Optical Filters for Space Instrumentation

Angela Piegari

ENEA, Optical Coatings Laboratory, Roma, Italy

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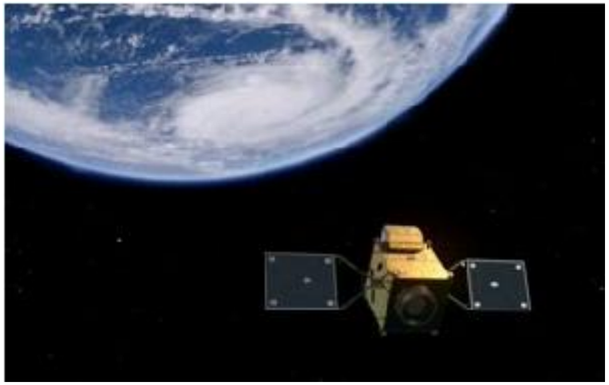
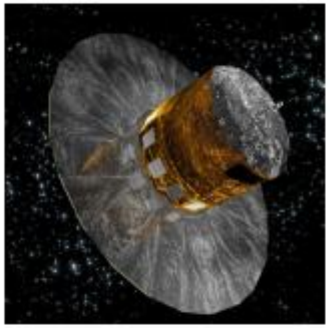
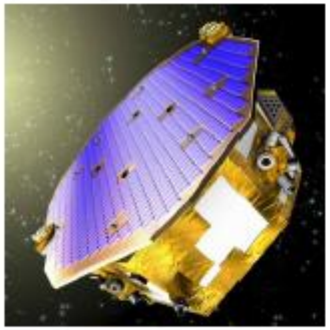
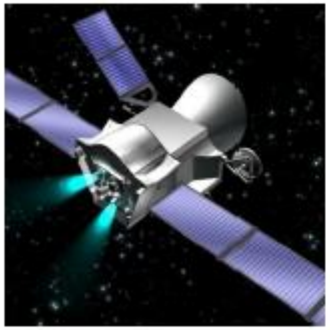
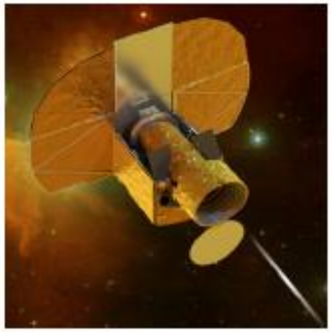
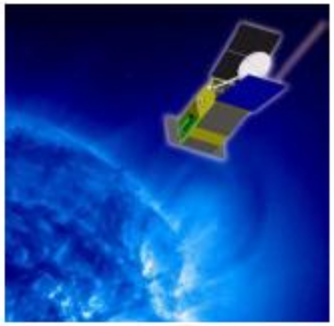
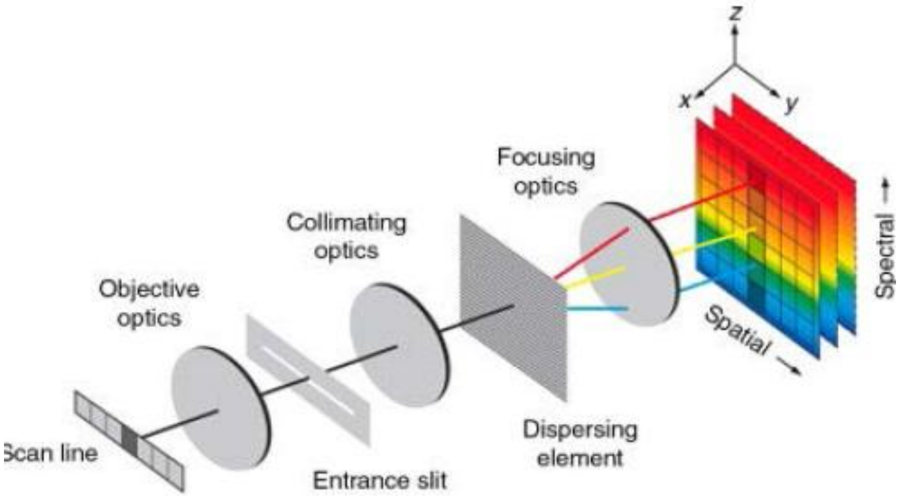
Optical coatings for Space

– Instrumentation
  • Spectrometers, imagers, interferometers, telescopes,….

– Optical coatings
  • Filters, mirrors, antireflection coatings,…



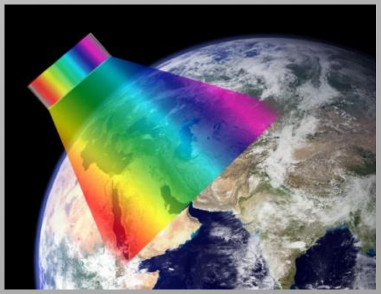
European Space Agency

Narrow-band filters for Space

- *Two examples with different characteristics*:

1) Spatially variable filter (for an imaging spectrometer)

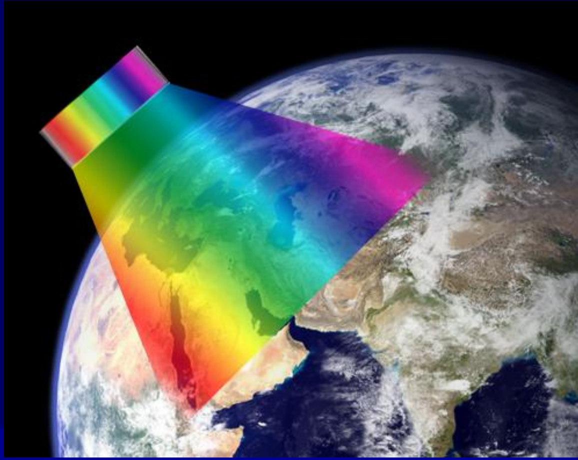
small dimensions (few mm)
high spatial gradient
wide spectral range (VIS-NIR)



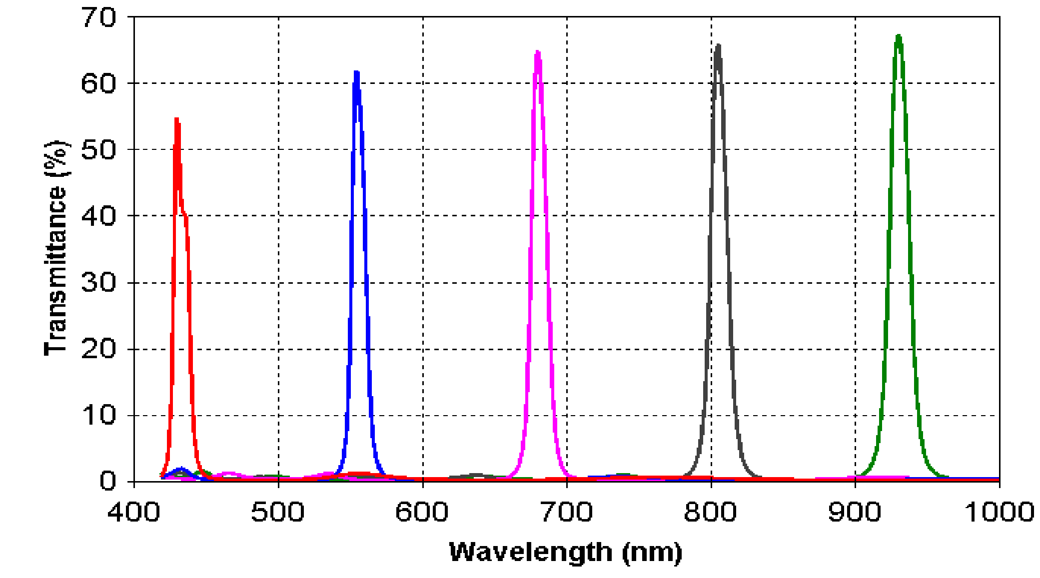
2) Very narrow band filter (for a lightning imager)

large dimensions (> a hundred mm)
very narrow bandwidth (< 1 nm)
oblique incidence

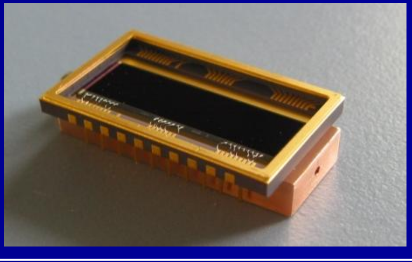
1. Imaging Spectrometer for Earth Observation



- Polar sun-synchronous orbit at an altitude of 700 km
- Compact image spectrometer with a graded narrow-band *transmission filter* coupled to an array detector



Linearly variable filter



CCD detector

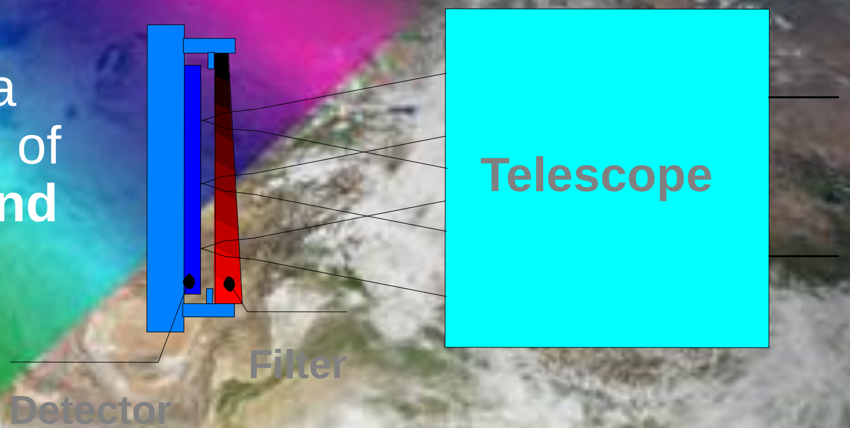
The transmission peak wavelength is varying linearly, in a continuous spectrum (VIS-NIR), over the component surface (hyperspectral imaging)

Mini-spectrometer for Earth imaging

ESA project: ULTRA-COMPACT MEDIUM-RESOLUTION SPECTROMETER FOR LAND APPLICATIONS

The compact spectrometer is not limited to Earth observation, but is also useful for planetary missions.

- Replacing classical optical components (prisms, gratings) with a variable filter allows the construction of a spectrometer with **reduced size and weight** and with **no moving parts**.

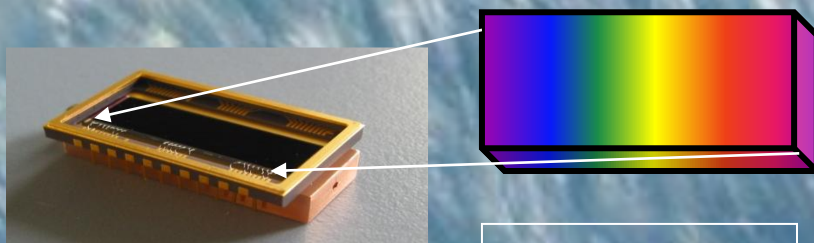


The filter is coupled to a CCD detector

Each line of a two-dimensional array detector, which is equipped with a variable narrow-band filter, will detect radiation in a different pass band

Filter specifications (variable filters)

The variable filter shows a narrow-band transmittance which peak wavelength is displaced over its surface



CCD detector

Variable filter

Operating spectral range: 440-2500nm
Spectral resolution: ~10nm

Wavelength range divided in two areas corresponding to different CCDs:

1) 440-940 nm, dimension 2.1 mm

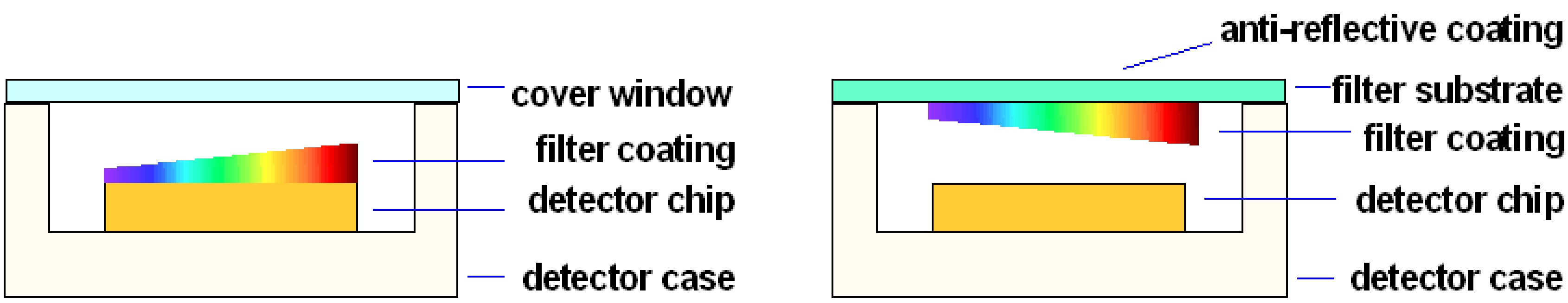
2) 940-2500 nm, dimension 6.3 mm

Spatial gap between two adjacent areas: 0.4 mm

2 adjacent Linearly Variable Filters

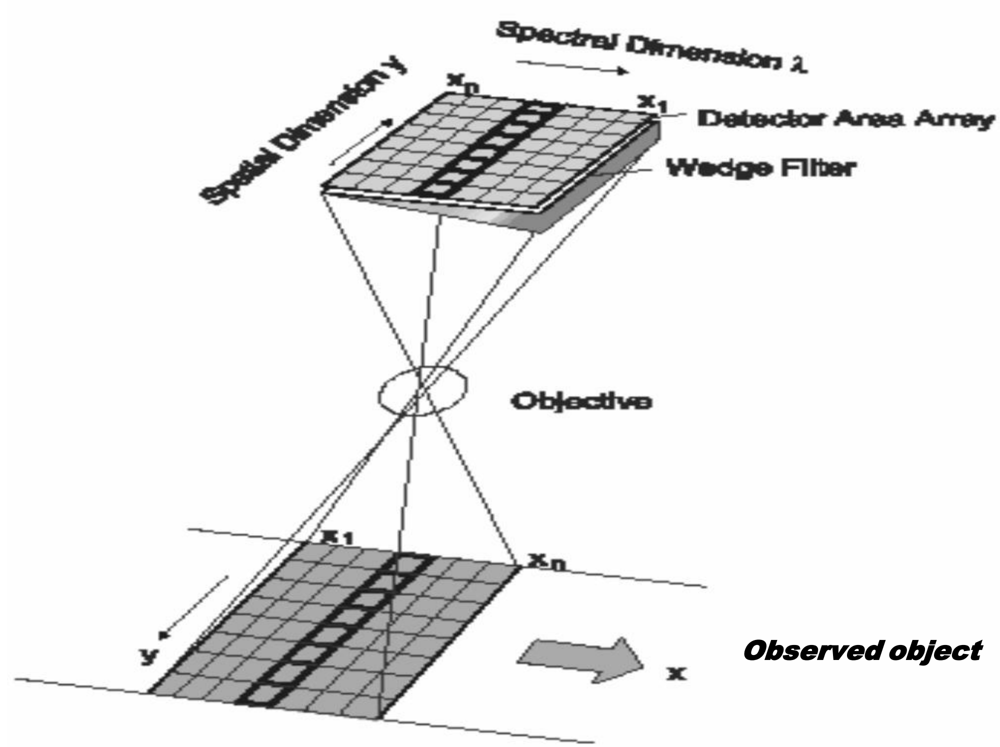
Linearly Variable Filter

The variable narrow-band transmission filter is combined with the array detector by depositing a wedge coating either directly on the CCD or on a separate glass substrate



The spatial variation is required along only one direction, the other is uniform

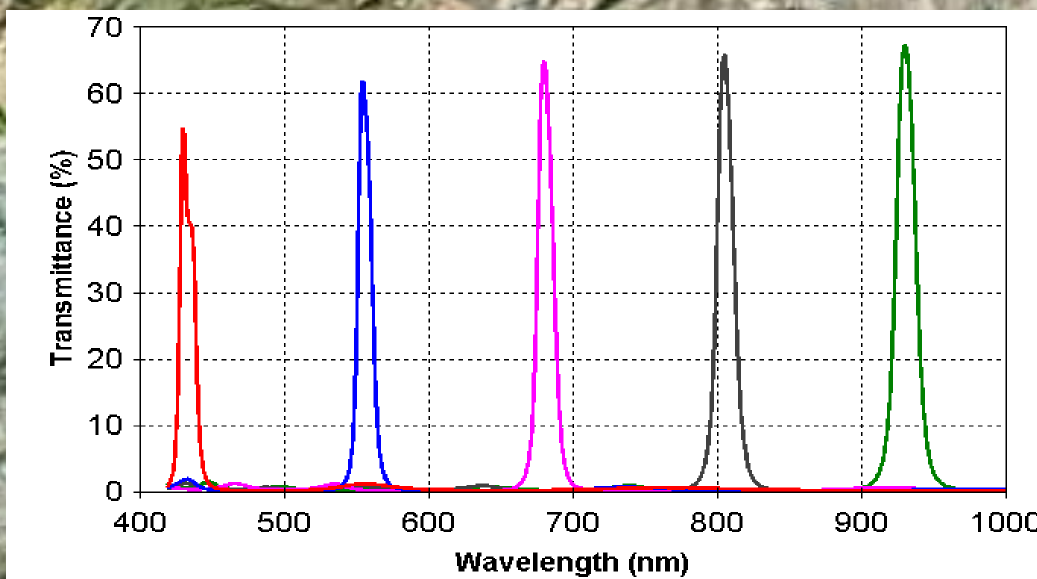
This optical sensor is the core element of a compact low-mass spectrometer for **hyper-spectral imaging**

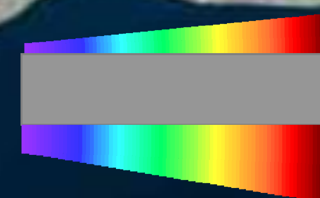


Linearly Variable Filter design

- **Induced Transmission filter: Ag - SiO_2 – Ta_2O_5, 21 layers**
- **Back-side blocking filter: SiO_2 – Ta_2O_5, 38 layers**

Operating range 440-940 nm (first area)





Bandwidth: 10-20 nm
Spectral gradient: 250 nm/mm

The transmittance curve is displaced over the filter surface, by a variation of the coating thickness with a linear gradient
(**IT filter in the VIS-NIR: min thickness ~ 1000nm, max 2500nm**)

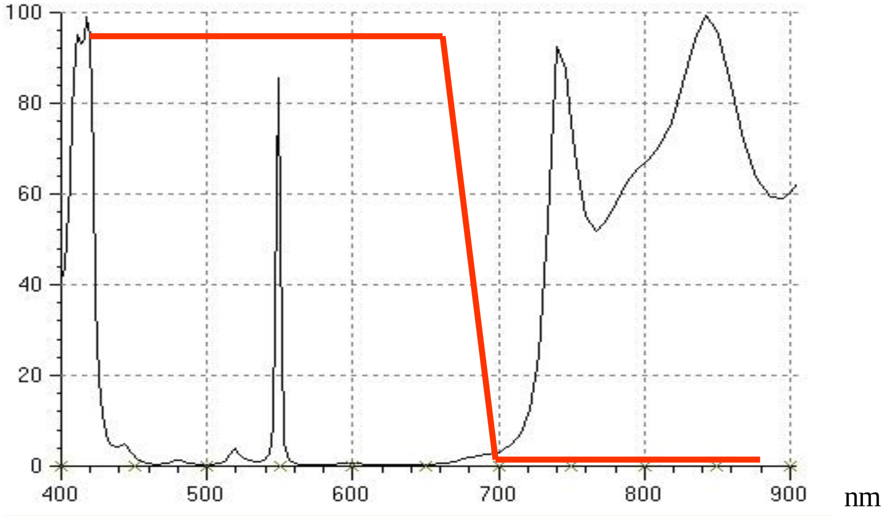
NASA/GSFC/METI/ERSDAC/JAROS, and the U.S./Japan ASTER Science Team and Jesse Allen

Metal-Dielectric Filters

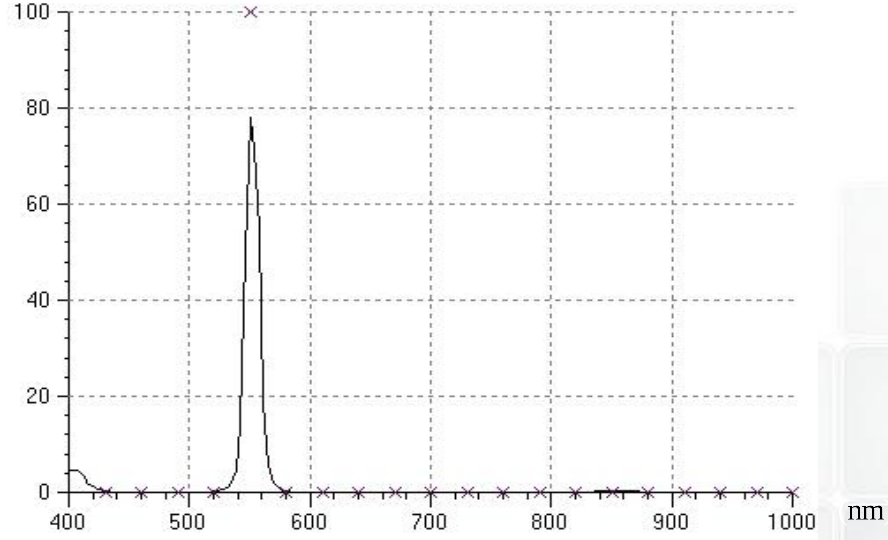
- **All-dielectric filters**
  - limited rejection range

- **Metal-dielectric filters**
  - useful in longwave blocking
  - disadvantage of intrinsic absorption

- **Induced transmission filters**:
  Air/ D / M / D /Substrate
  D = dielectric stack of high and low index layers
  M = silver
  - maximum possible peak transmission ψ at λ_0 for a given thickness of the metal



All-dielectric 31 layer coating

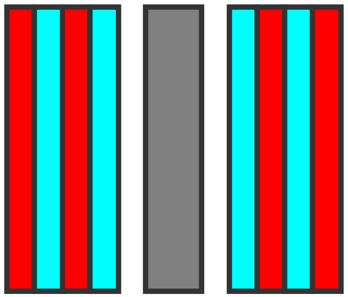


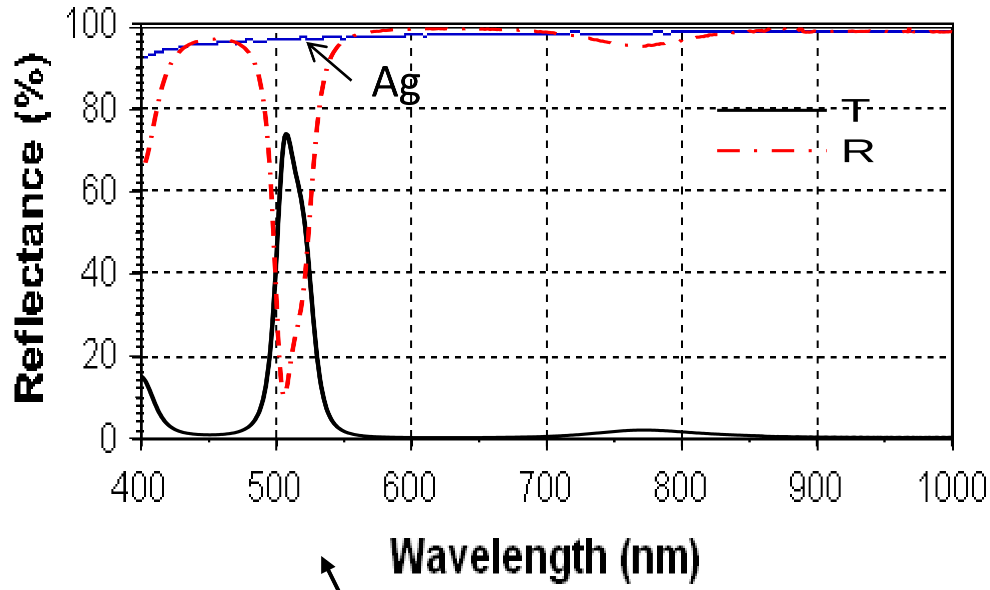
Metal-dielectric 17 layers stack

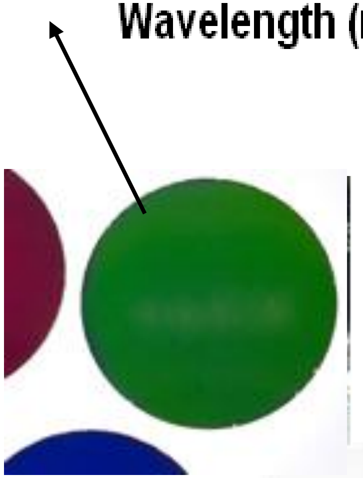
Induced transmission filter

▪ **metal layer (high reflection) matched with surrounding media (null reflection at one wavelength)**

Glass/ (...HLHL)L'M L'(LHLH…)/Air





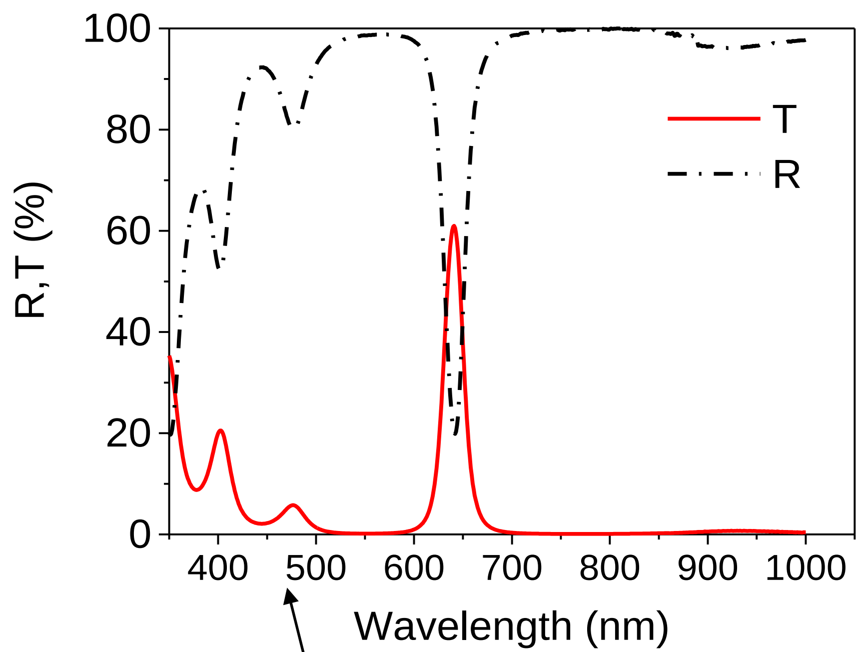


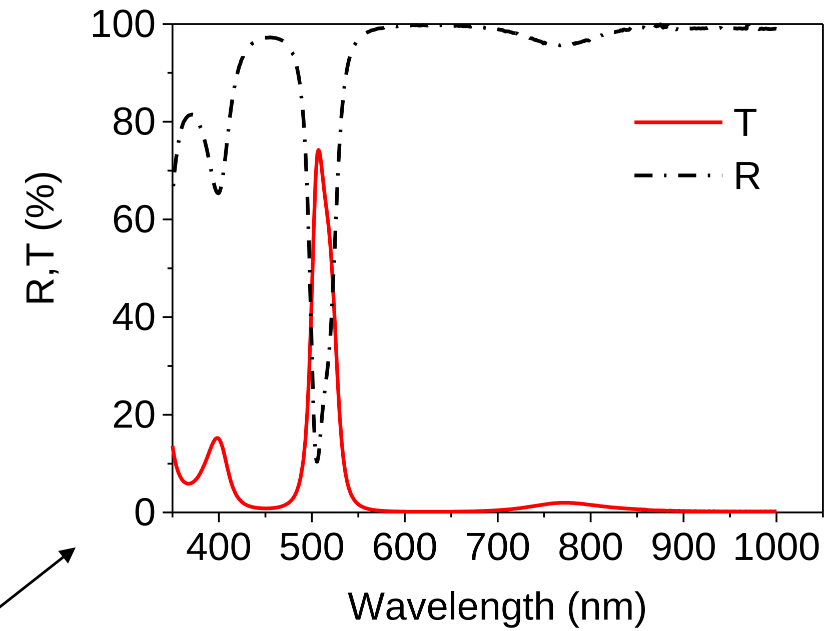
Optical constants of metals at λ_0 =550 nm

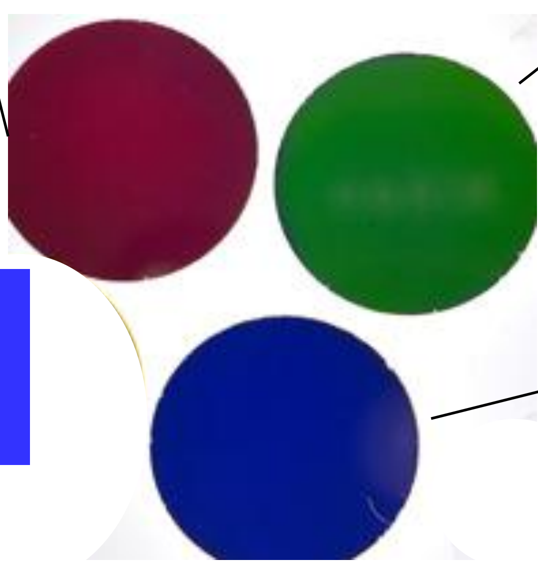
Metal	*n*	*k*	*k/n*
Ag (Schultz)	0.055	3.32	60.4
Ag (Palik)	0.12	3.45	28.7
Al	0.76	5.32	7
Ni	1.92	3.61	1.9
Cu	0.72	2.42	3.4
Pd	1.64	3.84	2.3

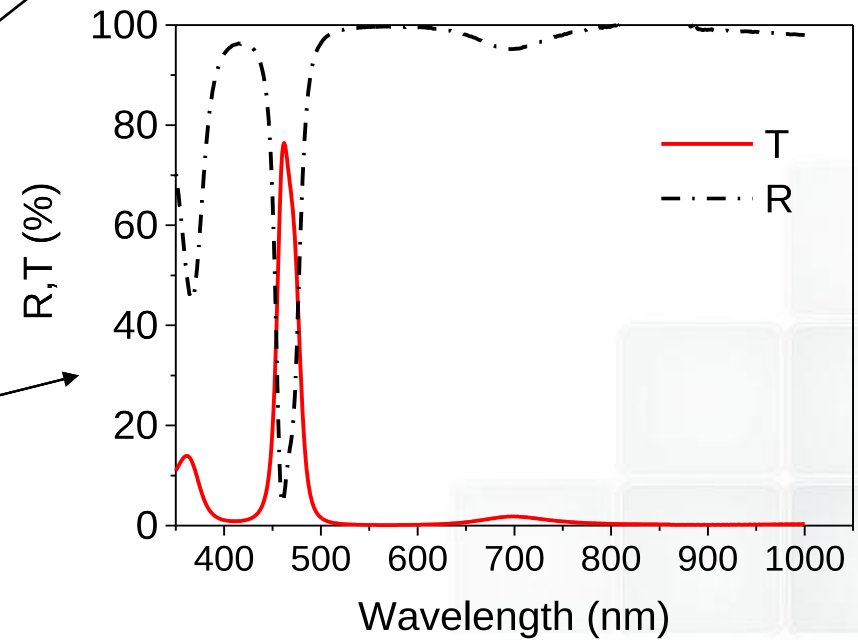
The outband rejection improves with a higher ratio k/n of the metal layer

Induced transmission filters









The peak wavelength is shifted by changing the coating thickness

Filter design at a given peak-wavelength

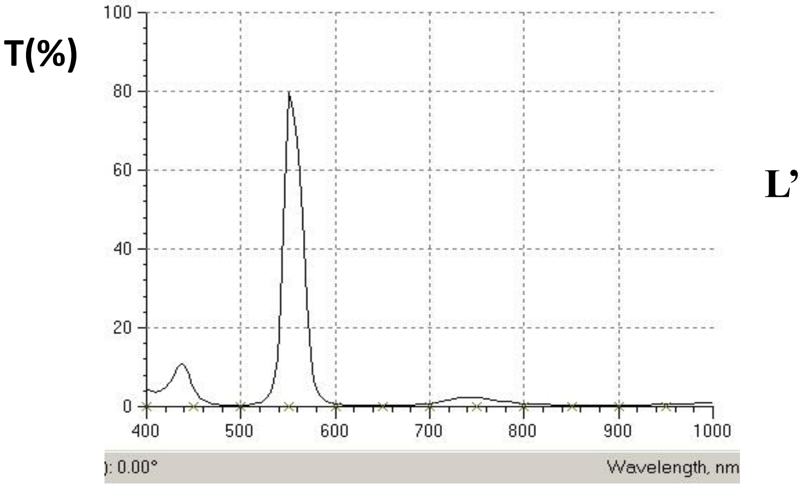
- Choice of the matching stack
  Glass/(HL….)L' Ag L' (….LH)/Air
  H'   H'

***Input data*:**
M= Ag (50 nm) nL=1.47 nH=1.96 λ_0= 550 nm

Output: Potential transmission: **ψ= 0.817**

thickness **L' = 0.1954**, **H' =0.1789**   (quarter-wave =0.25)

17 layers

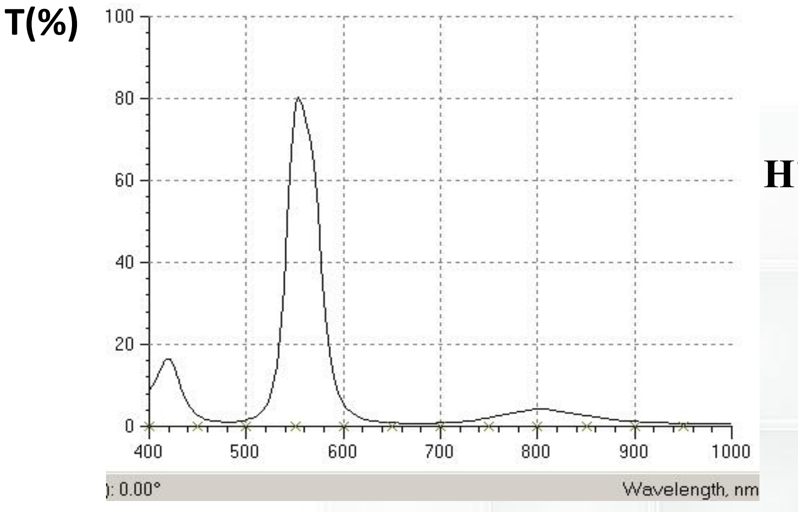


L'

Calculations of the matching index depending on the number of layers

Neff 1 =	19.68	11.99
Neff 2 =	0.19	0.32
Neff 3 =	11.01	6.71
Neff 4 =	0.35	0.57
Neff 5 =	6.16	3.75
Neff 6 =	0.62	1.02 (Glass-Air)
Neff 7 =	3.45	2.10
Neff 8 =	1.11 (Glass-Air)	1.83
Neff 9 =	1.93	1.18

15 layers



H'

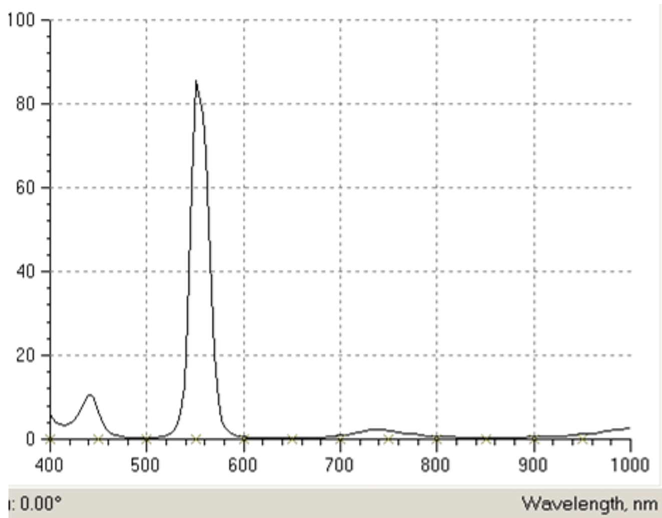
Optimization method

- Optimization is needed to reduce bandwidth and side-lobes

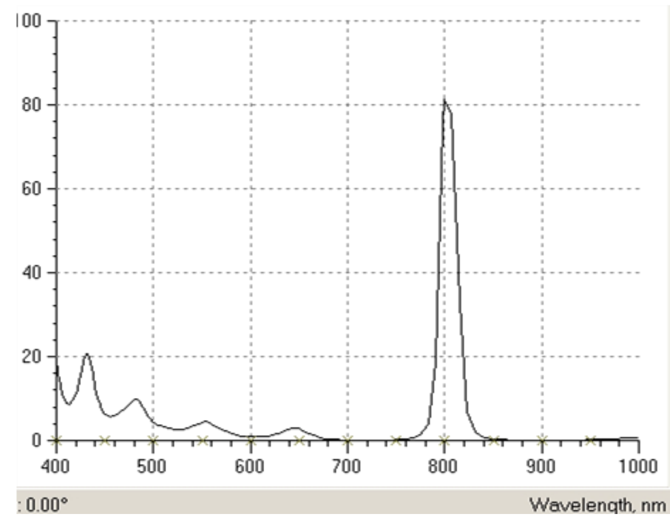
basic design:
Air/HL…L'AgL'…LH/Sub

The coating structure
(sequence and number of layers) must be maintained at different peak-wavelengths

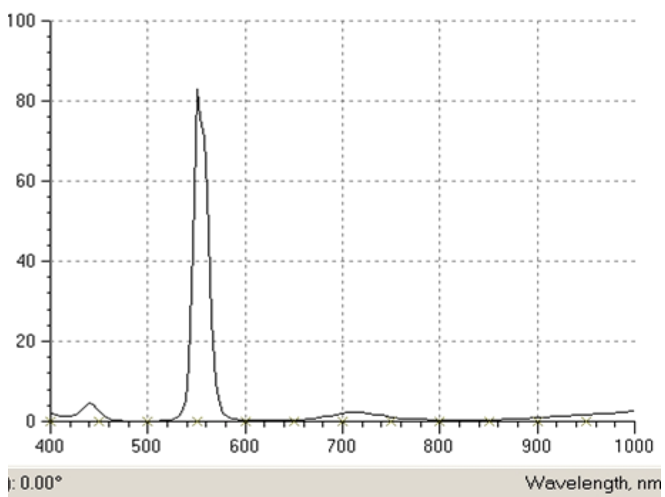
after optimization

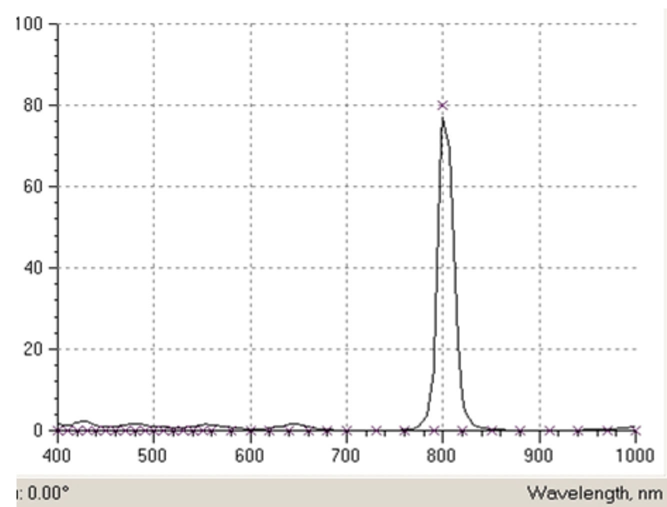


λ_0=550 nm 17 layers



λ_0=800 nm 19 layers



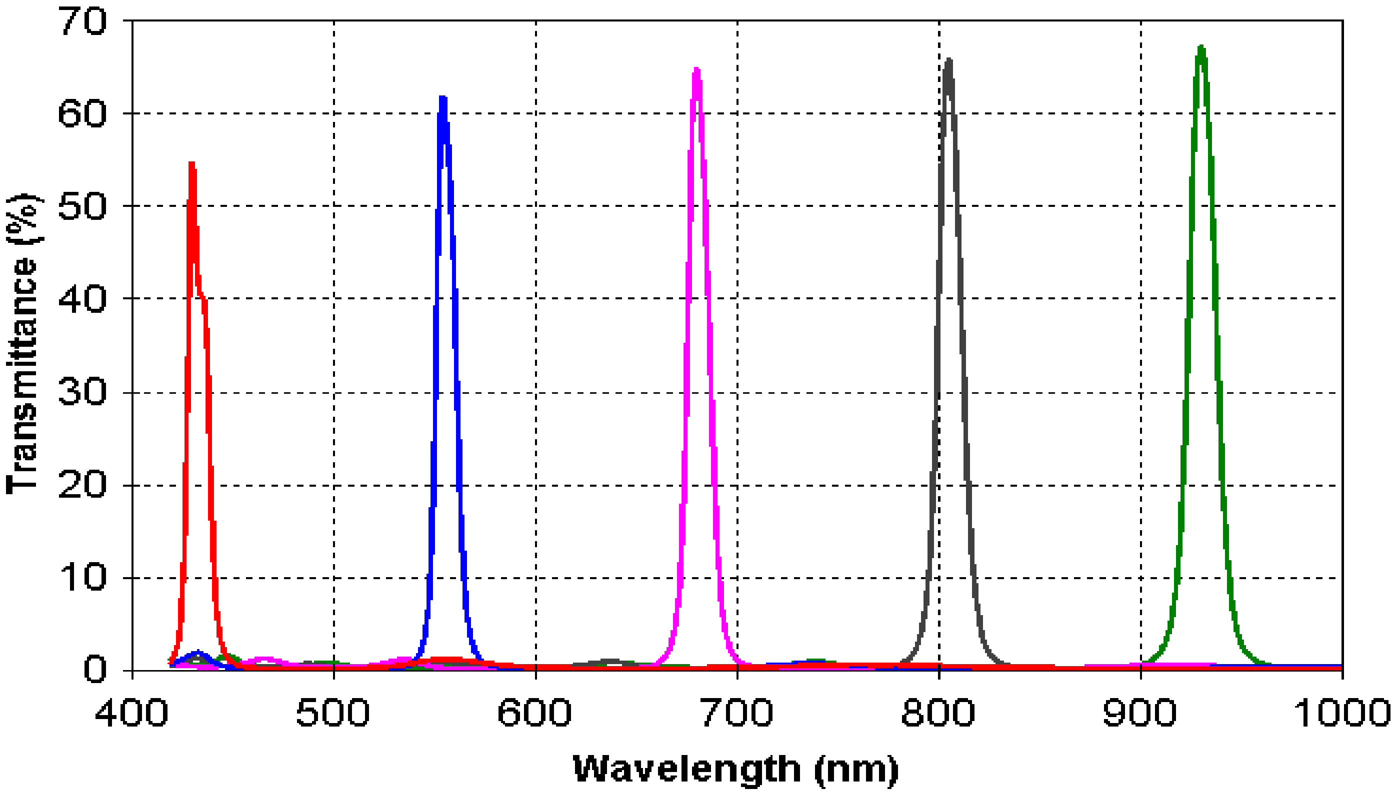


λ_0=550 nm (same number of layers) λ_0=800 nm

Final filter design

Induced transmission filter: 1 silver layer surrounded by 20 SiO_2/Ta_2O_5 alternate layers

Bandwidth 10-15 nm, T ~70% at λ_0=900nm



Variable MD filter: design process

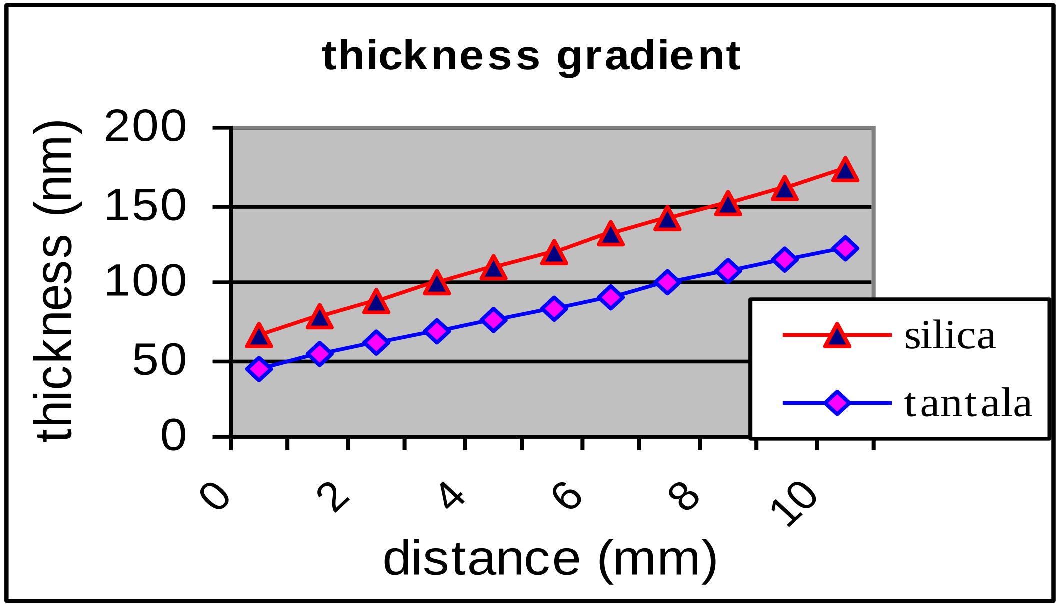
- Select the metal and its thickness
- Calculate the matching assembly
  (L' LHL……)
- Introduce measured index (dispersion) of all materials
- Optimize the design for a selected peak wavelength
  and control the performance at other peak positions
- Calculate the spatial variation of each layer thickness for obtaining the required variation of λ_0 , without changing the design (number and sequence of layers)

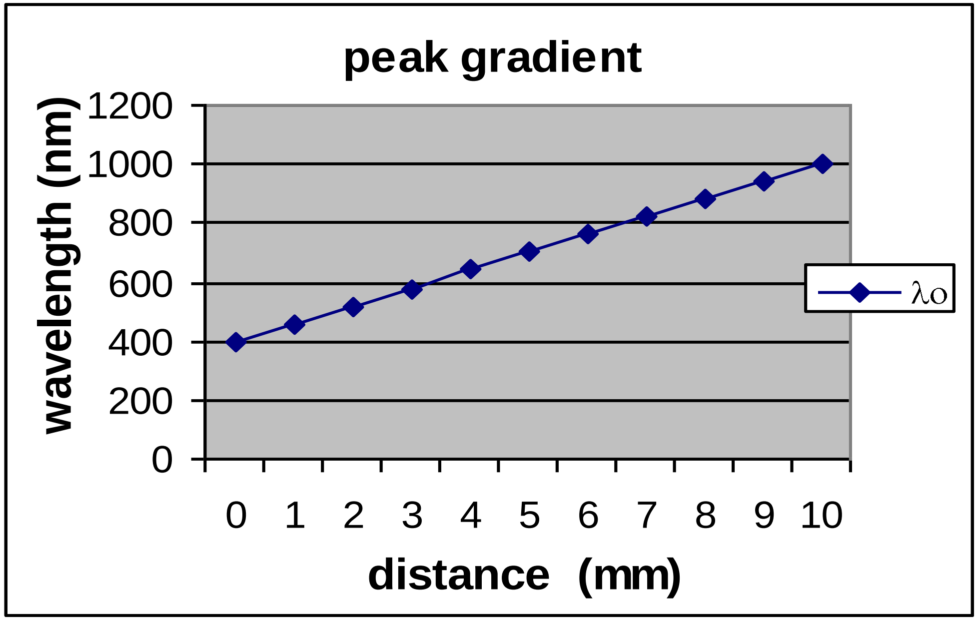
Peak-wavelength and thickness gradient

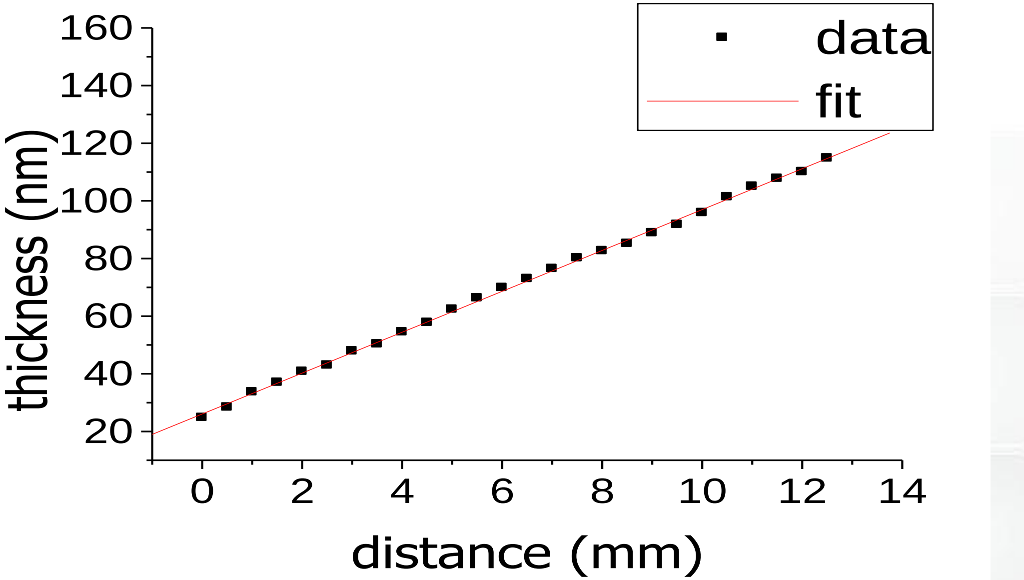
- Layer thickness

  $t = q\,(\lambda_0/4n)$

  $t_{max}/t_{min}=(1000/400)\,(n_{400}/n_{1000})$

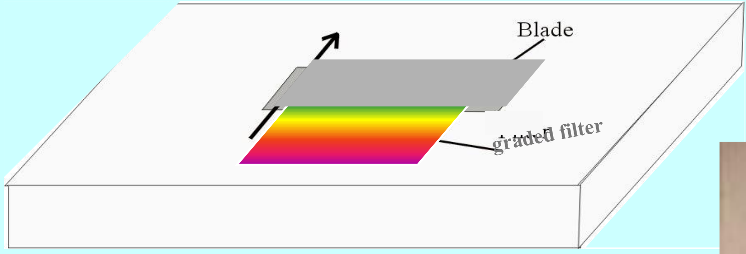


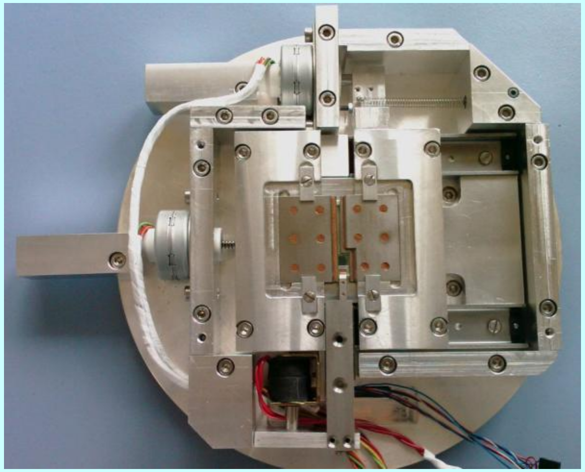




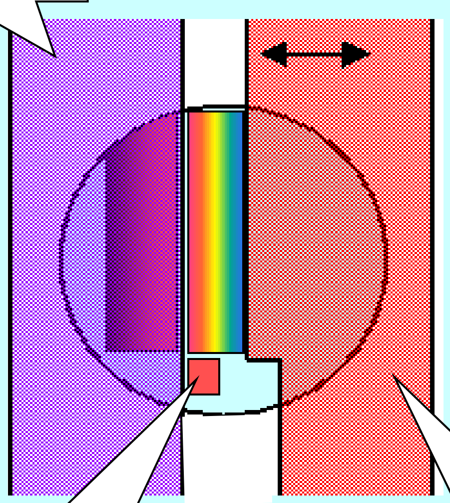
Masking apparatus for graded coatings

- Masking blade moved during film deposition
- Coating profile controlled by mask speed



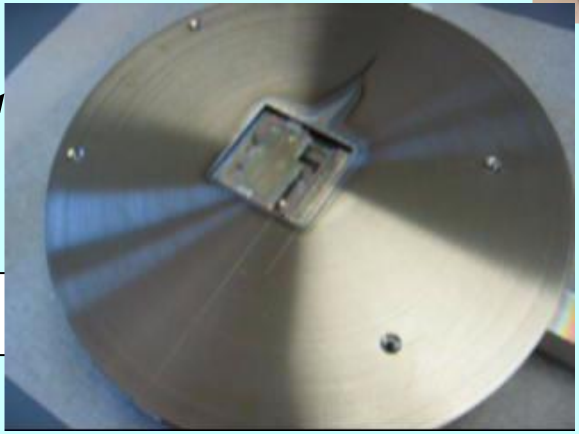


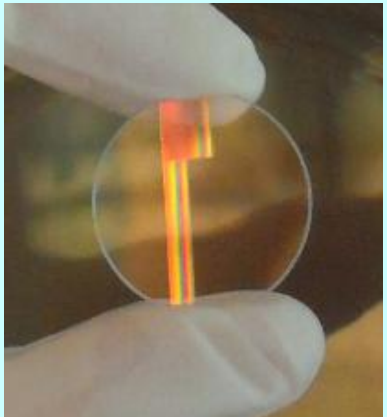
Fixed mask to cover the adjacent filter



Uniform area for optical monitoring

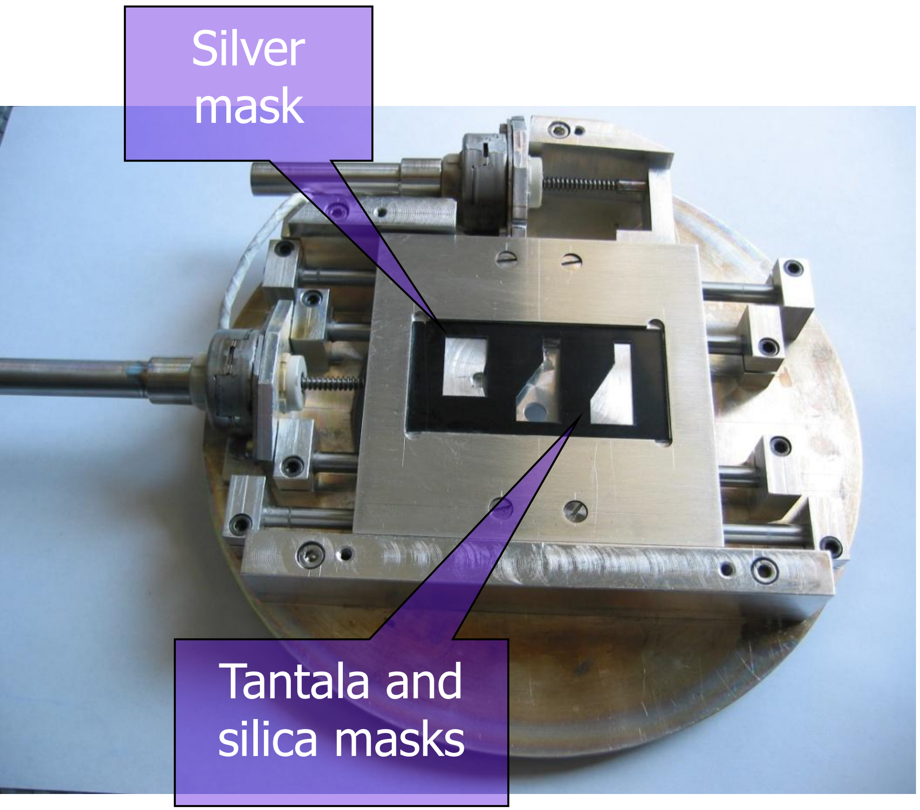
Movable mask

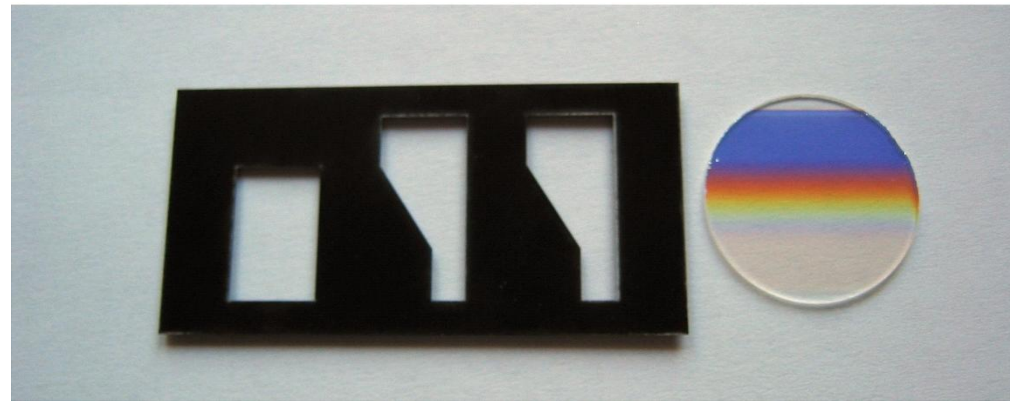


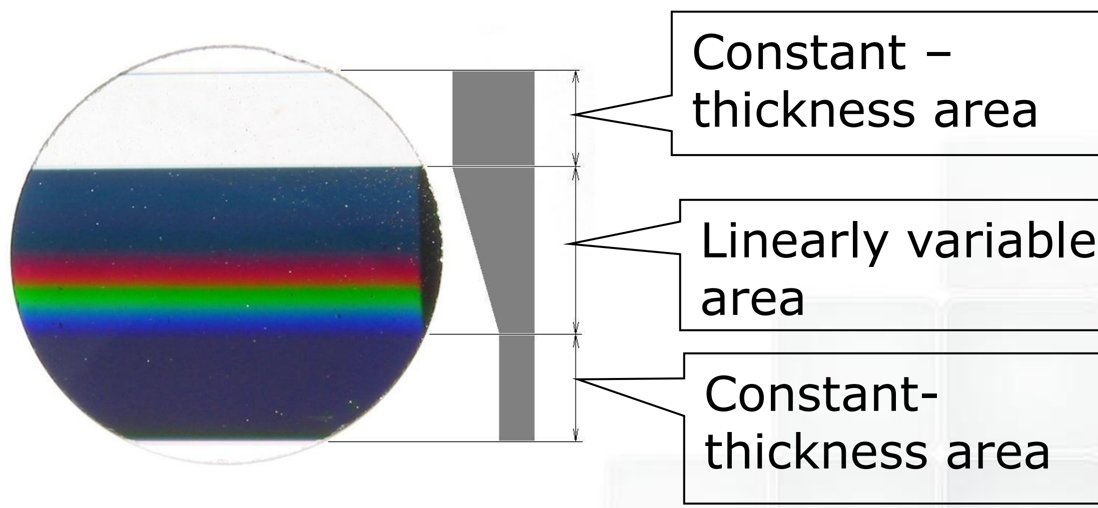


Filter fabrication: masking apparatus

Fixed mask: alternative method not suitable for adjacent filters

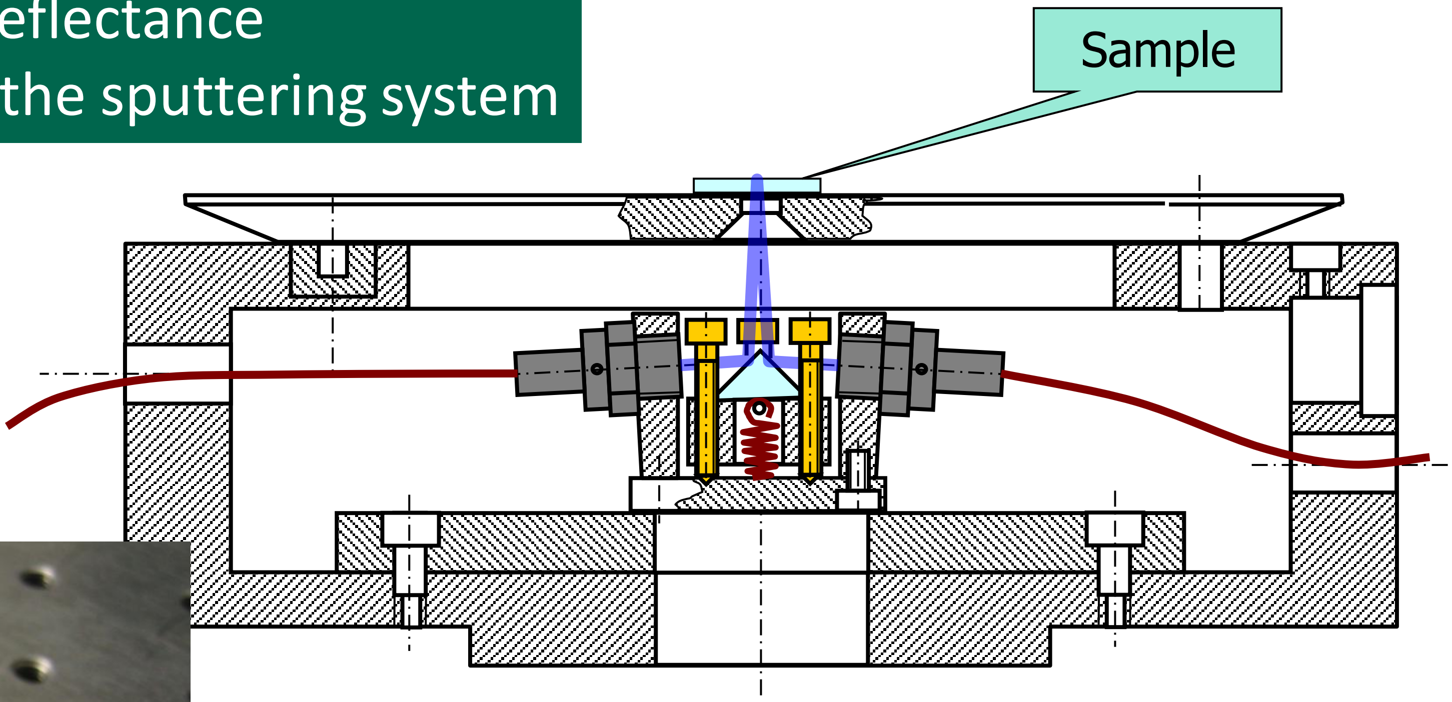


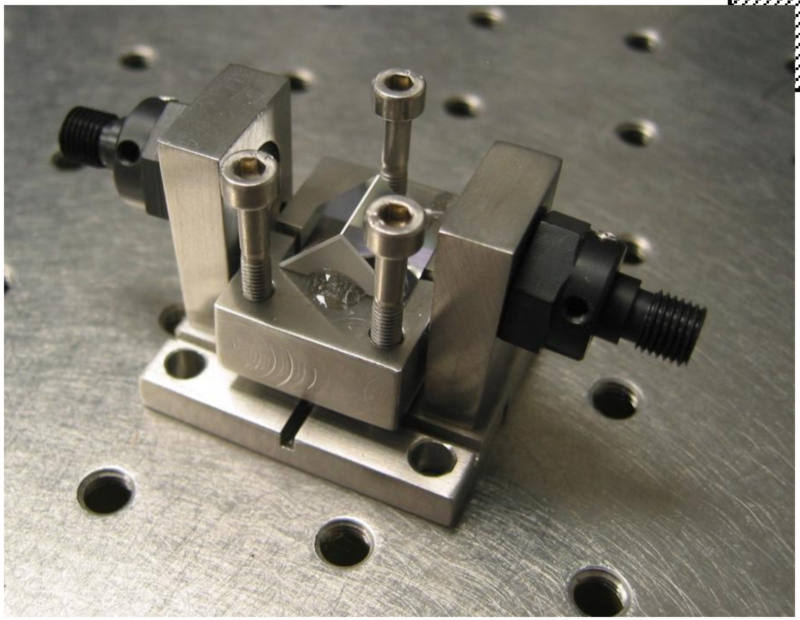




On-line reflectance measurements

Apparatus for online reflectance measurements inside the sputtering system



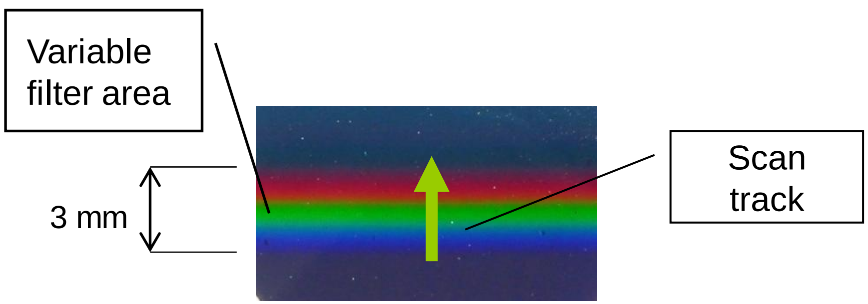


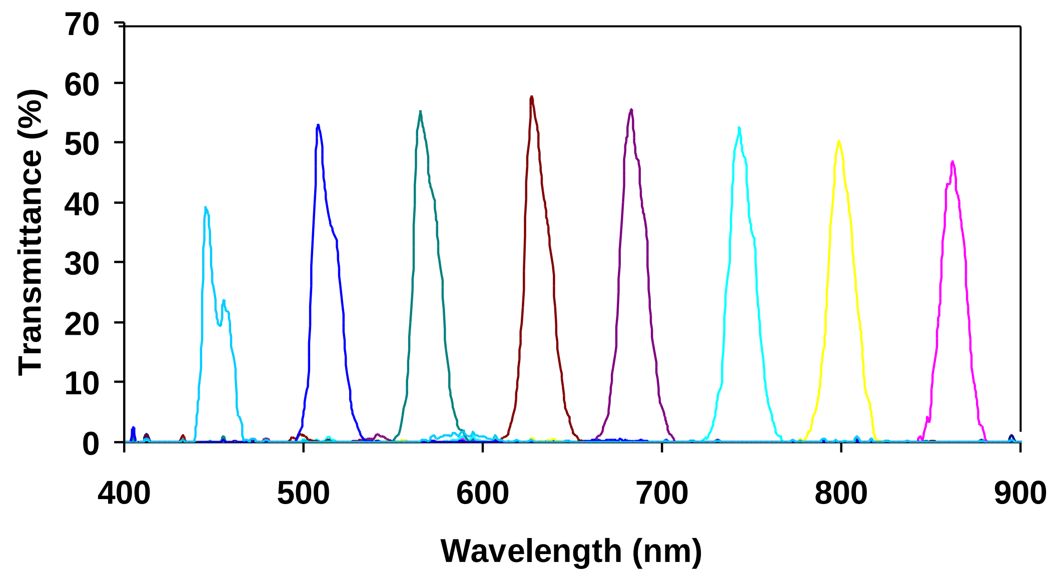
- Optical fibers
- Aluminum coated prism
- Collimating optics
- Adjusting screws

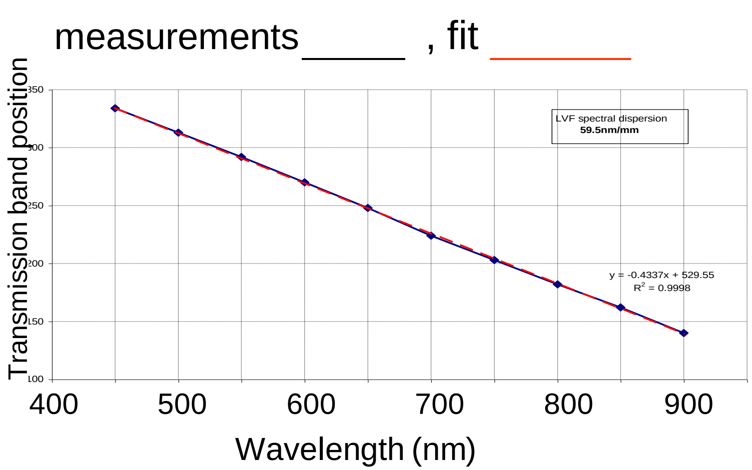
Localized Transmittance measurements

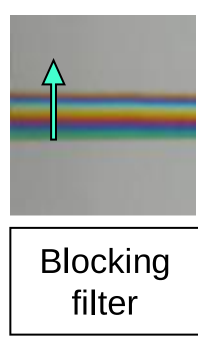
- Measurements are carried out by a dedicated set-up

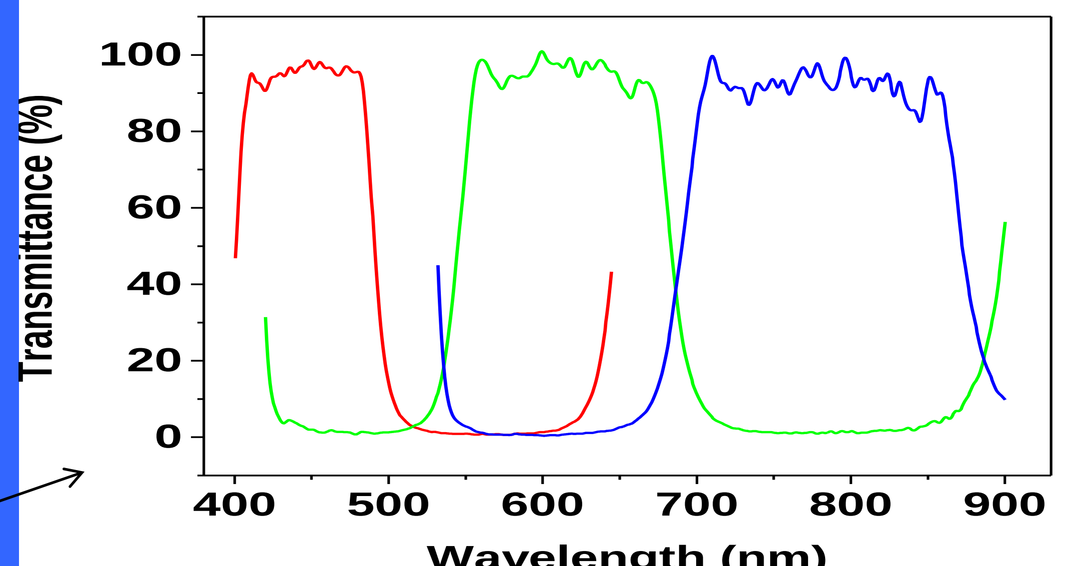
> - **Characterization range: 400 ÷ 1000nm**
> - **2-D translation micrometric system: min step 25 μm**
> - **Spectral resolution: < 2 nm**
> - **Spatial resolution: < 20 μm**





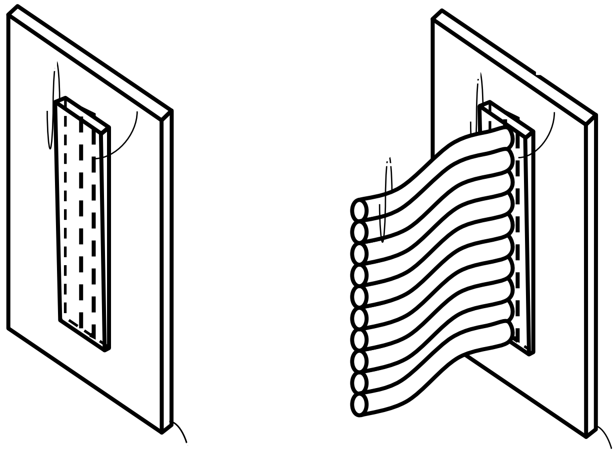






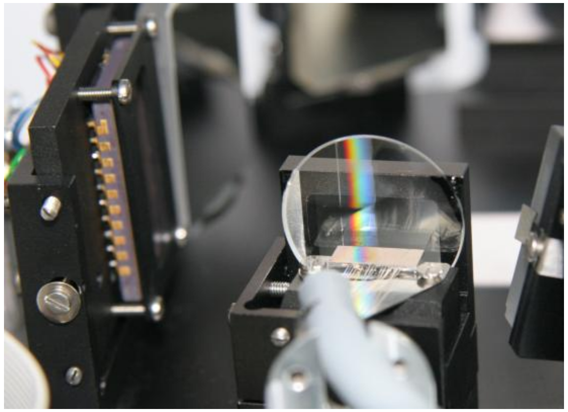
Non-linear Variable Filters

High-resolution spectrometer dedicated to planetary missions (ESA project)



Filter at the entrance slit of the spectrometer

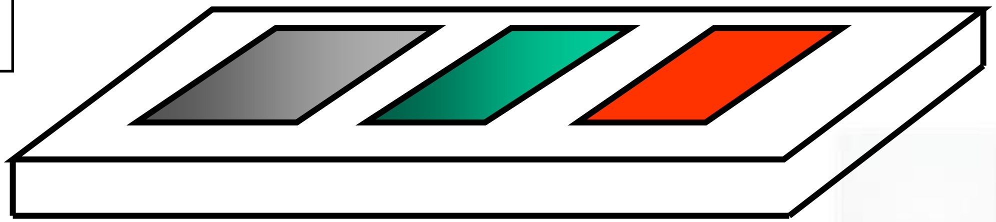
the beam is carried to the slit by optical fibers



Three filters operating in different wavelength ranges

Three different gradients or non-linear spatial profile

Filter dimensions: few mm



Operating spectral range: 300-800nm

Non-linear variable edge filters

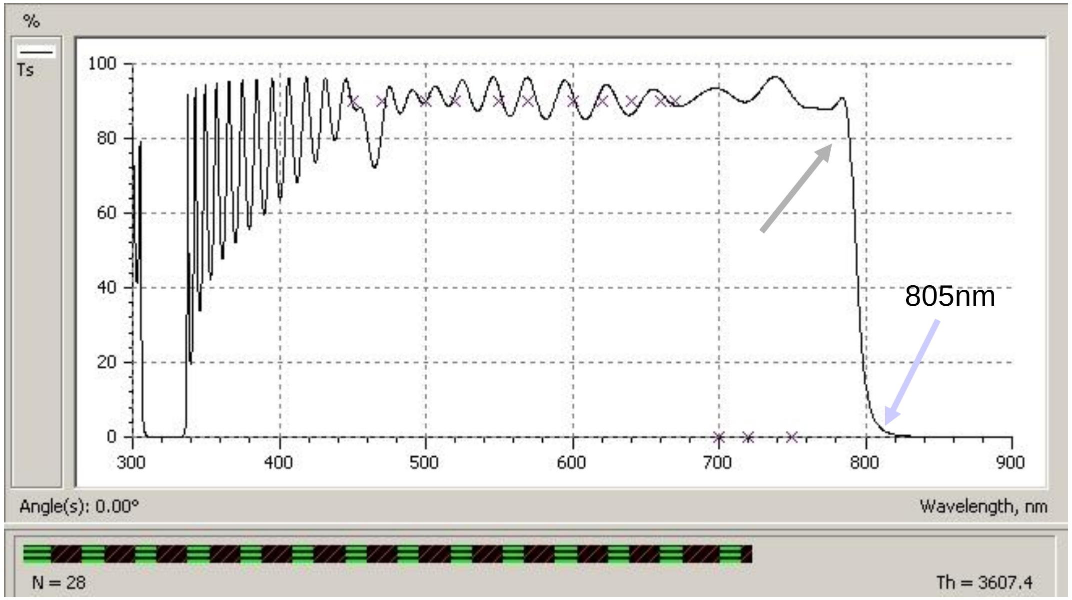
ENEA
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

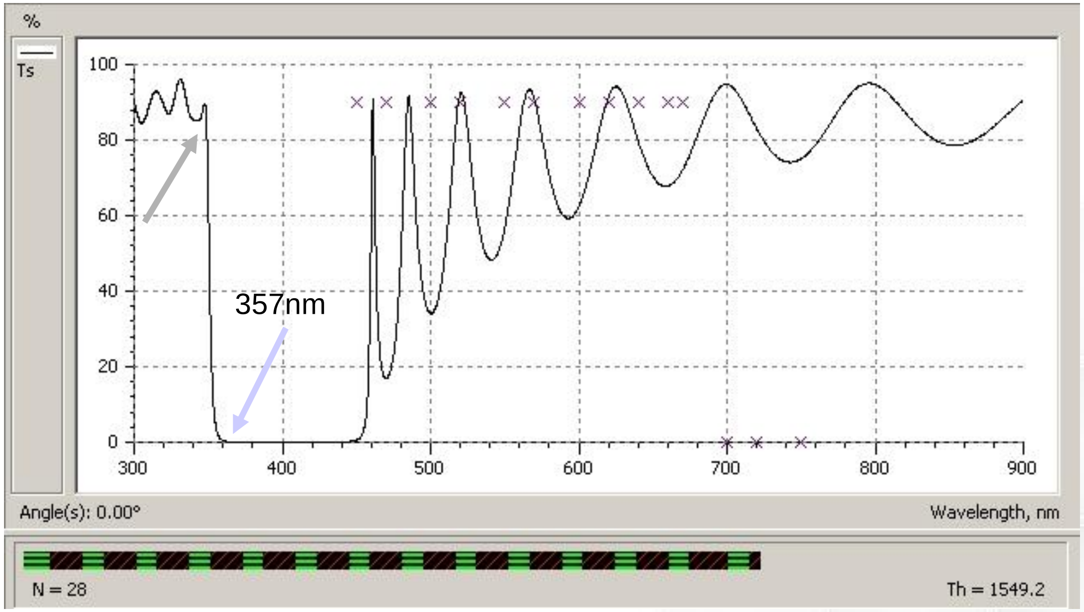
- Low-pass filter
  28 layers (SiO_2 - Ta_2O_5)

  Operating range
  339-805nm

The edge wavelength is moved according to a nonlinear equation, over a distance of 4 mm

The edge slope must be also controlled @T=5% and @T=80%



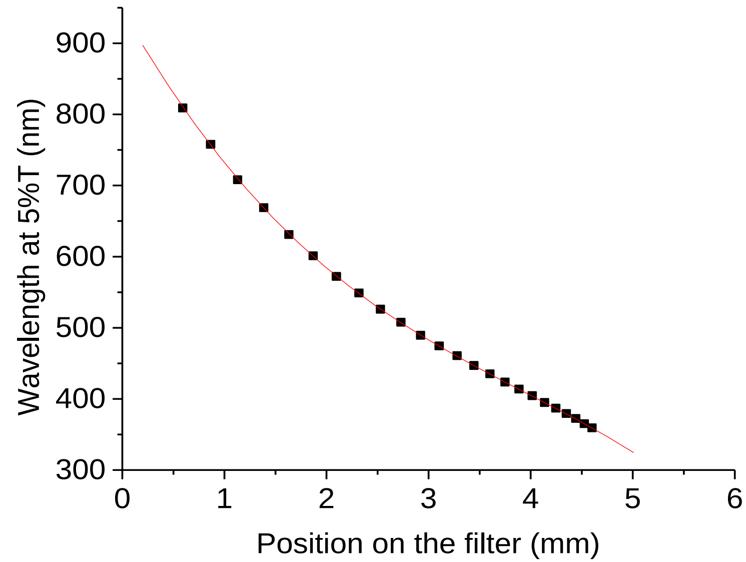


Non linear variable thickness

- variable filter design (non-linear)

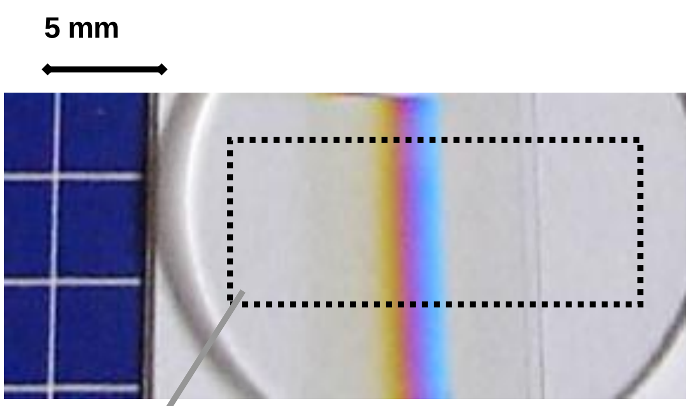
28-layer low-pass filter (tantala – silica)

Variation of edge wavelength as function of the spatial position →



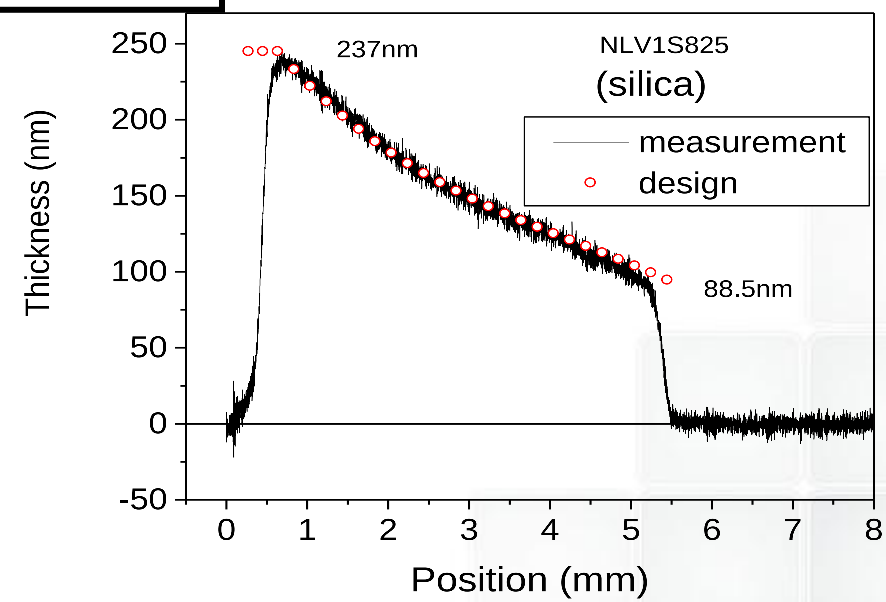
From this curve, the required variation of each layer thickness can be calculated

Sample picture

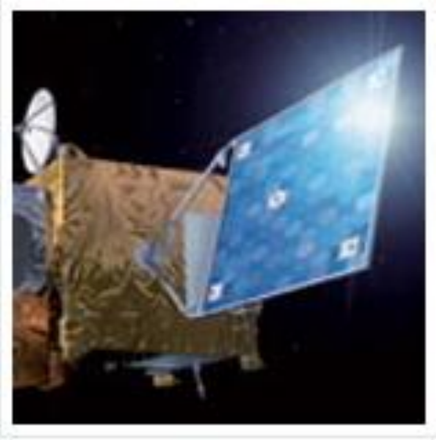


useful area

Silica thickness profile



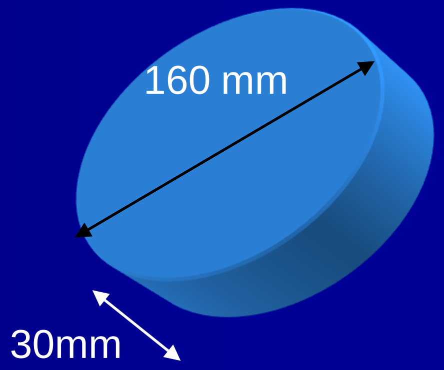
2. Lightning Imager



- The Lightning Imager is an instrument of METEOSAT (MTG), for the study of lightning phenomena in the atmosphere

- Filter must discriminate (from the background) the light generated by lightning

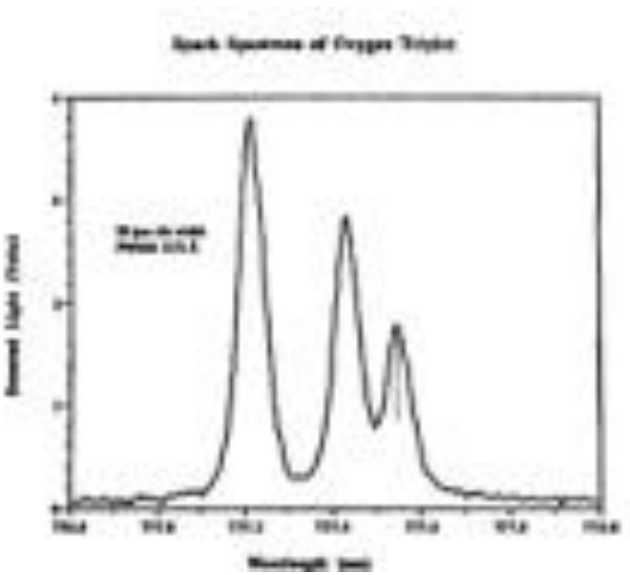
Filter requirements
- Transmission bandwidth 0.45 nm
- In-band Transmission: 0.8
- Out-band Transmission: 10^{-4}
- Dimensions: 160 mm diameter



Study of lightning phenomena

ESA Earth Observation Program:

- **Monitoring of lightning activities on Earth is an essential element in the Weather Prediction**
- **The strongest emission features in the cloud top optical spectra are produced by the neutral oxygen and neutral nitrogen lines. The Oxygen line triplet is located between 777.15 and 777.6 nm**



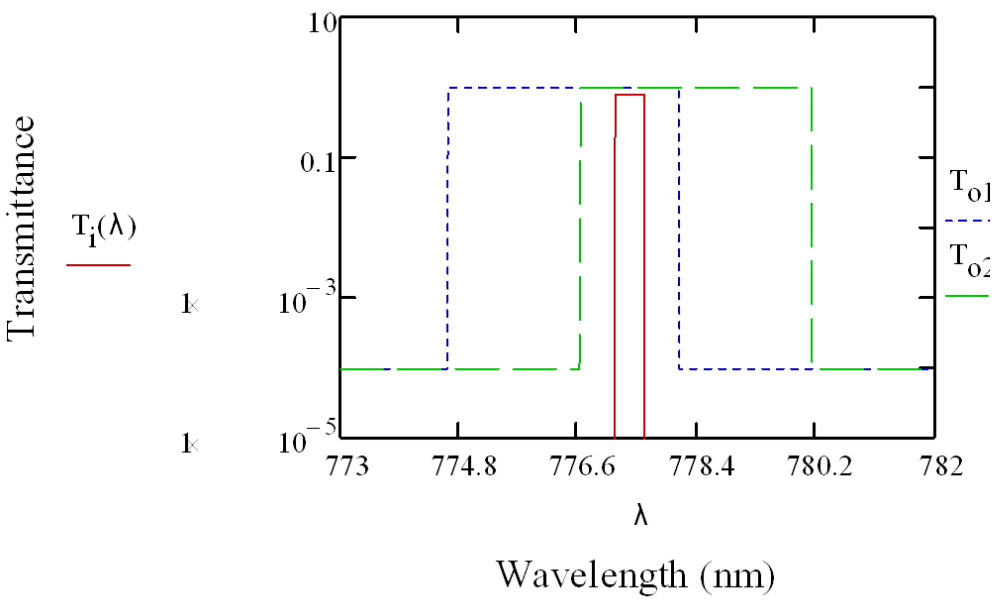
Lightning Imager as part of METEOSAT THIRD GENERATION

Transmitted bandwidth: 0.45 nm

Operating wavelength range: 300-1500 nm

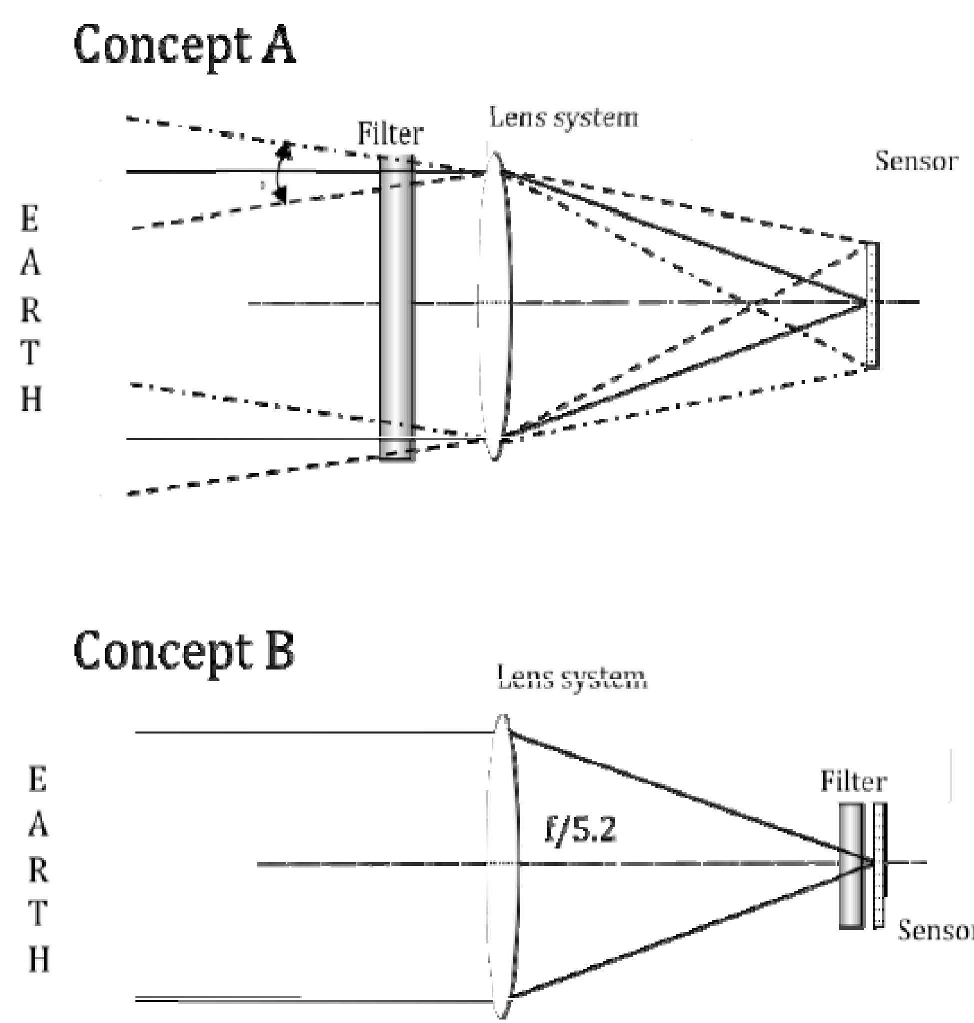
Filters for the Lightning Imager

Filter optical requirements



The wavelengths of interest must be transmitted for all incidence angles in a range of +/- 5.5° or in a cone angle of +/- 5.5°

Instrument possible configurations

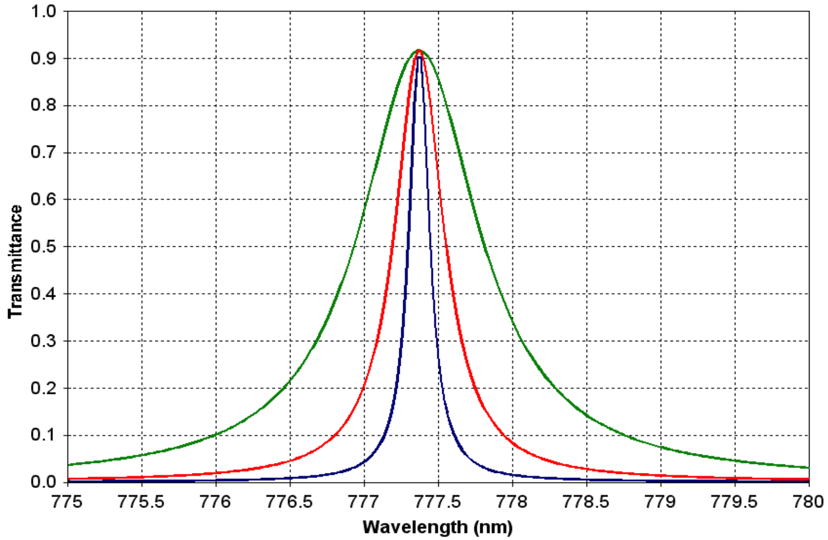


Filter Optical Requirements

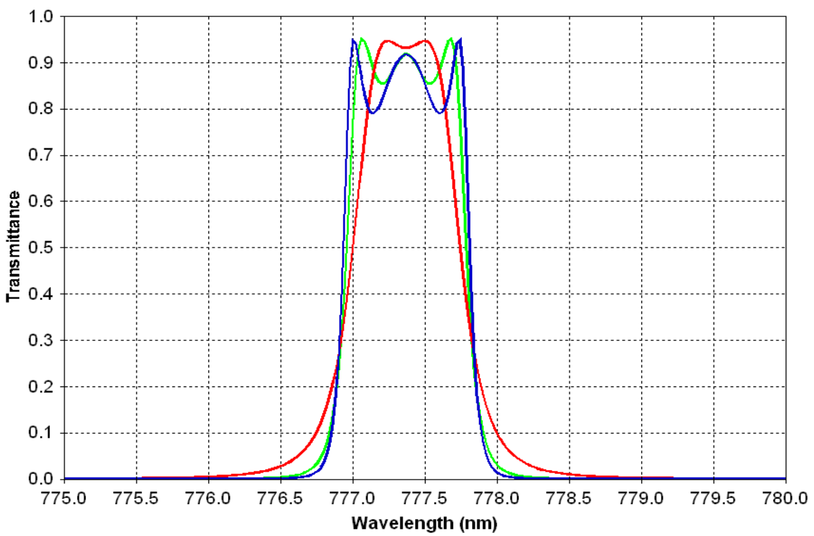
<u>Lightning useful spectral range and transmittance</u>

Useful spectral range:	777.145 – 777.595 nm
Transmittance in the useful spectral range:	0.8

The useful wavelength range is very narrow Δλ=0.45 nm.
If a high value of transmittance (> 80%) is required in this range, decreasing rapidly to a very low values (10^{-3} - 10^{-4}) out of this range, the transmission band should have an "almost" rectangular shape.



Fabry-Perot filter (single cavity, SiO2/TiO2), varying the number of layers (green 25, red 29, black 33)



Multiple-cavity filter, varying the number of cavities (red 2, green 3, blue 4) and of layers (red 51, green 77, blue 104)

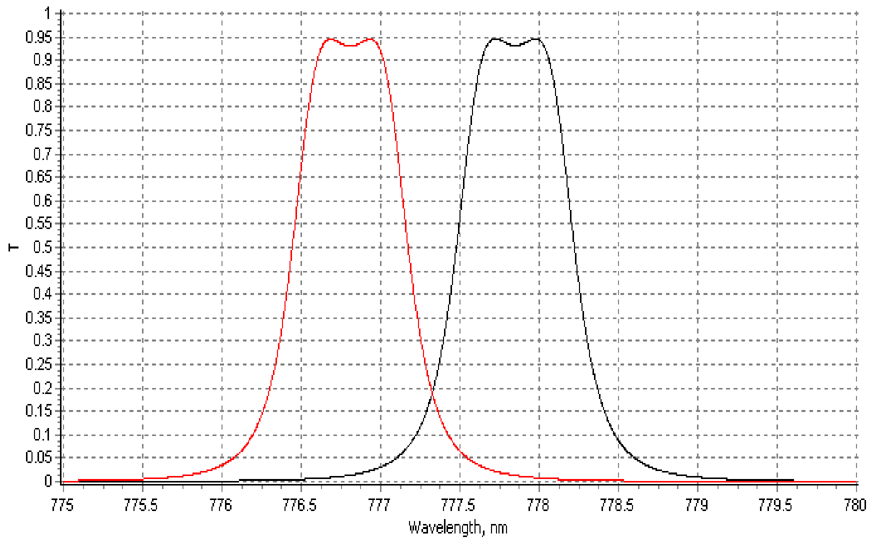
Filter Optical Requirements

ENEA
AGENZIA NAZIONALE PER LE NUOVE TECNOLOGIE, L'ENERGIA E LO SVILUPPO ECONOMICO SOSTENIBILE

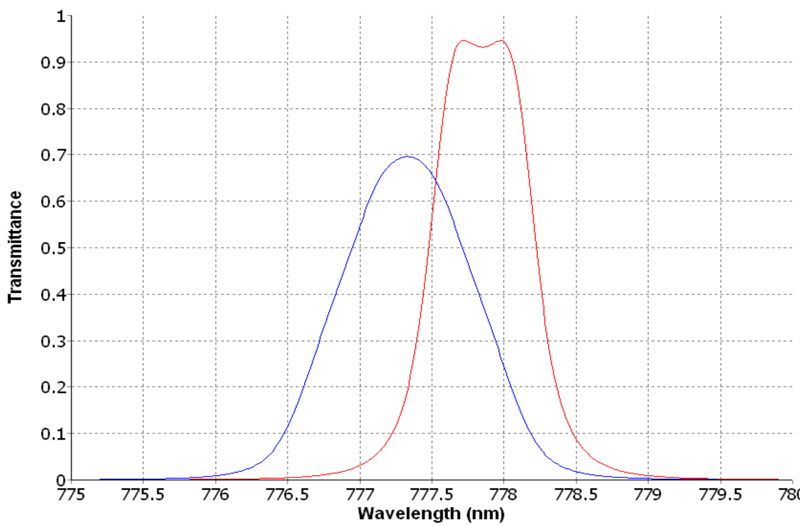
Angle of incidence

Angle of incidence:	8 degrees collimated beam (initial req.) 5.5 (new req.) 5.5 degrees semi-angle of convergent beam

This requirement is very critical because interference filters are very sensitive to angle variations. A narrow band filter which bandwidth is of the order of 1 nm can be completely out of specifications with an angle of incidence of only few degrees.



double-cavity filter (51 layers, TiO_2/SiO_2, bandwidth ≤1nm) with a variation of the incidence angle from 0 (black) to ±5.5 degrees (red)



double-cavity filter (51 layers) with a convergent beam of cone semi-angle 5.5 degrees (blue) compared to normal incidence (red)

Filter Optical Requirements

Angle of incidence

Theoretical formulas for small incidence angles (<20 degrees): change in position (δλ) and bandwidth (Δλ)

- *Concept A*

$\vartheta = \pm 5.5°$

$$\left(\frac{\delta\lambda}{\lambda_0}\right)_\theta = -\frac{\theta^2}{2\mu^{*2}}$$

$$\frac{(\Delta\lambda_{0.5})_\theta}{\Delta\lambda_{0.5}} = \left[1 + \left(\frac{\theta^2\lambda_0}{\mu^{*2}\,\Delta\lambda_{0.5}}\right)^2\right]^{1/2}$$

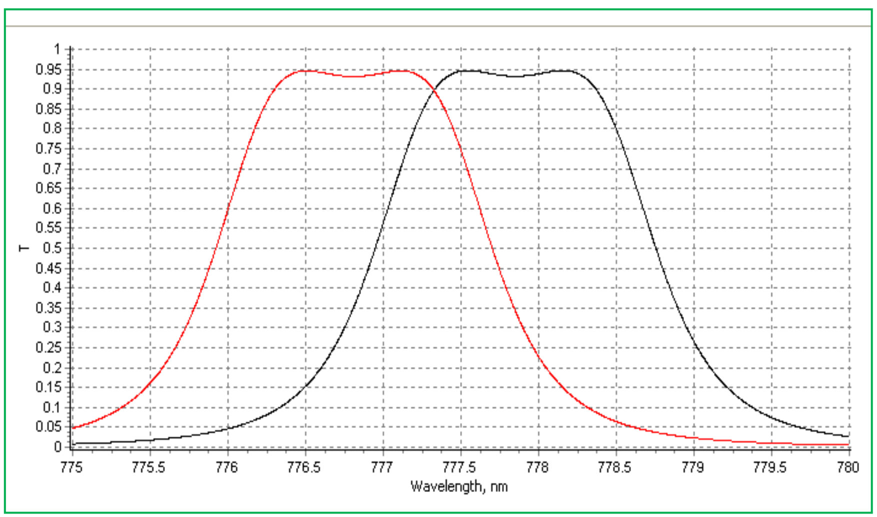
- *Concept B*

semi-angle *α = 5.5°*

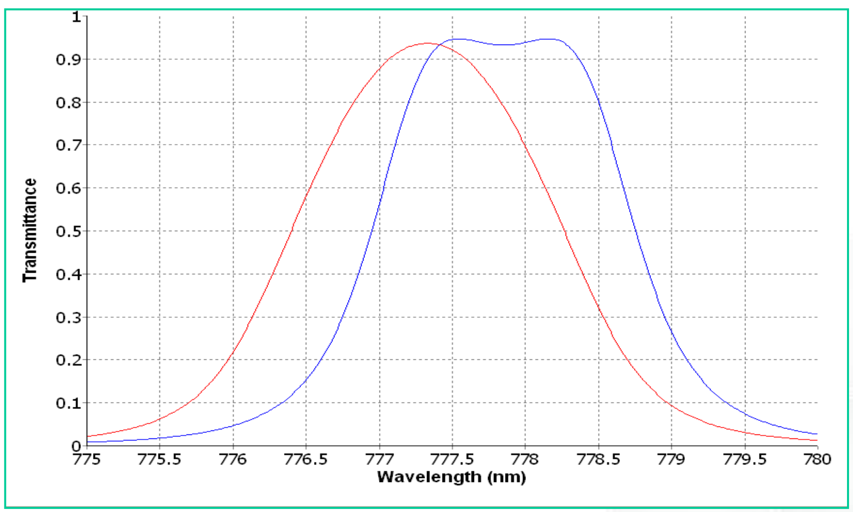
$$\left(\frac{\delta\lambda}{\lambda_0}\right)_\alpha = -\frac{\alpha^2}{4\mu^{*2}}$$

$$\frac{(\Delta\lambda_{0.5})_\alpha}{\Delta\lambda_{0.5}} = \left[1 + \left(\frac{\alpha^2\lambda_0}{2\mu^{*2}\,\Delta\lambda_{0.5}}\right)^2\right]^{1/2}$$

The higher is the value of μ^* (effective index), the lower is the performance deterioration



Double-cavity filter (43 layers, TiO2/SiO2, bandwidth 2 nm) with a variation of the incidence angle from 0 (black) to ± 5.5 degrees (red)

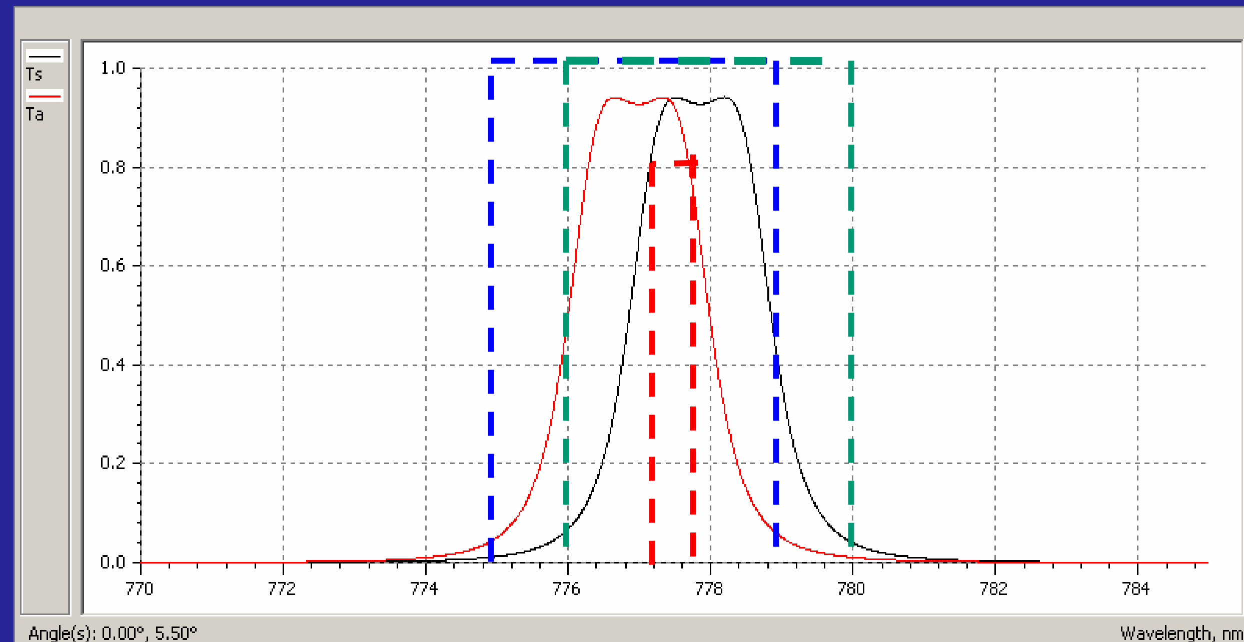


The same double cavity filter with a convergent beam of cone semi-angle 5.5 degrees (red), compared to normal incidence (blue)

Narrow-band filter design

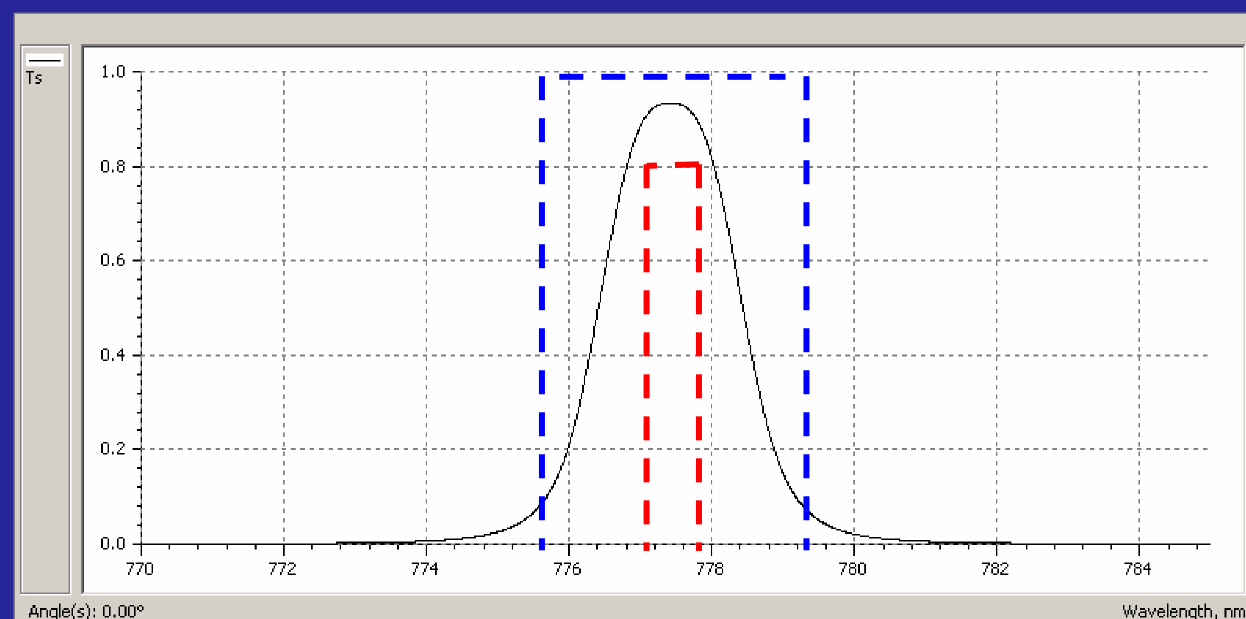
- Narrow-band filter:
  Fabry-Perot double cavity
  35 layers (SiO_2 - TiO_2)

  bandwidth FWHM = 3 nm



- **Collimated beam**
- **Convergent beam**

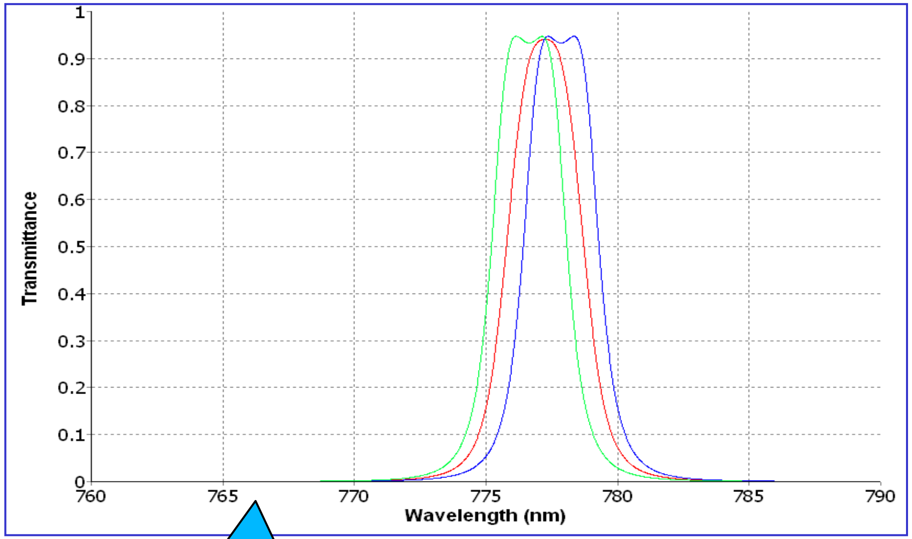
± 5.5°



- A sun-blocking filter is needed for the required outband rejection ($<10^{-4}$)

Alternative materials (and design)

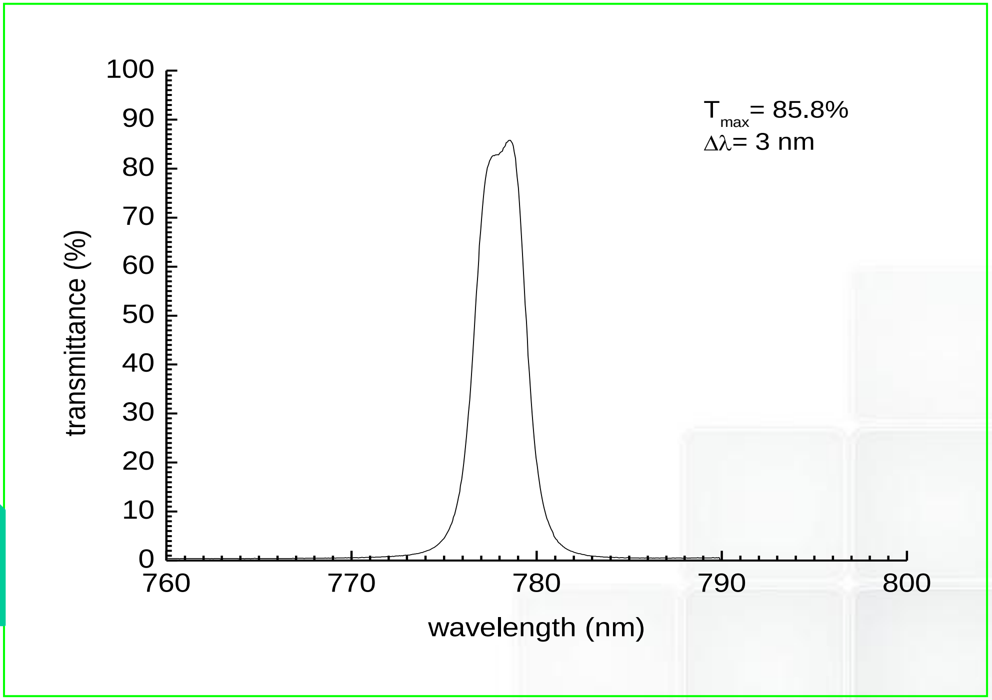
- Narrow-band Filter (51-layer double-cavity filter , HfO_2/SiO_2)



Calculated transmittance at normal (blue) and oblique incidence (red and green)

The use of a lower index material HfO_2 (as H layer) requires a higher total number of layers for obtaining the same result, and the filter is more sensitive to oblique incidence

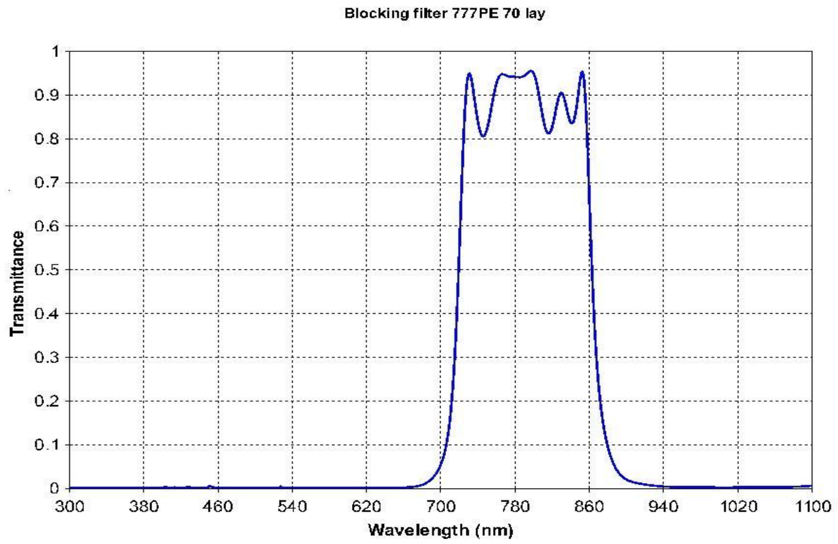
Experimental result

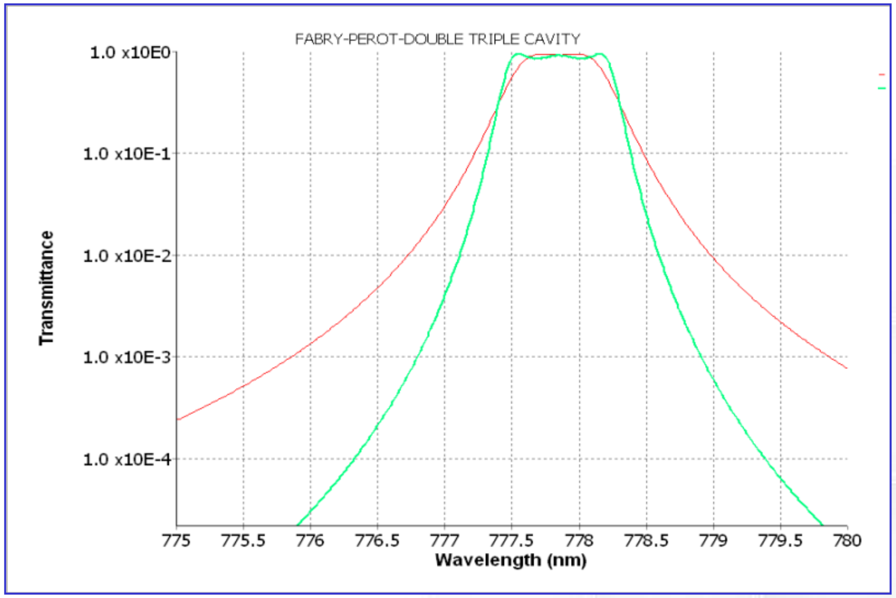


Filter Optical Requirements

Out of band spectrum

- The whole out-of-band spectrum (300-1100 nm) is quite large and a wide-band blocking filter must be added to the narrow-band filter.
- The most inner part of the spectrum (close to the pass band) is assumed to be rejected by the narrow-band transmittance filter itself.
- This point is important to avoid more complex blocking filters.

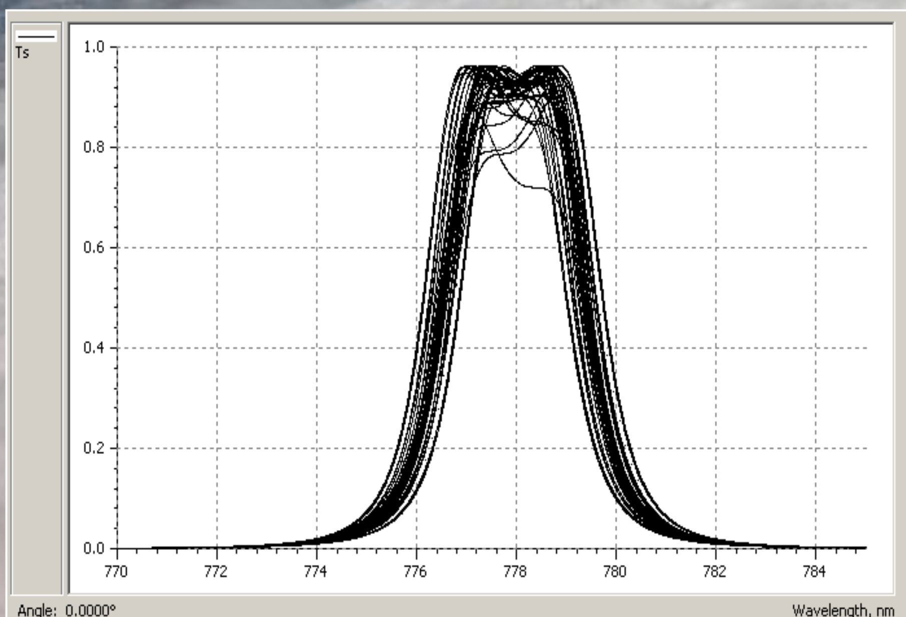


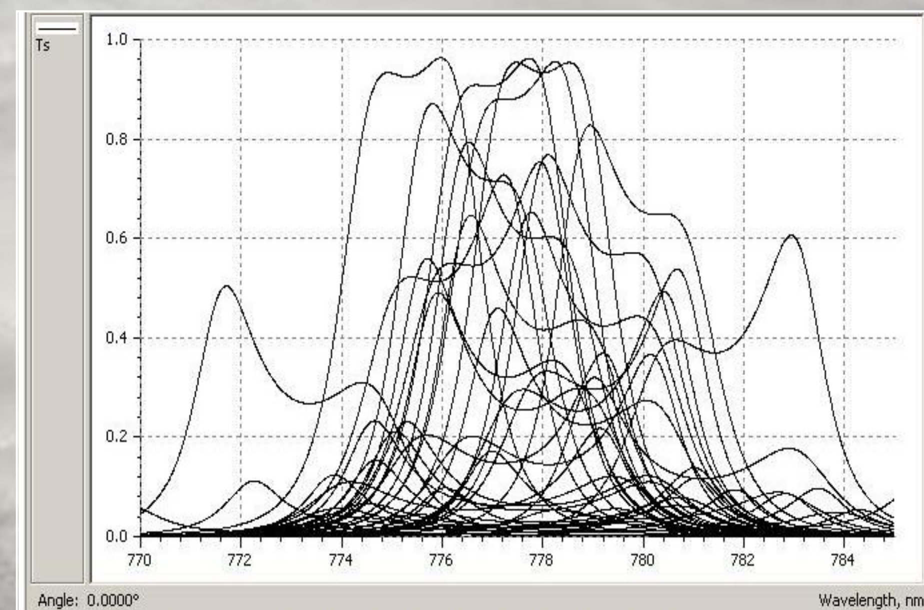


Manufacturing challenges

Challenging requirements:

- Precise spectral positioning
- Bandwidth accuracy
- High uniformity (diameter 100 -160 mm)

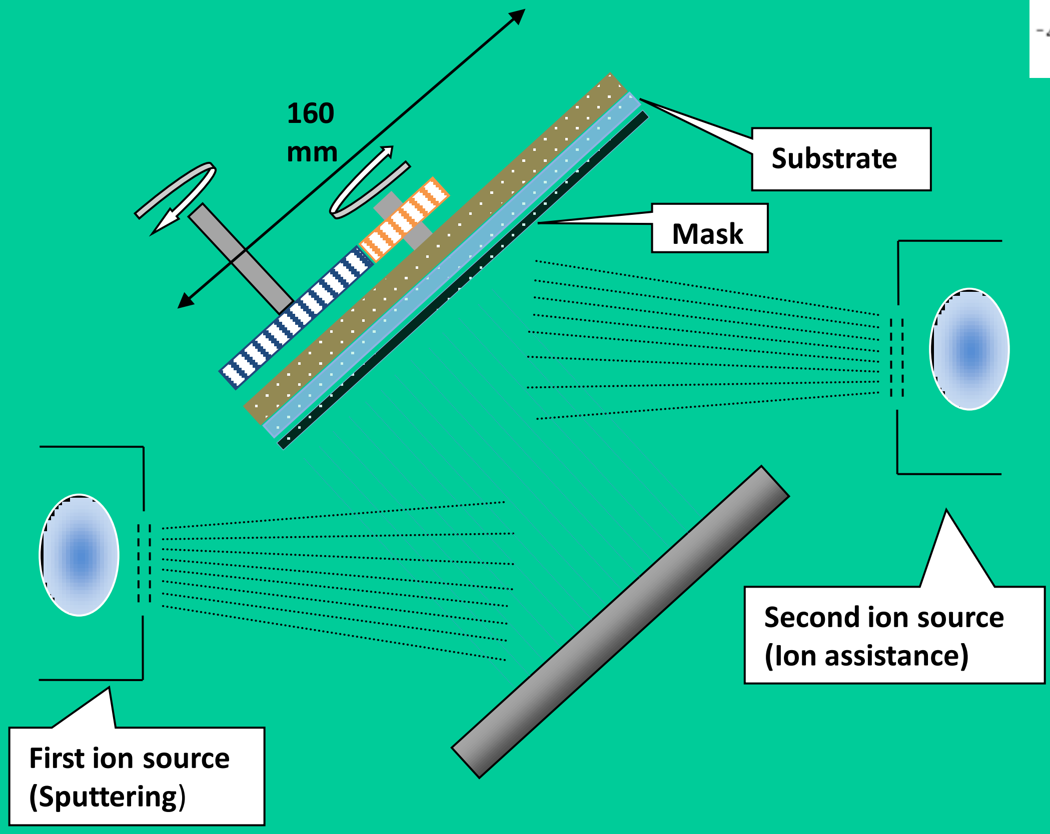


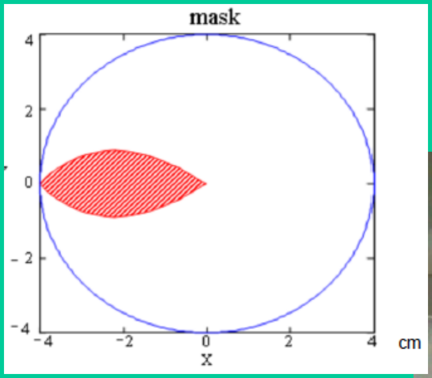


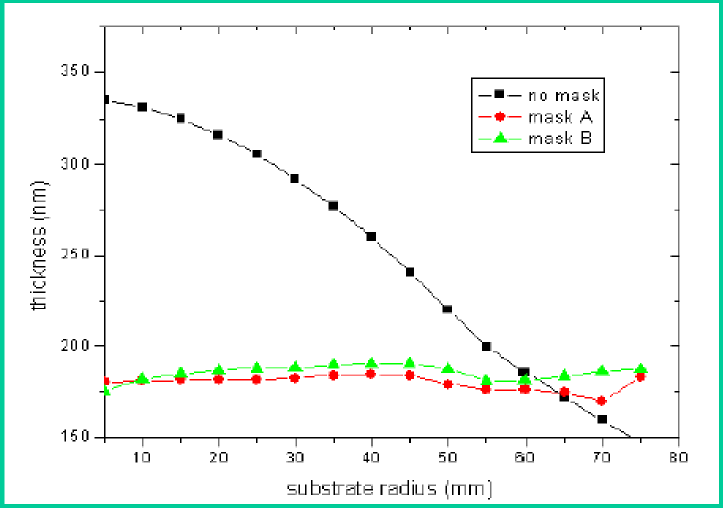
Effects on the transmission band of random errors of 0.1% and 1%, in all layer thicknesses

Masking apparatus for large area coatings

- **Ion beam sputtering deposition**
- **Profiled mask to improve uniformity designed by software**





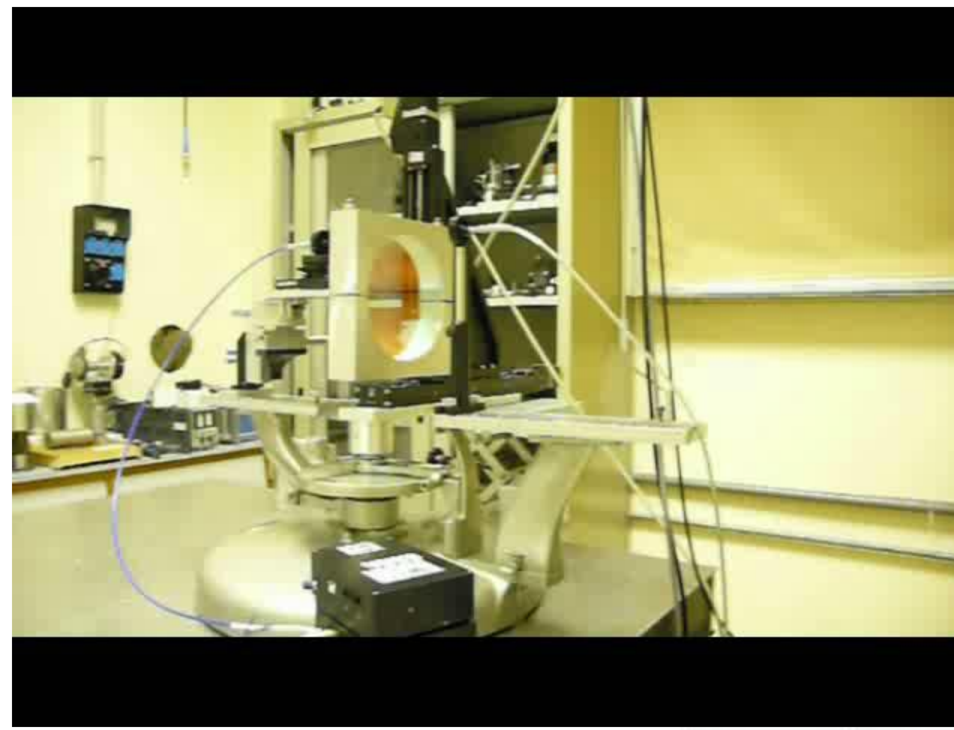


Comparison of the radial profile of a TiO_2 layer thickness with and without mask

Manufacturing techniques and testing

Two deposition techniques are used:

- Dual Ion Beam Sputtering, DIBS
- Electron beam evaporation with ion assistance, e-IAD

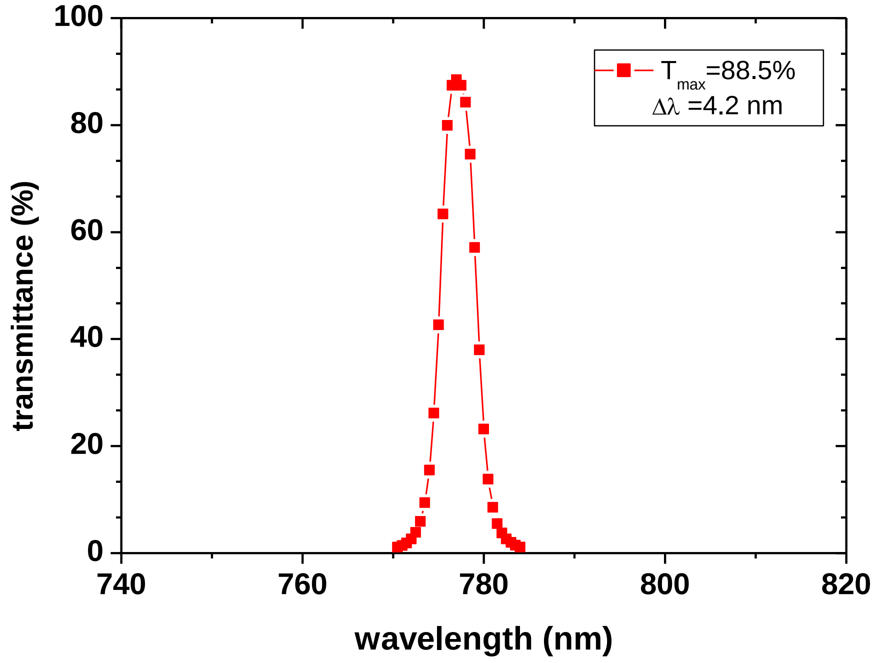


A dedicated setup is needed for mapping the transmittance over the whole surface

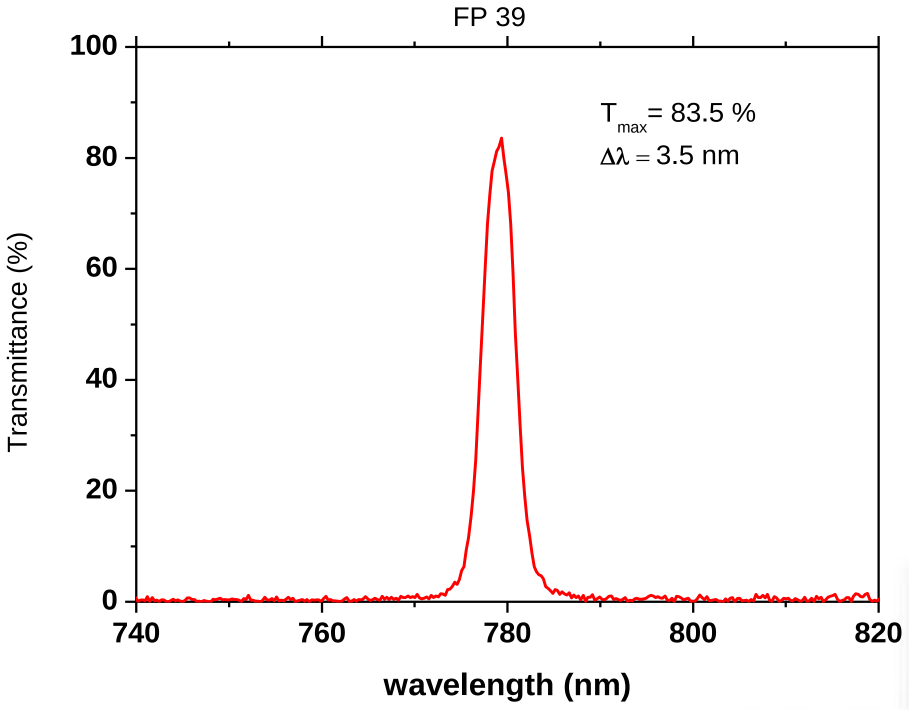
Measured optical performance

Narrow-band filter (35 layers)

electron beam evaporation



ion beam sputtering

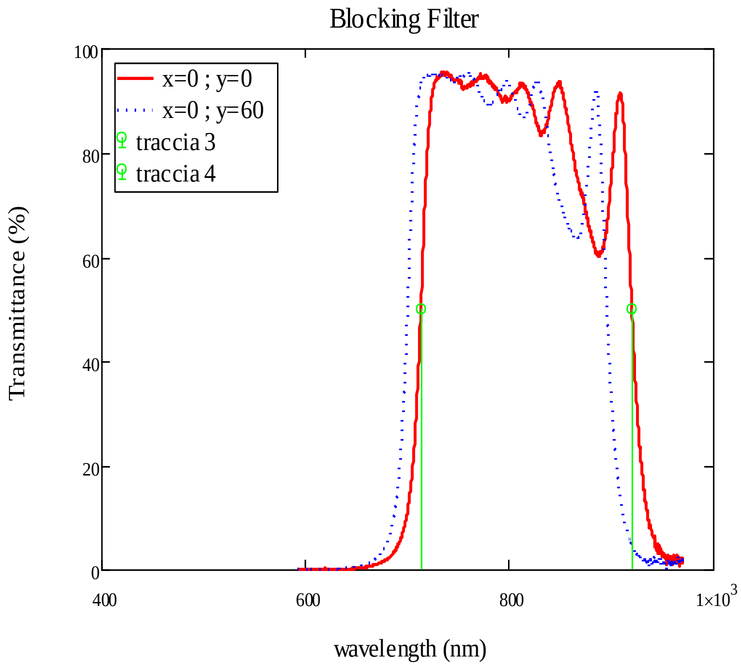


The maximum transmittance is lower than the calculated value owing to manufacturing errors

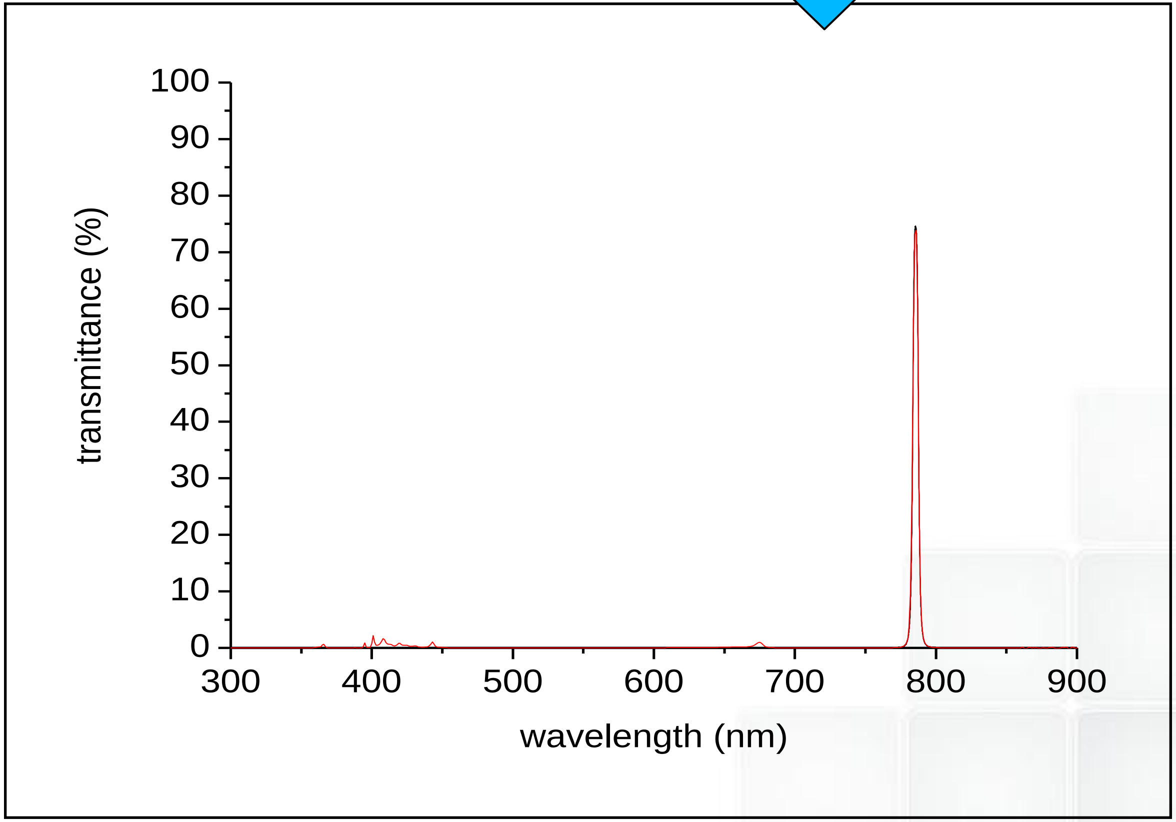
Wide spectrum characteristics

Spectral range 300 – 1100 nm

Combination of a narrow band filter with a blocking filter (70 layers)

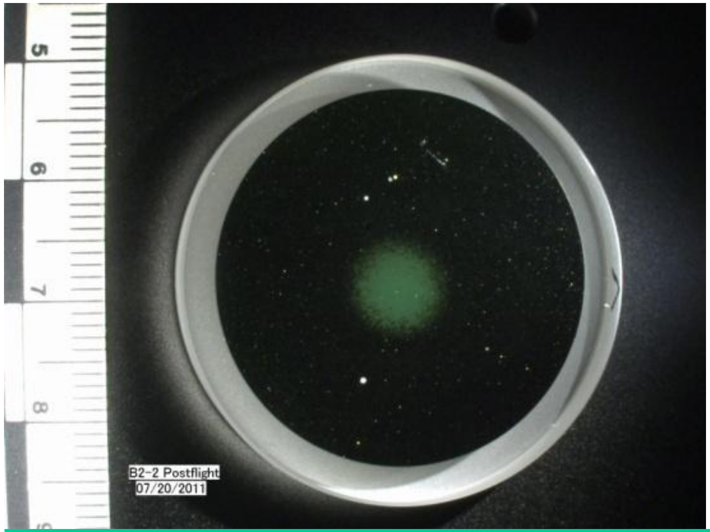


Wide spectrum performance



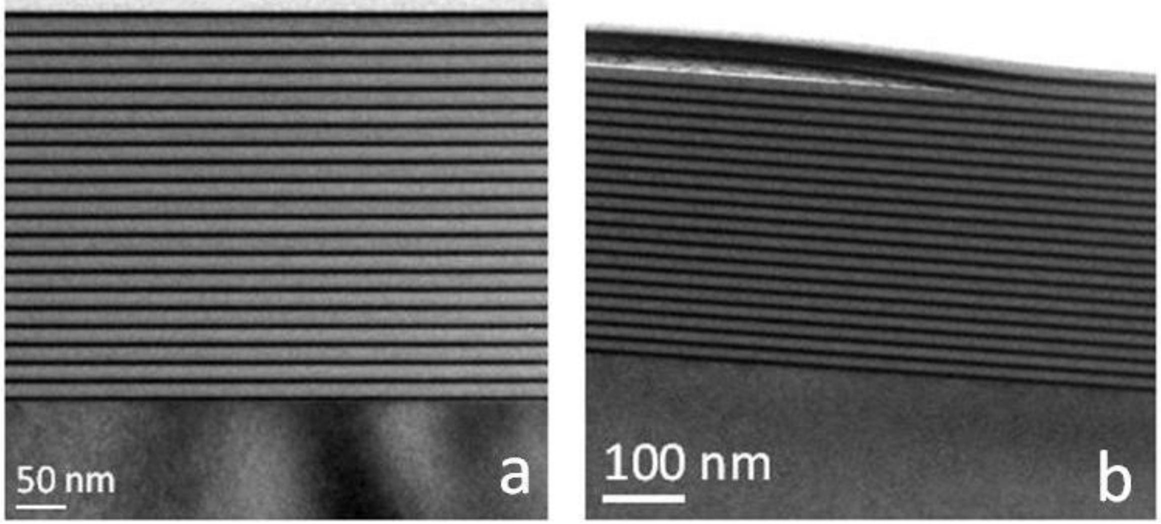
Environmental testing

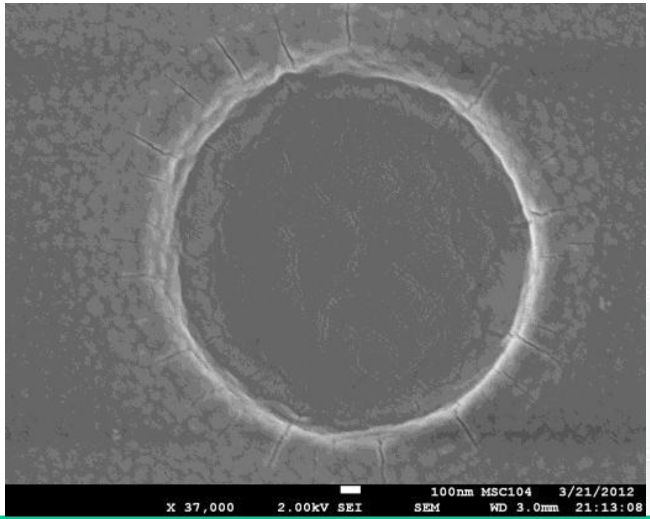
– Environmental durability
  - ✓ Mechanical resistance
    Adhesion, abrasion, humidity....
  - ✓ Thermal cycling (cryogenic temperature)
  - ✓ Exposure to ionizing radiation: gamma rays, protons, etc.
  - ✓ Solar irradiance



silver mirrors flown on MISSE-7 showing particulate contamination and haze near its center (C.Panetta et al, OIC20013)

Cross-sectional TEM image of a Mo/Si multilayer coating, (a) before and (b) after proton bombardment (M.G.Pelizzo et al. Opt Exp. 2011).



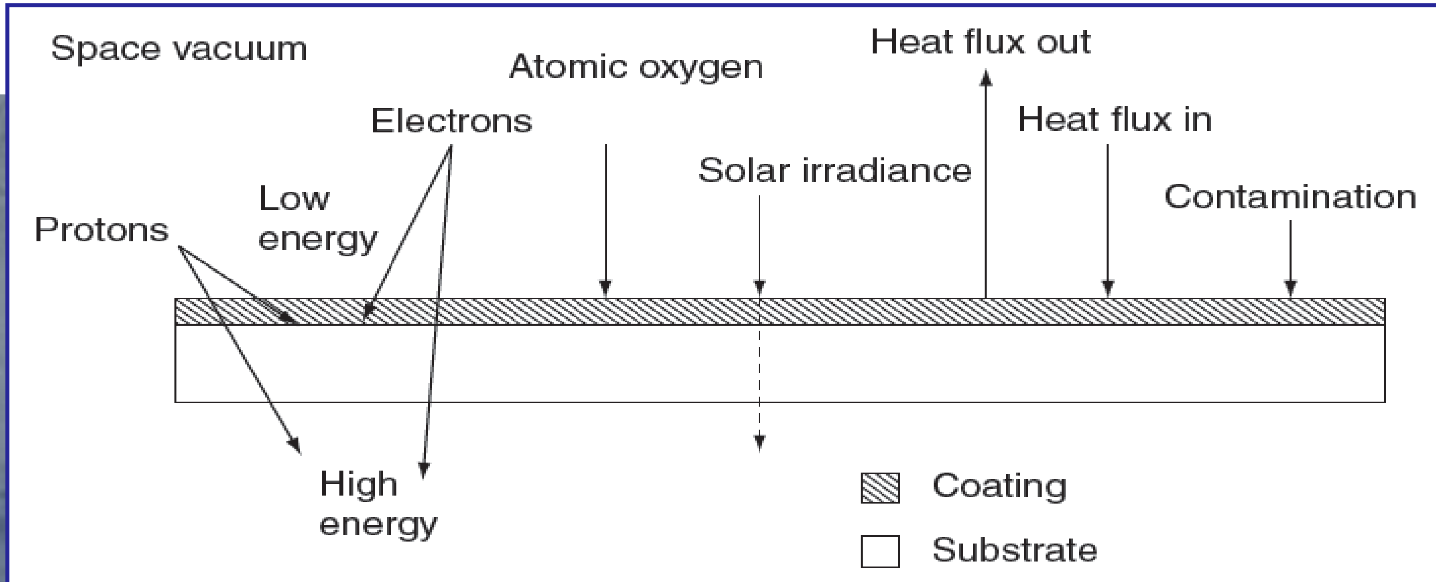


Impact crater on a MISSE-6 silver mirror

Space Environment and Coatings

The main environmental components of space that can have an impact on optical coatings

D.Wernham in "Optical thin films and coatings" Eds. A.Piegari, F.Flory (Elsevier, 2013)



Many interesting experiments on material behavior are carried out directly on the International Space Station: *MISSE (Materials International Space Station Experiment*) http://spaceflightsystems.grc.nasa.gov/SOPO/ICHO/IRP/MISSE/ and this is the best way to study synergic effects, even though more expensive than experiments on the ground.