The Gamma-Ray Imager on Board INTEGRAL

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ABSTRACT The Imager on-Board INTEGRAL Satellite (IBIS) is the high resolution Gamma-Ray imaging telescope on board INTEGRAL. Its scientific goal is to address, complemented by the high resolution Spectrometer (SPI), astrophysical processes from celestial sources and diffuse regions in the X and Gamma-ray domain. IBIS is an essential element with its powerful diagnostic capabilities of fine imaging source identification and spectral sensitivity to both continuum and broadened lines. It will observe, simultaneously with the other instruments on board INTEGRAL, celestial objects of all classes ranging from the most compact galactic systems to extragalactic objects. The telescope features a coded aperture mask and a novel large area ($\sim$3,000 cm^2) multilayer detector which utilises both Cadmium Telluride (16,384 detectors) and Caesium Iodide elements (4,096 detectors) to provide the fine angular resolution $\sim$12 arcmin , wide spectral response (20 keV to 10 MeV), high resolution timing (60 μs) and spectroscopy (6% at 100 keV) required to satisfy the mission's imaging objectives.

1. Instrument Main Characteristics

The basic IBIS characteristics have been already described by *Ubertini et al.*, 1996, and references therein. The present paper is an update of the intrument characteristics after the STM and EM programmes are almost completed.

The IBIS STM model is shown in Figure 1. The telescope is integrated with other instruments in the Payload Module and assembled with the satellite SVM. The picture was taken at ESA/ESTEC facilities during the 1998 qualification test campaign.

1.1. Bandwidth

IBIS is a wide band Gamma-ray Telescope operative in the energy range 20 keV-10 MeV. The lower end is due to the limited transparency of the mask support structure, and to a lesser extent to the FEE noise. The high energy cut-off is due to the limited efficiency of the CsI layer that has been optimised (since the Phase A design) at 511 keV: total detection efficiency at 10 MeV=10%. The transparency of the Tungsten elements of the coded mask causes a worsening of the MeV sensitivity. This effect has been minimised during Phase B increasing the Tungsten element thickness from 14 mm to 15mm. A further increase to 16mm is under evaluation and will imply an increase of the opacity of 3.5% @ 3MeV. This change is quite relevant for the high energy deconvolution process because of the high energy aperture modulation improvement.

Finally, the FEE design of PICsIT has implied a constrain on the dynamic range which has caused the introduction of an electronic energy cut-off of 4500 keV which has also limited the total and photopeak detection efficiency beyond 5 MeV. The total detection, and photopeak, efficiency of IBIS for on-axis sources is shown in

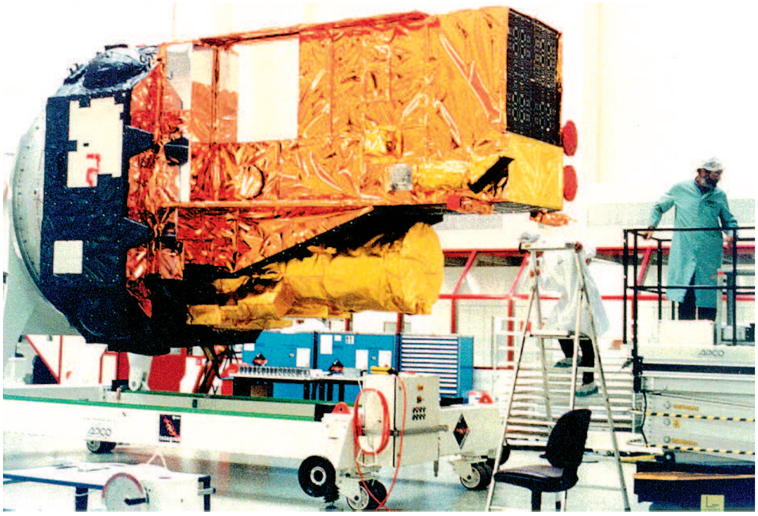

FIGURE 1.

figure 2a and 2b. The profiles associated with ISGRI alone, PICsIT alone, and coincidence events are shown.

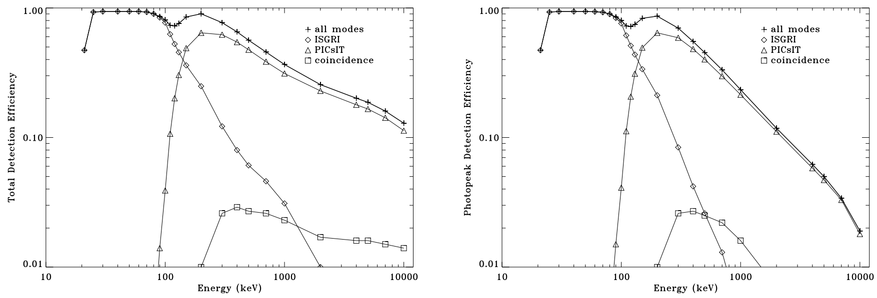

FIGURE 2a, b.

1.2. Field of View and Angular Resolution

One of the major requirements for the new generation of Gamma-Ray Telescopes is an outstanding angular resolution over a wide field of view. In particular the imaging capability is a key parameter for IBIS and for the INTEGRAL Mission as a whole. The choice of the large IBIS field of view will ensure a full compatibility with respect to the SPI one will allow for joint observations of any region of the sky. Such an extension of the FOV will also enable a better sky coverage increasing the number of detectable sources, and allows a monitoring as frequent as possible of sources, which is mandatory due to the high variability of the gamma ray sky. The IBIS angular resolution is 12 arcmin, whereas the point source location accuracy (for

Table 1. Scientific Parameter of IBIS compared with the EID-A requirement.

Parameter	EID-A IMAGER	Current IBIS
Energy Range	20 keV - 10 MeV	20 keV - 10 MeV
Energy Resolution		
% at 100 keV	7	7
% at 1 MeV	6	6
Field of View		
Fully coded	8°	9°
Partially coded	19° (0%)	19° (50%)
Continuum sensitivity		
3σ, 10^6s, at 100 keV (ph cm^{-2} s^{-1} keV^{-1}	4.10 10^{-7}	3.8 10^{-7}
3σ, 10^6s, at 1 MeV (ph cm^{-2} s^{-1} keV^{-1}	1.4 10^{-7}	2.1 10^{-7}
Line Sensitivity		
3σ, 10^6s, at 100 keV (ph cm^{-2} s^{-1} keV^{-1}	not specified	1.3 10^{-5}
3σ, 10^6s, at 1 MeV (ph cm^{-2} s^{-1} keV^{-1}	not specified	4.0 10^{-5}
Angular resolution	12 arcmin	12 arcmin
Point Source Location Accuracy (PSLA)	note specified	30 arcsec
Timing Resolution	Not specified	61μs (for E$<$200keV and Compton)
Subject to Telemetry allocation		1 ms (Spectral Timing)
and in-flight background		1000s (E$\geq$200 keV)

a strong source) would be around 30 arcsec or less. After the "phase A" study, the mask element size has been reduced to 11.2 mm keeping the mask-detector distance at 3133 mm above the upper detector to ensure 30% gain in angular resolution. The mask element reduction has not been coupled with a significant reduction of the detector pixel size implying a reduction of the imaging efficiency only from 90% to 81% for the first detector layer and from 75% to 63% for the second one.

1.3. The Coded Mask

The transparency of the mask supporting structure at 15, 20 and 50 keV is respectively 68%, 76% and 88% for on axis sources and 52%, 58% and 84% for sources 19 degree off-axix. The transparency of the mask elements (15mm Tungsten) is shown in Fig. 3.

1.4. Collimating System and Shielding

The current collimating system of IBIS is made of two subsystems mechanically independent based on tungsten and lead as passive material: (a) an hopper structure on the top of the ISGRI layer that is a truncated (at 550 mm height) pyramid with a profile that ideally joining the detector perimeter to the active mask sides; (b) a tube made of four walls (two vertical and two inclined) closing the aperture down to the hopper level. For the tube the adopted passive material is lead with a variable thickness distribution for mass minimisation while the hopper shielding is made of 1 mm thick tungsten layer. The passive shielding is designed to reduce the celestial

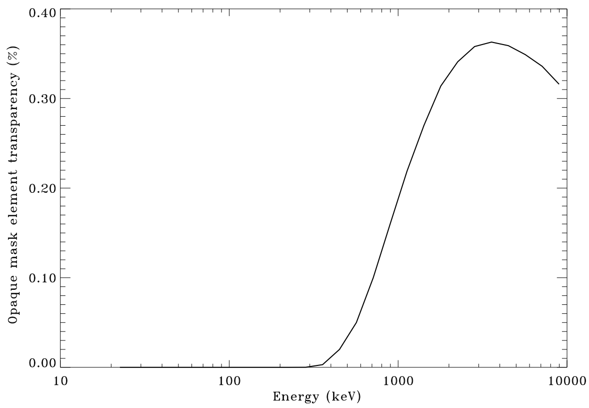

FIGURE 3.

diffuse X-ray background component as much as possible and it is opaque up to about 200 keV.

1.5. Active Shielding

The active shielding of IBIS consists in a 5 side BGO array made out of 16 independent BGO modules (2 slabs per module) read-out by 32 PMTs. At the beginning of the hardware phase has been built a Veto Development Model (DM) which is flight representative of the mechanical-optical configuration of a single BGO module. The DM is composed of two glued BGO slabs wrapped with white optical diffuser and integrated in its mechanical housing, and two 3" PMTs mechanically and optically coupled to the BGO slabs. Tests have been performed to measure the output of the module for a radiation source located at different places along the centreline of the two BGO slabs in order to study the uniformity of this detector system configuration, and to verify the capability of the detector to provide anti-coincidence pulses at the required minimum energy threshold (100 keV). The measurements, in spite of the different optical configuration have confirmed the results obtained from the light yield simulation studies. The detection efficiency is independent to energy (122 and 662 keV), due to a good light output uniformity, as a result of the good optical properties of the BGO slabs, performing an attenuation lenght better than 3m.

2. Energy Resolution

Good Spectral Resolution is a key feature for IBIS. The requirement to provide a moderately high energy resolution over the entire energy range is achieved by the use of innovative technologies. In the lower edge of the instrument has been employed of a novel type of solid state CdTe detector (4x4x2 mm^3) working at room temperature. In this way was possible to obtain a large area ($\sim$2600 cm^2) matrix of 128x128 elements resulted in good spectroscopic capability and outstanding angular resolution.

2.1. Low Energy Spectral Resolution

The figure 4 show spectra obtained with the first AMS polycell exposed to a mix of ^{57}Co and ^{133}Ba radioactive sources. The spectrum is obtained without selection on the rise-time. The spectral resolution improves using only the events presenting a rise-time shorter than 2 μs. Above 200 keV, the spectrum has been multiplied by 10 to allow for a better visibility of the details.

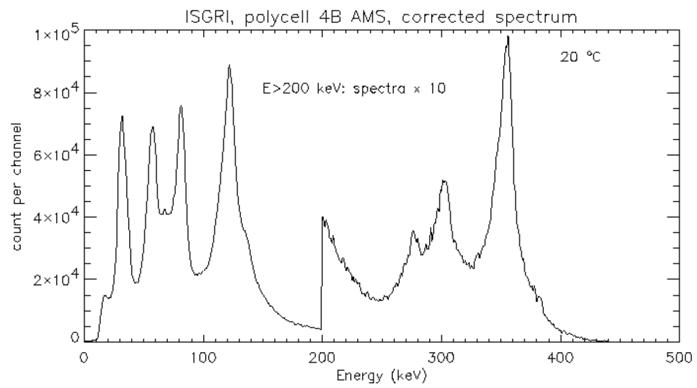

FIGURE 4.

2.2. High Energy Spectral Resolution

The high energy detection system is based on an array of small (8.55x8.55x30 mm^3) CsI detectors treated with a diffusing coating read out by a high efficiency photodiode coupled with a low noise ASIC. In this way is possible to obtain a large area matrix ($\sim$3000 cm^2) of 64x64 elements resulting in good spectroscopic capability, as shown in figure 5, and outstanding angular resolution up to 10 MeV.

3. Sensitivity

The IBIS continuum and line sensitivities is shown in figure 6a and 6b. The grey area is due to uncertainty in the background evaluation. In the case of events which trigger one detection unit both in ISGRI and PICsIT, it is in principle possible to increase the signal to noise ratio by exploiting the Compton kinematics information which is available through the double layer discrete eleme nt structure of the detectors. The sensitivity increase with respect to the PICsIT alone mode can be expressed as: $Is = (D_{COMPTON}/D_{PICsIT})\ [B_{PICsIT}/B_{COMPTON}]\ 0.5\ Fs\ (I_{COMPTON}/I_{PICsIT})$ where D are the detector efficiencies, B, the background count-rates, Fs, the sensitivity enhancement factor attained with the on-ground Compton selection and I, the imaging efficiencies.

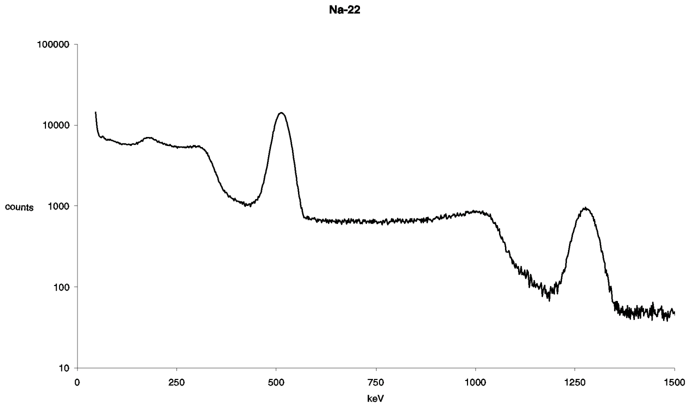

FIGURE 5. Na^{22} spectra (511 and 1275 keV)

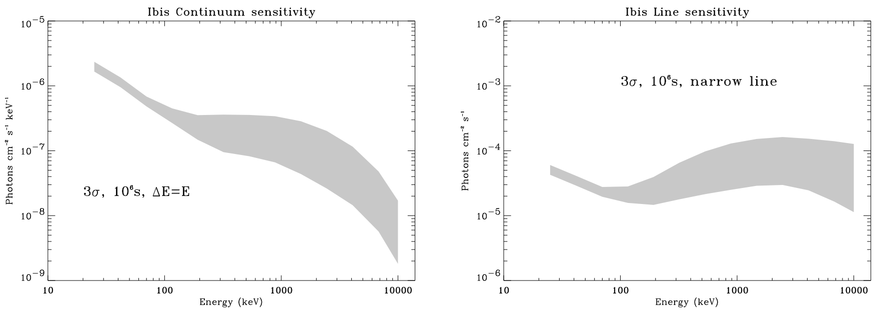

FIGURE 6a and 6b. IBIS Conntinuum (6a) and Line (6b) sensitivities (3, observing time 10^6s, ΔE=E/2). The grey area is due to uncertainty in the background evaluation.

4. Point Source Location Accuracy: **New Gamma Ray Sources Location Capability ~30 arcsec is an Outstanding IBIS Feature**.

The expected average Point Source Location Accuracy (PSLA) for an ideal coded aperture (CA) imaging system with a defined Point Spread Function (PSF) depends only on the signal to noise ratio (S/N) of the source (inversely proportional) and, for a strong source, the error can indeed be a small fraction of the angular resolution even for small values of the ratio mask element size/pixel size. To estimate the approximate IBIS PSLA we have performed the calculation for different values of mask/pixel size and S/Ns. The error depends on the source position and therefore we averaged over a large number of uniformly distributed positions. The average values for different ratios of pixel to mask linear sizes are reported in the figure 7 as a function of the source S/N. The expected error for the CsI layer will be comprised within values for 1 and 2 pixels/mask element (diamonds and triangles in the figure) while for the CdTe layer (ISGRI) the effective error will be within values for 2 and 3 (triangles and squares in the figure). Error in source location (half size of a square

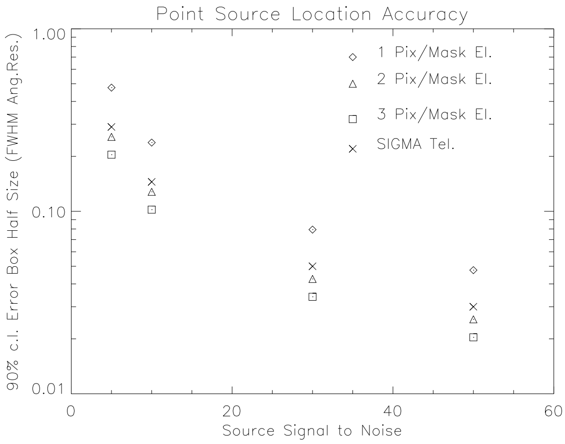

FIGURE 7.

error box) is evaluated at the 90% confidence level and 2 interesting parameters and it is expressed in units of projected mask element (= FWHM angular resolution). The S/N is defined here as number of reco nstructed source counts/SQRT (tot number of counts in the image). This method to calculate errors has been tested with simulations. Simulations have shown that these theoretical errors are correct down to S/N of 5-7. For an angular resolution of 12 arcmin and assuming no error in pointing axis reconstruction or other sy stematic effects ISGRI will locate a 30 sigma pointlike source at better than one arcmin: In figure 7 are also reported values calculated for the SIGMA telescope (crosses) in the 75-150 keV band.

5. Time Resolution

The highest IBIS time resolution is equal to the intrinsic time resolution of the two detector layers ISGRI and PICsIT, that is 250ns. However, due to telemetry limitations, we cannot send to ground all the informations with such a precision. Therefore, different time resolutions can be achieved depending on the scientific goal of the observation, whereas the full timing capability of 61μs will be the basic feature of the IBIS instrument below 1 MeV. For high energy observations of fast pulsars and QPOs, the spectral timing mode records the energy in 8 energy bands, and arrival time of each photon detected by PICsIT with a time resolution up to 1ms for E>200 keV. In the low energy range, E<200keV, the data will be transmitted in photon by photon mode with full time information. At higher energies, images of the sky will be accumulated into histograms with time bins of typically 965s for Galactic Plane Survey and 1000s for Galactic Central radian Deep Exposure and normal observation.

6. Gamma-ray Burst Philosophy

IBIS as a large area, high time resolution gamma-ray experiment is in itself very sensitive to gamma-ray bursts. We expect to have ~10-20/year in the IBIS FOV and ~1/orbit GRB detected out of the field of view. At GRB detection both detector layers will experience a high rate (up to several tenths of thousand counts per layer). However, due to system design constraints the possibility of exploiting 100% of the GRB science is severely compromised.The on board functions which can provide sufficient time resolution for GRB studies are: i) ISGRI Photon by Photon Mode (time resolution 64 microsec), ii) Compton Mode (time resolution 64 microsec)and iii) PICsIT Spectral Timing Mode (time resolution >1 millisec).

7. IBIS Calibration Plan

In order to meet the scientific objectives of IBIS, a comprehensive series of calibrations of the overall telescope are required. The calibrations will enable determination of the instrument response function(s) allowing observations to deduce location, spectral and temporal behaviour of X-ray and gamma-ray sources

7.1. Ground Calibration

A Science Group has been created within IBIS to oversee the interaction between the calibration, modelling and response generation tasks in order to provide the best possible final response functions. Calibrations will be performed at Component/Module Level, Detector Level, Instrument Level and Payload Level. End To End Test and Calibration of IBIS Flight Model integrated with the S/C are planned during spring 2000.

7.2. In-flight Calibration.

The level of calibration required to enable IBIS to operate at full efficiency has been the subject of a detailed study. In-flight calibration of IBIS will be provided for by both specific observations of point sources and empty fields at intervals through the mission lifetime. These observations will crucially include observations of the Crab to provide a strong stable point source for imaging and flux calibrations. The in-flight Calibration Unit will also provide a continuous flux of tagged photons. It is anticipated that results from in-flight calibrations with be incorporated into the calibrated model so as to enable updates to the IBIS response functions to be produced through the mission.

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REFERENCES

Ubertini, P. et al., ESA SP 382, 599, 1996