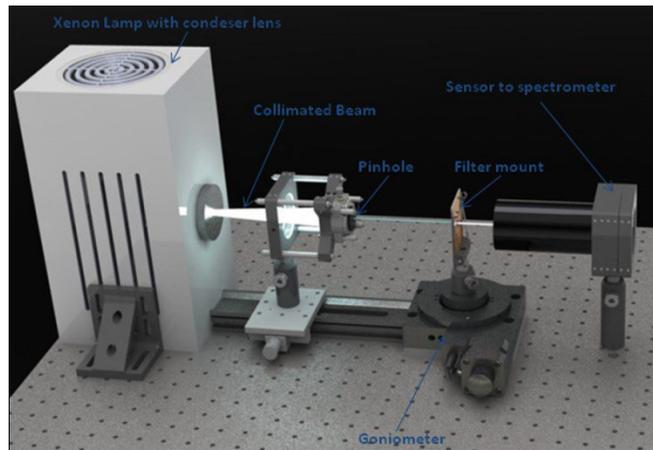


Fig. 2. Scheme of experimental setup

III. MULTILAYER THIN FILM MODELING

The Transfer Matrix method calculates the filter properties using the characteristic matrix approach, the method is presented in detail in most optical coating textbooks[3], [4],[5]. In the equations shown below n is the refractive index, n_i and n_s are the refractive index from external material and substrate respectively, d is the layer thickness, φ is the angle of the incident light, ψ is the refraction angle in the layer and k_0 is $\frac{2\pi}{\lambda}$.

For s-polarization the jth maxtrix is represented by:

$$M_j = \begin{pmatrix} \cos(k_0 n d \cos \psi) & \frac{-i}{n \cos \psi} \sin(k_0 n d \cos \psi) \\ -i n \cos \psi \sin(k_0 n d \cos \psi) & \cos(k_0 n d \cos \psi) \end{pmatrix} \quad (1)$$

and for p-polarization:

$$M_j = \begin{pmatrix} \cos(k_0 n d \cos \psi) & \frac{-i}{n \cos \psi} \sin(k_0 n d \cos \psi) \\ \frac{-i \cos \psi}{n} \sin(k_0 n d \cos \psi) & \cos(k_0 n d \cos \psi) \end{pmatrix} \quad (2)$$

The characteristic matrix describing the multilayer is:

$$\hat{M}_{\text{stack}} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = \prod_{j=1}^N M_j \quad (3)$$

Table 1, show the relation between the multilayer matrix and the optical property of transmittance for the filter, the total transmittance of the filter will be the average between the transmittance for s and p polarizations.

Table 1. Amplitude transmission and transmittance relations of a multilayer film.

s-polarization	Amplitude transmission	$t^s = \frac{2n_1 \cos \varphi}{(m_{11} + m_{12}n_s \cos \varphi_s)n_1 \cos \varphi + m_{21} + m_{22}n_s \cos \varphi_s} \quad (4)$
	Transmittance	$T_s = \frac{\text{Re}(n_s \cos \varphi_s)}{\text{Re}(n_1 \cos \varphi)} t^s ^2 \quad (5)$
p-polarization	Amplitude transmission	$t^p = \frac{2 \frac{\cos \varphi}{n_1}}{\left(m_{11} + m_{12} \frac{\cos \varphi_s}{n_s}\right) \frac{\cos \varphi}{n_1} + \left(m_{21} + m_{22} \frac{\cos \varphi_s}{n_s}\right)} \quad (6)$
	Transmittance	$T_p = \frac{\text{Re}\left(\frac{\cos \varphi_s}{n_s}\right)}{\text{Re}\left(\frac{\cos \varphi}{n_1}\right)} t^p ^2 \quad (7)$

IV. RETRIEVAL OF PHYSICAL PARAMETERS

Retrieval of physical parameters is a problem of optimization or inverse problem where the model described in the previous section is feedback with the physical parameters to produce the best fit of the theoretical transmittance respect to the experimental one.

To solve the optimization problem two algorithms has been used: (1) A heuristic optimization using a genetic algorithm (GA) performed by choosing the n^{th} best samples of the complete offspring at every iteration, and (2) a local optimization based on the Levenberg–Marquardt algorithm is used to refine the best offspring in the n^{th} iteration [6], [7].

The first one is based on the genetic processes of biological organism. They usually work with a population of individuals, each representing a possible solution of the problem. The best individuals, according with a fitness function, are selected to create new individual recombining and modifying the information stored in the old ones. The new individuals are then inserted in the population with some of the old ones generating a new offspring. This process continues until a stop condition is reached, and the best individuals found for the algorithm are considered the solution of the problem. Matlab software and toolbox has been used to implement this algorithm [8].

A. PROBLEM ENCODING

The following terms are referred to any GA:

- The population size, is the number of existing solutions.
- An individual, is a potential solution of the problem. For this case, Individuals are made of combination of High/Low refractive index layers (HL)ⁿ.
- The chromosomes, is each of the parameters that constitute an individual; see Fig. 3.

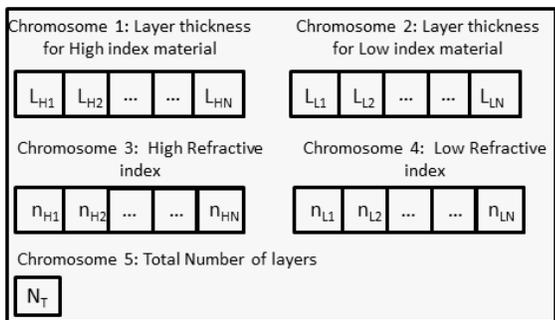


Fig. 3. Parameters of an individual for the optimization problem.

Some information about the physical parameters was provided by the manufacturer like the number of layer, the type of material used and the total physical thickness for the High & Low-Index-Layers. In this inverse problem the information from manufacturer was used, so the individual only has two chromosomes the layer thickness for material of High/Low refraction index.

- The cost function is the fitness function that will be minimized and is defined as a linear combination of:

$$J = \frac{(\sum_n (T_{exp} - T_{model})^2)^{1/2}}{n} + \alpha |L_H - \hat{L}_H| + \beta |L_L - \hat{L}_L| \quad (8)$$

The first term in (8) is the root-mean-square (RMS) error between the theoretical and the measured optical transmittance, the second and third terms are the difference between the physical thickness and the calculated thickness for the High/Low-Index-Layers respectively. α and β are constant used to weight these terms.

B. PROCEDURE OF GA OPTIMIZATION

For simplification, all calculations were performed with constant refractive index and at normal incident of light.

The population number was chosen between 50-60 individuals. The population initialization can be set up randomly or it is possible to use different strategies [9], [10] to choose new individuals like suppose the individual consists on quarter wave layers (QW) or similar allowing a random variation around the reference wavelength (9).

$$\begin{aligned} n_{Hi} d_{Hi} &= \left(\frac{\lambda_0}{4}\right) random(x_1, x_2) \\ n_{Li} d_{Li} &= \left(\frac{\lambda_0}{4}\right) random(x_1, x_2) \end{aligned} \quad (9)$$

The next step are common to any simple GA:

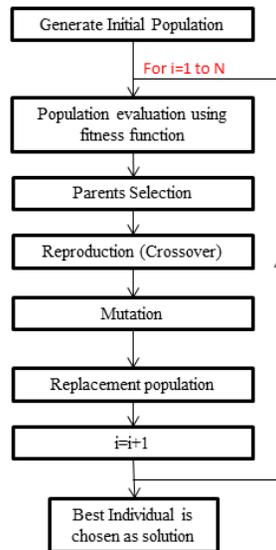


Fig. 4. Procedure for GA Algorithm

The number of generations N for the GA was establishing in 300-400.

C. REFINE GA SOLUTION

The Best Individual from GA during N generations is refined using a local search based on Levenberg–Marquardt algorithm, the cost function is the RMS error. A Maximum of 1000 iterations was established as stop condition for this method.

D. STOP CONDITION

The refine solution is introduced into the population of the GA and the process of optimization is continued until the next N generation. Then, the best individual is improved using Levenberg–Marquardt algorithm again.

The process is stopped manually when the cost function value is below or near to 0.5; if the fitting solution is successful the optimization is finished, otherwise the optimization process continues.

V. RESULTS

For these paper three filters has been optimized. The quality of the optimization has been successful as shown in the figures below:

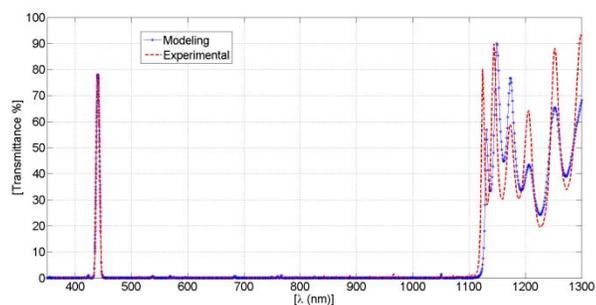


Fig. 5. Filter F12 (440 nm)

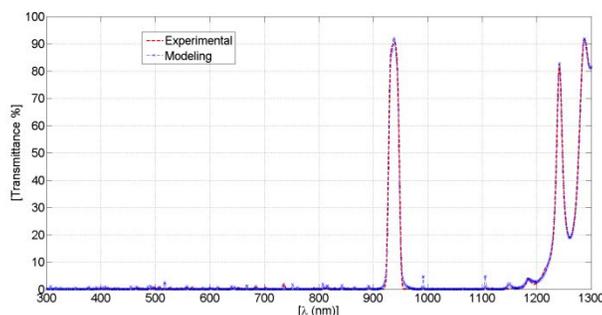


Fig. 6. Filter F5 (930-950 nm)

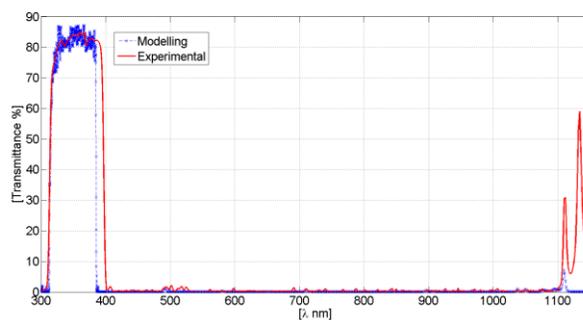


Fig. 7. Filter F7 (315-400 nm)

Table 2. Parameters value of the cost function when the optimization was stopped.

	F12	F5	F7
RMS	0.22	0.09	0.49
$ L_H - \hat{L}_H $	13.1	15.2	16.9
$ L_L - \hat{L}_L $	24.8	27.3	17.0

VI. CONCLUSIONS AND FUTURE PLANS

Combining the Matrix formulation for multilayer filter, global and local search algorithm a reverse-engineering software proces has been developed and validated succesfully to find an equivalent filter from experimental measurement of interference filters using.

We plan continue developing the algorithm to change the algorithm from a mono-objective cost function to a multi-objective optimization that include several cost function dependent on physical parameters.

- [1] Reid E. Basher and W. Andrew Matthews , “Problems in the use of interference filters for spectrophotometric determination of total ozone”. Journal of Applied Meteorology 16 June 1977.
- [2] H. Guerrero, et al. “Development of miniaturized instrumentation for Planetary Exploration and its application to the Mars MetNet Precursor Mission”. EGU. Viena, Austria. 02 – 07 May 2010.
- [3] O.Stenzel , “The Physics of thin film optical spectra: An introduction”. ISBN 10-3-540-23147-1, Springer-Verlag Berlin Heidelberg New York 2005.
- [4] H. Angus Macleod, “Thin-Film Optical Filters”, ISBN 978-1-4200-7302-7, CRC Press Taylor & Francis Group 2010.
- [5] Stéphane Larouche and Ludvik Martinu , “OpenFilters: open-source software for the design, optimization, and synthesis of optical filters” APPLIED OPTICS, Vol. 47, No. 13 , May 2008
- [6] Wolfram MathWorld, “Genetic Algorithm” , <http://marthworld.wolfram.com>
- [7] Wolfram MathWorld, “Levenberg-Marquardt Method” , <http://marthworld.wolfram.com>
- [8] Matlab, “Global Optimization Toolbox”.
- [9] Uwe B. Schallenberg, “Antireflection design concepts with equivalent layer”. APPLIED OPTICS, Vol.45, No. 7, March 2006
- [10] Ulrike Schulz, Uwe B. Schallenberg, and Norbert Kaiser, “Antireflection coating design for plastic optics”. Vol.41, No. 13, June 2002