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## PROBING OF HERMEAN EXOSPHERE BY ULTRAVIOLET SPECTROSCOPY: INSTRUMENT PRESENTATION, CALIBRATION PHILOSOPHY AND FIRST LIGHTS RESULTS

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### ABSTRACT

PHEBUS (Probing of Hermean Exosphere by Ultraviolet Spectroscopy) is a double spectrometer for the Extreme Ultraviolet range (55-155 nm) and the Far Ultraviolet range (145-315 nm) dedicated to the characterization of Mercury's exosphere composition and dynamics, and surface-exosphere connections. PHEBUS is part of the ESA BepiColombo cornerstone mission payload devoted to the study of Mercury. The BepiColombo mission consists of two spacecrafts: the Mercury Magnetospheric Orbiter (MMO) and the Mercury Planetary Orbiter (MPO) on which PHEBUS will be mounted. PHEBUS is a French-led instrument implemented in a cooperative scheme involving Japan (detectors), Russia (scanner) and Italy (ground calibration). Before launch, PHEBUS team want to perform a full absolute calibration on ground, in addition to calibrations which will be made in-flight, in order to know the instrument's response as precisely as possible. Instrument overview and calibration philosophy are introduced along with the first lights results observed by a first prototype.

### I. INTRODUCTION

#### A. Instrument overview

The instrument is basically composed of two Ultra-Violet spectrophotometers and one scanning mirror with a single axis of rotation. This movable mirror will collect the light coming from the exosphere above the limb onto the entrance slit of the spectrometer with a minimum number of reflections in order to maximize the UV count rate on the micro-channel plate detectors. The mirror is protected from straylight by an entrance baffle characterized by a good rejection capability. Each detector has a specific range of wavelengths: the EUV (Extreme UV) channel spreads from 55 to 155 nm, and the FUV (Far UV) channel from 145 to 315 nm. A couple of photomultipliers receive two additional wavelengths in the Near UltraViolet range (NUV) at 404.7 and 422.8 nm.

The main distinctiveness of PHEBUS will be to probe Mercury's exosphere in the spectral band (55 – 110 nm) for the first time.

#### B. Measurement objectives

The atmosphere of Mercury is very tenuous, with a pressure of a fraction of picobar. It results from a complex interplay of the solar wind, its planetary magnetic field and its rocky surface. It is nearly noncollisional, and is highly variable with time and space, characterized by a global asymmetry between dayside and nightside and rapid temporal variations, possibly related to varying magnetospheric activity.

The core scientific objectives of PHEBUS [1], are oriented toward a better understanding of the coupled surface-exosphere-magnetosphere system. The main measurement objectives are the following:

- To detect new species, including metallic species (Si, Mg, Fe, ...), atoms (C, N, S, ...), molecules and radicals (H<sub>2</sub>O, H<sub>2</sub>, OH, CO), noble gases (Ar, Ne), ions (He<sup>+</sup>, Na<sup>+</sup>, Mg<sup>+</sup>, ...), in addition to already detected species (Na, K, Ca, O, H, He).
- To measure an average exosphere (densities of constituents, vertical structure), with as much as possible species monitored together, at different positions of Mercury around the Sun.
- To measure sharp local and temporal variations of the exosphere content, at specific times and places of interest.
- To search for albedo variations of Mercury's nightside surface, lighted by the interplanetary H Ly- $\alpha$  glow, at 121.6 nm, in order to exhibit possible signatures of surface ice layers (H<sub>2</sub>O, SO<sub>2</sub>, N<sub>2</sub>, CO<sub>2</sub>) in high latitude polar craters.

## II. INSTRUMENT DESIGN

### A. Instrument concept

PHEBUS (Fig. 1) is a double spectrometer for the Extreme UltraViolet (EUV) range (55-155 nm) and the Far UltraViolet (FUV) range (145-315 nm) with an extension for some extra visible emission lines (Potassium and Calcium at 404.7 nm and 422.8 nm respectively).

The optical configuration of PHEBUS can be divided into two independent parts. The collecting part consists of a straylight rejection baffle, an off axis parabolic mirror and an entrance slit, allowing to scan Mercury's exosphere thanks to a rotating mechanism. This movable mirror collects the light from the exosphere above the limb and focuses it to the entrance slit. The parameters of the mirror were calculated so as to have a 170 mm effective focal length and a folding angle of 100°. This part determines the Field of View (FoV) and the Light of Sight (LoS). The spectrometer part determines the spectral resolution of the instrument and is composed by the entrance slit, two holographic gratings and the detectors.

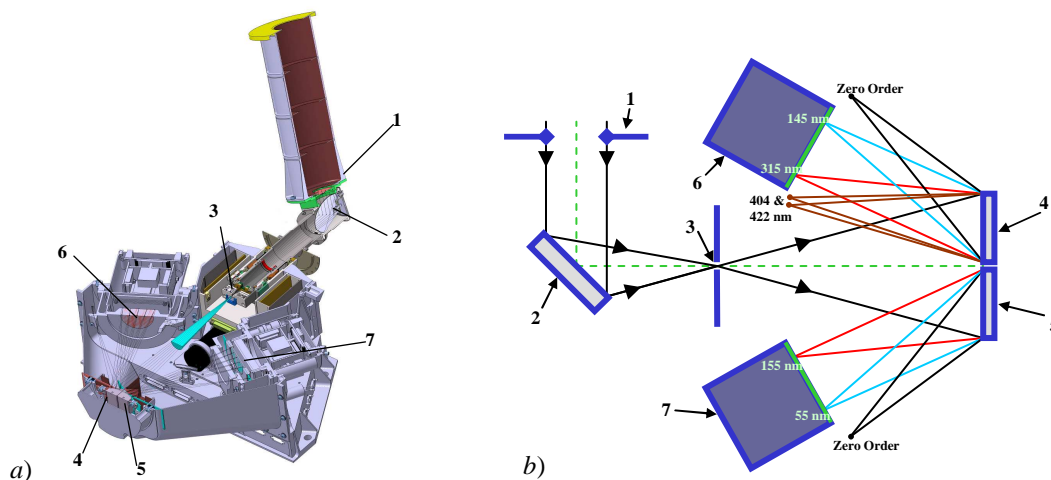
The spectrum detection is based on the photon counting method and is done using Micro-Channel Plate (MCP) detectors with Resistive Anode Encoder (RAE). Photocathodes are CsI for the EUV range, and CsTe for the FUV range. The size of the detectors active area is 40×25 mm<sup>2</sup> equivalent to a matrix of 1024×512 virtual pixels (spectral × spatial). Furthermore Calcium and Potassium lines are selected by the FUV grating. These extra visible lines are monitored using photomultipliers (PM) with bialkali photocathode also used in photon counting mode.

The main advantage of the MCP+RAE detectors is their very high sensitivity mainly due to a very low dark current. Thus photon counting is easily achievable on typical experiment temperature range (from -20°C to +40°C), avoiding mass and power expensive devices to cool the detectors. Five to six orders of magnitude for the detection are then a typical value and offer the monitoring of a wide range of emission.

Moreover PHEBUS is a very flexible instrument due to the rotating scan mirror at the entrance. The instrument is then quite independent from the spacecraft on an observation point of view, avoiding spacecraft slew for specific pointing requests. This scanning mirror is also very helpful to maintain the LoS close to the limb during long integrations, to make the search and monitoring geometry less dependent on orbit and to extend the vertical range of scanning.

### B. Optical specifications

The wavelength ranges are 55-155 nm for the EUV and 145-315 nm for the FUV. The spectral resolution is defined in terms of Full Width at Half Maximum (FWHM) and Full Width at 1% of maximum (FW1%). The required spectral resolution is 1 nm for EUV and 1.5 nm for FUV. These values are to be compared with the result of the optical design optimization: the FWHM is about 0.5 nm on EUV, and 0.8 nm on FUV. Furthermore, the FW1% is about 0.9 nm on EUV, and 1.5 nm on FUV. These calculated values do not include any spreading effects due to scattering by gratings.



**Fig. 1.** a: PHEBUS instrument, b: Optical configuration

1 – Entrance pupil; 2 – Entrance mirror; 3 – Slit;  
4 – FUV grating; 5 – EUV grating; 6 – FUV detector; 7 – EUV detector

The paraxial Field of View of the instrument is about  $2^\circ$  by  $0.1^\circ$ , and the straylight attenuation baffle is designed to protect from bright sources outside a guard angle of  $8.3^\circ$ . High level of attenuation is obtained by combining a very dark black treatment inside the entrance baffle and a superpolished entrance mirror (roughness: 0.5 nm RMS) compatible with EUV range. The two gratings of the PHEBUS instrument are aberration corrected holographic gratings. The mean groove density is  $\sim 1600$  grooves/mm for the FUV and  $\sim 2700$  grooves/mm for the EUV. Groove profile is laminar ion-etched optimized for the respective spectral range. AFM measurements on real prototypes show a micro-roughness of about 1nm RMS. The absolute efficiency can be deduced from AFM measurement of the groove profile via electromagnetic theory software codes: about 6% for EUV and 13% for FUV. The gratings are made of aluminium with a reflective platinum coating. Their active area size is 42 mm by 15 mm. A radiometric model of the PHEBUS instrument has been implemented in order to simulate recorded spectrum. The mean sensitivity of PHEBUS is in the order of 0.1 count per second per Rayleigh of emission, and the mean detection limit can be estimated to about 0.1 Rayleigh for EUV, and about 0.2 Rayleigh for FUV.

### III. GROUND CALIBRATION PHILOSOPHY

#### A. Overview

We decided to perform an instrument's absolute ground calibration as complete as possible. The error made on the in-flight measurements will depend on the quality of calibration made on ground: a precise calibration is essential to process relevant scientific data. Before knowing if ground calibrations are realistic on an experimental point of view, we put forward a theoretical calibration plan.

PHEBUS is a spectrophotometer, its objective is to determine the radiance  $L$  ( $\text{ph.s}^{-1}.\text{m}^{-2}.\text{sr}^{-1}$ ) of an extended source (with respect to the source's wavelength) measuring a count rate  $R$ . The relation  $R = f(L)$  between what we measure ( $R$ ) and what we want to know ( $L$ ) is the main purpose of the calibration. In the case of punctual source like a star, the calibration relation becomes  $R = f(E)$  where  $E$  is the irradiance of the source ( $\text{ph.s}^{-1}.\text{m}^{-2}$ ). Ground calibration will be done at subsystem and system levels and we will distinguish two kinds of calibration, the radiometric calibration and the spectral calibration.

#### B. Instrument radiometric calibration

The radiometric performance of the instrument is evaluated through the knowledge of the Efficiency ( $\eta$ ), the Etendue ( $G$ ) and the Effective Etendue ( $G_{eff}$ ). In a general way (1) defines the efficiency of the system:

$$\eta = \frac{\text{Number of counts}}{\text{Number of incoming photons inside the Etendue } G} \quad (1)$$

The Etendue is the geometric set of beam elements which enter inside the instrument and reach the detector without being subject to vignetting effect. In addition to these diaphragm losses, the Effective Etendue takes into account the efficiency of each optical element and thus the reflectivity losses. By definition, and assuming the approximation that the efficiency does not depend on the ray path we can write:

$$G_{eff} = \eta.G \quad (2)$$

This can also be seen as a averaging of  $\eta$  over all the ray paths. We can see that the Effective Etendue given by (2) includes both Efficiency and Etendue. These three parameters depend on several variables linked to the conditions of the measurement such as the wavelength, the polarization state, the scan angle, the type of source, the position of the slit. Wavelength will have to vary from 55 nm until 315 nm with two extra lines at 404.7 nm and 422.8 nm. It is worth pointing out that for the EUV and FUV channels, measurements made in the spectral range [55 – 315 nm] corresponds to the nominal diffraction order ( $k=1$ ) of the spectrometer. The overlapping diffraction order at  $k=2$  must also be studied, so we need to use a spectral range two times smaller: [27 - 158 nm]. Regarding the step, it will have to be sufficient in order to be significant (at least ten values per spectral range without wide gap). It would be also relevant to perform measurements out of the working spectral range in order to estimate the level of stray light inside the spectrometer.

As the irradiance of the entrance pupil projection on the gratings is not homogeneous due to the off-axis entrance parabola, the illumination pattern on the gratings and the signal distribution on the two channels will vary as a function of the scan angle. Therefore we must perform measurements for several angular positions of

the scanner mechanism. At least two points are required in order to evaluate the extreme cases, but to determine the variation between these two points others values are necessary.

In addition and to be rigorous, we must use two types of sources (uniform extended source and punctual source) and we must perform measurements with the two positions of the slit (nominal position and star position).

To describe the behavior of the instrument with respect to the incident polarization, we use the Stokes formalism and the Mueller matrix. Given  $M_{PHEBUS}$  the (4×4) PHEBUS Mueller matrix, since the information provided by the instrument is a number of counts (i.e. the total output intensity which corresponds to the first component of the output Stokes vector:  $S_0$ ), we can make some simplifications and we can conclude that we only need the first four parameters  $M_{00}, M_{01}, M_{02}, M_{03}$  of  $M_{PHEBUS}$ .

Finally, these four parameters will completely define the photometric response of the system. It means that the radiometric response of the instrument is no longer a simple scalar value  $G_{eff}$  but becomes this set of four scalars.

Given the Stokes vector of the source  $(L_0, L_1, L_2, L_3)$  in terms of radiance, the count rate is:

$$R = M_{00} L_0 + M_{01} L_1 + M_{02} L_2 + M_{03} L_3 \quad (3)$$

If we normalize (3) we can bring out a corrective factor to obtain:

$$R = L_0 M_{00} (1 + m_1 L'_1 + m_2 L'_2 + m_3 L'_3), \quad m_i = \frac{M_{0i}}{M_{00}}, \quad L'_i = \frac{L_i}{L_0} \quad (4)$$

The instrument measure  $R$ , we must know a priori the polarization state of the source  $(L'_1, L'_2, L'_3)$ , the calibration give us the values  $M_{00}$  and  $m_i$ , thus we can deduce the value of interest  $L_0$ .

The term  $M_{00}$  can be assimilated to the Effective Etendue  $G_{eff}$  for unpolarized light. The term inside the brackets of (4) represents a correction factor of  $G_{eff}$  taking into account the incident polarization state and the polarimetric response of the instrument. It can also be seen as an error factor if the polarization effect is not taken into account.

### C. Instrument spectral calibration

In addition to the radiometric calibration we must evaluate the Instrument Spectral Response Function (ISRF), characterizing the line profile at a detector level, for a given alignment of the whole system. It involves to know the position and orientation of each line with respect to the wavelength, but also to measure the resolution in terms of FWHM and FW1%. Since we want to characterize the spectral image, these tests must be done on both detectors EUV and FUV. Regarding the two photomultipliers, we must perform measurements of the spectral bandwidth imposed by the size of each deflection mirrors which work as slits.

### D. Subsystem radiometric calibration

A calibration at subsystem level is important in term of redundancy and also to be able to assess the source of any problem that may affect the overall operation of the instrument. Regarding subsystems, only the radiometric calibration are needed and we will proceed in the same way as for the system calibration, by representing each subsystem by its Mueller matrix. Theoretically, if we know individually each subsystem Mueller matrix we should be able to obtain the Mueller matrix of the whole instrument  $M_{PHEBUS}$ . We introduce here the approach only for the main subsystems.

#### Entrance mirror

The mirror is characterized by its Mueller matrix  $M_{mirror}$  (5) which contains sixteen elements of any value a priori. But according to classical model of mirror reflectance this matrix can be simplified as:

$$M_{mirror} = \begin{bmatrix} \frac{|r_{//}|^2 + |r_{\perp}|^2}{2} & \frac{|r_{//}|^2 - |r_{\perp}|^2}{2} & 0 & 0 \\ \frac{|r_{//}|^2 - |r_{\perp}|^2}{2} & \frac{|r_{//}|^2 + |r_{\perp}|^2}{2} & 0 & 0 \\ 0 & 0 & \text{Re}(r_{//} \bar{r}_{\perp}) & -\text{Im}(r_{//} \bar{r}_{\perp}) \\ 0 & 0 & \text{Im}(r_{//} \bar{r}_{\perp}) & \text{Re}(r_{//} \bar{r}_{\perp}) \end{bmatrix} \quad (5)$$

$r_{//}$  and  $r_{\perp}$  are respectively the reflection coefficients (possibly complex) in terms of amplitude for the parallel component of the electric field and for the perpendicular component of the electric field. Thus only two complex parameters have to be calibrated.

Measurements must be made at a fixed incidence angle which is the working incidence angle of the mirror: 50°. Each measurement must be done by varying wavelength from 55 nm to 315 nm and at 404.7 nm and 422.8 nm.

#### Gratings

Gratings are also represented by their own Mueller matrix  $M_{grating}$  composed by sixteen elements. Measurements must be performed in the spectral range of each grating for the nominal working order  $k=1$  and also in the spectral range corresponding to the diffraction order  $k=2$ .

#### Detectors (EUV & FUV)

In terms of radiometry, we must measure the dark count rate with respect to the temperature (-20°C, +40°C) and also regarding the high voltage (HV) of the MCP: the goal is to increase the HV during flight in order to compensate the ageing of the detectors. Solar blindness of EUV detector will also be verified, by using a visible calibrated source of variable intensity. The spatial uniformity of the detectors response will be tested with flat field illumination. Detector Efficiency will be measured at low signal level for photocathode characterisation, by using a few UV lamps covering the spectral range of the two UV detectors. Non-linearity mainly due to limited electronic sampling frequency will be estimated. Finally, along the whole life of the detectors, all the illuminations undergone by the detectors will be reported into a single document, in order to determine the ageing of the response.

In terms of geometry, an evaluation of the useful area of the detector (i.e. the area where the response is nominal) will be done. The spatial resolution depends on HV and it has to be evaluated by PSF (Point Spread Function) or MTF (Modulation Transfer Function). The evaluation of the distortion of the detector is needed.

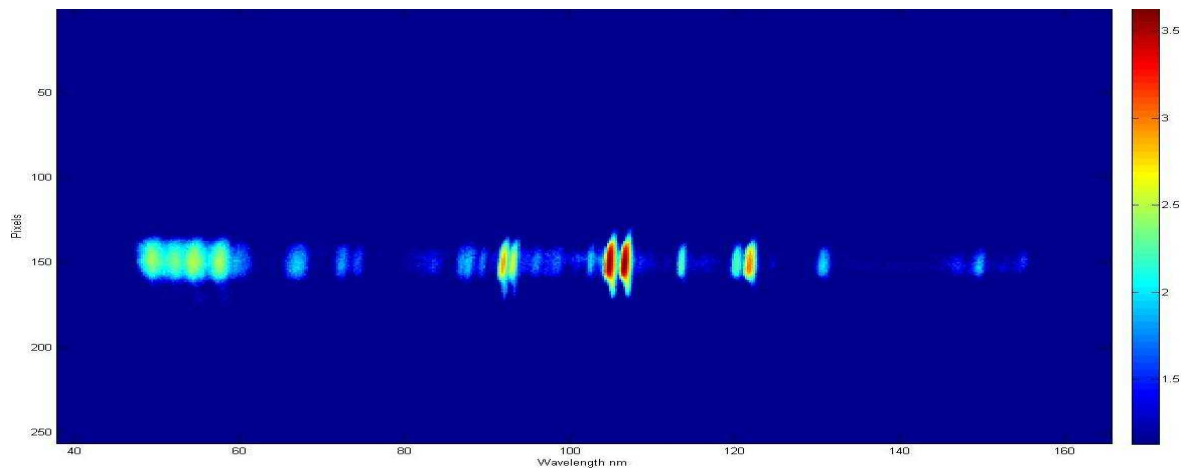
The distortion may depend on HV and is evaluated by calculating:  $\Delta = ((x', y') - (x, y))$ , where  $(x, y)$  is the real impact point of the photon on the photocathode and  $(x', y')$  is the position of the photon as read by the detector.

### IV. FIRST LIGHTS FROM PHEBUS

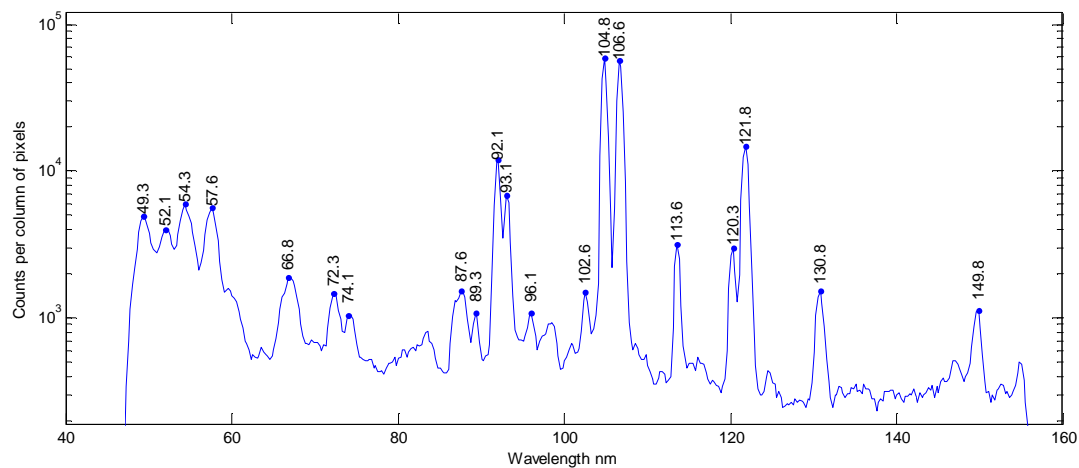
An optical prototype of PHEBUS is currently used to calibrate detectors down to the extreme UV, and also to enable the adjustment of the gratings and the slit. The optical breadboard is representative from an optical point of view but operated with a fixed baffle orientation. In order to have a first approach of the instrument behaviour, first measurements were performed with the EUV detector and using a facility under vacuum composed by a EUV radiofrequency flow lamp as source, a grazing incidence monochromator to select the wavelength and a test chamber. We fill the lamp with different gases such as Ne, He, Ar, N and O in order to emit quasi-monochromatic sharp lines typical of the gas used. The EUV detector is provided with its own software allowing to control detector parameters such as the high voltage but also to acquire data coming out of the detector. We introduce here results obtained with Argon gas and using the zero order position of the monochromator in order to record the full spectrum between 55-155 nm. Data were processed by numerical computing software in order to display the real image seen by the detector (Fig.2) and to plot a spectrum as shown in Fig.3.

Knowledge of the Argon theoretical emission lines allows us to calibrate the x-axis by replacing pixel values by wavelength values (calibration only valid for a given alignment of the components). The wavelengths written in Fig. 3 correspond to peak values of the detector data (and not the wavelengths of emission lines). We can clearly identify the two Argon doublets 104.8 & 106.6 nm (Ar I) and 92.0 & 93.2 nm (Ar II). Others Argon emission lines may be identified such as: 87.6 nm (Ar I), 72.3 nm (Ar II), 67.1 nm (Ar II), 57.7 nm, 54.3 nm, 51.9 nm (Ar II). We can also observe other lines maybe due to contamination such as H I at 121.6 nm, the lines seen at 113.6 nm seems to be N I triplet around 113.4 nm, and the one read at 130.8 nm seems to be O I triplet around 130.4 nm.

The spectral resolution in terms of FWHM was calculated at the doublet 104.8 nm – 106.6 nm levels and the value is 0.72 nm instead of 0.48 nm expected. However, it is a first calibration which allowed us to obtain the first lights from the instrument and to suggest improvements to optimize the measurements and alignments. Among others, a toroidal mirror will be put between the monochromator and the test chamber in order to shape the incident beam (either by collimating or by focusing according to the need). Alignments must be improved also and by the time this paper is written, calibration of the facility (EUV lamp, monochromator) is in progress.



**Fig. 1.** EUV detector Image for Argon gas: HV = -3436 V, this image corresponds to a cumulated integration time of 10 min. The count rate is about 1500 counts per second. (Levels are in  $\log_{10}$ -scale)



**Fig. 2.** EUV spectrum from the image Fig.2 (Levels are in  $\log_{10}$ -scale)

## V. CONCLUSION

The PHEBUS instrument, due to its wide spectral range, high sensitivity and high straylight rejection rate is well suited for the study of Mercury exosphere. A full ground calibration will be made in order to know in the best possible way the response of the instrument. The starting point of the calibration was to evaluate all the parameters which are feature of the instrument and to list all the variables that can vary these parameters. Some calibrations on optical subsystems prototype measurements were already performed [2] in collaboration with the University of Padova (LUXOR laboratory) and an optical breadboard allows us to perform preliminaries calibrations and alignments. The next steps will be to know if all the calibration requirements are feasible or not. On an experimental point of view, we can already say that the measurement of the elements of Mueller matrices will be performed mainly by judicious rotations between the source and the instrument while knowing the Stokes vector of the source.

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