OZONE MONITORING BY GOME-2 ON THE METOP SATELLITES

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ABSTRACT

The first Global Ozone Monitoring Experiment (GOME) has been successfully operated on board of ERS–2 since its launch in April 1995. The objective to measure the global distribution of ozone and several other trace gases has been achieved. Based on this heritage the advanced GOME-2 has been selected as payload for the first three METOP satellites to cover the need of operational ozone monitoring for the next 15 years.

GOME has shown its capability to monitor total column ozone, ozone profiles, nitrogen dioxide, sulphur dioxide, formaldehyde, and halogen oxides. Cloud parameters such cloud fraction within the field of view, cloud top height, and cloud optical thickness are measured as well. Aerosol properties like aerosol optical thickness have been retrieved successfully. Near real time data are being provided by KNMI, IFE Bremen and DLR for total column ozone and ozone profile by KNMI.

GOME was limited to the restricted resources (data rate, mass, power) of the ERS-2 satellite. GOME-2 is using the larger satellite resources of METOP:

- to increase the spatial resolution to 40 km * 40 km for the total column products,
- to provide the measurement of both s- and p- polarised components of the incoming radiation with a high spatial sampling (40 * 5 km), and
- to enhance its on-board calibration and characterisation capabilities by adding a white light source.

On-ground calibration and characterisation will be improved by allowing more calibration measurements under operational conditions. The ground processing of earth radiance and solar irradiance will use the knowledge of more than 4 years of operational processing.

1. Introduction

The “Global Ozone Monitoring Experiment” (GOME) was launched on board the ERS-2 spacecraft on 20 April 1995 and is successfully operating since then and providing ozone and other data even 2 years beyond its design lifetime of 3 years. Being the only European instrument with actual flight heritage measuring ozone and related species, GOME was selected as ozone monitoring instrument for the series of METOP satellites jointly developed by ESA and EUMETSAT for operational meteorology and climate monitoring. The phasing between the ERS-2 and METOP development schedules is so fortunate that it allows to a large degree to implement “lessons learnt” in terms of improving the sensor’s design, calibration and data processing. The new features of this second generation sensor, termed GOME-2, are presented in this article. However, there were not only improvements to the instrument driven by science and operations, also the different satellite and launcher imposed modifications which eventually left nearly no subsystem unchanged. Some of the driving considerations will be reported in chapter 3. Finally, the changes made to the sensor as such required subsequent changes to the calibration philosophy and to the processing of the scientific data. The latter is now under responsibility of EUMETSAT being in charge of the processing and user interfaces; however, ESA will provide the reference processor against which the operational one will be compared.

2. Success of GOME on ERS-2

For total ozone columns the comparison with ground based observations shows good agreement (2 to 4%) at northern mid latitudes, which is within the common error bar of both measurements. GOME has shown that it can continue the monitoring and documentation of the ozone distribution (Burrows et al, 1999) started by the series of TOMS instruments. The potential of GOME to provide global distribution data of nitrogen dioxide, bromine oxide, chlorine dioxide, sulfur dioxide and formaldehyde has been demonstrated. Ozone profile retrieval is highly demanding, but the available results clearly show the ability of GOME to deliver new information on ozone profiles in the troposphere and stratosphere.

A GOME Near real time (NRT) campaign (December 1999-May 2000) was set up as a support for the three major measurement campaigns SOLVE/EUROSOLVE, THESEO 2000 (Third European Stratospheric Ozone Experiment), and TOPSE (Tropospheric Ozone Production about the Spring Equinox), which are all aiming to increase the knowledge about ozone chemistry in the Arctic. The NRT data products derived from the GOME spectral data encompass ozone total columns and profiles, total columns of NO2 and BrO, and slant columns of OClO. Regular NRT GOME images (mainly ozone) can be found at the websites of the University of Bremen, KNMI, and DLR/DFD.

3. METOP Environment

Quite a number of changes to the instrument design are imposed by the fact that METOP is a different satellite than ERS-2:
METOP is designed for a different orbit than ERS-2. This imposes a different view angle to the sun, for in-orbit calibration purposes, and some moderate changes in the thermal environment.

METOP is designed for a launch on an ARIANE-5, whereas ERS-2 was launched by an ARIANE-4. This change imposes quite significantly higher mechanical loads in terms of random/acoustic and shock loads. (e.g. the random acceptance levels increased from 2.7 gRMS to 8.3 gRMS).

Because of the presence of sensitive microwave receivers on board METOP, quite stringent radiofrequence compatibility requirements are imposed on the satellite and its instrument. For the specific bands of the Search and Rescue payload, the imposed maximum tolerable emissions from the instrument are 70dB lower than what was acceptable on ERS-2.

Whilst on ERS-2 the GOME instrument was interfaced with the satellite avionics via the ATSR instrument’s main electronics, GOME-2 on METOP will have its own Instrument Control Unit (ICU) with interfaces to the satellite’s power distribution, On Board Data Handling (OBDH) bus, and science data handling subsystem. These changes are not very obvious in the instrument’s physical appearance (only a moderate increase in the size of electronic boxes is noticeable), but have significant impact on its internal architecture and design.

So, although at the first glance appearing virtually unchanged, nearly all subsystems had to be redesigned and will need re-qualification to demonstrate their compatibility with the new environment.

4. GOME-2 for METOP

The feedback from 5 years of GOME-1 operations and data evaluation, and the environmental and accommodation constraints imposed by satellite, orbit, and launcher, lead to a significant number of detailed changes, with still the basic concept being retained. Their detailed implementation is addressed for each subsystem affected.

As a general principle, the GOME-2 instrument collects light arriving from the sun-illuminated Earth’s atmosphere and decomposes it into its spectral components. In order to provide both the required spectral coverage from 240 to 790 nm and a good spectral resolution and ensuring a proper straylight level in channels 1 & 2 the instruments is set up as a double spectrometer. The entire instrument can be divided into following functional blocks: spectrometer, polarisation measuring unit, calibration unit, Control and Data Handling Unit (CDHU), focal plane assemblies (FPA) and scan unit (SU).

4.1 The spectrometer

The optical design of the GOME-2 main spectrometer (figure 1) is almost a copy of the GOME-1 concept. The major change between the two instruments is driven by the accommodation of the more complex polarisation monitoring unit (PU) of GOME-2, which is described in detail in chapter 4.2. However, a lot of minor improvements are included in the design and will be presented hereafter.The GOME-2 spectrometer is an across-track scanning spectrometer covering the wavelength region 240 to 790 nm in four different channels. A scan mirror directs the light emitted from the sun-illuminated atmosphere into an anamorphic telescope.

Table 1 summarises GOME-2 in a nut-shell.

Spectrometer type	double monochromator with pre-disperser prism and four holographic gratings
Spectral range	240 –790 nm
Inst. Field of view	0.286° (across track) * 2.75° (along track) 4 km * 40 km
Entrance slit	0.2 mm (across track) * 9.6 mm (along track)
Channels & resolution	1: 240 – 315 nm 0.24 – 0.29 nm 2: 311 – 403 nm 0.26 – 0.28 nm 3: 401 – 600 nm 0.44 – 0.53 nm 4: 590 – 790 nm 0.44 – 0.53 nm
Polarisation Monitoring Unit	200 detector pixels 312 – 790 nm in 12 programmable bands spectral resolution: 2.8 nm @312 nm to 40 nm @ 790 nm
Viewing modes	
Nadir across track	+/- 1920 km, +/- 960 km, +/- 480 km, +/- 360 km, +/- 240 km, +/- 120 km
Solar	fixed angle once per day
Lunar	fixed varying angle, ~ 6 times per year
Spectral calibration	fixed angle (once per day to once per month)
White Light Source	fixed angle (once per day to once per month)
Dark signal	fixed angle (night side of the orbit)
Spatial resolution	40 km * 40 km (960 km swath and integration time of 0.1875 s) 40 km * 5 km (for polarisation monitoring)
Data rate	400 kbit/s (GOME-1: 40 kbit/s)
Mass	73 kg (GOME-1: 55 kg)
Power	58 W (avg) (GOME-1: 32 W)
Dimension	Zenith nadir 656 mm, across track 848 mm, velocity 468 mm

The telescope is designed to match the two directions of the instantaneous field of view (0.286° across track times 2.75° along track) to the two directions of the entrance slit (0.2 mm times 9.6 mm). Additionally, the scan mirror can point to 2 internal calibration light sources and the sun diffuser. The slit width was increased from 0.1 mm in GOME-1 to 0.2 mm in GOME-2 in order to avoid spectral undersampling of the instrument.

Behind the entrance slit the light is collimated by an off-axis parabolic mirror (f=200 mm) onto the double Brewster/predisperser prism configuration, which generates the s- and p- polarised light beam for the polarisation monitoring unit and produces the pre-dispersion for the main spectrometer. Another off-axis parabolic mirror (f= 125 mm) focuses the dispersed beam on the channel separator prism. The pair of parabolas is forming a relay system of magnification of 0.625. The band separator prism is a quartz prism with the first surface partially coated with a reflective coating for channel 2 and a transmission coating for channel 1. The light for channel 3 and 4 is passing the prism edge. A dichroic filter separates the light into channels 3 and 4. The slow but steady outgassing of this coating is one of the unpleasant features of GOME-1 (ESA, 2000). Therefore, this coating is now manufactured using plasma ion-assisted deposition (IAD) technique with the advanced plasma source (APS) (Zoeller et al. 1996) to avoid air-vacuum shifts and provide high temperature stability.

Each of the four channels comprises a collimator off-axis parabolic mirror, a grating and a four-lens objective which focuses the spectrum on a linear detector array in the FPA (see. 4.4). Each combination of collimator/objective forms a main channel relay of magnification 0.4. The combined magnification of the optical path is 0.25 ensuring that the image of the entrance slit is completely imaged on the detector array. The design guarantees a field of view overlap amongst the main channels and the channels of the polarisation unit.

4.2. The New Polarisation Monitoring Unit (PU)

Nadir looking space–borne spectrometers have only 2 options to treat the atmospheric polarisation of the incoming light. Either the polarisation information is destroyed by scrambling, as in the American TOMS and SBUV type instruments and in the Dutch/Finish OMI instrument or the polarisation of the incoming light has to be measured with sufficient accuracy to correct for the polarisation dependence of the instrument. The benefit of the latter approach is that the polarisation detector information can be used for a other purposes like cloud detection, aerosol detection, and high spatially, low spectrally resolved radiance measurements of the atmosphere.

The new polarisation unit monitors the range between 312 to 790 nm by 200 detector pixels with a spectral resolution from 2.8 nm at 312 nm to about 40 nm at 790 nm with an integration time of 23 ms. Both the s- and p-polarised part of the light will be measured simultaneously. As the data rate of GOME-2 is limited, the information of the 200 detector pixels is co-added on board to 12 programmable bands.

The design driver for this new subsystem has been the optical identity of both s- and p- channel, to ensure an identical field of view amongst s- and p- channel, as well as the main channels and the use of the same detector array as in the main channels.

As shown in figure 2 the collimated beam of the 200 mm parabolic mirror is passing a double Brewster prism that extracts the s-polarised light into the s-channel. This light is leaving the prism group orthogonal to the optical bench. The prism group is composed of two prisms with two parallel surfaces tilted at the Brewster angle. By this, the wedge effect of the prism is compensated for the main channels. The light of the main channels enters a predisperser prism like on GOME-1, which generates the p-polarised beam and predispers the light of the main channel. In the two polarisation channels a disperser assembly composed of two prisms further dispers the light and redirects the light again parallel to the optical bench. A dioptric focusing objective (f=48 mm) together with the 200 mm parabolic mirror form a relay of magnification 0.24. Hence, the FOV overlap between the main channels and the 2 PU channels is guaranteed. For accommodation reasons an additional prism has been placed between the lenses and the detectors. The detector arrays are tilted by 30° in spectral dispersion to compensate chromatic aberrations.

4.3 The Calibration unit

The demanding requirements for the radiometric accuracy of the instrument call for in-orbit calibrations. The unit contains two light sources, of which one offers well isolated spectral lines in the required wavelength range, and a quartz tungsten halogen lamp called white light source (WLS) for a broad band continuum. The WLS is used to monitor the etalon which is present on the cooled Reticon detectors, due to freezing water vapour on the protective SiO2 layer. Although, this etalon stabilises in vacuum, it is irritating during the ground calibration and for the transfer of key calibration key data between the on-ground calibration and the in-orbit situation. The spectral light source is a hollow cathode lamp with Pt and Cr as anode/cathode material and filled with a mixture of Ne and Ar. Adding Ar to the gas fill mixture enlarges the number of spectral line in channel 3 and reduces the very strong Ne lines in the near infra-red, which would be saturated otherwise.

The calibration unit is complemented by a diffuser, which allows to perform a solar calibration. Due to the orbit geometry the sun can be seen via the solar calibration port once during an orbit. As in GOME-1 the diffuser is well protected against the hostile space environment and the harsh UV radiation by a mesh, attenuating the flux and a shutter, that only opens for a sun calibration. GOME-1 experience shows that one solar calibration per day is sufficient and no degradation of the sun diffuser itself has been detected in 4.5 years.

The beams of all three sources are leaving the calibration unit under different angles and the sources can therefore be separated by a proper selection of the scan mirror position.

4.4 The Focal Plane Assemblies

GOME-2 has a total of six Focal Plane Assemblies (FPAs), four devoted to the main spectrometer channels and two to the new polarization channels. The basic design of the four main spectrometer channels FPAs is very similar to GOME-1; each foresees the use of titanium for the structure and a quartz window at the side where it is assembled on the spectrometer objective. Each FPA contains a random access linear silicon photodiode array, consisting of 1024 elements of 2.5 x 0.025 mm^2 each (type Reticon RL 1024 SRU) which is reverse biased and operates in charge accumulation mode. To achieve maximum sensitivity, the detector has to be cooled at the nominal temperature of –38° C, by means of a thermoelectric cooler, which is directly glued on the bottom face of the detector itself. To reject the heat generated by the cooler, a low resistance thermal path to the main GOME-2 radiator is realised; it involves two heat pipes and some specially designed parts to absorb the effects caused by the thermal expansion. The detector temperature is controlled in closed loop by a suitable electronic circuit inside the CDHU; the actual target temperature can be programmed in-flight to any value between ambient and –38°.C.

To avoid ice growth during on-ground testing, each FPA realises a vacuum tight enclosure containing the detector and the cooler. The enclosure can be evacuated by a system of steel pipes located on the bottom of the optical bench and a flange with a tap situated on the backside of the instrument. The tap and the flange will be removed just before launch, so allowing the FPAs to evacuate naturally during the ascent phase. The FPA electronics is split onto two boards. The first carries the charge amplifier, made up of a dual-FET differential stage and a low noise amplifier. To achieve maximum noise immunity, this board is installed on the rear of the vacuum enclosure, just 3 cm from the detector. The second board is mounted on top of the spectrometer objective, and contains some filtering circuits, the 16 bit A/D Converter and the interfaces. Thanks to the modular approach,, each FPA can be tested and trimmed at module level before final integration on the instrument. Testing have shown that, due to the careful design, the FPA electronics have low noise and a dynamic range of about 30.000.

There are 255 integration times possible, ranging from 93.75 msec to more than 1 hour. In channel 1 and 2 two different integration times can be selected for two bands of the detector; and the border between the two bands is in-flight programmable.

The PU FPAs are slightly different. Due to the less demanding detection performance and more stringent requirements on mechanical accommodation, no closed loop thermal control has been implemented. Consequently, neither the thermal link to the radiator nor the vacuum tight enclosure is present, with very beneficial effects in terms of mass saving and structural robustness. The detector is anyway cooled in open loop configuration to about 0°C by a thermoelectric element, which rejects the heat to the main GOME-2 optical bench, through the PU mechanics itself. Although not stabilised, the detector temperature is kept low enough to neglect the dark current effect in this particular case. The detection electronics is the same as for the main channels FPAs. Integration time will normally be fixed at 23.4 msec, and the spectral information will be grouped in 12 fully programmable bands.

In addition, the integration time can be programmed as for the main channels FPAs, during calibration phases. Even if the PU FPAs cannot be cooled during normal testing in ambient, performance will be verified before launch during TV tests and instrument calibration.

4.5 The Scan Unit

To perform global earth coverage, the GOME-2 instantaneous on-ground field of view has to be scanned in across-track direction. This function is performed by a subsystem called Scan Unit (SU) containing a rotating mirror, optically situated in front of the spectrometer, and its related mechanics (SUMA) and electronics.

The unit's design is strongly based on the positive experience acquired with GOME-1, with some improvements in terms of functionality and reliability. The improvement with respect to the GOME-1 design is the presence of a wireless resolver. Another minor improvement of the SUMA is a better confinement of the debris generated by the wear itself. The SU is able to implement five scan profiles at constant angular speed (as per GOME-1) and five new scans, compensating the earth curvature and realising constant linear speed on ground.

A new wide amplitude scan, corresponding to 1920 km on-ground is also implemented; this will allow complete earth coverage in 1.5 days. All the scans are completely reprogrammable in-flight, allowing an almost unlimited choice of profiles. The basic timing of the scanning is 4.5 sec for the forward scan, 1.5 sec for the flyback.

Fixed pointings at any angular position are of course possible; they are needed to point to the several instrument calibration sources, both internal (radiometric lamp, spectral lamp) and external (sun, moon).

The overall SU performance remains unchanged with GOME-1; the mirror position accuracy in fixed pointing will be better than 0.03° (corresponding to about 800 m on ground) while in scanning modes it will depend on actual speed, but in all cases be better than 0.065°.

4.6 The Control and Data Handling Unit (CDHU)

All electrical and operational interfaces to GOME-2 are routed through the CDHU (figure 3). Within this unit, a primary processor is in charge of all ICU functions such as reception and expansion of macrocommands, maintenance of history area, monitoring of instrument parameters and preparation of housekeeping telemetry formats. The ICU controls the operations of the Scan Unit via a bi-directional serial interface and provides each of the four FPAs thermoelectric coolers with an individual thermal control loop. A secondary processor controlling the Science Data Management (SDM) board is in charge of the science data collection, processing and packetisation. The SDM provides all the timing signals needed to control the detector integration times and the synchronisation of the scan mirror movement with the detector readout. The command and control interface to the METOP OBDH bus is made of recurrent elements, the external DBU (Data Bus Unit) and the RBI chip implementing part of the low-level protocol between the OBDH bus and the ICU processor.

The instrument science packets, prepared by the SDM are sent, after date/time and cycling redundancy code (CRC) addition, to the Fast Multiplexer Unit (FMU) at 400 kbits/second. The discrete lines interfaces implement direct hardware control of relays and acquisition of thermistors to allow respectively the correct start-up and emergency instrument switching and the monitoring of the instrument temperature when the ICU is off.

5. On-ground Calibration

Although a number of on-board calibration sources are included in GOME-2 a thorough on-ground calibration is required. The most important measurements are the characterisation of the bi-directional scattering function (BSDF) of the diffuser in the calibration unit, the characterisation of the polarisation response of the instrument as function of the different optical paths for solar calibration and earth nadir view, as function of the scan mirror position and wavelength. These calibrations are performed in a thermal vacuum chamber at the instrument calibration contractor‘s site (TNO/TPD). A number of additional measurements are made for various purposes, including more comprehensive instrument characterisation and consistency cross checks. In particular full radiance and irradiance calibration using earth and sun observation path are performed with NIST calibrated light sources for the PU and the main channels. Furthermore, full characterisation of the straylight behaviour, the wavelength calibration, the field of view as well as the instrument response function is performed. The instrument calibration is complemented by cross checking the results using the NASA sphere as calibration source and measurements of scattered sky light offered to the instrument by light fibre.

6. Operations

The GOME-2 instrument has many measurement and calibration modes. Furthermore, the high variability of the light levels observed by the instrument over each orbit implies that the integration time of the detectors have to be changed frequently. To limit the command rate, and implement 36 hours of autonomy the concept of timelines validated by the GOME-1 experience has been extended. Each timeline contains 28 different commands to be automatically expanded when required to change integration times, sub-system modes or other parameter values. The CDHU will store 12 predefined timelines, each dedicated to a specific orbit sequence (nominal, calibration, sun calibration or test). The content of the default timelines will be changed by macrocommand to trim if necessary the integration times and the modes sequence to the actual on-flight conditions. If needed, the GOME-2 Timeline Table (GTT) may be used to start any of the timelines at specific on-board time in order to pre-program the operations for approximately one day. About once per month, an extensive calibration will be performed assessing the diffuser degradation, any changes in the dark signal and saturation level of the detectors and a wavelength mapping as function of the thermal variation. An etalon characterisation is also planned at this occasions. Lunar observations, which are restricted by the Sun-Moon-satellite scanner field of view geometry will be performed whenever possible.

7. Data processing

GOME-2 data will be transmitted from the METOP satellite to the receiving stations via an X-band link. From there they will be transmitted to the Core Ground Segment (CGS) operated at EUMETSAT in Darmstadt, Germany for processing. The CGS is a central facility providing command and control, near-real-time data processing and data dissemination for the METOP satellites. In a first processing step, the raw (or level 0) data will be augmented by the geolocation and calibratiotion parameters needed for further processing. One part of these calibration parameters comes from pre-flight calibration of GOME-2. Another part is derived from the regular in-flight calibration measurements using the sun and the on-board lamps as light sources. The calibration parameters are than applied on the raw data in order to obtain calibrated solar irradiance and earth radiance spectra, together with auxiliary geophysical information as e.g., on polarisation and cloud fraction. These level 1 products are then disseminated by the CGS to Satellite Application Facilities (SAF) and other users for further processing. For the GOME-2 level 0 to 1 processing, specifications and a prototype processor are currently being developed at DLR in Oberpfaffenhofen, Germany.

Column amounts of the target trace gases and vertical profiles of ozone will be derived from the GOME-2 level 1 spectra at the Ozone SAF. The aim is to derive the final trace gas product (level 2) within three hours from the measurement. In addition to this operational near-real-time processing chain, GOME-2 data will be evaluated by scientific users for their specific retrieval purposes. The exploitation of the new features GOME-2 offers compared to GOME-1 will certainly stimulate a number of interesting new possibilities for atmospheric research. An example of a GOME-1 fast delivery total ozone column product of KNMI is shown in figure 4.

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Fig. 1 Artist view of optical layout

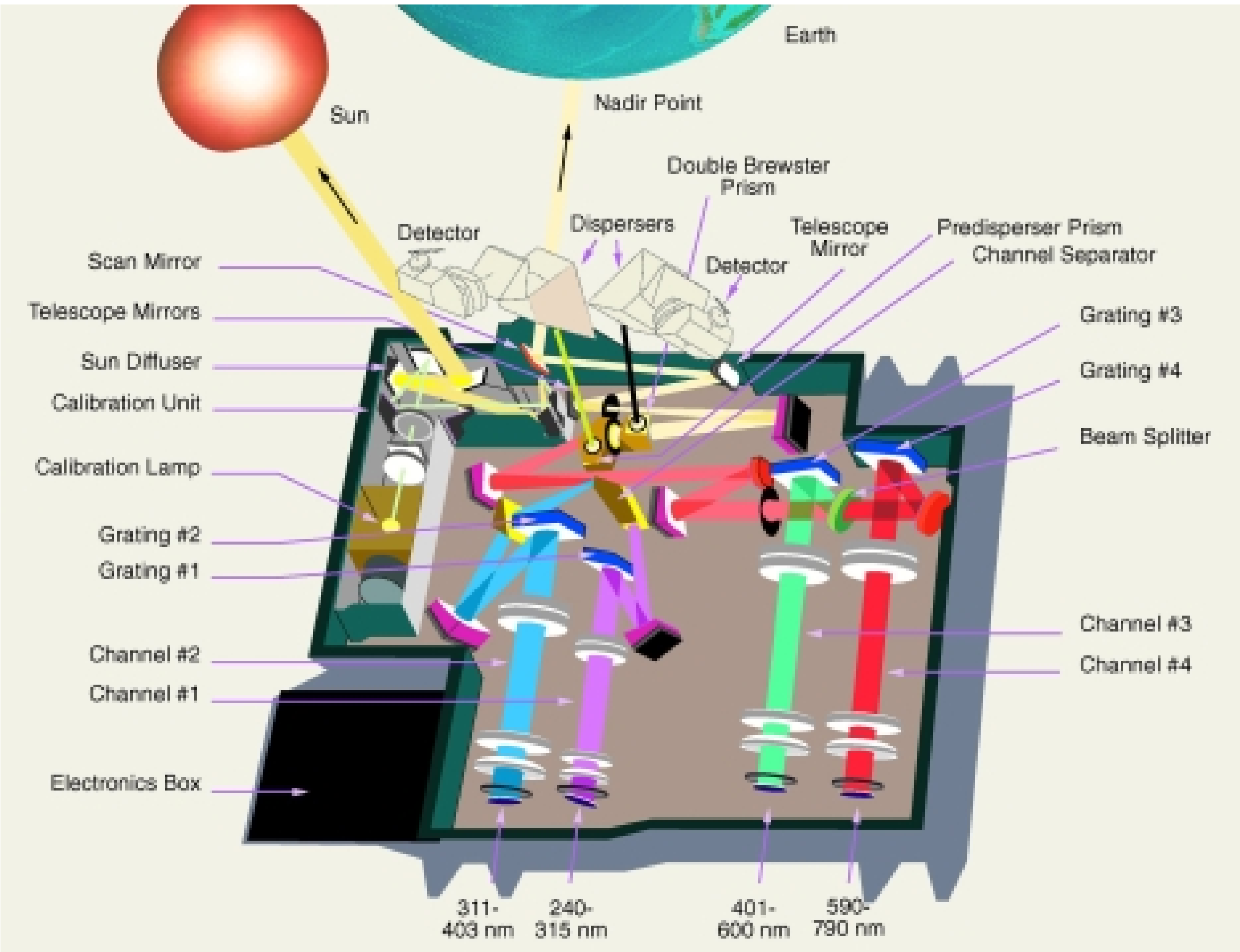
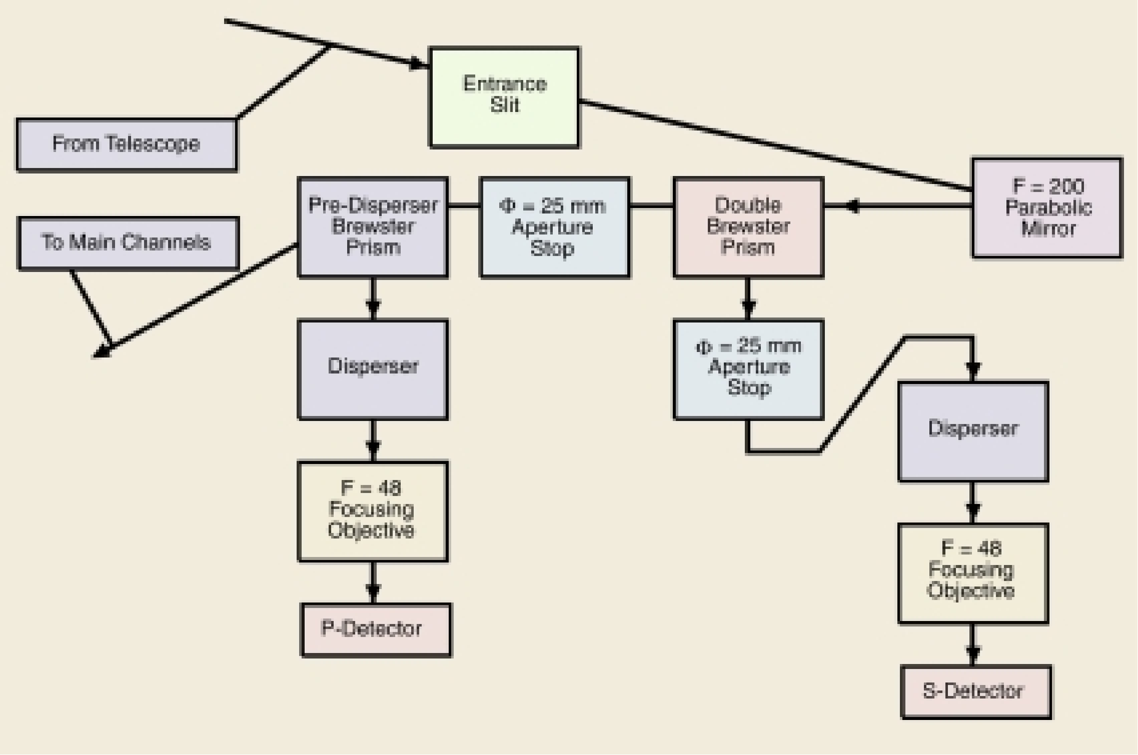


Fig. 2. Block diagram of the PU optics



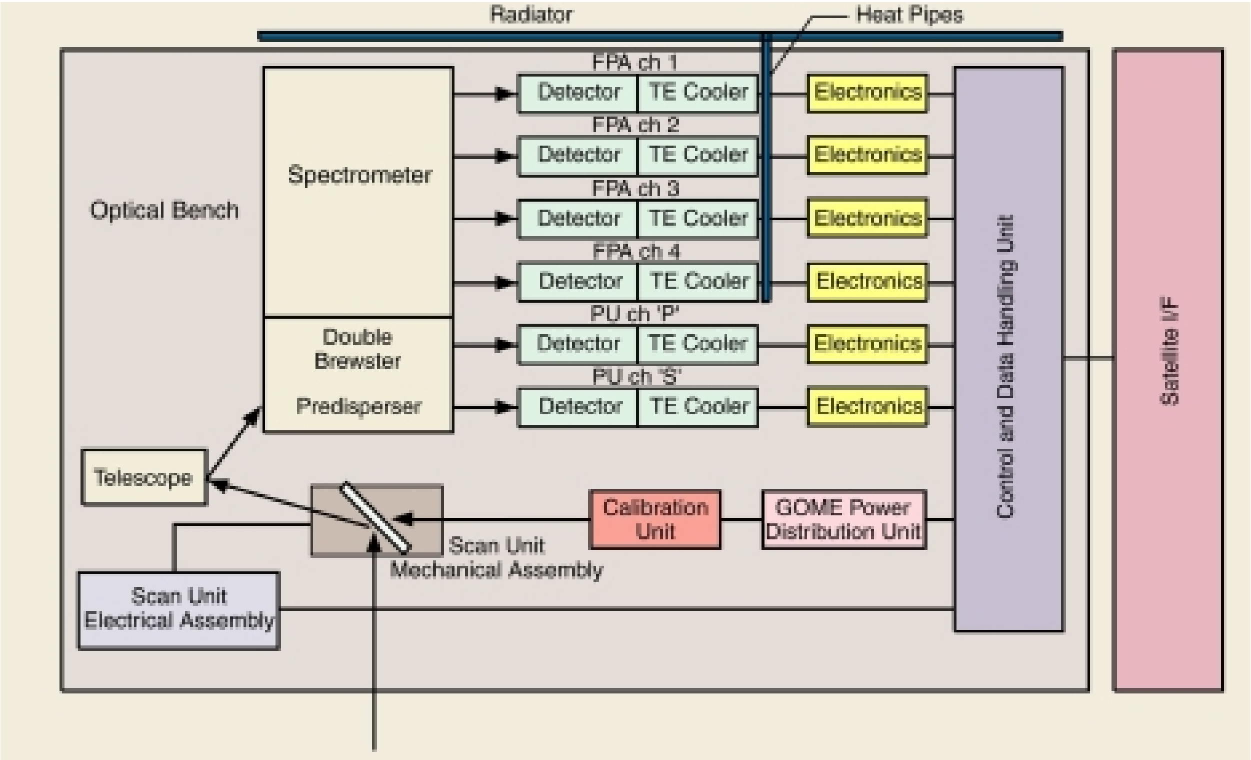


Fig 3: GOME-2 blockdiagram

Fig 4: Example of Fast Delivery Product

GOME Ozone Fast Delivery Service - KNMI

http://www.knmi.nl/neonet/atmo_chem/gome/fd/