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On noise treatment in radio measurements of cosmic ray air showers

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ABSTRACT

Precise measurements of the radio emission by cosmic ray air showers require an adequate treatment of noise. Unlike to usual experiments in particle physics, where noise always adds to the signal, radio noise can in principle decrease or increase the signal if it interferes by chance destructively or constructively. Consequently, noise cannot simply be subtracted from the signal, and its influence on amplitude and time measurement of radio pulses must be studied with care. First, noise has to be determined consistently with the definition of the radio signal which typically is the maximum field strength of the radio pulse. Second, the average impact of noise on radio pulse measurements at individual antennas is studied for LOPES. It is shown that a correct treatment of noise is especially important at low signal-to-noise ratios: noise can be the dominant source of uncertainty for pulse height and time measurements, and it can systematically flatten the slope of lateral distributions. The presented method can also be transferred to other experiments in radio and acoustic detection of cosmic rays and neutrinos.

1. Consistent definition of signal and noise

Noise definitions applied so far in the field of cosmic ray radio detection are originating from communication engineering. There, a signal usually has a power much larger than the noise and lasts for a time significantly longer than its oscillation period. Both are not true for air shower induced radio pulses. This has already been investigated in the frame of self-trigger development [1], where the signal-to-noise ratio plays the role of a threshold. For data analysis, the situation is more complex because noise has to be defined consistently with the definition of the radio pulse height, which is the maximum of the field strength, in the case of LOPES [2].

Independent of the specific signal and noise definitions, the following consistency criterion is demanded:

$$\text{for } \textit{true signal} = 0 \longrightarrow \frac{\textit{measured signal}}{\textit{noise}} \overset{!}{=} 1 \qquad (1)$$

The consistency criterion is supposed to hold only on average, because the noise level at the signal time can by chance be larger or

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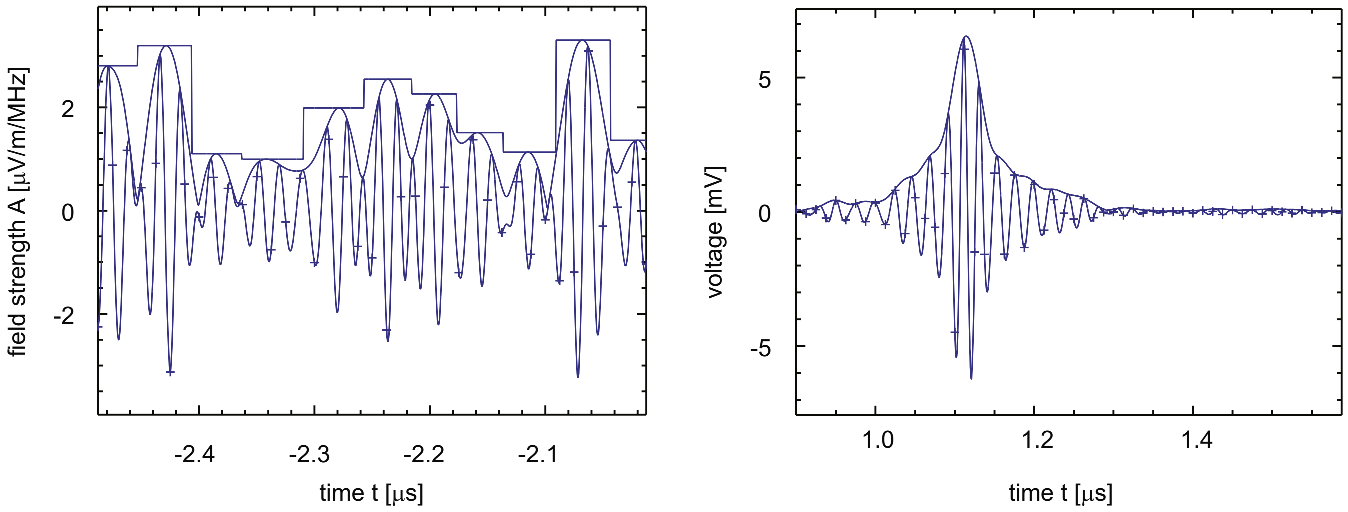

Fig. 1. Typical noise measured with a LOPES antenna (left) and a test pulse from a pulse generator (right): sampled data points, the up-sampled trace and a Hilbert envelope of the trace are shown in both cases. The noise level is calculated as the weighted average of the local maxima of the envelope. This corresponds to the average level of the plotted step function with a step exactly in the middle between two local maxima.

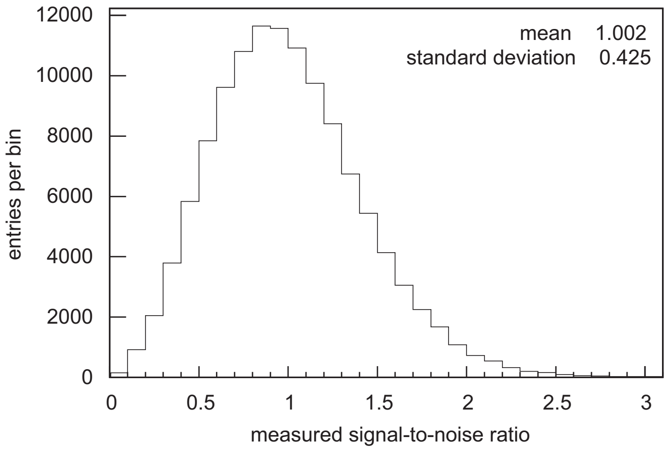

Fig. 2. Signal-to-noise ratios of pure noise for a selection of LOPES events without signal.

smaller than the average noise level. In addition, even for a positive true signal, the measured signal-to-noise ratio can in some cases be smaller than 1, since noise can interfere constructively or destructively with the air shower radio emission, and increase or decrease the measured signal compared to the true signal.

For LOPES, a consistent definition of signal and noise has been found for measurements at individual antennas, e.g., to reconstruct the lateral distribution [3]. The signal is defined as the amplitude (field strength) of the radio pulse which is determined as the local maximum of a Hilbert envelope closest to the pulse time known from a preceding interferometric cross-correlation beam analysis (c.f. Ref. [4]). The noise level is defined as average amplitude in a time window (10 µs) before the radio pulse, and is calculated by the mean of all local maxima of the envelope. Because lower local maxima are more likely to have a smaller distance to neighboring maxima than the higher maxima, it is necessary to weight each maximum with the distance to its neighbors when averaging (Fig. 1, left).

It has been tested that these definitions of signal and noise do indeed fulfill the consistency criterion. With a selection of 200 LOPES events without radio pulse, a large sample of 120,000 noise intervals of 10 µs width, each, has been obtained: the intervals are non-overlapping, cover different days and times of the day, as well as different antennas. The average signal-to-noise ratio of these intervals is compatible with 1, as required (Fig. 2).

With other definitions of noise, like the RMS of the field strength or its square (power), the mean of the absolute field strength or an unweighted mean of the local maxima of the envelope, the consistency criterion is not fulfilled. However, the ratio between the noise levels determined by different methods is constant within a few percent. Thus, results obtained with a different noise definition could be scaled to a consistent definition when accepting a small systematic error.

2. Influence of noise on pulse height measurements

The impact of noise on measurements of the pulse amplitude at individual antennas has been studied for LOPES with test pulses (Fig. 1, right) of different widths and noise from real measurements. Therefore, the test pulses have been scaled with the LOPES analysis software to a certain amplitude A_{true}, and added to the noise intervals presented in the previous section. Afterwards, the measured signal height A_{meas} can be obtained for each pulse, yielding a relation between the average true amplitude A_{true} and the measured amplitude A_{meas}. To simplify the relation, all amplitudes have been normalized to the noise level, i.e., the noise level corresponds to $A=1$, and A_{meas} is the measured signal-to-noise ratio.

Because the real probability distribution of A_{true} of air shower induced radio pulses is unknown, scaling factors for the test pulse heights have been generated for a flat distribution of A_{true}. As cross-check, also an exponentially decaying distribution has been tried, but the effect on the results is negligible.

To correct measured pulse amplitudes for the noise influence, the function $A_{\mathrm{true}}(A_{\mathrm{meas}})$ is required, which has been obtained by the following procedure. The test pulse data, which consist of 120,000 samples with known A_{true} and corresponding A_{meas}, have been sorted into bins. Thereby, each bin covers a certain interval of A_{meas}. The mean A_{true} of each bin is then the average true amplitude corresponding to the measured amplitude A_{meas} of the bin. At the same time, the standard deviation ΔA_{true} of each bin can be taken as error estimation of the true amplitude (Fig. 3). Other methods to determine $A_{\mathrm{true}}(A_{\mathrm{meas}})$ failed. The inverse function of $A_{\mathrm{meas}}(A_{\mathrm{true}})$, which would be available directly, is not defined for $A_{\mathrm{meas}} < 1$. Using confidence intervals instead of mean and standard deviation