DARE: Dedicated Aerosols Retrieval Experiment.

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ABSTRACT

At present there is an increasing interest in remote sensing of aerosols from space because of the large impact of aerosols on climate, earth observation and health. TNO has performed a study aimed at improving aerosol characterisation using a space based instrument and state-of-the-art aerosol retrieval algorithms, based on requirements for up-to-date regional and global aerosol transport models.

The study has resulted in instrument specifications and a concept design for aerosol detection from space.

Based on the study the main requirements for a dedicated aerosol spectrometer are: a spectral range from 330-1000 nm with a spectral resolution from 2 nm (UV) to > 30 nm (NIR), observation in at least 3 polarisation directions (Stokes parameters) over a field of view (FOV) in swath direction of > 114 degrees and observation in at least 3 viewing directions (backwards, nadir, forward).

The spectrometer design is a prism imaging spectrometer using a single detector array to measure the complete spectra for 2 polarisation directions. In this way the requirements for each viewing direction can be met with only 2 detector arrays. The system has a modular set-up, which makes the implementation of, for example, a change in the number of observation directions very simple.

The basic requirements to discriminate between aerosol types are currently only met POLDER, that combines multiple view angles with polarisation.

The DARE concept shows an attractive potential for the development of next generation aerosol sensors.

Keywords: Aerosol, detection, imaging spectrometer, earth observation

1. INTRODUCTION

There is an increasing interest in the detection of aerosols in the earth atmosphere for a variety of reasons.

In the first place there is an effect of aerosols on climate, which is one of the largest uncertainties in the climate system (ref: IPCC report 2001).In addition aerosols have a large influence on air quality and thus on health and finally aerosols play an important role in atmospheric chemistry. Satellite remote sensing of aerosols can provide daily global coverage with high spatial resolution.

Until now many (optical) sensors have been developed (or are being developed) for remote sensing from space of atmospheric composition. Instruments such as SCIAMACHY[1], GOME[2] and OMI[3] are primarily designed for detection of the chemical composition of the atmosphere such as ozone (see e.g. Global *Ozone* Monitoring Experiment, *Ozone* Monitoring Instrument), NO2, SO2, BrO, while other instruments, that are used for aerosol retrieval, such as ATSR were designed for SST retrieval. Also instruments such as MODIS and MISR, that were partly designed for aerosol retrieval lack polarisation information necessary to accurately retrieve information on non-spherical particles.

In Europe the only dedicated aerosol sensor until now is POLDER[4]. The sensor concept is based upon the application of polarisation filters and measurents in a number of spectral bands and at a range of observation angles.

NASA is planning now the development of a so-called Aerosol Polarimeter Sensor. This instrument is intended to fly aboard the national Polar Orbiting Environmental Satellite System from about 2010.

In the Netherlands TNO has performed a study called DARE (=Dedicated Aerosol Retrieval Experiment). The purpose of this study was to define the scientific and user requirements for an instrument for optimal retrieval of aerosols from Space[5]. This study has resulted in a concept instrument design that is described in this paper.

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2. AEROSOL DETECTION

The aerosols in the earth atmosphere have a large impact on the following aspects:

- Climate: at one hand the incoming short wave solar irradiation is scattered thus opposing the greenhouse effect, whereas absorbing particles such as soot cause warming; the absorbtion of outgoing long wave radiation also causes warming, thus reinforcing the greenhouse effect. In addition aerosols act as condensation nuclei and thus affect clouds and their albedo. Besides absorbtion of radiation effects the atmospheric circulation pattern. .
- Earth observation: the optical properties of aerosols have an influence on the accuracy of surface observation at EO wavelengths and need to be accounted for in atmospheric corrections.
- Health: aerosols have an influence on UV radiation at ground level, respiratory effects of dust, transport of pollutants and consequences for air and water quality.

It is very difficult to make an accurate, reliable prediction on the occurrence and effects of aerosols on regional and global scales.. Models are being developed, but the supply of accurate data on a daily basis and on a global scale is a primary condition for accurate prediction[6, 7]. Ground based observations provide local data for validation. Aeroplane measurements could provide maesurements on a larger scale, but these are too expensive to provide good temporal coverage.

Measurements from satellites are a cost effective method to provide on a routine basis accurate worldwide aerosol data. Until now many aerosol properties are retrieved from instruments that were designed for other purposes, such as measurement of ozone and water temperature.

The retrieval of aerosol properties is based on the intensity and spectral distribution of scattered light at the top of the atmosphere. These scattering properties depend on physical characteristics of the aerosol, such as chemical composition, refractive index, particle size and shape. Polarisation of the scattered light gives information about the shape of the particles, while from the wavelength dependence information on the aerosol size distribution can be derived. The polarisation properties of the scattered light are also angular dependent, which implies that observations of the scattered radiation at different angles gives extra information.

For optimum use of the polarisation information the three linear polarisation parameters are needed (the 3 Stokes parameters).

From these considerations the starting points for the design criteria of an optimal aerosol sensor are based on the measurement of polarisation properties of the scattered light at different angles and over a spectral range.

In the next chapter these starting points are elaborated until a set of instrumental requirements. The main goals of the TNO DARE study are:

1. Development of algorithms for retrieval of aerosol properties from space. This part of the study is presented in paper nr. 5235-44 of this conference[5].
2. Definition of instrument requirements for dedicated aerosol measurements from space and elaboration to concept instrument design.This part of the study is described in the following chapters of this paper.

3. INSTRUMENT REQUIREMENTS

The main instrument requirements of a space mission dedicated to aerosol retrieval are (Note that the instrument requirements as presented in table 3.1 are a compromise between all factors contributing to fulfilling the scientific goals and a feasible instrument):

1. ***Spectral range: 330 – 1000 nm***

   This is the Si detector range.

   The short wavelength ($\lambda < 400$ nm) is interesting because of increasing absorption of radiation by the aerosols. Extension of the spectral range to $\lambda = 1300$ nm would provide additional information on aerosol types, while a measurement at $\lambda = 1600$ nm can be used for elimination of land surface effects, analogue to the ATSR-2 retrieval algorithm.

2. ***Spectral resolution and spectral sampling distance***

   From a scientific point of view the requirement is a spectral resolution of < 5 nm in the spectral range of 400-500 nm, while for $\lambda > 500$ nm the spectral resolution can be relaxed. This has resulted in a (fused silica) prism spectrometer design with a spectral sampling distance ranging from about 1 nm in the UV, about 2.2 nm between 400 and 500 nm and up to about 15 nm at $\lambda = 1000$ µm.

3. ***S/N ratio***

   First calculations show, that the specified S/N ≥ 500 can be met without large problems.

4. ***Polarisation***

   For dedicated aerosol detection the measurement of the polarisation of the scattered radiation is necessary. In principle the 3 Stokes parameters (and thus the complete polarisation information) are determined by measuring the polarisation of the radiation in 3 directions (as mentioned e.g. 0°, +60°, -60°).
   In DARE two polarisation spectra are imaged on one detector, which implies, that at least 2 detectors are necessary, which can measure 4 spectra for each viewing angle. The preliminary choice for DARE is the measurement of 4 polarised spectra, one detector with 0° and 90° polarised spectra and the other one with + 45° and – 45° polarised spectra, although other combinations are also possible(e.g. 0°,+ 60°, -60° polarised spectra and one unpolarised spectrum)

5. ***Orbit type***

   For DARE two types of polar Low Earth Orbits (LEO) are considered:
   - Sun-Synchronous orbit, where the satellite passes over the same part of the earth at roughly the same local time each day.

     Orbit parameters: - Altitude: 710 km
     Inclination: 98.2°
   - LEO circular orbit with increased passing frequency over a target to be chosen.
     For example: target latitude 52°, longitude 6°.
     Orbit parameters: Altitude 710 km
     Inclination 115°
     Passage time to target up to 4 x / day

6. ***Viewing angles: 0°, +53°, -53°***

   Here some remarks can be made:
   1. The more angles the better. The drawback however, is that each additional observation angle makes the system more complex.
      In principle the added value of each extra observation angle must be balanced against the baseline requirement of 3 angles.
   2. The selection of the angles +53° and –53° is still under discussion. Both the value (53°) and the symmetry will be updated by evaluating the user's wishes w.r.t. the most interesting places on earth concerning aerosol monitoring (for example more emphasis on northern part of the earth globe with Europe and America, seasonal variation).
      The observation is nadir direction (angle 0°) is without discussion.

7. ***Spatial sampling in swath direction at nadir***

   The requirement is a nadir resolution on ground of 5-7 km. This implies a detector pixel size of 2.5-3.5 km (0.2-0.3°). Also this value is a compromise between the wish of the scientific users of a high spatial resolution with daily global coverage (so a fine spatial grid for their models) and a more moderate resolution for instrumental considerations. The specified resolution of 5-7 km is defined to be on ground, also for the oblique observation at 53°.

8. ***Field of view in swath direction: ≥ 114 degrees***

   A FOV of 114° makes a daily global coverage possible.
   The value is equal to the FOV of OMI.
   For DARE the OMI telescope configuration is used as starting point for the concept design.

9. ***Additional sensors***

   Additional information will increase the aerosol detection possibilities, but that a trade-off must be made between added value and sensor complexity (and thus development cost, mass, volume, etc.).

Two additional sensors have been considered:

- Cloud sensor
  This sensor is based on TIR detection (1 or 2 channels in the wavelength range of 10-12 µm with a nadir spatial resolution of about 5-7 km).
  Addition of this sensor is considered seriously. In the DARE study this sensor is not elaborated.
- LIDAR system
  This gives information on vertical distribution of aerosols. Because of the complexity, this system is not in the baseline.

These requirements are summarized in table 3.1

Requirement description	**Remarks**
Spectrometer requirements	
Spectral range 330-1000 nm	Si detector range.
Spectral sampling distance Varying from 1 nm in the UV until 15 nm at λ = 1000 nm	Between 400-500 nm the spectral resolution must be < 5 nm.
The signal to noise ratio S/N>500	
Polarization 3 Stokes parameters (e.g. 0°, +60° and –60°)	Corresponds to complete polarisation information
Observational requirements	
Orbit type Sun synchronous, altitude 710 km, inclination 98.7° or LEO, altitude 710 km, inclination 115°	AURA mission orbit type (OMI).
Observation angles 0°, +53° and -53°	Co-registration of the 3 measurements is needed.
Spatial sampling in swath direction at nadir A detector pixel = 0.2-0.3	Resolution should be 5-7 km on ground.
Scene Field of View ≥ 114° (OMI type telescope)	Results in a daily global coverage for latitude > equator.
Additional/optional sensor	
Cloud detection TIR detection (1 to 2 channels in the range λ = 10-12 µm with a spatial resolution of about 5-7 km on ground in nadir direction)	Considered. Not elaborated at this moment
Lidar information's on aerosol vertical distribution	Optional but not presently in the baseline

Table 3.1: Summary of DARE instrument requirements

4. DARE OPTICAL CONCEPT

4.1 Basic approach

For the instrument design of DARE the following starting points have been defined:

- DARE consists of 3 modules, one for every observation direction.
  Each module measures the same swath on earth (so each module has the same spectrometer, only the focal length of the telescope differs).
  Advantages of this modular approach:
  * similarity (development costs)

* flexibility (more observation angles → more modules, easy adaptation)

- DARE is an imaging spectrometer. This means, that on a 2-dimensional CCD detector array (e.g.512 x 512 detector elements) a spectrum of the spatial (swath) FOV is created.
  Because of the large spectral range (330-1000 nm) prisms are used as dispersive elements.
  In this way the problem of grating order overlapping is avoided, while a high optical efficiency over the entire spectral range can be obtained.
- To limit the number of detector arrays (calibrated space qualified detectors are cost drivers) on one detector 2 spectra with orthogonal polarisation are imaged. To determine the 3 Stokes parameters at least 3 polarised spectra are necessary. Each module contains 2 detectors so that each module measures (redundantly) 4 polarized spectra. The polarisation states of these spectra are chosen as:
  Detector 1: 0° and 90°
  Detector: 2: +45° and – 45°

A block diagram of the DARE spectrometer is given in figure 4.1.

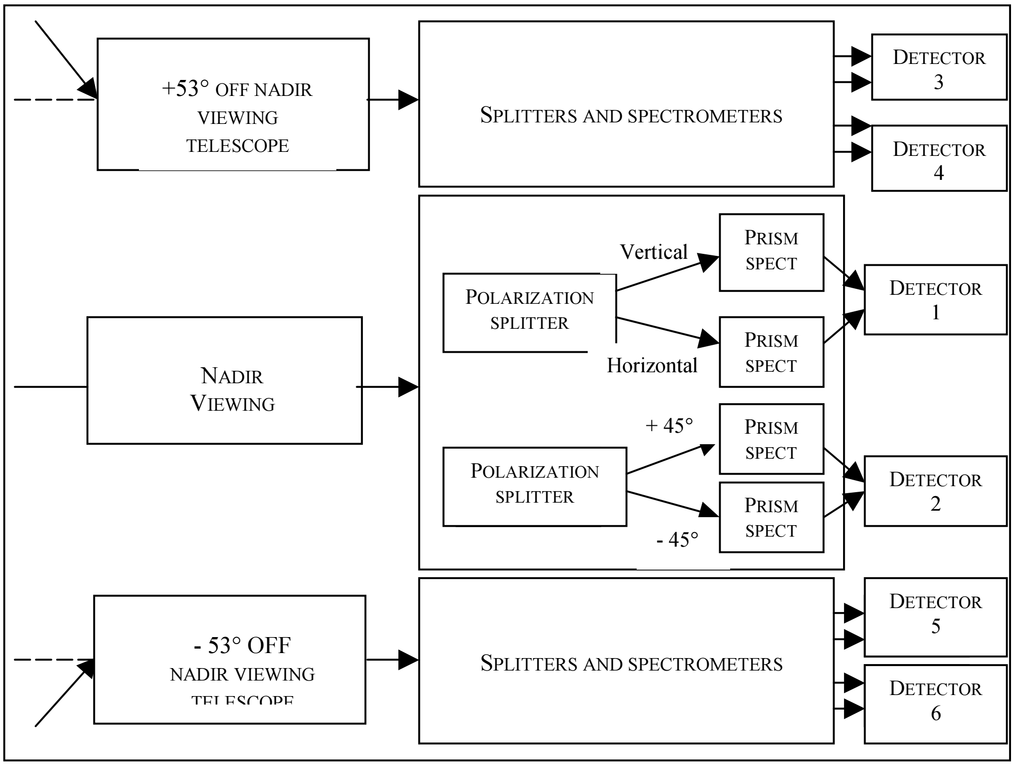

Figure 4.1: block diagram of the top-level DARE instrument concept.

Schematically the 3 modules, nadir viewing, +53° off nadir viewing and –53° off nadir viewing are presented. Each module consists of a telescope system, a “box” containing polarisation splitting elements, a (prism) spectrometer and 2 detector units.
In the nadir viewing module the parts inside the “splitters and spectrometer box” are indicated schematically.
In figure 4.2 the spectra on the detectors are indicated including the polarisation direction of the light. On detector 1 the 0° and 90° spectra of the whole FOV are positioned next to each other, on detector 2 the +45° and –45° spectra.

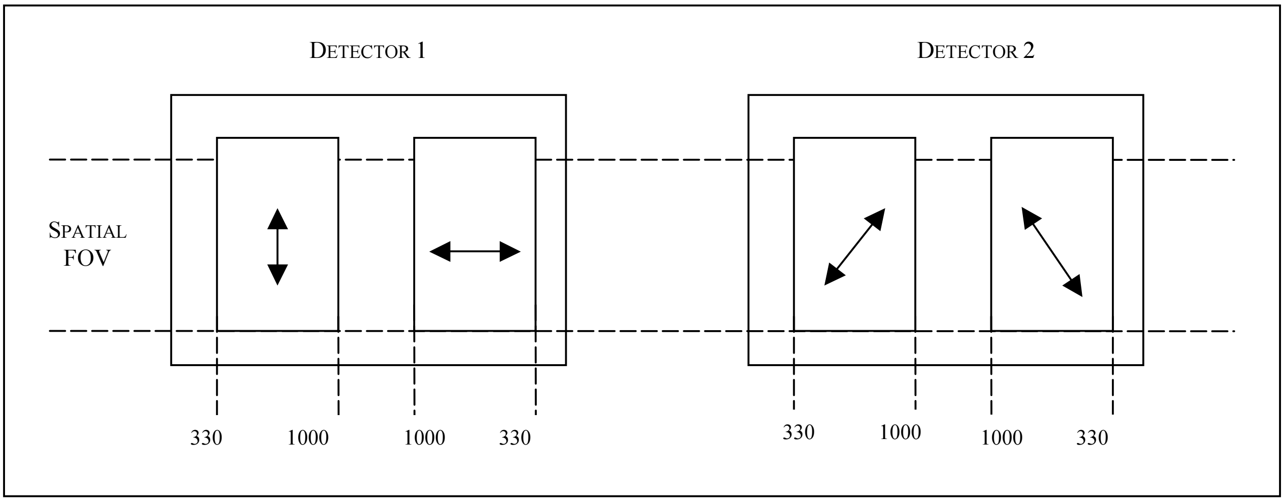

Figure 4.2 : DARE detectors. The arrows indicate the polarisation direction of the incident light

4.2 Optical system

From figure 4.1 is clear, that the optical train of each system consists of a telescope, a polarisation splitter, a prism spectrometer and a detector.

A concept optical design of this system has been made. Figure 4.3 gives the optical layout of the front optics telescope and and the beam splitting optics.

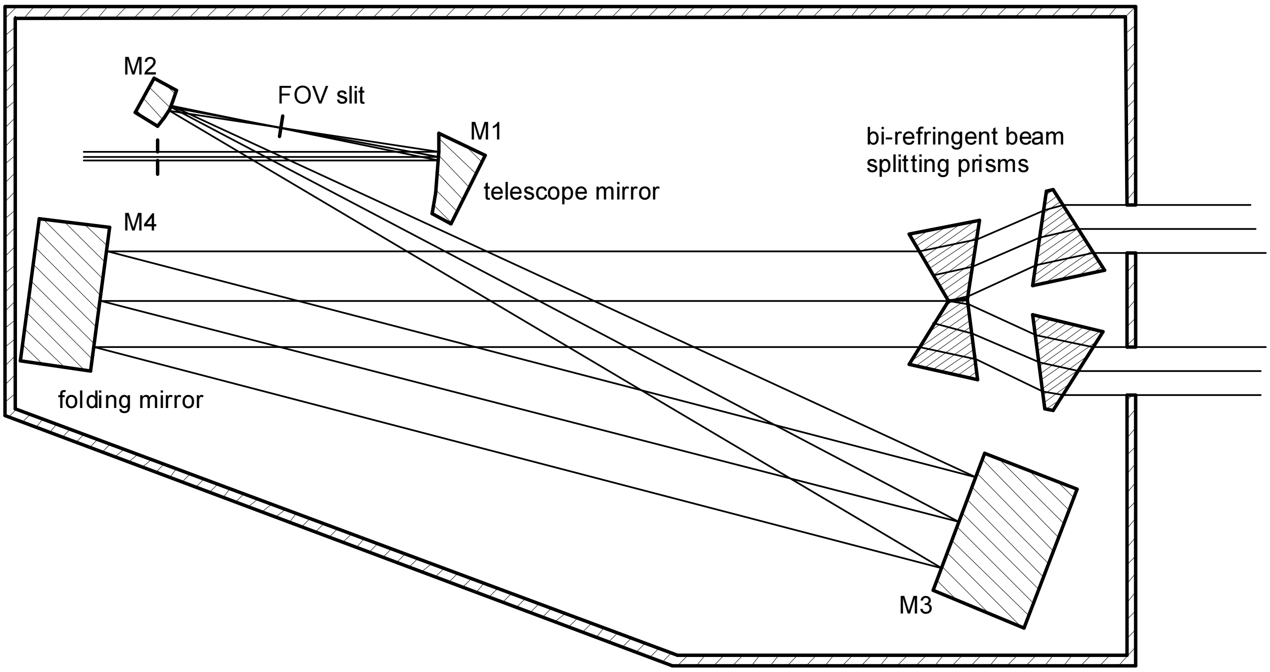

Figure 4.3: Telescope optics and beam splitting prisms

The front optics consists of a 3 mirror beamexpander (≈ 10x magnification). The first component M1 is a concave spherical telescope mirror (f = 36 mm). In the focal plane a curved FOV slit is positioned (≈ 0.25 x 75 mm^2), that defines the FOV (0.4 x114°). A convex second mirror M2 and a (slightly toroidal) concave third mirror M3 collimate the beam again with a total magnification of about 10x.
Because of the FOV in swath direction the shape of the mirrors is rectangular (e.g. the dimension of mirror M3 is ≈ 30 x 120 mm^2). Mirror M4 is only a flat folding mirror.

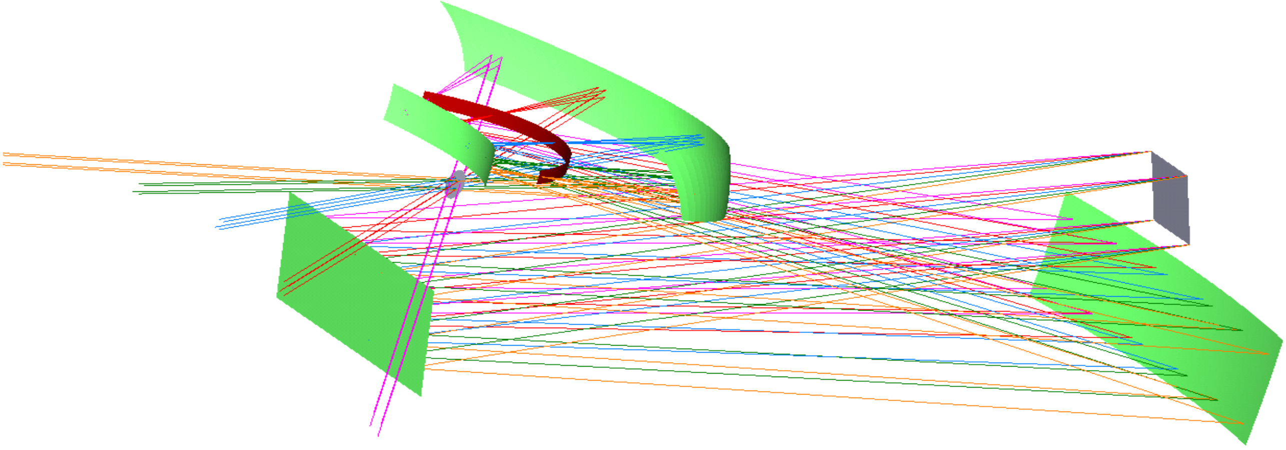

Figure 4.4: 3-D impression of the front optics

The collimated output beam has a dimension of 20x20 mm^2. With two sets of prisms the beam is split in two beams of 10x20 mm at a distance of 30 mm^2. The prisms are positioned in such a way, that the dispersion is compensated.
The material of each prism is bi-refringent quartz with the optical axis in such a way, that the output beam consists of 2 polarised beams (the so-called e and o beams with the polarisation at 0°/90° or +45°/-45°).
Behind each set of prisms a diaphragm (dimension 10 x 20 mm^2) is positioned at the location of the pupil image. These diaphragms are the actual pupil stops (the telescope entrance pupil is oversized). In swath direction the angular extent of the beams is about 12 degrees. In figure 4.5 the optical layout of the spectrometer is given.

At the image of each set of polarised beams a separation of these beams by a mirror edge takes place and both beams are folded, collimated, directed to a set of dispersing prisms and imaged on 1 detector. In this way with high efficiency, two spectra with orthogonal polarisation are imaged on a single CCD detector array.
The second set of beams (through the other pupil image) is separated, dispersed and imaged in the same way on a second CCD detector array.

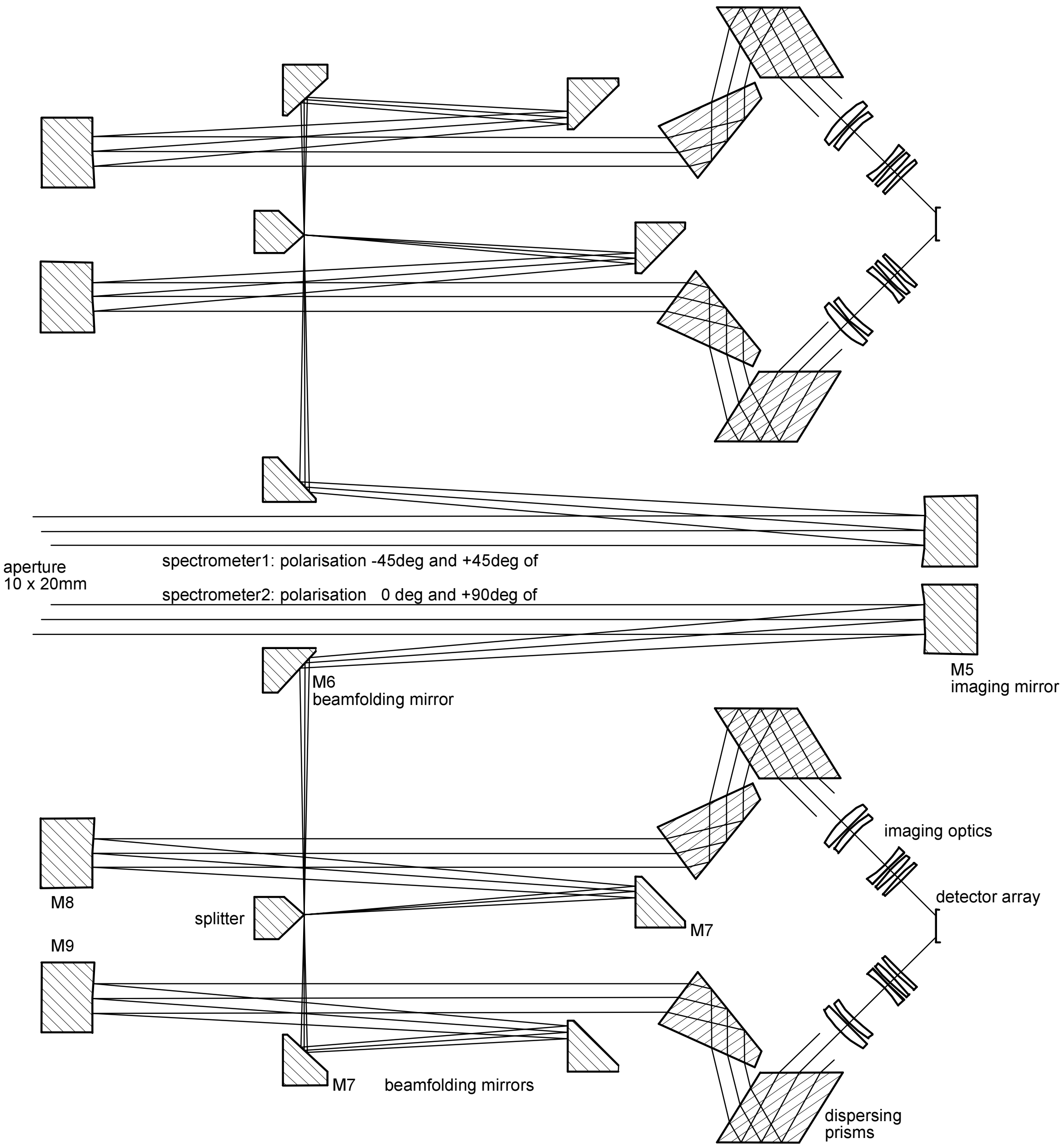

Figure 4.5: Concept spectrometer layout

Some data of the spectrometers:

- FOV:	0.4° x 114° (entrance slit width = 5 km on ground at nadir)
- Detector:	CCD with 512 x 512 pixels
- Spectrum:	436 (swath direction) x 176 (spectral direction) pixels
- Two spectra on one detector:	(0°/90° and +45°/-45° polarisation directions).
- Spectral sampling distance:	0.95 nm/pixel (330-360 nm) until 12 nm/pixel (800-1000 nm)

- Spatial resolution at nadir: 7x7 km^2
- S/N at 450 nm (albedo ≈ 0.1): 1100 (1 sec integr.)
- Dimension of telescope-spectrometer module: ≈ 500 x 500 x 150 mm^2

5. AEROSOL SENSOR COMPARISON

As already mentioned in chapter 2 many atmosphere sensors are used to retrieve aerosol properties. In table 5.1 the specifications of a number of sensors with respect to the requirements as presented in chapter 3 are given.
NB: The planned NASA Aerosol Polarimeter Sensor is not included in the table survey.

Name	Orbit type – (satellite)	Swath (km)	Spatial resolution at nadir (km)	Spectral range (nm)	Global coverage	Polarization detection
ATSR-2	Sun Synchronous (ERS 2)	500	1 x 1	VIS + NIR + TIR	3 days	No
AVHRR	Sun Synchronous (NOAA)	≥ 2400	1.1 x 1.1	VIS + NIR + TIR	1 day	No
GOME	Sun Synchronous (ERS 2)	960	320 x 40	240 – 790	3 days	Partial
MERIS	Sun Synchro (ENVISAT)	1150	0.26 x 0.3	390 – 1040	3 days	No
MISR	Sun Synchronous (Terra)	360	0.275 x 0.275	VIS + IR	9 days	No
MODIS	Sun Synchronous (Terra)	2330	0.25 x 0.25	400 - 14500	1 to2 day	No
OMI	Sun Synchronous (Aura)	2600	13 x 24	270 - 500	1 day	No
POLDER	Sun Synchro (ADEOS)	1140 x 2200	7 x 6	VIS + NIR	1 day	Yes
SCIAMACHY	Sun Synchro (ENVISAT)	960	32 x 16	240 - 2380	3 days	Yes
TOMS	Sun Synchro (ADEOS)	2795	50 x 50	UV	1 day	No
DARE	Sun Synchro or Polar LEO	≥ 2200	7 x 7	330-1000 + TIR	1 day or 2 to 4 per day	Yes

Table 5.1: Atmosphere sensors: comparison of detection properties

From this table the following can be remarked:

1. Most sensors for earth observation are far from optimal w.r.t. aerosol sensing. Especially detection properties such as polarisation detection and observation at different angles to determine physical characteristics of aerosols (particle size, shape and refractive index) are absent.
2. The only dedicated aerosol sensors are POLDER and DARE.
   POLDER and DARE are different concepts with some clear differences:
   - DARE is an imaging spectrometer (continuous spectrum from 330-1000 nm, no moving parts, spectral co-registration).
     POLDER is a filter spectrometer (2 dim. image in discrete spectral bands, filter wheel, no spectral co-registration).
   - The spectral range of POLDER is VIS/NIR, DARE also covers the important UV spectral range.

6. CONCLUDING REMARKS

In the DARE study the scientific and instrument requirements for dedicated aerosol detection from space have been defined.

Based on these requirements a concept design of an aerosol sensor has been made.

This concept is based on a modular approach, which makes extension to more observation directions easily possible.

The DARE concept shows an attractive potential for the development of next generation aerosol sensors.

The next step will be the development of a so-called Demonstration Model for on ground/airborne measurement of aerosols. Herewith the performance of the DARE concept can be optimized for the development of a future space sensor.

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