GOME-2 ON METOP

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ABSTRACT

The Second Global Ozone Monitoring Experiment (GOME-2) will perform operational global monitoring of ozone column densities and profiles, and column densities of other atmospheric trace gases such as NO_2, BrO, OClO, HCHO, SO_2 and H_2O. GOME-2 is an improved version of the Global Ozone Monitoring Experiment (GOME-1) launched in 1995 onboard the second European Remote Sensing Satellite (ERS-2) It will be embarked on the MetOp series of three polar-orbiting operational meteorological satellites, to be launched in 2006, 2010, and 2014. Although GOME-2 is considered a "recurrent" instrument - the basic design of GOME-2 being the same as that of GOME-1 - a number of technical improvements were made based on the experience with GOME-1 operations and data analysis and in response to more stringent user requirements. Particular improvements concern spatial resolution, polarisation measurements, and calibration. Level 0 to 1 processing will take place in the Core Ground Segment (CGS) at EUMETSAT while level 1 to 2 processing will be performed by the partner institutes of the Ozone Monitoring Satellite Application Facility (O3MSAF). This paper presents the GOME-2 instrument characteristics and the main improvements as compared to GOME-1. Instrument calibration aspects are discussed, covering on-ground calibration results, in-orbit verification during the first weeks after launch, and the scenario for routine in-orbit calibrations. An overview of the on-ground processing of GOME-2 data from raw instrument packets (level 0) via calibrated (ir)radiances (level 1) to geophysical data (level 2) is presented. As GOME-2 data will provide long time series of a number of trace gases, GOME-2 instrument and processing performance monitoring is also discussed. Additionally the post-launch GOME-2 calibration and validation activities, planned to be carried out centrally at EUMETSAT will be described. This includes real-time verification and quality checking of the GOME-2 level 1 products, in addition to full validation activities taking into account feedback from the retrieval of geophysical parameters.

1. INSTRUMENT OVERVIEW

The GOME-2 instrument is a medium resolution nadir-scanning UV/visible spectrometer. It comprises four main optical channels which focus the spectrum onto linear silicon photodioide arrays of 1024 pixels each, and two Polarisation Measurements Devices (PMDs) containing the same type of arrays for measurement of linearly polarised intensity in two perpendicular directions. The four main channels provide continuous spectral coverage of the wavelengths between 240 and 790 nm with a spectral resolution (FWHM) between 0.26nm and 0.51nm. Compared to the main channels the PMD measurements are performed at higher spatial but lower spectral resolution, comprising 15 programmable spectral bands per PMD channel. The PMD channels are designed such that maximum similarity of their optical properties is ensured. The wavelength dependent dispersion of the prisms causes a much higher spectral resolution in the ultraviolet that in the red part of the spectrum. In order to calculate the transmission of the atmosphere which contains the relevant information on trace gas concentration, the solar radiation incident on the atmosphere must be known. For this measurement a solar viewing port is located on the flight direction side of the instrument. When this port is opened, sunlight is directed via a ~40° incidence mirror to a diffuser plate. Light scattered from this plate, or in general, light from other calibration sources such as the Spectral Light Source (SLS or HCl) for wavelength calibration, and the White Light Source (WLS) for etalon (and optionally pixel-to-pixel gain) calibration are directed to the scan mirror using auxiliary optics. Diffuser reflectivity can be monitored internally using light from the SLS. All internal calibration sources with their optics are assembled in a sub-system called the calibration unit. The only exceptions are the light emitting diodes (LEDs) which are located in front of the detectors to monitor the pixel-to-pixel gain. For more information on the GOME-2 instrument see [1].

The default swath width of the GOME-2 scan is 1920km which enables global coverage of the Earth's surface within 1.5 days (note that other swath widths are also commandable). The scan mirror speed can be adjusted such that, despite the projection effect, the ground is scanned at constant speed. The along-track dimension of the instantaneous field of view (IFOV) is ~40km which is matched with the spacecraft velocity such that each scan closely follows the ground coverage of the previous one. The IFOV across-track dimension is ~4km. The actual integration time used (and thus the ground-pixel size) will depend on the light intensity. The integration time can be separately set for each channel; in channel 1 and 2 it is possible to sub-divide the channel in two parts (called 'band 1a', 'band 1b' and 'band 2a, 'band 2b' respectively) having separate integration times. It is anticipated that a default integration time of 0.1875ms will be used in all channels with two exceptions where longer integration times are needed because of low light intensity: (i) Band 1a has a default integration time of 1.5 seconds (yielding three spectra per scan and one from the fly-back with the possibility of co-adding spectra to improve signal to noise characteristics). (ii) The integration time for all channels will be increased for low solar elevations (high solar elevation angles). For the 1920km swath, the maximum temporal resolution of 187.5ms for the main channels (23.4ms for the PMD channels) corresponds to a maximum ground pixel resolution (across-track x along-track) of 80km x 40km (10km x 40km for the PMDs) in the forward scan. A summary of the GOME-2 instrument characteristics and the main improvements as compared to GOME/ERS-2 is given in Table 1.

Table 1. Summary of GOME-2 instrument characteristics and the main improvements as compared to GOME/ERS-2 (shown in red).

Principle	Nadir-scanning UV/VIS grating spectrometer	
Wavelength Range	240 – 790 nm in 4 channels 300 – 800 nm in **2** polarisation channels (s/p)	
Detectors	1024 element Reticon linear diode arrays	
Readout time	**46.875 ms (complete array)**	**(/2)**
Spectral sampling	0.12 – 0.21 nm (main channels)	
Spectral resolution	FWHM **0.26 – 0.51 nm** (main channels)	
Swath width	Default **1920 km**	**(*2)**
Swath type	**Earth-curvature compensating**	
Min effective IT	**187.5 ms**	**(/8)**
Spatial resolution	Default **80x40 km2**	**(/4)**
Internal calibration	LED, Spectral lamp (PtCrNe**Ar), White lamp**	
Sun diffuser	**Quartz quasi-volume**	
Data rate	**400 kbits/s or 300 MB/orbit**	**(*10)**

2 . ON-GROUND CALIBRATION AND CHARACTERISATION

The GOME-2 instrument was built by an industrial team lead by Galileo Avionica (I) with support from Laben (I), TNO-TPD (NL), Arcom Space (DK), Innoware (DK) and Finavitec (FIN) where TNO-TPD were responsible for the calibration and characterisation of the instrument. Calibration and characterisation measurements, needed to meet the accuracy requirements for measurements made in thermal vacuum and under ambient conditions, were taken during an extensive on-ground campaign. The detailed characterisation measurements are fully described in [2] and [3]. Characterisation measurements have been post-processed to provide Calibration Key Data files which are documented in terms of both content and format in [4], [5] and [6]. Verification of the Calibration Key Data was addressed during dedicated Calibration Results Reviews ([7], [8], and [9]) for each flight model. Verification of the on-ground instrument performance against instrument requirements was also carried out at this time. A sub-set of the Calibration Key Data are a required input to the GOME-2 level 0 to 1 processor e.g. the radiance, irradiance and polarisation response of the instrument. For a full list of those Key Data used by the GOME-2 level 0 to 1b processing chain see [10].

Other Key Data describe aspects of the on-ground behaviour of the instrument which will also be measured in-orbit using on-board calibration targets e.g. dark signal performance, pixel-to-pixel gain, spectral calibration, and etalon. For these aspects the Calibration Key data form the starting point for instrument monitoring activities. Additionally, the GOME-2 Error Assessment Study ([11] & [12]) showed for the first time that O_3 profile retrieval is very sensitive to knowledge of the shape of the slit-function in the wavelength interval of the ozone Huggins bands (320-340nm), which is used for retrieval at low altitudes. It was therefore concluded that, for height-resolved O_3 data products from GOME-2 to meet specified User Requirements ([13] & [14]) the slit-function shape must be characterised at sub-pixel resolution pre-flight, as this cannot be determined adequately from information available in-flight. As a result additional slit function characterisation data were acquired during the on-ground calibration and characterisation campaign [15] and further analysed by TNO-TPD and the Rutherford Appleton Laboratory to provide additional Calibration Key data that describe the slit-function shape at sub-pixel resolution, for use in level 1 to 2 processing [16]. Trace gas absorption spectra measurements have also been made with each flight model after completion of the other on-ground calibration and characterisation activities. This was a dedicated activity carried out by the University of Bremen with the support of TNO-TPD. In particular, absorption spectra of O_3, NO_2 and O_2 were measured in the wavelength region 230-800nm for a range of temperatures. These data will also be made available for use in level 1 to 2 processing.

3 . GOME-2 TIMELINES

The GOME-2 instrument may be operated using timelines (GTL). Timelines are used primarily to reduce the load on the satellite up-link and additionally to provide on-board autonomy. One GTL is pre-loaded as a series of up to thirty three individual instrument commands that are executed without the intervention of the Instrument Control Unit (ICU) or the Payload Module Controller (PMC). GOME-2 can store up to sixteen timelines. Twelve default timelines will be loaded prior to launch and represent a library immediately available for use at the start of instrument operations. GOME-2 operations and science data acquisition are strongly linked to the viewing geometry and the Solar Zenith Angle (SZA), which determine the expected intensity of light received and the corresponding integration times required. There is in principle no restriction to the duration of a timeline or when it can be activated during an orbit. However in order to simplify the sequencing and generation of timelines all default timelines start with a SZA equal to 90 degrees minus an arbitrary offset of 580 seconds and will have a duration of one orbit. The sequence of commands as well as their duration will remain constant over the year. The nominal scenario for the scheduling of GOME-2 timelines during routine operations, including both earth scanning and in-flight calibration measurements, is shown in Fig. 1 (below).

4 . IN-ORBIT VERIFICATION

GOME-2 In-Orbit Verification (GOME-2 IOV) will be under the responsibility of the European Space Agency (ESA) and will be carried out in the time period, launch to launch plus 8 weeks. The primary objective of GOME-2 IOV is to verify that the instrument meets its functional and performance requirements. This will be achieved by exercising specific instrument operations, first via manual commanding and then using dedicated test timelines, and by analysis of raw data from both the S and X bands using dedicated test tools. Demonstration of nominal instrument performance is a prerequisite for successful GOME-2 IOV and Commissioning Phase Hand-over Reviews. In addition GOME-2 IOV activities are expected to provide significant input to the planning of commissioning phase and routine operations. The specific functional and performance tests carried out during IOV are fully detailed in [17].

5 . INSTRUMENT MONITORING

Verification of the correct functioning of the GOME-2 instrument requires continuous instrument monitoring activities. These activities will start during the commissioning phase, specifically during in-orbit verification of the instrument function and performance, and continue during the remainder of the commissioning phase and during routine operations. Furthermore, instrument characteristics such as radiance and irradiance sensitivity will change during the GOME-2 lifetime due to in-orbit degradation of the instrument. A subset of level 0, 1a and 1b data necessary for instrument performance monitoring and for the calculation of correction factors to account for changes in the sensitivity of the instrument, will be produced. These monitoring data will be further analysed and degradation correction factors derived where appropriate. The starting point for monitoring activities using internal calibration sources are on-ground reference measurements contained within the set of Calibration Key Data files described in [4] and [5].

GOME-2 timeline planning per 412/29 repeat cycle. Version 1.0, 1 March 2005

day	orbit offset	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	0	D	P/X	S	P/X	S	P/X	M	P/X	X	P/X	X	P/X	X	P/X	X
2	15	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
3	29	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
4	43	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
5	57	D	N	N	N	N	N	N	N	N	N	N	N	N	N	N
6	72	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
7	86	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
8	100	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
9	114	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
10	128	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X
11	143	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
12	157	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
13	171	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
14	185	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
15	199	D	N	N	N	N	N	N	N	N	N	N	N	N	N	N
16	214	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
17	228	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
18	242	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
19	256	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
20	270	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X
21	285	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
22	299	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
23	313	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
24	327	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
25	341	D	N	N	N	N	N	N	N	N	N	N	N	N	N	N
26	356	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
27	370	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
28	384	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	
29	398	D	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	X	P/X	

D	Daily calibration (incl. Sun mode)
M	Monthly calibration (incl. LED, WLS, SLS, SLS over diffuser modes)
N	Narrow swath (320 km)
P	Polar (north/south, overrides nominal swath if used)
S	Nadir static
X	Nominal swath (1920 km)

Fig. 1. GOME-2 nominal timelines pattern for routine operations.

6 . DATA PROCESSING

The central processing facility, located at EUMETSAT headquarters in Darmstadt, is responsible for the processing of all GOME-2 data up to level 1b, and delivers level 0 and level 1b products to the User community. This level 0 to 1b processing is carried out within the Core Ground Segment (CGS) by the GOME-2 Product Processing Facility (PPF) which converts raw instrument data (level 0 data stream) into time-stamped, geolocated, and fully spectrally and radiometrically calibrated radiances or irradiances (level 1b data stream). Level 0, 1a and level 1b data products, product quality and monitoring information are also generated by the CGS.

6.1 Level 0 to 1b Data Processing

The level 0 to 1a processing comprises both the determination of geolocation information on a fixed time grid, and the determination of applicable calibration parameters. From measurements of the various calibration sources encountered during each run of the processor, new calibration constants are calculated and written into an in-flight calibration data storage location. They are also retained in memory for use in processing those data acquired after the satellite comes out of the dark side of the orbit and before the next dump. Calibration parameter usage will be updated at the terminator. Calibration parameters are stored for the lifetime of the mission. The calibration constant determination comprises: dark current correction, pixel-to-pixel gain correction, determination of spectral calibration parameters, etalon correction, determination of straylight correction factors for the sun and polarisation measurements, and determination of the solar mean reference spectrum, and atmospheric polarisation state. The geolocation of the measurements is calculated from the appropriate orbit and attitude information, and time correlation information in the level 0 data stream. Note: any application of calibration parameters in the level 0 to 1a processing should be regarded as interim, to facilitate the generation of new calibration parameters and correction factors. There is no application of calibration parameters to main channel earth observation measurements. The output of the level 0 to 1a processor is to be formatted into the level 0 and 1a products as specified in [18] and [19].

The level 1a to 1b processing comprises the calculation of geolocation parameters for the actual integration time of each measurement, determination of straylight correction factors for the Earthshine measurements, and the conversion of the raw binary readouts on the level 1a data stream to calibrated radiance and irradiance data. Effective cloud fraction and cloud top pressure are also determined. Furthermore, calibrated measurements from the on-board calibration sources, and the sun and moon are available in the level 1b product. Level 1b data are formatted as specified in [18] and [19].

A number of checks are performed during Level 0 to 1a Processing and Level 1a to 1b Processing and the results are stored in Product Confidence Data records (PCDs) in the Level 1a and Level 1b data products. PCDs are provided both at the product and scan level. PCDs containing information about the quality of applied calibration parameters is also included. A pre-processing function extracts the PCDs directly after processing of the level 1a and 1b data and a second function further condenses the extracted data to provide daily, weekly, monthly and yearly Product Quality Summaries and "Quick-Look" information. The highest level of detail, on measurement pixel level, is not covered by this automatic functionality.

6.2 Level 1b to 2 Data Processing

The responsibility for extraction of meteorological or geophysical (level 2) products from GOME-2 lies with the Satellite Application Facility on Ozone Monitoring (O3MSAF). The development of the O3MSAF was started in 1997 and is coordinated by the Finnish Meteorological Institute (FMI) in Helsinki (see http://o3saf.fmi.fi for further information). As part of the distributed element of the EUMETSAT Applications Ground Segment, the SAF on Ozone Monitoring will provide operational services to end-users, e.g. real time or off line product services, data management and related user services, including co-ordination of and support to relevant research and development. The SAF Visiting Scientist Programme allows involvement of scientific experts external to the SAF Consortium.

The O3MSAF will produce three classes of level 2 products from GOME-2. These are the Near Real Time (NRT) products, which will be made available and distributed to users within 3 hours of sensing, the Off-line products which will be available no later than 15 days after sensing from the O3MSAF archive, and experimental products whose dissemination and coverage is yet to be decided. Reprocessing the geophysical products for climate applications is also anticipated. The O3MSAF will also provide on-line Validation Services on an operational basis. The full level 2 product list includes: ozone profile and aerosol products, total column ozone and trace gas products, near-real time UV fields, and off-line UV fields including clouds and surface albedo. For further information see [14], [20] and [21].

7 . LEVEL 1 VERIFICATION, CONFIDENCE CHECKING AND VALIDATION

It is not possible to fully verify and validate all GOME-2 level 1 products without feedback from the validation of atmospheric constituent retrievals. The spectral solar irradiance data and the cloud parameters may be fully validated, but spectral radiance data can only be partially validated. There are however a number of other parameters in the level 1 product that can be verified or used for confidence checking. These include the geolocation information, spectral calibration measurements, measured stokes fractions, cloud parameters and solar irradiance measurements.

GOME-2 has a number of Earth scanning observation modes in which measurements of backscattered radiance spectra are made. The validation of Earthshine radiance measurements from GOME-2 is an extremely difficult task due to the inherent variability of the observed atmosphere, clouds, and ground scenes, and the dependence of the measured spectrum on the viewing geometry. These data cannot be completely validated without feedback from level 2 product validation. Further feedback will be provided by NOAA who plan to process GOME-2 level 1b data using the SBUV/2 ozone profile algorithm. Diagnostic information produced will provide useful feedback on the quality of the GOME-2 level 1b data product. A number of possibilities do exist and will be pursued however, for the preliminary checking and validation of GOME-2 radiance spectra. These include various UV albedo checks in the 240-290nm spectral region, comparison of GOME-2 backscattered radiance spectra with nadir backscattered radiance spectra measured by other satellite-based sensors, and comparison of measured GOME-2 spectra with back-scattered spectra simulated using a radiative transfer model. The utility of the latter two methods may also be restricted to the Ultra Violet region.

As described above the operational GOME-2 level 2 data products will be produced by the Ozone Monitoring Satellite Application Facility (O3MSAF), part of the EPS Distributed Ground Segment. O3MSAF level 2 product validation activities are expected to provide relevant feedback for level 1 product validation. In particular diagnostic output from the level 2 retrieval algorithms will contain useful information for analysis of level 1 product quality. Similarly information on instrument performance and level 1 product quality, obtained during the level 1 verification and validation activities, will provide valuable input to the level 2 validation activities. In addition a restricted processing capability for the retrieval of atmospheric constituents is required centrally at EUMETSAT in support of GOME-2 level 1 product validation. This will comprise at a minimum an ozone profile, a total column ozone, an Aerosol Absorbing Index (AAI), and a minor trace gas retrieval capability, in particular total column NO_2 and BrO. This capability will be used to provide an independent estimate, on the basis of the quality of the retrieved atmospheric constituents, of the quality of the level 1 data products. Validation of these products will be primarily based on comparison with other independently validated spatially and temporally collocated measurements. Sources of independent validation data sets include ground-based data, satellite-based data, and aircraft- and balloon-based data.

8 . REFERENCE DOCUMENTS

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