SECONDARY COMPTON IMAGING AND POLARIZATION CHARACTERISTICS OF IBIS

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ABSTRACT

The IBIS instrument on INTEGRAL comprises a two layer array of pixellated detectors making Compton kinematic reconstruction a feasible proposition for the suppression of background. Furthermore, direct Comptom imaging can used to achieve an angular resolution of three degrees (1σ) and a line sensitivity only a factor of 2-4 worse than that in coded mask imaging mode. We also demonstrate in this paper that the IBIS detector can be used as a powerful gamma-ray polarimeter and has a better than 20mCrab sensitivity in the 200-500 keV energy band to 100% polarized sources.

Keywords: Astronomy; Gamma-rays; Compton scattering; Polarization

1. INTRODUCTION

The current design of the IBIS/INTEGRAL instrument offers the opportunity of as a Compton imaging telescope and as a gamma-ray polarimeter which can function at the same time as it is operated as a coded mask imaging telescope. Compton images can be constructed using the scattered events between the CdTe and CsI detectors. The increased separation ($\sim$ 12cm) between the CdTe and CsI detector layers means that IBIS now has an angular resolution of the order of three degrees in its Compton imaging mode. The pixellated nature of the two IBIS detector layers implies that it has the capability in determining the azimuthal angle of the Compton scattered photon, which carries the polarization information of the incident photon. The characteristics and sensitivity of IBIS as a Compton imager and gamma-ray polarimeter are discussed in this paper.

2. COMPTON RECONSTRUCTION AND IMAGING

For each IBIS Compton scattered event between the CdTe and CsI detector layers, two angles can be reconstructed, see Figure 1. The first one is the kinematic scattering angle determined by the two energy depositions detected in the CdTe and CsI layers:

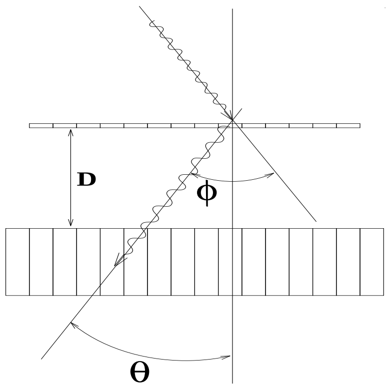

Figure 1: The definition of θ and Φ for Compton scattering in the IBIS detector

$$\Phi = cos^{-1}(1 - \frac{m_0c^2}{E_{CsI}} + \frac{m_0c^2}{E_{CdTe} + E_{CsI}})$$

for forward scattering (CdTe to CsI), or

$$\Phi = cos^{-1}(1 - \frac{m_0c^2}{E_{CdTe}} + \frac{m_0c^2}{E_{CdTe} + E_{CsI}})$$

for back scattering (CsI to CdTe). The angle Φ here is measured in respect to the incident photon direction. The second angle that can be calculated is the geometrical scattering angle θ defined as

$$\theta = tan^{-1}(\frac{r}{D})$$

for forward scattering, or

$$\theta = \pi - tan^{-1}(\frac{r}{D})$$

for back scattering. Here D is the CdTe layer to CsI layer distance and r the horizontal distance between the centers of the triggered CdTe pixel and CsI pixel. The angle θ is in respect to the telescope axis. If the

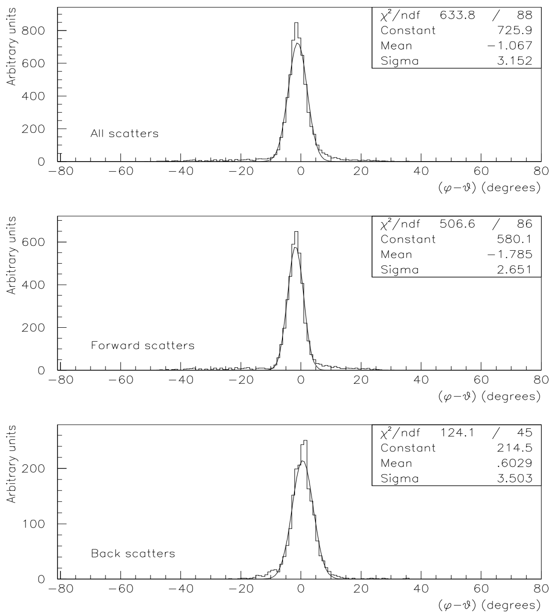

Figure 2: The PSFs of IBIS for 1 MeV on-axis photons. Events are classified as forward or back-scattered according to the smaller PSF value calculated. The smooth curves are the best Gaussian fits with the resulted fitting parameters displayed in the top-right corner in each panel.

incident photon direction is known, then θ can be easily transform to $\theta^{'}$ which is the geometrical angle with respect to the incident direction. The Compton Point Spread Function (PSF) is defined as

$$PSF = (\Phi - \theta^{'})$$

i.e. the distribution of the reconstructed scatter angles around the true scatter angle. For the on-axis incident case we have:

$$PSF = (\Phi - \theta)$$

The IBIS on-axis Compton PSF has been studied using Monte-Carlo simulations for many different types of source spectra. For each full-energy Compton event, the angles Φ and θ were calculated for both the forward and back scattering cases. Since IBIS has no time-of-flight information and it cannot tell whether a scattering is forward or backward. We classified the event to the case which gives the smaller PSF.

Figure 2 shows an example of the derived PSFs. The incident photons are 1 MeV on-axis and only full-energy events were used in the analysis. The top panel is the PSF for all Compton events and the middle and bottom panels are for forward and back scattered events respectively.

It is worth noting that the centroid positions of the PSFs are not at zero. In the calculation of θ it is assumed that the vertical distance between the events is D (i.e. the distance from the bottom of the CdTe layer to the top of the CsI layer). In reality the distance between interactions will be greater than D, and so the calculated angles will contain a systematic offset. Also one can tell from the large χ^2 values of the Gaussian fits that the PSFs are not ideal Gaussian shapes.

2.1. COMPTON BACKGROUND REJECTION

The shape of the PSF is determined by the energy resolution of the detectors and the (3D) positional resolution. The PSFs shown in Figure 2 are very representative of the PSFs expected from source signals. They show clearly that most of the events are concentrated in a narrow region around the centroid position. Studies of the background events show that the $(\Phi - \theta)$ distribution is much broader. This difference in width of the distribution leads to the possibility of rejecting some of the background events while retaining source events by selecting only events within a restricted region of the $(\Phi - \theta)$ distribution. A detailed study of the Compton kinematic reconstruction and background rejection has been carried out and been reported in an INTEGRAL internal report, Lei et al. (1996a). The main conclusions of the study can be summarised as follows:

1. The detection efficiency of IBIS in its Compton data mode decreases as the distance (D) between the ISGRI and PiCsIT detector planes increases. The efficiency is halved when D is increased from 2 cm to 20 cm.
2. For a source whose position is known, Compton reconstruction and event selection can reduce the background by a factor of 4 to 12, depending on the distance D and event energy, while maintaining a 70% selection efficiency for source events.
3. The optimal distance D for maximum sensitivity improvement in IBIS Compton mode is about 12 cm. The overall sensitivity improvement (taking into account the overall drop in detection efficiency due to increasing D, the 30% drop in efficiency due to event selection and the background reduction factor) is between 1.5 to 2 for on-axis sources.
4. A simple on-board reconstruction and selection algorithms can reduce the background, hence the telemetry rate, by a factor of 4, and making a modest improvement ($\sim$ 10%) in sensitivity.

2.2. DIRECT COMPTON IMAGING

IBIS is a coded mask imaging telescope and it images the gamma-ray sky by modulation and reconstruction. It has a fully coded field of view $\sim$ 9 degrees and an angular resolution of 12 arc-min. Coded mask imaging, while ideal for regions of discrete sources, has certain limitations when used to observe extended objects, Ubertini (1996). Hence one can foresee that IBIS will have difficulties in tacking some of the unsolved problems in observational gamma-ray astronomy, through coded mask imaging, such as the diffuse galactic annihilation 511 keV line and the

Energy (keV)	ϵ_{pp} (%)	A_{eff} (cm^2)	δE.(FWHM) (keV)	Background ($cs.s^{-1}keV^{-1}cm^{-2}$)	Line Sensitivity ($phs.s^{-1}cm^{-2}$)
511	1.5	20	65	1.53×10^{-5}	2.0×10^{-4}
1800	0.25	3.3	60	4.57×10^{-7}	1.9×10^{-4}

Table 1: The estimated IBIS performance in its direct Compton imaging mode at 511 keV and 1.8 MeV. The line-sensitivity is calculated at 3σ level and for 10^6 seconds. The mask effect which blocks off half of the detector area has been included in the calculations.

1.8 MeV Al^{26} line distributions as well as the cosmic diffuse gamma-ray distribution. The CdTe-CsI scattering data, however, allows the reconstruction of gamma-ray sky images via direct Compton imaging, either by simple back projection or maximum entropy or maximum likelihood algorithms, Schonfelder et al. (1993).

The angular resolution of IBIS in direct Compton imaging mode is in the order of three degrees (1σ) at 1 MeV, see Figure 2, which is comparable to that of COMPTEL at the same energy, Schonfelder et al. (1993). In Table 2.1. we summarises the key performance parameters of IBIS in direct Compton imaging mode at two astronomically important energies 511 keV and 1.8 MeV.

The estimated line sensitivity at 511 keV is about a factor of 4 worse than that predicated in its coded mask imaging mode for a point source, but at 1.8 MeV it is only a factor of 2 worse, Skinner (1996).

3. IBIS AS A GAMMA-RAY POLARIMETER

Gamma ray polarization data provide the measurement of important and unique information relating to the origin of the γ-ray emission. A number of astrophysically important γ-ray emission mechanisms are capable of producing polarized γ-rays: synchrotron radiation; curvature radiation; cyclotron emission; bremsstrahlung radiation; and Compton scattering etc. Each mechanism has its own polarization characteristics, eg. polarization angle of radio frequency emission from synchrotron should be at right angles to that of γ-rays, if the later is from curvature. The potential cosmic sources include X-ray pulsars, black-hole candidates as well as beamed AGNs. Solar flares are also strong candidate sources of polarized γ-rays.

Despite its great scientific importance, γ-ray polarization studies have not been realised in past γ-ray missions, mainly due to the instrumentation complications. Conventional Compton polarimeter designs have too low an efficiency for any astronomical application. The pixellated detector planes of IBIS which can act as both the scattering and absorbtion elements of a conventional Compton polarimeter will change this situation. In this section the polarization performance of IBIS is evaluated and its polarization sensitivity is derived.

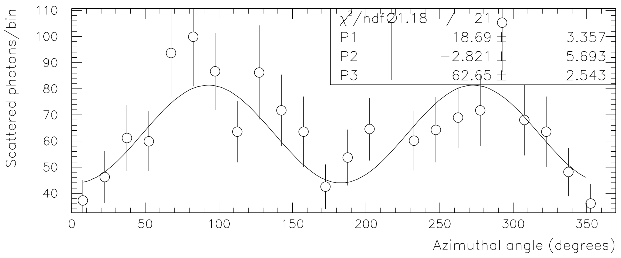

Figure 3: A M-C simulated azimuthal distribution of the CdTe - CsI scattered events between 200 - 1000 keV. The asymmetry in the distribution is clear and can be well fitted by the cos(2ϕ) form.

3.1. Polarization Characteristics of IBIS

Polarization of incident photons is detected via the asymmetrical distribution of the azimuthal angles (ϕ) of the scattered photons:

$$N(\phi) = Xcos(2(\phi-\eta)) + Y \qquad (1)$$

where η is the direction of the polarization vector of the incident photons. Figure 3 shows a M-C simulated azimuthal distribution of scattered events between the CdTe and CsI layers. The incident photons were on-axis and in the energy range between 200-1000 keV. The modulation factor of a Compton polarimeter is defined as:

$$Q = X/Y \qquad (2)$$

and the associated error is given by:

$$\Delta Q = X/Y\sqrt{(\Delta X/X)^2 + (\Delta Y/Y)^2} \qquad (3)$$

The sensitivity of a polarimeter to a 100% linearly polarized source is defined as:

$$S_{pol} = \frac{N_\sigma}{\epsilon Q}\sqrt{\frac{B}{AT\Delta E}} \qquad (4)$$

where B is the background rate in $counts.s^{-1}keV^{-1}cm^{-2}$, ΔE the energy band in keV, ϵ the detection efficiency, N_σ the significance

	Q	Δ Q	ϵ (%)	bkg. ($cs.s^{-1}keV^{-1}cm^{-2}$)	Sensitivity ($photons.s^{-1}keV^{-1}cm^{-2}$)
150 - 500 keV:					
CdTe-CsI	0.345	0.084	2.5	2.21×10^{-5}	2.61×10^{-6}
CsI- CsI	0.287	0.041	8.0	8.81×10^{-5}	1.96×10^{-6}
500 - 1000 keV:					
CdTe-CsI	0.264	0.076	2.0	1.08×10^{-5}	2.31×10^{-6}
CsI-CSI	0.196	0.021	12.0	9.55×10^{-5}	1.54×10^{-6}
1000 - 3000 keV:					
CdTe-CsI	0.144	0.056	1.0	8.2×10^{-7}	1.17×10^{-6}
CsI-CsI	0.109	0.014	7.0	2.41×10^{-5}	1.19×10^{-6}

Table 2: A summary of IBIS polarimetric characteristics in three broad energy bands: modulation factor, detection efficiency, background and sensitivity to 100% polarized gamma-ray sources.

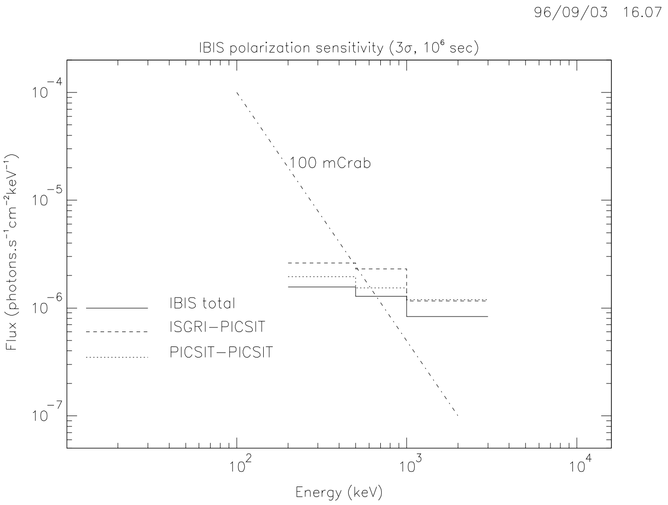

Figure 4: The 3σ polarization sensitivity of IBIS to 100% polarized source in 10^6 seconds.

level, T the observation time, and A the scattering area. Note that in the case of IBIS this area is only half of the ISGRI detector area (2621 cm^2), as the mask blocks the other half.

Only the scattered events retain polarization information. Hence as a polarimeter we are only interested in two of the interaction modes, i.e. CdTe single + CsI single and CsI double events. Our calculations shown that IBIS is most sensitive in the energy range between 200 keV and 3000 keV. We further divided this energy range into three broad bands: 200 - 500 keV, 500 - 1000 keV and 1000 - 3000 keV. In Table 3.1. we give a summary of IBIS polarimetric performance in the three energy bands.

The modulation factor, efficiency and background data were derived by M-C simulations using the GGOD suite and a detailed INTEGRAL/IBIS mass model (Lei et al. (1996b), Green et al. (1996)). The 3σ, 10^6 second sensitivities to 100% polarized sources have been calculated and are shown in the same table. The sensitivity in these two data modes are also plotted in Figure 4 together with the combined IBIS sensitivity and a 100 mCrab spectrum.

4. CONCLUSIONS

The ibis experiment on board INTEGRAL will act as a Compton telescope as well as its original design as a coded mask imager. This extension to the operation of the telescope enables the study of extended sources, and offers for an enhanced background rejection capability.

The design of the instrument also enables it to be used as an effective gamma-ray polarimeter. This will enable sensitive gamma-ray polarization studies of celestial objects to be performed for the first time.

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