The γ-Ray Burst-Detection System of SPI*

G. G. Lichti[1], R. Georgii[1], A. von Kienlin[1], V. Schönfelder[1], C. Wunderer[1], H.-J. Jung[2], and K. Hurley[3]

1) *Max-Planck-Institut für extraterrestrische Physik, PO Box 1603, 85740 Garching, Germany*
2) *Dornier Satellitensysteme GmbH, 88039 Friedrichshafen, Germany*
3) *University of California, Space-Sciences Laboratory, Berkeley, CA 94708, USA*

Abstract. The determination of precise locations of γ-ray bursts is a crucial task of γ-ray astronomy. Although γ-ray burst locations can be obtained nowadays from single experiments (BATSE, COMPTEL, BeppoSax) the location of bursts via triangulation using the interplanetary network is still important because not all bursts will be located precisely enough by these single instruments. In order to get location accuracies down to arcseconds via triangulation one needs long baselines. At the beginning of the next decade several spacecrafts which explore the outer planetary system (the Mars-Surveyor-2001 Orbiter and probably Ulysses) will carry γ-ray burst instruments. INTEGRAL as a near-earth spacecraft is the ideal counterpart for these satellites. The massive anticoincidence shield of the INTEGRAL-spectrometer SPI allows the measurement of γ-ray bursts with a high sensitivity. Estimations have shown that with SPI some hundred γ-ray bursts per year on the 5σ level can be measured. This is equivalent to the BATSE sensitivity. We describe the γ-ray burst-detection system of SPI, present its technical features and assess the scientific capabilities.

INTRODUCTION AND DESCRIPTION OF THE ACS OF SPI

INTEGRAL will be launched into an eccentric earth orbit at the end of 2001. The anticoincidence subsystem (ACS) of the INTEGRAL-spectrometer SPI will have the capability to measure the arrival times and light curves of γ-ray bursts with a high accuracy. It will therefore allow in conjunction with other distant spacecrafts the determination of precise γ-ray burst locations using the 4th interplanetary network (IPN) [1].

The ACS surrounds, with the exception of the field of view, the central Ge-detector array from all sides. It consists of 512 kg of BGO crystals. Each crystal is viewed by two photomultiplier tubes whose signals are measured. These signals are ORed in the Veto-Control Unit (VCU) yielding the overall-veto count rate R which is measured and for the purpose of γ-ray burst detection transmitted via the spectrometer's Digital Processing Electronics (DPE) to ground. A more detailed description of SPI can be found in [2] and [3].

* A detailed version of the paper can be found under http://ww.gamma.mpe-garching.mpg.de/integral/SPI/DOCUMENTATION/doclist.html under the document number SPI-MPE-TN-1-29

SENSITIVITY ESTIMATION

The sensitivity for measurements of γ-ray bursts is calculated using the total veto count rate R. This count rate is measured during a time interval Δt. A γ-ray burst manifests itself as a sudden and rapid increase of the veto rate. Assuming Poisson statistics the counts/bin fluctuate around the average bin count rate whereby the 1σ-statistical fluctuation is given by the square root of the bin count rate. To detect a γ-ray burst with a high certainty a significant positive deviation from this average count rate is required. In the following a deviation by at least 5σ is required. It is assumed that a burst has occurred when the number of counts per bin N exceeds a value of $5 \cdot \sqrt{R \cdot \Delta t}$.

The number of counts from a burst can be calculated for an average burst spectrum:

$$N = A \cdot \Delta t \cdot \int_{E_s}^{\infty} F(E)dE \tag{1}$$

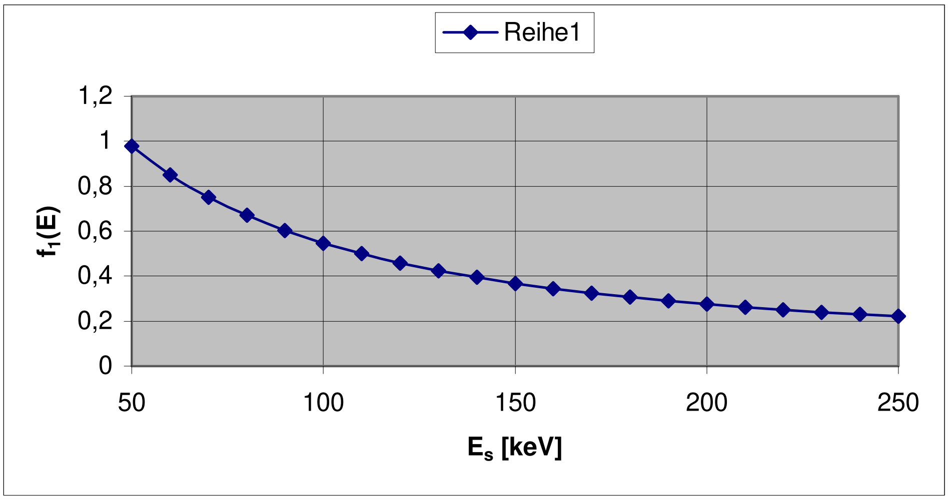

FIGURE 1: The dependence of $f_1(E_s)$ on the threshold energy E_s for the canonical value of E_o (= 150 keV).

Here A is the effective area of the ACS whose energy dependence is neglected and F(E) is the differential energy spectrum of a γ-ray burst approximated by the Band function [4] for which we use the canonical parameter E_o = 150 keV. E_s is the threshold of the anticoincidence subsystem.

Solving (1) for the trigger condition given above one can find the weakest γ-ray burst which can be detected with the ACS of SPI. Knowing the weakest burst one is able to derive the number of bursts/year which can be detected by SPI by calculating the energy flux P of a γ-ray burst.

To avoid a divergence in the calculation an upper cut-off energy E_m (= 10 MeV) has been introduced. One gets finally the minimal-detectable energy flux P as a function of all relevant parameters (the dimensionless function $f(E_s)$ is given in Figure 1):

$$P = \frac{5 \cdot \sqrt{R} \cdot E_o}{A \cdot \sqrt{\Delta t} \cdot f_1(E_s)} \cdot \left[e^{-\frac{E_s}{E_o}} + e^{-1} \cdot \left(\ln \frac{E_m}{E_o} - 1 \right) \right] \qquad (2)$$

In Figure 2 the dependence of P on the normal (i. e. non-burst) rate R is shown. The total rate of the ACS varies depending on the solar activity between ~80 000 cts/s and ~160 000 cts/s. According to Figure 2 this corresponds to minimal detectable burst energy fluxes between 4 • 10^{-7} erg/(cm^2 s) and 7 • 10^{-7} erg/(cm^2 s) for Δt = 1 s. The difference between the two fluxes is small and within the uncertainty of the estimation. Using the corresponding figure of [5] one finds that with SPI within one year ~280 bursts for Δt = 1 s can be observed.

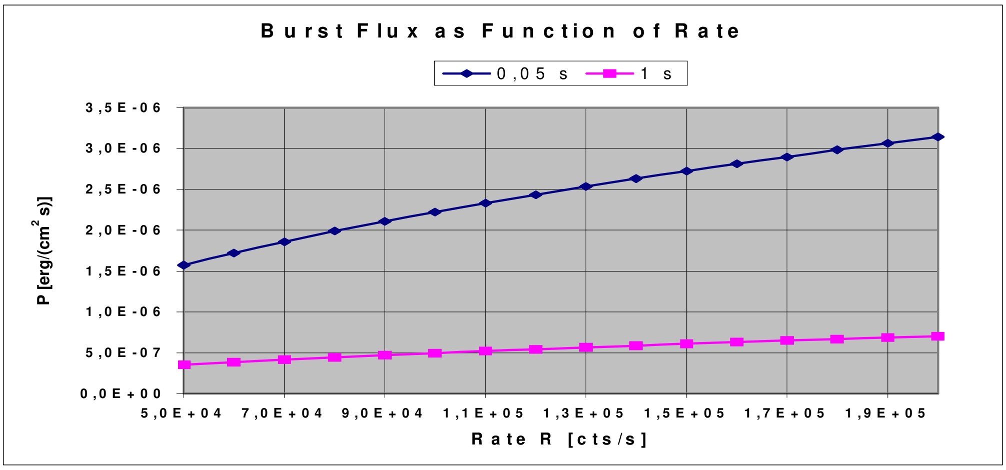

FIGURE 2: The minimal detectable energy flux P as a function of the overall-count rate R for two time intervals Δt, for a threshold of 80 keV, an effective area of 3000 cm^2 and for a cut-off energy of 10 MeV.

SCIENTIFIC AND TECHNICAL REQUIREMENTS

The width of the arrival-direction annulus of a γ-ray burst depends on the accuracy of the arrival-time measurement Δt and the distance d between the spacecrafts of the IPN:

$$\Delta\alpha = \frac{c \cdot \Delta t}{d \cdot \sin\alpha} \qquad (4)$$

c is the speed of light and α the angle of the arrival cone. If one takes d = 4.3 AU (= 6.45 • 10^8 km, the distance to the Ulysses spacecraft), α = 45^o and requires that Δα < 10” one finds Δt < 74 ms. Therefore a time resolution of 50 ms was chosen for the SPI-ACS γ-ray burst-detection subsystem.

Since the arrival time of a γ-ray burst has to be known in universal time (UT) this time has to be allocated to the start or end of the integration time of the count-rate measurement. The accuracy of this time shall be much less than 50 ms. A safe requirement is to know it with a precision of ~5%. Therefore the acquisition of the veto count rate shall be performed with an accuracy of ~2.5 ms with respect to UT.

REALISATION OF THE TECHNICAL REQUIREMENTS

The realisation of this requirement is achieved with the overall-veto-counter of the ACS, the 8 Hz clock pulse and the the on-board-time (OBT) of the DPE.

The overall-veto counter is a start/stop counter of the VCU which collects the ORed vetos from the 91 FEEs and is set to zero every 50 ms. The 8 Hz clock is a continuous rectangular pulse coming from the DPE which is directly linked to the VCU micro-controller. The OBT is a relative mission time with known relation to the UT. Inside the VCU a 50 ms VCU-timer interrupt is generated that is synchronized with the OBT every 8 s.

The overall-counter readings are stored in a “toggle buffer” with 10 records each inside the VCU-RAM. Each record contains the 8-bit record count s and the 16 overall-counter values. So in total one buffer contains 160 overall-counter values allowing the storage of count rates within a time interval of 8 s. The two buffers A and B will be filled and read out alternately. In addition the toggle buffer contains one header which holds the toggle-buffer start time t_B. This time is the VCU time derived from the OBT which is updated every 125 ms (see Figure 3).

Whenever SPI has been switched on by command the DPE 8 Hz clock will update the VCU internal time every 125 ms. At this moment it has the same accuracy as the OBT time of the DPE. Every 640 s the DPE sends the value of the OBT to the ACS. This value is the time of the last falling edge of the 8 Hz pulse prior to the reception of the OBT (see Figure 3).

The first interrupt from the 8 Hz pulse after the first start-time reading from the DPE will also start the acquisition sequence. The current value of the overall-counter register will be transferred to the first sample of buffer A and the overall-counter value is set to zero. Parallel to the writing of the first counter value to buffer A the actual time of the VCU (as derived from the OBT) is written into the header of the buffer. This time, the toggle-buffer start time t_B, lies, as is shown in Figure 3, between the start and end time of the current 50 ms interval. The time intervals τ_1 and τ_2 from this time to the previous or succeeding edges of the corresponding 50 ms (= τ_o) interval have been chosen to be 40 ms (= τ_1) and 10 ms (= τ_2). Thus the toggle-buffer start time t_B refers to the 50 ms time interval that started 40 ms (= τ_1) before.

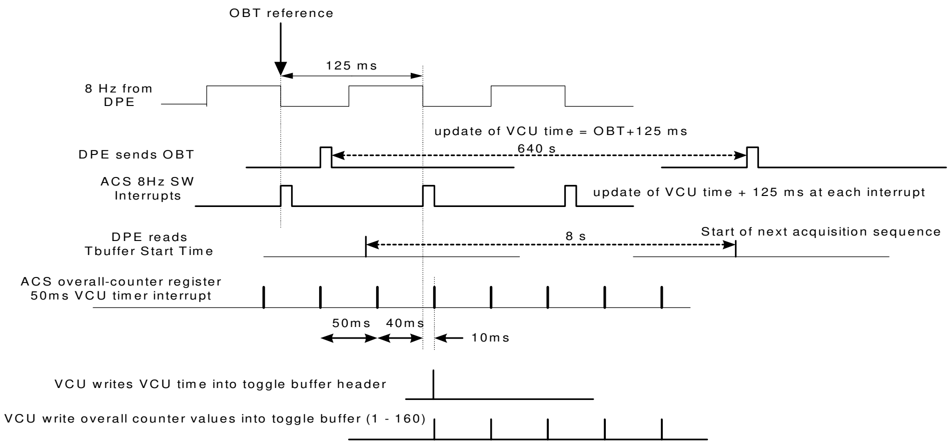

FIGURE 3: The time synchronization and γ-ray burst-acquisition procedure.

The start and end times t_s and t_e of a 50 ms interval are given by $t_s = t_B + s \bullet \tau_o - \tau_1$ and $t_e = t_B + s \bullet \tau_o + \tau_2$. Here s is the record counter and t_B the toggle-buffer start time, which is equivalent to the OBT in the moment of the first count writing into the buffer. The uncertainty of the time allocated to the count value is ± 1ms.

The total timing error depends on the accuracy of the falling edge (with a fall time of < 20 ns) of the 8 Hz interrupt signal with a time jitter < 0.1 μs, the numerical resolution of the OBT of ± 1.907 μs and the uncertainty of the falling edge of the 50 ms pulse which could be shifted by ± 1 ms due to the DPE interrupts.

Since every 125 ms the internal VCU clock is updated the error of τ_o is not given by $s \bullet \Delta\tau_o$ but by $2.5 \bullet \Delta\tau_o$ (2.5 = 125 ms/50 ms). The timing-error budget can therefore – under the assumption that the errors are of statistical nature - calculated according to the following formula:

$$\Delta t_s = \sqrt{\Delta t_B{}^2 + (2.5 \cdot \Delta\tau_o)^2 + \Delta\tau_1{}^2} \tag{5}$$

The errors of the three parameters are $\Delta\tau_B$ = 1.91 μs, $\Delta\tau_o$ = 1 ms and $\Delta\tau_1$ = 1 ms, yielding a total error of $\Delta\tau_s$ = 2.69 ms.

DATA-ANALYSIS SYSTEM AND CONCLUSIONS

A software which will be installed at the ISDC in Geneva will check automatically the stream of count-rate data for the occurrence of a γ-ray burst. Once this automatic system will recognize a burst an alert will be issued to the institution which is responsible for the 4th IPN. From the measured arrival times at the different spacecraft locations the arrival direction of the γ-ray burst will be calculated. This information will then be distributed worldwide to those observatories which participate in the search for counterparts of γ-ray bursts at other wavelengths.

For an assumed absolute timing error of the different arrival times of 100 ms an error region in the sub-arcminute range can be achieved due to the long baselines of the 4th IPN as was shown by [1]. For a γ-ray burst with a fluence of $2 \bullet 10^{-6}$ erg/cm^2 an error box of 0.5 square-arcminutes was obtained. With the γ-ray burst-detection subsystem of SPI as described above even smaller error regions can be achieved. This is small enough to make a search for counterparts promising.

ACKNOWLEDGMENTS

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REFERENCES

1. Hurley, K., Proc. of the 2nd INTEGRAL workshop St. Malo **SP-382**, 1997, pp. 491-493.
2. Lichti, G. G. et al., Proc. of the SPIE conference in Denver, Vol. **2806**, 1996, pp. 217-233.
3. Mandrou, P., G. Vedrenne, P. Jean et al., Proc. of the 2nd INTEGRAL workshop in St. Malo, ESA **SP-382**, 1997, pp. 591-598.
4. Band, D., J. Matteson, L. Ford, B. Schaefer, D. Palmer et al., Ap. J. **413**, 1993, pp. 281-292.
5. Fenimore, E. E., R. I. Epstein, C. Ho, R. W. Klebesadel et al., Nature **366**, 1993, pp. 40-42.