Absolute Radiometric Calibration Facility

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ABSTRACT

For earth observation instruments accurate on ground calibration is necessary to characterize sensor parameters, that are used for the in orbit calibration.
TNO Institute of Applied Physics has developed an absolute radiometric calibration facility for the calibration of both complete instruments and diffusers.
The facility operates in the wavelength range of 240-2400 nm. It incorporates an especially designed spectral irradiance source and a so called Brewster polarisation. For accurate diffuser calibration a detector assembly is developed.
In this paper the calibration facility with its features is described in some detail and a few calibration results are given.

Keywords: Calibration, Radiometric calibration, Sensor calibration, Absolute calibration facility, Diffuser calibration.

1. INTRODUCTION

During the last decennia a large number of satellite based instruments for observation of the earth in the optical domain has been developed. This development has started with instrumentation for observation of the land- and sea-surface, while at this moment especially in Europe much attention is paid to monitoring of the earth atmosphere. In this respect instruments like GOME [1] (= Global Czone Monitoring Experiment), SCIAMACHY [2] (- SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) and OMI (= Ozone Monitoring Instrument) can be mentioned.

With these instruments the global distribution and abundance of trace gases in the atmosphere (e.g. Ozone) are or will be measured using the light scattered by the earth surface or the earth atmosphere. From measurements performed during several years small changes must be determined in order to make reliable predictions about long term changes of the atmosphere. This requires from the instrumentation an accurate and reliable performance in space during many years. To achieve this an accurate calibration both on ground and in orbit is necessary. The purpose of the on ground calibration is to establish a data set of instrument parameters which enables the level 0 to 1 data processing with the best possible accuracy. In-flight calibration is necessary to update the calibrated instrument parameters at regular intervals during the mission.

For the pre-flight determination of the instrument parameters TNO Institute of Applied Physics has developed an Absolute Radiometric Calibration Facility (ARCF). The ARCF can be used for the calibration of diffusers and complete instruments in the spectral range of 240 - 2400 nm. The facility has already been used for the calibration of GOME and is being improved/extended now for the calibration of other sensors.

In the following chapters some aspects of the ARCF are described in more detail.

2. BACKGROUND

The calibration of the above mentioned optical instruments is in principle the determination of the relation between the incoming radiation and the detector signal (output). Not considering the verification of paraxial properties (focal length, dispersion etc.), instrument calibration on ground consists of:

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- Wavelength calibration.
- Radiometric calibration.
- Spatial calibration (= location of every detector pixel within the field of view).

In orbit only wavelength and radiometric calibration are performed.
Spatial calibration i.e. the determination of the FOV and the line of sight of each detector pixel is performed on ground. For this calibration generally a collimated test beam and an accurate turn-tilt table are sufficient.
Wavelength and radiometric calibration is described in some more detail hereafter.

Wavelength calibration

For wavelength calibration a number of tools can be used, such as:

- Spectral line sources (e.g. hollow cathode lamps) that generate a number of sharp emission lines at well defined wavelengths. These can be used both at pre-flight and in orbit condition.
- Broad spectral sources like a Xenon lamp or a Tungsten-Halogen lamp in combination with a monochromator (for preflight calibration).
- Filters with sharp transmission features (e.g. Holmium or Didymium filters).
- Fraunhofer line detection, to be used when the spectral resolution is large enough.

Radiometric calibration

More difficult is the radiometric calibration, especially when a high absolute accuracy is required.

The problem is simplified in fig. 1.

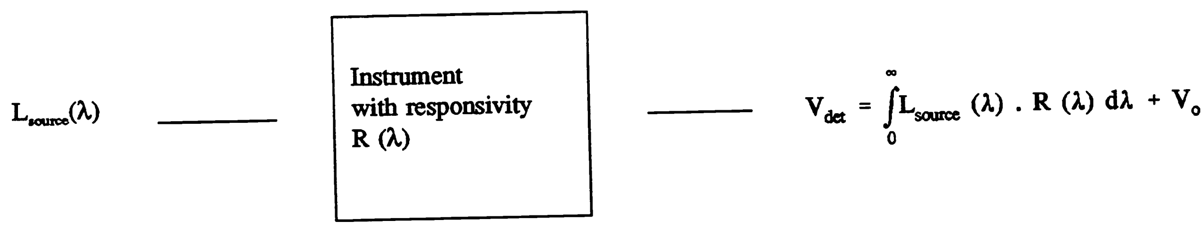

fig. 1.
Response of instrument to incoming radiation

$L_{source}(\lambda)$	=	Spectral Radiance from the object at the entrance pupil at the instrument.
$R(\lambda)$	=	Responsivity of the instrument
V_{det}	=	Detector output signal (e.g. in Volts)
V_o	=	Background signal of the detector when $L_{source}(\lambda) = 0$ (dark current).

When the instrument is a spectrometer and the spectral bandwidth of every detector element is small the relation between signal and radiance becomes:

$$V_{el,\lambda} = L_{source}(\lambda) \cdot R_{el,\lambda} \cdot + V_o \quad [1]$$

where: $V_{el,\lambda}$	=	Output signal of detector element which detects wavelength λ.
$R_{el,\lambda}$	=	$R'_{el,\lambda} \cdot \Delta\lambda$
$R'_{el,\lambda}$	=	Instrumental responsivity of detector element for wavelength λ ($v/W/cm^2$ sr)
$\Delta\lambda$	=	Spectral bandwidth of a detector element

On earth the responsivity $R_{el,\lambda}$ of the instrument is calibrated for each detector element

V_o being known $L_{source}(\lambda)$ can be determined directly from the detector signal $V_{el,\lambda}$

However in space $R_{el,\lambda}$ changes due to the influence of the environment and therefore has to be determined at regular intervals using an absolute reference source.
This reference source can be a (preflight) calibrated diffuser, that is irradiated by the sun. In this way the radiance of the earth (irradiated by the sun) is compared with the radiance from the diffuser (also irradiated by the sun).

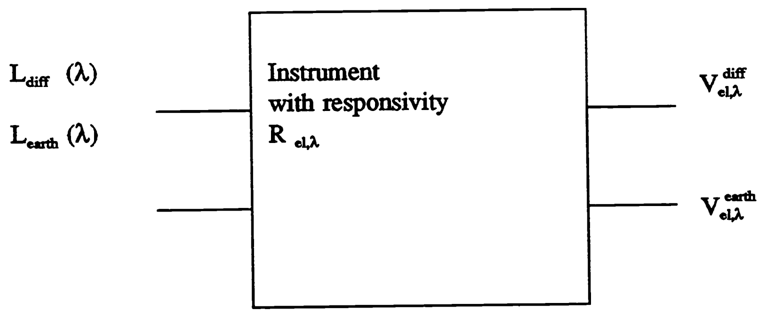

fig. 2.
Response in space to earth and diffuser radiation

This leads to:

$$V^{earth}_{el,\lambda} = L_{earth}(\lambda)\, R_{el,\lambda} + V_o = BSDF_{earth}(\lambda) \cdot E_{sun}(\lambda) \cdot R_{el,\lambda} + V_0 \quad [2]$$

$$V^{diff}_{el,\lambda} = L_{diff}(\lambda)\, R_{el,\lambda} + V_o = BSDF_{diff} \cdot (\lambda) \cdot E_{sun}(\lambda) \cdot R_{el,\lambda} + V_0 \quad [3]$$

$BSDF_{earth}(\lambda)$ = Bidirectional Scatter Distribution Function of the earth
$BSDF_{diff}(\lambda)$ = Idem of the diffuser
$E_{sun}(\lambda)$ = Spectral irradiance of the sun

From [2] and [3] can be derived:

$$L_{earth}(\lambda) = L_{diff}(\lambda)\, \frac{V^{earth}_{el,\lambda} - V_o}{V^{diff}_{el,\lambda} - V_o} \quad [4]$$

or

$$BSDF_{earth}(\lambda) = BSDF_{diff}(\lambda) \frac{V^{earth}_{el,\lambda} - V_o}{V^{diff}_{el,\lambda} - V_o} \quad [5]$$

There are two conditions for this type of radiometric calibration:

1. The optical properties of the diffuser must be known (Bidirectional Scatter Distribution Function (BSDF), to be determined on ground).
2. The degradation of reflectance of the diffuser must be monitored in space.

This relatively simple model for radiometric calibration in space is valid as long as polarisation effects of the incident radiation are neglected or the instrument responsivity R(λ) is polarisation independent. In this case theoretically an accurate calibration of the diffuser is sufficient to compare the measurement of the (diffuse) earth radiation with the (diffuse) solar reference source and to translate the detector output to the incoming radiation.
Actually when using sun-normalized measurements expressed by Eq. 5 knowledge of the instrument responsivity R (λ) is no longer needed to determine the BSDF of the earth, the latter being the quantity we are interested in.

However, radiation from the atmosphere generally is polarized, the degree of which depends on several factors like direction of observation and solar irradiation. The degree of polarisation cannot be predicted. When at the same time the transmission of the instrument is sensitive to polarisation (due to non perpendicular reflections, dichroics, gratings etc.) an unambiguous and accurate determination of the relation between incoming radiance and detector signal is very complex. It implies that the instrument should contain a device capable of measuring the polarisation of the incident radiation as a function of wavelength. Therefore instrumental parameters must be determined on ground, while offering the instrument a test beam with a linear polarisation in different directions. An analysis of this problem is given in ref. [3] and [4]

For the calibration of an instrument it requires an extensive measurement of many instrument parameters to translate correctly detector signals to level 1 data.

Therefore a facility for preflight calibration of optical sensors for earth observation must have the following possibilities:

1. Wavelength calibration within the spectral range of interest.
2. Radiometric calibration within the spectral range of interest and for different polarisation modes.

The ARCF offers these possibilities for a spectral range of 240 - 2400 mm. With the ARCF both complete instruments and diffusers can be calibrated in a class 100 clean room environment.

3. DESCRIPTION OF THE ARCF

3.1 Introduction

The calibration facility at our Institute consists of the following parts:

- Light Sources

  This contains a spectral irradiance source (monochromator + collimator) and a polarized white light source.
- Mechanical set up

  This includes a rotation assembly for irradiation and detection at various angles.
- Detector assembly.

These parts are described in detail hereafter. The ARCF is located in a class 100 clean room facility. For accurate characterisation of diffusers the suppression of straylight (the integrated reflection from the walls of the room or other parts in the vicinity of the diffuser) is very important. Therefore the calibration room in painted with black Electrodag paint. The ARCF is used for calibration at room temperature (20°C $\pm$ 1°C) and at a humidity level < 60%.

3.2 Light Sources

An outline of the spectral irradiance source is given in fig. 3. It consists of a lamp, a device for correction of the rest polarisation of the output beam, a subtractive double prismmonochromator and optical components for imaging and collimating.

The lamp (1) can be a 450W Xenon lamp or a 250W Tungsten-Halogen lamp. With lens (2) of fused silica the radiation of the lamp is collimated. In the collimated beam two plane fused silica plates (3) can be adjusted in angle to compensate for the polarisation, that is introduced by the optical system. By proper adjustment the polarisation of the collimated output beam is reduced to a negligible level. With lens (4) the beam is made divergent again. The negative lens of fused silica compensates for the aberrations of lens (2). With concave mirror (5) the lamp is imaged on the entrance slit (6) of the spectrometer.

The monochromator consists basically of two curved prisms. The first prism (7) creates a spectral image of the entrance slit on adjustable an intermediate slit (8). Using a computer controlled scanner mechanism the wavelength and the spectral bandwidth of the transmitted beam can be selected. The dispersion of the first prism (7) is compensated by the second prism (10), which creates a spectrally compensated, stigmatic reimage of the entrance slit on the exit opening (11) of the spectrometer. Finally the exit beam is collimated by a spherical mirror (13).

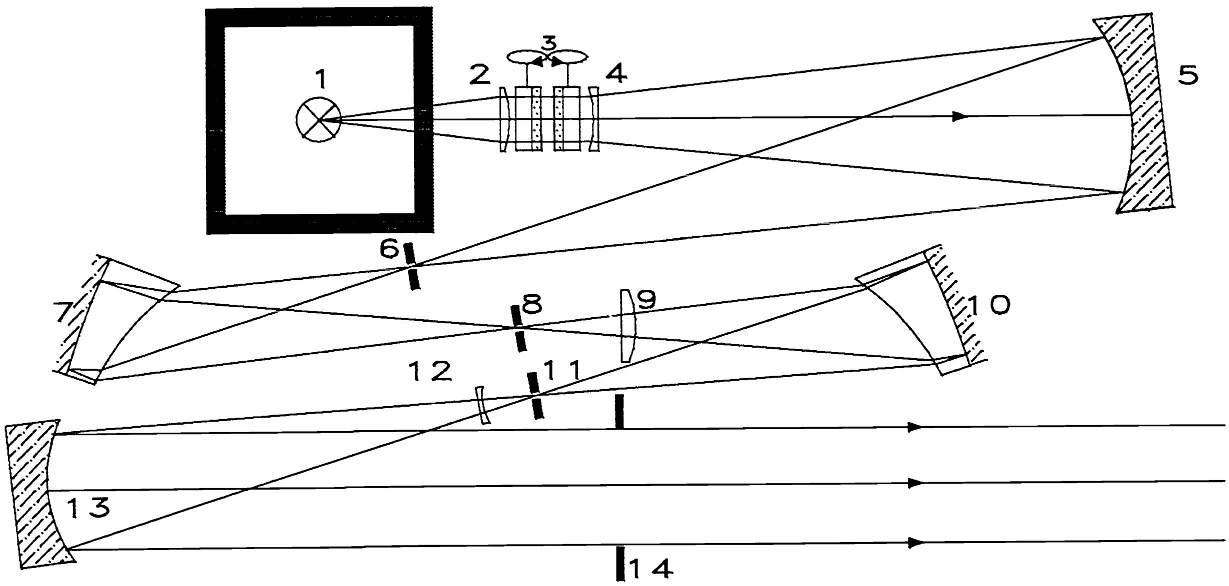

fig. 3.
Schematic of spectral irradiance source

The main characteristics of this source are:

Spectral range: 240 - 2400 nm.
Bandwidth: adjustable:
$\lambda = 350$ nm $\Delta\lambda_{min} = 3$ nm
$\lambda = 600$ nm $\Delta\lambda_{min} = 9$ nm
$\lambda = 1000$ nm $\Delta\lambda_{min} = 29$ nm
Output beam:

- Diameter $\varnothing = 50$ mm
- Divergence < 0.5 °
- Non uniformity within $\varnothing = 30$ nm $< 2\%$
  within $\varnothing = 50$ nm $< 5\%$
- Rest polarisation: $< 2\%$
- Flux density: $> 10^{10}$ photons/nm.s.cm^2
  (Xenon lamp)

Remarks:

- All transmission optics is manufactured from Suprasil 311. Compared to Suprasil 1 or Suprasil 2 the transmission at $\lambda = 2.2$ µm is superior.
- The used Xenon lamp is Hamamatsu Super Quiet Xenon Lamp with a rather smooth spectral output over the 200 - 710 nm spectral range.
  The Tungsten-Halogen lamp is spectrally smooth over the entire spectral range.
- For operation the intermediate slit is computer controlled. By adjusting the position and the width of the slit the spectral range of the beam can be selected.

The ARCF contains a second source for calibration, the polarized white light radiance source. As explained in chapter 2 the characterisation of sensor parameters for different polarisation of incoming radiation is very important.

An outline of the polarized white light source is given in fig. 4.

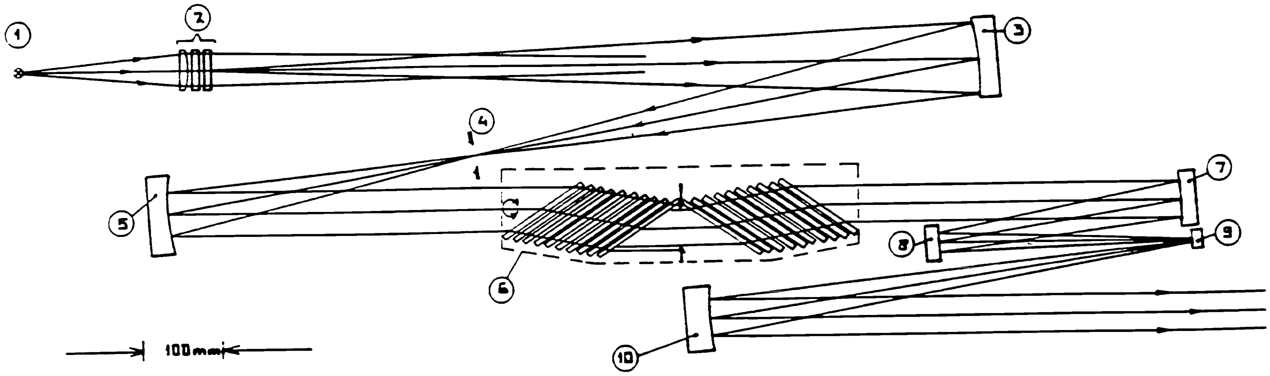

fig. 4.
Polarized white light source

It consists of a lamp, a transmission diffuser assembly, imaging and collimating optics and a special developed Brewster polarizer.

For the lamp the same 450W Xenon or 250W Tungsten-Halogen lamp as used for the spectral source is taken. This light source illuminates a transmission diffuser assembly (2), that consists of a (fused silica) lens and a diffuser to make a homogeneous light source for the polarizer.

Concave mirror (3) images the diffused source on an aperture opening (4), that acts as an extended homogeneous radiance source. With mirror (5) the radiation from this source is collimated and directed to the polarizer. This Brewster plate polarizer (6) is especially designed for the large spectral range (240 - 2400 nm). It consists of 20 plates of fused silica, that are positioned at the Brewster angle, so that almost complete linear polarisation is obtained at all wavelength simultaneously. The degree of polarisation of the transmitted beam is > 98%.
The Brewster polarizer is designed symmetrically in order to keep the incoming and outgoing beam in line. The consequence is, that the polarizer can be rotated around the optical axis, while the position (and direction) of the output beam remains the same. In this way the direction of the (linear) polarisation of the output beam can be varied in any desired direction. If unpolarized white light is required the Brewster plate polarizer is simple removed.

In fig. 5 the realized Brewster plate polarizer is presented. The mounting is supplied with a special coating, that has a low reflectance over the whole spectral range.

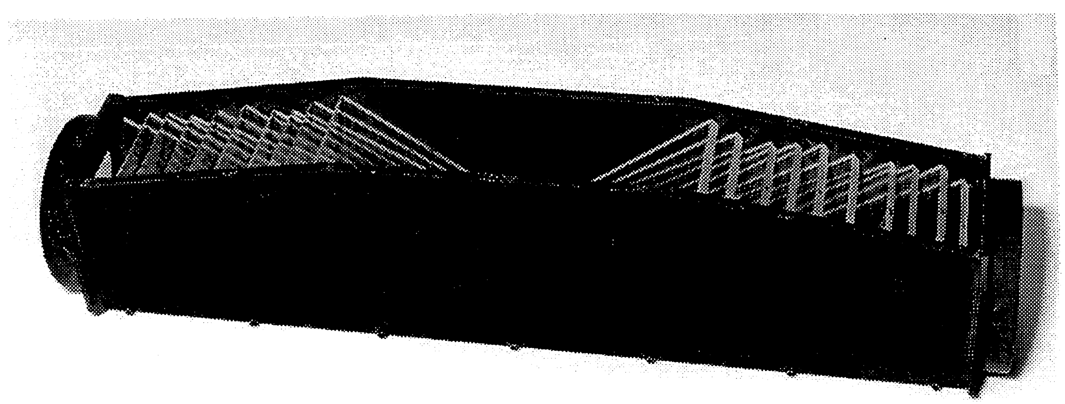

fig. 5.
Brewster plate polarizer

Behind the polarizer a 4 mirror system reimages the pupil of the beam to a suitable location outside the optical configuration. Here the entrance pupil of the sensor to be calibrated can be positioned.

Some characteristics are:

Wavelength range:	240 - 2400 nm
Transmission of Brewster polarizer:	> 25%
Output beam:	
- Diameter:	Ø = 50 mm
- Non uniformity	< 1%
- Degree of polarisation:	> 98%

Remarks:

- The field of view (FOV) of the configuration can be varied by changing the dimension of the aperture opening (4). In practice the FOV is limited to a few degrees.
- The rotation of the Brewster polarizer, and therefore the direction of the (linear) polarisation of the collimated output beam is computer controlled.

3.3 Mechanical set up

The mechanical set-up is schematically presented in fig. 6.

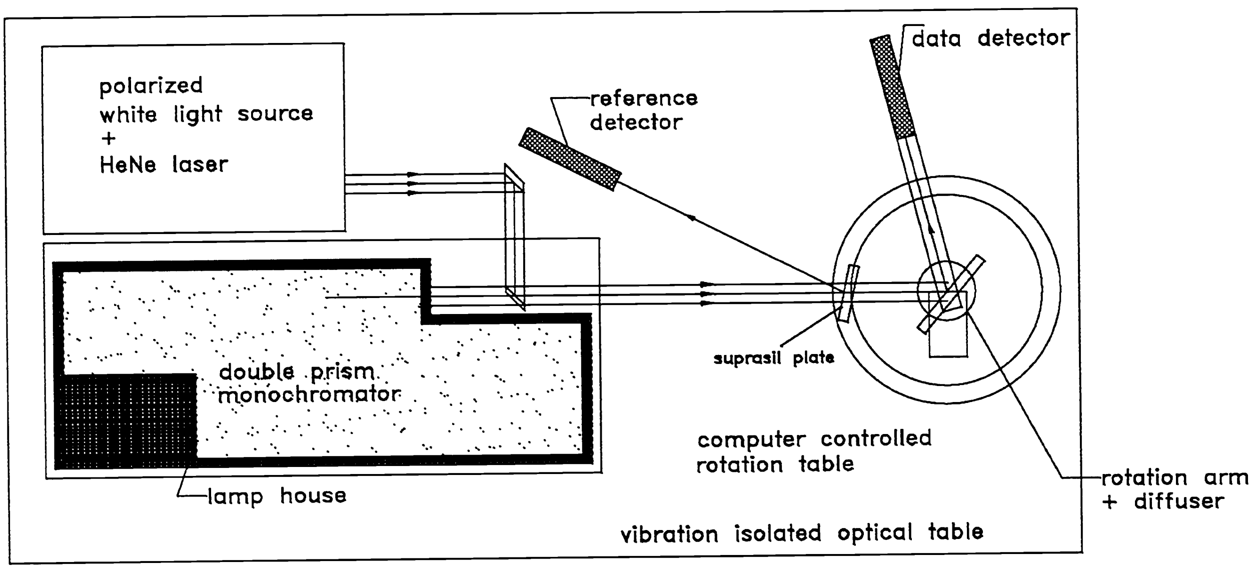

fig. 6.
Mechanical set-up of the ARCF

It consists of the following parts:

- A vibration isolated optical table top (1.5 x 3.75 m^2).
  The table top is both vertically and horizontally isolated and selflevelling.
- A housing with the lamps.
- A small table with the spectral irradiance source and the polarized white light source.
- A rotation table for diffusers or other samples to be measured.

The diffuser can be rotated over 3-axis and translated in one direction:

- X-axis ± 90°
- Y-axis ± 90°
- Z-axis (normal to diffuser): ± 45°
- Translation: ± 85 mm.

The detector is mounted on an arm, that can be rotated in the horizontal plane over an angle ± 180°. With this set-up diffusers can be measured at all orientations.

As already mentioned the set up is located in a clean room, that is painted completely black. In this room there is enough space near the table top to locate a complete instrument that has to be calibrated. Adjacent there is a separate data acquisition room.

3.4 Detector assembly

Especially for the diffuser calibration in the spectral region of 240 - 2400 nm a detector assembly is developed. At the ARCF two of these detectors are used, one for the actual measurements and one serving as reference detector.

The optical lay out of this detector is given in fig. 7. It basically consists of an entrance aperture (Ø = 25 mm), an imaging mirror, an exchangeable field of view opening and a detector module.

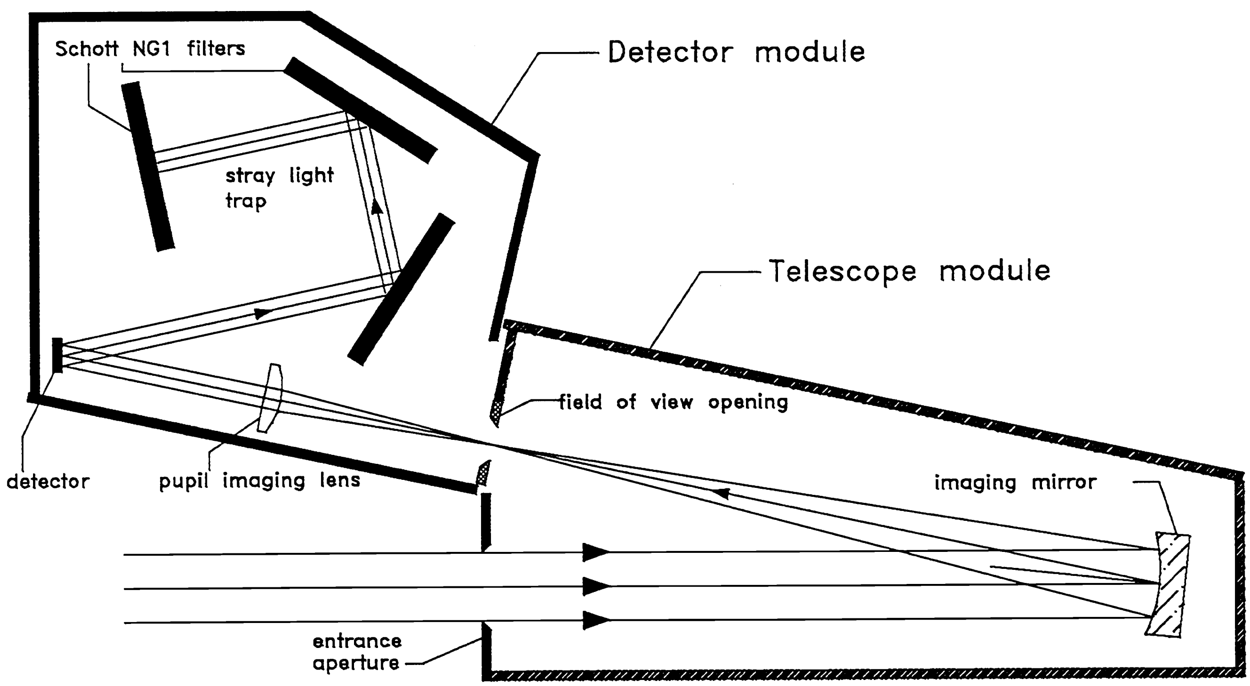

fig. 7.
Schematic view of detector assembly

The telescope part has a very well defined aperture and FOV. The detector part consists of a pupil imaging lens (Suprasil 311) and a detector.
To cover the whole spectral range from 240 - 2400 nm 3 different types of detector can be used:

- 240 nm - 1000 nm Si
- 950 nm - 1600 nm InGaAs
- 1000 nm - 2400 nm PbS

The detector surface is positioned 12° off-axis. A stray light trap captures the light, that is reflected by the detector. The detector assembly is also supplied with a mechanical position system, with which it can be rotated around 3 axes for accurate positioning. Both radiances and irradiances can be measured accurately. The realized assembly is pictured in fig. 8.

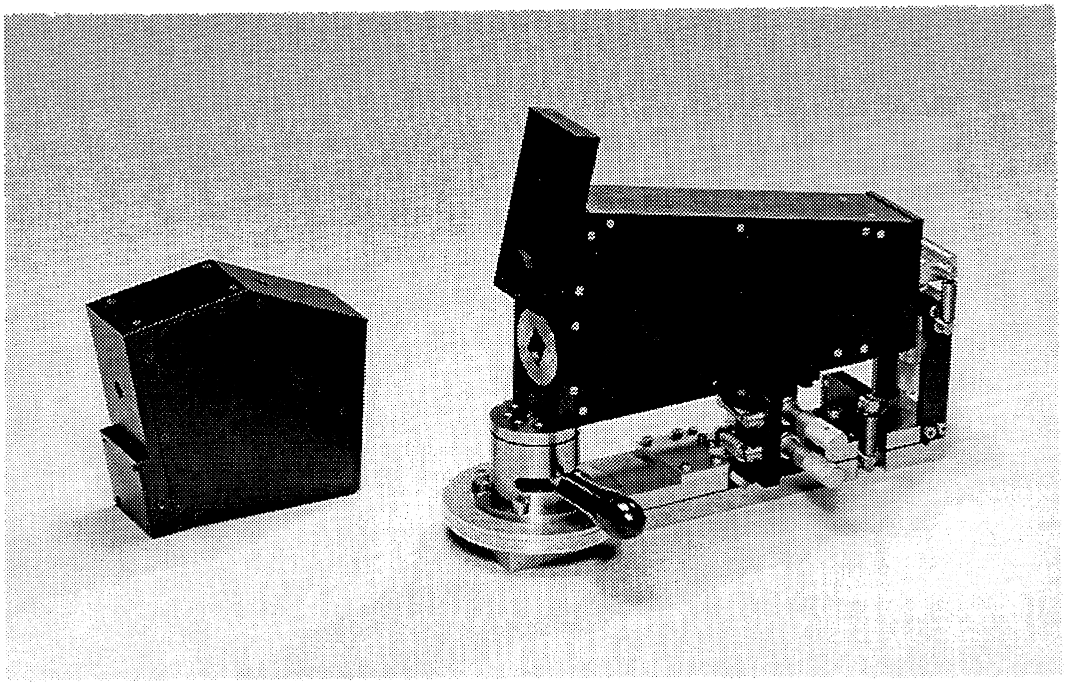

fig. 8.
Detector module (left) and telescope module (right) with adjustment device

3.5 Miscellaneous

Besides of these main parts, that are described more extensively above the ARCF contains a number of other optical/mechanical components, including:

- Standard lamps:
  1. NIST calibrated 1000W FEL Lamp.
  2. NIST calibrated 30W Deuterium Lamp.
- Standard detectors:
  1. UDT type UV 100 (NIST calibrated).
  2. Newport (NIST traceable).

These are used as standards for absolute calibration.
Moreover the facility contains lasers (HeNe), beam expanders, radiometers and of course computers for control, data acquisition and handling.

4. Experimental results

In this section we will present a few results, which are obtained using the calibration facility described above. Here we will focus on results related to the calibration of the GOME [5,6] (Global Ozone Monitoring Experiment) instrument, which was calibrated at TPD and recently launched on the ERS-2 (European Remote Sensing) satellite.

GOME is a 4 channel (grating) spectrometer measuring ozone profiles in the atmosphere from space. The spectral range of GOME is from 240-780 nm. The instrument is supplied with an onboard aluminium diffuser for calibration in space.

Fig. 9 shows an example of a Bidirectional Scatter Distribution Function (BSDF) of a Spectralon diffuser, which was measured using the monochromator, rotation table set-up and detector devices described in section 3. The angle of incidence and detection are 0° and 52.3°, respectively.

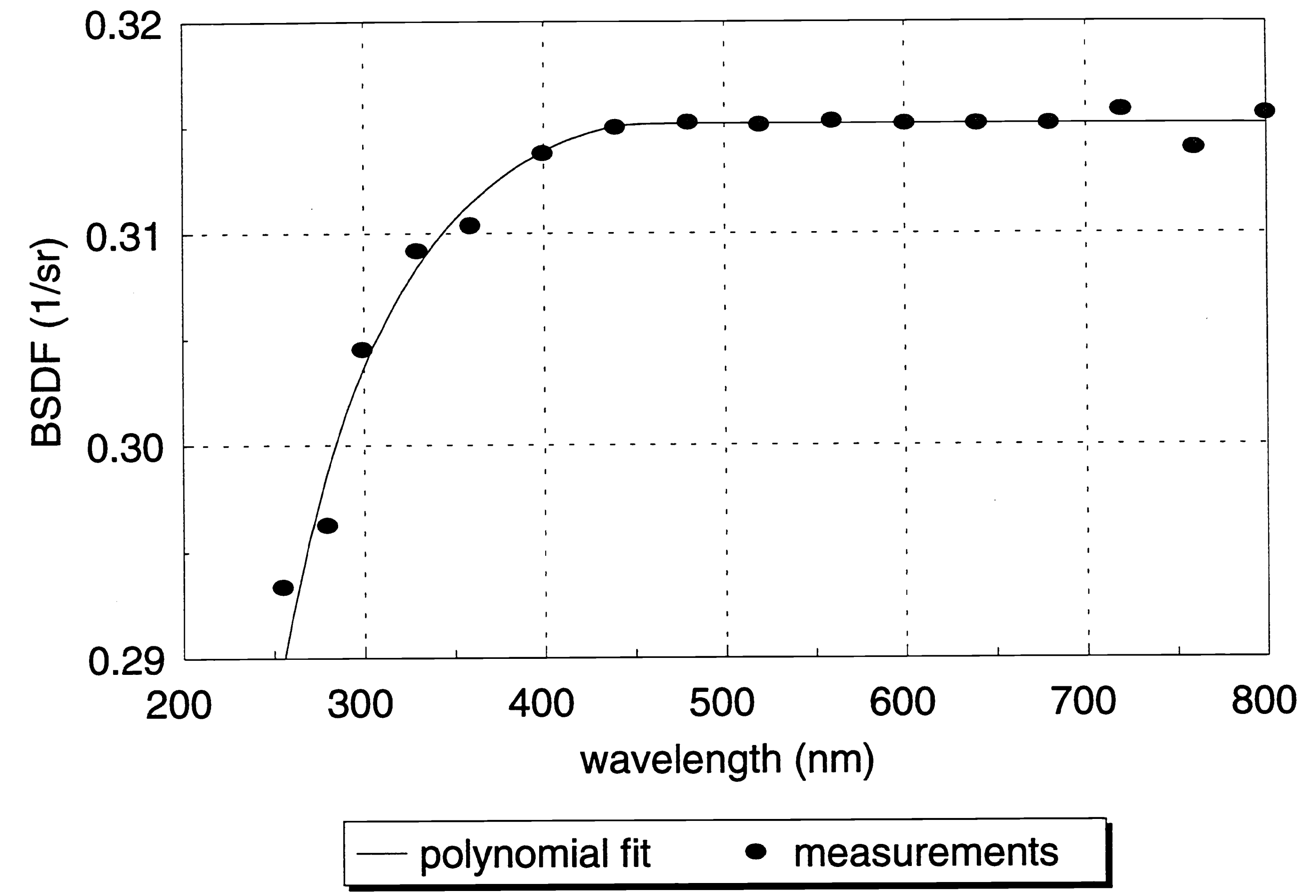

fig. 9.
BSDF of a Spectralon diffuser which was used for calibrating the radiance responsivity of the GOME instrument. The angle of incidence and detection are 0° and 52.3°, respectively

This particular Spectralon diffuser was used with the same geometry during the GOME calibration campaign to create, in combination with a NIST calibrated FEL (tungsten-halogen) lamp, a known radiance source. In order to establish a common radiometric scale between GOME and the USA instruments SBUV/2 (Solar Backscatter UltraViolet) and SSBUV (Space Shuttle Solar Backscatter UltraViolet), the NASA radiance source used for the calibration of the latter two instruments has been brought to TPD to be used on the GOME Flight Model. The NASA radiance set-up consists of an integrating sphere, corresponding light sources, a NIST calibrated FEL lamp and a diffuser, which does not have to be calibrated [7]. The GOME radiance calibration functions obtained by using the TPD radiance standards and by using the NASA standards are in excellent agreement as can be seen in fig. 10. The small differences in the oscillatory structures observed below 400 nm are due to a varying etalon effect of the GOME detectors.

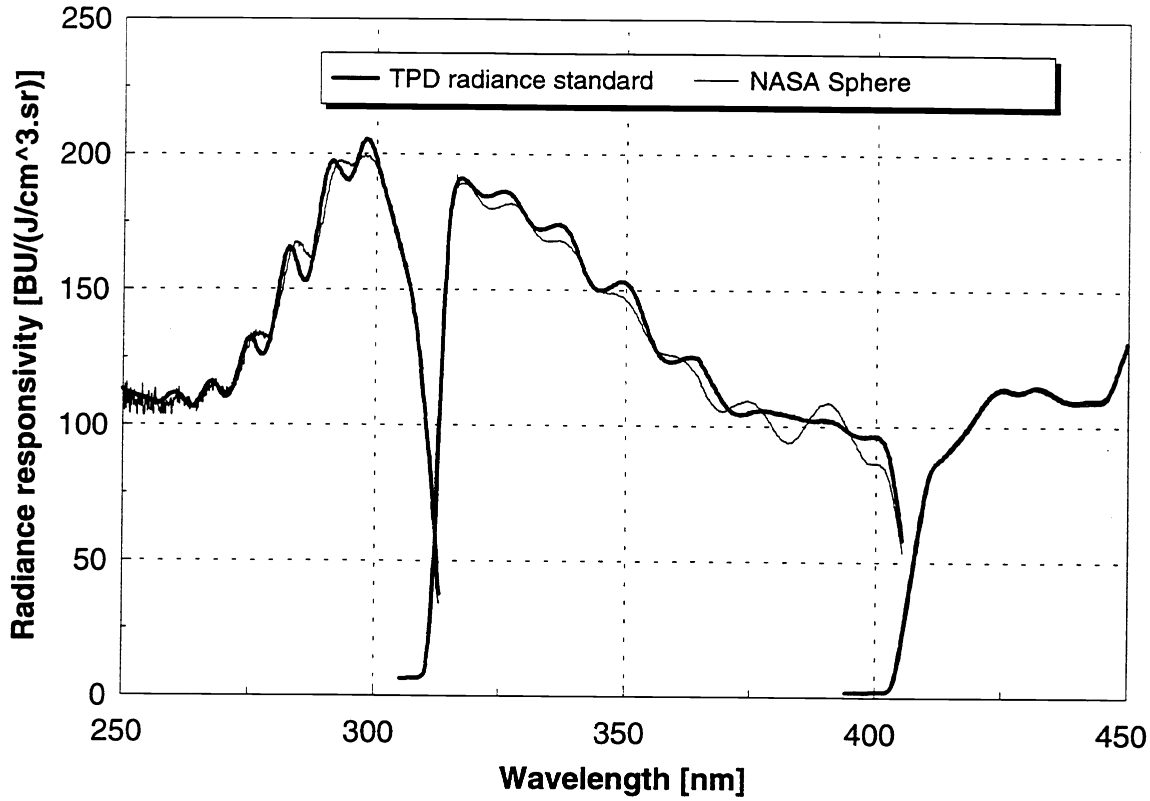

fig. 10.

Radiance responsivity of GOME as measured using the calibrated TPD radiance source and using a NASA radiance source containing an integrating sphere. Data are only shown for the part of the GOME wavelength range where "NASA results" are available

Another example of a calibration result obtained using the ARCF is shown in fig. 11 depicting the ratio of radiance responsivities of the GOME Flight Model for S and P polarized light. This result has been obtained using the TPD white light radiance source in combination with the Brewster-plate polarizer. Using this setup the field-of-view of GOME (2.8° x 0.14°) can be completely illuminated with light of near-perfect linear polarization. It is quite clear that the GOME instrument has a pronounced polarization sensitivity, which is mainly due to its diffraction gratings and the dichroic filter separating channel 3 and 4.

5. Concluding remarks

In this paper a calibration facility is described, with which accurate absolute preflight radiometric calibration can be performed.

The absolute accuracy level was demonstrated by comparison calibration results obtained by using TPD and NASA radiance standards.

An extremely useful part of the facility is the Brewster plate polarizer, with which over a broad spectral range (~240-2400 nm) a linearly polarized beam can be created. Its use for calibration of polarization sensitive optical instruments was demonstrated by calibration of the GOME flight model. At this moment the ARCF is updated for the calibration of SCIAMACHY. For the future a continuous effort will be necessary to improve further characteristics like non-uniformity of the output beam, rest polarisation etc. in order to meet the always increasing calibration requirements of the next generation remote sensing satellites.

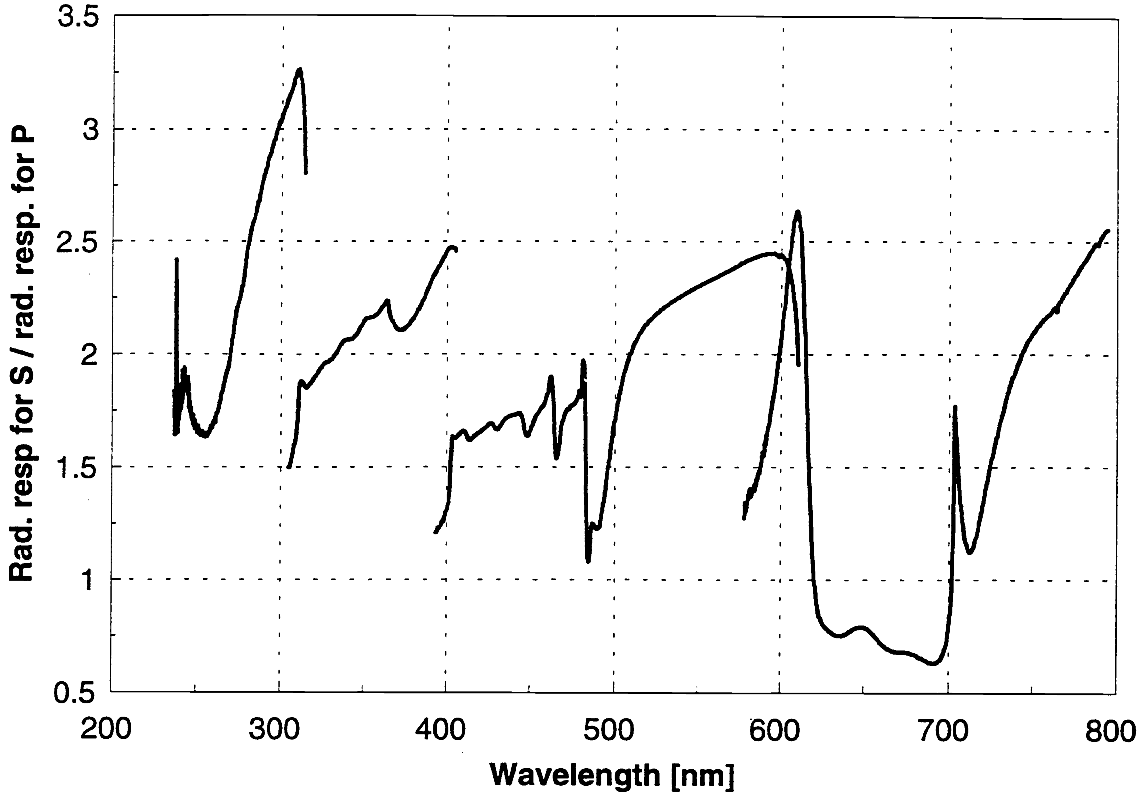

fig. 11.
The ratio of radiance responsivities of the GOME Flight Model for S and P polarized light

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