COMPTON TELESCOPE WITH A CODED APERTURE MASK: IMAGING WITH THE INTEGRAL/IBIS COMPTON MODE

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ABSTRACT

Compton telescopes provide good sensitivity over a wide field of view in the difficult energy range from a few hundred keV to several MeV. Their angular resolution is, however, poor and strongly energy dependent. We present a novel experimental design associating a coded mask and a Compton detection unit to overcome these pitfalls. It maintains the Compton performance while improving the angular resolution by at least an order of magnitude in the field of view subtended by the mask. This improvement is obtained at the expense only of efficiency, which is reduced by a factor of 2. In addition, the background correction benefits from the coded-mask technique, that is, simultaneous measurement of the source and background. This design is implemented and tested using the IBIS telescope on board the INTEGRAL satellite to construct images with 12′ resolution over a 29′ × 29′ field of view in the energy range from 200 keV to a few MeV. The details of the analysis method and the resulting telescope performance, particularly in terms of sensitivity, are presented.

Subject headings: gamma rays: observations — telescopes

1. INTRODUCTION

The development of Compton telescopes began in the 1970s with balloon flights (Schönfelder & Lichti 1973; Herzo et al. 1975; Lockwood et al. 1979) and culminated with the flight of COMPTEL (Schönfelder et al. 1993) on board the Compton Gamma Ray Observatory. COMPTEL demonstrated for more than 9 years the capabilities of a Compton telescope to image the sky between 1 and 30 MeV thanks to the information provided by Compton kinematics (Boggs & Jean 2000). The study of astrophysical sites of nucleosynthesis, as illustrated by the first $^{26}$Al sky map (Diehl et al. 1995), greatly progressed with the COMPTEL data. On the other hand, COMPTEL barely achieved an angular resolution of $5′$ (FWHM) at 1 MeV. Future Compton telescopes could benefit from very significant detector progress, particularly in the semiconductor domain, to improve spectral resolution and, thus, angular resolution (Limousin 2003). The latter is however intrinsically limited by what is referred to as electron Doppler broadening, which results from the fact that an electron scattering in a detector is bound. This limits the angular resolution to about $5′$ at 511 keV in the best case (Zoglauer & Kanbach 2003).

One way to overcome this limitation is to adjoin a coded aperture (mask) to a Compton telescope. This design, which has never been used for gamma-ray space telescopes, maintains the advantages of a Compton telescope (high-energy response, low background, wide field of view) over most of the field of view, but it adds the coded mask’s imaging properties (angular resolution, background subtraction) in the solid angle subtended by the mask. Indeed, in a coded-mask system, source and background are measured simultaneously, and the energy-independent angular resolution is more than an order of magnitude better than in classical Compton telescopes. With coded-aperture Compton telescopes (CACTs), one can obtain low-background images in the 200 keV–10 MeV energy range with an angular resolution better than a fraction of a degree (e.g., 10′).

A CACT generally has lower efficiency than a classical coded-mask telescope, with, for instance, a thicker detector layer. However, the background in the energy range from 200 keV to a few MeV is dominated by the telescope’s internal emission, which increases with detector volume. A thicker detector will thus suffer a higher background. Therefore, the decision to use only one layer or to use two layers in coincidence for detecting the photons through the mask is a trade-off between detector background level and efficiency.

On the other hand, CACTs can be used to obtain full energy deposition from a high-energy photon, even if imaging is done only using the mask’s projection on one layer. This will enable users to realize the improved energy response of a coded-mask telescope.

Lastly, CACTs are in general difficult to use at higher energies, near 10 MeV and above, as they would require a thick mask, even with tungsten, to stop photons, which will result in a large vignetting effect for off-axis sources. Also, at these energies, Compton scatterings and pair creation in the mask will affect the system’s imaging properties and may degrade its angular resolution, which therefore becomes slightly energy dependent.

In this paper, we present the general principles of CACTs, their application to the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) mission, the difficulties inherent to the use of CACTs, the analysis method for the Compton mode of the Imager on Board INTEGRAL (IBIS), and its resulting performance.

2. PRINCIPLES OF CODED-APERTURE COMPTON TELESCOPES

In a Compton telescope, consisting of two detector layers, gamma-ray photons are Compton scattered in one detector and absorbed in the second. The location of and energy deposit from each interaction are measured, as illustrated in Figure 1 for the IBIS detectors. The direction of the scattered photon, $\mathbf{u}_{\text{scat}}$, is determined from the interaction locations in the two detectors. The Compton scattering angle, $\theta_{\text{Com}}$, is measured from the energy deposits, $E_1$ and $E_2$, recorded in the two detectors and is given by, for a forward scattering,

$$\cos \theta_{\text{Com}} = 1 - \frac{m_e c^2}{E_2} + \frac{m_e c^2}{E_1 + E_2},$$

(1)
where $m_e c^2$ is the electron rest-mass energy. The direction of the incoming gamma-ray photon lies on the edge of a cone, the Compton cone, with axis $\mathbf{u}_{\text{sca}}$ and aperture $\theta_{\text{Com}}$. The density distribution of all the projected event circles, the intersection of the cones with the celestial sphere, allows one to reconstruct sky maps and to locate sources. Source polarization can also be measured, since the scattering azimuth is related to the polarization direction. The angular resolution of the telescope depends on the energy resolution and pixel size in each of the two detectors. Furthermore, background is hard to subtract, and as in optical cameras, several effects distort images. Use of a coded mask to reconstruct sky images can effectively address most of these difficulties.

In coded-aperture telescopes, the source radiation is spatially modulated by a mask of opaque and transparent elements. The projection of the mask shadow, recorded with a position-sensitive detector, produces a shadowgram. This allows simultaneous measurement of source plus background flux (shadowgram area corresponding to the opaque elements) (Caroli et al. 1987). The background is removed by deconvolution of the shadowgram using the mask pattern. The sky image is obtained by a simple deconvolution of this shadowgram. Compton events that are incompatible with a given source direction can be discarded from the shadowgram, so a CACT can be regarded as a coded-mask telescope in which the Compton kinematics is used to reduce the background.

Then, two cases are possible: Either one wants to study a given source with a known position $\mathbf{u}_{\text{sou}}$ on the celestial sphere, or one wishes to make an image of a given field of view. In the first case, we can select, using the Compton kinetics, events that fulfill the condition

$$\mathbf{u}_{\text{sou}} \cdot \mathbf{u}_{\text{sca}} = \cos \theta_{\text{Com}},$$

within instrumental uncertainties, as by definition $\theta_{\text{Com}}$ is the angle between the source and the scattered directions. In the case of an isotropic background, equation (2) typically enables one to remove more than 90% of the Compton forward background events while keeping 90% of the Compton forward source events, in the 200 keV–1 MeV energy range.

When one wants to study sources over a given field of view, the more conservative way of removing background events using the Compton kinetics is to remove all events whose Compton cones, within the uncertainties, do not intersect the field of view. This condition can be readily expressed in the plane containing the telescope axis and the source direction (for a forward scattering). Indeed, if we consider the case of a conical field of view of semiangle $\theta_{\text{FOV}}$, this selection condition means that the angle between the source direction and the telescope axis $\mathbf{u}_{\text{tel}}$, called $\theta_{\text{sou}}$, should be greater than the angle $\theta_{\text{FOV}}$. The angle $\theta_{\text{sou}}$ can be easily computed from the Compton angle and the scattered-photon ones ($\theta_{\text{sca}}$, such that $\cos \theta_{\text{sca}} = \mathbf{u}_{\text{sca}} \cdot \mathbf{u}_{\text{tel}}$). The background rejection condition then becomes

$$\theta_{\text{sou}} = \theta_{\text{sca}} - \theta_{\text{Com}} \geq \theta_{\text{FOV}}.$$  

A similar formula can be obtained in the case of backward scattering.

### 3. THE INTEGRAL/IBIS COMPTON MODE

#### 3.1. The IBIS Telescope as a CACT

The IBIS instrument (Ubertini et al. 2003) is one of two major coded-aperture telescopes on board the ESA INTEGRAL gamma-ray observatory, launched on 2002 October 17. It consists of a dual detection layer designed and optimized to operate in the energy range between ~15 keV and 10 MeV. The upper detector layer, ISGRI, covers the energy range from ~15 keV to 1 MeV and is made of $128 \times 128$ cadmium telluride (CdTe) semiconductor detectors (Lebrun et al. 2003). The lower detector layer, PICsIT, operates in the energy interval from ~190 keV to 10 MeV and is made of $64 \times 64$ cesium iodide (CsI) scintillation crystals (Labanti et al. 2003). Events from these two layers are timestamped, and an onboard hardware event processing unit (HEPI)
can associate the ISGRI and PICsIT events if their arrival times coincide within a given time window (actually 3.8 μs). In the following, these are referred to as tagged Compton events. The detector spectral drifts (gain changes) can be monitored with a 22Na onboard calibration unit (OBCU). The detector layers are actively shielded, encased on all but the sky side by bismuth germanate (BGO) scintillator elements. The detector is also passively shielded from the low-energy celestial background with tungsten and lead foils. The coded mask is made of 16 mm thick tungsten elements that are 11.2 mm on a side. This thickness guarantees 50% modulation at 1 MeV. Placed 3.2 m above the CdTe detector plane, this mask ensures a 12° angular resolution over a 29° × 29° PCFOV. Composed of two detector planes (ISGRI and PICsIT) able to work in coincidence and covered with a coded mask, IBIS is the first in-flight CACT.

3.1.1. Event Types

Tagged Compton events from the celestial source under study can be of two kinds:

1. True Compton events; and
2. Spurious events, where two independent ISGRI and PICsIT events, one of them coming from the source, fall by chance in the Compton coincidence time window and are recorded falsely as a true Compton event.

Below 500 keV, the vast majority of Compton scatters correspond to forward-scattering events (ISGRI → PICsIT). With higher energy, photons can pass through ISGRI without any interaction, interact in PICsIT, and scatter back onto the ISGRI detection layer. In some cases, more than one scattering occurs. Multiple interactions in ISGRI are, however, discarded on board. In this paper we use only the events that underwent a forward scattering in ISGRI with a single energy deposit in PICsIT.

3.1.2. Spectral Resolution

In standard Compton telescopes, the spectral resolutions of each detector are key parameters, since they directly affect the angular resolution, which, in turn, governs the sensitivity. For a CACT, the angular resolution is driven by the mask’s geometric properties (C and H), but the sensitivity strongly depends on background rejection. The latter is based on measuring $u_{\text{sca}}$ and $\theta_{\text{Com}}$. The uncertainty on $\theta_{\text{Com}}$, $\delta\theta_{\text{Com}}$, is

$$\delta\theta_{\text{Com}} = \frac{m_e c^2}{E^2 \sin \theta} \sqrt{\delta E_1^2 + \left( \frac{E_1}{E_2} + 2 \frac{E_1}{E_2} \frac{\delta E_2}{E_2} \right)^2 \delta E_2^2},$$

where $\delta E_1$ and $\delta E_2$ are the energy resolution of the first and second detector layers, respectively, is larger in IBIS than that on $u_{\text{sca}}$, which relates to pixel size. We have used the Compton data tagged as calibration events by the OBCU to measure the on-board spectral resolution of the IBIS Compton mode. The FWHM of the two lines of the 22Na source (511 and 1274 keV) and the resulting energy resolution are presented in Table 1.

### Table 1

| Energy (keV) | Energy Resolution (% FWHM) |
|-------------|-----------------------------|
| 511         | 20                          |
| 1274        | 15                          |

4. IMAGING THE SKY WITH THE IBIS CODED-APERTURE COMPTON TELESCOPE

In this section, we focus on imaging analysis and the performance of the IBIS Compton mode.

4.1. IBIS Compton-Mode Imaging Analysis

4.1.1. Event Selection

The first step in analyzing the IBIS Compton-mode data is to apply selections to the events: a selection in energy (generally between 200 keV and 1 MeV), and selection of ISGRI events with rise time between 0.6 and 3.8 μs (see Lebrun et al. 2003 for a description of ISGRI data). Then we remove background events using the Compton kinetics, as described in § 3.2. As discussed there, depending on the purpose, there are two types of selection:

Field-of-view selection. — The IBIS field of view semiangle being $\theta_{\text{FOV}} \approx 15^\circ$, only photons with $\theta_{\text{sca}} - \theta_{\text{Com}} < 15^\circ$ are kept.

Dedicated source selection. — For a source with known direction $u_{\text{sou}}$, a more restrictive selection given by equation (2) is applied. This condition can be rewritten as $|u_{\text{sou}} \cdot u_{\text{sca}} - \cos \theta_{\text{Com}}| < \delta_{\text{lim}}$, where $\delta_{\text{lim}}$ is related to the instrumental error.

We compute values of $\delta_{\text{lim}}$ in order to maximize the source signal-to-noise ratio, using ground calibration measures. We have used the Compton events obtained from three on-axis calibration sources, namely, $^{133}$Sn (392 keV), $^{22}$Na (511 keV), and $^{137}$Cs (662 keV). In fact, for an on-axis source, the telescope axis and source direction coincide, so

$$u_{\text{sou}} = u_{\text{sca}}.$$  \hspace{1cm} (5)

Then, from equation (2), we have

$$\cos \theta_{\text{Com}} = u_{\text{sou}} \cdot u_{\text{sca}} = u_{\text{scl}} \cdot u_{\text{sca}} = \cos \theta_{\text{sca}}$$  \hspace{1cm} (6)

from the definition of $\theta_{\text{sca}}$. Equation (2) then simplifies to

$$\Delta \theta = \theta_{\text{Com}} - \theta_{\text{sca}} = 0.$$  \hspace{1cm} (7)

Figure 2 shows the angular shift ($\Delta \theta$) diagrams. This distribution, centered on zero, is not a Dirac distribution because of instrumental uncertainties. Also, this distribution narrows with energy thanks to a better reconstruction of $\theta_{\text{Com}}$, which is linked...
to a better Compton-mode energy resolution at high energy. Yet, this variation with energy is small, and the optimal choice of δlim (related to the width of the distribution shown in Fig. 2) has been checked not to change much with energy between 200 keV and 1 MeV.

Figure 3 illustrates how the signal-to-noise ratio varies with the allowed range of Δθ ∈ [−θlim, θlim] for the 133Sn calibration source. The best value of θlim at 392 keV is around 10°–12°.

4.1.2. Subtraction of Spurious Events

Spurious events are generally neglected in standard Compton telescopes. Their uniform distribution does not induce false source detection. But the situation for a CACT is different.

Indeed, spurious events are caused by random events on the two layers. For a bright source, such as the Crab, the source’s low-energy photons make an important contribution to the detectors’ count rates. So, the probability that one of these random events is in fact a detected low-energy photon from the source is quite high. As such a photon has the mask signature induced by the source, it is not subtracted during the deconvolution process and would wrongly participate in the determination of source flux. We therefore have to take into account the contribution from spurious events with high accuracy in order to obtain a correct estimate of the source flux.

The dedicated source selection has the strong advantage of greatly reducing the number of spurious events, as most of them do not obey equation (2), but their residual contribution is not negligible. A statistical method must be applied to evaluate and subtract them.

To do so, we make use of ISGRI and PICsIT single events recorded in the same observation, that is, having the source signature, and artificially associate them to create a sample of spurious events, called hereafter the “fake spurious events sample.” We apply to this sample the same selections in energy, rise time, and scattering angle as described above, in order to produce a fake shadowgram. The latter is scaled, by a scaling factor called the “spuriousness factor” or α, to the number of spurious events recorded during the observation and then subtracted from the Compton data shadowgram.

The spurious count rate, Nsp, scales with the width of the time coincidence window (∼2ΔTr), the total number of PICsIT events (N_{PICsIT} = Np + NOBCU from PICsIT simple and multiple detections, and from calibration events), and the total number of ISGRI events (N_{ISGRI} = Nf + Nsp from ISGRI single events and spurious events). The calibration events in ISGRI are tagged and discarded on board. Using Poisson statistics in the coincidence window, one obtains the number of spurious events:

\[ N_{sp} = (1 - e^{-(2ΔT_{r}-δT)N_{PICsIT}})N_{ISGRI}, \]

where δT is the onboard time resolution, on the order of 250 ns. Yet, one measures only Nf, so the scaling factor is

\[ N_{sp}/N_{f} = e^{(2ΔT_{r}-δT)N_{PICsIT} - 1}. \]

One has to further correct this factor for the multiple PICsIT events in order to obtain the scaling factor for the single spurious events only. For a proportion of PICsIT single events of

\[ \beta = \frac{N_{simple}}{N_{simple} + N_{multiple} + NOBCU}, \]

(β is of order 80% between 200 keV and 1 MeV for IBIS), one obtains the spuriousness factor,

\[ \alpha = \beta e^{(2ΔT_{r}-δT)N_{PICsIT} - 1}. \]

Figure 4 shows the evolution of this factor for observations of the Crab over the mission’s lifetime. It varies from 2.82% early on (revolution 39), when ΔTr was about 5.0 μs, to around 1.1% after revolution 102, when ΔTr was decreased to 1.9 μs. The value of α is quite constant for a given coincidence window during short times, but it rises over longer periods (revolutions 102-103-170-239) because of the increase of the background flux, following the solar cycle.

The next step is to correct the resulting shadowgram (after subtraction of the spurious events) for nonuniformity and to deconvolve it.

4.1.3. Uniformity Correction

Compton-mode shadowgrams are not spatially flat. The count rate falls near the edges because we lose the events that scatter at the edge of ISGRI and miss PICsIT. This nonuniformity is magnified by the decoding process, so if it is not corrected, strong systematic structures may result in the deconvolved images, with spatial frequencies similar to those originally present in the shadowgram. The shadowgram, D, consists of a source component,
with count rate $S$ and a spatial response map $R_S$, and a background component, with count rate $B$ and response map $R_B$; thus,
\[
D = SR_S + BR_B.
\]

The modulation from the mask pattern is weak compared with the larger scale deformations we study here. To compare $R_S$ and $R_B$ under the same conditions, we need in-flight data from a strong enough source, as well as background. Whereas we have used the in-flight background distribution, no such source has been observed in-flight in Compton mode, so we used data from ground calibration to determine $R_S$.

Both the background and source response maps are well fitted by a two-dimensional Gaussian function (see Fig. 5). The results are presented in Table 2 for the in-flight background measurements and the ground calibration source data for on-axis sources. The background and source response maps in several energy bands are presented in Table 2 for the in-flight background measurements and the ground calibration source data for on-axis sources.

The final step is therefore to deconvolve the corrected shadowgram $D/R$, renormalized to the total number of events, to reconstruct the source flux, using standard deconvolution techniques.

### 4.1.4. Image Deconvolution

Representing the mask as an array $M$ with elements of 1 (transparent) and 0 (opaque) and the detector plane by an array $D$, and denoting by $G^{+}$ and $G^{-}$ the decoding arrays related to the coded mask (see Goldwurm et al. 2003), the image deconvolution in the FCFOV can be extended to the total (both fully and partially coded) field by correlation of $D$ in a noncyclic form with the $G$-array extended and padded with 0-elements outside the mask (Gros et al. 2003). Since the number of correlated (transparent and opaque) elements in the PCFOV is not constant as in the FCFOV, the sum and subtractions for each sky position must be balanced and renormalized. The sky flux map is given by
\[
F = \left[ \left( WD * G^+ \right) - \left( WD * G^- \right) \right] \frac{W * G^+}{W * G^-}
\]
\[
\left( W * G^+M \right) - \left( W * G^-M \right) \frac{W * G^+}{W * G^-}
\]
and the variance map by
\[
V = \left[ \left( W^2D * G^+ \right) + \left( W^2D * G^- \right) \right] \frac{(W * G^+)^2}{(W * G^-)^2}
\]
\[
\left( W * G^+M \right) - \left( W * G^-M \right) \frac{W * G^+}{W * G^-}.
\]

In these formulae, the $W$-matrix removes dead or noisy pixels.

### 4.1.5. Angular Shift Diagrams as a Check on the Analysis Method

Angular shift diagrams illustrate the effectiveness of the spurious-event subtraction. One can use tagged Compton events from an on-axis calibration source and analyze them in regularly
spaced $\Delta \theta$ bins. Then we select them based on energy and rise
time as above. Their shadowgram is corrected for the spatial
response and deconvolved to obtain the total source count rate,
displayed in red in Figure 8. The corresponding constructed
spurious events sample was analyzed in the very same way, and
its count rate per $\Delta \theta$ bin, scaled by the measured $\alpha$, is displayed
in blue, showing that the sparseness factor is adequate. The
angular shift distribution of real Compton events (after subtraction
of the spurious ones) is well centered around zero and falls to
zero for $|\Delta \theta| \geq 19^\circ$, whereas the spurious distribution is clearly
offset to negative values, as expected because most spurious
events have a low energy deposition in ISGRI.

For celestial gamma-ray sources above 200 keV, the spurious
rate dominates the source rate. Several Crab on-axis observations
have been used to construct a $\Delta \theta$ diagram, using the
variance-weighted sum of the flux at the source position in each
sky image. Thanks to the coded mask’s background subtraction
capabilities, only the true Compton and spurious contributions,
as defined in § 3.1.1, are visible in Figure 9. The spurious
component severely dominates, its negative offset being quite
marked. True Compton events are around zero, as foreseen, and
the small flux excess of events for $\Delta \theta \sim 20^\circ$ to $40^\circ$ is due to
backward scattering.

4.2. IBIS Compton-Mode Sensitivity

The analysis method described above has been applied to
evaluate the signal-to-noise ratio of the Crab pulsar in different
energy bands. The sensitivity of the IBIS Compton mode is
presented in Figure 10. It is greater than that of PICsIT for a
similar angular resolution. Yet, unlike PICsIT, the Compton
mode has no major strong background problems, allowing one
to study photons up to a few MeV in very small energy bands,
in particular around spectral lines, with an angular resolution
better than that of SPI (the Spectrometer on INTEGRAL). It also
allows for polarization studies and imaging studies of compact
objects with good timing resolution ($\sim 100 \mu s$).

The next step we foresee in our analysis is to incorporate
backward-scattering events and PICsIT multiple events and to
compute background Compton correction maps (first-order back-
ground shadowgram from empty-field observations and second-
order summed sky images after source subtraction) to reduce the
residual structures in the response maps.

Fig. 7.—Left, ISGRI significance map for the Crab pulsar between 200 and 500 keV; right, significance map computed from the fake spurious events sample with the same algorithms as used for the map shown in Fig. 6.

Fig. 8.—Angular shift distribution of events for a $^{133}\text{Sn}$ source at 392 keV
during ground calibration. Red data points represent all the Compton data (real
Compton plus spurious data). Blue data points show the spurious contribution,
which peaks at negative offset, and black data points are the derived Compton
ones. The line is a Gaussian fit (FWHM $\sim 19^\circ$) to these derived Compton data.

Fig. 9.—Crab count rate between 200 and 500 keV in different $\Delta \theta$ bins. The
total observation time is about 700 ks. Red data points represent all the Compton
data (real Compton plus spurious data). Blue data points show the spurious contri-
bution, and black data points are the derived Compton ones. The line is a Gaussian
fit to the Compton data.
An important goal of the IBIS Compton mode is also polarimetry. The interest of the astrophysics community in such detection is growing. It is in fact a powerful and direct tool to constrain theoretical models of gamma-ray bursts, pulsars, solar flares, etc. The calibration and results of the IBIS Compton-mode polarimeter will be presented in a forthcoming paper.

5. CONCLUSIONS

The IBIS Compton mode is functional and provides an efficient new means to observe the sky at energies beyond $\sim 190$ keV and up to a few MeV. With only forward-scattering events and thanks to the ISGRI shadowgram, we can reconstruct images with high spatial resolution by taking advantage of the coded aperture mask system. We have devised a scheme for subtracting the large contribution from spurious coincidences between the two detector planes. The resulting sensitivity, evaluated with in-flight data from the Crab pulsar, opens new perspectives for polarimetric and imaging studies in the $0.2 - 5$ MeV energy band.

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