SPEX:
An in-orbit spectropolarimeter for planetary exploration

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ABSTRACT

SPEX (Spectropolarimeter for Planetary EXploration) is an innovative, compact remote-sensing instrument for detecting and characterizing aerosols. With its 1-liter volume it is capable of full linear spectropolarimetry, without moving parts. High precision polarimetry is performed through encoding the degree and angle of linear polarization of the incoming light in a sinusoidal modulation of the intensity spectrum. This is achieved by using an achromatic quarter-wave retarder, an athermal multiple-order retarder and a polarizing beamsplitter behind each entrance pupil. Measuring a single intensity spectrum thus provides the spectral dependence of the degree and angle of linear polarization. Polarimetry has proven to be an excellent tool to study microphysical properties (size, shape, composition) of atmospheric particles. Such information is essential to better understand the weather and climate of a planet. Although SPEX can be used to study any planetary atmosphere, including the Earth's, the current design of SPEX is tailored to study Martian dust and ice clouds from an orbiting platform: a compact module with 9 entrance pupils to simultaneously measure intensity spectra from 350 to 800 nm, in different directions along the flight direction (including two limb viewing directions). This way, both the intensity and polarization scattering phase functions of dust and cloud particles within a ground pixel are sampled while flying over it. In the absence of significant amounts of dust and clouds, the surface properties can be studied. SPEX provides synergy with instruments on rovers and landers, as it provides a global view of spatial and temporal variations of the planet.

Keywords: Aerosols, dust, Mars, spectropolarimetry

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1. INSTRUMENT CONCEPT

The Spectropolarimeter for Planetary EXploration (SPEX) is an innovative, compact instrument designed to detect and characterize atmospheric aerosols from orbit around a planet. The sunlight that is scattered within a planetary atmosphere is generally polarized, with its polarization properties depending sensitively on the characteristics of the scattering aerosol particles, such as their size, shape and chemical composition.[7] Spectropolarimetric observations of a patch of atmosphere at different scattering angles are required in order to unambiguously determine all aerosol parameters. As shown in figure 1, SPEX has nine fields of view along the flight direction. This way, the instrument samples the intensity and polarization scattering phase function over a large range of scattering angles while flying over a ground pixel, yielding a more precise characterization of the atmospheric aerosols. Two limb viewers are used for the study of high clouds and vertical profile information on aerosols.

The linear polarimetry is achieved by encoding the polarization properties in the measured intensity spectra, as elaborated in section 4. The polarization optics are located in the pupils of the telescopes corresponding to the individual viewing directions. This novel approach to linear spectropolarimetry requires no active (moving) components nor any in-flight calibration and still yields precise measurements. The images of the ground pixels from all telescopes are combined onto a single slit, feeding a grating spectrograph. Due to the spectral encoding of the linear polarization, the required spectral resolution is higher than the required resolution of the data-product.

The SPEX concept is versatile and can be adapted to missions orbiting any celestial body like Mars, Titan, the Moon and also the Earth. In case of the Earth, SPEX will yield vital information about pollutants and their health hazards and about the relation between aerosols and global warming. Also a ground-based sensor network based on the SPEX remote-sensing measurement principle can be foreseen for these purposes, complementing the current in-situ measurements of particulates in the Earth's atmosphere. An excellent flight opportunity for SPEX would be ESA's proposed Mars Next mission, the status of which will be decided upon at the end of 2008. Another flight opportunity might be onboard NASA's Mars Science Orbiter (MSO). The current instrument concept is based on and tailored to this mission. The numbers of the baseline design for MSO are presented in table 1.

Table 1. Baseline requirements and design parameters for SPEX onboard MSO.

spectropolarimeter volume	$\sim$ 1 l
mass including electronics	$\sim$ 5 kg
maximum power consumption	$\sim$ 5 W
spectral range	350-800 nm
data-product spectral resolution	20 nm
spectrograph resolution	2 nm
ground pixel	6$\times$6 km
flight altitude	300 km (Sun-synchronous)
viewing directions	$0°$, $\pm18°$, $\pm36°$, $\pm54°$ + 2 limb viewers
field of view for each viewing direction	$1° \times 7°$ (cross-flight, to deal with planet's rotation)
pupil size for each viewing direction	1 mm^2
measured polarization properties	Stokes I, Q & U
polarization sensitivity	0.5% degree of linear polarization
polarization accuracy	5% (minimally required)

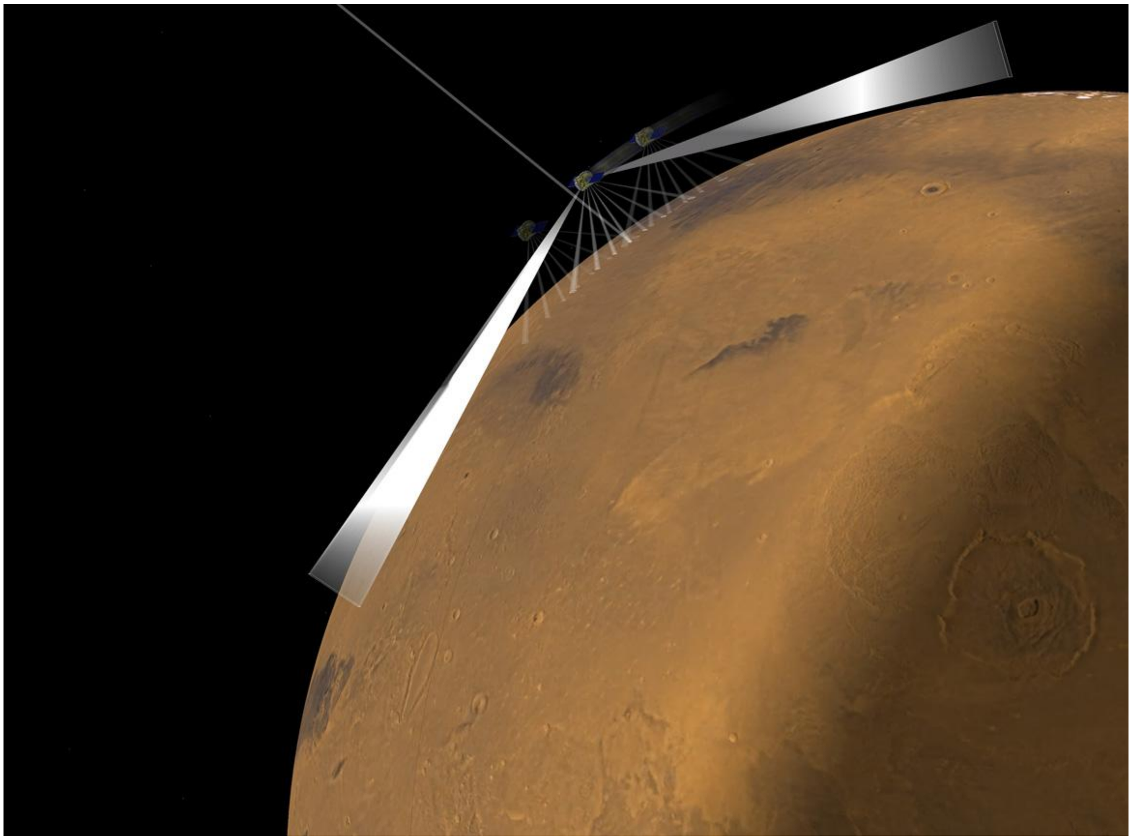

Figure 1. Impression of SPEX on an orbiter around Mars flying over a patch of atmosphere that is illuminated by the Sun (one ray coming in from the upper left). The patch is observed from all different viewing directions. The two limb viewers observe high clouds in the atmosphere.

2. SCIENCE CASES

Planetary atmospheres contain various types of so-called aerosol particles: small, airborne particles, such as dust and cloud particles. The spatial and temporal distribution of the aerosol particles holds important information on the chemical composition and balances in the planetary atmosphere, and influences e.g. the climate on the planet. To better understand and predict the contribution of aerosols in planetary atmospheres, we have to know more about these particles: their sizes, shapes, composition, and their distribution in space and time. With SPEX we focus on detecting and characterizing aerosol particles.

The influence of aerosol particles on a planet and its atmosphere has many facets. To start with, aerosol particles scatter and absorb solar radiation (visual to near-infrared wavelengths), and they absorb and emit thermal radiation that originates from the planetary surface (at infrared wavelengths). Through their interaction with radiation, these particles thus directly influence the planet's radiation and energy balance, and its weather and climate. This is especially true for Mars, with its very thin gaseous atmosphere (the average surface pressure is only about 7 mbar). On Mars, most of the aerosol particles are dust particles that are swept up from the surface. The amount of airborne dust particles varies strongly both in time and space, causing the color of the Martian sky to range from blueish (when there is little dust) to orange. Sometimes the airborne dust forms relatively small, local events, such as the so-called dust devils that can reach altitudes of about 1000 m and that have cross-sections of a few hundred meters. At other times, however, regional or even planet encircling dust storms develop that can last for weeks. During such storms, dust particles are lifted up into the Martian stratosphere (i.e. up to altitudes of about 40 km), and the temperature in the lower atmosphere increases several degrees whilst the surface temperature could drop tens of degrees during such events.

Aerosol particles also serve as condensation nuclei for atmospheric gases, such as water vapor on both Earth

and Mars. Most of the clouds that are observed on Mars are cirrus-like ice clouds composed of H_2O-ice crystals. However, clouds of CO_2-ice crystals have also been detected, in particular over the polar ice caps. Even clouds as thin as those found on Mars play an important role in the climate on a planet and the radiation balance, because the clouds remove dust and other aerosol particles from the atmosphere. And, like the aerosol particles around which they form, cloud particles interact with the radiation in the atmosphere. In addition, clouds provide the vertical and horizontal transport of condensates, such as water vapor on Mars. Interestingly, model studies show that CO_2 cloud condensation might have limited the development of a greenhouse effect on Mars, a finding that is crucial in understanding the early and the current Martian climate. Aerosol particles and the cloud particles that form around them also influence chemical processes, for example, by providing the area for heterogeneous reactions to take place. Recent research has shown that heterogeneous chemical reactions on dust in the Martian atmosphere could significantly decrease the mixing ratio of methane, especially when the dust particles are electrically charged, as happens during dust storms. Without knowledge of the dust particles, methane observations such as those by an orbiting spectrometer instrument are thus hard to interpret. Finally, in view of ESA's Aurora program, studying the Martian dust is important for habitability considerations.
The precise contribution of aerosol particles to an atmosphere's radiation and chemical balances, as well as their role as condensation nuclei in cloud formation processes depends on their number density, their spatial and temporal distribution and on their microphysical properties, such as their size, shape, and chemical composition or refractive index. A powerful tool for deriving information on the distribution and the microphysical properties of aerosol particles is the observation of sunlight that has been scattered within the planetary atmosphere. On the current Mars missions, there are various instruments that are capable of measuring the reflected sunlight, e.g. PFS and Omega on Mars Express. These instruments measure only the intensity of the scattered light, which depends both on the amount of particles and on their optical properties, and as such cannot distinguish between the two. In addition, the scattered intensity is not very sensitive to the microphysical properties of the aerosol particles. Only measuring the degree of linear polarization, which is very sensitive to the microphysical properties of the scattering particles, would enable us to make a distinction and to obtain these properties and the distribution of the particles. This is the specific niche that will be targeted by SPEX.
Other applications of SPEX would be on a Titan mission (in-orbit or in-situ) to study the famous hydrocarbon haze particles, a Moon mission to study the dust that is lifted off the surface[12] and Earth-orbiting missions to study (anthropogenic) aerosols and pollutants in the atmosphere that might pose health hazards and influence global warming. The SPEX instrument is currently part of a feasibility study for a joint microsat programme between Delt University of Technology and Tsinghua University from China. The FAST (Formation for Atmospheric Science and Technology Demonstration) mission foresees a synoptic evaluation of global aerosol data and altitude profiles of the Earth's cryosphere with two cooperating micro-satellites with SPEX instruments flying in formation in 2011.

3. OPTICAL DESIGN

The optical design for SPEX is presented in figure 2. The light enters the polarization (pre-) optics at the lower left from the various viewing directions and after being focussed onto a slit plane by a beam combiner it continues via a spherical (collimating) mirror and a folding flat towards the transmission grating and camera lenses and finally the detector. In order to determine the intensity spectra without any influence from the polarization encoding (see next section), the beams are split according to perpendicular linear polarization directions with Wollaston prisms. Consequently, the 9×2 beams are focused with individual objective lenses. The beam combiner consists of a row of folding prisms and lines up all individual images on the slit along the cross-flight direction, except for the two limb viewers that are oriented vertically and therefore rotated by 90° within the beam combiner. After passing the slit at a focal ratio of F/10, the light is collimated into a parallel beam by a spherical mirror. A folding flat shortens the dimension of the optical system. After being dispersed by the transmission grating the beam enters the camera lens which converts the beam into F/3.3 to have a good match with the detector and the specified spectral resolution.

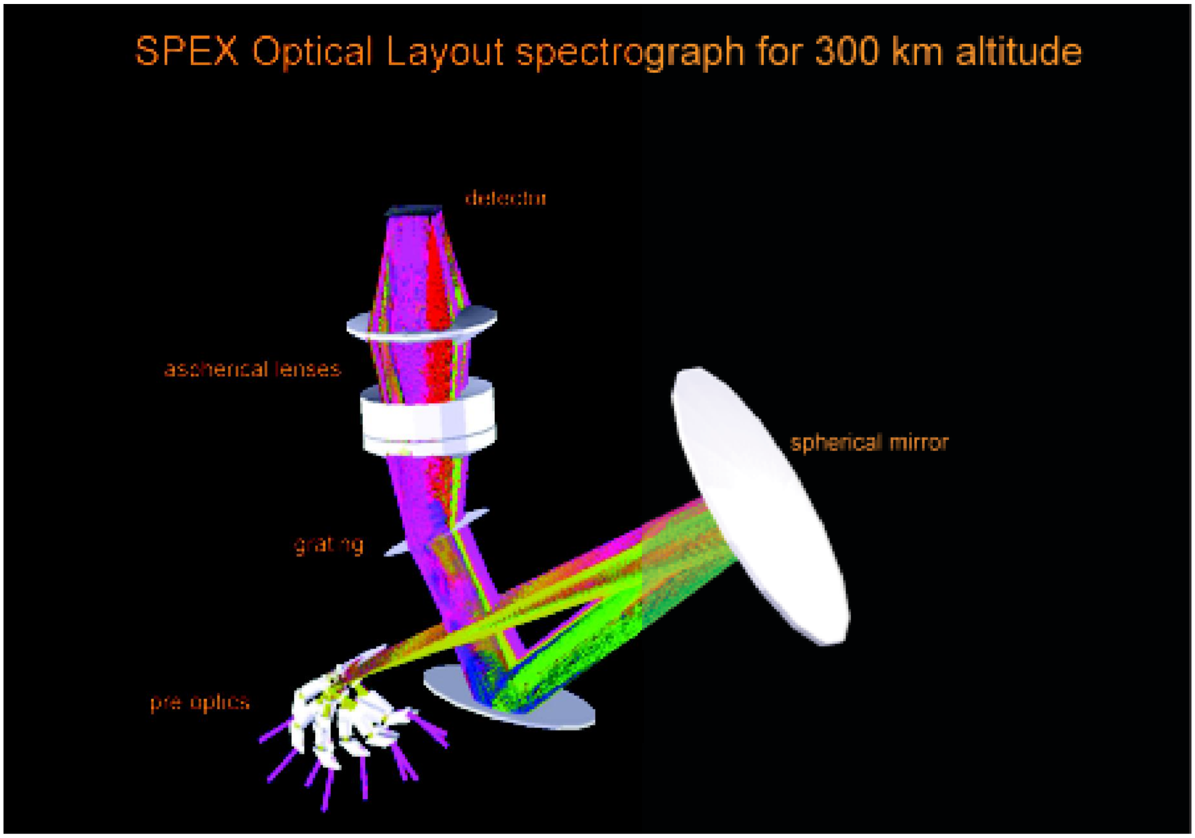

Figure 2. Baseline optical design of SPEX. The outer dimensions are ~130x130 mm.

4. POLARIMETRIC DESIGN

4.1 Spectral Modulation

The compact and energy-efficient design of SPEX is enabled by the use of a novel approach to linear spectropolarimetry. Classically, two types of polarization modulation are discerned:

- *Spatial modulation.* The beam is split up according to at least three, but usually four linear polarization directions at angles 0°, 90° and ±45°:

$$S_1 = \frac{1}{4}(I+Q) \tag{1}$$

$$S_2 = \frac{1}{4}(I-Q) \tag{2}$$

$$S_3 = \frac{1}{4}(I+U) \tag{3}$$

$$S_4 = \frac{1}{4}(I-U), \tag{4}$$

from which the Stokes parameters I, Q and U can be trivially obtained. The degree of linear polarization (DoLP) and angle of linear polarization (AoLP) are then obtained from:

$$\text{DoLP} = \frac{\sqrt{Q^2+U^2}}{I} \tag{5}$$

$$\text{AoLP} = \frac{1}{2}\arctan\frac{U}{Q}. \tag{6}$$

However, next to the fact that the instrument size scales with the number of beams per viewing direction, the precision of polarimetry using just spatial modulation is very limited: the relative transmissions between the beams need to be very accurately calibrated as well as the instrumental polarization due to the optical components before the polarizing beam splitters. Both the beams' transmissions and the instrumental polarization are likely to change in-flight and therefore various active calibration units are required. Moreover, polarimetry by spatial modulation is very sensitive to noise. Considering the volume and energy requirements and the polarimetric accuracy requirements for SPEX, this polarimetric principle is not favored.

- *Temporal modulation.* The measurements of the different polarization directions according to equations 1-4 can also be obtained sequentially by positioning an active birefringent component as a rotating half-wave plate or an appropriate liquid crystal device in a beam before a single polarizer. This active component requires energy and is likely to fail in-flight. A birefringent liquid crystal device does not need to be physically rotated, but currently liquid crystal materials are not space-qualified because UV radiation and charged particles cause permanent damage. Another disadvantage is that the sequentially recorded images are not cospatial. For these reasons also any type of temporal modulation is not viable for SPEX.

Therefore a novel approach for linear spectropolarimetry is put forward for SPEX. The linear polarization can neither be mapped onto the spatial dimension nor onto the temporal dimension, so it needs to be mapped onto the spectral dimension.[11] This *spectral modulation* is ideally achieved when a sinusoidal modulation of known periodicity is superimposed on the measured spectra for which the amplitude of the modulation scales with the degree of linear polarization (DoLP, as defined by equation 5) and the phase of the modulation is determined by the angle of linear polarization (AoLP; equation 6). Inspired by the work of Lyot[8] on birefringent filters, this principle is relatively easily effectuated with an optical train consisting of:

1. An achromatic quarter-wave retarder.
2. A multiple-order retarder with retardance δ with its axes at 45° from the first retarder.
3. A polarizer or polarizing beam-splitter aligned with the orientation of the quarter-wave retarder.

Any spectrum $S_0(\lambda)$ is then spectrally modulated as:

$$S(\lambda) = \frac{1}{2}S_0(\lambda) \cdot \Big[1 \pm \mathrm{DoLP}(\lambda) \cdot \cos\Big(\frac{2\pi \cdot \delta(\lambda, T)}{\lambda} + 2 \cdot \mathrm{AoLP}(\lambda)\Big)\Big], \tag{7}$$

with the $\pm$ sign depending on the orientation of the polarizer. The retardance δ of the multiple-order retarder is generally very dependent on temperature. This effect to first order changes the phase of the modulation and therefore makes it impossible to unambiguously retrieve the AoLP information. We construct an "athermal" multiple-order retarder by combining two different materials such that their temperature effects cancel, but the net retardance is still $\gg 0$.[6]

The advantage of using spectral modulation for linear spectropolarimetry is that the full linear polarization information is obtained with a single spectral measurement. Within one period of modulation, the mean intensity, the DoLP and the AoLP can be retrieved by a dedicated algorithm based on the information from equation 7. Because the retrieval is based on curve-fitting algorithms, this polarimetric principle is much less sensitive to noise compared to classical methods. Of course, the required spectral resolution for spectral modulation is much higher than the required data-product resolution. Also, the retrieval algorithm on a single spectrum only works well when the original intensity spectrum only has spectral features broader than the modulation periodicity, as determined by δ. In the case of spectropolarimetry of the Martian atmosphere, a lot of spectral lines from the solar spectrum are present. Therefore we choose to record two spectra per viewing angle after a polarizing beam-splitter. Adding both spectra and compensating for transmission differences between the two beams, one obtains the intensity spectrum without modulation. The signals in both beams are then normalized to this intensity spectrum and the DoLP and AoLP are consequently obtained by the retrieval algorithm.

A patent for the polarimetric measurement principle based on spectral modulation is now pending.[13]

4.2 Modulator Design

Several options exist for the achromatic quarter-wave retarder of the spectral modulator:

- A composite "superachromatic" crystal retarder having three (or five) wavelength-compensated crystal combinations or zero-order wave-plates in Pancharatnam configuration.
- A retarder based on total internal reflections, like a Fresnel rhomb or a K-prism.

The latter option is selected for SPEX due to its robustness (only a single piece of glass) and its large wavelength range. The field of view behavior for Fresnel rhombs and K-prisms is very bad in one direction. But in the case of SPEX this is acceptable, because the field of view per viewing angle is anamorphic (see table 1). Unfortunately, due to its low refractive index it is impossible to make a Fresnel rhomb out of fused silica, which is the optimal material for use in the UV and has very low intrinsic retardance due to internal stresses. Therefore we designed a fused silica rhomb with three total internal reflections, which functions as a retroreflector and an image rotator. The angles of the internal reflections are computed for optimal field of view behavior. A rhomb with internal reflections of 47.5°, 50° and 82.5° has a field of view limited to ± 3° in only one direction, which is superior to the Fresnel rhomb and the K-prism. Outfitting the optical design of SPEX with these retroreflecting prisms complicates the design, so the current baseline design utilizes BK7 Fresnel rhombs.

For the athermal multiple-order retarder the selection of materials was determined by the following considerations:

- The combination shall be (close to) athermal in the SPEX wavelength range.
- The field of view needs to be optimized.
- The materials need to be robust and transparant in the UV.

In order to adhere to the second requirement, the birefringence of the two materials needs to be opposite,[4] i.e. $n_{e,1} > n_{o,1}$ and $n_{e,2} < n_{o,2}$. The only common materials that fulfill the above requirements are crystalline sapphire (Al_2O_3) and MgF_2. Using tabulated values[5] for their birefringence and thermal behavior thereof, we compute that a thickness ratio of ∼1:2.7 makes for an "athermal" retarder. The literature values of the thermal properties of crystals are very uncertain and therefore thermal tests are performed to experimentally determine the precise thickness ratio for athermal behavior. The results of these tests are presented in the next subsection. An overall thickness of 4 mm of this combination of sapphire and MgF_2 has a retardance $\delta = \sim 27\mu$m, which creates a modulation periodicity of ∼25 nm in the red to ∼10 nm in the blue. The field of view for this combination of crystals is ±2° in both directions. The multiple-order retarder is also athermal for larger field angles, although at slightly different values from the design value. For SPEX, this drives the requirement for a (pre-flight) calibration of the spectral modulation for each ground pixel. Because of the "wide-field" combination of crystals, the retardance can be assumed constant for each pixel.

As mentioned above, we choose Wollaston prisms as the polarizing beam-splitters. They are made out of quartz, which also is a robust material with good transmission properties.

4.3 Thermal Tests

We constructed a prototype spectral modulator from a fused silica K-prism, a combination of sapphire and (wedged) MgF_2 in a Soleil-Babinet set-up such that we can control the thickness ratio, and a Glan-laser polarizer. We fiber-feed light from a UV-VIS light source and (linearly) polarize it with a Glan-laser polarizer at a certain angle. The light after the spectral modulation is fiber-fed into an off-the-shelf UV-VIS spectrograph with a spectral resolution of 0.6 nm. First of all, we found that the measurement principle according equation 7 does indeed work for varying the AoLP by rotating the first polarizer. Next, we put the set-up in a thermal chamber, with the fiber-fed light source and spectrograph outside. Varying the thickness ratio and varying the temperature from 5-50°C whilst keeping the AoLP constant, the derivative of the total retardance with temperature can be detirmined invoking equation 7 and the AoLP retrieval algorithm: any measured change of AoLP is due to thermal variation of δ. The results of the thermal tests as well as the models based on tabulated values for the retardance behavior of sapphire and MgF_2 are presented in figure 3.

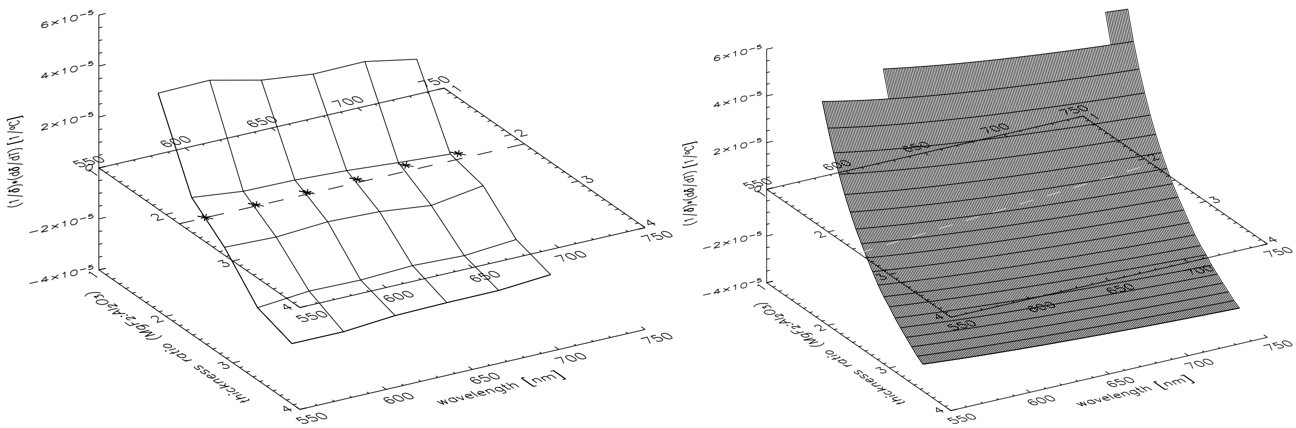

Figure 3. Results from the thermal tests on the combination of a birefringent sapphire and MgF_2 crystal plus the results from the model with literature values as input. The (normalized) derivative of the retardance with temperature is plotted as a function of wavelength and thickness ratio between the two crystals. The trend of the model is reproduced in the measurements. The thickness ratio for which the combination is athermal is smaller than for the model by an amount of 0.3

The measurements reproduce the trend of the derivative of the retardance with wavelength, but the exact thickness ratio for which this derivative is zero, is smaller by 0.3. The ideal thickness ratio for the wavelength range of the measurements (500-750 nm; the measurements at lower wavelengths were too noisy) is 1:2.2, but for the wavelength range of SPEX we choose a ratio of 1:(2.7-0.3)=1:2.4. Both the model as well as the measurements indicate that for a given thickness ratio the combined retarder is only perfectly athermal at one specific wavelength. The influence on the AoLP retrieval at the boundaries of the spectral range is maximally $1.5{\cdot}10^{-2}$ radian/°C and therefore within an operational temperature range of 10±20°C, the maximum deviation of the retrieved AoLP is $3{\cdot}10^{-1}$ radian. However, with the knowledge of the trend of the thermal variation with wavelength, and assuming that most of the spectrum has the same AoLP due to single scattering, one can compensate for the residual thermal variation.

5. END-TO-END STUDY

With the numbers of our baseline design, we conducted an end-to-end study. As photon flux input to the instrument we use the results of radiative transfer computations with the doubling-adding code[3] on solar flux impinging on the martian atmosphere. Empirical scattering matrices of martian-analog particles[9] were used to calculate the polarization properties of the scattered sunlight. The spectral measurements are computed with equation 7 assuming an optical transmission of 5% and implementing a typical quantum efficiency curve. Realistic photon and electronic noise is added before sampling the spectra on a 10 bits signal.

We developed a retrieval algorithm based on equation 7, which assumes that the value of δ is perfectly known and athermal. First, the intensity spectrum is obtained by adding the two beams out of the Wollaston prism. If this spectrum still shows residual signs of spectral polarization modulation, the differential transmission between the two beams must have degraded. It is compensated for by varying the transmission ratio until the modulation has disappeared. Next, the modulation envelopes for both beams are obtained by division of the measured signal with the intensity spectrum. The algorithm scan these envelopes in bins that contain at least one period of the modulation. Within each bin a curve-fit with DoLP and AoLP as free parameters delivers the observables at the corresponding wavelength position. Since the polarization information has lower spectral resolution than the spectrograph resolution, the results are smoothed by a kernel with a width comparable to the bin size.

The first results from the end-to-end study are presented in figure 4. It shows that the AoLP and DoLP are retrieved to within the accuracy limits.

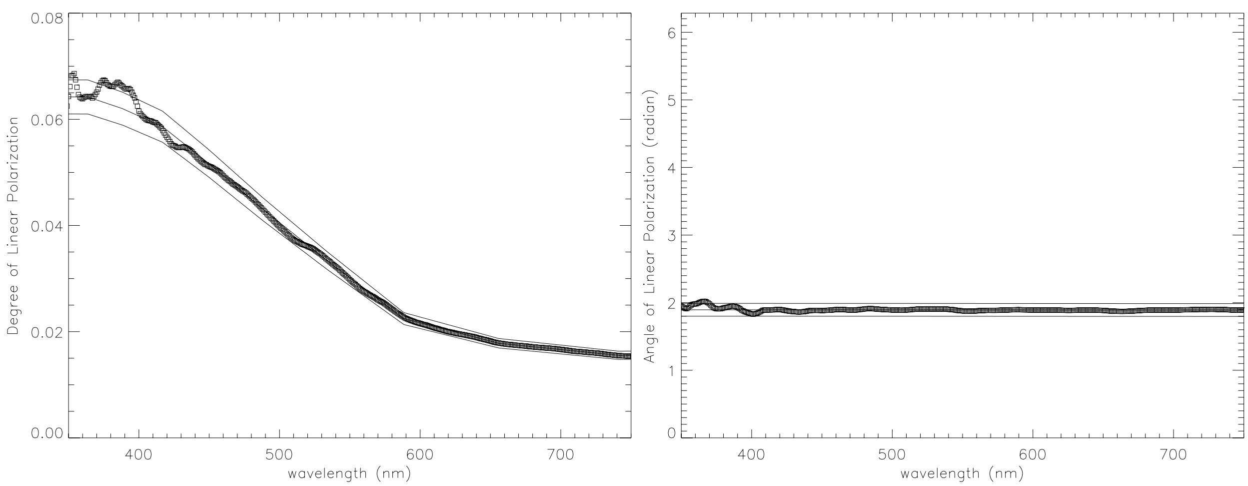

Figure 4. First results from the end-to-end study. The lines represent the input signal and the margin from the accuracy requirements. The square symbols represent the values obtained with the retrieval algorithm after a realistic instrument simulation.

6. CONCLUSIONS AND OUTLOOK

The main result of the design study for SPEX is that the compact instrument concept is viable and flexible enough for application to different planets and moons. The application of spectral polarization modulation makes SPEX a factor of 10 lighter and a factor of 10 more energy-efficient than NASA's GLORY-APS,[10] which has similar instrument requirements as SPEX. Based on the current design, we plan to develop a breadboard model of SPEX that characterizes aerosol particles in the Earth's atmosphere from ground-based zenith sky measurements.[1,2] With such measurements, we aim not only at detecting and characterizing natural aerosol particles, but also anthropogenic aerosol particles such as fine dust particulates.

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