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OPTICAL DESIGN OF ARAGO'S SPECTROPOLARIMETER

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I. ABSTRACT

The space mission Arago is proposed as a candidate to ESA's Cosmic Vision M5 call by the UVMag consortium. Arago is dedicated to the study of the dynamic 3D environment of stars and planets. Thanks to a high-resolution UV and visible spectropolarimeter, the instrument will detect and characterize the magnetic fields of the stars, their environment and its impact on exoplanets. Scientific requirements impose a wide spectral range from 119 to 888 nm with a single full-Stokes polarimeter followed by two high-resolution spectrographs. To achieve these stringent specifications, a polychromatic concept of polarimeter has been studied and tested thanks to a R&T study funded by CNES. Using an optimized combination of Magnesium Fluoride plates followed by a polarization analyzer, it measures all four Stokes parameters with a constant efficiency over the spectral range. This is performed with a sequence of 6 sub-exposures acquired with different plate angles. The two orthogonal polarized beams coming out of the polarimeter feed two spectrographs. The UV spectrograph has a spectral resolution of at least 25000 over its spectral range, while the visible spectrograph works at least at 35000. Finally, to image the high-resolution spectra, a CCD detector and a MCP were chosen for the visible and UV arms of the instrument respectively.

This paper describes the complete optical design of Arago's instrument, as proposed to ESA as an answer to its M5 call, from the 1.3-m diameter telescope to the detectors. The design of the polarimeter is presented as well as the unusual way of demodulating the polarization information, in order to have a polychromatic polarimeter working with the same efficiency from FUV to NIR. The optical design of the UV and visible échelle spectrographs and their detection chains are also presented, as well as the achieved performances.

II. SCIENCE GOALS & SPECIFICATIONS

A. Science goals

The Arago space mission is an ambitious project with a 1.3-m diameter telescope in space dedicated to spectropolarimetry in the UV and in the visible [1].

The measurements of stellar spectra in the UV and visible domains give important insights into the formation and evolution of all types of stars. The visible spectrum allows us to gain information about the surface of the star itself, while the UV domain is crucial because it is very rich in atomic and molecular lines, contains most of the flux of hot stars and the signatures of the stellar environment (e.g. of the chromosphere). The reconstruction of 3D maps of stars and their environment simultaneously is made possible by performing UV and visible spectroscopy over a full stellar rotation period. Adding polarimetric power to the spectrograph will multiply tenfold the capabilities of extracting information on stellar magnetospheres, winds, disks, and magnetic fields.

Moreover, the changing stellar UV radiation and magnetic fields affect the formation of planets around stars and the emergence of life on these exoplanets. Thanks to Arago we will study the interaction between stars and their planets, in particular magnetospheric interactions and tides. This will allow us to study the environmental conditions for the emergence of life on rocky planets.

Considering these different science cases we are designing Arago with some requirements on the performances of the instrument. The requirements and the detail of the instrument structure of Arago are presented in the following sections.

B. General requirements

Following the scientific goals, technical specifications were defined to develop the instruments needed. The main requirement for Arago is on the spectral range covered by the instruments. On top of the particular interest for specific photospheric lines, the absolute number of observed lines is indeed also very important for the study of magnetic fields with the Least-Square-Deconvolution (LSD) method [2]. This technique enables us to significantly increase the signal-to-noise ratio (SNR) with the number of observed lines, by combining the measurements of all lines into a weighted mean profile. This thus increases at the end the sensitivity of the magnetic field measurement. **The spectral coverage for Arago was therefore fixed to 119-320 nm and 355-888 nm**. Considering the needs in terms of radiometric efficiency, the SNR needed is fixed to 100 in 30 min for a magnitude V=7 star for all kinds of stars in the visible and for OBA stars in the UV. For FGK stars in the UV, the specification is also set to 100 but with 1h exposure time and for magnitude V=5 stars. Chromospheric lines in M-type stars have to be observed with a SNR of 10 in 1h exposure time for magnitude V=10 stars.

III. OPTICAL DESIGN & PERFORMANCES

A. Polarimeter

Arago's polarimeter is the key component of the mission, placed directly after the Cassegrain focus of the telescope to minimize instrumental polarization. Therefore it has to be transparent for the complete spectral range (119-888 nm) but efficient only from 123 nm. Under this wavelength it is too difficult to separate spatially both orthogonal polarization states because of the very low value of the birefringence of the material. The only material available, transparent and birefringent on this spectral range is the Magnesium Fluoride (MgF_2). The complete description of the design of the polarimeter is detailed in [3].

To achieve the measurement of all four Stokes parameters (I the intensity, Q and U the linear polarization, and V the circular polarization) from 123 to 888 nm, a custom design is needed. The concept chosen is to achromatize extraction efficiencies of the Stokes parameters over the spectral range (see also [4]). This is achieved by tuning the value of some variables (in our case the thicknesses and fast-axis angles of 3 pairs of MgF_2 plates) to find the optimal configuration, in which all Stokes parameters can be mathematically extracted with the same efficiency at all required wavelengths. **Fig. 1** shows the optical design of the final configuration, with a stack of 3 pairs of MgF_2 taking 6 different angular positions to achieve the temporal modulation, followed by a Wollaston polarization analyser.

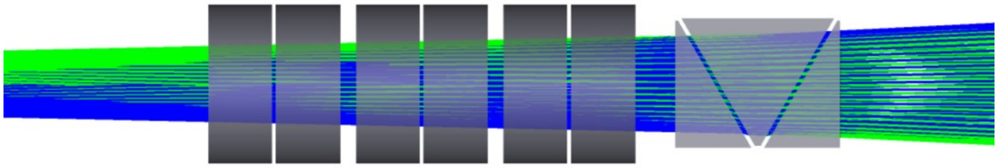

Fig. 1 Optical design of the polarimeter. The modulator is a stack of 3 pairs of MgF_2 plates and the polarization analyzer is a 3-prism Wollaston made of MgF_2 as well.

The theoretical efficiencies obtained with this design are very close to the optimal value [3]. The modulator has been built and tested in the laboratory (thanks to a R&T study funded by CNES) in the visible range. The extraction efficiencies of the measured Stokes parameters, fit perfectly with the theoretical values. The three-prism Wollaston analyser imposes a spatial separation of both orthogonal polarization states corresponding to at least 4 pixels in the detector plane.
The polarimeter is finally followed by a dichroic plate, separating the two spectral range to feed the two high-resolution spectrographs.

B. Visible Spectrograph

To be able to sample correctly the photospheric lines, the minimal spectral resolution required is 35,000 over the given spectral range, 355-888 nm. The relative radial velocity precision needed between the 6 sub-exposures is critical and leads to a need in stability of the spectrum on the detector of 1/15th of a pixel, corresponding to 1 µm when using 15 µm pixels. This requirement impacts directly the need of a very high pointing stability of the satellite. To relax this constraint, the maximal optical magnification of the visible spectrograph is set to 0.4.
Considering these specifications, the optical design of the echelle-spectrograph is presented in **Fig. 2**.

The fold mirror placed after the dichroic plate allows the spectrograph to be in a plane parallel to the primary mirror. An off-axis parabola collimates the F/13 beam and illuminates an echelle grating. The cross-disperser is then composed by a LF5 prism and a diffraction grating, to create an almost constant cross-dispersion between the 72 different spectral orders. Finally, a Three-Mirror-Anastigmat (TMA) telescope focuses all the orders onto a classical CCD detector. The chosen CCD is a classical 4k × 4k frame transfer CCD from the company e2v.

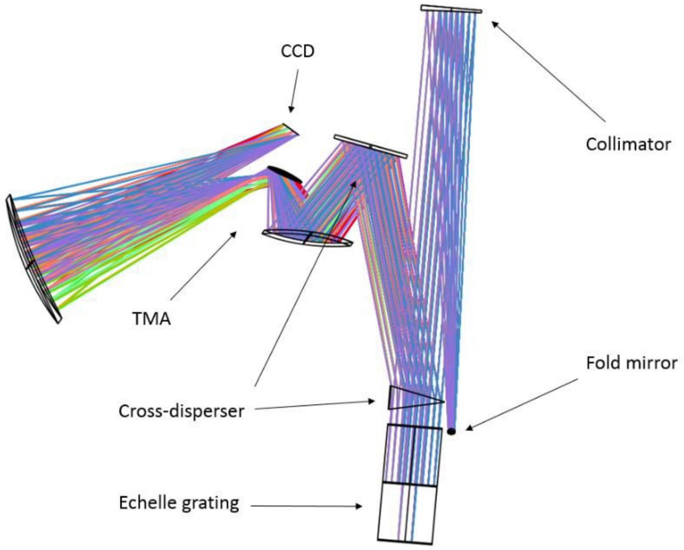

Fig. 2 Optical design of the visible echelle spectrograph working from 355 to 888 nm.

The image quality achieved with the spectrograph is excellent and the spectral coverage goes from 355.64 to 894.64 nm. The spectral resolution varies within every spectral order, with a minimal value of 35950 and a maximal value of 59440 for the lowest order (red side of the spectrum).

Taking into account the optical transmission of the telescope, of the polarimeter, of the visible spectrograph presented above, and the quantum efficiency of the CCD, the end-to-end transmission value of Arago in the visible spectrum is computed and plotted in **Fig.3**. Its value varies between 10 and 20%, mostly following the quantum efficiency curve of the detector.

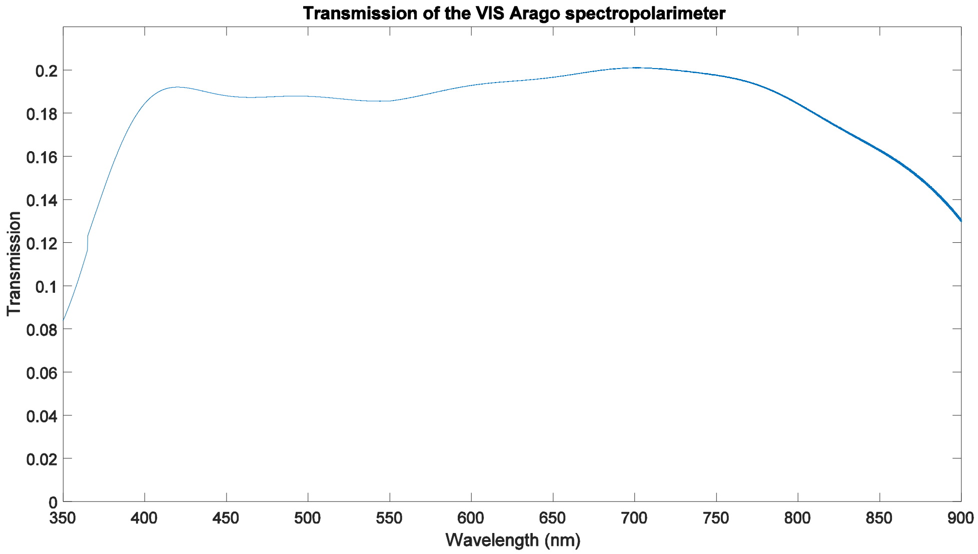

Fig. 3 End to end efficiency of the visible arm of Arago, from the telescope to the CCD detector.

C. UV Spectrograph

The UV spectrograph has been designed by an Arago team at Universidad Complutense de Madrid (UCM) in Spain. The requirements were to have at least 25,000 of spectral resolution from 119 to 320 nm. For the same reason as for the visible spectrograph, the optical magnification is limited to 0.52. The optical design (**Fig. 4**) is also an echelle spectrograph, using as few optical elements as possible, to optimize the radiometric efficiency. After the dichroic plate, only three optical elements define the spectrograph: an off-axis parabola as a collimator, an echelle grating, and finally a toroidal grating to perform the cross-dispersion and the focusing objective at the same time. All of the orders are focused onto a Micro Channel Plate (MCP) detector followed by a CMOS-APS as read-out system. This system was developed by an Arago team at the Max Plank Institute (MPS) in Göttingen.

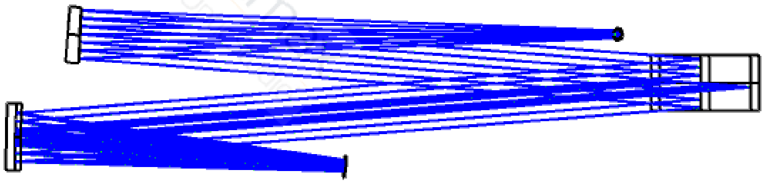

Fig. 4 Optical design of the UV echelle spectrograph working from 119 to 320 nm.

With the current design, the covered spectrum goes from 118.96 to 321.91 nm spread on 35 different spectral orders. The spectral resolution varies within the orders from 22000 to 36000.

As for the visible part of the spectrum, the end-to-end transmission, from the telescope to the quantum efficiency of the detectors is calculated, see **Fig. 5**.

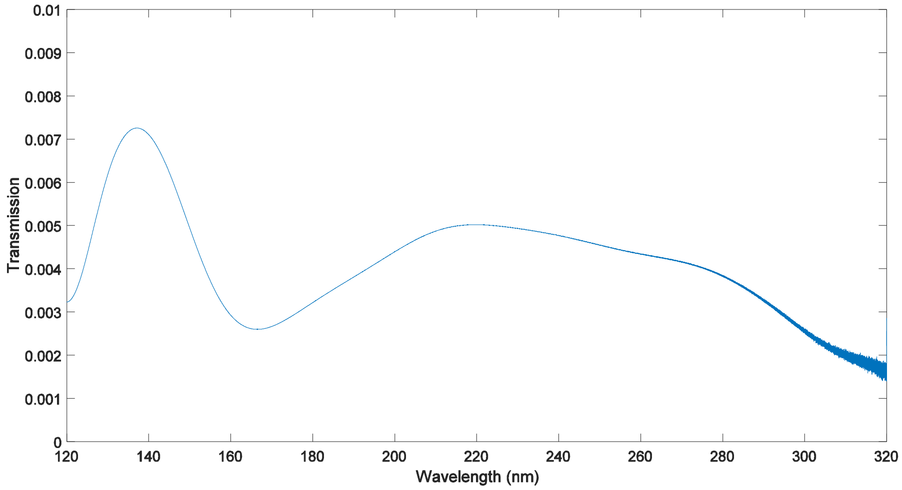

Fig. 5 End to end efficiency of the UV arm of Arago, from the telescope to the MCP detector.

The total transmission is very low, between 0.2% and 0.75%, mainly due to the transmission of the polarimeter in the UV and the quantum efficiency of the MCP detector. This leads to a low SNR for cool stars, for which the UV flux is also very low.

D. SNR

Using synthetic spectra as inputs, our instrument model computes the final SNR obtained with Arago for a given exposure time. The specification of 100 in 30 min for all kinds of star in the visible is easily satisfied. **Figs. 6** and **7** show two examples, respectively for stars with an effective temperature of 20,000 K and 5,750 K. The periodic modulation we can observe is due to the diffraction efficiency of the echelle grating within each order. These curves are computed considering 30 min exposure time and a magnitude V=7 star.

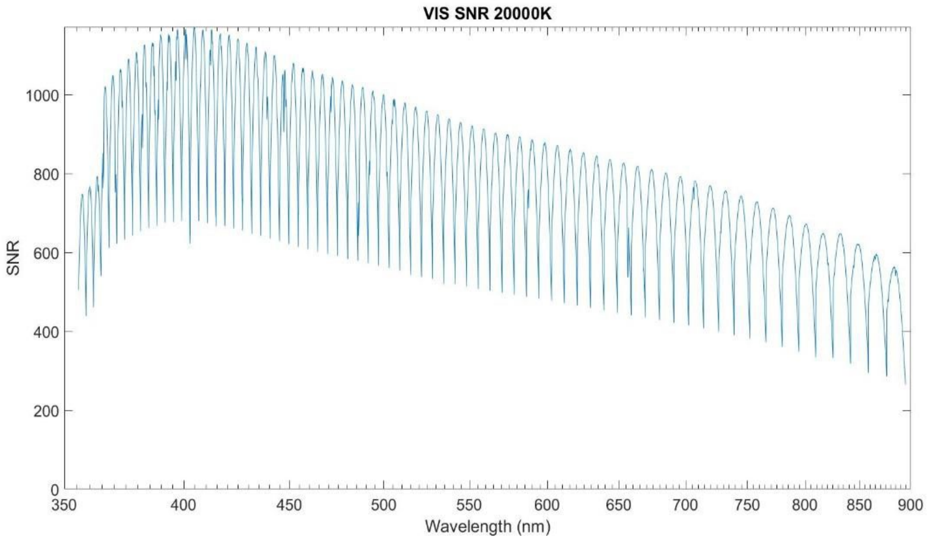

Fig. 6 SNR obtained with Arago in the visible range for 30 min exposure time on a magnitude V=7 star with T_{eff}=20,000 K.

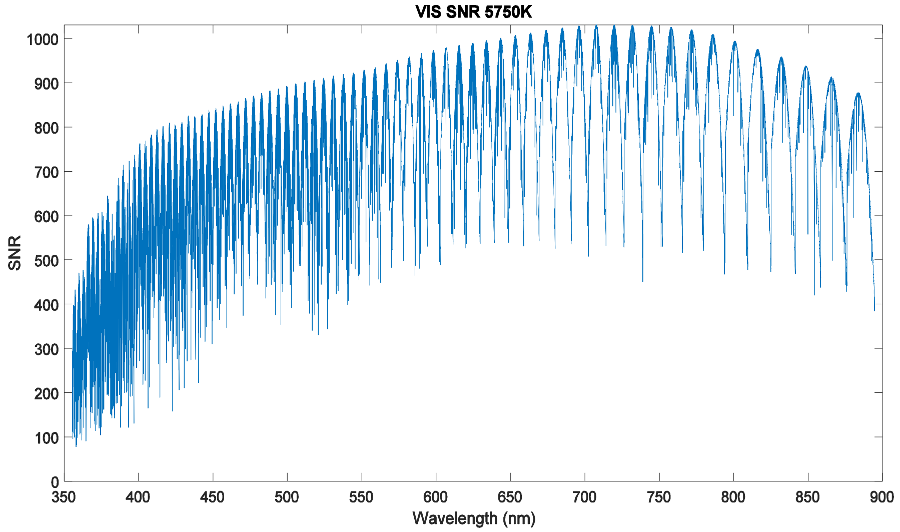

Fig. 7 SNR obtained with Arago in the visible range for 30 min exposure time on a magnitude V=7 star with T_{eff}=5,750 K.

The same process is applied for the UV part of the spectrum. For hot stars, the specification of SNR=100 is also well satisfied, as shown in **Fig. 8** with the example of a T_{eff}=20,000 K star. The periodic decrease in this curve is due to the change in spectral resolution within each order, impacting the SNR. In this calculation and in contrary to the visible model, the variation of the diffraction efficiency within the orders is not taken into account.
As expected, a high SNR is harder to reach for cool stars. **Fig. 9** shows the example of a solar type star of magnitude V=5. The SNR remains above around 100 down to 200 nm but is close to 0 between 119 and 175 nm. To achieve a good SNR in the Far-UV for cool stars, we will need to use longer exposure times on brighter stars. This is in line with the scientific requirement of SNR=100 for V=5 in 1h.

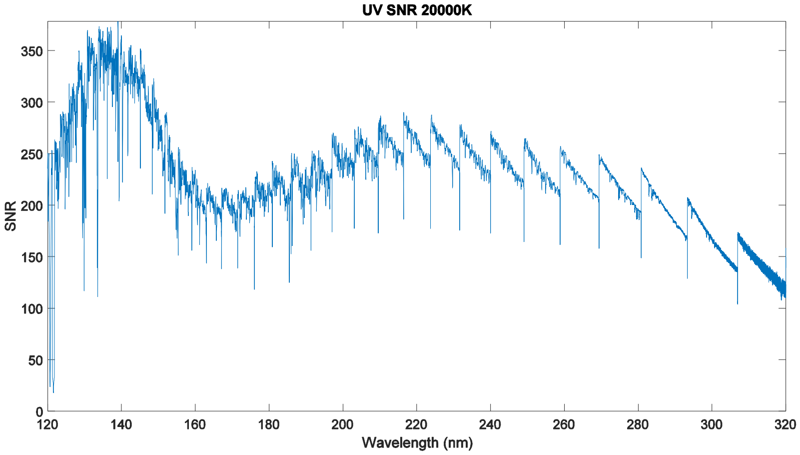

Fig. 8 SNR obtained with Arago in the UV range for 30 min exposure time on a magnitude V=7 star with T_{eff}=20,000 K.

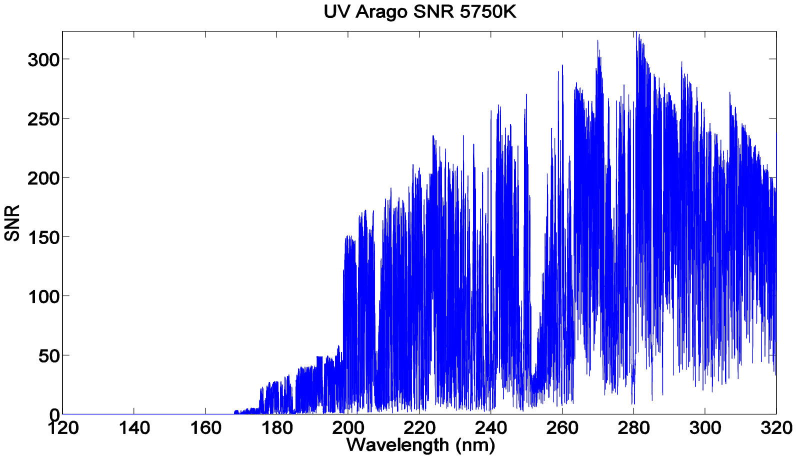

Fig. 9 SNR obtained with Arago in the UV range for 60 min exposure time on a magnitude V=5 star with T_{eff}=5,750 K.

IV. CONCLUSIONS

The optical design of Arago's instrument will offer unique capabilities to measure UV and visible high-resolution spectra of stars. While the spectrographs and detection chains present a conservative design and components, the polarimeter uses a less common approach with an optimisation of the extraction efficiencies. A first prototype was therefore built and tests were already performed in the visible domain. Further design optimisation and tests for Arago's instrument will be performed during Phase A.

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