

1 A method to localize gamma-ray bursts using POLAR

2 E. Suarez-Garcia^{*,a,b}, D. Haas^{a,b}, W. Hajdas^d, G. Lamanna^c,
3 C. Lechanoine-Leluc^a, R. Marcinkowski^e, A. Mtchedlishvili^d, S. Orsi^a,
4 M. Pohl^a, N. Produit^b, D. Rapin^a, D. Rybka^e, J.-P. Vialle^c

5 ^a*DPNC, 24 Quai Ernest-Ansermet, Université de Genève, 1205 Genève, Switzerland.*

6 ^b*INTEGRAL Science Data Centre, 16 Chemin d'Écogia, 1290 Versoix, Switzerland*

7 ^c*Laboratoire d'Annecy-le-vieux de Physique des Particules, 9 Chemin de Bellevue,
8 F-74941 Annecy-le-Vieux, France*

9 ^d*Paul Scherrer Institut, 5232 Villigen PSI, Switzerland*

10 ^e*The Andrzej Soltan Institute for Nuclear Studies, 69 Hoza str., 00-681 Warsaw, Poland*

11 Abstract

The hard X-ray polarimeter POLAR aims to measure the linear polarization of the 50 – 500 keV photons arriving from the prompt emission of γ -ray bursts (GRBs). The position in the sky of the detected GRBs is needed to determine their level of polarization. We present here a method by which, despite of the polarimeter incapability of taking images, GRBs can be roughly localized using POLAR alone. For this purpose scalers are attached to the output of the 25 multi-anode photomultipliers (MAPMs) that collect the light from the POLAR scintillator target. Each scaler measures how many GRB photons produce at least one energy deposition above 50 keV in the corresponding MAPM. Simulations show that the relative outputs of the 25 scalers depend on the GRB position. A database of very strong GRBs simulated at 10201 positions has been produced. When a GRB is detected, its location is calculated searching the minimum of the χ^2 obtained in the comparison between the measured scaler pattern and the database. This GRB localization technique brings enough accuracy so that the error transmitted to the 100% modulation factor is kept below 10% for GRBs with fluence $F_{\text{tot}} \geq 10^{-5}$ erg cm⁻². The POLAR localization capability will be useful for those cases where no other instruments are simultaneously observing the same field of view.

12 *Key words:* Gamma-ray burst, source localization, polarization, POLAR

*Corresponding author. Tel.: +41 22 379 6923. Fax: +41 22 379 6992

Email address: estela.suarez@unige.ch (E. Suarez-Garcia)
Preprint submitted to Astroparticle Physics Journal

September 14, 2009

13 1. Introduction

14 Gamma-ray bursts (GRBs) are short flashes of γ -rays likely produced
15 during the creation of a black-hole at cosmological distances. In a few seconds
16 a huge amount of energy between 10^{51} and 10^{53} erg is released such that
17 GRBs are the most violent explosions in the Universe. This prompt emission
18 presents a great variability of lightcurves and its spectrum follows a broken
19 power law function, often described using the Band model [1]. The Band
20 model fits the spectrum using four parameters: an amplitude (A), the low-
21 and high-energy spectral indexes (α and β , respectively), and the peak energy
22 (E_{peak}) of the power density spectrum νF_{ν} , which represents the total energy
23 flux per energy band.

24 After the prompt γ -ray emission has finished, a long lasting afterglow can
25 be observed at various longer wavelengths. The current theoretical picture is
26 that GRBs are produced when a massive star collapses at the end of its life
27 or when two compact objects merge, giving birth in either case to a black
28 hole. The collapsar scenario would be responsible for the long duration [2]
29 and the merger scenario for short duration GRBs [3]. The separation line
30 between short and long GRBs was traditionally taken at 2 seconds [4], but
31 recently suggested rather at 5 seconds [5]. For recent reviews on GRBs, see
32 e.g. [6, 7, 8].

33 Several theoretical models have been proposed to explain which processes
34 are responsible for the GRB emission. In the standard *fireball* model [9] the
35 explosion produces a jet in which expanding shells cause internal shocks
36 when a fast shell overtakes a slower moving one. In these shocks relativistic
37 electrons are accelerated, generating through synchrotron emission the X-
38 and γ -ray photons that we see as the GRB prompt emission. The resulting
39 photon polarization is typically low ($\approx 10\%$) reflecting the hydrodynamic
40 nature of the model. In the *electromagnetic* model [10] the energy is extracted
41 from the central engine by an electromagnetic field, transported in a plasma
42 to large distances by strongly magnetized wind, and dissipated through fast
43 magnetic reconnections that generate the GRB radiation. Photons emitted
44 in this process can present polarization as high as 50%. In the *cannonball*
45 model [11] the γ -ray emission is generated by inverse Compton scattering
46 of soft photons that hit the previously ejected material. The polarization
47 level depends on the opening angle and Lorentz factor of the jet, predicting
48 therefore all possible values between 0 and 100% polarization.

49 Precise polarimetry measurements of the GRB prompt emission can dis-

50 distinguish between different theoretical models, offering unique information on
51 the emission mechanism of the GRBs and on the composition and geomet-
52 ric structure of their jets [12, 13]. To date, only a few measurements of
53 the prompt GRB polarization have been performed, all of them with instru-
54 ments that had not been designed for this purpose and lacked in many cases
55 a good characterization of their systematic effects, enough effective area, or
56 good background rejection mechanisms for polarimetry. Using data from the
57 RHESSI satellite an $80\% \pm 20\%$ linear polarization level from GRB 021206
58 was reported [14], but disproved afterwards [15, 16]. By simulating the scat-
59 tering of GRB photons off the Earth’s atmosphere, the polarization levels
60 of two BATSE bursts (GRB 930131 and GRB 960924) could be obtained
61 [17] as $>35\%$ and $>50\%$ respectively, but the result could not be constrained
62 beyond systematics. Also inconclusive were the two measurements [18, 19]
63 obtained using INTEGRAL data from the GRB 041219A. Although they
64 found a high level of polarization ($\sim 60\%$ and $98\% \pm 33\%$, respectively) they
65 could not statistically claim a polarization detection.

66 In view of the power and the lack of precise polarization studies of GRBs,
67 several X- and γ -ray polarimeters have been proposed and are under develop-
68 ment. Some examples are POLAR [20], GRAPE (Gamma-Ray Polarimeter
69 Experiment, [21]) POET (Polarimeters for Energetic Transients, [22]), CI-
70 PHER (Coded Imager and Polarimeter for High Energy Radiation, [23]),
71 PHENEX (Polarimetry for High ENERgy X rays, [24]), XPOL [25] and PO-
72 LARIX [26]. In addition, polarimeters designed for studying fixed sources,
73 like PoGOLite [27], could also measure GRB if they happen to appear in
74 their field of view.

75 POLAR [20] is a small and compact instrument designed to determine
76 the level of linear polarization of the 50 – 500 keV photons arriving from the
77 prompt emission of GRBs. Totally dedicated to polarimetry, the large field of
78 view ($\sim 1/3$ of the sky) of POLAR and its lack of imaging capability would
79 in principle force the detector to rely on other instruments to provide the
80 location of the observed GRBs. Such a limitation would reduce the number
81 of GRBs to be measured by POLAR depending on whether another GRB
82 detector would be observing the same portion of the sky or not. To minimize
83 this drawback we have developed a method to roughly localize GRBs using
84 only POLAR. For this purpose, scalars are attached to the output of the
85 multi-anode photomultipliers (MAPMs) that collect the light from the PO-
86 LAR scintillator target. Simulations demonstrate that the relative output of
87 those scalars, accumulated over the duration of a GRB, shows a dependency

88 on the source position above POLAR.

89 This paper is organized as follows. Section 2 describes the POLAR de-
90 tector and its Monte Carlo simulation package. In section 3 we present the
91 working principle of the GRB localization method in detail. To characterize
92 its capabilities several GRB observations have been simulated. The results
93 obtained are presented in section 4, where the influence on the polarization
94 determination of the uncertainty associated to the estimated GRB position
95 is also quantified. Several systematic effects that could influence the out-
96 come of the method are discussed in section 5, including GRB polarization,
97 background sources, GRB spectral variations, and satellite backscattering.
98 Finally, section 6 summarizes the paper.

99 **2. Description of POLAR**

100 POLAR, see figure 1, consists of a target of 40×40 plastic scintillator
101 bars (BC400, Saint-Gobain), each one $6 \times 6 \times 200$ mm³ wrapped in a highly
102 reflective foil (Vikuiti, 3M). The optical photons produced when a hard X-
103 ray photon interacts with the target are collected using 25 MAPMs (H8500,
104 Hamamatsu) whose channels are optically coupled to the bottom of the scin-
105 tillator bars. The electrical signal coming from the MAPM is then processed
106 by ASIC and FPGA at the front-end electronics, and collected by the PO-
107 LAR central computer which is responsible for data storage and transport
108 to ground. The scintillator target is divided into 25 modules, each consisting
109 of 64 scintillator bars, optical coupling, one MAPM, and its correspond-
110 ing front-end electronics, all together enclosed in a thin carbon fiber socket.
111 This modular design gives a good mechanical stability and facilitates the
112 interchange of modules during the testing phase of the detector. The 25
113 modules are kept together with two aligning frames located at the top and
114 at the bottom of the carbon fiber sockets, respectively and connected with
115 mechanical fixations. The whole target, together with the central computer,
116 the power supplies and the rest of the electronics, is further enclosed in a
117 box that serves not only as container but also as shield against low energy
118 charged particles. Finally, the whole instrument will be mounted onto a
119 satellite, to be able to study photons in the energy range between 50 and
120 500 keV, which cannot reach the ground because they are absorbed by the
121 Earth atmosphere. A flight opportunity for POLAR on the future Chinese
122 Tian-Gong Space Station is currently under consideration. An alternative
123 option of flying with the International Space Station is evaluated.

124 An incoming particle is called an *event* when it deposits more than 5 keV
125 in at least one of the POLAR scintillator bars, i.e when it produces a *hit*.
126 Hard X-ray photons arriving from a GRB have a high probability of expe-
127 riencing Compton scattering in the target, generating a signal in more than
128 one channel. The POLAR trigger logic selects those events with at least two
129 hits. When an incoming particle produces more than two hits above the 5
130 keV threshold, the two highest energy depositions are selected offline. Each
131 of those pairs of hits is a *selected event* in POLAR. The position of the active
132 bars in a selected event is related to the azimuthal Compton-scattering angle
133 of the incoming photon. If the γ -ray emission from the GRB was not polar-
134 ized, the modulation curve, i.e. the azimuthal distribution of the ensemble of
135 selected events, is flat. Otherwise it follows a sinusoidal curve whose ampli-
136 tude is the so-called *modulation factor*, and whose phase-shift indicates the
137 angle of linear polarization of the GRB photons [28, 29]. The modulation
138 factor (μ), divided by the response of the detector to a 100% polarized flux
139 (μ_{100}), is the polarization level (Π) of the incoming photons: $\Pi = \mu/\mu_{100}$.
140 This principle allows POLAR to measure the level of polarization of the
141 prompt emission of GRBs.

142 The main part of the POLAR front-end electronics is devoted to collect
143 the signals produced in the 1600 MAPM anodes, to implement the trigger,
144 and to transport the triggered signal to the central computer. The trigger
145 condition is fulfilled when the target registers at least two hits above the 5
146 keV single channel threshold in a time window of ~ 70 ns. Only the events
147 with this characteristic will arrive to the central computer and be available for
148 analysis. The probability of registering an accidental coincidence is negligible
149 considering the counting rates expected during a GRB.

150 For the GRB localization method, the electronics need to include in ad-
151 dition 25 scalers, one per MAPM, counting all photons that pass a higher
152 energy threshold. If the final electronics design includes a 2-level ASIC, it is
153 possible to define a low energy single channel threshold of 5 keV to use in
154 the trigger logic, and a higher energy threshold of 50 keV per channel, useful
155 for the GRB localization method implementation. A simple "or" operation
156 on the signals that have passed the high level threshold, during a time span
157 of about 70 ns, would be enough to know if at least one hit with more than
158 50 keV energy deposition has been produced in the corresponding MAPM.
159 An alternative option for the case where a single level ASIC is used would
160 be to attach the scaler to the dynode output of each MAPM, that provides
161 an analog sum of the 64 channels. All the results presented in this paper

162 have been obtained with Monte Carlo simulations that reproduced the first
163 approach. Nevertheless, independently of which approach is taken, the final
164 scaler output for one event is a collection of 25 numbers with values 0 or
165 1. When accumulating the scaler output for all events produced during a
166 GRB one obtains the number of photons that interacted above the given
167 high energy threshold inside every MAPM. The counting pattern is sensitive
168 to the direction of incoming photons since the size of the target corresponds
169 to several absorption lengths. The scalars cannot distinguish between GRB
170 photons and background. For this reason the influence of the background
171 has been studied and is presented in section 5.2. The algorithm is relatively
172 simple and suitable to be implemented in a FPGA or in the small on board
173 processor. The needed computing power is negligible as the algorithm has to
174 run only infrequently when a candidate GRB has been detected.

175 An important part of the POLAR design and the evaluation of its polari-
176 metric capabilities is performed using GEANT4 [30] simulations. The 1600
177 scintillator bars of the target have been simulated with their standard dimen-
178 sions and wrapped with a 50 μm thick aluminum foil. The target is further
179 placed inside an aluminum box of 1 mm thickness that serves as a shield
180 from low-energy charged particles and represents the outer enclosure of the
181 detector. The incoming direction, the spectrum, and the type of particles
182 to be used are generated following the user instructions. A specific routine
183 has been developed to produce hard X-ray photons following the Band model
184 spectrum [1] and its parameters. The most important physical processes that
185 photons can undergo in the detector are taken into account, including polar-
186 ized Compton scattering, photoelectric effect, and pair production, among
187 others. The scintillation and optical light collection processes have not been
188 considered. The simulation generates a ROOT [31] file containing all the
189 necessary data for the subsequent analysis: the incoming photon energy, the
190 number and position of the bars fired, the energy deposited at each bar, etc.

191 **3. GRB Localization Method**

192 The pattern of the scalars output (SO) presented in section 2 depends
193 on the position of the GRB above the target. A GRB located at POLAR
194 zenith will produce an SO with more counts in the entries corresponding to
195 the central MAPMs. On the other hand, a GRB at a large polar angle will
196 present more counts in the MAPMs more directly illuminated by the GRB

197 because of the exponential interaction probability. Using this relation it is
 198 possible to localize the sources observed by POLAR.

199 For this purpose a database of SOs has been created using the POLAR
 200 Monte Carlo simulation package. Non-polarized GRBs have been simulated
 201 at numerous incoming angles. To get enough statistics for the comparison
 202 with future GRB measurements, we simulated very strong bursts for the
 203 database, with a total energy fluence $F_{\text{tot}} = 10^{-4}$ erg cm $^{-2}$ and Band spectral
 204 parameters $\alpha = -1.0$, $\beta = -2.5$, and $E_{\text{peak}} = 200$ keV [1]. The selected Band
 205 parameters correspond to the approximate average values calculated with a
 206 selection of strong GRBs observed by BATSE [32, 33].

207 Defining in spherical coordinates the positions of the simulated GRBs in
 208 the sky would imply an indetermination of the incoming photon azimuthal
 209 angle (ϕ_γ) when its polar angle (θ_γ) approaches 0. To avoid this numerical
 210 problem the database has been produced in Cartesian coordinates:

$$\begin{aligned} x &= (1 - \cos \theta_\gamma) \cdot \cos \phi_\gamma \\ y &= (1 - \cos \theta_\gamma) \cdot \sin \phi_\gamma \end{aligned} \tag{1}$$

211 Simulations were uniformly distributed in the (x,y) plane, for x and y
 212 running between -1 and 1 in steps of 0.02. We obtain in this way a grid with
 213 10201 nodes. Note that, since the detector is symmetric and the influence of
 214 the satellite behind it is negligible (see section 5.4), it is enough to simulate
 215 one quadrant of the grid. The SOs of the other three quadrants can be
 216 inferred from the simulated ones. The selection of the coordinate system
 217 from equation 1 guarantees a uniform grid where all points are equally distant
 218 from each other and the center of the coordinate system corresponds to the
 219 zenith of the detector.

220 The output of the scalers was calculated considering only hits with more
 221 than 50 keV deposited energy, following the first approach presented in sec-
 222 tion 2. Although there are no intrinsic limitations that prevent the detection
 223 of weaker energy depositions, the inclusion of this threshold is necessary to
 224 reduce the spectral dependence of our localization method (see section 5.3
 225 for details). Furthermore, a normalization of the simulated SOs is needed
 226 due to the dependency of the absolute number of counts registered in each
 227 MAPM on the total flux that the source produced. We scaled the rates di-
 228 viding by the sum of all counts in the given SO. The result is a normalized
 229 scaler output (NSO) like the ones graphically represented in figure 2. The
 230 final database is constituted by 10201 text files containing the NSO and its
 231 statistical error for each of the 25 MAPM of POLAR target.

232 The process to localize the GRBs detected by POLAR is based on the
 233 minimization of the Pearson's χ^2 [34, 35]:

$$\chi^2 = \sum_{i=1}^n \frac{(c_i - m_i)^2}{m_i}, \quad (2)$$

234 where n is the number of MAPMs, c_i is the number of counts observed in
 235 MAPM i , and m_i is the number of counts predicted by a given model for the
 236 same MAPM i . When POLAR observes a GRB, we calculate c_i as the i^{th}
 237 entry of its measured SO, and m_i is obtained from the database of simulated
 238 NSOs. Supposing that the GRB was at coordinates (x,y) , the predicted
 239 number of counts in the i^{th} MAPM is the i^{th} entry of the database file at
 240 this position of the sky ($m_i(x,y)$) multiplied by the total number of entries
 241 (c_{tot}) in the measured SO:

$$\chi^2(x,y) = \sum_{i=1}^{25} \frac{(c_i - c_{\text{tot}} \cdot m_i(x,y))^2}{c_{\text{tot}} \cdot m_i(x,y)}. \quad (3)$$

242 To localize a GRB we calculate all of 10201 χ^2 values, one at each point
 243 of the database grid, obtaining a 2-dimensional χ^2 distribution (see upper
 244 part of figure 3 for an example done with a burst of same spectral shape
 245 as the database, but fluence $F_{\text{tot}} = 10^{-5}$ erg cm $^{-2}$). The minimum of the
 246 distribution is found selecting the node of the grid with the lowest χ^2 and
 247 fitting two parabolas around it, one in the x -direction and the other in the
 248 y -direction, using 5 points in each case. The grid is fine enough so that
 249 the result obtained in this way is a good approximation to the absolute
 250 minimum of the two-dimensional distribution. To perform the parabolic fits
 251 with ROOT one needs to assign an error to each of the points. Since the
 252 χ^2 itself has no associated error we assigned a fixed value, equal for all the
 253 points. We have chosen this value equal to 23, which is the number of degrees
 254 of freedom of our experiment. On the horizontal axis the error of each point
 255 is the half-width of the bin, in our case 0.01. The positioning of the minimum
 256 of the parabolas $\chi_{\text{min}}^2(x)$ and $\chi_{\text{min}}^2(y)$ corresponds to the estimated position
 257 of the source. The error on the estimation is calculated with the values of
 258 the abscissa located at $\chi_{\text{min}}^2(x) + 1$ and $\chi_{\text{min}}^2(y) + 1$ respectively. Figure 3
 259 shows an example of the two-dimensional distribution of χ^2 values, and the
 260 two fitted parabolas.

261 In figure 3 one can notice that the χ^2 values do not grow monotonously
 262 from the minimum, but decrease at the four corners of the plane. These four

263 corners of the Cartesian space correspond to situations where the GRB is
 264 below the POLAR detector, i.e. $\theta_\gamma > 90^\circ$. The χ^2 decreases there because
 265 POLAR cannot measure the point of interaction of the photons along the
 266 length of its bars, and is therefore incapable of distinguishing a GRB at $(\theta_\gamma,$
 267 $\phi_\gamma)$ from one at $(180^\circ - \theta_\gamma, \phi_\gamma)$. To avoid this ambiguity, and since GRBs
 268 will never appear below POLAR, we have introduced an extra condition in
 269 the localization method that takes it into account. Namely, every time that
 270 the method gives an output below POLAR it will be transformed into the
 271 equivalent position above POLAR and only this one will be given as final
 272 result. In practice one would actually not need to simulate those points of
 273 the database. Our reason to do it is the numerical advantage of working with
 274 a uniform and square grid that can be treated as a regular matrix.

275 4. Method verification

276 Simulations were made to produce *example measurements* with which we
 277 could test the localization method. The GRBs simulated as examples were
 278 non-polarized *standard* strong GRBs. Hereafter, *standard* strong stands for
 279 a GRB with total energy fluence $F_{\text{tot}} = 10^{-5}$ erg cm $^{-2}$ and Band spectral
 280 parameters [1] $\alpha = -1.0$, $\beta = -2.5$, and $E_{\text{peak}} = 200$ keV, from which
 281 POLAR will detect about 22000 photons in the whole duration of the burst.
 282 Note that the spectral shape, i.e. the Band parameters, is the same as used
 283 for the database bursts, but the total fluence is here ten times smaller. We
 284 expect, considering the BATSE catalog and the POLAR field of view, to
 285 observe about 12 such *standard* strong GRBs per year [36]. To facilitate
 286 the visualization we present only GRB positions above POLAR and in the
 287 quadrant of the space where $x > 0$ and $y > 0$. The behavior on the other
 288 three quadrants is equivalent due to the symmetry of the detector.

289 We compared the x and y values taken as input in the *measurements* with
 290 the ones reconstructed using the χ^2 minimization method. Ten samples were
 291 run at each selected (x,y) position to study the repeatability and the spread
 292 of the reconstructed results around each input value. Figure 4 shows the
 293 performance of the GRB localization method. The localization procedure
 294 works well reconstructing both x and y without apparent bias within a root-
 295 mean-square (r.m.s.) smaller than 0.07. The average minimum χ^2 obtained
 296 for the 380 measurements simulated to produce figure 4 was $\chi_{\text{min}}^2(x,y) =$
 297 22.9 ± 6.6 . Taking into account that there are 23 degrees of freedom, this
 298 corresponds to a reduced $\chi_{\text{red}}^2(x,y) = 0.996 \pm 0.287$. When performing the

299 equivalent GRB localization in spherical coordinates θ_γ could be determined
 300 within a r.m.s $\approx 4^\circ$ and ϕ_γ within a r.m.s $\approx 5^\circ$ for $\theta_\gamma > 30^\circ$. As comparison,
 301 the localization accuracy of the Fermi-GRB burst monitor (GBM) [37] is
 302 for bright bursts $< 1.5^\circ$ using a detailed offline analysis, and the Swift Burst
 303 Alert Telescope (BAT) [38] provides positions to an accuracy of $1' - 4'$ within
 304 20 seconds of GRB observation.

305 When a GRB is detected by POLAR its level of polarization (Π) is de-
 306 termined from the amplitude (μ) of the modulation curve and the 100%
 307 modulation factor (μ_{100}) using: $\Pi = \mu/\mu_{100}$ (see section 2). The error on the
 308 polarization level can be calculated as:

$$\frac{\sigma_\Pi}{\Pi} = \sqrt{\left(\frac{\sigma_{\mu_{100}}}{\mu_{100}}\right)^2 + \left(\frac{\sigma_\mu}{\mu}\right)^2}, \quad (4)$$

309 where σ_Π , σ_μ and $\sigma_{\mu_{100}}$ are the errors on Π , μ and μ_{100} , respectively.

310 The second term in equation 4 depends only on the strength and level
 311 of polarization of the observed GRB. Since μ_{100} varies with the burst po-
 312 sition and spectral shape, Π must be calculated using a μ_{100} derived from
 313 simulations of a GRB with the same spectrum and position in the sky as
 314 the observed one. The highest μ_{100} is obtained when the GRB is located
 315 at POLAR zenith and it diminishes when photons come from POLAR side
 316 (see figure 5). When the location of the GRB is unknown, the value of μ_{100}
 317 needed to calculate Π is also unknown. Therefore the uncertainty on the
 318 position of the GRB is translated to an uncertainty in the value of μ_{100} and,
 319 through the first term of equation 4, further into an error on the resultant
 320 level of polarization.

321 One can calculate the error of μ_{100} with standard error propagation:

$$\sigma_{\mu_{100}} = \sqrt{\left(\frac{\partial\mu_{100}}{\partial x}\sigma_x\right)^2 + \left(\frac{\partial\mu_{100}}{\partial y}\sigma_y\right)^2} \quad (5)$$

322 For each of the positions simulated as examples, the spread and bias of the
 323 reconstructed values were determined. When the spread of the reconstructed
 324 coordinates was larger than their bias, the spread was introduced as σ_x and
 325 σ_y in equation 5. Otherwise, the value of the bias was taken. To calculate
 326 the partial derivatives of the μ_{100} with respect to x and y we fitted the 2-
 327 dimensional distribution from figure 5 with the following polynomial function:

$$\mu_{100}(x, y) = a_0 + a_1x + a_2x^2 + a_3y + a_4y^2 + a_5xy \quad (6)$$

328 whose partial derivatives are:

$$\left\{ \begin{array}{l} \frac{\partial \mu_{100}}{\partial x} = a_1 + 2a_2x + a_5y \\ \frac{\partial \mu_{100}}{\partial y} = a_3y + 2a_4y + a_5x \end{array} \right. \quad (7)$$

329 From equations 7 and 5 one can calculate the error induced on μ_{100} by
 330 the uncertainty in the location of the GRB. The final result can be seen in
 331 figure 6 and represents the value of the first term in equation 4 ($\sigma_{\mu_{100}}/\mu_{100}$)
 332 at various source locations. The error caused to μ_{100} is always smaller than
 333 6% of its absolute value.

334 The total error in the measured polarization is given by equation 4. Its
 335 second term (σ_{μ}/μ) depends on the strength and level of polarization of the
 336 GRB. In figure 7 we present an example calculated for *standard* strong bursts
 337 of fluence $F_{\text{tot}} = 10^{-5} \text{ erg cm}^{-2}$, located at POLAR zenith, and with various
 338 levels of polarization. For this calculation we have substituted $\sigma_{\mu_{100}}/\mu_{100} =$
 339 0.10 in equation 4, instead of the 0.06 previously mentioned, because 10%
 340 was the maximal error found on μ_{100} for such a *standard* strong GRB when
 341 variations of the spectral shape were taken into account (see section 5.3). One
 342 can notice that the error due to the position uncertainty is negligible for low
 343 levels of polarization, with respect to the error associated to the modulation
 344 factor itself. At large levels of polarization the localization contribution to
 345 the error is more important. The final error in Π is in that case $\sigma_{\Pi} \leq 15\%$
 346 of the absolute polarization level. The values represented in figure 7 should be
 347 considered for bursts of total fluence $F_{\text{tot}} = 10^{-5} \text{ erg cm}^{-2}$ as upper limits to
 348 the error on the polarization level.

349 5. Systematic effects

350 The results presented in figure 4 represent the best case example, since
 351 the measurements to which the method was applied were produced in the
 352 same conditions as the localization database, and considering POLAR as
 353 an instrument with a perfectly uniform response. During a real observation
 354 there are several issues that could influence the outcome of the GRB local-
 355 ization method. We will discuss here the most important ones: asymmetries
 356 produced by GRB polarization, diffuse photon background, GRB spectral
 357 variations, satellite backscattering, fluctuations in light-collection efficiency,
 358 and MAPM non-uniform sensitivity.

359 *5.1. GRB polarization*

360 The database of the localization method was constructed simulating un-
 361 polarized sources. Although the polarization introduces an asymmetry in the
 362 POLAR hit pattern, it does not strongly affect the output of the scaler used
 363 for the localization procedure. Some examples were made with simulations
 364 of *standard* strong GRBs, 100% polarized in the direction parallel to POLAR
 365 X-axis, to confirm that statement. As with the non-polarized examples, 10
 366 simulations were produced at each position of the sky and the spread and
 367 bias in the reconstruction of their locations were calculated. It was clearly
 368 seen that the outcome of the localization procedure was not affected by the
 369 polarization of the source. Both the spread of the reconstructed values and
 370 the bias of their average were within the errors equal to the non-polarized
 371 case.

372 *5.2. Diffuse γ -ray background*

373 Outside of the South Atlantic Anomaly the largest source of background
 374 that will affect POLAR on orbit is the diffuse γ -ray photon background
 375 [20]. This source of background illuminates approximately isotropically the
 376 POLAR instrument. Since the surface of the most external MAPMs is more
 377 exposed, the SO produced by the γ -ray diffuse photon background presents
 378 higher number of counts for the external MAPMs and lower in the internal
 379 ones. When analyzing the SO of the total signal, i.e. GRB+background, the
 380 result of the localization method may be different than the obtained from
 381 the GRB alone. POLAR will store data from before, during, and after the
 382 GRB, making possible the subtraction of the diffuse γ -ray background. We
 383 will discuss here how accurately the interpolation and subtraction need to
 384 be made so that the localization method is not affected.

385 The spectrum of the γ -ray diffuse photon background has been parametrized
 386 [39] using the function:

$$\begin{aligned}
 & 3\text{--}60 \text{ keV} : \\
 & f(E) = 7.877E^{-0.29}e^{-E/41.13} \\
 & > 60 \text{ keV} : \\
 & f(E) = 0.0259 \left(\frac{E}{60}\right)^{-5.5} + \\
 & \quad + 0.504 \left(\frac{E}{60}\right)^{-1.58} + \\
 & \quad + 0.0288 \left(\frac{E}{60}\right)^{-1.05}
 \end{aligned} \tag{8}$$

387 with $f(E)$ in units of $\frac{\text{keV}}{\text{keV cm}^2 \text{ s sr}}$. An increment of 10% in the absolute
 388 normalization factor has been needed to fit recent measurements of the cosmic
 389 hard X-ray spectrum performed by INTEGRAL instruments [40].

390 To study the background influence it is important to consider the
 391 duration of the burst. Unlike GRBs, where for a constant fluence the flux
 392 diminishes when the duration increases, the diffuse background produces a
 393 flux approximately constant with time. Since we accumulate the output of
 394 the scaler during the whole GRB, the shape of its lightcurve has no influence
 395 on the localization method. For simplicity we considered both the lightcurves
 396 of the burst and the background as flat. Figure 8 shows the lightcurve and
 397 spectra of the diffuse photon background together with a short GRB of 1
 398 second duration and *standard* Band parameters located at POLAR zenith.
 399 The equivalent plots for a 20 seconds long GRB are presented in figure 9.

400 We have simulated the diffuse γ -ray background using equation 8 with a
 401 10% higher normalization factor as suggested in [40], and we calculated its
 402 SO. The result was added to the SOs of a series of *standard* strong GRBs
 403 as the ones presented in figure 4. Then, a second diffuse γ -ray background
 404 was simulated and its SO was subtracted from the previous data successively
 405 with an excess of 8%, 10%, 20%, and 30% over its average value. The whole
 406 procedure was performed twice, using a 1 second and 20 seconds duration
 407 GRB, to reproduce a short and long GRB, respectively.

408 We observed that, while for a short GRB the background did not influ-
 409 ence the performance of the localization method, its contribution was very
 410 important in the case of the long GRB, inducing an error of $\sim 50\%$ in μ_{100} if
 411 not subtracted. If the background is overestimated by a 8% of its real level,
 412 the error transmitted to μ_{100} was $\sigma_{\mu_{100}} \leq 10\%$, increasing to $\sigma_{\mu_{100}} \leq 14\%$ for a
 413 10% overestimation, and to $\sigma_{\mu_{100}} \sim 20\%$ and $\sigma_{\mu_{100}} \sim 30\%$ for a 20% and 30%
 414 overestimation, respectively.

415 As a conclusion, background subtraction is important not only for the
 416 polarimetric performance of POLAR, but also for its capability of localizing
 417 GRBs. In the case of short GRBs the diffuse γ -ray background can be ne-
 418 glected, but for long GRBs the background calculation must not differ from
 419 the real background level by more than 8%. When the background is not
 420 strongly variable, it is sufficient to average two background measurements
 421 one taken immediately before and the other immediately after the GRB. If
 422 the total time span measured outside the GRB is equal to the burst duration,
 423 one obtains the level of background with r.m.s. equal to $\sim 7\%$ of its absolute

424 value.

425 *5.3. Variations of the GRB spectral shape*

426 The GRBs used for the NSO database have been simulated taking the
 427 Band parameters corresponding to a *standard* strong GRB, summarized in
 428 the first row of table 1. The NSOs and SOs depend on the spectrum since the
 429 penetration length of photons in the POLAR target is an exponential function
 430 of their energy. To study the possible influence of different GRB spectra on
 431 the localization method, several series of simulations have been performed.
 432 We selected from the BATSE catalog [33] the bursts with energy fluence
 433 $F_{\text{tot}} \approx 10^{-5} \text{ erg cm}^{-2}$ which had the Band parameters most different from
 434 our standard ones. The selection of GRBs studied is presented in table 1.

GRB	F_{tot} ($\times 10^{-5}$) [erg cm $^{-2}$]	α	β	E_{peak} [keV]
Standard	1.0	-1.0	-2.5	200
911104	1.1	-0.6	-1.95	265
920718	1.1	-1.09	-3.06	192
930922	2.0	-1.40	-2.88	94
951016	1.4	-1.61	-2.02	118
980828	1.7	-0.25	-2.08	223
981130	1.1	-0.54	-2.25	649

Table 1: Details of the spectrum of the *standard* strong GRB compared to the bursts from BATSE catalog selected for studying the influence of the spectral shape into the localization procedure. From the BATSE catalog we selected the six bursts that, having a similar total energy fluence, presented the most different Band parameters with respect to our *standard* GRB.

435 We made a series of simulations locating each BATSE burst at several
 436 positions in the sky and applied to them the localization method to study the
 437 spread and bias of the reconstructed values, in the same way as presented in
 438 section 4. When using a very low 5 keV energy threshold to the scalars, it was
 439 observed that the modification of the GRB spectral parameters introduced
 440 in some cases a large bias on the reconstructed x and y coordinates. The
 441 sign of the bias changed from GRB to GRB, and its absolute value was
 442 the largest (taking values up to 0.25) when α and E_{peak} strongly differed
 443 from the values used for the database, while variations on β did not affect

444 it significantly. The main reason is that most of the photons that POLAR
445 detects, and which mostly define the shape of the SO, have low energies.
446 Low energy photons do not penetrate far inside POLAR target, producing
447 hits only on the side where the GRB is coming from. Although this makes
448 them in principle very good to localize a GRB, the fact that POLAR cannot
449 measure the spectral shape precisely enough makes it impossible to correct
450 for the bias in the reconstructed coordinates for GRB spectrally very different
451 from our standard one.

452 One possible solution would be to measure the GRB spectrum with a
453 small spectrometer that could be mounted somewhere close to POLAR. In
454 such a case it would be enough to produce a new NSO database with the
455 observed burst spectrum and apply the localization method to determine
456 the GRB position with a few degrees uncertainty. When no spectrometer is
457 available, the only alternative to mitigate the problem is, as we have done, to
458 raise the energy threshold of the scaler, which in principle could be as low as
459 5 keV, to 50 keV. In this way we largely reduce the sensitivity of the method
460 to spectral variations, so that the bias of the reconstructed coordinates is
461 below 0.15 and the error inflicted into μ_{100} is below 10% for all GRBs from
462 table 1. We show in figure 10 the case of GRB 981130, for which the method
463 performance was the worst of the six examples (the absolute values of the
464 coordinates bias were the largest).

465 Unfortunately, when reducing the method sensitivity to spectral varia-
466 tions, we cut out a large number of counts from the SOs and NSOs, dimin-
467 ishing the statistical power. As a consequence, the error produced on μ_{100}
468 from the uncertainty in the localization of GRBs with fluence $F_{\text{tot}} = 10^{-6}$
469 erg cm^{-2} and same spectral parameters as the database bursts, can reach
470 14%. For weaker GRBs our technique will not be able to provide the posi-
471 tion of the source with sufficient accuracy, especially taking into account the
472 spectral variability.

473 *5.4. Satellite backscattering*

474 Photons coming from the GRBs can reach POLAR indirectly after being
475 backscattered in the spacecraft where the polarimeter is mounted. We have
476 simulated a very simple description of the Chinese Tiang-Gong Space Lab
477 as a "bottle-like" assembly of two cylinders (1.65 m radius, 4 m high, and
478 1.4 m radius, 3.2 m high, respectively) joint by a 1.4 m long trunked cone.
479 All volumes were simulated in aluminum with a thickness of 4 cm, so that
480 the total mass of the spacecraft is ≈ 8 tons. POLAR was placed outside the

481 Space Lab at 12.5 cm from its trunked cone part, pointing with the front of
 482 its target to the zenith. The GRB photons were uniformly illuminating an
 483 area of 2 m radius with POLAR at its center. A series of simulations with
 484 *standard* strong GRBs at several positions in the sky, as done for figure 4,
 485 were produced and the localization method was applied. The results were
 486 found to be within errors the same as when the satellite was not considered.
 487 The 50 keV energy threshold applied in the scalers is rejecting most of the
 488 photons coming to POLAR from the satellite, since they have lost energy in
 489 the backscattering process.

490 5.5. *Statistical fluctuations in light collection*

491 Plastic scintillators are a good choice to perform hard X-ray polarime-
 492 try because the probability that a photon of this energy range experiences
 493 Compton scattering in the target is very high. The price one pays in ex-
 494 change is a low energy sensitivity, not enough to make spectroscopic studies.
 495 GEANT4 simulations of optical photon tracking show that about $\approx 60\%$
 496 of the optical photons produced in a POLAR scintillator bar never reach the
 497 MAPM [41]. The detector will be calibrated taking this into account but,
 498 due to the statistical fluctuations in the number of optical photons collected,
 499 the spectral resolution will be poor. We have simulated the scintillation pro-
 500 cess in a single bar and fired it with bunches of photons at various energies.
 501 For each run a gaussian fit of the photo-peak spectral line was performed.
 502 We found an expression to relate the σ of this gaussian fit with the incoming
 503 energy of the photon, i.e., the broadening (σ) of the lines as a function of the
 504 deposited energy (E_{dep} , expressed in keV):

$$\sigma = 0.215 \cdot E_{\text{dep}}[\text{keV}] + 2.953 \text{ keV}. \quad (9)$$

505 The main consequence of this line-broadening for POLAR measurements is
 506 that the signal collected at the MAPM anode does not correspond exactly to
 507 the deposited one. Therefore, the 50 keV threshold introduced at the scalers
 508 will be blurred.

509 The influence of the spectral line broadening into the GRB localization
 510 method has been studied. *Standard* strong GRBs were simulated at different
 511 positions in the sky as it was done to produce figure 4. Before applying the
 512 localization method to these GRBs, each value of the energy deposition E_{dep}
 513 was substituted by a number that had been randomly generated following a
 514 Gaussian distribution with mean E_{dep} and sigma the result from equation 9.

515 The application of the localization method to the modified data gave the
516 same results as when E_{dep} was perfectly determined, with no increment on
517 the coordinates uncertainty.

518 *5.6. Sensitivity variations between MAPM anodes*

519 Two photons of the same energy can produce different signals if they come
520 to two MAPM channels that do not have the same sensitivity. According to
521 the H8500 MAPM data-sheet [42] sensitivity differences up to a factor of 3
522 can exist between the anodes of the same MAPM. We have observed that
523 the sensitivity usually varies following a smooth function with a maximum
524 close to one of the corners of the MAPM, and monotonously decreases when
525 moving away from that point. We have assigned to each of the 64 elements
526 of a MAPM a number in the range from 0.4 to 1, distributed according to an
527 example data-sheet, but with variations of the order of 5% at each channel.
528 Such a sensitivity mask was produced for each of the 25 MAPMs of POLAR,
529 taking random orientations so that the corner with maximum sensitivity was
530 not always at the same side of the target. In this study we have assumed
531 that the average sensitivity is the same for all 25 MAPMs. The 40×40
532 mask created in this way was applied as a multiplicative factor to the energy
533 depositions of a series of *standard* strong GRBs like the ones from figure 4.
534 No change in the localization uncertainty with respect to the results shown
535 in figure 4 was found.

536 **6. Summary and conclusions**

537 Relevant information on the magnetic composition, geometric structures,
538 and emission mechanism of GRBs, not accessible by spectroscopic and pho-
539 tometric approaches, can be obtained through polarization measurements of
540 the GRB prompt emission. POLAR aims to determine the level of linear
541 polarization of GRBs in the energy range from 50 to 500 keV by measuring
542 the azimuthal distribution of the photons that Compton-scatter in its plastic
543 scintillator target. To keep the design as simple and compact as possible,
544 POLAR is totally devoted to polarimetry and is not optimized for imaging
545 and spectroscopic purposes. The level of polarization of a GRB can only be
546 determined when knowing its position in the sky.

547 We have presented a method, using only POLAR, able to estimate the
548 position of GRBs with enough precision so that the error transmitted to the
549 100% modulation factor due to the location uncertainty is kept below 10%

550 for strong GRBs of total fluence $F_{\text{tot}} \geq 10^{-5}$ erg cm $^{-2}$. A scaler is connected
551 to the output of each MAPM to record the number of GRB photons that
552 produce at least one hit with energy above 50 keV. The outputs of the 25
553 scalars, accumulated over the whole duration of the GRB, present a pattern
554 that depends on the direction where the photons are coming from.

555 We have performed several series of simulations to estimate the capabili-
556 ties of the GRB localization method and the influence of its uncertainty on
557 the measured level of polarization. When simulating strong non-polarized
558 GRBs with a fluence $F_{\text{tot}} = 10^{-5}$ erg cm $^{-2}$ and a similar spectral shape
559 to the ones used to create the database, the position coordinates could be
560 determined with a maximal error of 0.07, equivalent to being able to deter-
561 mine the position in spherical coordinates $(\theta_\gamma, \phi_\gamma)$ within $\sim 5^\circ$ for $\theta_\gamma > 30^\circ$.
562 This would inflict an error in the μ_{100} of the measured GRB of less than
563 6%. Considering GRBs of similar strength but different spectral shapes, the
564 coordinates could be determined with a maximal error of 0.14, keeping the
565 error on μ_{100} below 10%. For weaker GRBs of fluence $F_{\text{tot}} \approx 10^{-6}$ erg cm $^{-2}$
566 the error in μ_{100} will be below about 20%.

567 Several effects that could potentially modify the performance of the GRB
568 localization technique have been studied. It was found that the influence of
569 the diffuse photon background will be negligible for short GRBs, but it needs
570 to be subtracted from long ones. Its estimation in the later case should be
571 done with a precision better than 8% around the real value. Neither the
572 level of polarization of the source, nor the presence of a spacecraft behind
573 POLAR that backscatters part of the GRB photons show any influence in
574 the output of the localization method. The limited energy resolution due
575 to light collection inefficiencies and MAPM non-uniformities will blur the 50
576 keV energy threshold but this will not diminish the localization capabilities
577 of our method.

578 The GRB localization technique will provide enough accuracy to allow for
579 the measurement of the GRBs polarization level with only a small increase
580 on its error. For a GRB of total fluence $F_{\text{tot}} = 10^{-5}$ erg cm $^{-2}$, the added
581 error is negligible at low polarization levels, compared with the one from the
582 measured modulation factor itself. At large polarization levels the error from
583 the localization is larger than the one from the measured modulation factor,
584 but all together reaching no more than 15% of the measured polarization.

585 The method presented here can be experimentally tested when uniformly
586 illuminating the complete POLAR target with a radioactive source to be
587 placed at various locations. Such a kind of test will be performed when

588 the POLAR engineering qualification model will be ready. In flight, if other
589 instrument can provide the position of one or several GRBs detected by
590 POLAR, a direct comparison with the output of the localization method can
591 be done. In general, the precision in the localization provided by instruments
592 with imaging capabilities will be much better than that of POLAR alone, and
593 preferred to it. The POLAR localization capability will be useful for those
594 cases where no other instruments are simultaneously observing the same field
595 of view.

596 **7. Acknowledgements**

597 We wish to thank the technical staff at the University of Geneva, in
598 particular F. Masciocchi and F. Cadoux, for their crucial contribution to the
599 POLAR mechanical design, and for producing figure 1 for this paper. This
600 work was funded by the Fonds National Suisse pour la Recherche Scientifique.

601 **References**

- 602 [1] D. Band, J. Matteson, L. Ford, et al., *ApJ*. 413 (1993) 281.
- 603 [2] S.E. Woosley, *ApJ* 405 (1993) 273.
- 604 [3] D. Eichler, M. Livio, T. Piran, et al., *Nature* 340 (1989) 126.
- 605 [4] C. Kouveliotou, C.A. Meegan, G.J. Fishman, et al., *ApJ* 413 (1993)
606 L101.
- 607 [5] T.Q. Donnaghy, D.Q. Lamb, T. Sakamoto, et al., arXiv:astro-
608 ph/0605570 (2006).
- 609 [6] S.E. Woosley and J.S. Bloom, *Annu. Rev. Astro. Astropys.* 44 (2006)
610 507.
- 611 [7] B. Zhang, *Adv. in Space Res.* 40 (2007) 1186.
- 612 [8] B. Zhang, *Chin. J. Astron. Astrophys.* 7 (2007) 1.
- 613 [9] T. Piran, *Rev. of Modern Phys.* 76 (2004) 1143.
- 614 [10] M. Lyutikov, V.I. Paiev, and R.D. Brandford, *ApJ* 597 (2003) 998.

- 615 [11] A. Dar, and A. de Rujula, Phys. Rep. 405 (2004) 203.
- 616 [12] D. Lazzati, New Journal of Physics Vol 8, Issue 8 (2006) 131.
- 617 [13] K. Toma, T. Sakamoto, B. Zhang, et al., submitted ApJ,
618 arXiv:0812.2483v1(2008).
- 619 [14] W. Coburn and S.E. Boggs, Nature 423 (2003) 415.
- 620 [15] R.E. Rutledge, and D.B. Fox, Mon. Not. R. Astron. Soc. 350 (2004)
621 1288.
- 622 [16] C. Wigger, W. Hajdas, K. Arzner, et al., ApJ 613 (2004) 1088.
- 623 [17] D.R. Willis, E.J. Barlow, A.J. Bird, et al., A&A 439 (2005) 245.
- 624 [18] S. McGlynn, D.J. Clark, A.J. Dean, et al., A&A 466 (2007) 895.
- 625 [19] E. Kalemci, S.E. Boggs, C. Kouveliotou, et al., ApJS 169 (2007) 75.
- 626 [20] N. Produit, F. Barao, S. Deluit, et al., Nucl. Instr. and Meth. A550
627 (2005) 616.
- 628 [21] P.F. Bloser, J.S. Legere, J.R. Macri, et al., Chin. J. Astron. Astroph.
629 Suppl. Vol. 6 Issue S1 (2006) 393.
- 630 [22] J.E. Hill, M.L. McConnell, P. Bloser, et al., AIP Conf. Proc. 1065 (2008)
631 331.
- 632 [23] R.M. Curado da Silva, E. Caroli, J.B. Stephen, et al., Exp. Astron. Vol
633 15, Issue 1 (2003) 45.
- 634 [24] S. Gunji, H. Sakurai, F. Tokanai, et al., SPIE Conf. Proc 686 (2007)
635 668618.
- 636 [25] E. Costa, R. Bellazzini, G. Tagliaferri, et al., SPIE Conf. Proc. 6686
637 (2007) 6686Z.
- 638 [26] E. Costa, R. Bellazzini, P. Soffitta, et al., SPIE Conf. Proc. 6266 (2006)
639 62660R.
- 640 [27] T. Kamae, V. Andersson, M. Arimoto, et al., Astropart. Phys. Vol. 30,
641 Issue 2 (2008) 72.

- 642 [28] M.L. McConnell, J.M. Ryan, D.M. Smith, et al., *Solar Phys.* 210 (2002)
643 125.
- 644 [29] F. Lei, A.J. Dean, and G.L. Hills, *Space Sci. Rev.* 82 (1997) 309.
- 645 [30] S. Agostinelli, J. Allison, K. Amako, et al., *Nucl. Instrum. Meth. A* 506
646 (2003) 250.
- 647 [31] R. Brun, F. Rademakers, *Nucl. Instr. and Meth. A* Vol 389, Issues 1-2
648 (1997) 81.
- 649 [32] R.D. Preece, M.S. Briggs, R.S. Mallozi, et al., *ApJS* 126 (2000) 19.
- 650 [33] Y. Kaneko, Ph.D. Thesis, The University of Alabama in Huntsville
651 (2005).
- 652 [34] T. Hauschild and M. Jentschel, *Nucl. Instr. and Meth. A* 457 (2001) 384.
- 653 [35] S. Baker and R.D. Cousins *Nucl. Instr. and Meth.* 221 (1984) 437.
- 654 [36] W. Hajdas, N. Produit, E. Suarez-Garcia, et al., *SPIE Conf. Proc.* 6266
655 (2006) 62662W.
- 656 [37] G.G. Lichti, M. Briggs, R. Diehl, et al., *Baltic Astronomy* 13, 311 (2004)
657 311.
- 658 [38] S.D. Barthelmy, L.M. Barbier, J.R. Cummings, et al., *Space Sci. Rev.*
659 120 (2005) 143.
- 660 [39] D.E. Gruber, J.L. Matteson, L.E. Peterson, et al., *ApJ* 520 (1999) 124.
- 661 [40] E. Churazov, R. Sunyaev, M. Revnintsev, et al. *A&A* 467 2 (2007) 529.
- 662 [41] E. Suarez-Garcia, D. Haas, and the POLAR collaboration, *NSS Conf.*
663 *Record* (2008).
- 664 [42] Hamamatsu, H8500 Technical Data Sheet,
665 [http://209.73.52.252/assets/pdf/parts_H/-](http://209.73.52.252/assets/pdf/parts_H/-H8500C_H8500D_TPMH1308E01.pdf)
666 [H8500C_H8500D_TPMH1308E01.pdf](http://209.73.52.252/assets/pdf/parts_H/-H8500C_H8500D_TPMH1308E01.pdf)

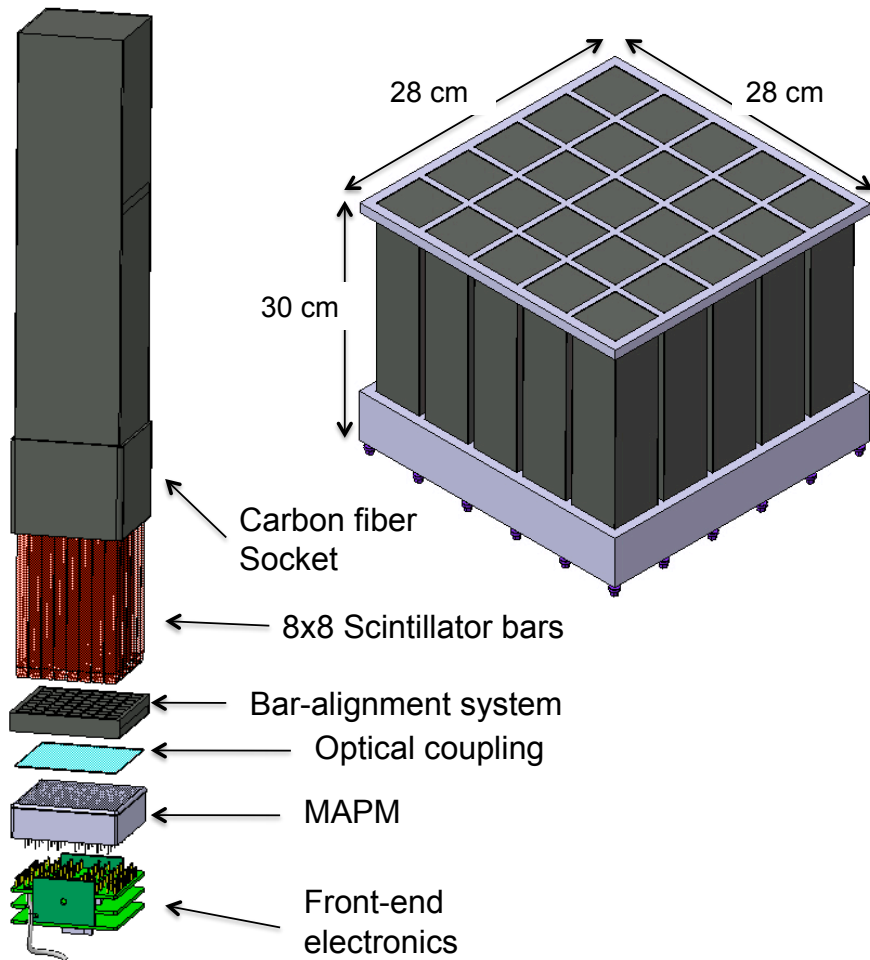


Figure 1: Scheme of POLAR detector. *Left*: Exploded view of one module from POLAR target. *Right*: Complete POLAR target, i.e., the assembly of 25 modules, with its approximate dimensions.

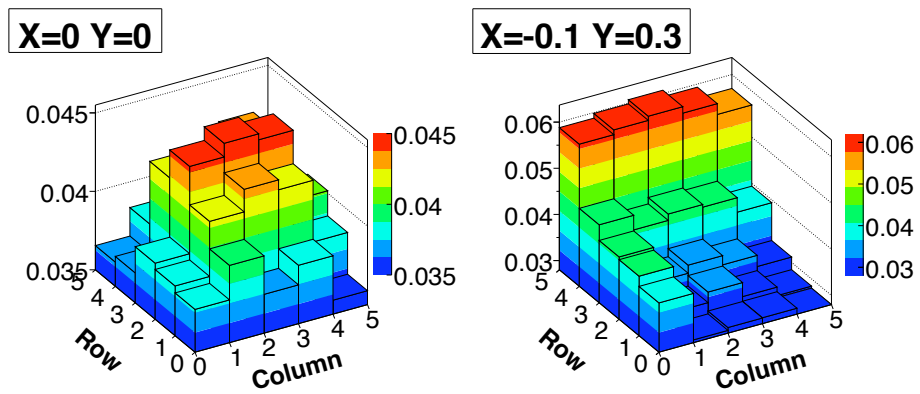


Figure 2: Graphical representation of two of the normalized scalar output (NSO) patterns that constitute the database.

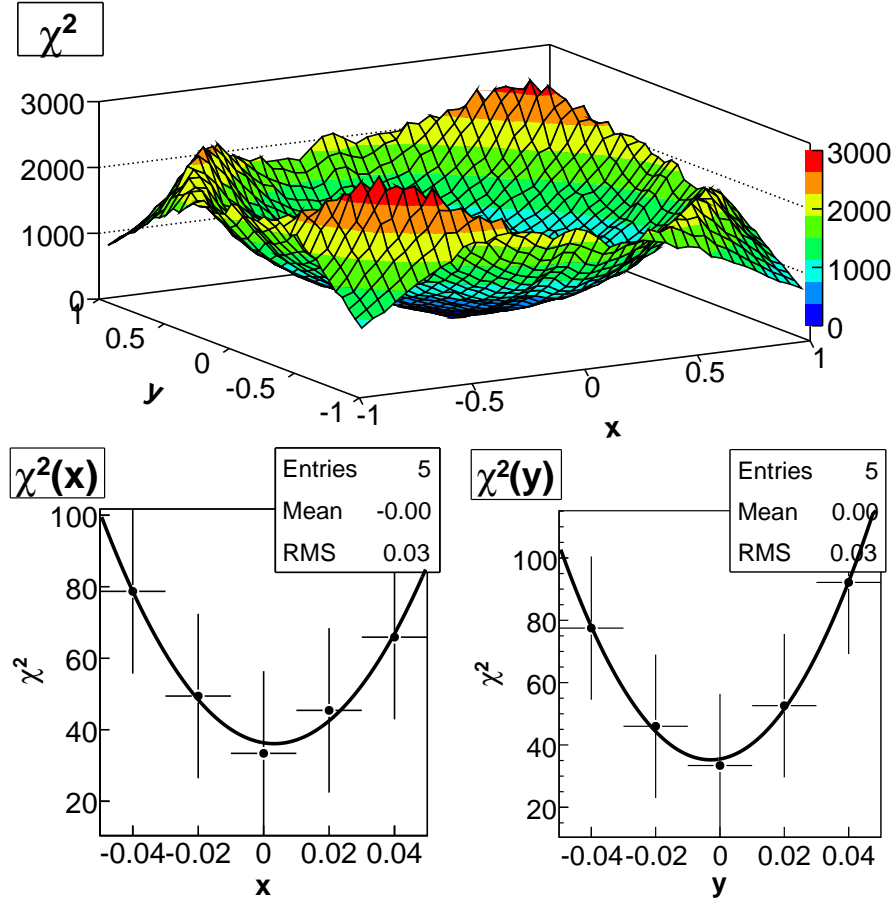


Figure 3: Example of χ^2 minimization. The distribution of χ^2 in the (x, y) plane is shown in the top, and the parabolic fits of both variables in the bottom. The measurement used in this example was produced using the POLAR simulation package with a non-polarized GRB of $F_{\text{tot}} = 10^{-5} \text{ erg cm}^{-2}$, $\alpha = -1.0$, $\beta = -2.5$, $E_{\text{peak}} = 200 \text{ keV}$ located at POLAR zenith.

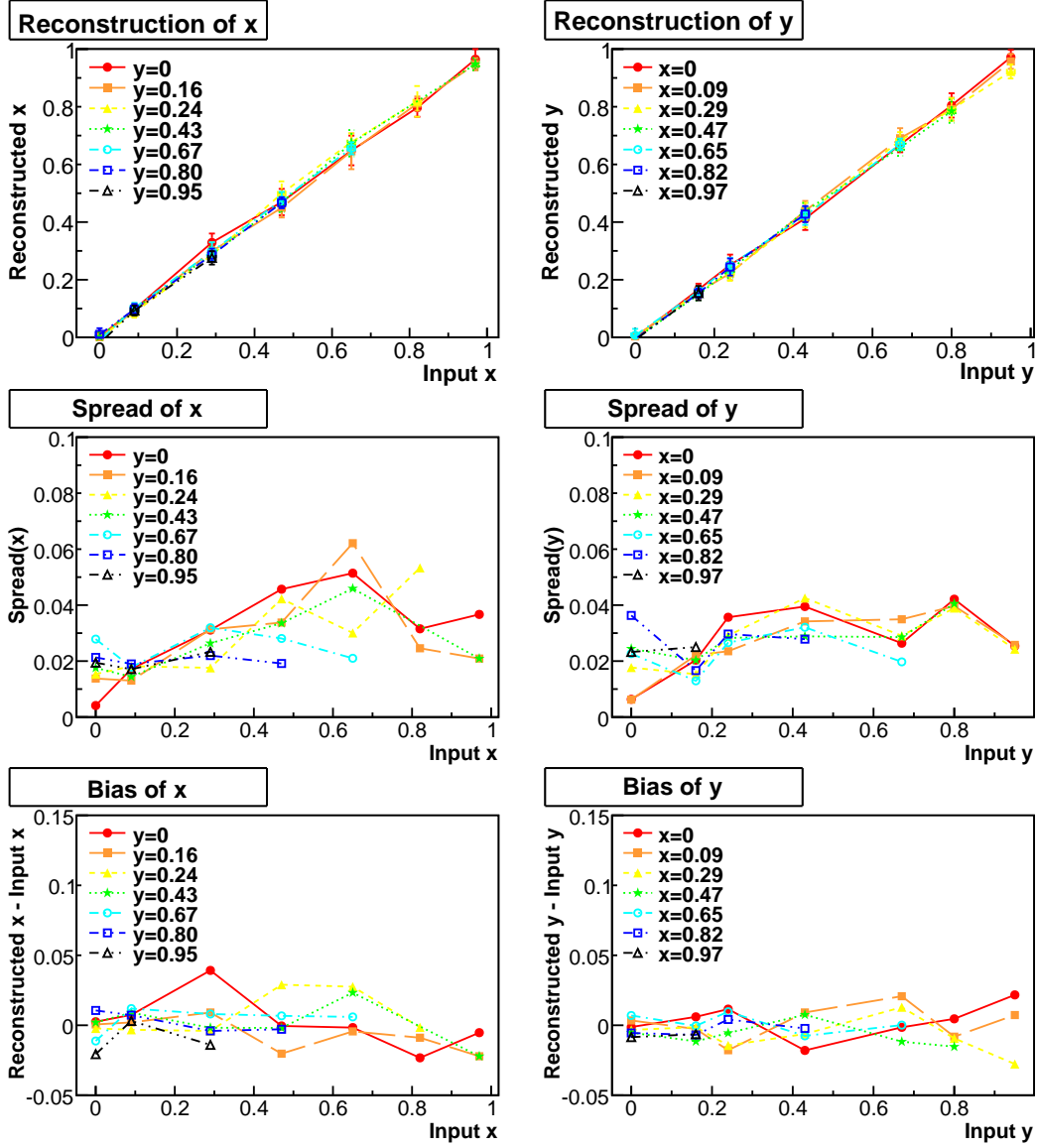


Figure 4: Results from simulated non-polarized *standard* strong GRBs. *Top left:* Linearity plot in x , i.e. reconstructed x vs. input x for several fixed y values. Each point on this graph represents the average of the 10 simulations made at each position. *Middle left:* Spread of the reconstructed x , i.e. the standard deviation of the 10 reconstructed x values. *Bottom left:* Bias in the reconstruction, i.e. the difference between the reconstructed average x value and the input x . The plots on the right are the equivalent to the left ones, but calculated for y at several fixed x positions. In all the plots lines of different styles have been drawn to guide the eye.

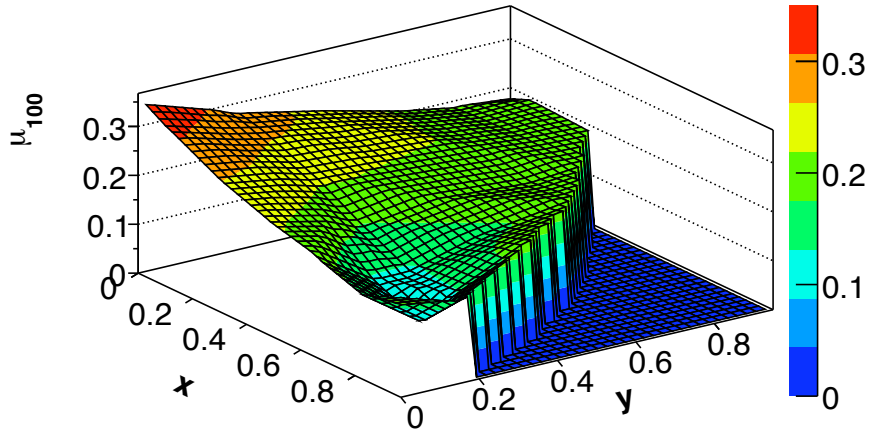


Figure 5: Distribution of 100% modulation factor (μ_{100}) vs. x and y , calculated for a standard strong GRB (see text). The empty area at the right of the image corresponds to positions where the GRB would be below POLAR. Such a situation will never happen during flight and therefore was not considered in the analysis.

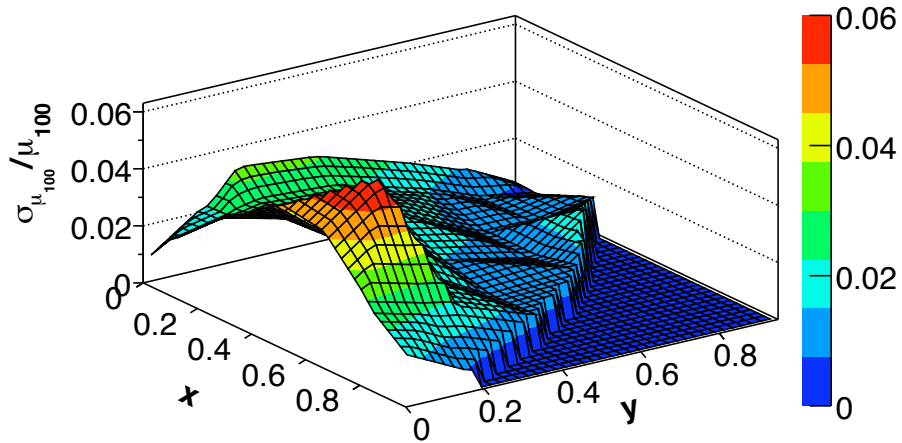


Figure 6: Error caused to μ_{100} due to the uncertainty on the localization of GRBs, divided by μ_{100} .

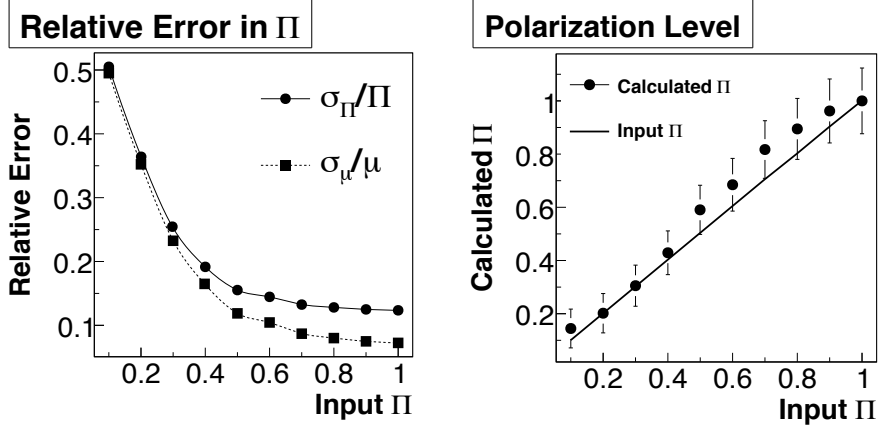


Figure 7: Upper limits to the error on the polarization level for a GRB of total fluence $F_{\text{tot}} = 10^{-5} \text{ erg cm}^{-2}$. These plots have been calculated using the upper limit of the error inflicted to μ_{100} due to the localization procedure. *Left*: Relative error of the modulation factor for different levels of polarization (*dotted*), together with the final relative error on Π (*solid*), where $\sigma_{\mu_{100}}/\mu_{100} = 0.1$ has been included. The increase due to the localization uncertainty is visible at high polarization values. *Right*: Calculated polarization level (*points*), together with the simulation input values (*line*), plotted as a reference. For polarization levels above 60% the uncertainty in the GRB position is the largest source of error.

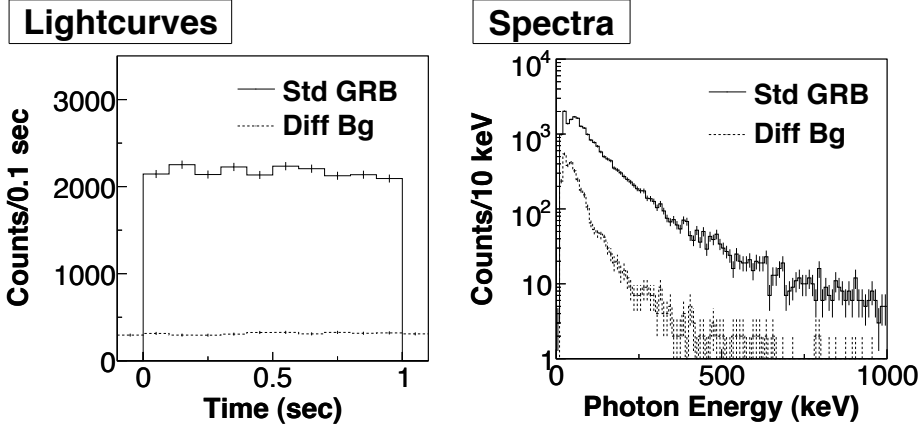


Figure 8: Comparison between the flux of a short (1 sec) *standard* strong GRB and the diffuse photon background. *Left*: Assumed lightcurve of the GRB signal (*solid*) and the diffuse photon background (*dotted*). All photons producing a hit above 5 keV in POLAR target have been included. *Right*: Spectrum for the same two sources.

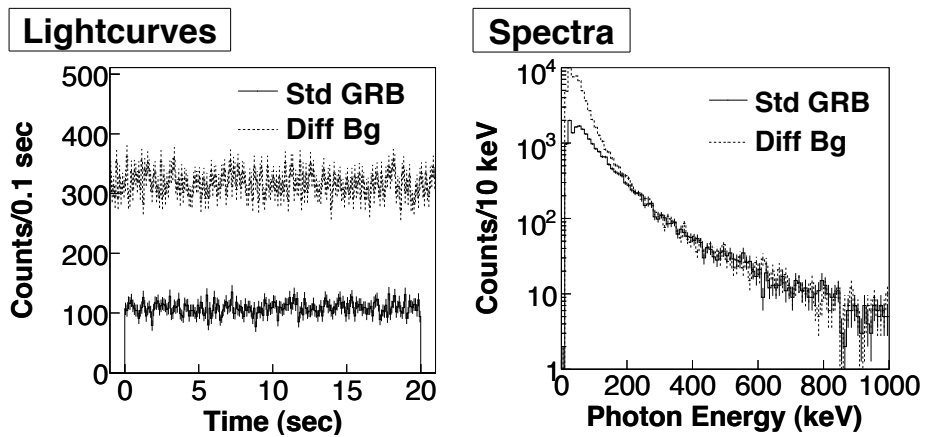


Figure 9: Comparison between the flux of a long (20 sec) *standard* strong GRB and the diffuse photon background. *Left*: Assumed lightcurve of the GRB signal (*solid*) and the diffuse photon background (*dotted*). All photons producing a hit above 5 keV in POLAR target have been included. *Right*: Spectrum for the same two sources.

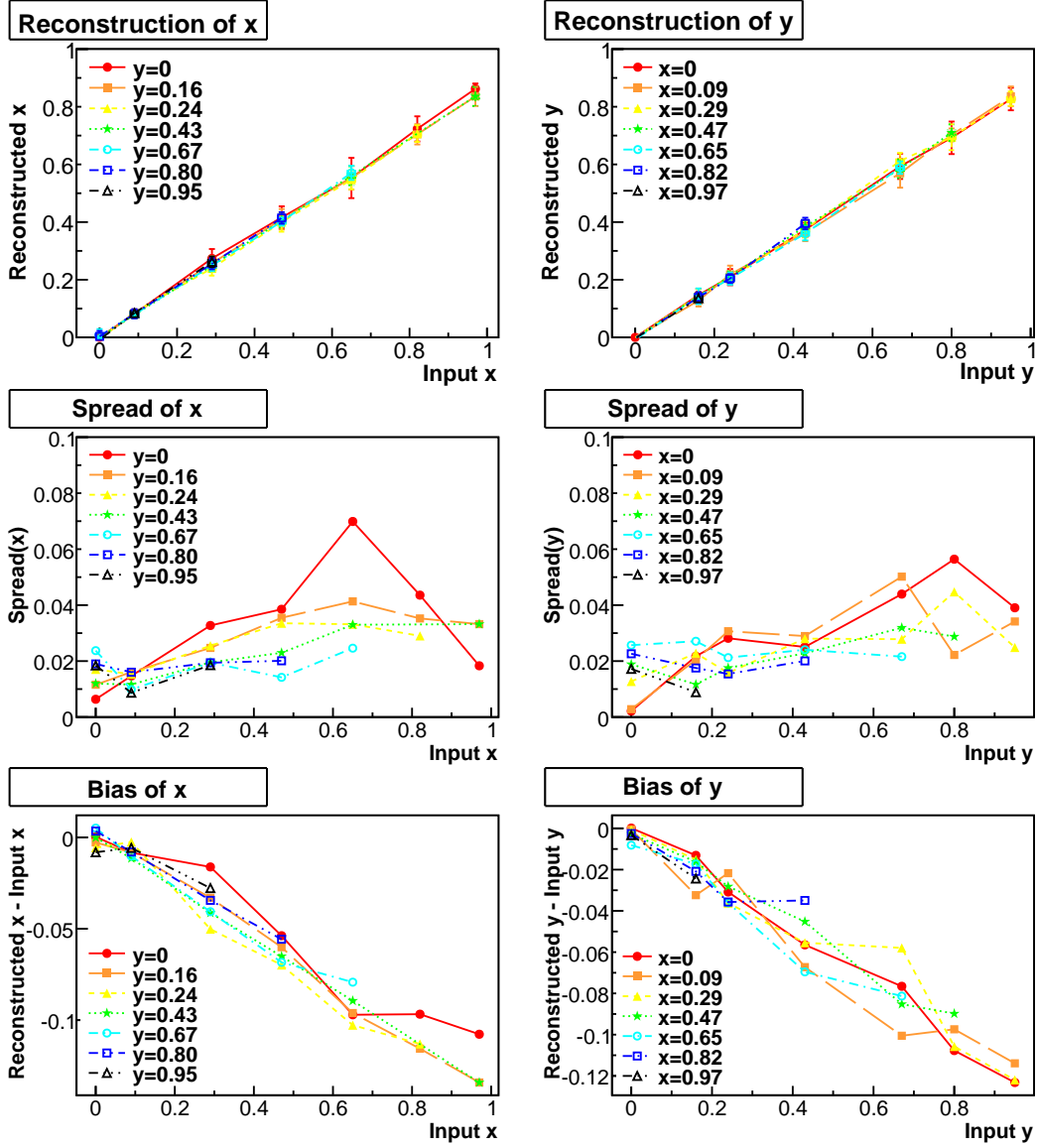


Figure 10: Results from GRB 981130, simulated non-polarized and without background. *Top left*: Linearity plot in x , i.e. reconstructed x vs. input x for several fixed y values. Each point on this graph represents the average of the 10 simulations made at each position. *Middle left*: Spread of the reconstructed x , i.e. the standard deviation of the 10 reconstructed x values. *Bottom left*: Bias in the reconstruction, i.e. the difference between the reconstructed average x value and the input x . The plots on the right are the equivalent to the left ones, but calculated for y at several fixed x positions. In all the plots lines of different styles have been drawn to guide the eye.