THE OPTICAL MONITORING CAMERA ONBOARD INTEGRAL

J.M. Mas-Hesse[1], A. Giménez[1,2], A. Domingo[3], D. Rísquez[3], and M.D. Caballero[3]

[1]*on behalf of the OMC team*
[1]*Centro de Astrobiología (CSIC-INTA), POB 50727, E-28080 Madrid, Spain; mm@laeff.inta.es*
[2]*Research and Scientific Support Department, ESA, ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands*
[3]*Laboratorio de Astrofísica Espacial y Física Fundamental (LAEFF-INTA), POB 50727, E-28080 Madrid, Spain*

ABSTRACT

The Optical Monitoring Camera (OMC) is observing the optical emission from the prime targets of the gamma-ray instruments onboard the ESA mission INTEGRAL, with the support of the JEM-X monitor in the X-ray domain. This capability provides invaluable diagnostic information on the nature and the physics of the sources over a broad wavelength range. Its main scientific objectives are: (1) to monitor the optical emission from the sources observed by the gamma- and X-ray instruments, measuring the time and intensity structure of the optical emission for comparison with variability at high energies, and (2) to provide the brightness and position of the optical counterpart of any gamma- or X-ray transient taking place within its field of view. The OMC is based on a refractive optics with an aperture of 50 mm focused onto a large format CCD (1024 $\times$ 2048 pixels) working in frame transfer mode (1024 $\times$ 1024 pixels imaging area). With a field of view of $5^\circ \times 5^\circ$ OMC is able to monitor sources down to magnitude V = 18. Typical observations are performing a sequence of different integration times, allowing for photometric uncertainties below 0.1 magnitude for objects with V $\leq$ 16.

Key words: Optical photometry; optical space telescopes; variable stars.

1. INTRODUCTION

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is dedicated to the fine spectroscopy and imaging of sources in the energy range between 15 keV and 10 MeV. INTEGRAL was launched on Oct. 17, 2002, from Baikonur with a PROTON rocket, into an initial 72-hour orbit with an inclination of 52.5 degrees, a height of perigee of 9000 km and a height of apogee of 154000 km. More details on the INTEGRAL mission can be found in [1] and [2]. The instrumentation includes a Spectrometer (SPI) and an Imager (IBIS), both using a coded-mask aperture. Two monitors provide additional data in the X-ray and optical domains. The Optical Monitoring Camera (OMC) offers the first opportunity to make photometric observations of long duration in the optical band simultaneously with those in X and gamma-rays. OMC has the same field of view (FOV) as the (fully coded) FOV of the X-ray Monitor (also based on a coded-mask aperture), and is coaligned with the central part of the larger fields of view of the Spectrometer and Imager. Additional information about the Spectrometer (SPI), Imager (IBIS) and X-Ray Monitor (JEM-X) can be found in this volume. Variability patterns ranging from minutes or hours, up to months and years are being monitored. For bright sources, fast optical monitoring at intervals down to 3 s is possible.

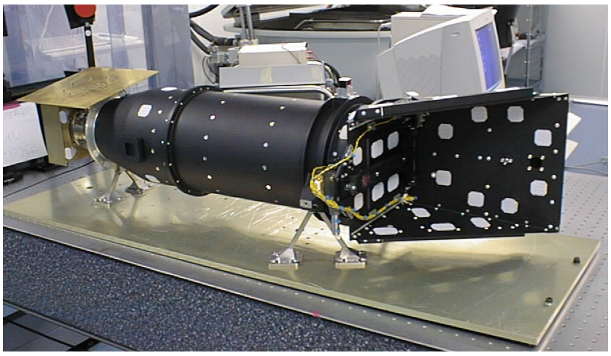

Figure 1. OMC Camera Flight Unit Model during integration and before the installation of the thermal blankets.

Multiwavelength observations are particularly important in high-energy astrophysics, where variability is typically rapid, unpredictable and of large amplitude. In particular, transient events are associated with many kinds of astrophysical phenomena and are of paramount importance in the X and gamma-ray Universe. Arranging simultaneous multifrequency observations for both ground-based and space-borne instruments might be quite difficult. Therefore, having onboard INTEGRAL an optical monitor like the OMC, adapted to the spatial resolution and field of view of the high-energy instruments, is a powerful additional tool for the understanding of high-energy astrophysical processes. The main scientific objectives of the OMC are:

- To monitor during extended periods of time the optical emission of all high-energy targets within its field of view, simultaneously with the gamma and X-ray instruments. This will allow the correlation of the optical light curves with the variability patterns derived from the hard X-ray and gamma-ray measurements.
- To provide simultaneous and calibrated standard V filter photometry of the high-energy sources for comparison with previous or future ground-based optical observations.
- To monitor serendipitously a large number of optically variable sources within its field of view. This will lead to the delivery at the end of the mission of a catalogue of thousands of variable sources with a well calibrated optical monitoring, covering periods of minutes to weeks and months.

The following European institutes have contributed to the development of OMC: Instituto Nacional de Técnica Aeroespacial – Madrid, Centre Spatial de Liège, Mullard Space Science Laboratory – University College London, University College Dublin and Dunsink Observatory Dublin, Astronomical Institute Ondrejov and University of Barcelona.

The main characteristics of OMC were described in [3–6]. In this contribution we summarize again for completeness the main performance and characteristics of the instrument, and describe the functionalities of the OMC Data Server.

2. INSTRUMENT DESIGN

The Optical Montoring Camera (OMC) consists of an optical system focused onto a large format CCD detector working in frame transfer mode. The optics is based on a refractive system with entrance pupil of 50 mm, focal length of 154 mm, and a field of view of $5^\circ \times 5^\circ$. The optical design consists of six radiation-hard glass lenses (F/3) housed in a titanium barrel. The filter assembly holds two colored filters (Schott BG39 and GG495) defining a V filter (passband centered at 550 nm) to allow for a straightforward comparison with previous photometric data of the observed targets obtained from ground. An additional BK7G18 glass plate protects the filters from radiation. The optical throughput of the system is slightly higher than 70% at this wavelength, and the CCD quantum efficiency within the V filter passband is about 88%. An LED light source within the optical cavity provides "flat-field" illumination of the CCD for on-board spatial non-uniformities calibration. Both the Titanium lens barrel and the focal plane cavity where the CCD is mounted, made of Invar, were coated with black Chromium plating to minimize straylight. The combination of Titanium for the lens barrel and Invar for the focal plane cavity allowed to have an almost athermal design, with the system focused over a wide range of temperatures, so that no focusing mechanism was required.

The stray-light requirements are very stringent and an optical baffle has been designed using ray-tracing simulations to achieve the necessary reduction of scattered sunlight and also the unwanted stray-light coming from non solar sources outside the field of view. A once-only deployable cover protected the optics from contamination during ground preparations (mostly dust particles) and early operations in orbit (outgassing from the spacecraft). The OMC Flight Unit model is shown in Fig. 1 during the integration activities.

The CCD (1024×2048 pixels) uses one section (1024×1024 pixels) for imaging and the other for frame transfer before readout. The frame transfer time of about 0.2 ms avoids the need for a mechanical shutter. The selected chip for the OMC is an EEV CCD 47-20, with an imaging area of 13.3×13.3 mm. It required a full qualification program for space applications which was carried out by the OMC consortium. The CCD head is cooled by means of a passive radiator to an operational temperature of about -80 C degrees.

The OMC instrument includes also an Electronics Unit, housing the CCD readout electronics, the necessary power conditioning electronics and the corresponding interface with the standard dedicated DPE (Data Processing Electronics) of the spacecraft. The readout mode allows the extraction of only given sections from the CCD instead of the complete frame in order to permit, when needed, fast monitoring of selected stars (while the CCD readout is at a frequency of 300 kHz, the time required to transfer a full image to the DPE memory is about 30 seconds). The Analogue to Digital Converters (ADC) work with 12 bits, providing a sampling of up to 4096 digital levels.

Several trade-off studies had to be performed during the preliminary design of the OMC. First the field of view was adopted to fit the high-energy instruments, in spite of the loss of photometric accuracy by the increase in the background contribution (diffuse light and source confusion). OMC is thus designed as a monitoring camera adapted to the spatial and photometric resolution required by gamma-ray astronomy, rather than a telescope with high optical performances. The field of view of the OMC complies with the requirement to monitor the main central region of both the Spectrometer and the Imager and is the same as the fully-coded field of view of the other monitor in the X-ray range, so that simultaneous optical and X-ray monitoring of the prime targets can be guaranteed. On the other hand, important science results are expected from simultaneous long-duration V photometry and X-ray data of additional sources in a wide field of $5^\circ \times 5^\circ$.

The scientific performance and additional parameters of the OMC are finally summarized in Table 1.

Table 1. OMC Scientific Performance and characteristics.

Parameter	Value
Field of view	$4^\circ.979 \times 4^\circ.979$
Aperture	50 mm diameter
Focal length	153.7 mm (f/3.1)
Optical throughput	$>$70% at 550 nm
Straylight reduction factor (within the unobstructed field of view)	$<10^{-5}$ (for diffuse background)
Point spread function	Gaussian with FWHM $\sim$1.4 pix (corresponding to ~ 24.5 arcsec)
Point source location accuracy	~ 5 arcsec
CCD pixels	2061 $\times$ 1056 (1024 $\times$ 1024 image area) (13 $\times$ 13 μm^2 per pixel)
Image area	13.3 $\times$ 13.3 mm^2
Angular pixel size	17.504×17.504 arcsec
CCD Quantum efficiency	88% at 550 nm
Full well capacity	120,000 electrons per pixel
Analogue to digital converter levels	12 bits: $\sim$30 cts/digital level (low gain) $\sim$5 cts/digital level (high gain)
Frame transfer time	$\sim$2 ms
Time resolution	$\geq$3s
Typical integration times	10 – 200 s
Wavelength range	V filter (centered at 550 nm)
Limit magnitude (10$\times$100 s, 3σ)	17.6 (V)
(50$\times$100 s, 3σ)	18.2 (V)
Sensitivity to variations (10$\times$100 s, 3σ)	δm$_V$ $<$ 0.1 mag for V $<$ 16
Average number of stars per pixel	0.6 (full sky)
(m$_V$ $<$ 19.5)	2.0 (b = 0°); $<$ 0.1 (b $>$ 40°)

3. OMC CHARACTERISTICS AND SCIENTIFIC PERFORMANCES

3.1. Optical performance

The optical properties of the OMC can be appreciated in Fig. 2, in which we show the detail of a star image, well centered on a specific pixel. The resulting Point Spread Function has a Full Width at Half Maximum FWHM $\approx$ 1.4 pix, so that most of the energy is contained within a matrix of 3×3 pixels. The PSF is constant over the whole field of view, with no apparent aberrations (the images are monochromatic, within the Johnson V filter passband). OMC data can therefore be used to derive the pointing of its optical axis with an accuracy close to 5 arcsec.

3.2. Photometric performance

The photometric performance of the instrument is largely limited by its large pixel angular size, which implies significant contributions by faint stars and zodiacal light. The background associated to faint stars will be particularly significant in the Galactic Plane. At the 3 σ level, and assuming the minimum level of expected background (outside the Galactic Plane), the limiting magnitude of the OMC is m(V) = 18.2 (combining 50 images of 100 s integration each). Note that during a typical pointing of 30 minutes, the total effective integration time that can be achieved is about 1000 seconds. For the highest expected background level, i.e., within the Galactic Plane and with largest zodiacal light, the limiting magnitude will be below m(V) $\approx$ 17.4 (also for 5000 s effective integration).

On the other hand, the full-well capacity of the CCD determines the brightest stars that can be measured without pixel saturation for a given integration time. OMC is following an observing strategy that combines consecutive integrations of different duration (presently in cycles of 10, 50, 200 seconds), thus allowing the effective dynamic range in V magnitude to be extended to the range $V = 6.5 - 16$ in a single sequence of 30 minutes.

The absolute photometric calibration of the OMC is being done on a monthly base by monitoring the countrate measured on a large number of photometric standard stars. Figure 3 shows the light curve of a typical standard star, extended over a time range of 1100 days. Its luminosity remains very stable over the mission, with $\sigma \approx 0.025$ over 3 years. In Fig. 4 we plot one example of the regression analysis we are performing with the reference stars. It can be seen that the CCD is very linear over a factor 50 in flux. By fitting the catalogued V magnitude to the observed countrate we obtain the absolute calibration function, with an accuracy better than 3%. Part of the dispersion in the curve is due to the intrinsic uncer-

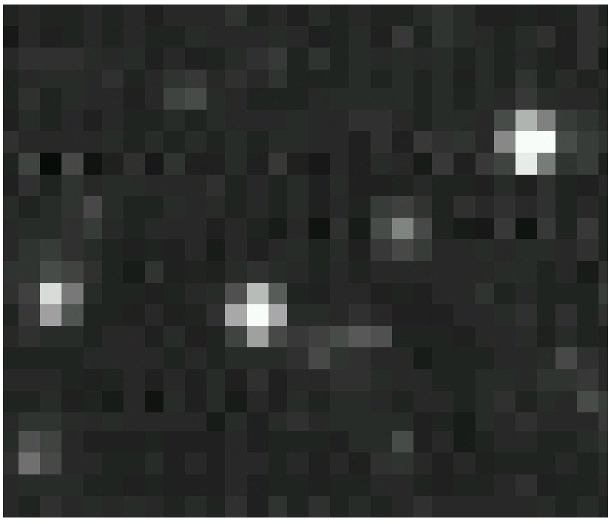

Figure 2. Typical OMC image, showing the Point Spread Function of the system.

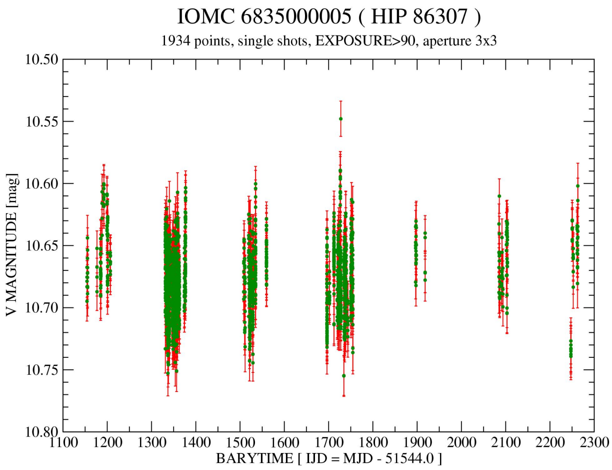

Figure 3. Light curve of a photometric reference star used for the OMC calibration, observed over a time span of 1100 days.

tainty in the V magnitude of the reference stars, taken from the Hipparcos and Tycho catalogues, as explained below. In any case, since the OMC is intended to detect relative variations, the absolute calibration is not critical, but allows mainly to monitor the possible degradation of the sensitivity.

The OMC is able to measure variations in V smaller than 0.1 mag for objects brighter than magnitude 16-17 (depending on background) and smaller than 0.03 mag for objects brighter than magnitude 14, as listed in Table 2. These values have been measured on the set of 10 photometric reference stars per field that are being continuously observed for photometric characterization of the instrument. These reference stars were selected to minimize the effects of nearby overlapping stars. The photometric accuracy achievable on scientific targets will depend strongly on the crowding of the field: stars falling

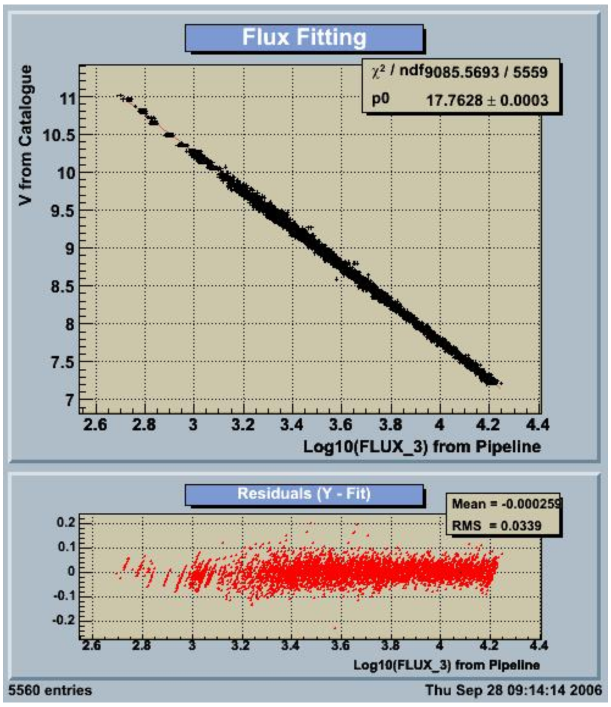

Figure 4. Example of the regression analysis being performed routinely to derive the OMC absolute photometric calibration. A large number of reference stars is being observed continuously to monitor and calibrate their measured flux.

within less than about 50 arcsec of the target source will contaminate the extraction region of 3×3 pixels. Furthermore, a field with many stars will induce a highly structured background, leading also to lower photometric accuracy.

In any case, very good V photometry can be performed with the OMC for objects of different brightness. For the faintest optical sources to be observed by the OMC, at about magnitude V = 17 – 18, photometric detections with sufficient accuracy can be obtained in a similar time to that devoted to the high-energy observations. Several individual photometric points can be produced in the optical band during the gamma-ray measurements and thus light variations as small as 0.5 magnitudes can be detected in those weak objects. In brighter sources, like several of the objects observed by INTEGRAL, faster and more accurate photometry is being obtained with the OMC.

3.3. OMC operations

OMC has been operating without major anomalies since INTEGRAL launch. OMC performs an auto-centering onboard at the beginning of each new pointing, to correct for possible errors in the pointing, or misalignments due to thermoelastic deformations. The INTEGRAL pointing is extremely good and only in relatively few cases an

Table 2. Photometric accuracy in V magnitudes of the OMC for different V values and various effective integration times. A typical pointing totals about 1000 s effective integration time. The pipeline processing is producing one photometric point every 10 minutes, corresponding to about 300 s effective integration time. No systematic biases have been considered. Uncertainties in Flat-Field calibration restrict the photometric accuracy to around $\sigma \approx 0.02$ when the target is measured on different CCD locations.

	V magnitude				
Effective integration time	8	10	12	14	16
10 s	0.007	0.02	0.1	–	–
300 s	–	0.005	0.01	0.04	0.3
900 s	–	0.003	0.006	0.026	0.17

offset of about 1 pixel ($=17.5$ arcsec) has been required.

We are monitoring continuously the dark current originated at the CCD and the degradation of any individual pixel or full columns. At the time of writing this contribution the dark current is still negligible (below 5 electrons in 200 s), and no radiation induced damage has been identified yet in any individual pixel.

Nevertheless, the OMC CCD has suffered the deposition of some contaminants on its surface, especially during the first months of operation. While the effect can be corrected through the flat-fielding process, some residuals at the level of about 2% can still appear. The effects of this contamination evolve within a period of 1 month, so that the flat-field calibration changes already from one calibration run to the next. As a result some photometric errors might be produced occasionally, especially for observations performed in between calibration runs.

Since only a number of windows (typically 100, and in any case less than 228) of 11×11 pixels can be normally downloaded to Earth, the targets to be monitored have to be pre-selected on ground. For this purpose, an OMC Input Catalogue has been compiled containing: Most gamma-ray sources, most X-ray sources, most AGNs within the photometric limits of the OMC, most variable stars (including eruptive variable stars, novae and cataclysmics), several known additional optical variable objects and HIPPARCOS and Tycho reference stars for astrometric and photometric calibration ([4]).

The Catalogue contains currently more than 500,000 targets. During the mission, additional sources of interest are being included, namely, newly discovered optical counterparts of high-energy sources (in particular sources discovered during the Galactic Plane Survey - see [1]), regions of special interest for INTEGRAL science, new supernovae and transient sources, or any other Target of Opportunity.

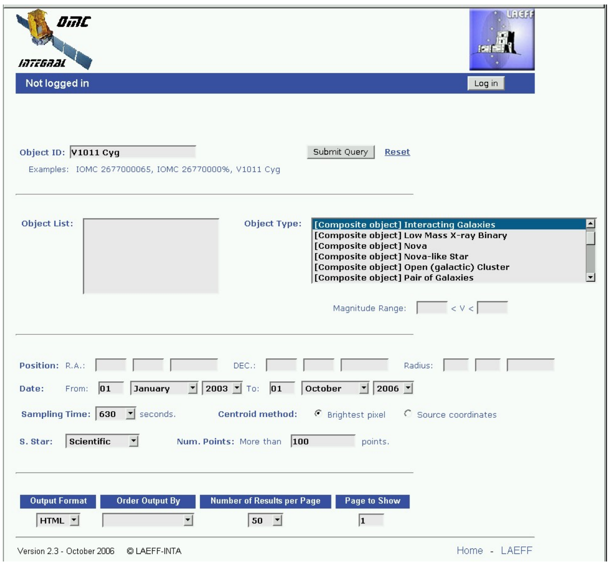

Figure 5. OMC Data Server user interface at http://sdc.laeff.inta.es/omc/.

4. THE OMC DATA SERVER

The OMC team at LAEFF[1] has developed a scientific archive, containing the data generated by the OMC, and an access system capable of performing complex searches, complementary to the INTEGRAL Archive hosted at ISDC [7]. A remarkable point is the existence of visualization and analysis tools, available from the user's interface, aimed to optimizing the scientific return of the OMC data. The system has been open to the scientific community since November 2003 and can be reached at `http://sdc.laeff.inta.es/omc/`. At the time of writing the system contains more than 100,000 light curves, each of them processed using three different sampling times (1, 630 and 9000 seconds). Figure 5 shows the main user interface to the server.

4.1. Functionalities

The main functionalities of the system are outlined below:

Archive Search: The query to access the archive is made by means of an HTML fill-in form which permits to perform queries by object name, coordinates, object type, V-magnitude range, date of observation, number of points of the light curve and/or sampling time. The output data may be ordered by object name, coordinates, magnitude or date and time of observation. Two output formats are available: HTML or ASCII.

Name Resolver: The system has a built-in name resolver utility which makes it possible to query the archive us-

[1] `http:/www.laeff.inta.es`

ing any of the object names provided by SIMBAD[2]. The name resolver gives more than three million and a half identifications for the astronomical objects contained in the OMC catalogue. The full list of the names associated to a given object can be obtained by simply clicking on the target name in the output form.

Results from Search: The following utilities are provided in HTML output format to the users:

Plot utility: A browse plot of a light curve can be generated on-the-fly by clicking on the corresponding link, with selectable zoom options.

FITS Header Display: Links are provided to display the FITS headers of each requested light curve file.

Data Retrieval: Light curves may be retrieved individually or in groups. If a single light curve is requested, it is delivered as an uncompressed FITS file. Multiple light curve retrieval generates a packed file in either tar.gz or zip format.

On-line Help: Help on a specific keyword can be obtained by simply clicking on it.

Help-Desk: A Help Desk facility to channel questions and to provide continuous support to users of the archive is available.

Setting of the extraction window size: The system offers different choices in the size of the extraction window.

Setting of the sampling time: Currently the light curves are sampled at three different intervals: 1, 630 and 9000 seconds. Subsequent releases of the OMC data server will also perform on-the-fly data processing according to the sampling time selected by the user.

5. SUMMARY

The Optical Monitoring Camera onboard INTEGRAL (OMC) is monitoring routinely the optical emission from the high energy targets being observed by INTEGRAL. In addition it is obtaining serendipitously optical light curves for hundreds of (potentially) variable objects. These sources are being selected automatically from the OMC Input Catalogue by the OMC Pointing Software, including all known variable objects as well as the known X and gamma-ray emitters, even those yet without identified optical counterparts.

OMC has been working without major anomalies since launch. The sensitivity has remained stable since then, as derived from the photometrical calibrations being performed on a monthly base. No damages induced by radiation have yet been detected on the CCD.

[2]SIMBAD database, operated at CDS, Strasbourg, France.

ACKNOWLEDGEMENTS

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REFERENCES

1. Winkler C., Courvoisier T.J.-L., DiCocco G. et al. 2003, A&A, 411, L1

2. Jensen P.L., Clausen K., Cassi C. et al. 2003, A&A, 411, L7

3. Mas-Hesse J.M., Giménez A. et al 2003, A&A, 411, L261

4. Domingo A., Caballero M.D., Figueras F. et al. 2003, A&A, 411, L281

5. Walton D., Thomas Ph.D., Culhane J.L. et al. 2003, A&A, 411, L275

6. Mazy E., Defise J.M., Plesseria J.Y. et al. 2003, A&A, 411, L269

7. Courvoisier T.J.-L., Walter R., Beckmann V. et al. 2003, A&A, 411, L253