Analysis of Scaler Data from GRB 970417a

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1 A Brief Primer on Analysis of the Scaler Data

The Milagro scaler system uses CAMAC scalers to count the hits from several outputs of the digital front-end boards. An input register is used to record the time from the GPS clock, and two output registers are used to set a bitmask used by the system. Every second, the clock (i.e. the input register) and scalers are read, the bitmask is reset, and the scalers are cleared. The data are read into `mgroems`, the EMS system computer.

There are three types of scaler output from the digital boards: Low, High, and Masked. On each board there are four Low outputs, labeled A, B, C, and D, which are used to monitor the rate of hits which cross the low threshold. Each of the sixteen tubes is hardwired to exactly one of the four outputs, as shown in Figure 1. Each of the four outputs is a logical OR of the four tubes in the group. Consequently, two tubes in the same group which get hit within about 30 ns of one another only generate one output count. The layout is chosen so that no pair of nearest or next-to-nearest neighbors is in the same group, in order to maximize the probability that a particle which produces hits in several nearby tubes will generate multiple counts.[1] The four groups can be further combined (again as a logical OR) by jumpers on the digital board in order to reduce the total number of scaler channels needed. For Milagrito, we operated all four outputs independently. For Milagro, in the air shower layer we have combined groups A and D and groups B and C to form two outputs, which we refer to as "A" and "B." For the Milagro muon layer, all four groups are combined into a single output for the patch, called "A."

16 D	15 C	14 D	13 C
12 B	11 A	10 B	9 A
8 D	7 C	6 D	5 C
4 B	3 A	2 B	1 A

Figure 1: The assignment of tubes within a patch of 16 to the Low Scaler groups A, B, C, and D.

The High output for each patch is hardwired as a logical OR of the high threshold hits of all 16 tubes in the patch. The two hit time resolution is a little worse for the High output: 40 or 50 ns between hits is required for them to register separate counts.

The Masked output is a logical OR of the low threshold hits from all 16 tubes in the patch, but with the addition of a bitmask used to set which tubes participate in the OR. The bitmask is distributed to the modules on the crate backplane, so it is common to all modules in a crate. A special card in the last slot in the crate receives the mask pattern on a ribbon cable and puts it on the backplane. We use this output to look at each tube individually, so at any moment, only one bit is set in the mask. With each readout cycle, the bit which is on is shifted to the next higher channel number, so each tube is monitored for 1 second every 16 seconds.

There also scalers for two trigger rates. One is the "raw" trigger rate, which is the rate at which the multiplicity requirement for a trigger is satisfied. The other is the "gated" trigger rate, which is the rate for events which are actually accepted by the FASTBUS data acquisition system. The ratio of the gated rate to the raw rate is the experiment live time.

The CAMAC readout is initiated by `mgroems` after sleeping for the necessary time to make for 1 second elapsed since the start of the previous readout cycle. The elapsed time is usually quite close to 1 second, but because of varying system load and process scheduling on `mgroems` (as well as a fast system clock on `mgroems`), there are variations. A reference counter derived from the GPS clock is used to correct for such effects. For Milagrito the reference was 1 MHz, and for Milagro it is 10 MHz. Four scaler channels (two channels, each with a second channel for carries when the 24 bit counter rolls over) count the reference clock and are read out with the rest of the scaler channels. For Milagrito, each scaler module was

[1]The design is based on the 4x4 patch shown, but is implemented by channel number within the patch. Hence for any patch, regardless of shape, tubes 1, 3, 9, and 11 are connected to group A, etc.

read and cleared independently. This could result in slightly different acquisition times for each module, and small differences from the elapsed time measured by the reference counter. For Milagro, the system asserts a crate-wide Inhibit on the backplane (via a CAMAC command to the controller) before starting the readout. All the modules are read and cleared, and then the Inhibit is released to resume counting.

The scaler data are written to a series of files with name `JD0xxxx.sca`, where "xxxx" is the modified Julian day(MJD)-50000. There is one file for each day. The data are compressed in a home brew format. The compression scheme is similar in some ways to techniques Miguel Morales has described for the raw TDC data. For each scaler channel, the difference between the present value and the average value for that channel is stored. A certain number of bits is allocated for the typical case, and if the number is beyond that range, a flag is used to invoke the necessary extra space. The averages are updated once an hour. The compressed data are in a short int array, so the data are easily byte swapped to cross between the Linux and SGI platforms. The data are swapped before being written out by `mgroems`, so the data files are in SGI format.

Versions of the scaler code including makefiles for both the SGI and PC architecture for Milagrito and for Milagro are installed at LANL in `/disk02/Milagro/analysis/offline_v23/scalers/` and `/disk02/Milagro/analysis/offline_v32/scalers/`, respectively. `scalerJob.c` is an example main program. The header file `scaler.h` defines the structures into which the scalers are unpacked, and `packScalers.c` is the compression/decompression code. `swappack.c` is needed only for the PC and does the byte swapping on the packed scaler data. The only difference between the Milagro and Milagrito versions is the header file, which contains the information on how many scaler channels there are of each type.

The `scalerJob.c` program has the directory in which to find the `JD0xxxx.sca` files hardwired in the code. You will need to edit `scalerJob.c` to have the right directory to look for the scaler data files. Once you do that, this job makes a bunch of histograms of rate distributions and time histories (using hbprof) for the range of input data files you specify at execution. E.g.
`scalerJob 1330 1337`
will run on files `JD01330.sca` through `JD01337.sca`, inclusive. The output histogram file will be `jd01337.paw`. There is a `.kumac` file which is nice for looping through all the tubes and checking their time histories for light leaks. It is `scalerHistories.kumac`.

The each 16 seconds of scaler data are loaded into a structure `SCALER_CYCLE` which has the data for one loop over the sixteen values of the bitmask, and the corresponding values from the sixteen reads of the other information. The structure is defined as follows:

```
typedef struct {
unsigned int clock[3][16];
unsigned int julDate[16];
double eventTime[16];
short int timeErr[16];
int oref[16];
int mref[16];
int ocnts[NUMSOR][16];
int mcnts[NUMSMASK][16];
int rawTrg[16];
int gateTrg[16];
} SCALER_CYCLE;
```

`clock` is the array of three raw clock words read by the input register for each of the sixteen reads in the cycle. `julDate`, `eventTime`, and `timeErr` are the sixteen decoded time values, in the same style as the air shower data.[2] `oref` and `mref` are the reference counts for the two reference scalers. `oref` is used to correct the Low OR's, High OR's, and trigger rates; `mref` is used to correct the masked trigger rates. `ocnts` is the array of counts for the OR'ed scaler channels. The assignment of channels to the NUMSOR array elements is not obvious, and is given in Table 1. For a given value of `i`, the sixteen

[2] The clock information is read at the end of each 1 s period of data accumulation, immediate prior to reading out the scalers themselves.

Milagrito Scaler Channel Assignments for `ocnts[i][j]`									
`i`	Group	`i`	Group	`i`	Group	`i`	Group	`i`	Group
0	Patch 15 A	1	Patch 15 B	2	Patch 15 C	3	Patch 15 D	4	Patch 15 High
5	Patch 14 A	6	Patch 14 B	7	Patch 14 C	8	Patch 14 D	9	Patch 14 High
10	Patch 13 A	11	Patch 13 B	12	Patch 13 C	13	Patch 14 D	14	Patch 13 High
	...		...		...		...		...
65	Patch 2 A	66	Patch 2 B	67	Patch 2 C	68	Patch 2 D	69	Patch 2 High
70	Patch 1 A	71	Patch 1 B	72	Patch 1 C	73	Patch 1 D	74	Patch 1 High

Milagro Scaler Channel Assignments for `ocnts[i][j]`							
`i`	Group	`i`	Group	`i`	Group	`i`	Group
0	Patch 1 A	1	Patch 1 B	2	Patch 2 A	3	Patch 2 B
4	Patch 3 A	5	Patch 3 B	6	Patch 4 A	7	Patch 4 B
8	Patch 5 A	9	Patch 5 B	10	Patch 6 A	11	Patch 6 B
	...		...		...		...
52	Patch 27 A	53	Patch 27 B	54	Patch 28 A	55	Patch 28 B
56	Patch 29 A	57	Patch 29 B	58	Patch 30 A	59	Patch 31 A
60	Patch 32 A	61	Patch 33 A	62	Patch 34 A	63	Patch 35 A
	...		...		...		...
72	Patch 44 A	73	Patch 45 A	74	Patch 46 A	75	Patch 47 A
76	Patch 1 High	77	Patch 2 High	78	Patch 3 High	79	Patch 4 High
80	Patch 5 High	81	Patch 6 High	82	Patch 7 High	83	Patch 8 High
	...		...		...		...
116	Patch 41 High	117	Patch 42 High	118	Patch 43 High	119	Patch 44 High
120	Patch 45 High	121	Patch 46 High	122	Patch 47 High		

Table 1: The assignment of scaler channels to elements of the `ocnts` array in the `SCALER_CYCLE` structure.

elements `ocnts[i][j]` are sixteen consecutive measurements of the same quantity, to be corrected by `oref[j]` and corresponding to time stamp julDate[j] and eventTime[j]. `mcnts` is the array of values for the masked scaler channels. `mcnts[i][j]` is the rate of tube (j+1) in patch (i+1), with corresponding reference counter mref[j] and time stamp julData[j] and eventTime[j]. `rawTrg` and `gateTrg` are the raw and gated trigger rates respectively, and correspond to the `oref` and time stamps similarly to the other rates.

2 GRB 970417a

The BATSE trigger time for this burst is 50016.7135 on MJD 50555. So the scaler data file containing the burst is JD00555.sca. The BATSE offset of T90 is -1.024 s, and given the BATSE position at the time of the burst, the arrival time in Milagro is 0.0015 s earlier than at BATSE.[3] So the start of T90 in Milagro is at 50015.688 s. The length of T90 is 7.936±0.63 s. Hence the burst "ends" at 50023.624.

In general, there are a few tubes which behave badly in the scaler data because they are noisy, and there are many tubes which have rate variations because of light leaks. Note that the time of the burst is 13:53:35 UT, or 6:53:35 MST on April 17, 1997 (although perhaps we were on daylight time by then). The sun rose at the Milagro site 82 minutes prior to the burst, so light leaks cannot be ignored. At the time of the burst, 9 tubes were dead: 81, 96, 101, 105, 150, 194, 195, 207, 213. Dead tubes don't cause any problem when looking for rate variations, but need to be accounted for when determining the effective area. Seven other tubes have problems and are removed from the analysis. These are summarized in Table 2, and the time histories for these tubes are shown in Figures 2 and 3. Since the only way to remove these tubes is to exclude the group of four tubes containing each one, a total of 18 live tubes must be excluded, as listed in the Table.

[3] See R. Schnee, Ph.D. Thesis, University of California, Santa Cruz, 1996, SCIPP Report 96/37, p. 72.

Bad PMT	problem	Patch& Group	Scaler Channel	PMT's disabled
45	noisy	3C	62	37,39,45,47
109	big light leak	7C	42	101(dead),103,109,111
111	very noisy	7C	42	above
170	big light leak	11B	21	162,164,170,172
179	big light leak	12A	15	177,179,185,187
202	small light leak	13B	11	194(dead),196,202,204
204	small light leak	13B	11	above

Table 2: Groups of tubes which are removed from the analysis of GRB 970417a because of a bad tube in the group.

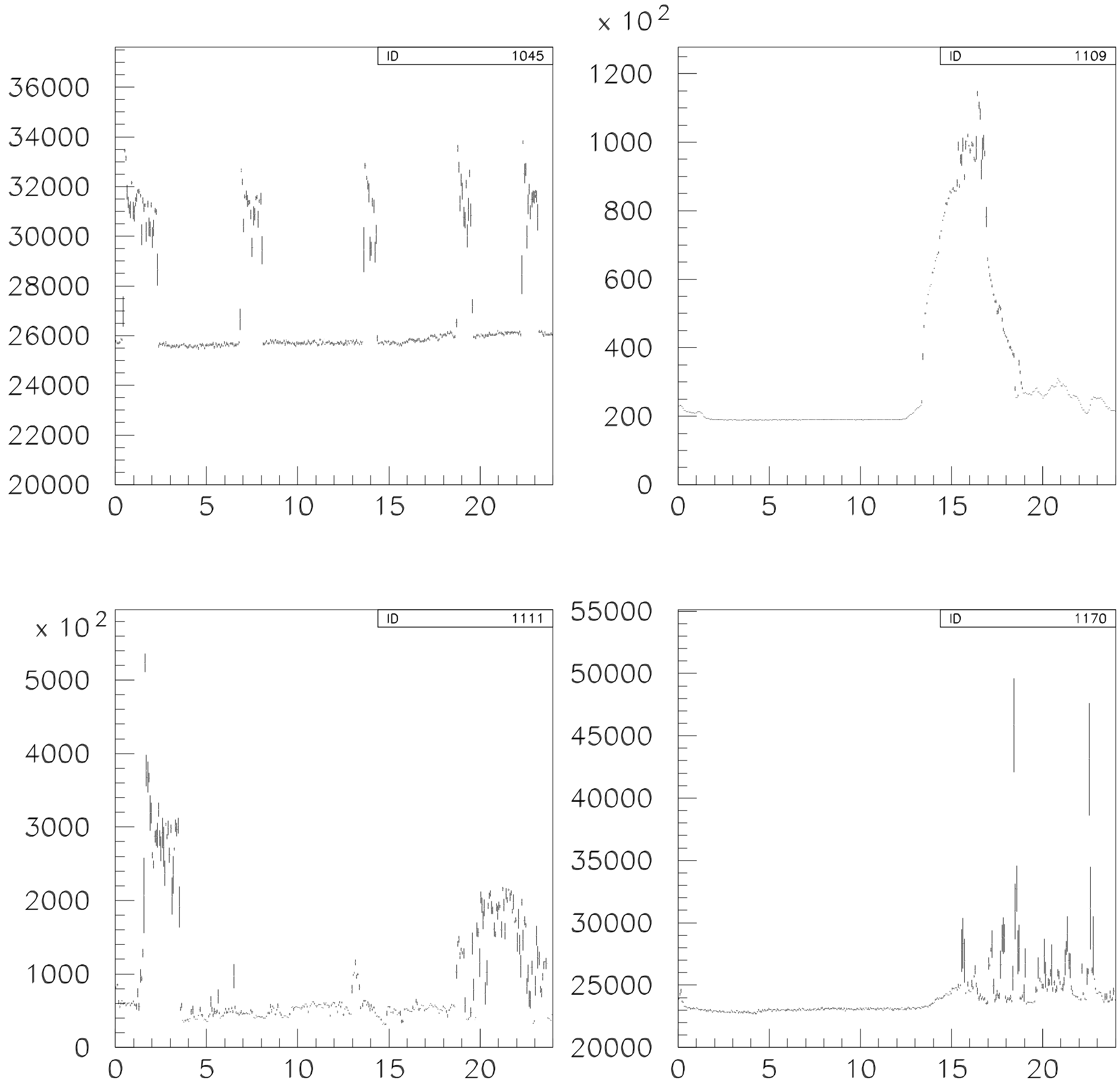

Figure 2: Time histories of phototubes 45, 109, 111, and 170 on the day of GRB 970417a. Histogram 1045 is tube 45, etc. The x-axis is hours UT during the day. Note that some graphs have suppressed zeroes.

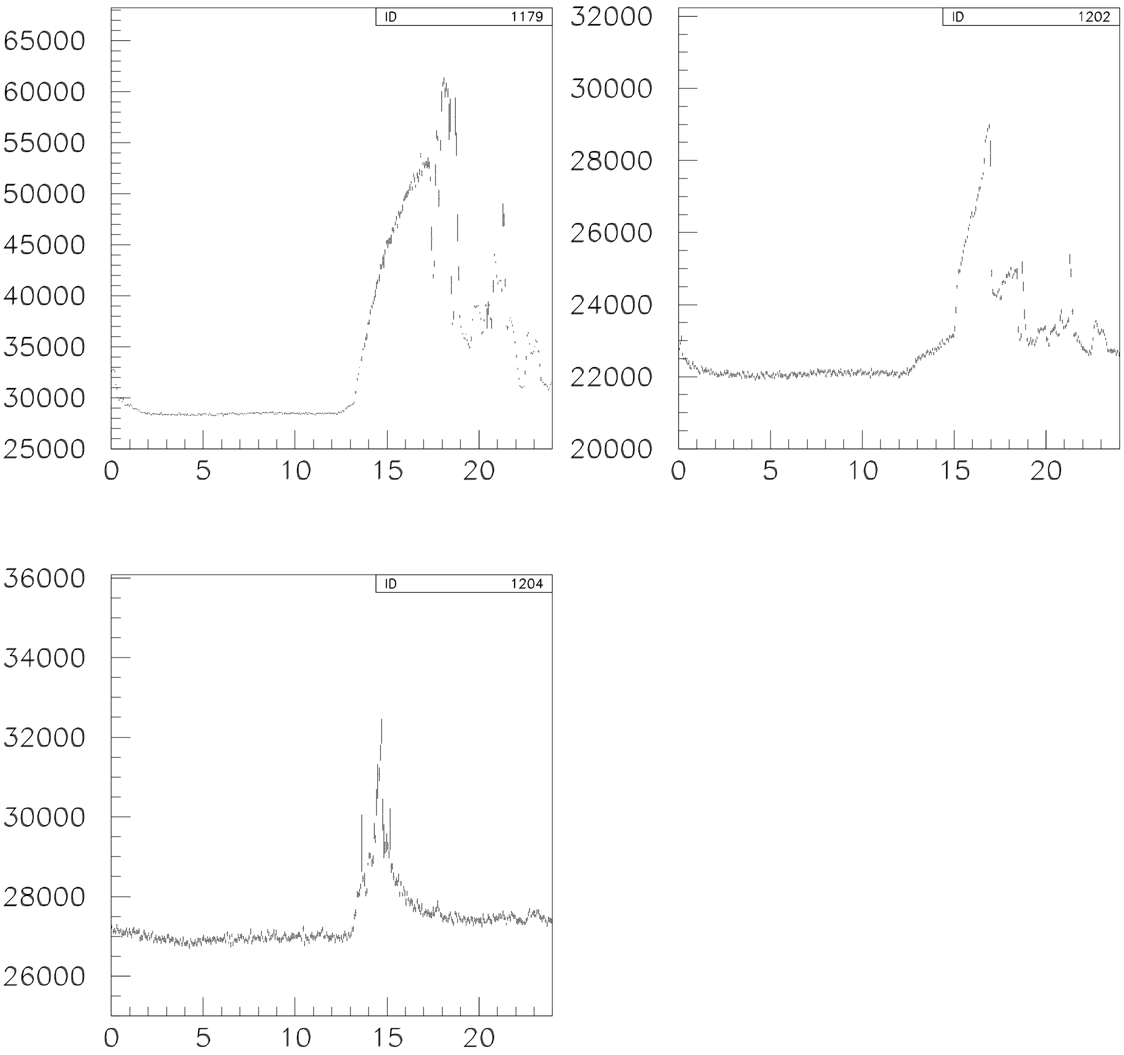

Figure 3: Same as Figure 2, but for tubes 179, 202, and 204.

As discussed above, the scalers are read out about once per second. The times of scaler readings near the time of the burst are:

...
50011.876219
50012.875892
50013.875813
50014.875540
50015.875867
50016.875301
50017.875089
50018.874921
50019.874709
50020.874535
50021.874158

50022.873991
50023.873717
50024.873643
50025.873493
50026.873579
...
Recalling that the time stamp is the time at the *end* of the counting interval, the nine readings in boldface contain the BATSE T90. So we desire to determine whether the counting rate summed over these nine readings was higher than the background.

The background counting rate is estimated using the data from 45 seconds prior to the burst and 45 seconds after the burst, for a total of 90 seconds. The total of 90 seconds is chosen in order to use 10 times the data of the burst itself, so that the error from the background measurement makes a small contribution. The interval is chosen symmetrically around the burst to accurately account for slowly varying increases or decreases in the rate. Such variations might arise from pressure changes or from tubes that are weakly affected by light leaks. (Removing all tubes that showed any hint of being affected by a light leak would leave us with almost none left to use.)

For each scaler reading, the rate of all of the low threshold groups, except those listed in Table 2, are summed to obtain the total rate in the pond. The rate has been corrected using the reference counter for the elapsed time and is not simply the number of counts.

For the moment, what Poisson tells us about the fluctuations can be ignored. Instead, the data can tell us what the fluctuations are. There are 90 measurements in the background sample, and 9 measurements in the signal sample. For each sample, the mean value is calculated, and the error on the mean is calculated from the scatter of the data points in the standard manner:

$$\sigma_{mean} = \frac{RMS}{\sqrt{N}}, \tag{1}$$

where N is the number of data values in the sample. The significance, s, of the deviation during the signal interval from the background rate is then also given in the usual way,

$$s = \frac{rate_{signal} - rate_{background}}{\sqrt{\sigma^2_{signal} + \sigma^2_{background}}}. \tag{2}$$

The behavior of the statistic s can be tested on a set of data. Using all the data from the day of the burst, every 100 s interval is used to calculate one value of s. Scaler readings occurring during seconds 0–45 or 54–99 are used for the background rate, and readings during seconds 45–54 are used as background. (The reading between 99 and 100 is ignored.) The distribution of values obtained in this way is shown in Figure 4. Ideally, the distribution of values of s for background fluctuations alone would be a Gaussian with unit RMS. In fact, for the selected good PMTs the distribution has roughly the expected shape, with an RMS of 1.12. The statistic s appears to be a good choice to test for burst emission.

At this point is it also possible to see the value of removing the noisy channels. When all tubes are used, the distribution has an RMS of 2.4, and has longer tails than a Gaussian. So by removing 18 out of the 219 live Milagrito PMTs, the background fluctuations are reduced by more than a factor of two. This supports the choice to remove these tubes *a priori*.

It is instructive to consider how the fluctuations compare to the expectation for a Poisson distribution. For each of the background averages formed to make the distribution of values of s, the RMS of the 90 values has been divided by the Poisson expectation of the the square root of the rate. The results are histogrammed in Figure 5. In the case where only the good tubes are used, the values are tightly clustered around the mean of 3.3. So the fluctuations are between 3 and 4 times larger than would be expected from Poisson statistics alone. This suggests that the scaler counts are not really independent hits, but that there are correlations between hits, such as from the detection of small air showers or from muons which hit multiple tubes. For example, if most of the scaler counts are from small air showers that hit an average of about 10 tubes, then the Poisson fluctuations would be in the number of showers rather than the number of tube hits, and the Poisson RMS would be $\sqrt{10}$ times larger than the prediction from the tube hits alone.

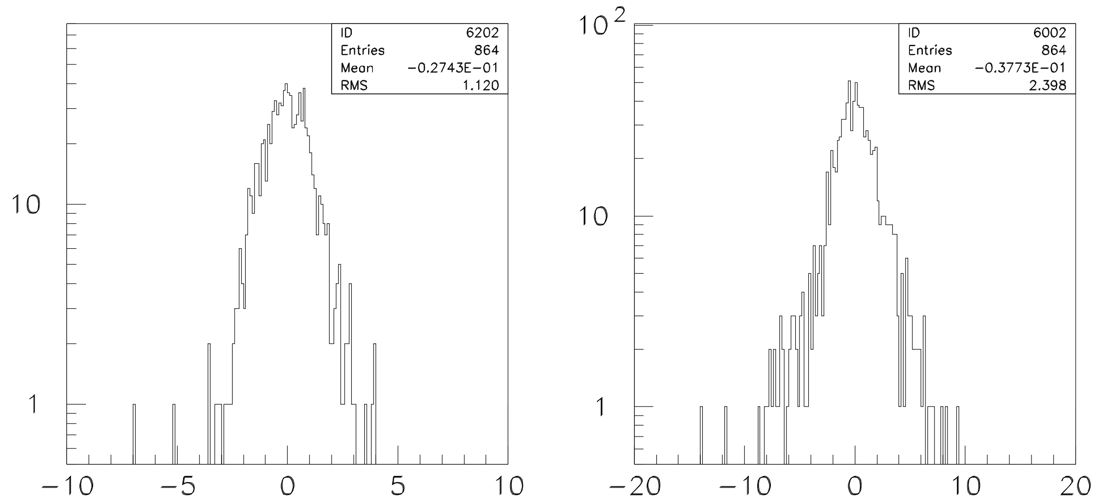

Figure 4: The distribution of the significance as defined in Eq. 2 for independent 99 s intervals on April 17, 1999. The plot on the left shows the distribution after removing the groups with bad PMTs. On the right (with a different scale) is the distribution with all tubes included.

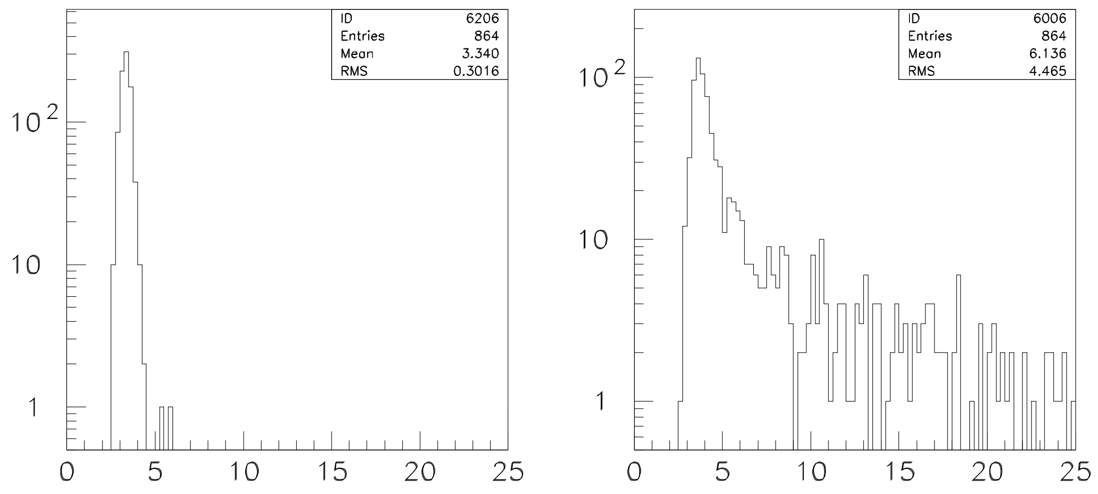

Figure 5: The distribution of the factor by which the RMS of 90 scaler measurements exceeds the Poisson expectation of $\sqrt{rate}$. The plot on the left shows the distribution after removing the groups with bad PMTs. On the right is the distribution with all tubes included.

Once again, the value of removing the few bad tubes can also be seen in Figure 5. The fluctuations are much larger when the bad tubes are included in the analysis.

The signal interval for GRB 970417a, discussed previously as the 9 measurements covering the BATSE T90, has a small deficit, with $s = -0.61$. Figure 6 shows the rate for the 9 bins of the signal interval, as well as the 45 bins on each side used to establish the background level. The average rate during the burst is $4328790 \pm 2560\ \mathrm{s}^{-1}$ and the background rate is $4330410 \pm 740\ \mathrm{s}^{-1}$. Clearly there is no evidence of a

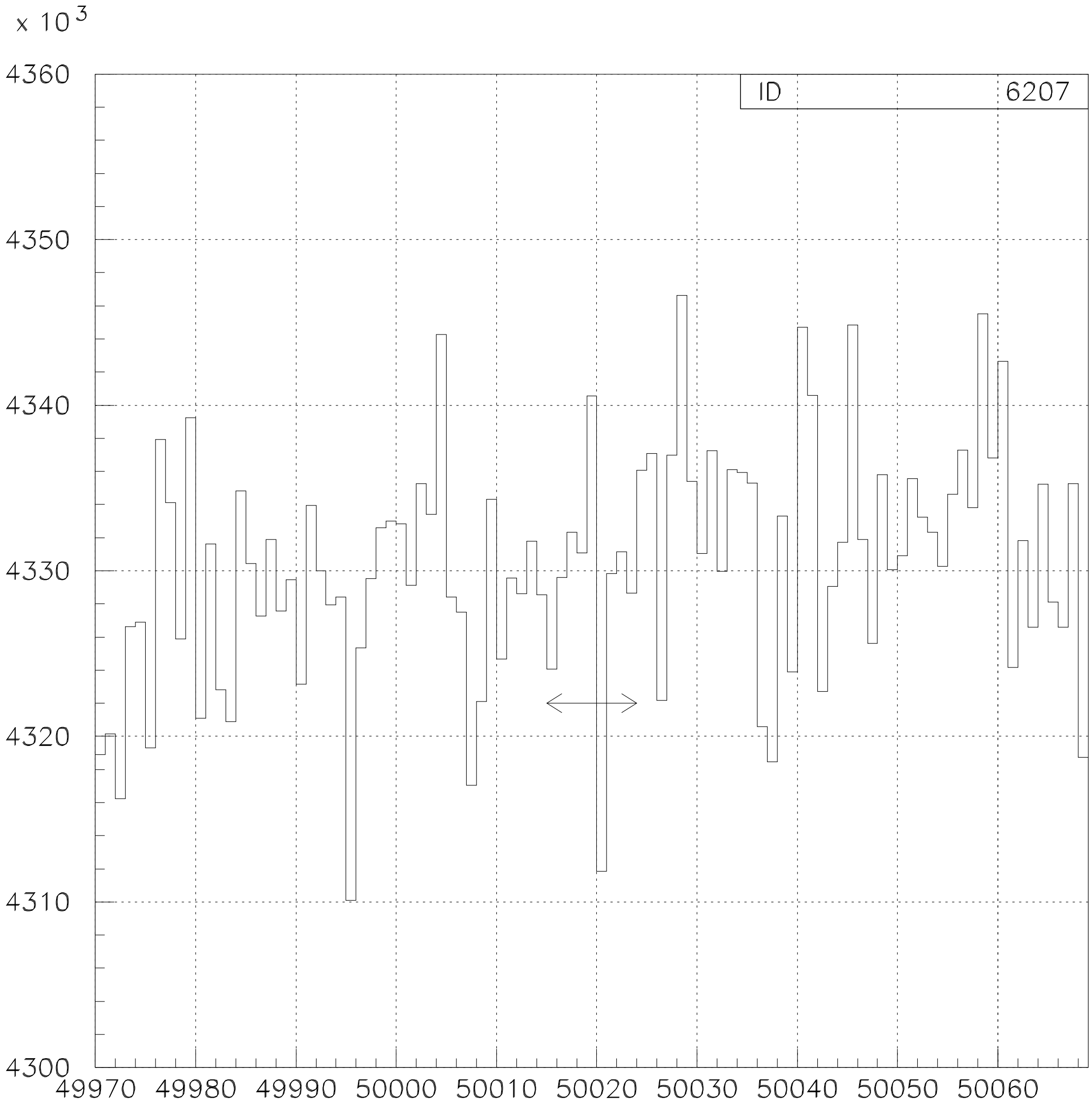

Figure 6: The rate measurements near the time of GRB 970417a. The arrow indicates the 9 bins overlapping BATSE T90. The other 90 bins, 45 before the burst and 45 after, are those used to estimate the background rate.

scaler signal from the gamma-ray burst.

In the absence of a signal, we would like to determine an upper limit on the scaler counting rate from the burst. Such a limit on the rate, when combined with the effective area for the scalers, will give a limit on the burst flux. A limit depends crucially on the distribution of the more extreme fluctuations, so even though the distribution of the significance s was shown to be reasonably Gaussian, we do not rely on that to obtain the limit. Instead, we use the data from the rest of the day to obtain the limit, in much the same way that the background distribution in Figure 2 was obtained. However, we now add a specified number of signal counts to the sum of the 9 bins representing the signal, before calculating the significance s. Then, the fraction of cases in which the s exceeds -0.609 is determined. The 90% confidence level upper limit on the number of signal counts is the signal which gives $s > -0.609$ in 90% of the cases. Figure 7 shows the fraction of cases with $s > -0.609$ as a function of the number of added signal counts.

Interpolating between the data points on the curve in Figure 7, the 90% confidence limit on the rate

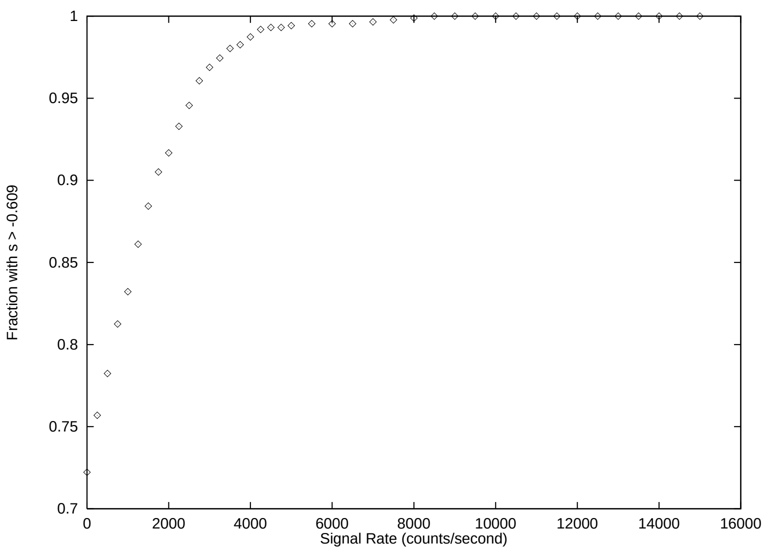

Figure 7: The fraction of simulated signals, created by adding a specified signal to the background rate, which has significance s greater than the value -0.609 observed for GRB 970417a.

during the burst is 1690 s^{-1} and the 95% confidence limit on the rate during the burst is 2570 s^{-1}. To get the limit on the total number of events during the burst, these rates must be multiplied by the length of the burst signal interval, which is

$$50023.873717\,s - 50014.875540\,s = 8.998\,s\ .$$

Note that this is not the duration of the BATSE T90, but the duration of the interval containing T90 which we have defined as the signal region and use to integrate the counts. The limits on the total number of scaler counts from the burst are therefore:

$$< 15,200\,\text{scaler counts}\ (90\%\ c.l.),$$

and

$$< 23,100\,\text{scaler counts}\ (95\%\ c.l.).$$

An independent analysis by Julie McEnery and Andy Smith has obtained an upper limit at higher confidence level (private communication of a forthcoming memo). The size of the background sample for this analysis is too small to extend it beyond 99% confidence level, but we appear to be in general agreement on the limit.

Converting these limits into fluxes or fluences requires the effective area for the scaler system as a function of energy. Values for the effective area will also be reported in the memo by Julie and Andy.