GOME-2 – Metop's Second-Generation Sensor for Operational Ozone Monitoring

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The Global Ozone Monitoring Experiment (GOME) was first launched on ESA's ERS-2 spacecraft on 20 April 1995. It is still operating extremely successfully, providing ozone and other valuable data even two years beyond its original design lifetime. As the only European ozone-monitoring instrument with an actual flight heritage, GOME was therefore selected for the Metop series of satellites being jointly developed by ESA and Eumetsat for operational meteorology and climate monitoring. The phasing between the ERS-2 and Metop development schedules has been such that many 'lessons learnt' could be implemented to improve the sensor's design, calibration and data processing. In addition, various spacecraft- and launcher-imposed modifications have meant that eventually almost no subsystem has remained totally unchanged. The changes made to the sensor itself have also resulted in changes to the calibration philosophy and to the processing of the scientific data. The new features of this second-generation sensor, known as GOME-2, are presented here.

GOME's success on ERS-2

GOME was the only new instrument selected for inclusion in ERS-2's payload compared with ERS-1, and therefore had to live with the resources provided by the system margins established for its predecessor. Consequently, not all performance features that were scientifically desirable could be implemented. In particular, the available science data telemetry bandwidth imposed rigid constraints. Nonetheless, the instrument basically accomplished all of its mission objectives (see ESA SP-1151, SP-1212 and Earth Observation Quarterly No. 58).

GOME lead scientist Prof. J. Burrows' conclusion was:
"GOME-1 has successfully passed its initial validation phase and demonstrated its capability to provide valuable information about the state of the earth's atmosphere... Continuous improvement of the quality of the data is necessary and is an ongoing activity, which will enable GOME to make an optimal contribution to important and challenging issues such as long-term trend analysis of atmospheric composition."

Comparison with ground-based observations of total ozone columns shows good agreement (within 2–4%) at northern mid-latitudes, which is within the common error bar of both sets of measurements. GOME has shown that it can continue the monitoring and documentation of the ozone distribution started by the TOMS series of instruments. Its potential to provide global-distribution data for nitrogen dioxide, bromine oxide, chlorine dioxide, sulphur dioxide and formaldehyde has been demonstrated (see Fig. 1). Ozone-profile retrieval is highly demanding, but the available results clearly confirm GOME's ability to deliver new information on ozone vertical distribution in both the troposphere and stratosphere of our planet.

A GOME near-real-time campaign lasting from December 1999 until May 2000 was set up to support the three major measurement campaigns SOLVE/EUROSOLVE, THESEO 2000 (Third European Stratospheric Ozone Experiment), and TOPSE (Tropospheric Ozone Production about the Spring Equinox), all of which are aimed at increasing our knowledge of ozone chemistry in the Arctic. The near-real-time data products derived from the GOME spectral data encompass ozone total columns and profiles, total columns of NO_2 and BrO, and slant columns of OClO. Regular GOME images (mainly ozone) can be found at the web sites of the University of Bremen (D), KNMI (NL), and DLR/DFD (D). The list of retrieved products is complemented by a GOME-based solar activity index (based on the Mg II line) and some limited aerosol information.

The Metop environment

Quite a number of changes to the GOME instrument design have been imposed by the fact that Metop is a very different satellite from ERS-2, designed for a different orbit, and launched by a different launcher (Ariane-5). The new orbit imposes a different viewing angle to the Sun, for in-orbit calibration purposes, and some moderate changes in the instrument's thermal environment.

Because of the presence of sensitive microwave receivers on Metop, stringent radio-frequency compatibility requirements are imposed on the satellite and its instruments. For the specific bands used by the Search and Rescue payload, the maximum tolerable emissions from GOME-2 are 70 dB lower than what was acceptable on ERS-2.

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

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

GOME-2 for Metop

The feedback from five years of GOME-1 operations and data evaluation, and the environmental and accommodation constraints imposed by satellite, orbit and launcher, have led to a significant number of detailed changes, but with the basic concept still being retained. Their detailed implementation is addressed here for each of the main subsystems 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, as well as ensuring a proper stray-light level in channels 1 and 2, the instrument is set up as a double spectrometer. It consists of the following

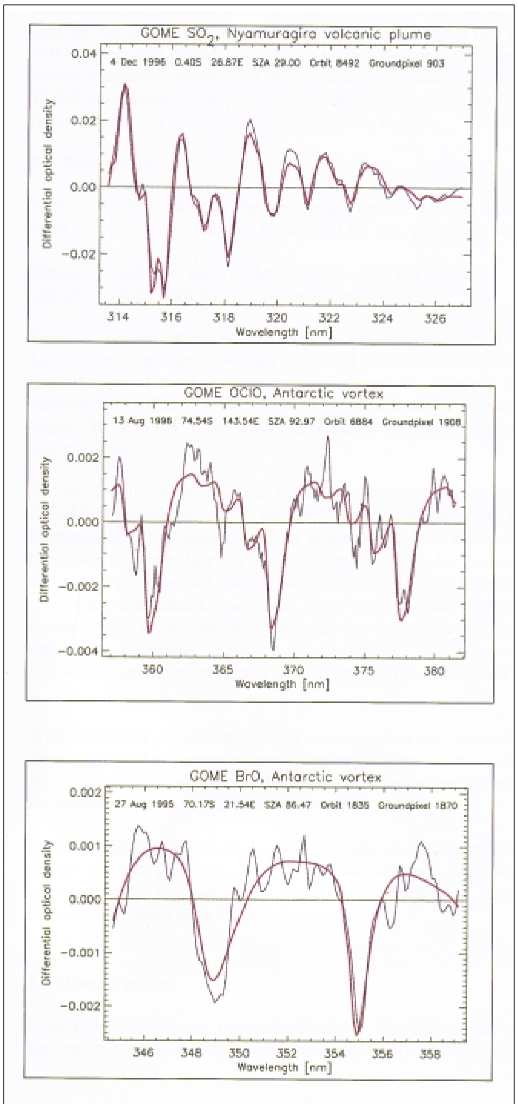

Figure 1. GOME-DOAS fit results for SO_2, OClO and BrO, together with the corresponding reference spectra

Table 1. GOME-2's main characteristics

Spectrometer type	Double monochromator with pre-disperser prism and four holographic gratings
Spectral range	240 –790 nm
Field of view	0.286 deg (across-track) x 2.75 deg (along-track) 4 km x 40 km
Entrance slit	0.2 mm (across-track) x 9.6 mm (along-track)
Channels and 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, ± 960, ± 480, ± 360, ± 240, ± 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 x 40 km (960 km swath and integration time of 0.1875 s) 40 km x 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)
Dimensions	Zenith nadir 656 mm, across-track 848 mm, velocity 468 mm

functional blocks: Spectrometer, Polarisation Monitoring Unit, Calibration Unit, Focal-Plane Assemblies, Scan Unit and Command and Data Handling Unit.

The Spectrometer
The optical design of the GOME-2 main spectrometer is almost a carbon 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 (PMU) of GOME-2 (Fig. 2). There have also been a number of minor improvements to the design.

The GOME-2 spectrometer is an across-track scanning spectrometer covering the 240 to 790 nm wavelength region in four different channels. A Scan Mirror directs the light emitted from the Sun-illuminated atmosphere into an anamorphic telescope. The telescope is designed to match the two directions of the instantaneous field of view (0.286 deg across-track and 2.75 deg along-track) to the two directions of the entrance slit (0.2 x 9.6 mm^2). In addition, the Scan Mirror can point to two internal calibration light sources and the Sun diffuser. The increase in slit width from 0.1 mm for GOME-1 to 0.2 mm for GOME-2 was necessary to avoid spectral undersampling.

Behind the entrance slit, the light is collimated by an off-axis parabolic mirror (f = 200 mm) onto the double Brewster/pre-disperser 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 (Fig. 3). An off-axis parabolic mirror (f = 125 mm) focuses the dispersed beam onto the channel separator prism. The pair of parabolas forms a relay system with a magnification of 0.625. The band separator is a quartz prism, the first surface of which is partially coated with a reflective coating (for channel 2) and a transmission coating (for channel 1). The light for channels 3 and 4 passes the prism edge, and a dichroic filter separates it into the two channels. To avoid the slow but steady outgassing of this coating experienced with GOME-1, it was manufactured using plasma ion-assisted deposition technique to provide high-temperature stability.

The four channels are built from a collimating off-axis parabolic mirror, a grating and a focusing objective that images the spectrum on the detector. Each collimator/objective combination 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 optical analysis shows that even taking aberration into account, the photometric barycentre of the spots relevant to the maximum field of view falls within the detector pixel dimensions. The margin between the barycentre and the outline of the detector is sufficient to absorb the manufacturing tolerances of the optical elements. This design therefore guarantees a field-of-view overlap between the main channels and those of the polarisation unit.

All refractive optics are made of quartz (Suprasil 1) and are multilayer-coated for maximum efficiency and low stray light. The off-axis parabolas are made of aluminum, nickel-coated and machined with a single-point diamond turning technique. Polishing then achieves a surface quality compliant with the low-stray-light application in the ultraviolet.

The four holographic gratings have demanding requirements in term of stray-light reduction and diffraction efficiency, and so only master gratings can be used. The stray-light performance of the UV channel requires that the grating blanks have a micro-roughness of better than 0.5 nm RMS. The groove density is determined by the angles of incidence, which are adjusted to the required densities of 3600 l/mm (channel 1), 2400 l/mm (channel 2) and 1200 l/mm (channels 3 & 4). Particular care is taken to avoid and shield against false light generated with the recording set-up. The symmetrical photoresist groove profile is transformed to a sawtooth-like shape by ion-beam etching. Due to the high spectrometer angles of 45 to 50 deg, the efficiency very much depends on the shape of the groove profile. The polarisation sensitivity of the GOME-2 gratings is considerably lower than for GOME-1. The dispersed light is focused by a four-lens objective onto a silicon linear detector array in the Focal-Plane Assembly.

The new Polarisation Monitoring Unit
Nadir-looking space-borne spectrometers have only two options for treating 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 the Dutch/Finish OMI instrument, or the polarisation 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 also be used for other purposes such as cloud or aerosol detection, or for high spatially, low spectrally resolved atmospheric-radiance measurements.

The new polarisation unit monitors the 312 to 790 nm range using 200 detector pixels with a spectral resolution that varies 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 parts of the light will be measured simultaneously. As GOME-2's data rate is limited, the information from the 200 detector pixels is co-added on board to form 12 programmable bands.

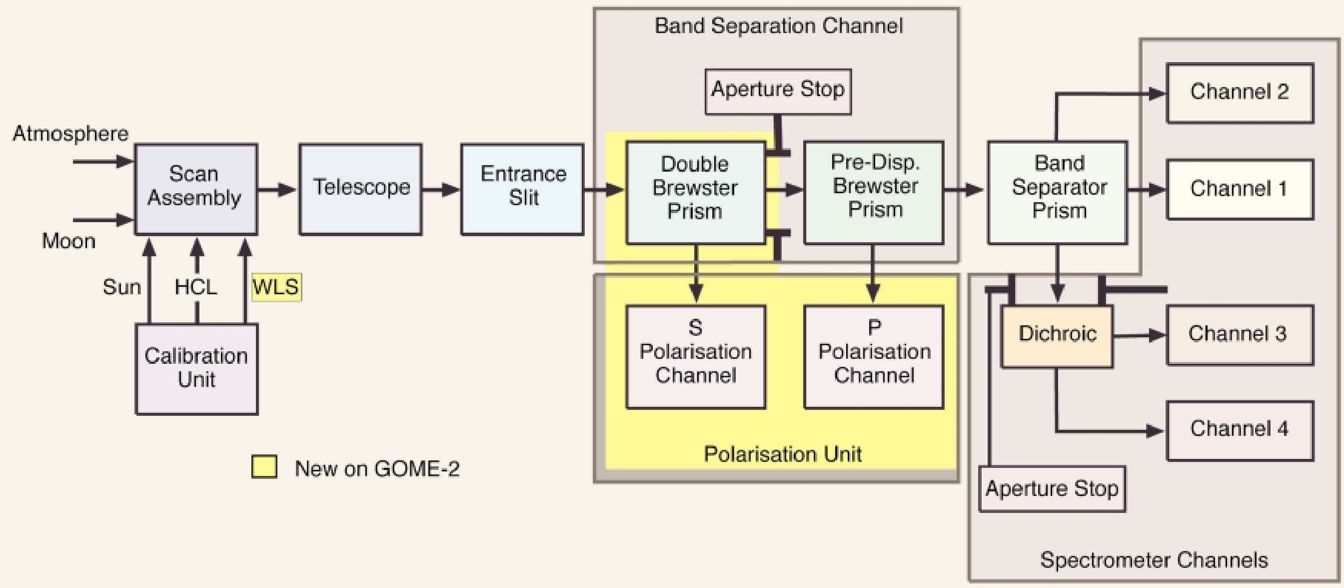

Figure 2. Block diagram of GOME-2 optics, with the differences compared with GOME-1 highlighted

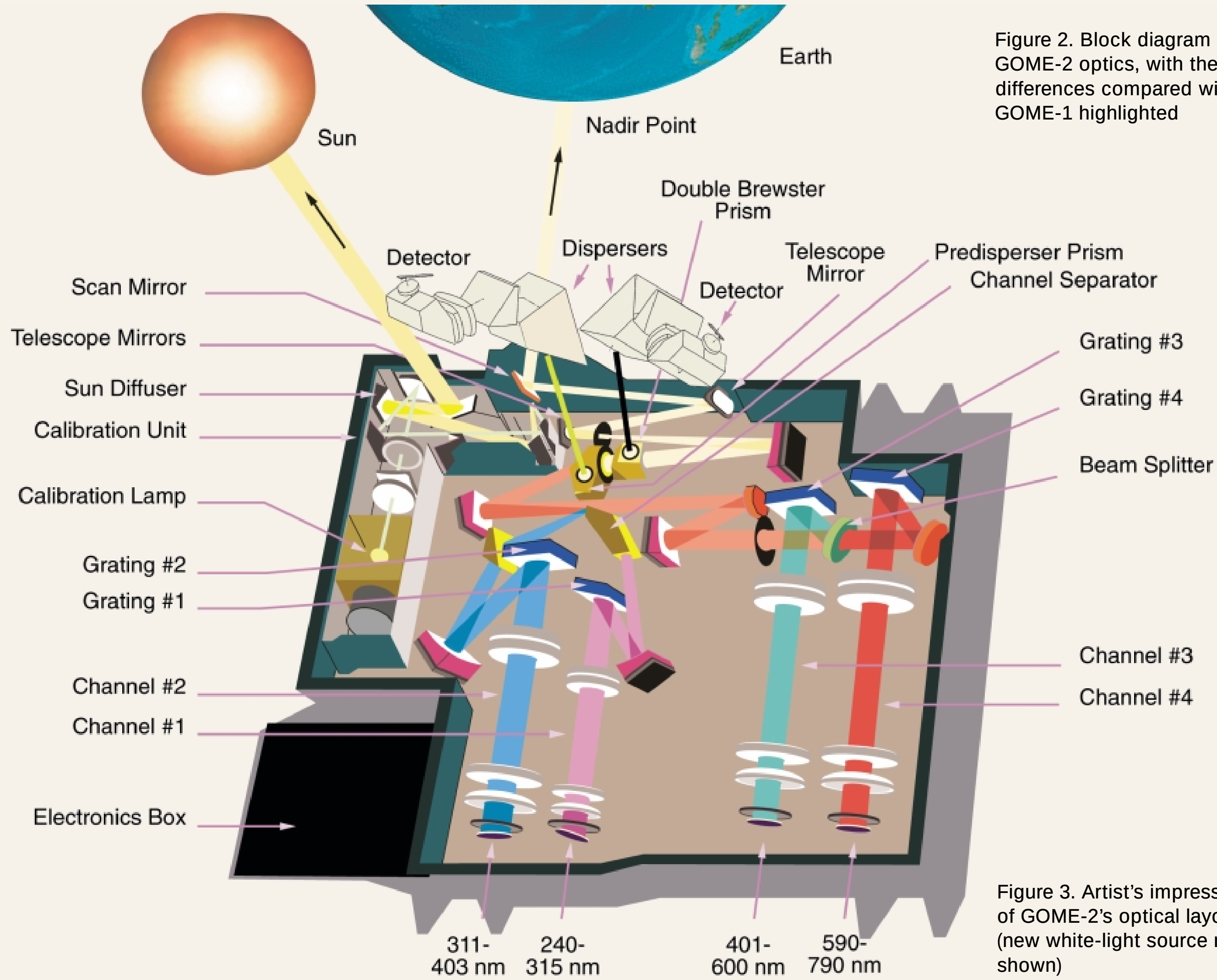

Figure 3. Artist's impression of GOME-2's optical layout (new white-light source not shown)

The design drivers for this new subsystem have been the optical identities of the s- and p-channels, to ensure identical fields of view for both these and the main channel, using the same detector array as the latter. Given the need for a compact lightweight system, a trade-off comparison was made of a grating solution and a prism solution. The latter proved both simpler and more robust, and was therefore selected.

As shown in Figure 4a, the collimated mirror (200 mm) beam passes through a double Brewster prism that extracts the s-polarised light into the s-channel. This light leaves the prism group orthogonal to the optical bench. The prism group (Fig. 4b) consists of two prisms with two parallel surfaces tilted at the Brewster angle, thereby compensating the wedge effect for the main channels. The light of the main channels enters a pre-disperser prism like that on GOME-1, which generates the p-polarised beam and pre-disperses the light of the main channel. In the two polarisation channels, a two-prism disperser assembly disperses the light and redirects it again parallel to the optical bench. A dioptric focusing objective (f = 48 mm) forms, together with the 200 mm parabolic mirror, a relay of magnification 0.24. The field of view (FOV) overlap between the main channels and the two PMU channels is thereby guaranteed. For

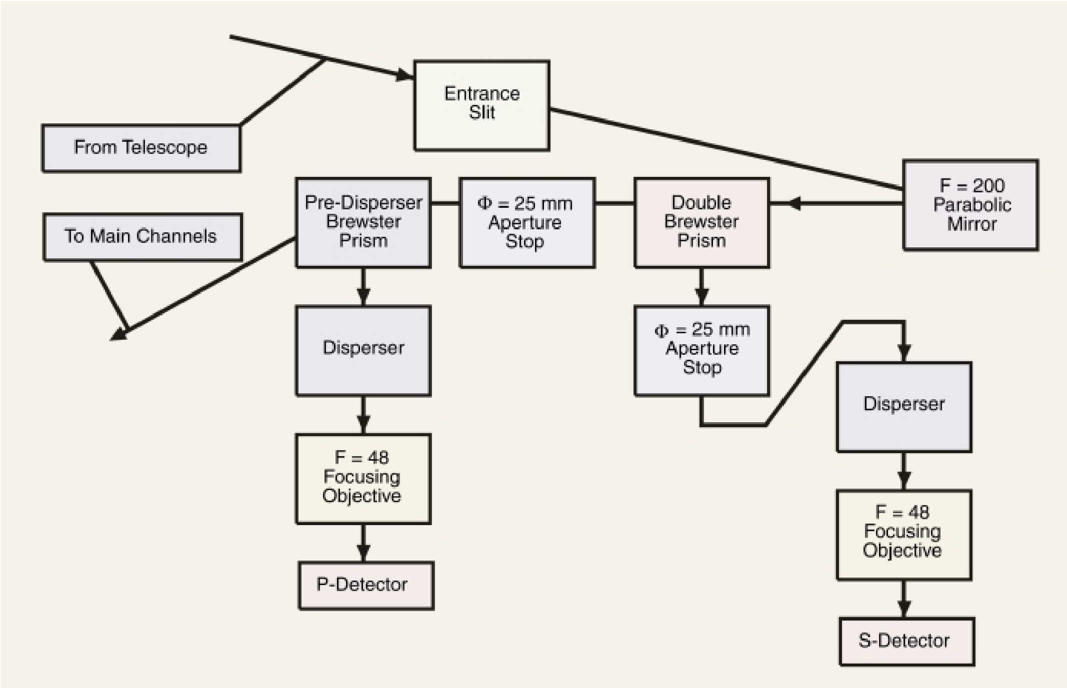

Figure 4a. Block diagram of the new Polarisation Monitoring Unit (PMU) optics

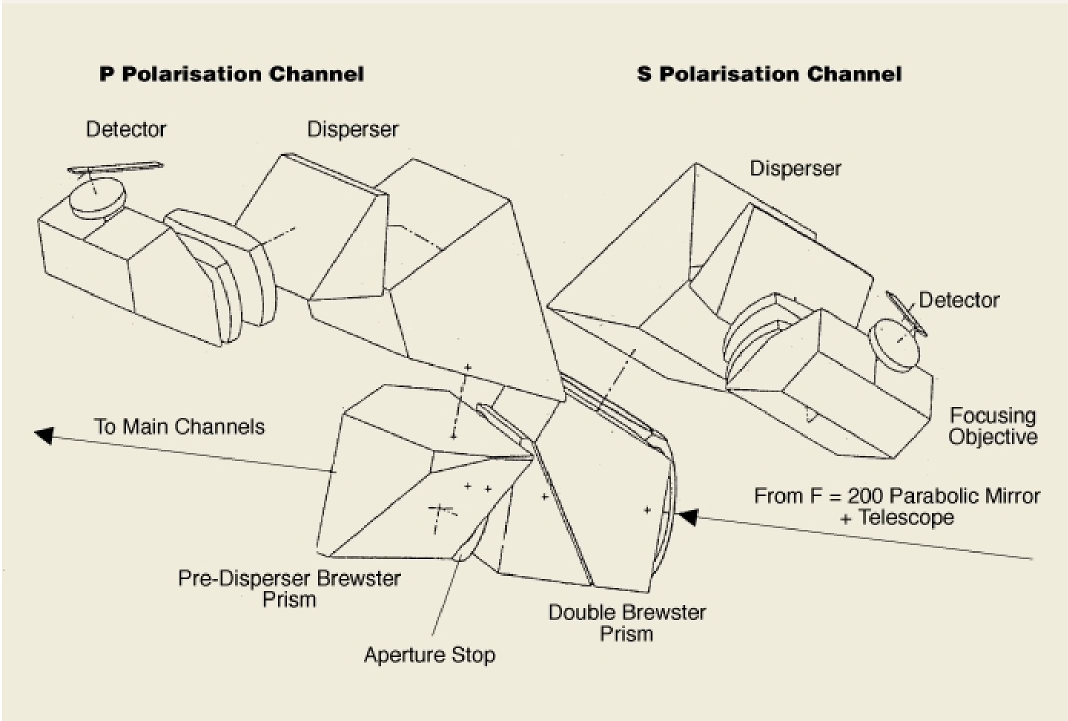

Figure 4b. The PMU detailed optics

accommodation reasons, an additional prism has been placed between the lenses and the detectors. The detector array is tilted by 30 deg in spectral dispersion to compensate for chromatic aberrations.

The Calibration Unit

The demanding radiometric-accuracy requirements for the instrument call for in-orbit calibrations. The unit contains two light sources, one of which offers well-isolated spectral lines in the required wavelength range, and a quartz tungsten halogen lamp (White Light Source, WLS) for a broad-band continuum. The WLS is used to monitor the etalon that is present on the cooled Reticon detectors, due to freezing water vapour on the protective SiO_2 layer. Although this etalon stabilises in vacuum, it is irritating during the ground calibration and for the mapping of key calibration data between the on-ground calibration and the in-orbit situation. The spectral light source is a hollow cathode lamp (Pt anode/Cr cathode) filled with a mixture of neon and argon. Adding argon to the gas mixture increases the number of spectral lines in channel 3 and reduces the very strong neon lines in the near-infrared, which would otherwise be saturated.

The Calibration Unit is complemented by a diffuser, which allows a solar calibration to be performed. Due to the orbital geometry, the Sun can be seen via the solar calibration port once per orbit. As with GOME-1, the diffuser is well protected against the hostile space environment and the harsh ultraviolet radiation by a mesh that attenuates the flux and a shutter that opens only 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 the three sources leave the Calibration Unit at different angles (Fig. 5) and the sources can therefore be separated by proper selection of the Scan Mirror position.

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 polarisation channels. The basic design for the four main-spectrometer FPAs is very similar to that for GOME-1, with titanium being used for the structure and a quartz window on the side where it is assembled on the spectrometer objective. Each FPA contains a random-access linear silicon photodiode array, consisting of 1024 elements each 2.5 x 0.025 mm^2 (type Reticon RL 1024 SRU), which is reverse-biased and operates in charge accumulation mode.

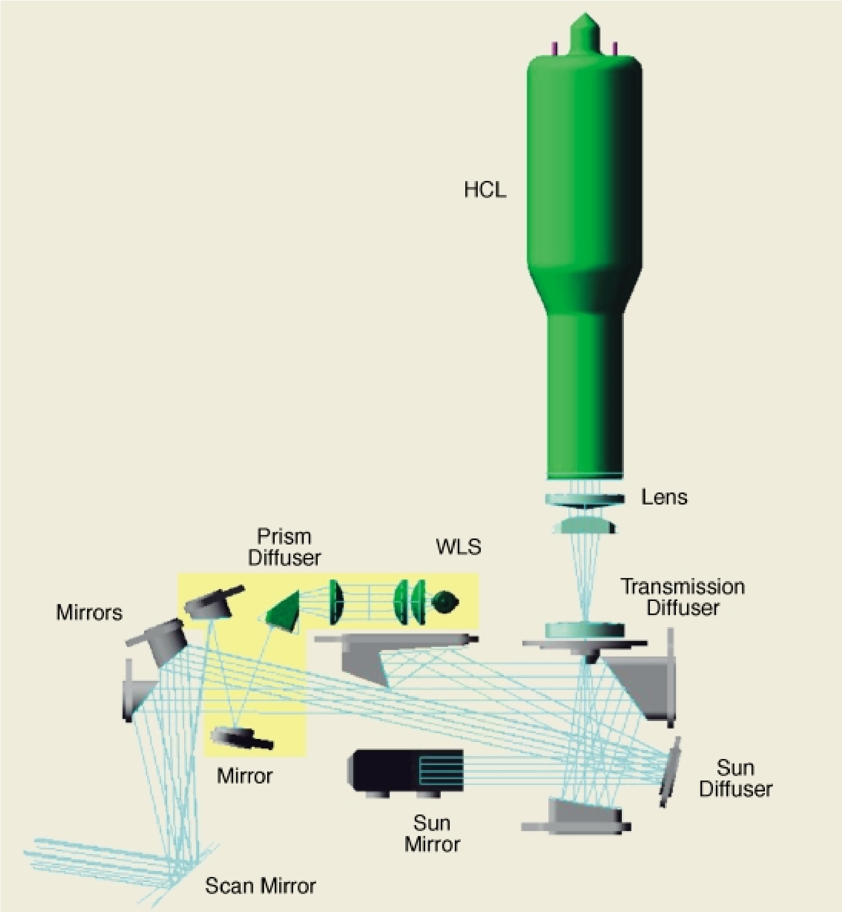

Figure 5. The Calibration Unit optics (new WLS part highlighted in yellow)

To achieve maximum sensitivity, the detector has to be cooled to –38°C by means of a thermoelectric cooler, glued directly 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 provided by two heat pipes, and some specially designed parts to absorb the effects of thermal expansion. The detector temperature is controlled in closed loop by a suitable electronic circuit inside the Command and Data Handling Unit; the actual target temperature can be programmed in-flight to any value between ambient and –38°C. Based on GOME-1 experience, stability is better than ± 0.1°C.

To avoid ice formation during ground testing, each FPA has a vacuum-tight enclosure containing the detector and cooler. This enclosure can be evacuated via a system of pipes on the bottom of the optical bench and a tap on back of the instrument, which will be removed just before launch, 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 has shown that, due to their 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 h. In channels 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 two Polarisation Monitoring Unit FPAs are slightly different. Due to the less-demanding detection performance needs and the 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 savings and structural robustness. The detector is anyway cooled in open-loop configuration to about 0°C by a thermoelectric element, which rejects heat to the main optical bench through the PMU mechanics. Although not stabilised, the detector temperature is kept low enough for the dark current effect to be neglected in this particular case. The detection electronics is the same as for main-channel FPAs. Integration time will normally be fixed at 23.4 msec, and the spectral information will be grouped in 12 fully programmable bands. The integration time can be programmed as per the main-channel FPAs during calibration phases.

The Scan Unit

To perform global Earth coverage, GOME-2's instantaneous on-ground field of view has to be scanned in the across-track direction. This function is performed by a subsystem called the Scan Unit (SU) containing a rotating mirror, situated optically in front of the spectrometer, and its related mechanics 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 SU is physically subdivided into two assemblies: the Mechanical Assembly (SUMA) and the Electronics Assembly (SUEA). The SUMA is almost identical to that of GOME-1, with a rotating mirror installed on an axis actuated by a brushless three-phase motor. A major improvement with respect to the GOME-1 design is the presence of a wireless angular-position resolver; which removes all electrical connections between fixed and rotating parts, leading to a notable reliability gain.

Another positive consequence of such a design is the possibility to perform continuous (360 deg) rotations of the Scan Mirror at a speed of 10 rpm. This feature, exercised every now and then, will allow redistribution of the lubricant that could accumulate in some parts of the bearing races due to wear, so recovering the original smoothness and precision of movement. Another minor improvement is better confinement of the debris generated by the bearing wear itself.

The SUEA is a separate box, which contains all of the electronics needed for closed-loop control of the scan mirror angular position. It is able to implement five scan profiles at constant angular speed (as per GOME-1) and five new scans, compensating for the Earth's curvature and providing a constant linear scan speed on the ground. A new wide-amplitude scan corresponding to 1920 km on the ground is also implemented, which will allow complete Earth coverage in 1.5 days. All scans are completely in-flight reprogrammable, allowing an almost unlimited choice of profiles. The basic scan timing is 4.5 sec for the forward scan and 1.5 sec for the flyback.

The mirror movements are synchronised with the global instrument timings (detector integration times, etc.). In the event of a failure in the synchronisation interfaces, the Scan Unit can autonomously perform a pre-programmed series of operations, in order to partially recover the mission. The Unit's overall performance remains the same as for GOME-1; mirror positioning accuracy in fixed pointing will be better than 0.03 deg (corresponding to about 800 m on the ground), while in scanning modes it will depend on actual speed, but will anyway be better than 0.065 deg.

The Command and Data Handling Unit

All electrical and operational interfaces to GOME-2 (Fig.6) are routed through the Command and Data Handling Unit (CDHU). Within this unit, a primary processor is responsible for all ICU functions such as the reception and expansion of macrocommands, maintenance of history file, monitoring of instrument parameters and preparation of housekeeping telemetry formats. The ICU controls the operation of the Scan Unit via a bi-directional serial interface and provides each of the four FPA thermoelectric coolers with an individual thermal-control loop. A secondary processor controlling the Science Data Management board takes care of science data collection, processing and packetisation.

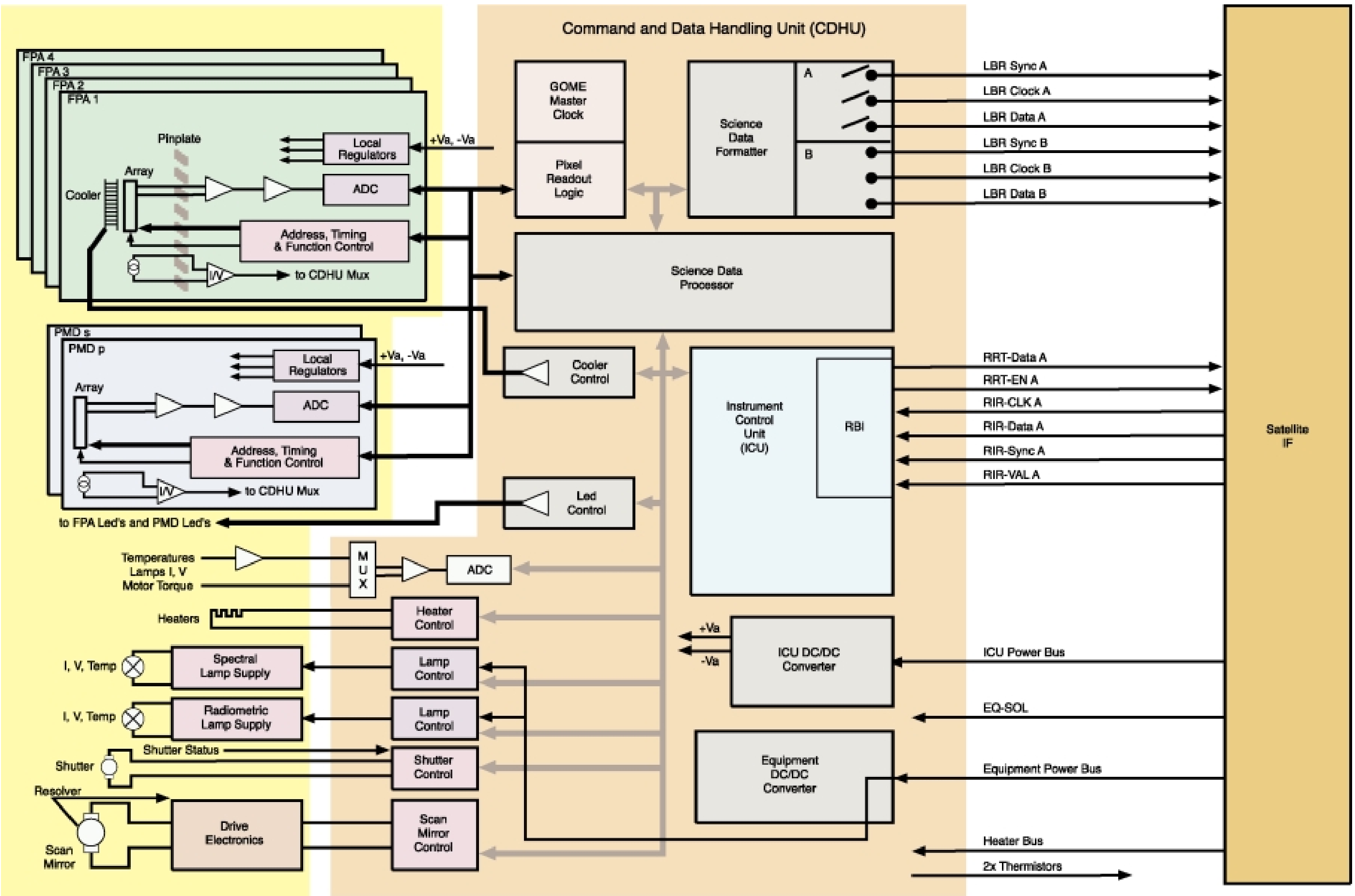

Figure 6. GOME-2 block diagram and electrical interfaces

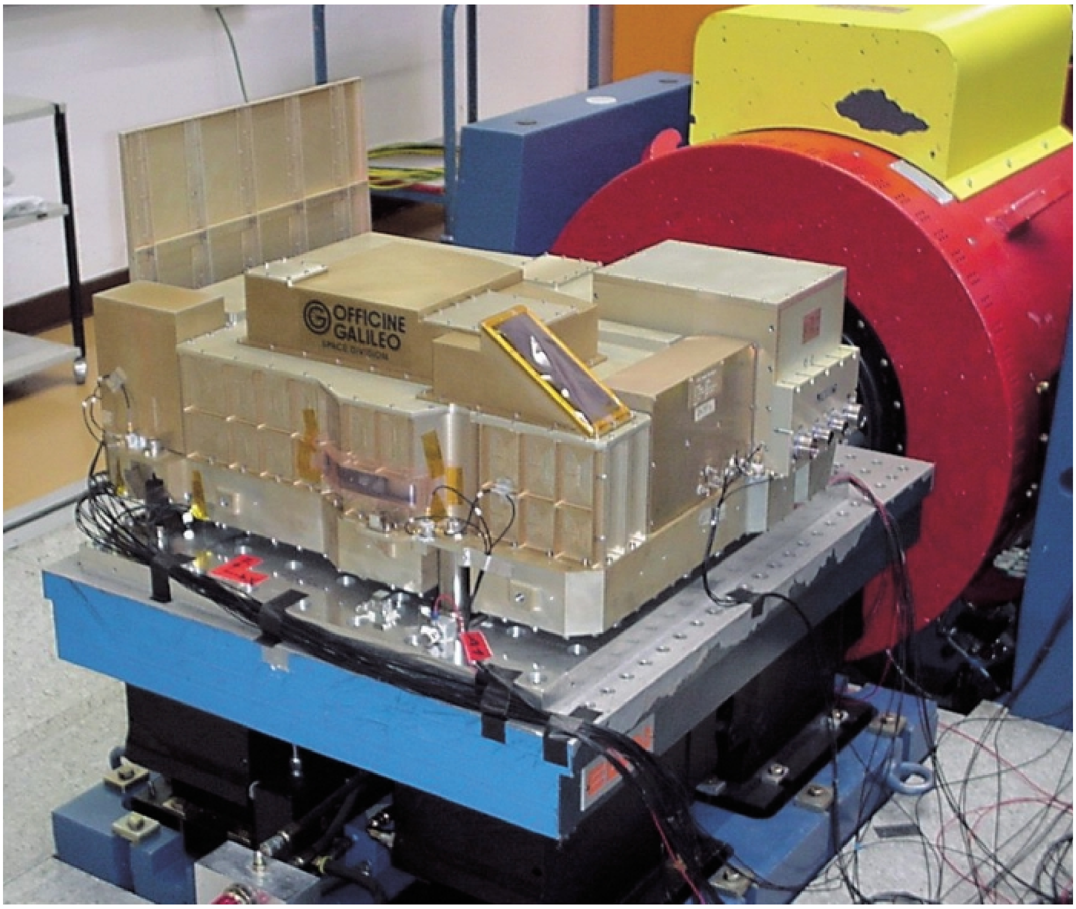

Figure 7. GOME-2 structural model during vibration testing

Pre-flight calibration

Although GOME-2 includes a number of on-board calibration capabilities, a thorough on-ground calibration exercise is required prior to launch. The most important measurements are: the characterisation of the Bi-Directional Scattering Function (BDSF) of the diffuser built into the Calibration Unit; and the characterisation of the polarisation response of the instrument as a function of the different optical paths for solar calibration and Earth nadir viewing, as a function of scan mirror position and wavelength. These calibrations are performed in a thermal-vacuum chamber at the instrument calibration contractor's site (TNO/TPD, NL). A number of additional measurements are made for various purposes, including more comprehensive instrument characterisation and consistency cross-checking. In particular, full radiance and irradiance calibrations using Earth and Sun observation paths are performed with NIST calibrated light sources for the PMU and the main channels. A full characterisation of the instrument's stray-light behaviour, the wavelength calibration, the field of view as well as the instrument response function, is performed as part of the calibration.

Operations

The GOME-2 instrument has many measurement and calibration modes. Moreover, the high variability of the light levels observed by the instrument over each orbit implies that the integration times of the detectors will have to be changed frequently. To limit the command rate, and implement the 36 h autonomy, the timeline concept validated by the GOME-1 experience has been extended. Each timeline now contains 28 different commands to be automatically expanded when required to change integration times, subsystem modes or parameter values. The CDHU will provide 12 predefined timelines, each dedicated to a specific orbit sequence (nominal, calibration, Sun calibration or test). The contents of the default timelines will be changed by macro command if necessary to tune the integration times and the modes sequencing to the actual in-flight conditions.

About once per month, an extensive calibration exercise will be performed, assessing any diffuser degradation, any changes in the dark signal currents and saturation levels of the detectors and making a wavelength mapping as function of the thermal variation. An etalon characterisation is also planned on these occasions. Lunar observations, which are restricted by the Sun-Moon-satellite scanner field of view geometry, will be performed whenever possible.

Data processing

GOME-2 data will be transmitted from the Metop to the receiving stations via an X-band link. From there they will be transmitted to the Core Ground Segment (CGS) 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 calibration parameters needed for further processing. Some of these calibration parameters come from the pre-flight calibration of GOME-2, while others will be derived from regular in-flight calibration measurements using the Sun and the on-board lamps as light sources. The calibration parameters are then applied on the raw data in order to obtain calibrated solar irradiance and Earth radiance spectra, together with auxiliary geophysical information, such as polarisation and cloud-fraction data. These level-1 products will then be disseminated by the CGS to Satellite Application Facilities (SAF) and other users for further processing. Specifications and a prototype processor for the GOME-2 level-0 to level-1 processing are currently being developed at DLR in Oberpfaffenhofen (D).

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 just three hours of the satellite measurement being made.

In addition to this operational near-real-time processing chain, GOME-2 data will be evaluated by scientific users for their own specific retrieval purposes. Exploitation of the new features that GOME-2 offers compared to GOME-1 will certainly stimulate a number of interesting new possibilities for atmospheric research.

Acknowledgement

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