LUVOIR
Large UV/Optical/Infrared Surveyor

l'Observatoire de Paris | LESIA
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

R&D for space polarimeters working in the UV

Coralie Neiner (Paris Observatory),
Martin Pertenaïs (DLR & Paris Observatory),
Arturo Lopez Ariste (IRAP)

Polarimetry: basics

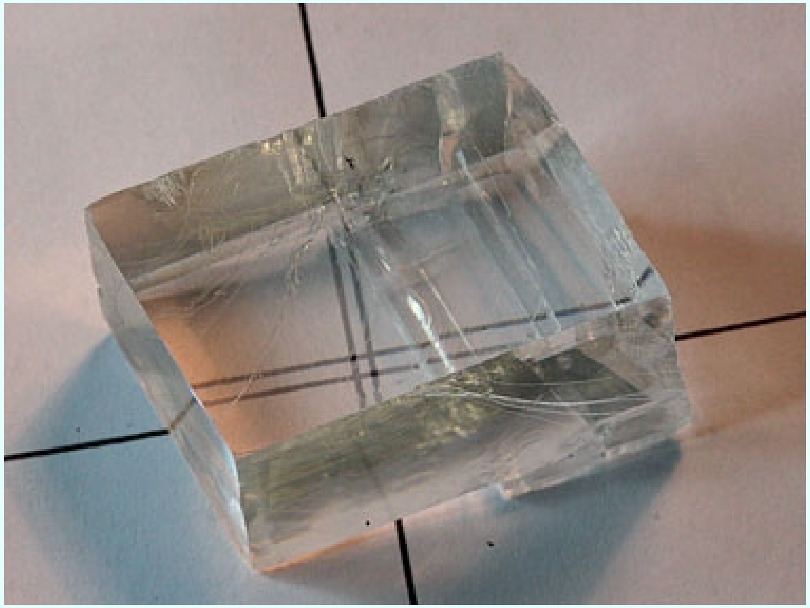
Polarimetry allows to measure the circular and linear polarisation of light. This allows to, e.g.:

- measure magnetic fields at the surface of stars or in the ISM
- study flat geometries (circumstellar disks,...)
- study the surface of planets

Polarisation is defined thanks to the Stokes parameters:

- Stokes V = circular polarisation
- Stokes Q and U = linear polarisation
- Stokes I = intensity

To perform polarimetry one requires to separate and record 2 states of polarisation, e.g. with a birefringent material.



polarimeter = modulator + analyzer

Space UV polarimeters

A polarimeter for a space mission such as the LUVOIR must be:

- efficient → SNR
- polychromatic → wide wavelength range
- small / light → cost
- robust → launch, temperature changes,...

Only a few solutions exist to perform polarimetry on a wide wavelength domain:

- Polychromatic wave plates
- Fresnel rhombs
- Liquid crystals
- Temporal modulation
- Spatial modulation
- Mirrors

Space UV polarimeters

A polarimeter for a space mission such as the LUVOIR must be:

- efficient
- polychromatic
- small / light
- robust

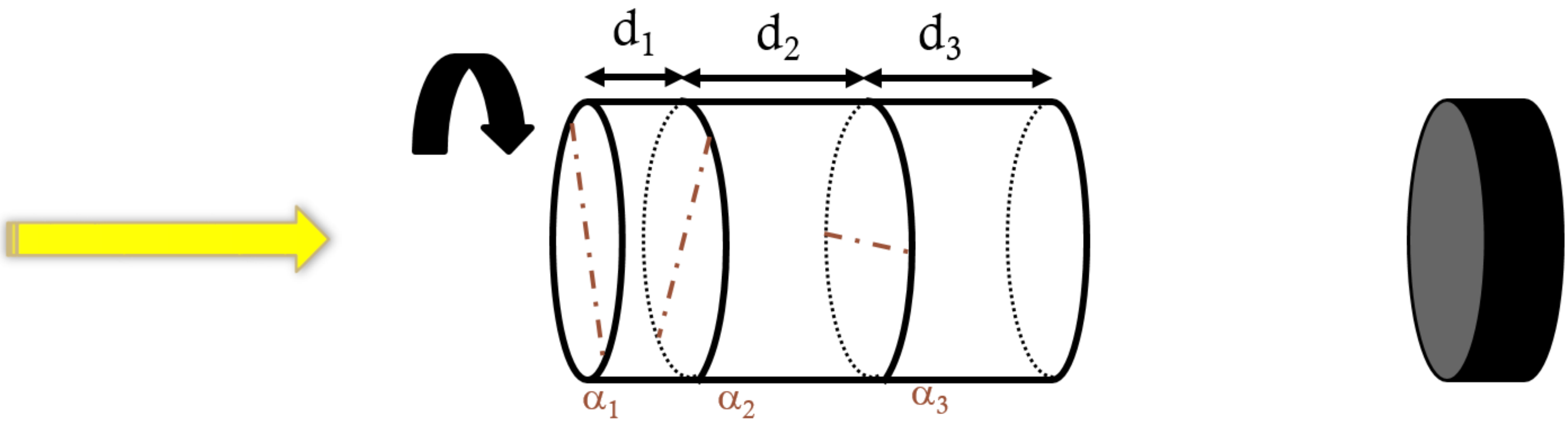
Only a few solutions exist to perform polarimetry on a wide wavelength domain:

- ~~Polychromatic wave plates~~ → only one material (MgF_2) available for the UV, thus cannot be polychromatic on a very wide domain
- ~~Fresnel rhombs~~ → problem for transmission in the UV
- ~~Liquid crystals~~ → opaque <250 nm, UV radiation
- Temporal modulation
- Spatial modulation
- Mirrors

} possible

Temporal modulation

Concept: create a polychromatic polarisation modulator, thanks to a rotating stack of several (3) plates of MgF_2 Snik et al. 2012



Pertenaïs et al. 2016 Rotating stack of plates Fixed analyzer

→ optimise d_i and α_i

→ rotate the stack of plates to several (6) pre-defined positions and take one measurement at each position

Temporal modulation

Demodulation matrix D: $\boldsymbol{S_{in}=D.I_{out}}$ (known theoretically and calibrated)

At each wavelength:

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} D_1^I & D_2^I & D_3^I & D_4^I & D_5^I & D_6^I \\ D_1^Q & D_2^Q & D_3^Q & D_4^Q & D_5^Q & D_6^Q \\ D_1^U & D_2^U & D_3^U & D_4^U & D_5^U & D_6^U \\ D_1^V & D_2^V & D_3^V & D_4^V & D_5^V & D_6^V \end{pmatrix} \cdot \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{pmatrix}$$

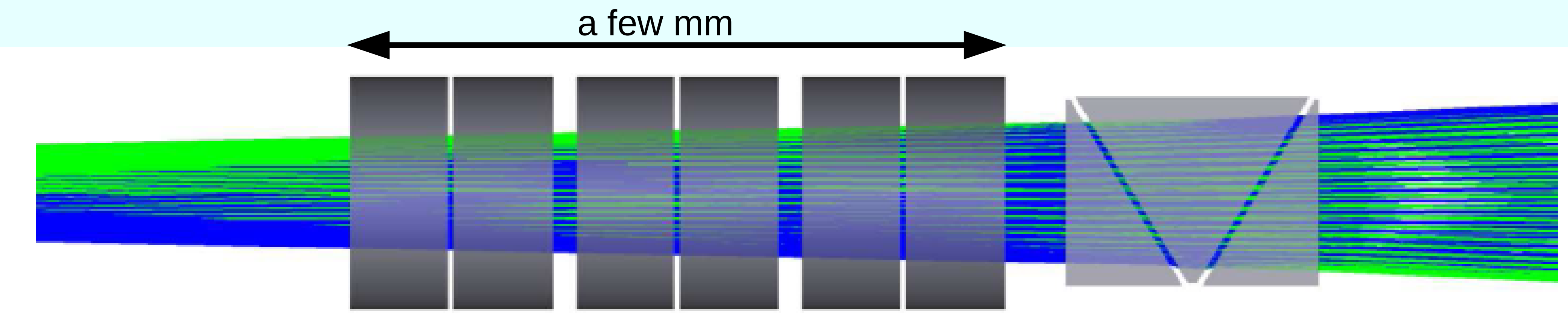
Extraction efficiency for the Stokes parameters:

$$\epsilon_i = \left(n \cdot \sum_{j=1}^{n} D_{ij}^2 \right)^{-1/2}$$

→ optimal extraction is for $\varepsilon_I=1$ and $\varepsilon_{Q,U,V}=1/\sqrt{3}$

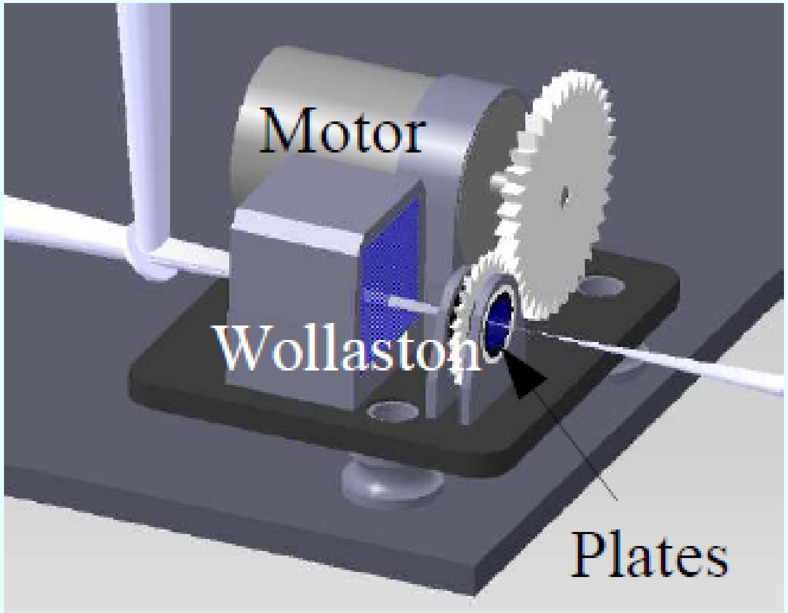
Temporal modulation

This solution was adopted for Arago (ESA M5 candidate, 123-888 nm) → tested successfully in Visible, will be tested in UV in Spring



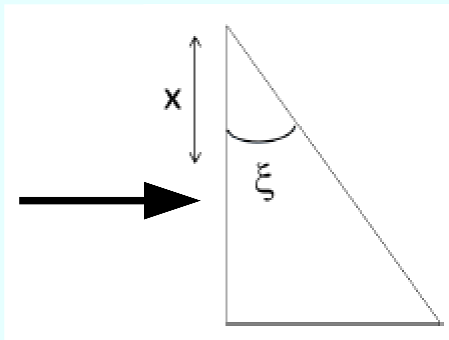
Rotating stack of 3 pairs of plates

3-prisms Wollaston



Spatial modulation

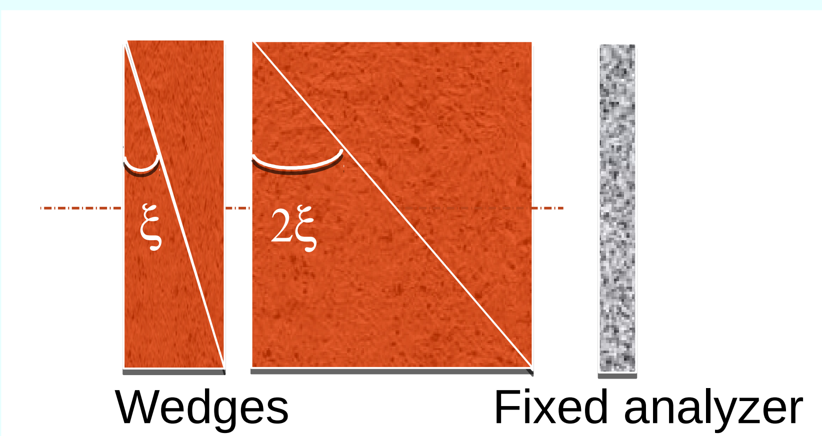
Concept: create a spatial polarisation modulator, thanks to a wedge (or more) of MgF_2



$$\phi(x,\lambda) = \frac{2\pi\Delta n(\lambda)\tan\xi}{\lambda}\cdot x$$

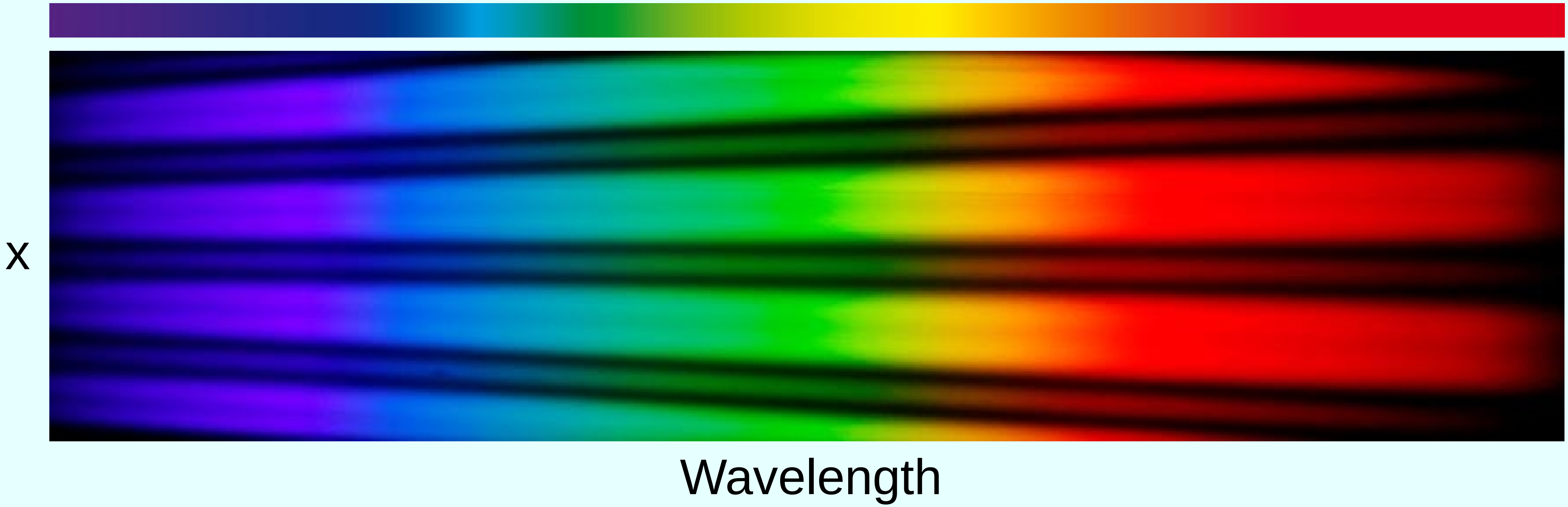
Sparks et al. 2012

→ the polarisation varies depending on the position (x) on the wedge



$$I_{out} = 0.5\,(I + U\cos 2\phi 2\theta$$
$$+ Q\,(\cos\phi\cos 2\theta - \sin\phi\sin 2\phi\sin 2\theta)$$
$$+ V\,(\cos\phi\sin 2\phi\sin 2\theta + \sin\phi\cos 2\theta))$$

Spatial modulation

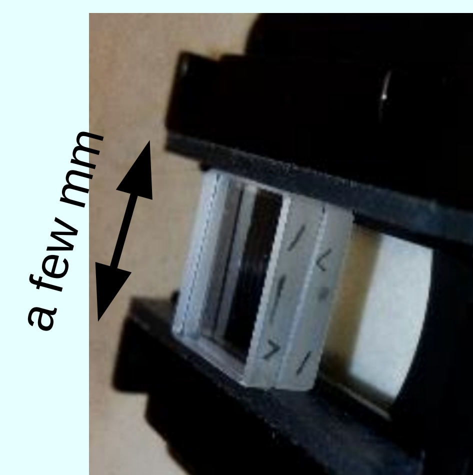


We obtain a 2D image: the polarisation is modulated in the direction perpendicular to the wavelength, i.e. in the thickness of the spectral order

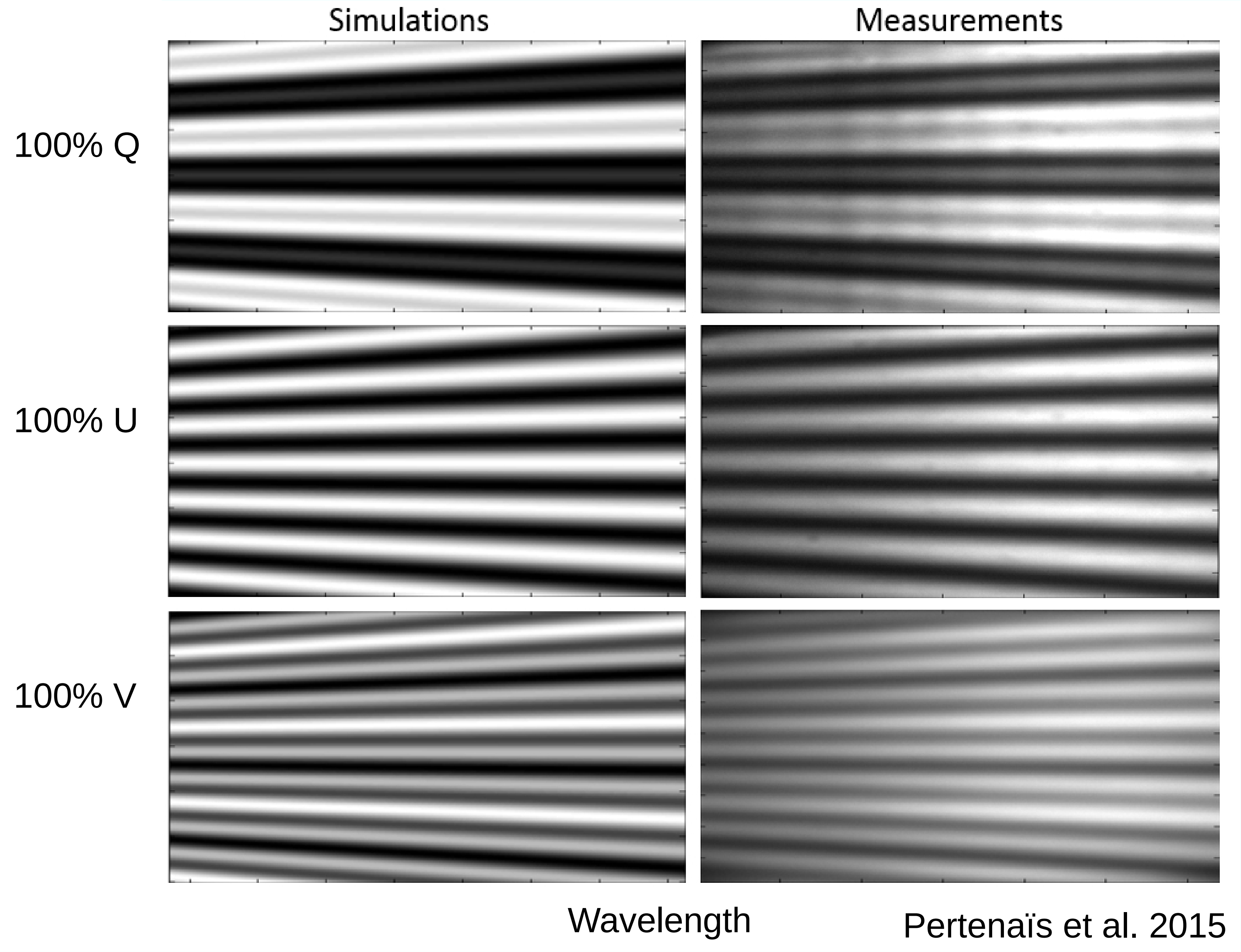
→ tested successfully in Visible, will be tested in UV in 2018

→ could be an improved design for Arago

Pertenaïs et al. 2015



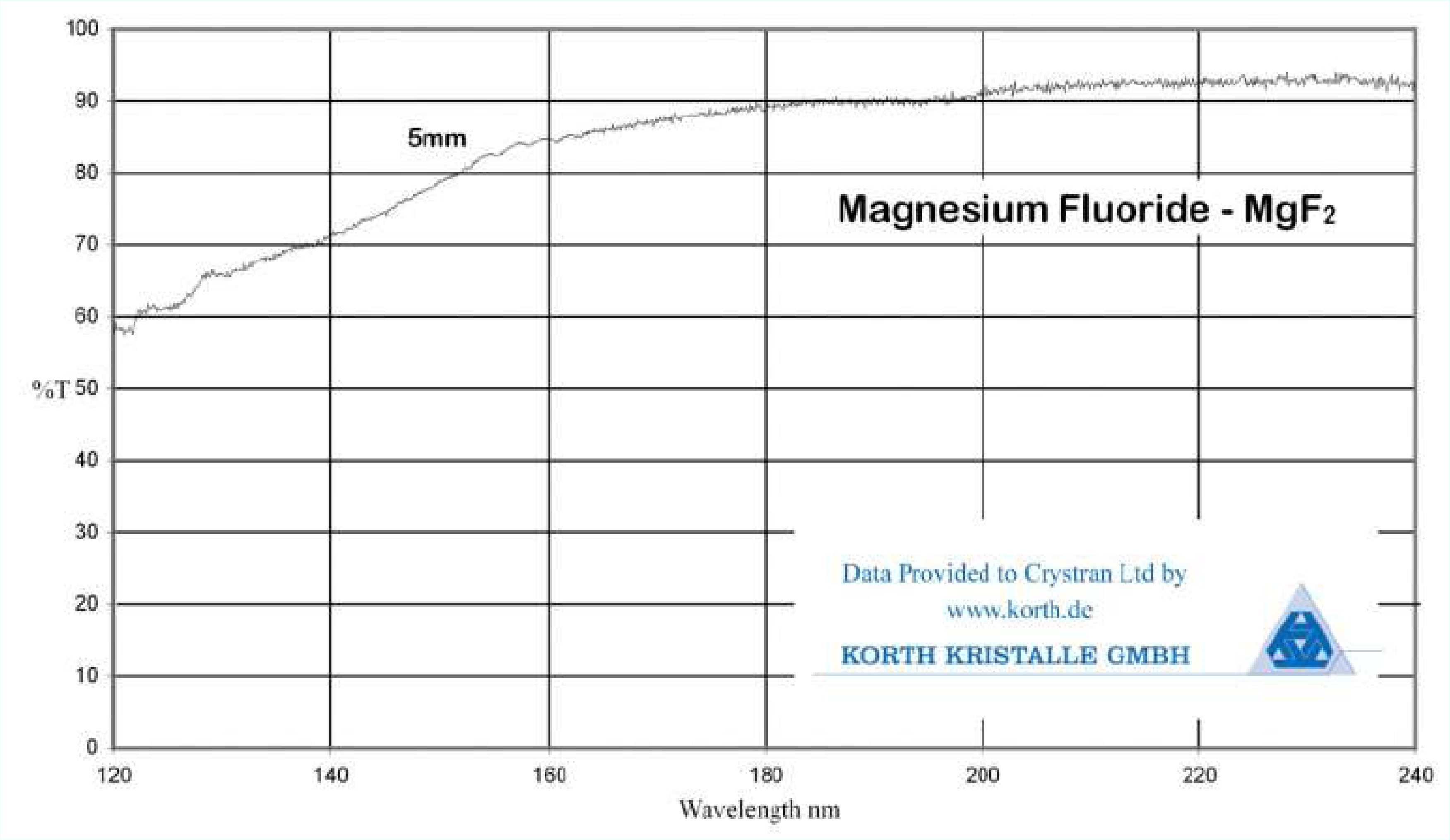
Spatial modulation



MgF_2

MgF_2 is the only material that is both birefringent and transparent in the UV, but:

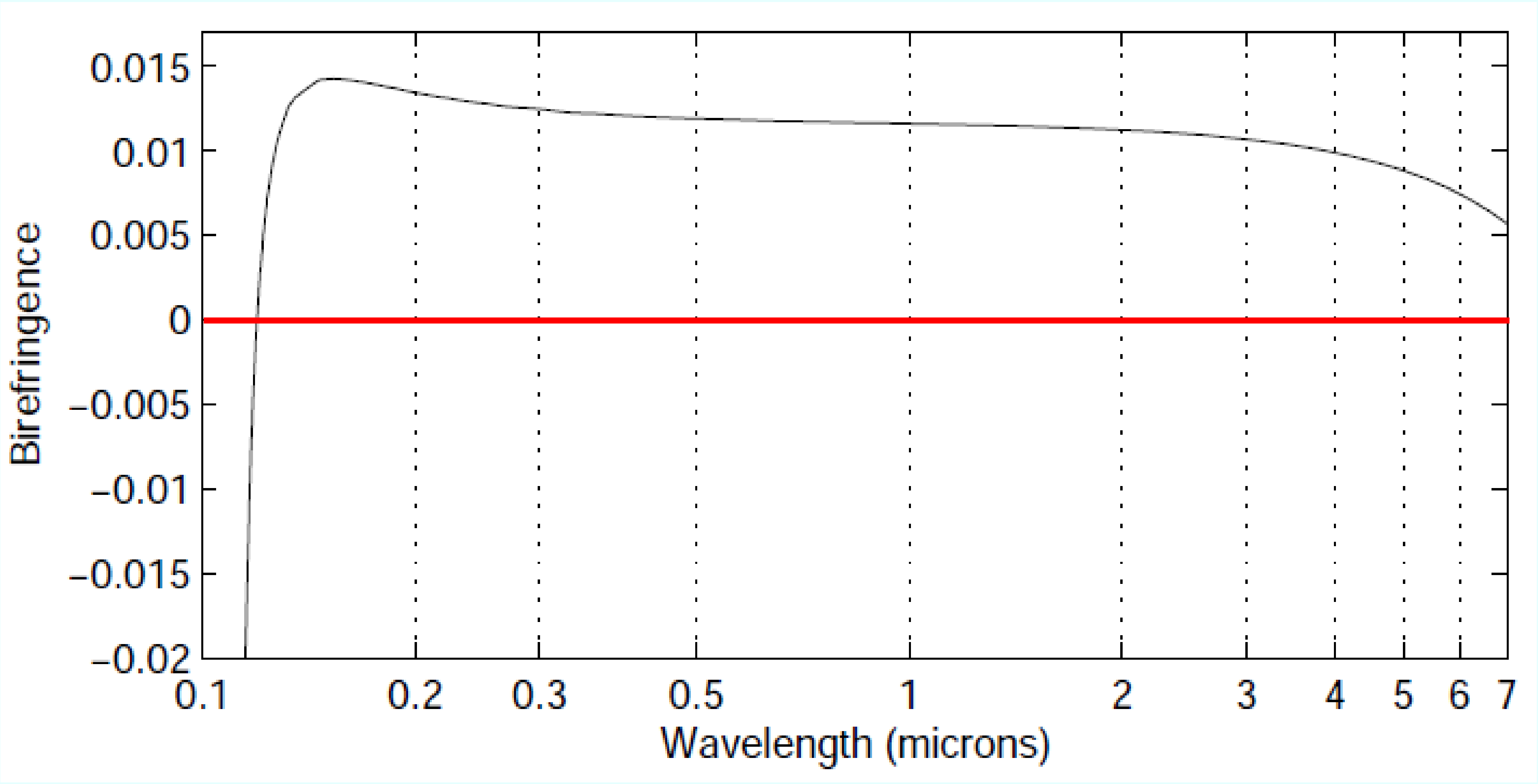
- it is not transparent in the FUV: 50% transmission for 5 mm at 120 nm



MgF_2

MgF_2 is the only material that is both birefringent and transparent in the UV, but:

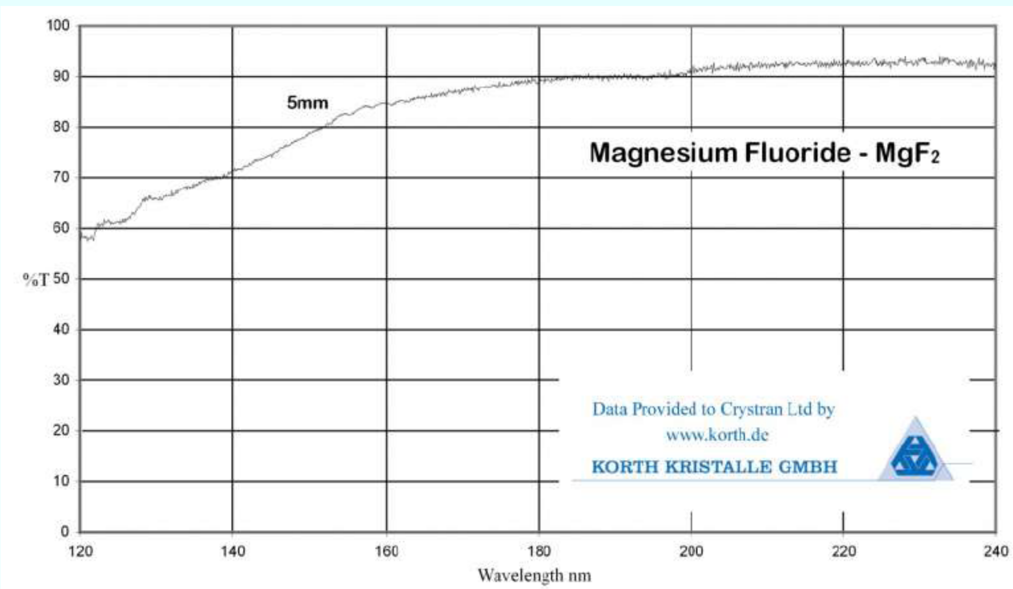
- it is not transparent in the FUV: 50% transmission for 5 mm at 120 nm
- its birefringence is 0 at 119.5 nm

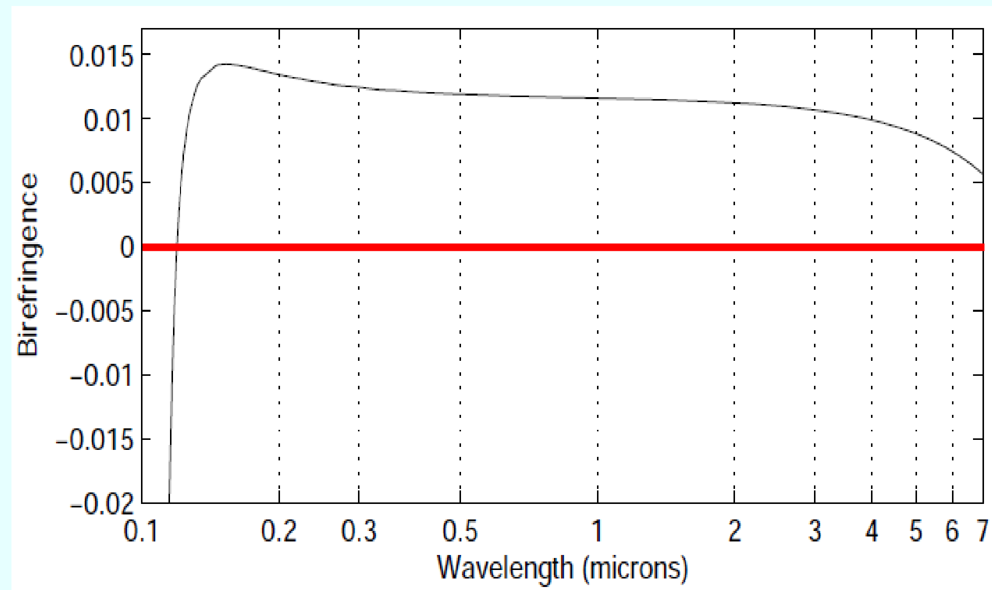


MgF_2

MgF_2 is the only material that is both birefringent and transparent in the UV, but:

- it is not transparent in the FUV: 50% transmission for 5 mm at 120 nm
- its birefringence is 0 at 119.5 nm





→ temporal and spatial modulations cannot be used below ~120 nm

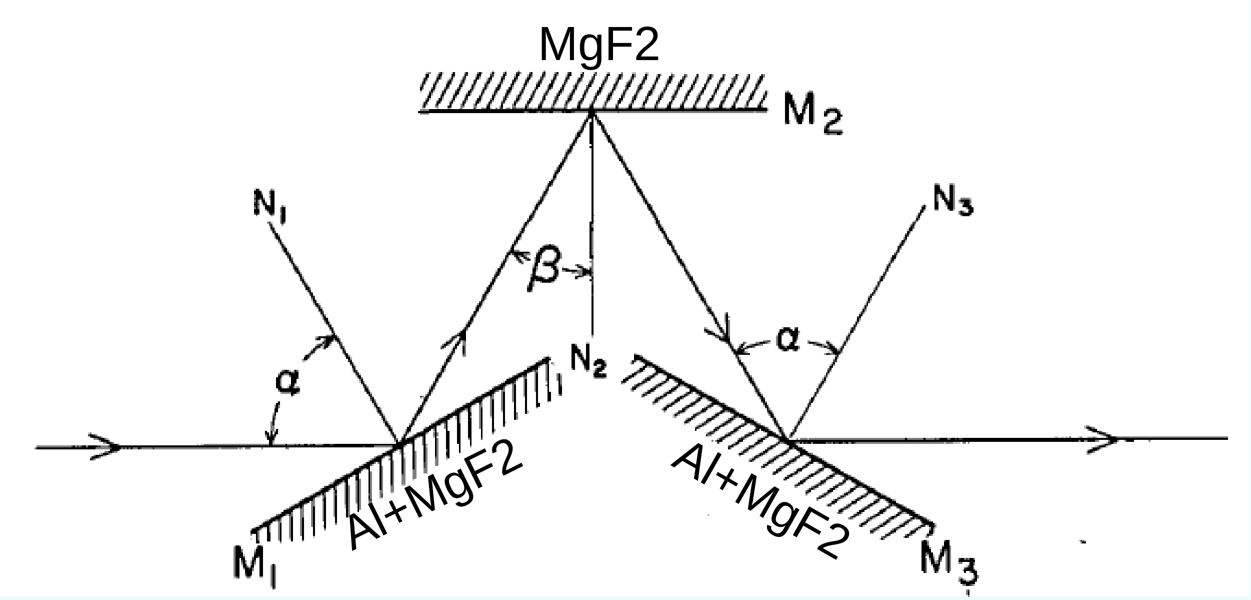
… unless we use stressed material (MgF_2 or LiF) → difficult in space!

Modulation with mirrors

Concept: create a polarimeter with mirrors only

Mirrors polarise (= analyzer) and introduce a delay (= modulator)
→ they can be used to built polarimeters
→ polarisation depends on mirror coating, wavelength, and incidence angle
→ complete polarisation at Brewster angle

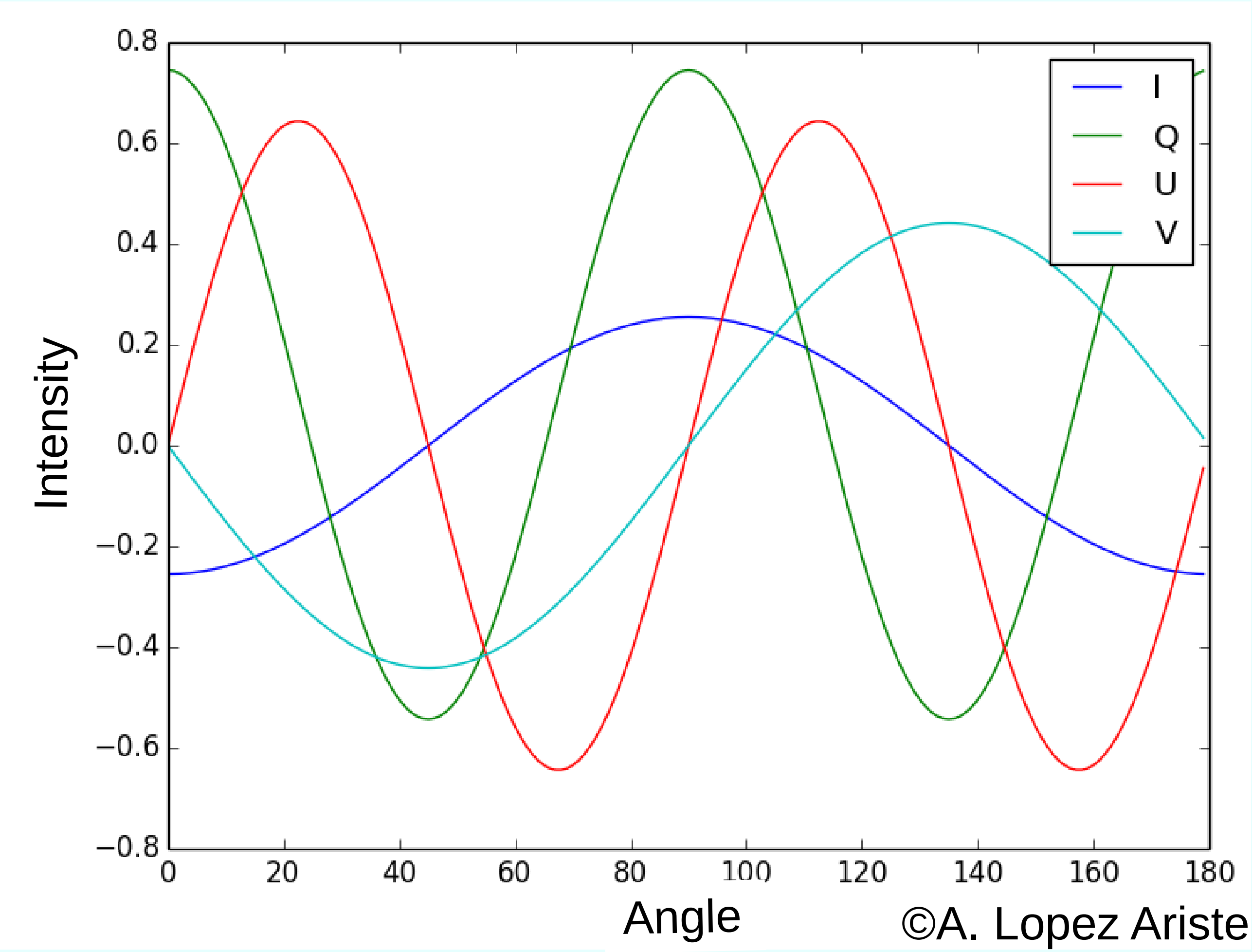
A combination of 3 mirrors is sufficient to create a polarimeter



Hass & Hunter 1978

Modulation with mirrors

Use 3 mirrors and rotate them together while maintaining the optical axis + add a Wollaston to increase intensity modulation



→optimise demodulation by choosing the best 3 angles

Comparison between the 3 possible methods

Temporal modulation

- **+** well known, sufficient TRL, small
- **+** baseline for Arago
- **–** plate assembly can create polarised interference fringes
- **–** low transmission, MgF_2 → does not work below ~120 nm
- **–** rotating → consuming + single point failure

Spatial modulation

- **+** static, small
- **+** studied for Arago
- **–** new concept, low TRL
- **–** big detectors needed, unless we find a solution for λ-dependence
- **–** MgF_2 → does not work below ~120 nm

Mirrors

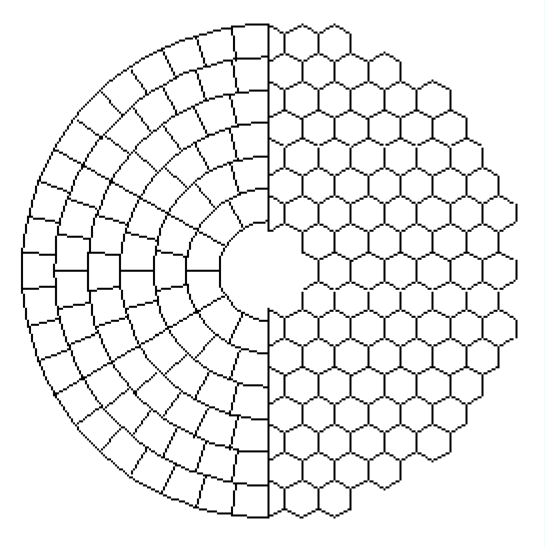
- + works at any wavelength (but chromatic!)
- **–** coatings → transmission and polarisation in UV?
- **–** moving mirrors → consuming + single point failure
- **–** big / heavy

Other potential difficulties for the LUVOIR

It is important to control the instrumental polarisation in the path before the polarimeter:

- LUVOIR's primary mirror will be segmented
- LUVOIR's primary mirror may not be axi-symmetrical
- the telescope should rather be on-axis
- the polarimeter should rather be at the Cassegrain focus

→ to be taken into account at telescope level



The precision of polarisation depends on the stability of the system:

- pointing stability
- thermo-mechanical stability

→ to be taken into account at spacecraft/system level

→ many of these points are also relevant for the coronograph and already considered by NASA

Other potential difficulties for the LUVOIR

The polarimeter should be adapted to the science objectives:

- choose design (temporal modulation, spatial modulation, mirrors) according to lowest required wavelength
- not all LUVOIR's objectives require polarimetry → the polarimeter should be removable → additional mechanism
- plan the appropriate (re-)calibration each time the polarimeter is inserted back into the beam

Conclusions

In the frame of Arago, thanks to R&D funding by CNES:

- we developed and tested 2 types of compact polarimeters: temporal modulation and spatial modulation
- both give good results, both use MgF_2

For the LUVOIR:

- we can reuse the same concepts as for Arago but restrict the polarimetry above ~120 nm → loss in science
- we can develop a 3rd type of polarimeters with mirrors → will be part of the Phase 0 instrument study for LUVOIR funded by CNES