SPEXone: A compact multi-angle spectro-polarimeter

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ABSTRACT

We have developed a 6 dm^3-sized optical instrument to characterize the microphysical properties of fine particulate matter or aerosol in the Earth atmosphere from low Earth orbit. Our instrument can provide detailed and worldwide knowledge of aerosol amount, type and properties. This is important for climate and ecosystem science and human health [1, 2]. Therefore, NASA, ESA and the European Commission study the application of aerosol instruments for planned or future missions. We distinguish molecular Rayleigh scattering from aerosol Mie-type scattering by analyzing multi-angle observations of radiance and the polarization state of sun light that is scattered in the Earth atmosphere [3]. We measure across the visible wavelength spectrum and in five distinct viewing angles between -50° and +50°. Such analysis has been traditionally done by rotating polarizers and band-filters in front of an Earth observing wide-angle imager. In contrast, we adopt a means to map the linear polarization state on the spectrum using passive optical components [4]. Thereby we can characterize the full linear polarization state for a scene instantaneously. This improves the polarimetric accuracy, which is critical for aerosol characterization, enabling us to distinguish for example anthropogenic from natural aerosol types. Moreover, the absence of moving parts simplifies the instrument, and makes it more robust and reliable. We have demonstrated this method in an airborne instrument called SPEX airborne [5, 6] in the recent ACEPOL campaign together with a suite of state-of-the art and innovative active and passive aerosol sensors on the NASA ER-2 high-altitude research platform [7]. An earlier report on the SPEX development roadmap was given in [8]. In this contribution we introduce SPEXone, a compact space instrument that has a new telescope that projects the five viewing angles onto a single polarization modulation unit and the subsequent reflective spectrometer. The novel telescope allows the observation of five scenes with one spectrometer, hence the name. We describe the optical layout of the telescope, polarization modulation optics, and spectrometer and discuss the manufacturability and tolerances involved. We will also discuss the modelled instrument performance and show preliminary results from optical breadboards of the telescope and polarization modulation optics. With SPEXone we present a strong and new tool for climate research and air quality monitoring. It can be used to study the effect of atmospheric aerosol on the heating/cooling of the Earth and on air quality. Also, SPEXone can improve the accuracy of satellite measurements of greenhouse gas concentrations and ocean color that rely on molecular absorption of reflected sunlight by providing detailed knowledge of the aerosol properties, required to accurately trace the light path in presence of scattering.

SPEXone is developed in a partnership between SRON Netherlands Institute for Space Research and Airbus Defence and Space Netherlands with support from the Netherlands Organisation for Applied Scientific Research (TNO) as a Dutch contribution to the NASA PACE observatory launching in 2022.

Keywords: polarimetry, spectrometry, aerosol, telescope, free-form, Earth Observation, satellite, constellation

1. SCIENCE CASE

Aerosols affect the climate directly by scattering and absorption of solar radiation and indirectly by altering the micro- and macro-physical properties of clouds. In contrast to the climate effect of greenhouse gases, which is understood relatively well, the forcing caused by aerosols represents the largest reported uncertainty in the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC) [1]. Aerosols are also known to strongly affect air quality, especially in regions with high industrial activity and large amounts of traffic, or in regions that are influenced by biomass burning. Exposure to particulate matter air pollution has major adverse human health impacts, including asthma attacks, heart and lung diseases, and premature mortality [2].

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To improve our understanding of the complex role of aerosols in the climate system and on air quality, global measurements are needed of aerosol optical and microphysical properties. In addition to the Aerosol Optical Thickness (AOT), there is a particular strong need for measurements of aerosol absorption (to quantify to what extend aerosols cool or warm the atmosphere), aerosol composition (to quantify aerosol emissions - e.g. natural or anthropogenic), aerosol size and number concentration (effect on cloud formation, air quality), and aerosol height (effect on cloud formation, direct effect) [9-15].
The aim of the SPEXone instrument is to provide this information with the accuracy needed to significantly advance of the effect of aerosols on climate. The high level science goals and the geophysical data products that are foreseen for SPEXone are summarized in Figure 1. SPEXone is planned to fly on the NASA Phytoplankton, Aerosols, Clouds and ocean Ecosystems (PACE) mission, scheduled for launch in 2022 [16]. The science impact of SPEXone will be increased considerably by making use of the synergy with the other instruments on PACE: The Ocean Color Instrument (OCI) and the Hyperangular Rainbow Polarimeter-2 (HARP-2). The aspects for which the different instruments on PACE will benefit from each other include:

- Aerosol cloud interaction: OCI and HARP will provide detailed and accurate cloud measurements that can be used with SPEXone aerosol measurements to investigate aerosol cloud relationships.
- HARP-2 resolves the cloud bow in polarization that allows to separate aerosols from clouds. Using SPEXone and HARP2 together will give unprecedented capability for aerosol above cloud retrievals.
- Combination of SPEXone with OCI even further enhances the capability for determining aerosol absorption, because OCI measures further into the UV.
- The wider swath of OCI and HARP-2 can be used to spatially extend the highly accurate aerosol information for the SPEXone swath (100 km).
- SPEXone can provide a benchmark for atmospheric correction for ocean color remote sensing.

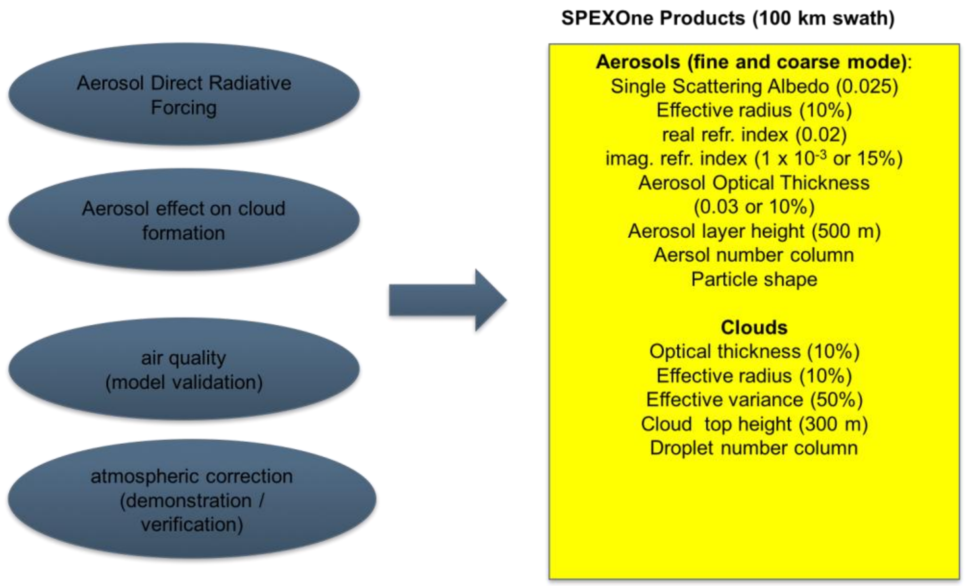

Figure 1: High level science goals and foreseen data products of SPEXone.

Another important application of SPEXone technology would be its use for light path correction for Greenhouse gas retrievals, in particular CO2. Current retrievals of CO2 are based on single viewing angle spectrometer measurements where light path modification due to aerosol scattering is the main source of error. Already for low to moderate values of the Aerosol Optical Thickness (AOT) < 0.25 this hampers the ability to achieve the required accuracy of CO2 of ~0.5 ppm. Using a polarimeter like SPEXone, the light path can be accurately determined making CO2 retrievals possible in regions with high aerosol load, such as cities, biomass burning regions, and regions affected by desert dust. This application is of interest to the CO2M mission which is currently under study by ESA.

2. INSTRUMENT OVERVIEW

The SPEXone instrument is a multi-angle spectro-polarimeter with five viewing angles operating in the visual part of the spectrum, from 385-770 nm. A block diagram of the instrument is shown in Figure 2. A three-mirror segmented telescope assembly gathers light from 0°, ±20° and ±50° and directs the light towards a common entrance slit of a single spectrometer. Before and after the slit several optical components are placed that together form the polarization modulation optics (PMO) that encode the state of linear polarization in the intensity spectrum as a sinusoidal modulation. The polarizing beam splitter in the PMO results in two complementary light beams that both enter the spectrometer and are focussed onto the detector as two pairs of five spectral images, as shown in Figure 2.

Figure 2 SPEXone multi-angle polarimeter instrument building blocks along the signal path; five-viewing angle telescope assembly, polarization modulation optics module, spectrometer module projecting two orthogonally polarized spectra per viewing direction, detector module that records the ten spectra and instrument control unit.

The spectrometer is based on Dutch heritage with the Sentinel-5 precursor Tropomi instrument [17] and the derived compact version Spectrolite [18]. The Spectrolite and SPEXone compact spectrometers are developed so that they can be flown on very small platforms. This allows to fly multiple instruments in a satellite constellation, improving both global coverage and temporal sampling, like studied in the SCARBO project [19]. A constellation of low-cost instruments may complement the larger operational satellite missions such as the Copernicus Sentinels. We design these compact instruments using modular and low-technology-risk subsystems and ready for production in small series. In SPEXone we employ a lean development and manufacturing approach; we keep strictly to the minimum required functionality to fulfil the science goal while, at the same time, maintaining sufficient design margin to deliver optimal performance within the cost-cap.

The focal plane assembly is a detector module from 3Dplus that is equipped with a 2k x 2k CMOSIS CMV4000 CMOS image sensor, a Microsemi FPGA, SDRAM and FLASH memory. This detector module enables image acquisition and processing with a high level of flexibility. In SPEXone advanced binning and co-addition capabilities are implemented. Due to this detector module functionality, the complexity of the Instrument Control Unit (ICU) can be kept limited. The main function of the ICU are: receiving commands from the spacecraft, commanding the camera module, LED-calibration source control, collecting data from the camera module, gathering housekeeping data, transmitting science and housekeeping data to the spacecraft, and performing thermal control of the instrument.

Multi-angle polarimetry for atmospheric aerosol characterization requires the ability to re-grid data from all viewing angles onto a common spatial grid. Therefore we require Nyquist sampling of the ground scene in both along-track (ALT) and across-track (ACT) directions. SPEXone has optimized telescopes for each viewing angle, that all image a 100 km swath (ACT direction) with a spatial resolution close to 5.4 km onto the detector at a spatial sampling distance (SSD) of 2.7 km. In the ALT direction, Nyquist sampling is achieved by performing two image acquisitions per 4.6 km sub-satellite point movement, while ensuring that the effective ALT spatial resolution (which includes the IFOV of the slit projection and motion smear) is close to 4.6 km.

SPEXone will perform science observations during the dayside of the orbit, and perform detector calibration measurements during the eclipse part of the orbit. These include dark signal measurements, and pixel response and non-linearity measurements using the on-board LEDs. Calibration measurements can be executed using the science observation acquisition scheme (which includes binning and co-adding) and by using full frame read-out of the detector. Radiometric and polarimetric monitoring and in-flight vicarious calibration will be performed using selected natural scenes, such as dark ocean, bright clouds, stable and homogeneous desert sites, and sun-glint observations. Radiometric cross-calibration of the ±20° viewports with the Ocean Color Instrument [16] is possible since the spectral range of SPEXone is fully covered by OCI, the primary payload on PACE.

A summary of the SPEXone instrument performance specifications are listed in Table 1.

Table 1: SPEXone performance specification

Parameter	Specification
Swath	100 km
angular range (**on ground**)	+/- 55°
# viewing angles	5
spectral range	385 - 770 nm
spectral resolution intensity	4 nm
spectral resolution DoLP	20 – 40 nm
spatial resolution ALT x ACT (for all angles)	4.6×5.4 km^2
spatial sampling	2.3×2.7 km^2
polarimetric accuracy	0.003
radiometric accuracy	2%
SNR for ocean scene at SZA = 70°	300

3. OPTICAL LAYOUT

3.1 Telescope assembly

To accommodate spectro-polarimetry for five different along-track viewing directions within a 6 dm^3 overall instrument envelope we have chosen to use single, common, polarization modulation optics, spectrometer and detector module for all five viewing directions. These common building blocks are kept unchanged with respect to our wide-field-SPEX concept presented in [8]. To feed the five fields of view into the common optics we have recently developed a novel "SPEXone multi-angle imager" telescope that is subject to an SRON patent. The SPEXone telescope assembly is inspired by integral field units known from astronomy, see Figure 3.

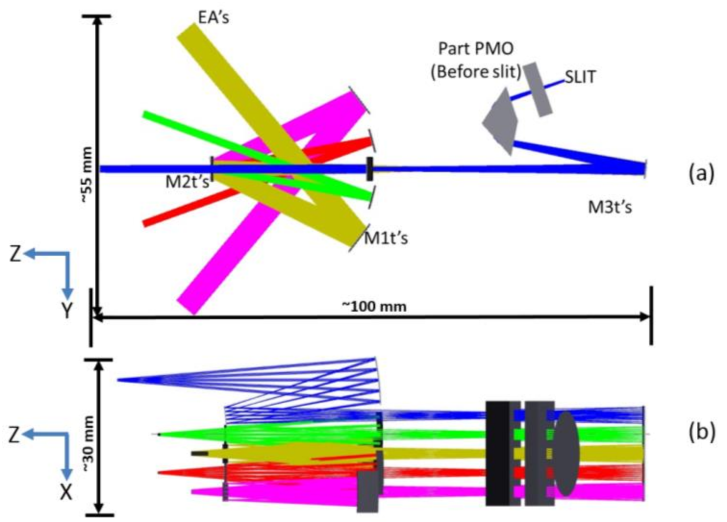

Figure 3: (a) Top view, (b) Side view of SPEXone telescope

A stack of five individual three-mirror telescopes map five "push broom" swaths onto a single spectrometer entrance slit, separated by masked-out areas. The individual telescopes are designed such that the mirrors m1t–m3t of each telescope can be grouped into three compound mirrors M1t–M3t, with five sub-mirrors each. Every sub-mirror has its individual shape and tilt, produced through single-point diamond turning. To minimize instrumental polarization in the telescope, the necessary folding angles to achieve the along-track viewing directions are spread evenly over M1t and M2t (i.e. 12.5°

angle-of-incidence for the ±50° viewing directions, and 5° AoI for the ±20° directions), while a small tilt of M3t gives sufficient beam clearance for the PMO.

3.2 Polarization Modulation Optics

The SPEX polarimetry concept is based on spectral polarization modulation; the degree and angle of linear polarization are encoded in a modulation of the radiance spectrum. This is achieved through a dedicated subsystem; the polarization modulation optics (PMO). The subsystem contains the following optical components: an achromatic quarter-wave retarder, an athermal-multiple-order retarder and a polarizing-beam-splitter assembly. The quarter-wave retarder and multiple-order retarder ensure that incident linearly polarized light is modulated in the spectral domain.

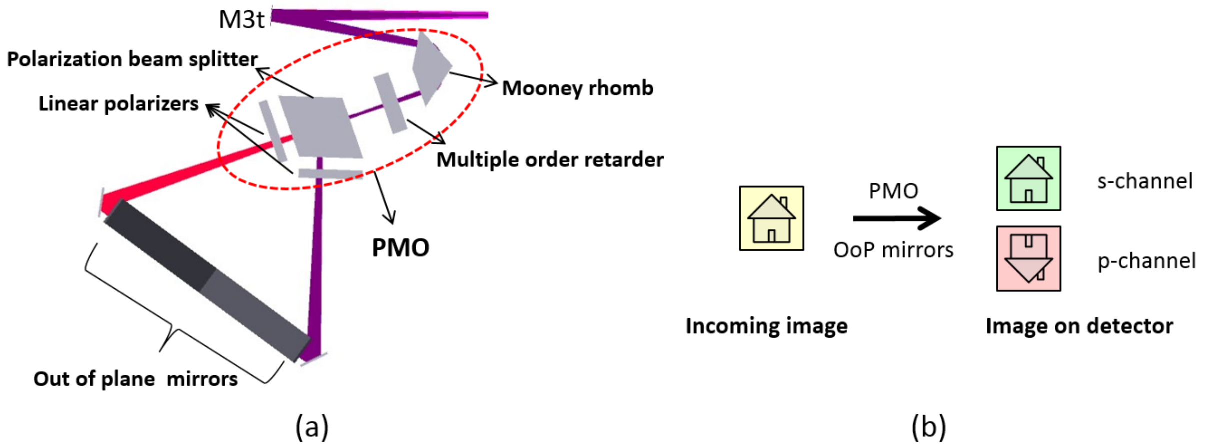

Figure 4: (a) PMO optics (b planar symmetry of beam combining concept.

The polarizing beam splitter assembly transforms the spectral polarization modulation into two spectrally modulated intensities, such that amplitude and phase of the modulation are proportional to the degree and angle of linear polarization respectively, see Figure 4 (a). The quarter-wave retarder will be implemented as a Mooney rhomb, while the multiple-order retarder will be an athermal combination of MgF2 and Quartz. The polarizing beam splitter is based on an off-the-shelf beam-splitter cube, that has been customized to reduce the angles of incidence on the entrance and exit ports, in combination with a set of wire-grid polarizers to achieve the required polarization purity >1000. The two orthogonally polarized beams are recombined, symmetrically around the detector center line, for spectral analysis using flat folding mirrors and a roof mirror, Figure 4 (b). As the polarization modulation optics require proper mechanical mounting, a breadboard program with environmental testing was executed, results are reported in Section 5.2.
All optical components of the PMO are adhesively bonded into a monolithic titanium (TiAl6V4) housing. This housing is specifically designed to allow the subsequent adhesive bonding of the components to within 0.2 degrees from the design values. Titanium was chosen for the housing material as this best fits the CTE mismatches with the three optical materials used: fused silica, crystal quartz and MgF2. Scotch weld 2216 from 3M was chosen as adhesive, because of our extensive heritage with this material for space use. Bond spots were sized to be both strong and flexible enough to hold the optical components in place under the required thermal and vibration conditions.

3.3 Spectrometer

The spectrometer design is based on Dutch heritage with the ESA Sentinel-5p TROPOMI instrument and the derived compact version Spectrolite [18]. It is an all-reflective, off-axis design, including four free-form mirrors and a flat reflective grating in the spectrometer. The free-form mirrors are based on TNO heritage in manufacturing with single point diamond turning [17]. The operational spectral range is 385 nm – 770 nm, the spectral resolution is 4 nm. The image sensor size is 11 mm x 11 mm. The required spatial resolution (Table 1) translates to a required FWHM spot size on the detector <22 micrometer including manufacturing, alignment and environmental deformation tolerances. A combination of a gradient filter and a short-pass filter are implemented to perform grating order sorting and to block out-of-band light.

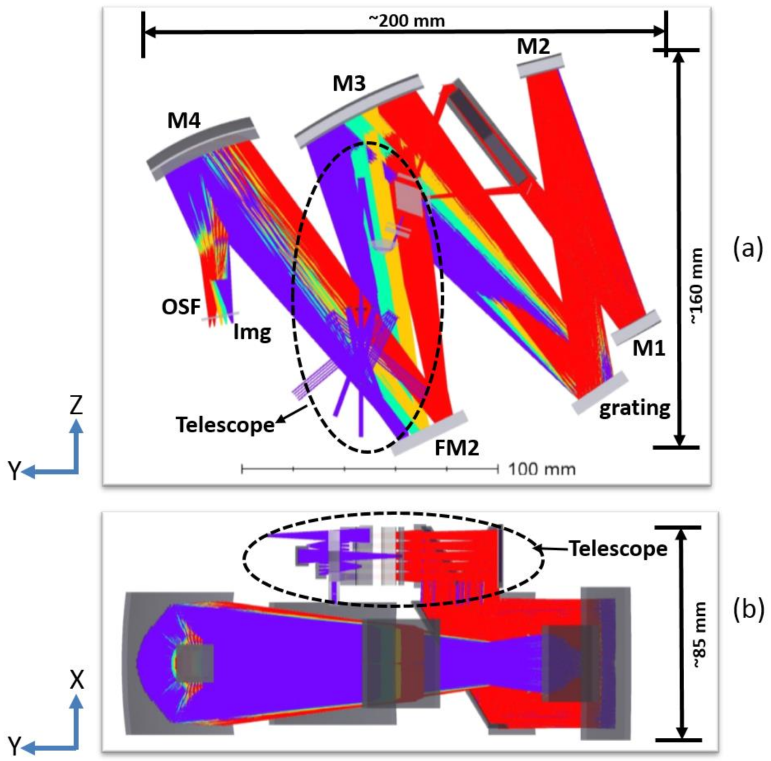

Figure 5: (a) Top view, (b) Side view of SPEXone complete optical layout.

See Figure 5 (a) and (b) for top and side views of the complete optical design. X and Y are the across (ACT) and along track (ALT) coordinates respectively, Z is pointing in zenith direction. The SPEXone spectrometer is made of a two-mirror collimator, a planar grating and a two-mirror imager plus a flat folding mirror inside the imager. The four powered mirrors are all free-form, with their surfaces parametrized using a XY-polynomial up to sixth order. Thanks to the instrument's planar symmetry, all odd powers in x (across-track coordinate) cancel out so each mirror surface is defined with 14 coefficients:

$$z(x,y) = \frac{C_X}{2}x^2 + \frac{C_Y}{2}y^2 + A_{31}x^2y + A_{33}y^3 + A_{40}x^4 + A_{42}x^2y^2 + A_{44}y^4 + \ldots$$
$$\ldots + A_{51}x^4y + A_{53}x^2y^3 + A_{55}y^5 + A_{60}x^6 + A_{62}x^4y^2 + A_{64}x^2y^4 + A_{66}y^6.$$

In this expression, the two second-order coefficients are proportional to the mirror curvatures C_X and C_Y; while the other terms control geometrical aberrations.

The spectrometer design is approached as follows. We choose the ACT paraxial focal lengths of the collimator and the imager such that the physical size of the spectrometer does not exceed 60 mm along x, leaving 40 mm for the telescope and enveloping structure, within the available 100 mm. The ALT paraxial focal lengths are chosen to meet the spectral resolution requirements for an available off-the shelf grating of 500 grooves/mm. The XY-polynomial coefficients are then optimized to correct for aberrations using Zemax OpticStudio. Rms spot radii at selected wavelengths and fields are used as a performance indicator during the optimization of the design. The maximum FWHM spot size for the nominal design is 16 micrometer.

To facilitate easy integration of the mirrors, their positions and tilts are optimized with a limited freedom in space with respect to initially chosen positions at the edges of the cubic volume of the instrument. The spectrometer has a residual peak-to-valley keystone aberration of ~160 µm over the operational spectral range and a wavelength dependent smile with a maximum value of ~125 µm at 385 nm. Figure 6 shows the image plane of SPEXone showing 10 spectra corresponding to the five ALT viewing directions and the s- and p-polarizations states.

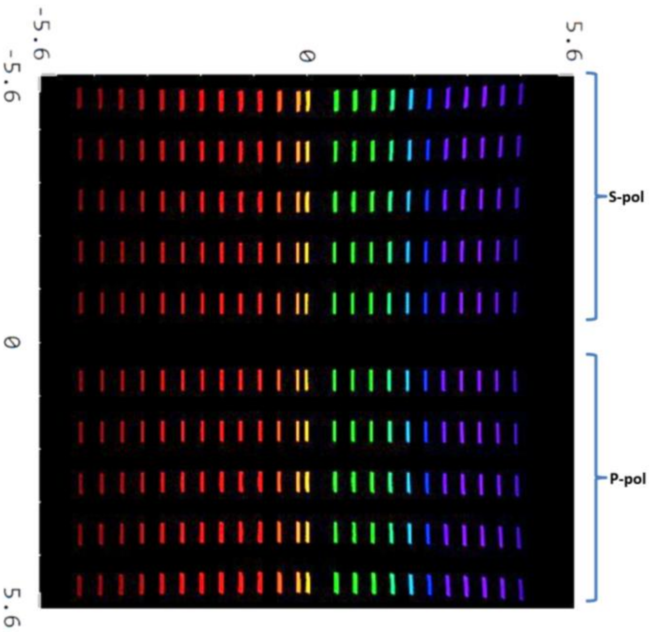

Figure 6: Simulated image plane of SPEXone with spectra for each of the 5 along track viewing directions for s- and p-polarization, yielding a total of 10 spectra. The detector size is 11 mm x 11 mm.

A tolerance analysis is performed on the design to derive the alignment and manufacturing tolerances. Most of the mirrors need to be positioned within decenter tolerances of ±20 μm and tilt tolerances of ±100 μrad around x and y and ±200 μrad around z.
To assess the manufacturability of the four spectrometer mirrors, their sizes and maximum sag (peak to peak z-deviation) are reported in Table 2 and compared with the TROPOMI telescope mirrors that have been successfully manufactured with single-point diamond turning [18]. The peak to peak deviation from the best-fit sphere is also given to evaluate the freeform strength: a freeform is considered mild when this quantity ranges from 0.1 mm to 0.5 mm which is the case of SPEXone. We see that the TROPOMI M1t mirror has a significantly larger sag amplitude and therefore surface slopes, a larger length and aspect ratio, and finally a larger deviation from the best-fit sphere than all SPEXone mirrors. This clearly shows that the SPEXone spectrometer mirrors can be manufactured within the current state-of-the art at TNO.

Table 2 SPEXone spectrometer mirrors compared to Tropomi

		X semi-aperture (mm)	Y semi-aperture (mm)	max sag (mm)	P2P deviation from best-fit sphere (mm)
SPEXone	M1	30.0	10.0	0.72	0.42
	M2	28.0	9.0	0.86	0.15
	M3	24.0	27.0	3.22	0.25
	M4	28.0	22.0	7.73	0.35
Tropomi	M1t	69.0	11.0	25.33	0.62
	M2t	47.5	15.0	5.15	0.03

See Figure 7 for a rendering of the opto-mechanical housing and its nested build-up. Overall instrument size is 10 x 20 x 30 cm^3. It shows the high level of integration with, from large to small, the spectrometer, the telescope and the PMO. The spectrometer and telescope housing and mirrors are manufactured from Aluminum. The PMO is machined from Titanium. The spectrometer optical bench is designed for ease of assembly. The mechanical housing is manufactured to very high accuracy (~2 micrometer) removing the need for dedicated alignment with shims, except for a limited number of selected compensator elements.

Figure 7 Rendering of the SPEXone opto-mechanical housing and its nested build-up showing from large to small: the spectrometer, the telescope and the PMO. Overall size 10 x 20 x 30 cm^3.

3.4 Detector Module

We have selected a commercial-off-the-shelf detector module (DEM) from 3Dplus in France. The detector was initially developed and qualified together with CNES for the MARS 2020 rover SuperCam. The compact-sized detector module consists of a 2k x 2k pixel CMOS image sensor with 5.6 µm square pixels integrated with front-end-electronics containing an FPGA and volatile and non-volatile memories. Dedicated pre-development of the read-out, special binning and interfacing through Spacewire was done within the SPEXone project. The full 2k x 2k pixel image sensor is read-out at 15 frames per second in 10 bit mode. Subsequently we perform 2 x 2 binning and apply 5 temporal co-additions. Finally a special binning scheme is applied that can flexibly be configured to select the spectral data at the desired sampling while dumping unused rows in-between the spectra. The resulting 16 bit data meet the SNR requirement at an orbit average data rate below 9 Mbit/s.

3.5 Instrument Control Unit

The Instrument Control Unit is the electrical interface between the spacecraft platform and the SPEXone instrument. The ICU executes commands and configures and synchronizes the DEM within the system. Once image data is available in the DEM, the ICU will retrieve the digitized output from the DEM, packetize the data and forward the packets to the spacecraft for recording or direct downlink through a dedicated interface. The ICU also provides pre-conditioned power to the DEM and controls the temperatures of the instrument and DEM to within sufficiently stable limits. Another ICU function is to control a redundant pair of LED broad band visible light sources placed close to the detector for calibration/monitoring purposes. The ICU provides event reporting and event action. In addition, specific operation procedures, memory management control and fault management control functions are implemented matched to the PACE platform operations. The pre-development of the ICU is performed as a co-development between the SPEXone consortium and Hyperion in the Netherlands.

4. MODELLED PERFORMANCE

4.1 Structural thermal optical properties

The optical bench is robust against temperature changes and gradients over the bench on the order of ± 1K by design because both the bench and the reflective optics are made almost completely of one material (Aluminium) and because the design is highly integrated and therefore compact. Beams that encounter transmissive optics in the PMO and close to the detector are telecentric and have small angles with the surface normal. Extensive structural-thermal-optical-properties (STOP) analysis was performed for a similar optical bench (Spectrolite) that confirmed that named temperature excursions and gradients do not degrade the performance in operation significantly. Also, the effect of gravity release on the final performance is negligible due to low mass and high stiffness of the mirrors. In the SPEXone study we have performed STOP analysis for the novel telescope. The effect of thermal variation of ± 1K around 293 K is analyzed. In this work we have used a pipeline of concatenated commercial software packages for finite element modelling, for thermal and mechanical modeling, and the combination of Sigfit and Zemax for optical analysis. We have taken the following steps: Initially, a temperature distribution is simulated using Nonlinear Steady State Heat Transfer Analysis, with thermal boundary conditions. Then the results are used as input for structural deformation. Structural deformation is assumed to change the toroidal mirror shape as well as the position of the mirror vertices. Lastly, the results are converted to Zernike coefficients (in Sigfit) to enable optical software (ZEMAX) to add the results into alignment and manufacturing tolerances. The results for this first iteration of the STOP analysis shows that the performance degradation in the telescope due to the operational thermal loads accounts for about 10% of the available error budget in the allowable spot size increase. Displacement of the mirrors are dominant over mirror deformations. These deformations of the mirror surfaces yield not more than several tens of nanometers rms surface shape error. A more detailed analysis that includes all mirrors in the system will be performed in the next design phase.

4.2 End-to-end performance model

An assessment of the performance in terms of signal-to-noise ratio (SNR) has been carried out using an end-to-end instrument performance model. This model takes as input spectral radiance files that are obtained by forward model calculations of the expected radiance for ocean and land scenes with different aerosol optical thickness. The model takes into account the full Stokes vector and calculates the Mueller matrix for each optical interface, taking into account the finite angles of incidence for each field point. This way the full polarization properties of the instrument can be simulated. The image at the focal plane is constructed based on the spatial resolution, spectral dispersion and spectral range, taking into account the spectral smile and keystone from the ZEMAX optical design.

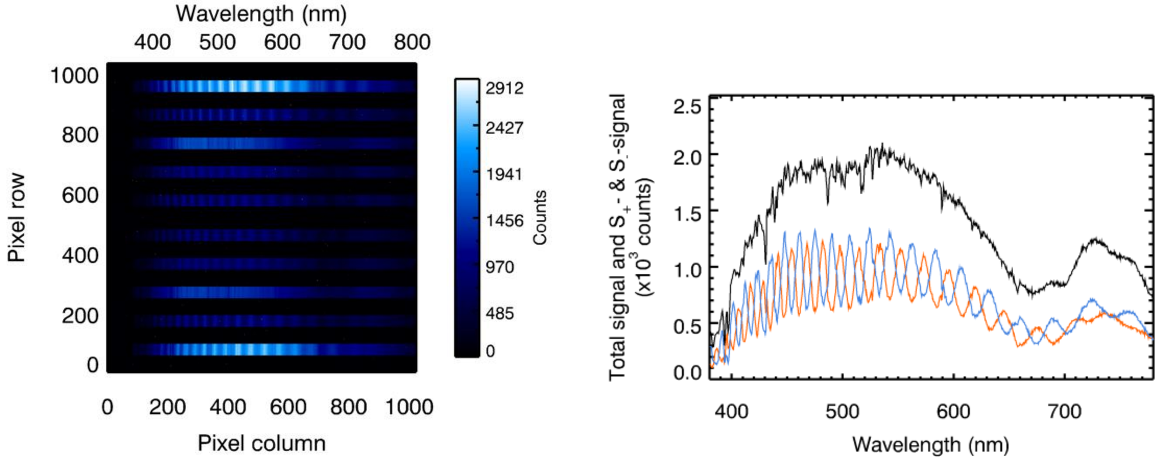

Figure 8 Simulated final detector image for the SPEXone instrument viewing a homogeneous vegetation scene (left). Simulated detector signals for the viewport with the lowest signals (right).

The detector response is calculated based on the Stokes spectrum after the last optical component and the quantum efficiency, by accounting for the pixel pitch, pixel size and co-additions and by including photon noise and detector noise sources. An example of a simulated detector image is shown in Figure 8-left, while the simulated modulated spectra of a single viewport are shown in Figure 8-right.The signal-to-noise ratio that can be obtained for such a scene after averaging over 10 nm is plotted in Figure 9 for each of the five viewports. The detector response has been analyzed for a variety of scenes in order to assess the instrument response to the full (spectral) dynamic range of incident radiance (ranging from bright clouds to a clear atmosphere over a dark ocean). Although the instrument throughput drops at the blue and red edge of the spectral range, an SNR of 300 over a modulation period can be obtained for the most challenging dark ocean scenes.

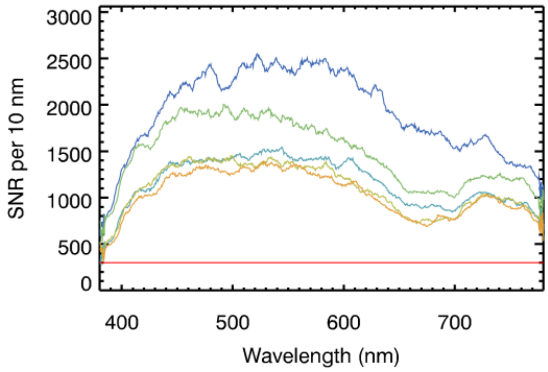

Figure 9 Simulated signal-to-noise ratio for all five viewports for the simulated detector image for a homogeneous vegetation scene.

5. OPTICAL BREADBOARD RESULTS

5.1 Telescope

A first prototype of the, from a manufacturing prespective, most challenging telescope mirror M2t, comprising the five sub-mirrors of M2t but without the mounting interfaces, has been produced by our supplier VDL in the Netherlands using single point diamond turning in Aluminium, see Figure 10. It verifies that the sub-mirrors can indeed be placed very close together, with separations down to a few 100 µm, and that the surface quality is within specification with an rms roughness ~2.5 nm. To further pre-develop the telescope with its compound mirrors M1t–M3t a telescope breadboard is under construction. It is intended to confirm that the required individual sub-mirror parameters (relative position and orientation, surface form, figure, and finish) can indeed be achieved.

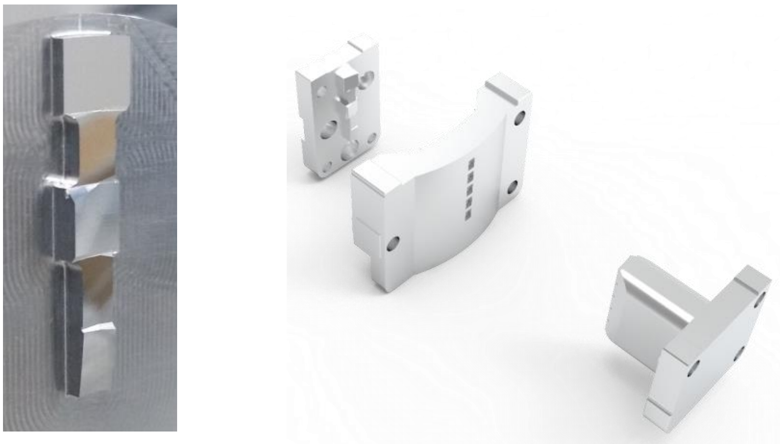

Figure 10 (left) prototype SPEXone telescope M2t, (right) rendering of telescope showing from left to right M2t, M1t, M3t.

To further pre-develop the telescope with its compound mirrors M1t–M3t a telescope breadboard is under construction. It is intended to confirm that the required individual sub-mirror parameters (relative position and orientation, surface form, figure, and finish) can indeed be achieved. It will also demonstrate whether the telescope assembly housing can be manufactured to the necessary tolerances, and whether the foreseen approach for AIT, without the need for alignment using shims, is feasible. Finally, the telescope breadboard will be used for verifying the inter-viewing-direction crosstalk performance, and for prototyping baffling where necessary. The manufacturing partner in this breadboard VDL is well-placed for manufacturing the compound mirrors and telescope assembly housings in larger volumes, appropriate for an instrument with the potential to become a recurring product.

5.2 Polarization modulation optics

We have assembled a dedicated breadboard of the PMO, to assess the optical functionality and the technology readiness level of the optical unit, see Figure 11. It consists of the precision-machined monolithic titanium enclosure with adhesively bonded optical components that generate the spectral modulation pattern and leaf spring mounted slit plate. The polarimetric functionality of this PMO breadboard was tested by means of a simple optical setup in which a light beam originating from a fiber coupled quartz-tungsten-halogen white light source is linearly polarized by means of a wire-grid polarizer and is then sent through the PMO components. The beam emerging from the unit is subsequently collected and analyzed by means of a fiber coupled miniature spectrometer, to register the spectral modulation pattern. This pattern was found to be in good agreement with the spectrum calculated based on the crystal retardances and thicknesses.

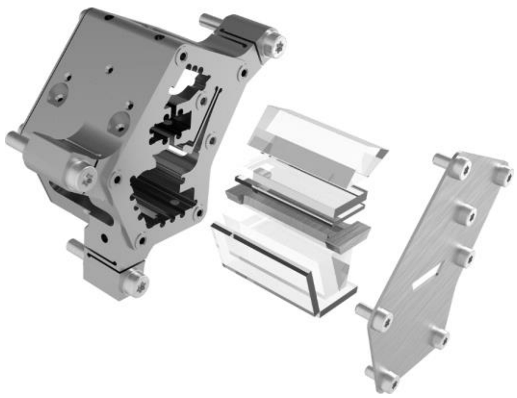

Figure 11 Rendering of the polarization modulation optics module. Housing is machined from Titanium

To test whether the design of the PMO subsystem (with in particular the glue concept of the optical components and spring mount of the slit plate) can endure the environmental stresses that will be encountered during rocket launch and in-orbit, the breadboard was first subjected to thermal cycling in ambient conditions at proto-flight level (-30°C up to +40°C), was subsequently exposed to both sine and random vibration sweeps of increasing load level along three orthogonal axes, the random loads were applied for one minute per axis up to 14 g rms. The assembly was then post-vibe thermally tested at more severe temperatures (10°C beyond survival; -40°C up to +60°C; ambient). Close visual inspection of the interior of the PMO breadboard revealed no signs of damage or mechanical failure of the housing nor the optical components, not after the (pre- or post-vibe) thermal cycling, and not in between or after the vibration tests. And the response signatures from pre- and post-test low level sine-sweeps (resonance surveillance) all were identical to well within the required margins. In addition, using the functionality test setup, the pre-test modulation pattern was successfully reproduced after the test campaign, convincingly demonstrating that no significant changes have occurred in the structure of the unit.

5.3 Coatings

To optimize light transmission and minimize scattering of the PMO, high quality anti-reflection (AR) coatings with an average reflectance below 0.4% over the operational wavelength range have been specifically designed for both sides of the MgF_2 and SiO_2 crystals forming the MOR, the wire grid polarizers, and the entrance and output windows of the Mooney rhomb. The QWR functionality of the Mooney rhomb was iteratively optimized by applying a custom phase change coating. An order-sorting (gradient) filter and a short-pass filter are placed in front of the detector to block higher-order diffractions from the spectrometer and out-of-band stray light. All coatings are based on existing space-proven materials and processes.

6. CONCLUSION AND OUTLOOK

Dutch knowledge institutes and industry collaboratively develop a spectro-polarimeter SPEXone for space use to measure atmospheric Aerosol. The SPEX method of spectral modulation is proven in lab, field and Airborne tests and yields very high accuracy in the degree of polarization. The concept is modular and can be easily configured for across track field of view, spatial resolution and number of viewing angles. Moreover, it is cost-effective because it is designed for scale production. SPEXone is developed as a contributed payload for the NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) with a notional launch in 2022. It can also be employed as supporting instrument for future missions targeting CO_2 measurements. This greenhouse gas is so well mixed in the atmosphere that polarimetry may be imperative to distinguish direct from scattered sunlight when retrieving the concentrations from spectroscopy of the Earth radiance. This application is currently studied in the context of the ESA CO2M for the European Commission and also in the context of the EC funded SCARBO project studying a constellation of small satellites for greenhouse gas monitoring.

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