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(71) Applicants: **STICHTING NEDERLANDSE WETENSCHAPPELIJK ONDERZOEK INSTITUTEN** [NL/NL]; Winthontlaan 2, 3526 KV Utrecht (NL). **AIRBUS DEFENCE AND SPACE NETHERLANDS B.V.** [NL/NL]; Mendelweg 30, 2333 CS Leiden (NL).

(72) Inventors: **VAN AMERONGEN, Aaldert Hidde**; c/o Winthontlaan 2, 3526 KV Utrecht (NL). **CAMPO, Jochen Ignace Geert**; c/o Winthontlaan 2, 3526 KV Utrecht (NL). **RIETJENS, Jeroen Henricus Hubertus**; c/o Winthontlaan 2, 3526 KV Utrecht (NL).

(74) Agent: **WITMANS, H.A.**; P.O. Box 87930, 2508 DH Den Haag (NL).

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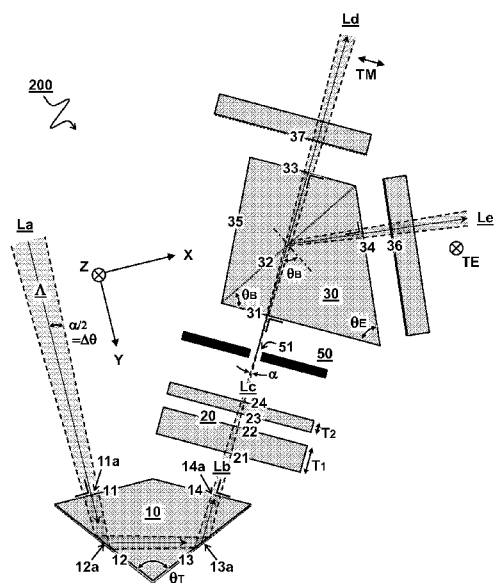


FIG 1

(57) Abstract: A polarization modulation optics (200) comprises an achromatic quarter-wave retarder (10) configured to receive a first beam (La) of light, and output the light as a second beam (Lb). An athermal multiple-order retarder (20) is configured to receive the second beam (Lb) and output a third beam (Lc) for which the polarization state of the light is projected onto the spectrum. A polarizing beam splitter (30) is configured to receive the third beam (Lc) and output a fourth beam (Ld) with a first polarization (TM), and a fifth beam (Le) with a perpendicular second polarization (TE). A slit plate (50) is disposed in the third beam (Lc). The slit plate (50) forms at least one physical slit (51) having its slit length direction (Z) parallel to each of the optical interfaces (11-14, 21-24, 31-34) of the components.

Title: POLARIZATION MODULATION OPTICS

TECHNICAL FIELD AND BACKGROUND

The present disclosure relates to polarization modulation optics
5 for use in spectral modulation, e.g. as part of spectropolarimeter designed to operate from an orbiting or in situ platform.

Snik *et al.* [APPLIED OPTICS, Vol. 48, 1337, 2009] describe a method of spectral modulation for full linear polarimetry. The prior art notes that linear (spectro) polarimetry is usually performed using separate
10 photon flux measurements after spatial or temporal polarization modulation. However, such classical polarimeters are limited in sensitivity and accuracy by systematic effects and noise. To resolve this, the prior art discloses a spectral modulation principle that is based on encoding the full linear polarization properties of light in its spectrum. Such spectral
15 modulation is obtained with an optical train of an achromatic quarter-wave retarder, an athermal multiple-order retarder, and a polarizer.

With regards to the technical implementation of an achromatic quarter-wave retarder, Snik *et al.* notes a major advantage of total internal reflection (TIR) retarders is the achromaticity of the retardance, which only
20 varies with the wavelength variation of the refractive index. Noted examples of TIR retarders are the Fresnel rhomb and K-prism. The prior art notes that, unfortunately, Fresnel rhombs for the visible range cannot be manufactured out of fused silica. According to the prior art, it is possible to tweak the overall retardance of a Fresnel rhomb by means of a coating on
25 the TIR surface, but temperature variations can still lead to unacceptable variations of the rhomb's retardance. On the other hand, a K-prism based on three TIRs can be made out of fused silica and has the additional advantage of the lack of lateral beam shift, but it yields a much thicker optical component than a Fresnel rhomb. Furthermore it is noted that the FOV
30 behavior of both a Fresnel rhomb and a K-prism is very anamorphic.

With regards to positioning, Snik *et al.* notes that, as with any polarimeter, the modulator is best located as early in the beam as possible in order to minimize the number of optical components that modify the polarization of the source under investigation or introduce instrumental polarization. Ideally, the spectral modulator is located in the entrance pupil of a spectropolarimetric instrument. The objective lens(es) are then positioned after the polarizer or polarizing beam splitter to image the source onto the entrance (slit) of the spectrometer.

Rietjens *et al.* [Proc. SPIE 10565, International Conference on Space Optics — ICSO 2010, 105651C] further developed the teachings of Snik *et al.* in a Spectropolarimeter for Planetary Exploration (SPEX). The prior art discloses that the optical system of SPEX can be divided into two main parts: the pre-slit polarization encoding optics, and the spectrometer optics. The spectropolarimetry is achieved by encoding the degree of linear polarization (DoLP) and angle of linear polarization (AoLP) of the incident light in the measured flux spectra.

It is yet desired to further improve the known designs, e.g., for application in a satellite instrument. For example, the broad-band spectral polarization modulator needs not only to be compatible with a space environment, but also allowing for a very compact, high performing optical design.

SUMMARY

Aspects of the present disclosure relate to a polarization modulation optics (PMO). Typically, the PMO comprises an optical element such as an achromatic quarter-wave retarder having its (ordinary and extraordinary) axes in the direction of Stokes parameter $\pm Q$ to transform e.g. linearly (Stokes U) polarized light into circularly (Stokes V) polarized light. An athermal multiple-order retarder having its ordinary and extraordinary axes in the Stokes $\pm U$ direction may receive this light and

project the polarization state of the light onto the spectrum by means of spectral modulation of the polarization state (from linear over elliptical to circular, and back over elliptical to linear). A polarizing beam splitter with polarization directions in the Stokes $\pm Q$ directions may receive this light and output spectrally intensity modulated, orthogonally polarized beams. Accordingly, the spectral polarization modulator may transform incident light into two spectrally modulated intensities, such that amplitude and phase of the modulation are proportional to the degree and angle of linear polarization, respectively.

Preferably, a slit plate is arranged inside the PMO and forms at least one physical slit having its slit length direction parallel to each of the optical interfaces of the optical components. The inventors find that placing the physical slit inside the PMO and parallel to the optical interfaces, may provide a relative compact design with good performance. For example, placing the entrance slit of the spectrometer inside the PMO may enable sufficiently tight alignment of the two images from the polarizing beam splitter for them to fit on the detector. A too large distance from the slit would lead to a too large beam divergence and thereby to a too large distance between the two images. Furthermore, placing the slit inside the PMO may be beneficial to accommodate telescope back focal length and/or the spectrometer collimator front focal length. By placing the slit imaging plane between the optical components of the PMO, preferably, at or near the center along the propagation direction of the PMO beam path, the maximum beam size can be kept relatively small.

BRIEF DESCRIPTION OF DRAWINGS

These and other features, aspects, and advantages of the apparatus, systems and methods of the present disclosure will become better understood from the following description, appended claims, and accompanying drawing wherein:

FIG 1 illustrates a plan view of light beams traversing a polarization modulation optics;

FIG 2 illustrates a perspective view of the polarization modulation optics;

5 FIG 3 illustrates an exploded perspective view of the polarization modulation optics and corresponding frame;

FIG 4 illustrates a perspective view of the polarization modulation optics and combining optics;

10 FIG 5A schematically illustrates a satellite comprising a multi-angle spectropolarimeter;

FIG 5B schematically illustrates a top view of an embodiment for a multi-angle imager;

FIG 6A schematically illustrates a side view the multi-angle imager;

15 FIG 6B schematically illustrates a perspective view of the multi-angle imager;

FIG 7 illustrates a schematic view of a spectropolarimeter;

FIG 8A illustrates an image of different view angles imaged at a slit plane onto a slit plate;

20 FIG 8B illustrate an image of polarization modulated spectra projected at an imaging sensor;

FIG 9A shows a graph of retardance measurements of the SPEX PMO Mooney Rhomb, as described herein;

25 FIG 9B shows graphs of total internal reflection phase change in a fused silica rhomb with double reflection;

FIG 10 shows a graph of maximum ghost intensity due to double reflections in the PMO; and

FIG 11 illustrates a table of polarimetric error budget for a spectral polarization modulator.

DESCRIPTION OF EMBODIMENTS

Terminology used for describing particular embodiments is not intended to be limiting of the invention. As used herein, the singular forms "a", "an" and "the" are intended to include the plural forms as well, unless
5 the context clearly indicates otherwise. The term "and/or" includes any and all combinations of one or more of the associated listed items. It will be understood that the terms "comprises" and/or "comprising" specify the presence of stated features but do not preclude the presence or addition of one or more other features. It will be further understood that when a
10 particular step of a method is referred to as subsequent to another step, it can directly follow said other step or one or more intermediate steps may be carried out before carrying out the particular step, unless specified otherwise. Likewise it will be understood that when a connection between structures or components is described, this connection may be established
15 directly or through intermediate structures or components unless specified otherwise.

The invention is described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. In the drawings, the absolute and relative sizes of systems,
20 components, layers, and regions may be exaggerated for clarity. Embodiments may be described with reference to schematic and/or cross-section illustrations of possibly idealized embodiments and intermediate structures of the invention. In the description and drawings, like numbers refer to like elements throughout. Relative terms as well as derivatives
25 thereof should be construed to refer to the orientation as then described or as shown in the drawing under discussion. These relative terms are for convenience of description and do not require that the system be constructed or operated in a particular orientation unless stated otherwise.

FIG 1 illustrates a plan view of light beams (La,Lb,Lc,Ld,Le) traversing a polarization modulation optics (PMO) 200.

In one embodiment, the PMO comprises an (achromatic) quarter-wave retarder 10. In one embodiment, e.g. as shown, the quarter-wave
5 retarder (10) having its ordinary and extraordinary axes in the direction of Stokes parameter $\pm Q$, has a first set of optical interfaces 11-14 configured to receive a first beam La of light in a wavelength range Λ , and output the light as a second beam Lb of light, wherein a Stokes U component of the light in the first beam La is transformed into a Stokes V component of the
10 light in the second beam Lb. Preferably, the polarization is substantially independent of its wavelength λ in the operating range Λ , e.g. visible wavelength range (385 – 770 nm) as described herein, or other wavelength range.

In another or further embodiment, the PMO comprises an
15 (athermal) multiple-order retarder 20 having its ordinary and extraordinary axes in the Stokes $\pm U$ direction, with a second set of optical interfaces 21-24 configured to receive the second beam Lb and output a third beam Lc for which the polarization state of the light is projected onto the spectrum by means of spectral modulation of the polarization state (from linear over
20 elliptical to circular, and back over elliptical to linear).

In another or further embodiment, the PMO comprises a polarizing beam splitter 30 with polarization directions in the Stokes $\pm Q$ directions, with a third set of optical interfaces 31-34 configured to receive the third beam Lc and output a fourth, spectrally intensity modulated beam
25 Ld with a first polarization TM (p-polarized), and a fifth beam Le with a perpendicular second polarization TE (s-polarized). Accordingly, the spectral polarization modulator may transform incident light into two spectrally modulated intensities, such that amplitude and phase of the modulation are proportional to the degree and angle of linear polarization, respectively.

For example, with reference to the orientations shown, the Stokes $\pm Q$ parameter is parallel/perpendicular to the Z axis, and the Stokes $\pm U$ parameter is at a ± 45 degree angle with the Z axis.

In a preferred embodiment, a slit plate 50 disposed in the third
5 beam Lc. Most preferably, the slit plate 50 forms at least one physical slit 51
having its slit length direction Z parallel to each of the said optical
interfaces 11-14, 21-24, 31-34 of the optical components. So each optical
interface that interacts with the light is in a respective plane parallel to the
slit. An optical interface of an optical component is generally understood as
10 a plane or surface forming a common boundary between two optical media.
For example, the optical interface may be formed at an outer surface of the
component, or at an internal plane e.g. in case of two interconnected
monolithic parts forming the component. More specifically, an optical
interface as used herein may refer to an interface having an optical function
15 in the system, e.g. wherein the optical interface is arranged in the beam
path. For example, the optical interface has a function in the optical system
of reflecting, transmitting, and/or refracting a light beam impinging the
interface. The optical interface may thus be distinguished from possibly
other component surfaces or boundaries which do not have a specific optical
20 function. For example, a non-optical surface has no function in the optical
design of the system e.g. wherein the intended beam path according to the
optical function of the design does not traverse the non-optical surface.

Preferably, the beam entering the PMO is telecentric with angles
of incidence on the transmissive optical components relatively small. This
25 may be expressed e.g. by the half angle $\alpha/2$ between the central optical axis
and rays of the beam, as shown. Alternatively, or in addition, this may be
expressed as the opening angle α of the light beam at the physical slit 51. It
may be noted that the angle α may relate to a deviation from the intended
angle of incidence at the various optical interfaces. In a preferred
30 embodiment, an opening angle α of the third beam Lc between chief rays at

the physical slit 51 is less than six degrees, more preferably less than four degrees, e.g. between one degree and two degrees. It will be appreciated that the effect of angular deviation can be alleviated by the advantageous selection of specific optical component, e.g. as shown for the Mooney rhomb
5 in FIG 9B (middle, right). In any case it is preferably that the largest angle made by any ray is kept as small as possible while still providing a sufficient field of view.

In one embodiment, e.g. as shown, the quarter-wave retarder 10 comprises a first set of optical interfaces including one or more transmitting
10 interfaces, i.e. where the light beam is transmitted through the respective interface, such as the input port 11 and/or output port 12. In some embodiments, the transmitting interfaces 11,14 are provided with respective anti-reflection coatings 11a,14a. In a preferred embodiment, as shown, the interface of the input port 11 is substantially normal to the direction Y of
15 the first beam La. Furthermore it is preferred that the interface of the exit port 14 is substantially normal to the direction of the second beam Lb.

In one embodiment, e.g. as shown, the quarter-wave retarder 10 comprises a first set of optical interfaces including one or more reflecting
20 interfaces, i.e. where the beam is partially or fully reflected off the respective interface. In some embodiments, the reflection may affect a polarization state of the light such as the phase changing internal reflecting interfaces 12,13 shown here. For example, each reflection may introduce a relative phase retardance between the two polarization directions to achieve a total of ninety degree or quarter wave retardance. In some embodiments,
25 the reflecting interfaces are provided with phase changing coatings 12a,13a.

In a preferred embodiment, e.g. as shown, relative phase change is achieved by consecutive reflection off two non-parallel interfaces. Preferably, the reflecting interfaces are arranged such that the beam rotates twice in the same direction. In this way misalignment of the reflection on
30 the first interface may be partly compensated by the reflection on the second

interface. For example, the reflecting interfaces may have a relative (top) angle θT between forty and hundred-forty degrees (plane angle), more preferably between seventy and hundred-ten degrees, e.g. hundred-five degrees, as in the embodiment shown. Furthermore, providing the top angle
5 θT close to ninety degrees may provide back reflecting behavior which may increase compactness. Having θT slightly above ninety degrees may allow easier placement of components so they may be clear of the incoming beam.

In one embodiment, the quarter-wave retarder 10 comprises a retarder based on total internal reflection (TIR), more specifically a
10 monolithic piece of material wherein the polarization of the light is altered by total internal reflection in the material at one or more of its (internal) optical interfaces 12,13. In a preferred embodiment, the achromatic quarter-wave retarder 10 is formed by a Mooney rhomb. Most preferably, the monolithic piece of material comprises fused silica (SiO_2). For example,
15 fused silica is a favorable material because of its low amount of birefringence induced by internal stresses or by temperature variations.

In some embodiments, the internal reflection interfaces 12,13 of the Mooney rhomb are provided with a phase changing coating 12a,13a. The phase changing coating on e.g. a fused silica Mooney rhomb may yield more
20 equal phase change over a wider wavelength band. For example, the coating may compensate dispersion in the monolithic piece of material. In one embodiment, a single layer phase change coating on Fresnel rhomb may thus improve achromatic performance. In a preferred embodiment, the monolithic piece is provided with multiple layers of different coating
25 materials to even further improve achromatic performance. For example, the monolithic pieces may be provided with two, three, four, five, or different coating layers. For example, two different material may be used in alternating layers. One of the coating materials, e.g. the second layer, may be the same as the monolithic material. For example, possible coating

materials on a fused silica rhomb may include SiO₂ and MgF₂. Also other or additional materials may be used.

In a preferred embodiment, the achromatic quarter-wave retarder comprises a Mooney rhomb of fused silica with four coating layers having
5 the following layer thicknesses and material compositions in sequence from the rhomb outward: 20 nm MgF₂, 110 nm SiO₂, 33 nm MgF₂, 200 nm SiO₂. The inventors find this combination of layers provides particular good achromatic performance over the desired visible wavelength range as illustrated in FIG 9A. Of course it will be understood there may be a small
10 tolerance on the layer thickness, e.g. plus-minus five percent deviation, preferably less than one percent. Such deviation may lead to less ideal but still acceptable performance depending on the application. While the inventors find that SiO₂ and MgF₂ are particularly suitable for the present applications due to their high optical qualities as well as precise
15 manufacturability, also other birefringent materials (and corresponding thicknesses) may be envisaged. While the inventors find that the total of four coating layers provides a desired performance, in principle also more layers could be added though this may add manufacturing cost against diminishing performance gain.

20 In a preferred embodiment, the multiple-order retarder 20 is implemented as an athermal combination of a MgF₂ crystal with a first thickness T₁, and crystal quartz with a second thickness T₂. Advantageously, the inventors find these materials have relatively low birefringence so the crystal thicknesses T₁, T₂ (along the beam direction)
25 can be on the order of a millimeter making it relatively robust and easy to handle. At the same time, the inventors find that this subtractive combination can provide relatively low temperature sensitivity. Most preferably the first thickness T₁ is more than one millimeter and a ratio of the first thickness divided by the second thickness T₁/T₂ is between one and
30 half and three. For example, a thickness ratio T₁/T₂ of 2.25 can be chosen to

have the athermal point in a desired visible wavelength slightly below 500 nm. Importantly, for good functioning of the spectral modulation principle, the multiple-order retarder 20 is oriented with its ordinary and extraordinary axes under opposite 45 degree angles with the Z axis, i.e. along the Stokes $\pm$ U directions.

In one embodiment, the polarizing beam splitter 30 is formed by an internal optical interface 32 inside a monolithic component. Preferably, the third set of optical interfaces 31-34 of the polarizing beam splitter 30 comprise one entry interface 31 and two exit interfaces 33,34, said interfaces arranged normal to the third beam Lc, fourth beam Ld, and fifth beam Le, respectively, wherein all non-optical interfaces such as the interface 35 and the (non-indicated) top and bottom interfaces of the polarizing beam splitter 30 are non-parallel to any of the optical interfaces 31-34. This configuration may alleviate undesired stray reflections.

In a preferred embodiment, the polarizing beam splitter 30 comprises a pair of optically bonded fused silica prisms forming an internal optical interface 32 there between at an angle θ_B of fifty-seven degrees with respect to the entry interface 31, wherein the first exit interface 33 is parallel with the entry interface, and the second exit interface 34 is at an angle θ_E of sixty-six degrees with respect to the entry interface. The inventors find that this provides overall good performance in robustness, stability, and polarization splitting efficiency at visible wavelengths with the least stray reflections. In some embodiments, the polarizing beam splitter 30 comprises a pair of wire grid polarizers 36,37 aligned along the polarization directions outputted by the monolithic component. This may further improve polarization distinction. Preferably, the optical interfaces of the wire grid polarizers 36,37 are also parallel to the slit length direction Z, most preferably parallel to the corresponding exit optical interfaces 34,33 of the polarizing beam splitter 30.

FIG 2 illustrates a perspective view of the polarization modulation optics 200. The figure illustrates a preferred embodiment, wherein the slit plate 50 has multiple sub slits as will be discussed later with reference to FIG 8A. Also it is illustrated that the slit plate may have a trapezoidal cross-section which is found advantageous in mounting the slit plate in a frame. Preferably, the spectrometer entrance slit is placed inside the PMO, just before the polarizing beam splitter. This allows for a very compact design of the combination of telescope PMO and spectrometer. Compactness is key for space applications because of the launch cost but compactness is also favorable for thermal stability.

FIG 3 illustrates an exploded perspective view of the polarization modulation optics 200 and corresponding frame 60 for mounting the various components. In one embodiment, the optical components 10,20,30 of the polarization modulation optics 200 are adhesively bonded to a monolithic frame 60. In a preferred embodiment, the monolithic frame 60 comprises a titanium-aluminum alloy such as TiAlV6. In one embodiment, the monolithic frame is made using milling in combination with wire erosion. The inventors find this may enable micrometer accuracy of placement of optical parts. Angular tolerance of positioning of the flat optics is assured by adhesive bonding of the optical surface to the frame.

In a preferred embodiment, the optical components 10,20,30 are disposed in respective cavities 10a,20a,30a of the monolithic frame 60. For example, the respective cavities comprise a plurality of abutment or alignment surfaces (not indicated). Accordingly, the optical interfaces of the optical components 10,20,30 can be bonded to the respective alignment surfaces. In some embodiments, the alignment surfaces comprise beam passages for passing the light beams between the respective components. For example, the passages may allow the first light beam La to pass into a first cavity 10a of the frame comprising the quarter-wave retarder 10. For example, the passages may allow to pass the second beam to a second cavity

20a comprising the multiple-order retarder 20. For example, the passages may allow to pass the third beam Lc to a third cavity 30a comprising the polarizing beam splitter 30. For example, the passages may allow to pass the fourth beam Ld and fifth beam Le out of the monolithic frame 60.

5 In a preferred embodiment, the optical parts are adhesively bonded, e.g. using 3M Scotch-Weld Epoxy Adhesive EC2216 applied with a syringe dispenser through dedicated holes that are made in the frame in open connection to the respective alignment surfaces, as shown. In another or further preferred embodiment, the trapezoidal cross-section of the slit
10 plate 50 is pushed in place using a blade spring (not shown). The blade spring may ensure accurate and reproducible positioning. No gluing is needed. Post alignment in the long direction of the slit is easily achieved. Transverse adjustment is possible with shims. Preferably, no screws are employed. Screws need locking with glue and may provide irreproducible
15 stress. In some embodiment, e.g. as shown, the monolithic frame 60 forms a plurality of leaf springs 61. This may improve robustness, e.g. during launch.

 In some embodiments, the polarization modulation optics preferably has mechanical mounting that is compatible with both the
20 vibration and shock loads of a rocket launcher and the thermal environment in space. In order to fulfill this need, a PMO concept has been designed and tested in which 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
25 angles within 0.2 degrees with respect to the surface normal as designed . 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. 3M Scotch-Weld Epoxy Adhesive EC2216 was chosen as adhesive, because of extensive heritage with this material for space use.
30 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. The titanium slit plate was mounted using a leaf spring that is sufficiently strong to prevent slip thereby maintaining the precise alignment

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) and 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.

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.

FIG 4 illustrates a perspective view of the polarization modulation optics 200 with combining optics 70. In some embodiments, e.g. as shown, the optical system further comprises combining optics 70 for receiving the fourth beam Ld with the first polarization TM (p-polarized) and receiving the fifth beam Le with the second polarization TE (s-polarized), and outputting a combined beam Lh in a common direction. In one embodiment, e.g. as shown, the combining optics 70 comprises a set of folding mirrors 71,72 for directing the fourth beam Ld with the first polarization TM (p-polarized) and the fifth beam Le with the second polarization TE (s-polarized) towards a roof mirror 73. In another or further embodiment, the roof mirror 73 is configured to receive the respective beams Lf from the folding mirrors (or directly from the PMO), and direct the beams Lg towards a combining mirror which sends them as the combined beam Lh to a next stage in the optical system, e.g. spectrometer.

FIG 5A schematically illustrates a satellite comprising a multi-angle spectropolarimeter 1000. FIG 5B schematically illustrates a side view of an embodiment for a multi-angle imager 100, e.g. as part of the spectropolarimeter 1000 in FIG 5A.

FIG 6A schematically illustrates a different side view of the multi-angle imager 100. FIG 6B schematically illustrates a perspective view of the multi-angle imager 100.

In the following, the index “i” as in “Si”, “Vi”, “ai”, “Li”, “Mi1”, “Mi2” may be interpreted as indicating the number of the respective field of view, angle or imaging branch in the multi-angle imager 100. In the embodiment shown there are five imaging branches corresponding to five view angles, so here the index has values 1,2,3,4,5. In other embodiments there may be more or fewer imaging branches than shown. Furthermore a

second index “j” as in “Mij” may be used to differentiate the primary mirror (Mi1) or secondary mirror (Mi2) in the respective imaging branches. There may also be more or fewer mirrors per imaging branch.

In the embodiment shown, the multi-angle imager 100 comprises
5 at least one entrance pupil A1 configured to pass through light beams Li of an object P0 to be imaged from multiple entry angles α_i into the imager 100. In other embodiment (not shown), the imager may comprise multiple entrance pupils, e.g. one for each imaging branch. For example, multiple apertures can be used instead of a single aperture to minimize the angle of
10 incidence on the Mi1 and Mi2 mirrors. Generally, the entrance pupil can be described as the optical image of the physical aperture stop, as 'seen' through the front of the imaging system. It is typically, located at the vertex of the imager's angle of view.

In some embodiments, an imaging array Mij is configured to
15 receive the light beams Li via the one or more entrance pupils A1, e.g. according to distinct fields of view Vi of the object P0 along each of the multiple entry angles α_i . In other or further embodiments, the imaging array Mij is configured to image subsections Si of the object P0 according to the distinct fields of view Vi onto an imaging plane. For example, an
20 imaging plane P2 can be at the surface of a detector (not shown here). Alternatively, or in addition, an (intermediate) imaging plane Ps can be at a slit plane (not shown here).

As described herein, it is preferred that an (intermediate) image plane of the imaging array Mij (e.g. imaging the distant object P0) coincides
25 with a slit 51 that is disposed between optical elements of the polarization modulation optics 200, e.g. at a slit plate 50 between the optical elements 20,30, as shown in the embodiments of any of FIGs 1-4.

In some embodiments, the imaging array Mij comprises multiple imaging branches, e.g. indicated in FIG 6B by the references M1j,M2j, etc.
30 The imaging branches are configured to form respective optical paths for the

light beams through the imager 100 for imaging the respective subsections of the object P0. Preferably, each imaging branch comprises a distinct set of optical elements, e.g. the mirrors M11, M12, etc. for imaging branch M1j. The optical elements in each imaging branch are configured to receive the
5 respective light beam along the respective entry angle α_1 and/or redirect the respective light beam towards the imaging plane P1 (or intermediate imaging plane).

In a preferred embodiment, e.g. as shown in FIG 6A, the light beams L1, L2 from each of the multiple imaging branches M1j, M2j are
10 redirected to travel in a common direction "Y" between the imaging array Mij and the imaging plane P1. More preferably, the redirected light beams travel along substantially parallel paths in the common direction "Y". For example, the paths are parallel to within ten degrees plane angle, or less, e.g. within five degrees, or even within one degree, or less than a tenth of a
15 degree. In other or further preferred embodiments, the imaging array Mij is configured to combine the incoming light beams Li to have a common effective focal plane, e.g. at an imaging sensor or slit (not shown here). For example, the imaging branches M1j, M2j, etc. may have optical elements each having different curvatures but the branches preferably have a focal
20 length optimized to achieve a common size on the detector for each subsection Si. For imaging sections of e.g. a planet under various angles, the imaging branch for each angle may have its own distinct focal length in order to achieve common magnification of each strip on the detector

By providing the light beams with a common direction and
25 common effective focal plane or collimation, the plurality of beams can be effectively treated as a single extended beam. This has the advantage that further optical elements in an optical path after the imaging array Mij can be combined or integrated. For example, a single polarization modulation optics (not shown here) can be used to modulate the multiple beams, a
30 single grating (not shown here) can be used to spectrally resolve the

multiple beams, one mirror or lens combination (not shown here) can be used to collimate or focus the multiple beams, single spectral filter, single beam splitter, et cetera. It will be appreciated that this combination or integration of optical elements can save space, weight and/or improve
5 robustness and/or manufacturability.

In some embodiments, e.g. as shown in FIGs 6A and 6B, the light beams, e.g. L1,L2 from each of the multiple imaging branches M1j,M2j, etc. are stacked in a line or row along a direction "Z" transverse to their direction of travel "Y". Preferably, the multiple imaging branches M1j,M2j,
10 etc. are configured to stack their respective light beams one above the other along a direction "Z" transverse to a plane (X,Y) spanned by the multiple entry angles α_i .

In some embodiments, each imaging branch M1j has its own set of at least two optical elements M11,M12, etc. For example, the optical
15 elements are distinct from any other imaging branch M2j. In a preferred embodiment, each imaging branch M1j,M2j, etc. has a distinct primary mirror M11,M21, etc. Preferably, the primary mirrors Mi1 are distributed to receive the light beams Li from the one or more entrance pupils A1 at a range of multiple entry angles α_i . Typically, the primary mirrors Mi1 have a
20 concave reflecting surface to at least partially focus the reflected beams. In another or further preferred embodiment, each imaging branch M1j,M2j, etc. has a distinct secondary mirror M12,M22, etc. Preferably, the secondary mirrors Mi2 are stacked in a row to receive the light beams Li reflected from the primary mirrors Mi1 and reflect parallel light beams in a common
25 direction. In some embodiments, the secondary mirrors Mi2 have a concave reflecting surface e.g. to at least partially collimate or focus the reflected beams. Alternatively, the secondary mirrors Mi2 can be convex in some designs, e.g. with three mirrors per imaging branch.

Preferably, the directions of the primary, secondary, and
30 optionally further mirrors of each of the imaging branches are distinctly

oriented to provide a common direction of the light beams exiting the imaging array Mij. Preferably, the primary, secondary, and optionally further mirrors of each of the imaging branches are distinctly curved to provide a common back focal length for the different imaging branches.

5 Most preferably, this may provide a common imaging plane for each of the imaging branches at a common slit plane, e.g. in the PMO. For example, the corresponding mirrors for different imaging branches can have different radii of curvature but as a set provide the same effective back focal length. In some embodiments, a common back focal length can be achieved by
10 adjusting mirror separation of the mirrors and/or their radius of curvature. In some embodiments off-axis mirrors are used; alternatively, or in addition, also on-axis mirrors may be used. In some embodiments, the mirror surfaces can be described by a biconic design. The biconic design can e.g. be arranged to provide a desired anamorphic ratio. In some embodiments it is preferred
15 to have a telecentric image space. To achieve this, a pupil stop can be positioned at any (intermediate) focal point of the telescope system.

The optical elements adjacent imaging branches M1j, M2j, etc. are preferably distinct. For example, corresponding optical elements of different imaging branches M1j, M2j, etc. are separate from each other, e.g. spaced
20 apart. Typically each optical surface provides a distinct optical function. For example, each optical surface has its own geometric definition. In some cases, the optical elements may be interconnected but with an optical discontinuity between the optical surfaces. For example, the stack of secondary mirrors can be embodied as a monolithic element with stepped
25 reflective surfaces (not shown).

In some embodiments, the combination of a concave primary mirror and concave secondary mirror may form a so-called Gregorian telescope. In the current design it is preferred to use separate imaging branches for each of the multiple entry angles α_i . For example, each imaging
30 branch can have a distinct (off-axis) Gregorian telescope design.

Alternatively, the combination of a concave primary mirror and convex secondary mirror may form a so-called Cassegrain telescope. In the current design it is preferred to use separate imaging branches for each of the multiple entry angles α_i . For example, each imaging branch can have a distinct off-axis Cassegrain telescope design. Of course the same optical functionality as described herein can also be provided by more than two optical elements per imaging branch, e.g. three, or more mirrors, though at the cost of extra weight. Also other combinations of convex/concave elements can be used to provide similar optical results. Alternative, or in addition to mirrors, also lenses can be used. While the current embodiment shows five imaging branches, there can also be more or less, e.g. two, three, four, five, six, seven, eight, nine, or more.

FIG 7 schematically illustrates an embodiment of a multi-angle spectropolarimeter 1000. In one embodiment, e.g. as shown the spectropolarimeter 1000 comprising a multi-angle imager 100, e.g. as described with reference to FIGs 5B,6A,6B. In another or further embodiment, e.g. as shown, the spectropolarimeter 1000 comprises a polarization modulation optics 200, e.g. as described with reference to FIGs 1-4. In another or further embodiment, e.g. as shown, the spectropolarimeter 1000 comprises a spectrometer 300 which may include a spectral resolving element 310 and/or imaging sensor 320.

In some embodiments, the optical elements M11,M12, etc. in each imaging branch M1j are configured to focus their respective light beam L1 onto a slit 51. In a preferred embodiment, the multiple imaging branches M1j,M2j, etc. are configured to project respective images of the respective subsections S1,S2, etc. onto the slit 51. In one embodiment, the images are extended along a length direction "Z" of the slit 51 to provide spatial information of the respective subsections S1,S2, etc. at least along said length direction "Z", while the width direction of the slit 51 can be used for

e.g. subsequent spectral and/or polarization analysis. Most preferably, the direction “Z” of the slit 51 is parallel with each of the optical interfaces of the polarization modulation optics 200, as described herein. In some embodiments, the subsections S1,S2, etc. of the object P0 to be imaged have
5 a length that is greater than their width by at least a factor two, three, five, or more, e.g. a factor ten. In some embodiments (not shown), the system can be modified by adding (folding) mirrors, to relocate the aperture, slit or lens set. Possibly, this may further compactify the system.

In a preferred embodiment, as shown, the imager 100 is combined
10 with polarization modulation optics 200 to form a multi-angle spectro-polarimeter. In some embodiments, the spectropolarimeter comprises a single integrated polarization modulator optics (PMO), preferably disposed in a plurality of light beams Li after the imaging array Mij. In some
15 51. In a preferred embodiment, the slit 51 is arranged between optical elements of the polarization modulation optics 200, most preferably between the multiple-order retarder 20 and polarizing beam splitter 30, as described herein.

In some embodiments, as shown, the imager 100 is combined with
20 a single spectrally resolving element 310 and/or imaging sensor 320 to form a multi-angle spectrometer 300. Preferably the multi-angle spectrometer 300 has as a single grating or prism configured to resolve the plurality of light beams Li traveling in parallel and/or having common degree of collimation. In some embodiments, the spectrally resolved light beams Li
25 are imaged onto a single detector surface, e.g. pixel array. While not all depicted in the schematic figure, typically a spectrometer comprises the following elements: collimator, spectrally resolving element, objective; these are typically followed by a single detector surface, e.g. pixel array.

In a preferred embodiment, the spectropolarimeter 1000
30 comprises one or more of the polarization modulation optics 200 as described

herein, an imager 100, configured to project a distant object P0 onto the physical slit 51 in the polarization modulation optics 200; and a spectrometer 300 with its entrance slit formed by the physical slit 51 in the polarization modulation optics 200.

5

FIG 8A illustrates an image of different view angles imaged at a slit plane Ps onto a slit plate 50. In some embodiments, the physical slit 50 comprises a number of distinct sub slits arranged in a sequence along the slit length direction Z. This may allow to use the same PMO for different view angles. In one embodiment, the physical slit 50 has an absorbing black coating between the openings. The inventors find by analysis that reflections on the slit plate may have secondary reflections on other surfaces inside the PMO and may end up on the detector. To achieve performance in-line with the error budget given in the table of FIG 11, a black coating is added to the Titanium slit plate. The black coating may be compatible with space use.

FIG 8B illustrate an image of polarization modulated spectra S1-S5; S1'-S5' projected at an imaging sensor 320. The spectra S1-S5 and S1'-S5', respectively, may correspond to the different view angles of the multi-angle imager 100. In a preferred embodiment, the spectropolarimeter 1000 is configured to project sets of polarization modulated spectra S1-S5; S1'-S5' at an imaging sensor of the spectrometer 300. For example, the projection comprises a first set of spectra S1-S5 corresponding to the first polarization TM (p-polarized) and a second set of spectra corresponding to the second polarization TE (s-polarized). For example, the sets of spectra are projected along a spatial resolving direction Z' corresponding to the slit direction Z, and projected along a spectral direction corresponding to their respective wavelengths λ .

20
25

As mentioned, the spectral polarization modulator can be used to transform incident light into two spectrally modulated intensities, such that amplitude and phase of the modulation are proportional to the degree and angle of linear polarization respectively.

5 In a preferred embodiment, the spectral polarization modulator comprises an achromatic quarter-wave retarder, an athermal multiple-order retarder, and a polarizing beam splitter that each have a dedicated function. The quarter-wave retarder, having its ordinary and extraordinary axes in the direction of Stokes parameter $\pm Q$, transforms e.g. linearly (Stokes U)
10 polarized light into circularly (Stokes V) polarized light (operation 1). The multiple-order retarder, having its ordinary and extraordinary axes in the Stokes $\pm U$ direction, projects the polarization state of the light onto the spectrum by means of spectral modulation of the polarization state (from linear over elliptical to circular, and back over elliptical to linear (operation
15 2). The polarizing beam splitter, having polarization directions in the Stokes $\pm Q$ directions, projects the polarization modulated spectrum onto a set of spectrally intensity modulated TM (p) and TE (s) polarized spectra (operation 3).

A polarimetric uncertainty budget has been composed for each of
20 these three components, see FIG 11. In a preferred embodiment, the PMO is placed in a telecentric beam. In that case, the creation of instrumental polarization is found to be of the order of 10^{-4} only and can be neglected. The uncertainty budget therefore contains sources that result in a deviation from unity of the modulation efficiency, also called the polarimetric scaling
25 parameter. The polarimetric scaling parameter usually depends on the wavelength, temperature, angle of linear polarization, and time. Some sources of uncertainty are fixed and can be well calibrated, such as those resulting from misalignments. Other sources vary in-orbit and sometimes in a unpredictable manner and can be characterized by vicarious calibration,
30 which is assumed to be less accurate than the on-ground calibration.

Examples are potential changes in coating response and residual mechanical stress than can vary with temperature.

As can be seen in FIG 11, the correction accuracy has been assumed 90% for the on-ground calibration, 80% for the in-orbit vicarious calibration, and 50% when no dedicated vicarious calibration measurement can be defined to monitor the parameter and indirect data has to be used. The combined contribution of the PMO to the uncertainty in the polarimetric scaling factor of all sources has been calculated by taking the RSS of the individual sources. With the proper choice of materials, coatings, alignment procedure, and optical design choices the RSS uncertainty can be limited to slightly over $1 \cdot 10^{-3}$, while using conservative estimates and including stray light generated in the PMO. This leaves sufficient budget for the telescope and spectrometer subsystems.

In some embodiments, e.g. for use as part of an instrument in a (space) orbiting platform, preferred properties of the PMO may be as follows:

- Wavelength range larger than 385 nm – 770 nm
- Low dispersion that is compatible with a fully reflective optical design (e.g. telescope and spectrometer)
- Modulator performance compatible with a polarimetric accuracy $< 10^{-3}$
- Use of optical element materials and processes that are compatible with space flight, in particular in Low Earth Orbit, and for the duration of about 10 years
 - withstanding radiation environment, TID > 25 krad
 - withstanding vibration and shock loads during launch
 - surviving a thermal environment, at least $-40\text{ °C} < T < 60\text{ °C}$
 - compatible with humidity environment

The inventors find that these properties may be achieved with the knowledge of materials and processes, accurate positioning and mounting concept, and full (sub)system knowledge of the polarimetric performance. As

part of the design process, a polarimetric error budget has been used to derive preferred characteristics of the individual components and can be summarized by the following preferred embodiments of the various components, preferably used in combination for achieving the preferred properties of the PMO.

In some preferred embodiments, the quarter-wave retarder (QWR) has one or more, preferably all of the following characteristics:

- low sensitivity to angle of incidence
- fused silica as material
- entrance and exit surface perpendicular to chief ray
- induced $90^\circ \pm 1^\circ$ phase retardance between TM (p) and TE (s) polarized light over the full spectrum
- Anti Reflection (AR) coatings with maximum reflection coefficient (R_{max}) < 1% and average reflection coefficient (R_{ave}) < 0.5%
- alignment accuracy < 1°

In one embodiment, e.g. as shown in FIG 1, a QWR is manufactured from fused silica that has good transmission properties from the UV up to the IR wavelengths. This glass is compatible with the space radiation environment. In the embodiment, the QWR is designed for an angle of total internal reflection of 52.5 degrees. Therefore the top angle is 105 degrees. The angle between the entrance and exit surfaces and the surface of total internal reflection is 150 degrees. Most preferably, a fused silica Mooney rhomb-type with a broadband phase changing coating is used as the QWR.

An implementation of the QWR Mooney rhomb has been designed, manufactured and tested. The result is a QWR that operates in the wavelength range from 385 nm to 770 nm with a retardance of $45^\circ \pm 0.5^\circ$, see FIG 9A. This can be compared with an uncoated Mooney rhomb or with a Mooney rhomb with a single layer enhancement coating. Compared to a Fresnel rhomb, the inventors find a Mooney rhomb is less sensitive to

misalignment of the incoming beam with respect to the design angle of incidence because such misalignment is compensated in the second reflection. Another relevant aspect may be that the phase change coating can be used to increase the phase change to 45° with a single TIR at a
5 nominal angle of incidence (or corresponding Mooney rhomb wedge angle) that is close the maximum phase change angle of incidence without coating, see FIG 9B (left). Therefore, the Mooney rhomb is much more insensitive to deviations from normal incidence on the entrance surface compared to e.g.
10 an uncoated BK17 Fresnel rhomb. For example, FIG 9B (middle) shows the effect of deviation in the direction " $\Delta\theta$ " perpendicular to the TIR-plane as indicated in FIG 1. In the other direction " $\Delta\Phi$ ", FIG 9B (right), the sensitivity to the angle of incidence is a factor two smaller compared to a BK7 Fresnel rhomb. For example, the grey shading in FIGs 9B, middle and right, indicates the phase change from the nominal value caused by a
15 deviation of plus-minus two degrees in either the " θ " or " Φ " or direction.

In some preferred embodiments, the multiple-order retarder has one or more, preferably all of the following characteristics:

- MgF2 and SiO2 as materials
- athermal point at 450 ± 50 nm
- 20 • entrance and exit surface perpendicular to chief ray
- AR-coatings with $R_{\text{max}} < 1\%$ and $R_{\text{ave}} < 0.5\%$
- alignment accuracy $< 1^\circ$

In principle, a multiple-order retarder can be made of any birefringent material. However, the desire for a relatively low total
25 retardance (e.g. less than 14 micron) and the desire for a low temperature sensitivity may limit the available materials. To achieve low temperature sensitivity the use of two materials in a subtractive combination may be used. The birefringence of the material is preferably low enough such that the crystal thickness can be of the order of a millimeter, which may simplify
30 handling and mounting, and preferably has sufficient mechanical strength.

The inventors find that two crystals that can be well manufactured with high dimensional accuracy and have extremely predictable optical properties are MgF_2 and SiO_2 . In a preferred embodiment, a thickness ratio of 2.25 may be chosen in order to have the athermal point slightly below
5 500 nm. In another embodiment, a different combination of bi-refrigent crystals may be used (e.g. MgF_2 and sapphire) with a different thickness ratio such that the athermal point is located slightly below 500 nm. In another embodiment, the total retardance of the multiple-order retarder may be chosen much higher or much lower than 14 microns, e.g. in
10 applications that require a much higher or much lower polarimetric spectral resolution.

In some preferred embodiments, the polarizing beam splitter has one or more, preferably all of the following characteristics:

- fused silica as material
- 15 • extinction ratio > 70 over the full spectrum
- splitting angle independent of wavelength
- entrance and exit surface perpendicular to chief ray
- AR-coatings with $R_{\text{max}} < 1\%$ and $R_{\text{ave}} < 0.5\%$
- alignment accuracy $< 1^\circ$

20 In one embodiment, the polarizing beam splitter is based on an off-the-shelf beam-splitter cube based on optically bonded fused silica prisms and a dedicated polarizing multilayer coating. The inventors have customized the angle between the surface normal of the entrance- and exit surfaces and the normal to the internal beam splitting surface to reduce the
25 angles of incidence on the entrance and exit ports, e.g. see FIG 1. Moreover the inventors have truncated the unused fourth surface (37) so that it is not parallel to one of the exit ports (33,34), or the entry port (31). This may be useful e.g. to reduce reflections.

In one embodiment, a fused silica beam splitter was chosen for its
30 large transmission in the desired wavelength range, its resilience to space

radiation and low dispersion. Also, a cube or cube-like polarizing beamsplitter has the advantage that the splitting angle does not depend on wavelength, as is e.g. the case with a Wollaston type of beam splitter. The relatively low extinction ratio compared to crystal based beam splitters can
5 be mitigated by applying dielectric coatings at the beam splitting surface and using an additional pair of wire-grid polarizers.

In some preferred embodiments, the polarizers (e.g. following the PBS) have one or more, preferably all of the following characteristics:

- extinction ratio larger than 1000 over full spectrum
- 10 • entrance and exit surface perpendicular to chief ray
- AR-coating with $R_{\text{max}} < 1\%$ and $R_{\text{ave}} < 0.5\%$
- alignment accuracy $< 1^\circ$

In some embodiments, to achieve the desired polarization purity (contrast ratio > 1000), two orthogonally oriented polarizers (36,37) can be
15 placed after the corresponding exit windows of the polarizing beam splitter to further purify the polarization state. Preferably, the polarizers comprise fused silica wire-grid polarizers. The wire-grid polarizers preferably have a contrast ratio of > 650 , and perform within specifications up to an angle of incidence of $\pm 20^\circ$.

20 The above preferred characteristics may form the starting point for the design of what the inventors refer to as the SPEX Polarization Modulation Optics (PMO) module.

In a preferred embodiment, the SPEX Polarization Modulation Optics (PMO) module may be constructed such as shown e.g. in FIG 1. In
25 one embodiment, e.g. as shown, the optical train comprises an achromatic quarter-wave retarder that is preferably implemented as a Mooney rhomb (10), a multiple-order retarder (20) that is preferably implemented as an athermal combination of MgF2 (21, 22) and crystal quartz (23, 24), and a polarizing beam splitter (30). In a preferred embodiment, the polarizing
30 beam splitter (30) is based on beam-splitter cube, that has been customized

to reduce the angles of incidence on the entrance port 31 and exit ports (33,34). In combination with a set of wire-grid polarizers (36,37) the desired polarization purity >1000 may be achieved.

To optimize light transmission and minimize scattering of the PMO, high quality anti-reflection (AR) coatings with an average reflectance below 0.5% over the 385-770nm wavelength range have been specifically designed for the entrance and exit windows of the Mooney rhomb QWR, both sides of the MgF₂ and SiO₂ crystal plates forming the multiple order retarder (MOR), and the unstructured side of the wire grid polarizers.

The maximum ghost intensity that can be expected from the measured AR-coating performance, when including all double-reflections, is shown in FIG 10. The peak ghost intensity is smaller than 0.3%, while the spectrally averaged ghost intensity is of the order of 0.1%. The actual intensity will be lower since most of the ghosts will be slightly defocused at the focal plane, reducing the intensity. Since all reflections occur close to an image plane (the slit), all ghosts will form close to the nominal image, preventing (ghost) stray light from one part of the image to another part relative far away. This is especially important since this prevents cross-talk between images from different telescopes and limits the impact of bright areas in an image on dark areas in the same image.

In interpreting the appended claims, it should be understood that the word "comprising" does not exclude the presence of other elements or acts than those listed in a given claim; the word "a" or "an" preceding an element does not exclude the presence of a plurality of such elements; any reference signs in the claims do not limit their scope; several "means" may be represented by the same or different item(s) or implemented structure or function; any of the disclosed devices or portions thereof may be combined together or separated into further portions unless specifically stated otherwise. Where one claim refers to another claim, this may indicate synergetic advantage achieved by the combination of their respective

features. But the mere fact that certain measures are recited in mutually different claims does not indicate that a combination of these measures cannot also be used to advantage. The present embodiments may thus include all working combinations of the claims wherein each claim can in
5 principle refer to any preceding claim unless clearly excluded by context.

CLAIMS

1. A polarization modulation optics (200) comprising
 - an achromatic quarter-wave retarder (10) with a first set of optical interfaces (11-14) configured to receive a first beam (La) of light having a spectrum and polarization state, and output the light as a second
5 beam (Lb) of light;
 - an athermal multiple-order retarder (20) with a second set of optical interfaces (21-24) configured to receive the second beam (Lb) and output a third beam (Lc) for which the polarization state of the light is projected onto the spectrum of the light by means of spectral modulation of
10 the polarization state;
 - a polarizing beam splitter (30) with a third set of optical interfaces (31-35) configured to receive the third beam (Lc) and output a fourth, spectrally intensity modulated beam (Ld) with a first polarization (TM), and a fifth, spectrally intensity modulated beam (Le) with a
15 perpendicular second polarization (TE); and
 - a slit plate (50) disposed in the third beam (Lc), the slit plate (50) forming at least one physical slit (51) having its slit length direction (Z) parallel to each of the said optical interfaces (11-14, 21-24, 31-34).
- 20 2. The polarization modulation optics (200) according to claim 1, wherein the achromatic quarter-wave retarder (10) is formed by a Mooney rhomb.
3. The polarization modulation optics (200) according to claim 2,
25 wherein the internal reflection interfaces (12,13) of the Mooney rhomb are provided with a phase changing coating (12a,13a).
4. The polarization modulation optics (200) according to claim 3, wherein the Mooney rhomb is formed by a rhomb shaped block of fused

silica with four coating layers having the following layer thicknesses and material compositions in sequence from the rhomb outward: 20 nm MgF₂, 110 nm SiO₂, 33 nm MgF₂, 200 nm SiO₂.

5 5. The polarization modulation optics (200) according to any of the preceding claims, wherein the multiple-order retarder (20) is implemented as an athermal combination of a MgF₂ crystal with a first thickness (T1), and crystal quartz with a second thickness (T2), wherein the first thickness (T1) is more than one millimeter and a ratio of the first thickness divided by
10 the second thickness (T1/T2) is between one and half and three.

6. The polarization modulation optics (200) according to any of the preceding claims, wherein the third set of optical interfaces (31-34) of the polarizing beam splitter (30) comprise one entry interface (31) and two exit
15 interfaces (33,34), said interfaces arranged normal to the third beam (Lc), fourth beam (Ld), and fifth beam (Le), respectively, wherein all non-optical interfaces (35) of the polarizing beam splitter (30) are non-parallel to any of the optical interfaces (31-34).

20 7. The polarization modulation optics (200) according to any of the preceding claims, wherein the polarizing beam splitter (30) comprises a pair of optically bonded fused silica prisms forming an internal optical interface (32) there between at an angle (θ_B) of fifty-seven degrees with respect to the entry interface (31), wherein the first exit interface (33) is parallel with the
25 entry interface, and the second exit interface (34) is at an angle (θ_E) of sixty-six degrees with respect to the entry interface.

8. The polarization modulation optics (200) according to any of the preceding claims, wherein the polarizing beam splitter (30) comprises a pair
30 of wire grid polarizers (36,37) aligned along the polarization directions

outputted by the monolithic component.

9. The polarization modulation optics (200) according to any of the preceding claims, wherein the optical components (10,20,30) of the
5 polarization modulation optics (200) are adhesively bonded to a monolithic frame (60), wherein the optical components (10,20,30) are disposed in respective cavities (10a,20a,30a) of the monolithic frame (60), wherein the respective cavities comprises a plurality of alignment surfaces, wherein optical interfaces of the optical components (10,20,30) are bonded to the
10 respective alignment surfaces, wherein the alignment surfaces comprise beam passages for passing the first light beam (La) into a first cavity (10a) of the frame comprising the quarter-wave retarder (10), passing the second beam to a second cavity (20a) comprising the multiple-order retarder (20), passing the third beam (Lc) to a third cavity (30a) comprising the polarizing
15 beam splitter (30), and passing the fourth beam (Ld) and fifth beam (Le) out of the monolithic frame (60).

10. The polarization modulation optics (200) according to any of the preceding claims, wherein the slit plate (50) has a trapezoidal cross-section,
20 the slit plate (50) is pushed in place using a blade spring.

11. The polarization modulation optics (200) according to any of the preceding claims, wherein further comprising combining optics (70) for receiving the fourth beam (Ld) with the first polarization (TM) and receiving
25 the fifth beam (Le) with the second polarization (TE), and outputting a combined beam (Lh) in a common direction, wherein the combining optics (70) comprises a set of folding mirrors (71,72) for directing the fourth beam (Ld) with the first polarization (TM) and the fifth beam (Le) with the second polarization (TE) towards a roof mirror (73), wherein the roof mirror (73) is
30 configured to direct the receive the respective beams (Lf) from the folding

mirrors, and direct the beams (Lg) towards a combining mirror which sends them as the combined beam (Lh) to a next stage in the optical system.

12. A spectropolarimeter (1000) comprising
- 5 – the polarization modulation optics (200) according to any of the preceding claims,
- an imager (100), configured to project a distant object (P0) onto the physical slit (51) in the polarization modulation optics (200); and
- a spectrometer (300) with its entrance slit formed by the physical
- 10 slit (51) in the polarization modulation optics (200).

13. The spectropolarimeter (1000) according to claim 12, wherein the imager (100) has a number (N) of different view angles, wherein the imager (100) is configured to project each of the images of the respective view
- 15 angles at a slit plane (Ps) onto the physical slit (51), wherein the physical slit (50) comprises a corresponding number (N) of distinct sub slits arranged in a sequence along the slit length direction (Z), wherein the physical slit (50) has an absorbing black coating between the openings.

- 20 14. The spectropolarimeter (1000) according to claim 13, wherein the spectropolarimeter (1000) is configured to project sets of polarization modulated spectra (S1-S5; S1'-S5') at an imaging sensor of the spectrometer (300), wherein the projection comprises a first set of spectra (S1-S5) corresponding to the first polarization (TM) and a second set of spectra
- 25 corresponding to the second polarization (TE), wherein the sets of spectra are projected along a spatial resolving direction (Z') corresponding to the slit direction (Z), and projected along a spectral direction corresponding to their respective wavelengths (λ).

15. The spectropolarimeter (1000) according to any of claim 12-14 preceding claims, wherein a maximum opening angle (α) of the third beam (Lc) between chief rays at the physical slit (51) is less than five degrees.

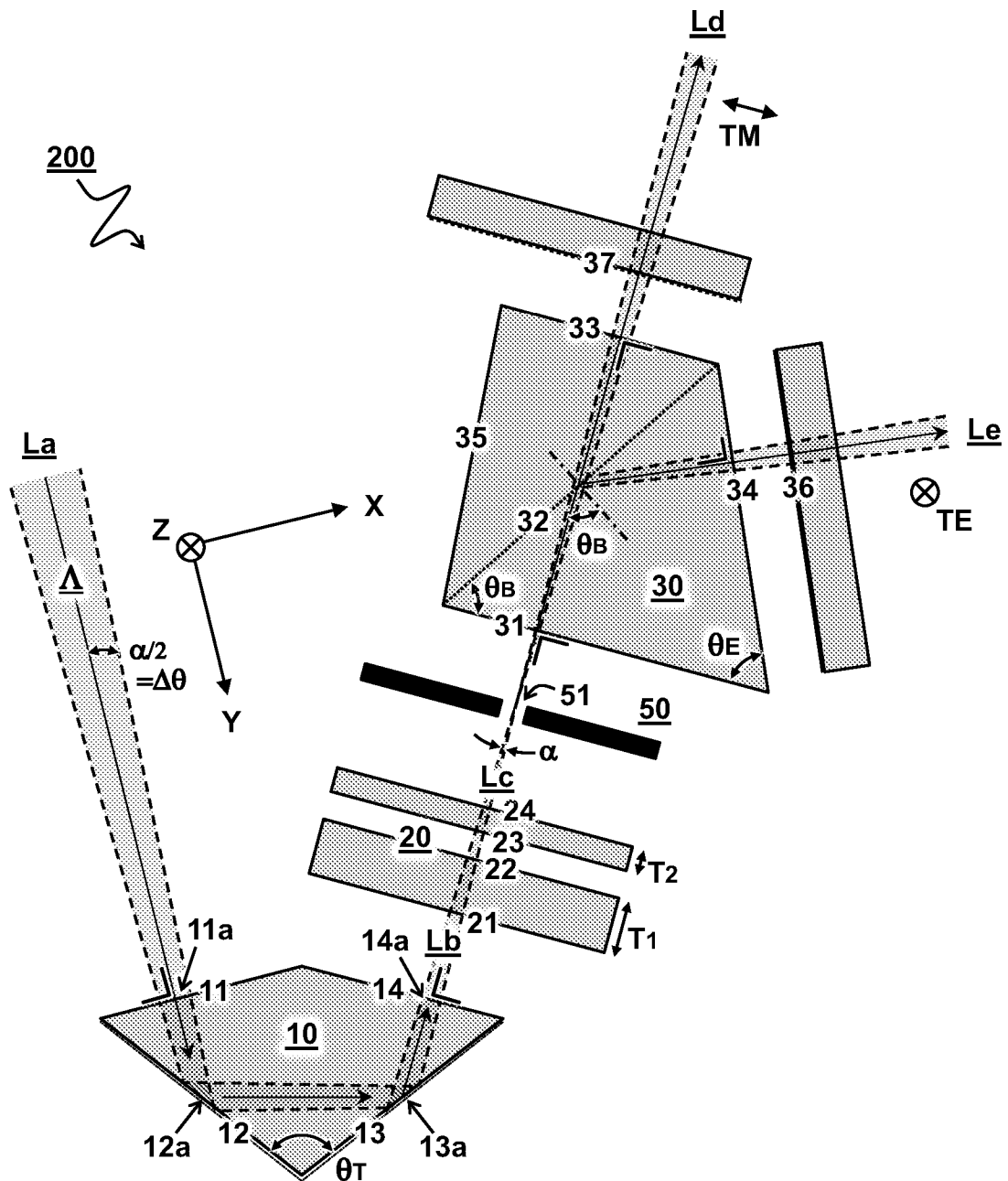


FIG 1

2/11

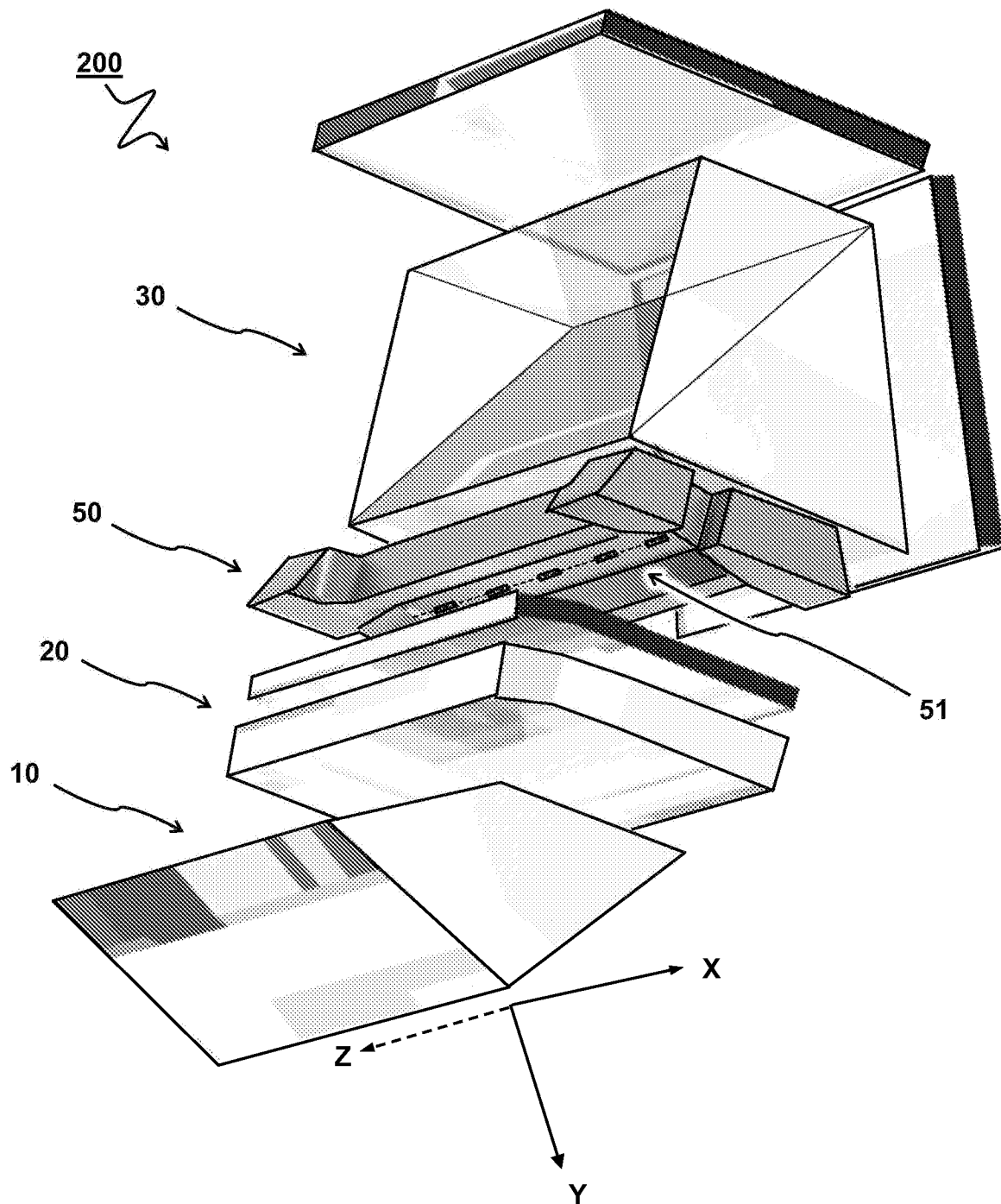


FIG 2

3/11

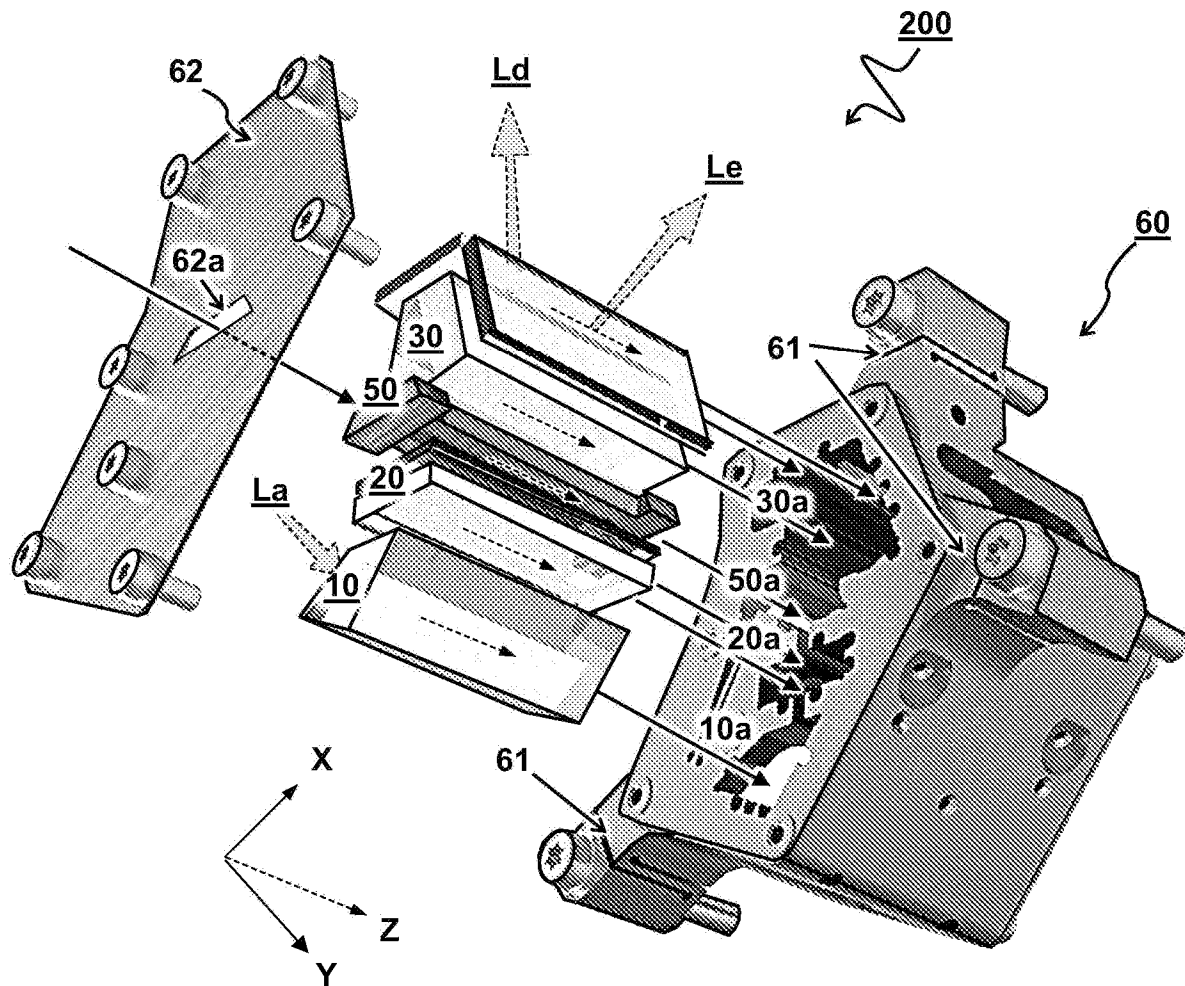


FIG 3

4/11

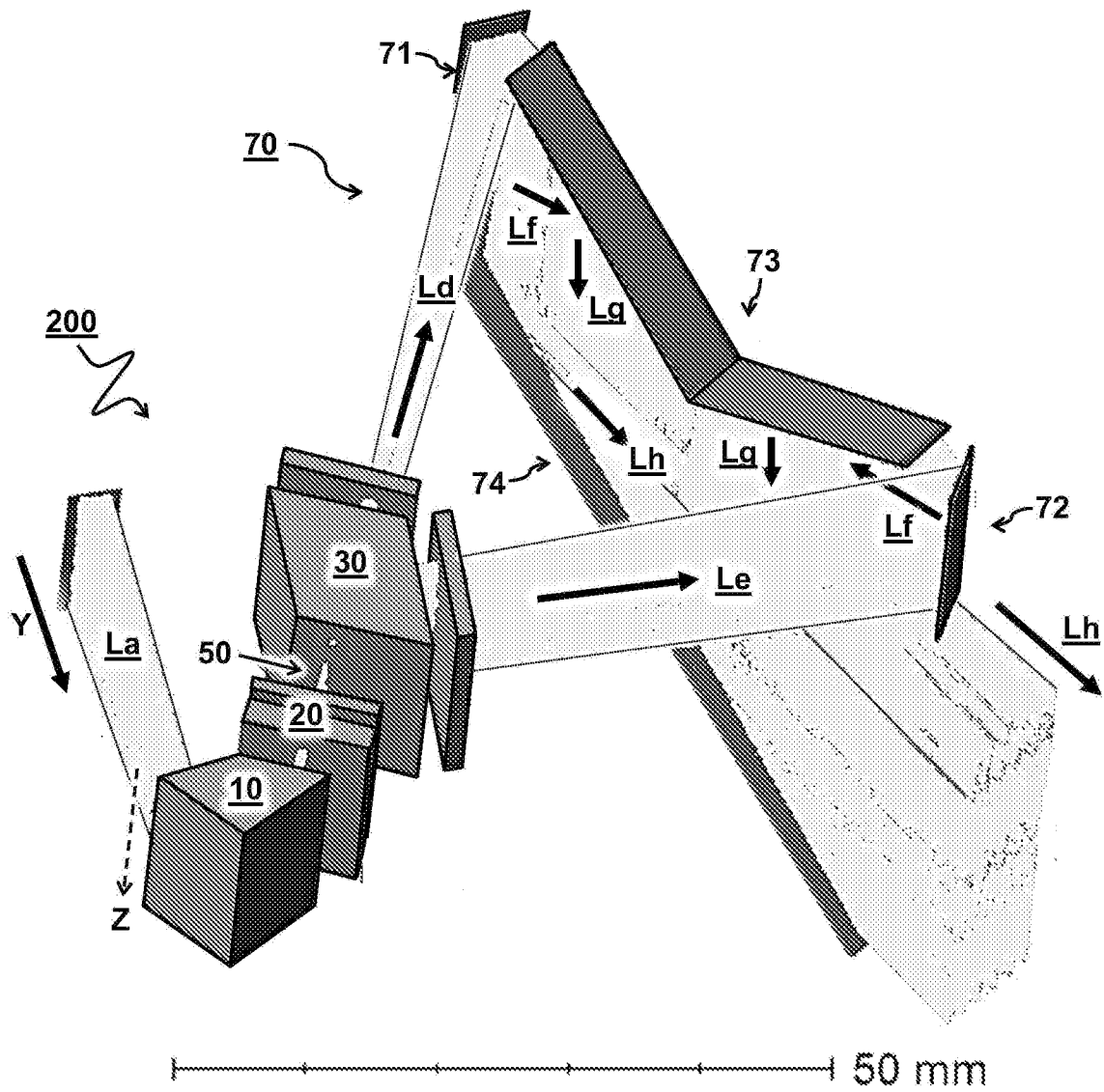


FIG 4

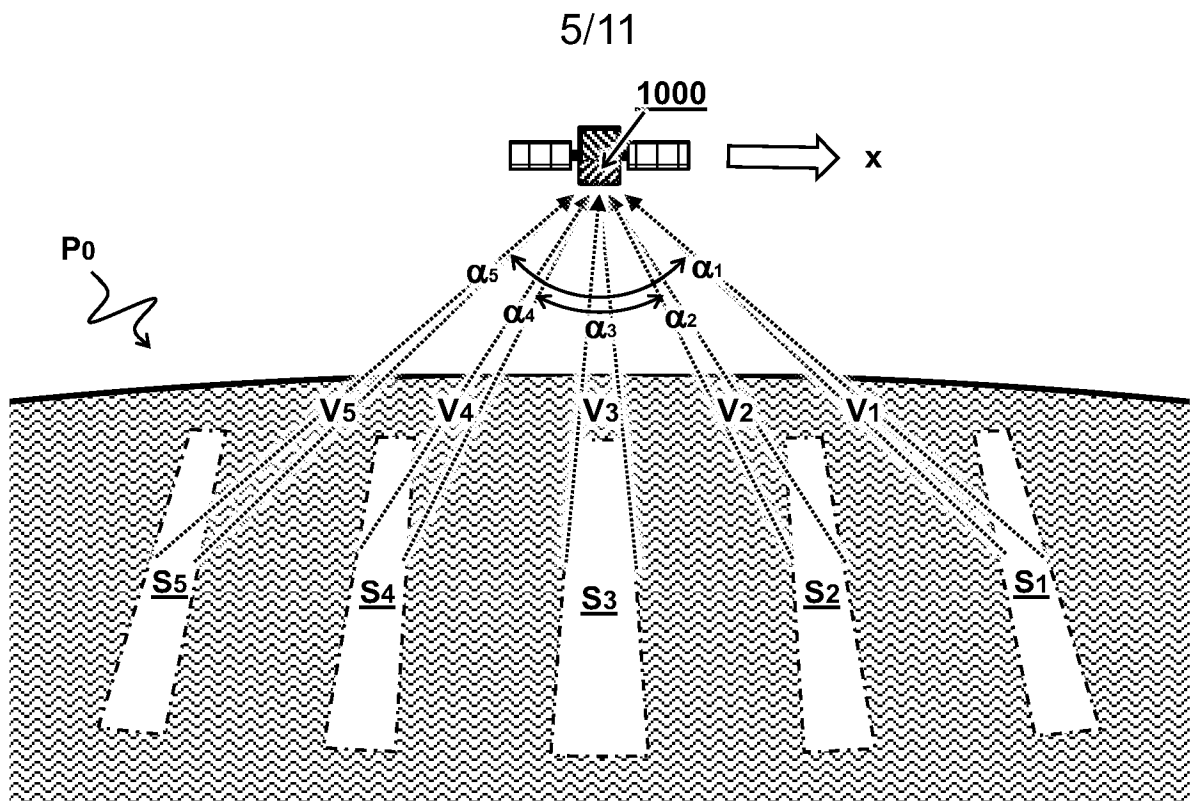


FIG 5A

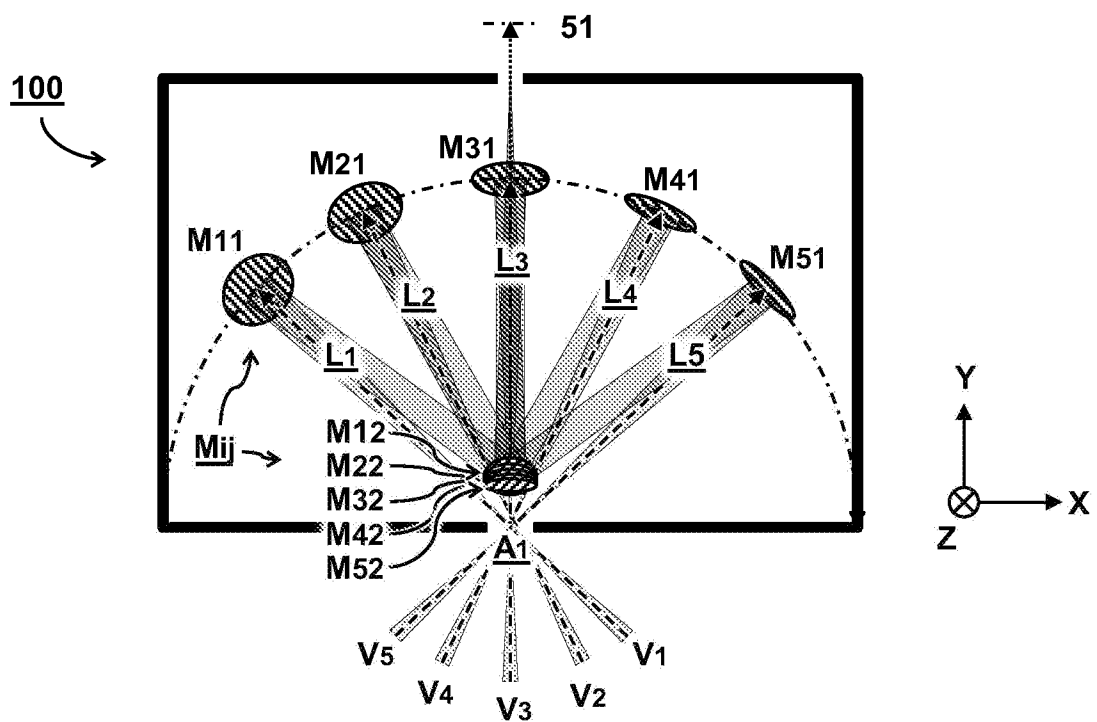


FIG 5B

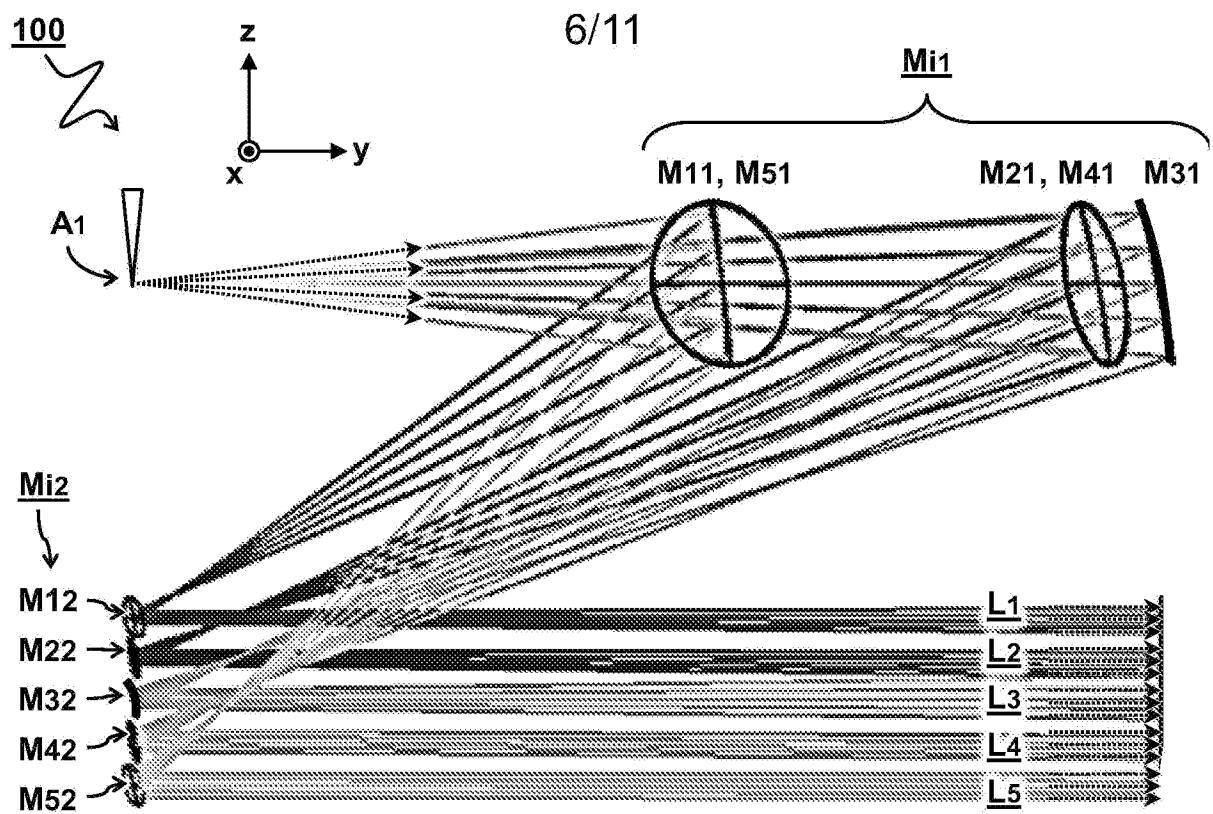


FIG 6A

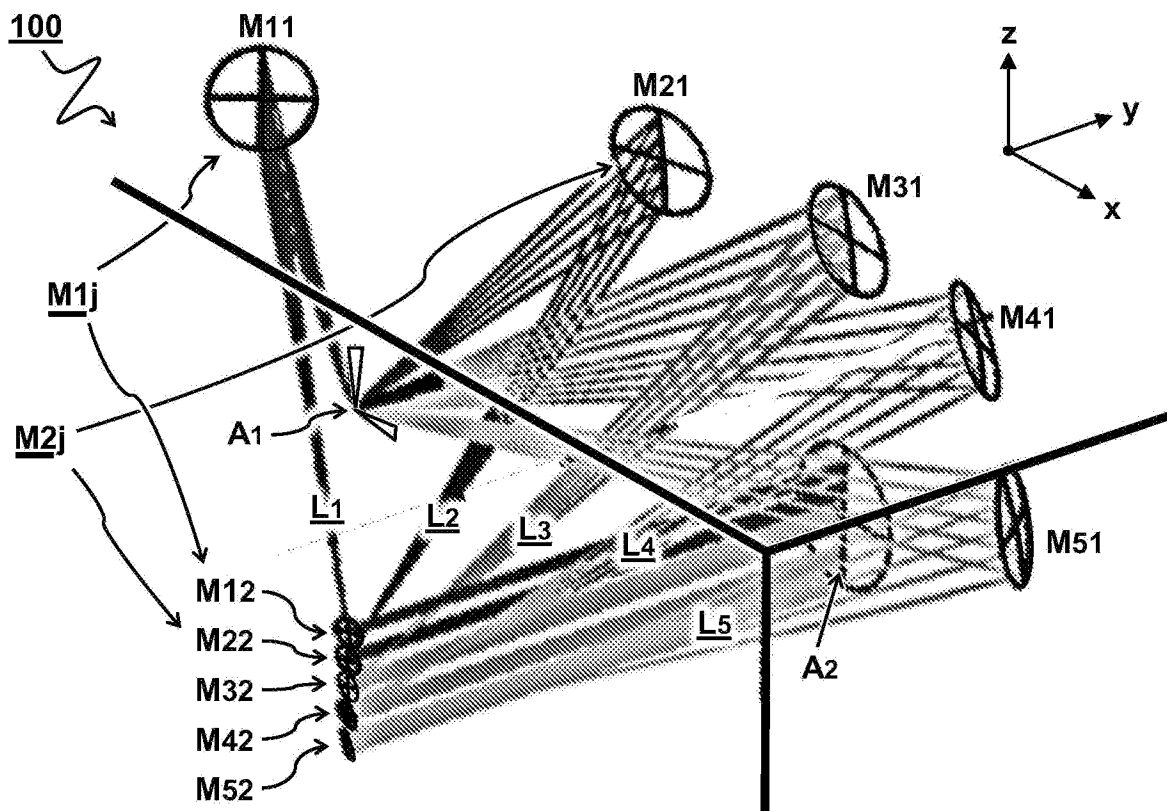


FIG 6B

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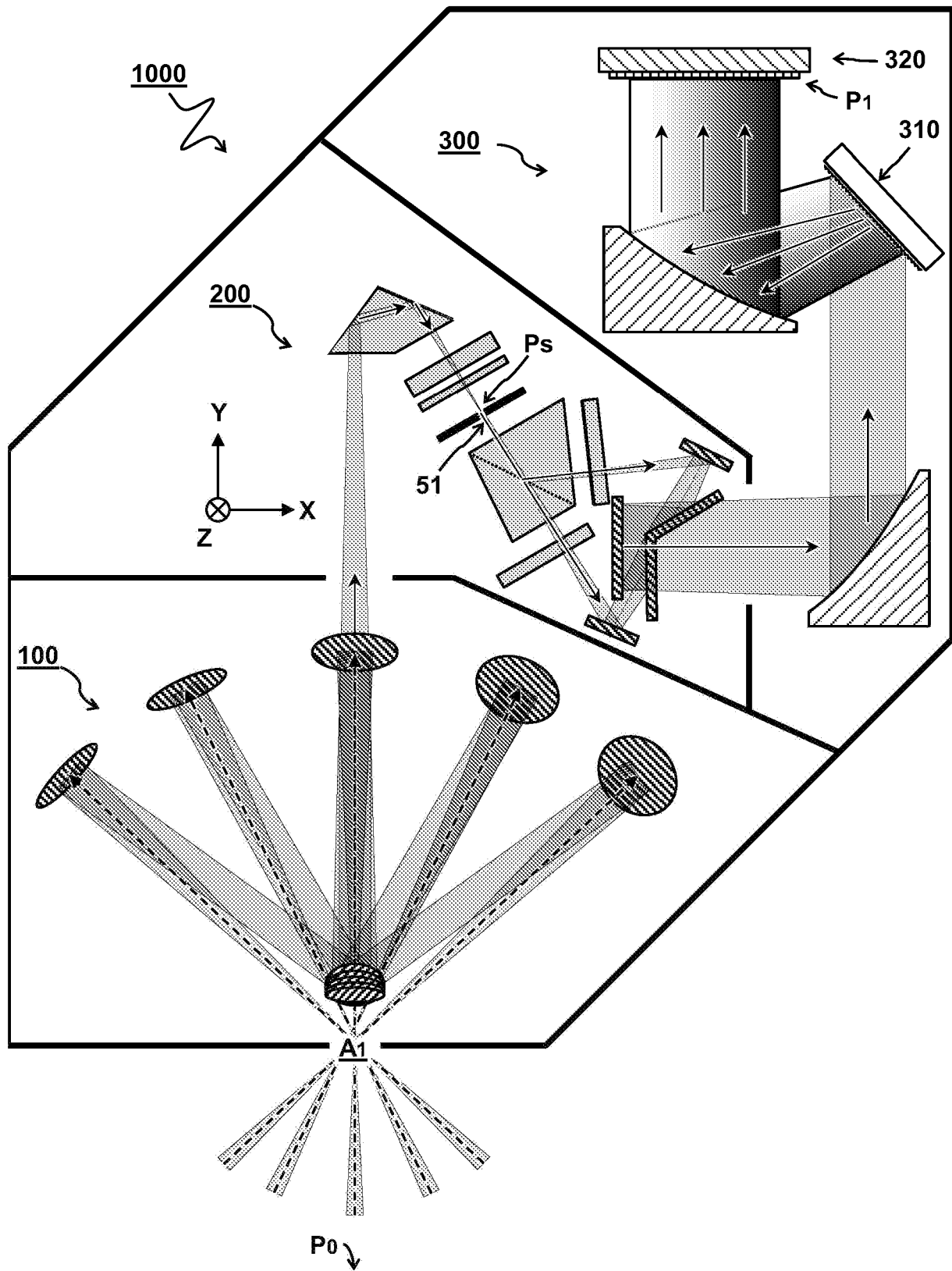


FIG 7

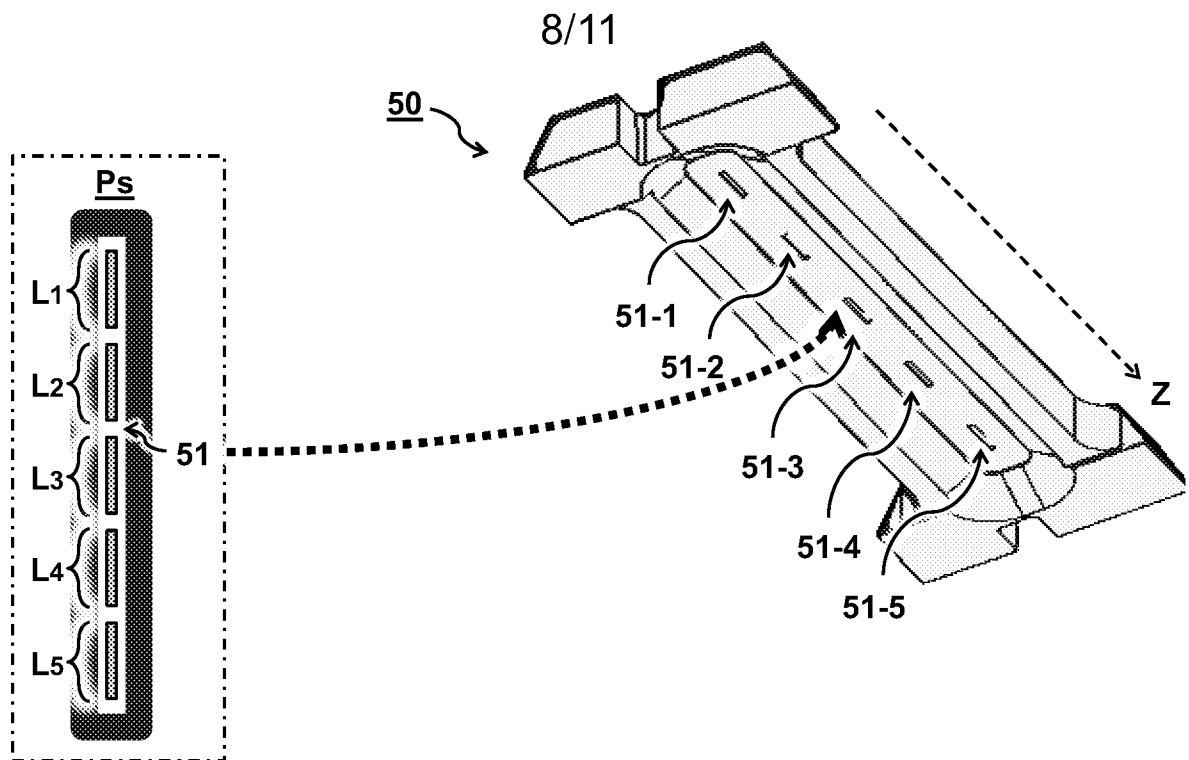


FIG 8A

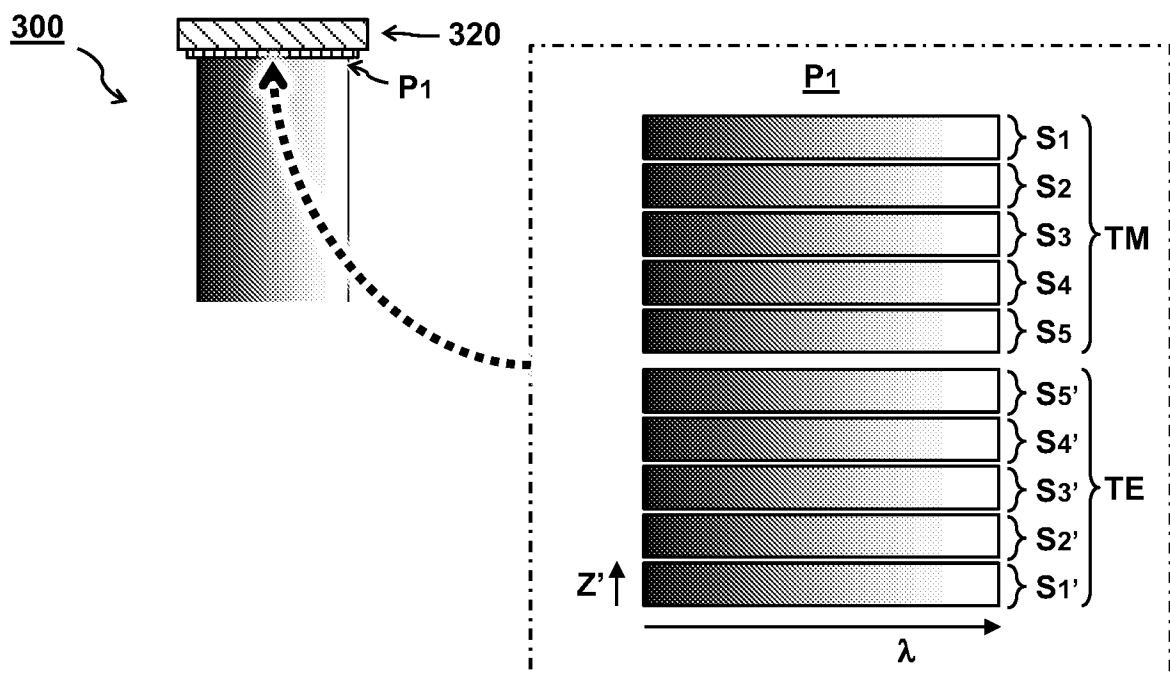


FIG 8B

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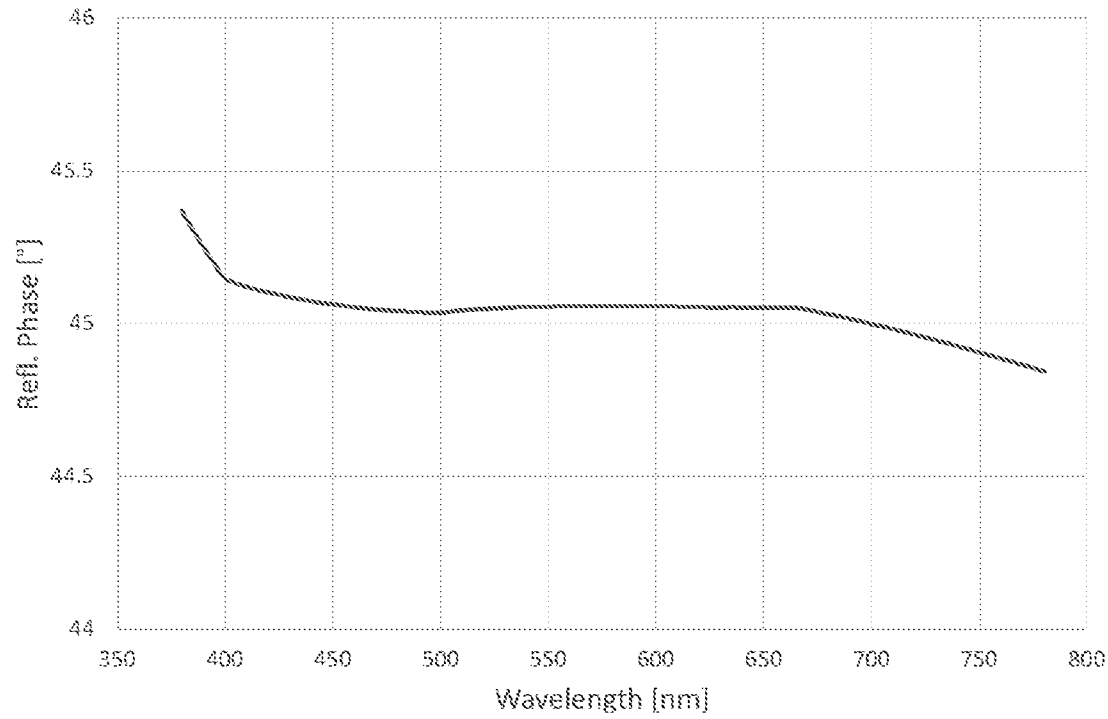


FIG 9A

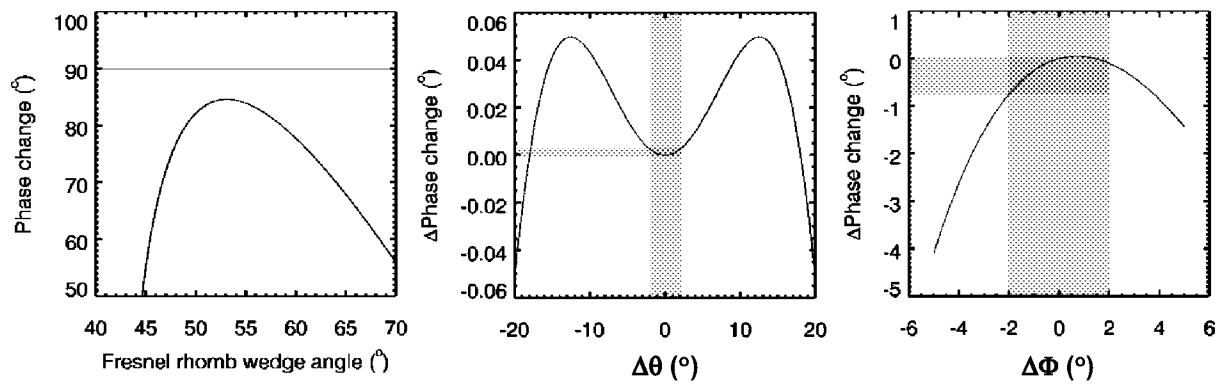


FIG 9B

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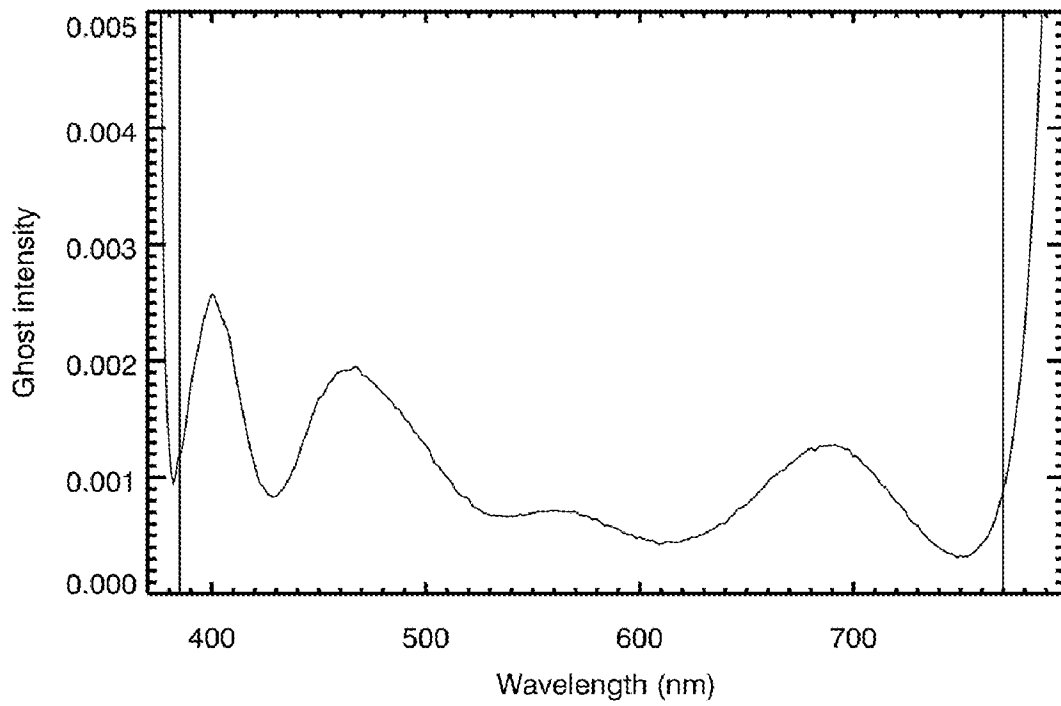


FIG 10

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Polarimetric error budget for a spectral polarization modulator

Component	Aspect	Perturbation	Type	Remark	Parameter	Change	Error	Mitigation		Error
								Type	Efficiency	
Mooney rhomb	Misalignment 'fast' axis	Mechanical	Static	Stokes Q	d(a) [deg]	1	2.4E-03	OG Calibration	90%	2E-04
	Wedge angle	Mechanical	Static	Stokes U; via retardance	d(a) [deg]	1	2.0E-03	OG Calibration	90%	2E-04
	OG spectral variation retardance	-	Static	Stokes U; $P_S \sim \cos(\text{ret})$	d(ret) [deg]	2	6.1E-04	OG Calibration	90%	6E-05
	In-flight instability	Vacuum	Dynamic	Stokes U; $P_S \sim \cos(\text{ret})$	d(ret) [deg]	1	1.5E-04	IF Correction	50%	8E-05
	Temperature dependence	Thermal	Dynamic	Stokes U; $d(n)/d(T)$; $<5 \times 10^{-5}$			5.0E-05	IF Calibration	80%	1E-05
	Mounting induced SB	Mechanical	Static	Typically 0.1 MPa	P [MPa]	0.1	6.7E-03	OG Calibration	90%	7E-04
	Temperature induced SB	Thermal	Dynamic	Typically 10 kPa/K	d(T) [K]	1	6.7E-05	IF Correction	50%	3E-05
	ARC induced SB	Thermal	Dynamic	Typically 10 kPa/K; Stokes U; via retardance	d(T) [K]	1	6.7E-05	IF Correction	50%	3E-05
Multiple order retarder	Misalignment crystal axis	Mechanical	Static	$P_S \sim \cos^2(2*a)$	d(a) [deg]	1	1.2E-03	OG Calibration	90%	1E-04
	Angle fast crystals axis	Mechanical	Static	Typically <2.5 arcmin	Angle [arcmin]	25	2.8E-04	OG Calibration	90%	3E-05
	Temperature dependence	Thermal	Dynamic	$d(\text{ret}) < 3 \times 10^{-4}$ when $d(T) = \pm 20$			2.0E-04	IF Calibration	80%	4E-05
Polarization beam splitter	Extinction ratio		Static	ext-rat: $<1 \times 10^{-4}$?			5.0E-04	OG Calibration	90%	5E-05
	Misalignment axis w.r.t. retarder	Mechanical	Static	$P_S \sim \cos^2(a)$	d(a) [deg]	1	6.1E-04	OG Calibration	90%	6E-05
	ARC induced SB	Thermal	Dynamic	Typically 10 kPa/K?	d(T) [K]	1	3.33E-05	IF Correction	50%	2E-05
Wire grid polarizer	Misalignment transmission axis	Mechanical	Static	$P_S \sim \cos^2(a)$	d(a) [deg]	0.2	2.4E-05	OG Calibration	90%	2E-06
	Misalignment axis w.r.t. retarder	Mechanical	Static	$P_S \sim \cos^2(a)$	d(a) [deg]	1	6.1E-04	OG Calibration	90%	6E-05
PMO overall	Stray light - ghost	Optical	Static	$<0.5\%$				OG Calibration	90%	5E-04
	Stray light - diffuse	Optical	Static	$<1\%$				OG Calibration	90%	8E-04

1.21E-03

FIG 11

INTERNATIONAL SEARCH REPORT

International application No
PCT/NL2020/050034

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01J3/447 G01J3/02
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01J

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	AALDERT VAN AMERONGEN ET AL: "SPeXone: a compact multi-angle polarimeter", ICSO 2018, INTERNATIONAL CONFERENCE ON SPACE OPTICS, 9-12 OCTOBER 2018, CHANIA, GREECE, 16 November 2018 (2018-11-16), pages 1-13, XP055630678, DOI: 10.1117/12.2535940 ISBN: 978-1-5106-3078-9 pages 4-6 pages 10, 12 ----- -/--	1-15



Further documents are listed in the continuation of Box C.



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Date of the actual completion of the international search

22 April 2020

Date of mailing of the international search report

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Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Schmidt, Charlotte

INTERNATIONAL SEARCH REPORT

International application No

PCT/NL2020/050034

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	VAN AMERONGEN AALDERT ET AL: "Spex the Dutch roadmap towards aerosol measurement from space", PROC. SPIE 10562, INTERNATIONAL CONFERENCE ON SPACE OPTICS, ICSO 2016, vol. 105620, 25 September 2017 (2017-09-25), pages 1-9, XP060093793, DOI: 10.1117/12.2296227 ISBN: 978-1-5106-1533-5 pages 4, 5 -----	1,5,6,8, 9,12,15
A	SNIK F ET AL: "Spectral modulation for full linear polarimetry", APPLIED OPTICS, OPTICAL SOCIETY OF AMERICA, WASHINGTON, DC; US, vol. 48, no. 7, 1 March 2009 (2009-03-01), pages 1337-1346, XP001522180, ISSN: 0003-6935, DOI: 10.1364/AO.48.001337 the whole document -----	1-15
T	KOKHANOVSKY A A ET AL: "Space-based remote sensing of atmospheric aerosols: The multi-angle spectro-polarimetric frontier", EARTH-SCIENCE REVIEWS, ELSEVIER, AMSTERDAM, NL, vol. 145, 28 February 2015 (2015-02-28), pages 85-116, XP029169424, ISSN: 0012-8252, DOI: 10.1016/J.EARSCIREV.2015.01.012 the whole document -----	1-15