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Spectropolarimetry for Earth observations: a novel method for characterisation of aerosols and clouds

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Aerosols affect Earth's energy level by scattering and absorbing radiation and by changing the properties of clouds. Such effects influence the precipitation patterns and lead to modifications of the global circulation systems that constitute Earth's climate. The aerosol effects on our climate cannot be at full scale estimated due to the insufficient knowledge of their properties at a global scale. Achieving global measurement coverage requires an instrument with a large instantaneous field of view that can perform polarization measurements with high accuracy, typically better than 0.1%. Developing such an instrument can be considered as the most important challenge in polarimetric aerosol remote sensing.

Using a novel technique to measure polarization, we have designed an instrument for a low-Earth orbit, e.g. International Space Station, that can simultaneously characterize the intensity and state of linear polarization of scattered sunlight, from 400 to 800 nm and 1200 to 1600 nm, for 30 viewing directions, each with a 30º viewing angle. In this article we present the instrument's optical design concept.

***Index Terms*—aerosols, SPEX, ISS, polarimetry, optical design**

I. SCIENTIFIC BACKGROUND

Aerosols are particles which interact both directly and indirectly with the Earth's radiation budget and climate. As a direct effect, the aerosols scatter sunlight directly back into space. As an indirect effect, aerosols in the lower atmosphere can modify the size of cloud particles, changing how the clouds reflect and absorb sunlight, therefore affecting the Earth's energy budget. The lack of knowledge of their properties affect the way we model the greenhouse effect on the global temperature. We propose a science mission, SPEX2Earth, that has as goals:

1. to determine and retrieve the key aerosol properties such as the optical thickness, the albedo, refractive index, shape
2. to measure the cloud properties, e.g. optical thickness, albedo, phase, height, droplet effective radius, etc.
3. to characterize the twilight zone, a gradually transition from a cloudy area to a cloud-free one.
4. to improve the climate models.

An additional objective is to provide information during disaster events. For example, in case of volcanic eruptions, the instrument would be able to retrieve the size and composition of the volcanic ash, information that will help the authorities in charge in taking security measurements, e.g. flight interdictions.

II. INSTRUMENT REQUIREMENTS

To obtain a global overview of the Earth's atmosphere SPEX2Earth will perform multi-angle, multi-wavelength measurements of intensity and polarization of light reflected by our planet. The requirements for those measurements are given in Table 1. The spectral range is 400-1600 nm. The low wavelength range band is used for the accurate measurements on aerosols, while the infrared range is aimed at detection of thin cirrus clouds and volcanic aerosols. The polarimetric accuracy requirement assures the retrieval of aerosol properties.

TABLE I. REQUIREMENTS FOR SPEX2EARTH SCIENTIFIC MISSION.

Requirement description	**Requirement**	
	Goal	**Minimum**
Wavelength range	400-1600 nm	400-800 nm
Polarimetric accuracy	0.001 + 0.005·DoLP	0.001 + 0.01·DoLP
Radiometric accuracy	2%	4%
Angular resolution	3º	5º
Angular range	+/- 55º	+/- 45º
Spectral resolution intensity	continuum: $\lambda/\Delta\lambda = 50$ O_2A-band(755-775nm): $\lambda/\Delta\lambda = 500$	
Spectral resolution DOLP	400-800 nm: $\lambda/\Delta\lambda = 10$ 800-1600 nm: $\lambda/\Delta\lambda = 15$	
Across track swath	30º (210 km @ 400km height)	
Ground pixel size	3 km × 3 km	7 km × 7 km

The specific requirement on spectral resolution for the O_2A-band permits the retrieval of aerosol height, information unavailable with current aerosol measurement instruments. The spectral resolution of intensity and polarization is sufficient to resolve the aerosol size distribution in both visible and infrared domains. A key objective is to acquire spectropolarimetric measurements over a range of scattering angles. The required angular range of +/-55º is sufficiently large to achieve this objective.

III. OPTICAL DESIGN

The requirements that drive the design of the optics are the orbit height, the spatial sampling, the swath, the polarimetric accuracy, the SNR and the number of viewing angles. Orbit height and spatial sampling determine the required effective focal length for a given detector pixel (18 µm pixel). Orbit height, spatial sampling and SNR, together with the detector noise define the required diameter for the entrance aperture of each viewing aperture: 1 mm. From the spectral band requirements the specifications for the coatings of the optical surfaces will be derived.

A spectral resolution of 1 nm cannot be achieved with the same optics from 400 nm to 1600 nm. Our choice was to split the wavelength band from 400-800 nm and 1200-1600 nm. This approach also relaxes the spectral resolution requirement as the O_2A band is fully covered in the first channel (400-800 nm).

The sunlight scatterd by Earth's atmosphere is polarized, with polarization properties depending on the aerosols characteristics such as size, shape and chemical composition. For measuring the polarization state a new method is used, which encodes the degree and angle of linear polarization of the incoming light as a sinusoidal modulation of the intensity spectrum [1], [2], [3]. The principle is achieved using an optical configuration (see Fig. 1) comprising:

1. a retarder based on total internal reflections, e.g. Fresnel rhomb;
2. an athermal multiple-order retarder consisting of MgF_2 and Al_2O_3
3. a Wollaston prism as polarization beam-splitter made out of quartz.

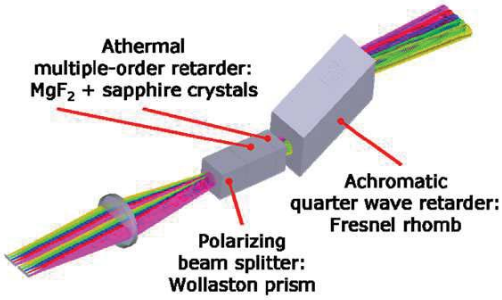


Fig. 1: Optical configuration for the polarization encoding system.

Through this series of optics, the incident light with flux I_0, and degree and angle of linear polarization DoLP and AoLP, respectively, is split into two modulated flux spectra $S_{\pm}$, which are in anti-phase with each other, as follows (transmission losses are ignored):

$$S_{\pm}(\lambda) = 0.5\, I_0(\lambda)\left(1 \pm DoLP(\lambda)\cos\left(\frac{2\pi\delta_{ret}}{\lambda} + 2AoLP(\lambda)\right)\right)$$

The amplitude of the modulation is proportional to the DoLP, its periodicity is determined by the multiple-order retardance δ_{ret}, and the phase shift of the modulated spectrum by the AoLP. Spectra $S_{\pm}$ are collected separately but simultaneously. Using a demodulation algorithm DoLP and AoLP are obtained. In the baseline investigation, the high-spectral resolution spectra S_+ and S_- are sent down to Earth, and the spectra of the flux, the degree and angle of polarization are retrieved on-ground.

The design is such that spectral flux and the state of linear polarization are measured simultaneously. The range of viewing angles provides multiple views of scenes below. The optical system is mounted onto a yaw compensation steering mechanism to counteract the yaw motion of the ISS, needed to optimize co-location of ground pixels. A dedicated star-tracker is part of the SPEX payload to provide attitude information with 0.1º degree accuracy from which the relative orientation of the viewing angle footprints is derived.

The following sections will describe separately the optical design concept covering the visual (VIS) light spectrum (400-800 nm) and the short wave infrared (SWIR) spectrum (1200-1600 nm). The optical concept for both channels is defined by implementing 30 viewing angles, each equipped with polarization optics and a telescope. Light is focus onto a common slit, which is further reimaged by a spectrometer onto a detector.

A. VIS Channel optical design

The system requirements for a field of view of 30º and 30 viewing directions cannot be both achieved simultaneous by using one optical configuration, as radiation coming from an optical surface is obstructed on the path to the detector by neighboring components. To overcome this problem, we have chosen for the VIS band as approach the use of four subsystems, each having half of the total requested field of view, and half of the required number of viewing apertures. Combining two subsystems by placing them side by side will achieve the required 30º swath. Two of these combined subsystems provide a total of 30 different viewing directions. Each of the combined subsystems with 15 viewing apertures will have one viewing aperture directed towards nadir, for cross-comparison of measurements of the separate subsystems, as a check on the stability of the system.

The incoming beam, having a field of view of 16 º, enters the system (see Fig. 2) through an aperture of 1 mm and is transmitted first through a set of polarization optics as described above. A telescope comprising a doublet lens with a focal length of 8 mm focuses the two polarized beams onto a double entrance slit (2.4 mm × 36 µm). The slit is further reimaged onto the detector by an Offner spectrometer which consists of three spherical mirrors, a transmission grating and two cylindrical lenses.

The grating is currently used in the first order at normal incidence. The spectral overlap of orders due to the use of a transmission grating in the design can be corrected by using a blocking filter.

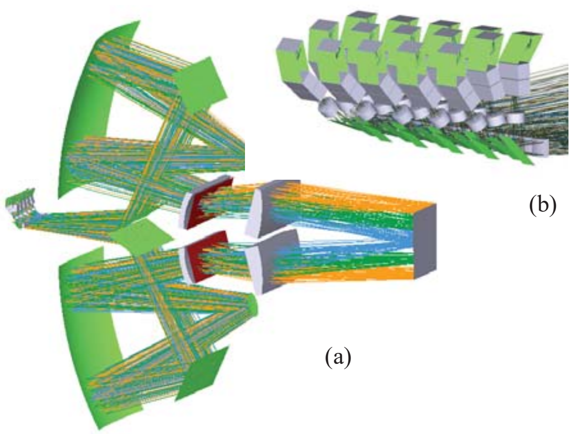


Fig. 2: 3D view of (a) 16 degrees FOV SPEX optical concept for ISS; (b) zoom on the entrance optics showing 15 viewing directions each consisting of polarization optics, telescope, folding mirror and field lens with a double slit.

Each of the viewing apertures has a field of view (FOV) of 0.22º×30º, generating at nadir an instantaneous footprint of 1.5×215 km at a height of 400 km. The ground resolution varies with height, but the operational principle is compatible with the full range of heights (330km-480km) of the ISS.

Fig. 3 illustrates the optical footprint diagram at the detector plane indicating the location of the three field objects in the swath direction defined on axis, at the edge of the field in both positive and negative directions. On the x-axis the full swath is imaged 15 times, which is the number of viewing directions. Along the y-direction, the spectrum is imaged for both S_+ and S_- polarization. The footprint diagram size is 36 mm X 36 mm, equivalent to 2000 pixels of 18 µm per direction. A 1 nm spectral resolution is achieved on the entire VIS spectral waveband.

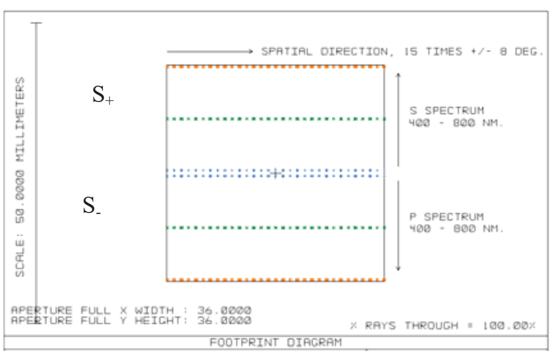


Fig. 3: Footprint diagram at detector indicating both S_+ and S_- polarisations in the spectral direction. In the spatial direction a 16º swath is imaged 15 times. For each of the 15th viewing directions three field points are indicated: one on-axis and two at the edges of the field (±8º).

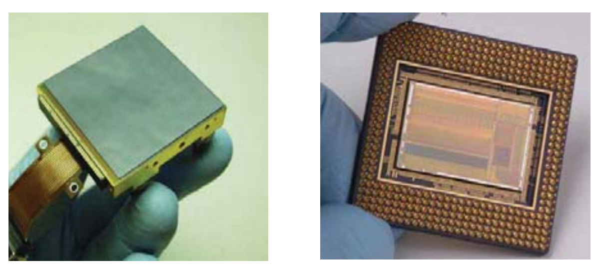
The optical system fits within a volume with overall dimensions of about 80 X 220 X 250 mm^3. The mass expectancy is at this moment approximately 4 kg per sub-system, with a total of 4 subsystems for the VIS spectral range.

Below a table comparing the achieved performance in the VIS band with the instrument requirements. The comparison shows that all requirements are satisfied.

TABLE II. VIS SYSTEM PERFORMANCE IN COMPARISON WITH THE BASIC REQUIREMENTS TABLE I.

Requirement description	**Requirement**		**Nominal optical design performance**
	Goal	**Minimum**	
Wavelength range	400-1600 nm	400-800 nm	400 – 800 nm
Angular resolution	3º	5º	3.33º
Angular range	+/- 55º	+/- 45º	+/- 50º
Spectral resolution intensity	continuum: λ/Δλ = 50 O2A-band(755-775nm): λ/Δλ = 500		continuum: λ/Δλ = 500
Spectral resolution DOLP	400-800 nm: λ/Δλ = 10		λ/Δλ = 20
Across track swath	+/- 15º		+/- 16º
IFOV	0.44º × 0.44º	0.9º × 0.9º	0.22º × 0.22º
Ground pixel size	3 km X 3 km	7 km X 7 km	1.5 km X 1.5 km nadir viewports 4 km X 4 km fore/aft viewports

The information content of a multi angle spectro-polarimeter is very high. In order to record this information it is currently foreseen that two or more large detectors are needed. In the current concept design it has been determined that an existing detector, the H2RG detector from Teledyne coupled with their SIDECAR ASIC would be an excellent possibility (see Fig. 4). This is a 2k X 2k hybrid CMOS detector with a pixel pitch of 18 microns.



(a) (b)

Fig. 4: (a) Teledyne H2RG detector; (b) Teledyne SIDECAR ASIC

However, CCDs have a long and excellent history in scientific space instrumentation and are still the best choice when it comes to performance, e.g. generally dark current and readout noise are much lower than current CMOS detectors and they generally have a better performance on pixel crosstalk and linearity. On the other hand, the random access to pixels, the superior radiation hardness and significantly lower power consumption are among the advantages of CMOS detectors. The final selection of a (space qualified) detector will be performed at a later stage in the project.

B. Compact SWIR concept

In the SWIR band, the optical design concept should achieve a maximum resolution of 40 nm. In principle the VIS concept can be easily adapted to work between 1200-1600 nm while keeping the same form (e.g. use of different grating and same type of detector, but having a sensitivity in the SWIR band). However, since the spectral resolution requirement is more relaxed in the SWIR than in the VIS waveband, a more compact optical design can be generated (see Fig. .

A 2K X 2K detector with 18 µm pixels, similar to the one for VIS but sensitive in the infrared waveband is used. A Teledyne H2RG with a HgCdTe hybridized image sensor offers excellent quantum efficiency and is also compatible with the SIDECAR ASIC. The detector is divided in six parts.

Each of these parts will receive radiation from five viewing directions, resulting in a total of 30 viewing directions per spectral channel. One viewing direction configuration consists of three main parts: the pre-slit polarization optics similar to that of VIS, the telescope and the spectrometer. A telescope formed by two spherical mirrors focuses the light received from the polarisation optics onto a curved slit plane.

Light is further reimaged onto the detector by an Offner spectrometer, which consists of two spherical mirrors and is equipped with prisms for spectral dispersion. Prisms are used instead of a diffraction grating to avoid stray light and unwanted grating orders. Special attention will be given to avoiding unwanted grating orders reaching the detector, e.g. by using a filter. The spectrometer has for each viewing direction a double entrance slit for S_+ and S_- polarizations. The entrance slit length is 9 mm and the width is 36 µm.

The design offers a compact alternative to an adapted VIS design for SWIR that satisfies most of the requirements. The optical system fits into a volume with the following dimensions: 60 mm X 170 mm X 260 mm.

Five viewing directions are combined into one arm and reimaged by the same Offner spectrometer (see Fig. 5 above). Three such arms can be further combined using the mirror array situated after the slit plate to be reimaged by the same Offner spectrometer onto the detector. Three arms will thus fill one half of the detector. A mirror system will fill the other half of the detector, yielding in total 30 viewing directions. All viewing directions have the same pre-slit polarization optics and telescope configurations.

The optical concept comprises components which are expected to be easily manufacturable. In terms of materials, we use at this moment: BK7G18, SF2, SF6, Silica, Aluminum and Calcite, all space qualified.

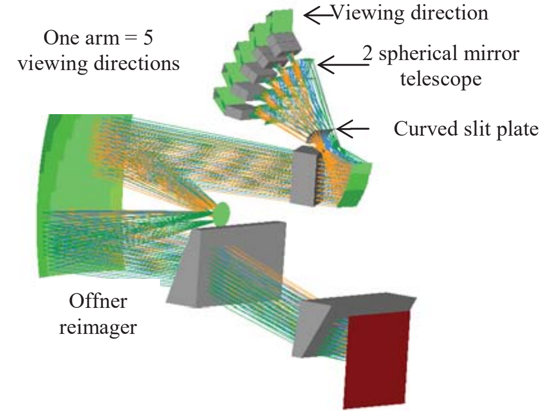


Fig. 5: 3D view of a wide field SPEX2Earth optcal concept for SWIR wavelength range, showing the light coming through a set of five viewing directions being combined at the slit and reimaged onto one of the sixth detector parts by an Offner system. Five viewing directions form one arm.

Figure 6 shows the footprint diagram on one of the sixth detector parts. The entire detector size is 36 mm X 36 mm.

TABLE III shows a comparison between the achieved performance and the requirements presented in TABLE I. It has to be noted that originally an optical system was designed for a wavelength range between 600-1600 nm. Based on this design, we have conservatively estimated the expected performance for the reduced wavelength range of 1200-1600 nm.

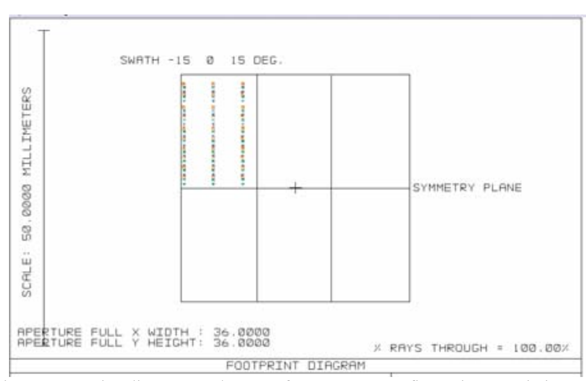


Fig. 6: Footprint diagram at detector for one arm configuration consisting of 5 viewing directions. Each arm is imaged onto one detector compartment to reach a total of 30 viewing directions.

TABLE III. SWIR SYSTEM PERFORMANCE IN COMPARISON WITH THE BASIC SCIENCE REQUIREMENTS IN TABLE I.

Requirement description	**Requirement**		**Nominal optical design performance**
	Goal	**Minimum**	
Wavelength range	400-1600 nm	400-800 nm	1200 – 1600 nm
Angular resolution	3°	5°	3.33°
Angular range	+/- 55°	+/- 45°	+/- 50°
Spectral resolution intensity	continuum: $\lambda/\Delta\lambda$=50		continuum: $\lambda/\Delta\lambda \sim 100$
Spectral resolution DOLP	1200-1600 nm: $\lambda/\Delta\lambda = 15$		$\lambda/\Delta\lambda \sim 20$
Across track swath	+/- 15°		+/- 15°
IFOV	0.44° × 0.44°	0.9° × 0.9°	0.095° X 0.095°
Ground pixel size	3 km x 3 km	7 km x 7 km	0.65 km x 0.65 km nadir viewports 1.75 km X 1.75 km fore/aft viewports

In order to reach the challenging accuracy requirement on the DoLP, SPEX is designed such that the DoLP measurements are inherently insensitive to in-flight changes in optical properties. This means that an extensive and accurate on-ground calibration provides the key to the required DoLP accuracy. Additionally, in flight performance checks will be made.

IV. CONCLUSIONS

Aerosols represent the largest uncertainty in climate research. We have presented two optical concepts feasible for a mission having as objectives the retrieval of aerosol properties and therefore the improvement of climate models.

ACKNOWLEDGMENT

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