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Optimization of Time Of Flight of the AMS-02 experiment

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The AMS-02 detector has a strong magnetic fringing field where the Time Of Flight PhotoMultiplier Tubes (PMTs) are installed. Each Time Of Flight (TOF) counter has 2 or 3 PMTs per side for redundancy, but the limits on AMS-02 total weigth and power budget imposed severe constraints on the HV channels number. Each HV channel is connected to two PMTs and, due to the different performances of each PMT, which depend critically on the PMT position in the TOF, two meta-heuristic algorithms were used to optimize the TOF performances. This paper describes the results obtained with a combination of simulated annealing and genetic algorithms.

1. Introduction

The Alpha Magnetic Spectrometer (AMS-02) is a particle detector that will be installed on the International Space Station to measure cosmic ray fluxes for at least three years [1]. The AMS-02 Time Of Fligth (TOF) system [2] consists of four layers of scintillator counters, above and below a superconducting magnet. Its goals are to provide the fast trigger to the AMS readout electronics, to measure particles velocity (β), direction, crossing position and charge. In total the TOF has 34 counters and 144 PMTs installed in a region where there is a strong magnetic fringing field. Each counter has 2 or 3 PMTs per side for redundancy which should ideally have the same gain, have equalized responses, the same voltage and similar transit time. Limits on detector weight and power budget impose that most of the PMTs will be powered in couple with the same high voltage. We had to optimize the disposition of the 144 PMTs on the TOF, considering that the effect of the magnetic field changes with position, that the PMTs have to work with a voltage below 2300V, and that the PMTs are powered in couple. These forced us to use meta-heuristc algorithms to resolve the problem, in particular we used a combination of simulated annealing and genetic algorithm (the last one is addressed by [3]).

2. The genetic algorithm

Genetic Algorithm (GA) [4] is a search algorithm which seeks for optimal solution by sampling the solutions space and creating a population of candidate solutions. These candidates are recombined and mutated to evolve into a new generation of solutions which may or may not be better, that is closer to the desired optimum. Recombination is fundamental to the GA and provides a mechanism for genetic mixing within the population. Mutation is vital in introducing new genetic material thereby preventing the search from stagnating. The next population of solutions is chosen among the parent and offspring generations in accordance with a survival strategy that normally favours the best individuals but nevertheless does not preclude the survival of the worst. In this way, a diverse pool of genetic material is preserved for the purpose of breeding yet better individuals. Chance plays an important role in GAs, though their success in locating an optimum strongly depends on a judicious choice of a fitness function. The fitness function must be designed carefully to reflect the nature of the optimum and to direct the search along promising pathways. GAs operate on a population of individuals each of which has an assigned fitness. The population size should be sufficiently great to allow a substantial pool of genetic material, but not so large to degenerate into a random search. Those individuals that either undergo recombination or survive are chosen with a probability which depends on the fitness in some way [5]. To find an optimized disposition of the 144 PMTs of 34 TOF counters we have chosen a population of 1000 candidate solutions and a mutation probability μ=5%. Particular care was put in the design of the recombining and the fitness function, because our problem presented many local minima. For the GA we have chosen a number of generations equal to $5 \cdot 10^5$, because as one can see in Fig. 1, over this number of generations the fitness function slow down sligthly. The fitness function is a sum of three functions, each one reflecting the TOF requests, weighted with different coefficients. The first function requires that PMTs with the same HV channel have the same voltage; the second one requires that these PMTs have also the same gain to voltage dependence. For these two functions we have chosen a weight coefficient equal to 35%. The last function asks for similar voltage of PMTs on the same side of the same counter, in order to have comparable transit time. The weigth coefficient for this request is equal to 30%. Finally we want HV values below 2150V, to be able to increase the PMT gain during the long duration AMS-02 mission (the counter ageing problem is addressed by [6]).

3. The simulated annealing algorithm

The method of simulated annealing (SA) is a technique that has attracted significant attention for optimization problems of large scale, especially when a desired global optimum is hidden among many local extrema. At the heart of this method there is an analogy with thermodynamics: a system with high temperature has molecules moving freely, but by cooling the system we arrive to a crystalline system with ordered molecules in the state of minimum energy. For slowly cooled system, nature is able to find this minimum energy state. In our case with the SA we start from a random PMTs distribution on the TOF counters and, after each step, we slow down the temperature. The better disposition is evaluated with a cost function[1]. After several steps we arrive to a state of minimum energy of the system, which corresponds to an optimized distribution of the PMTs on the TOF counters.

4. Results

The initial parameters for the SA and GA are the same: PMTs voltage and HV channel links; also the cost/fitness function is equal, with the same weigth coefficients. The two algorithms had similar (but not very satisfying) performances. Then we decided to use the result of SA, which is more adapted to search solutions in a space with many local minima, as input to the GA, which is a greedy algorithm. So, the genetic algorithm searched a solution in the neighborhood of the one chosen with simulated annealing. The final solution is an acceptable PMTs disposition for the TOF. As one can see in the figures below, the PMTs connected to the same HV channel, that should have the same voltage, have a maximum voltage difference equal to 30V (Fig. 3). For these PMTs, we will finally set the mean of the voltages yield by GA (HV_{mean}). As a consequence, the maximum relative gain difference[2] will be $\Delta G/G_{eq}$=12% (Fig. 4). The gain as a function of the voltage is:

[1] Equivalent to the fitness function for the GA.

[2] The gain is relative to the G_{eq}, the value of the gain when the PMTs response is equalized to the counter center (the HV_{eq} is the relative voltage set of the PMT).

$$\log_{10} G = P_1 + P_2 \log_{10} V \qquad \Rightarrow \qquad \frac{\Delta G}{G} = P_2 \frac{\Delta V}{V} \tag{1}$$

where P_1 and P_2 are constants found by PMTs calibration.

Fig. 5 shows that the maximum variation of P_2, for PMTs with the same HV (HV_{mean}), is about[3] 1%. For PMTs on the same side of the same counter, we obtain a mean voltage difference of about 7V (Fig. 6), and a maximum difference of 25V. Finally the PMTs mean voltage is 1942V (see Fig. 2), much less then 2150V, the limit voltage imposed by the algorithm.

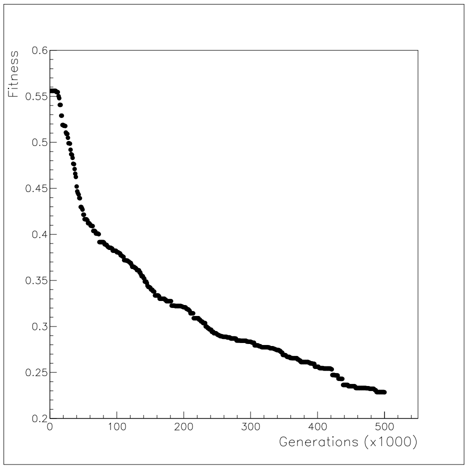

Figure 1. Fitness function for the genetic algorithm.

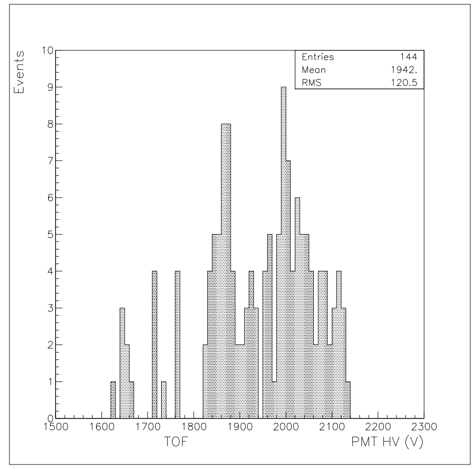

Figure 2. PMTs voltage distribution.

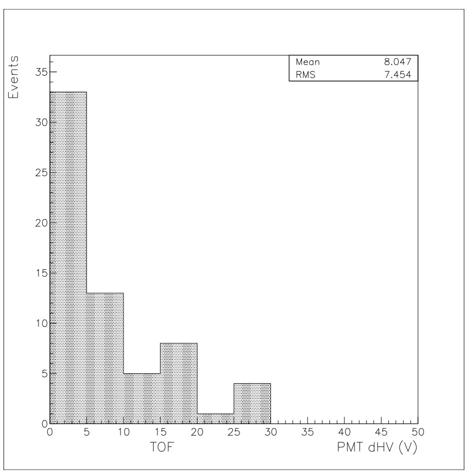

Figure 3. Differences of voltage calculated by the genetic algorithm for PMTs with the same HV channel.

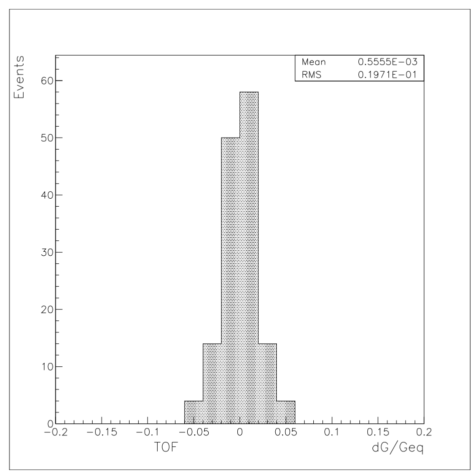

Figure 4. Relative gain difference for PMTs connected to the same HV channel, at HV_{mean} (§4).

[3]The mean value of P_2 is 7.

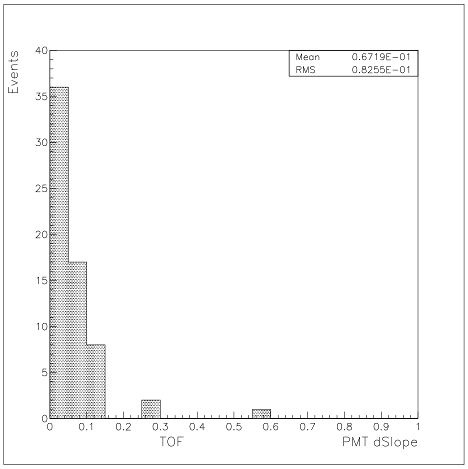

Figure 5. Difference on P_2 (see Eq. 1) for PMTs connected to the same HV channel, at HV_{mean} (§4).

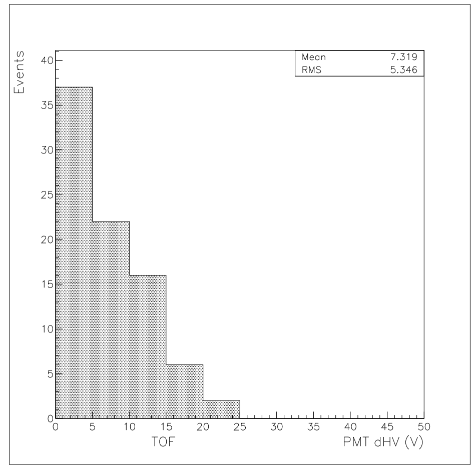

Figure 6. HV_{mean} difference for PMTs on the same side of the same counter.

5. Conclusions

The wide spread characteristics of fine-mesh PMTs pose a difficult problem for the optimization of the TOF system performance. Combining two meta-heuristic algorithms was crucial to obtain a satisfying PMTs disposition that will bw used for the construction of the TOF.

6. Acknowledgements

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