PROCEEDINGS OF SCIENCE

Quantifying energy fluence and its uncertainty for radio emission from particle cascades in the presence of noise

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Measurements of radio signals induced by an astroparticle generating a cascade present a challenge because they are always superposed with an irreducible noise contribution. Quantifying these signals constitutes a non-trivial task, especially at low signal-to-noise ratios (SNR). Because of the randomness of the noise phase, the measurements can be either a constructive or a destructive superposition of signal and noise. To recover the electromagnetic energy of the cascade from the radio measurements, the energy fluence, i.e. the time integral of the Poynting vector, has to be estimated. Conventionally, noise subtraction in the time domain has been employed for energy fluence reconstruction, yielding significant biases, including even non-physical and negative values. To mitigate the effect of this bias, usually an SNR threshold cut is imposed, at the expense of excluding valuable data from the analyses. Additionally, the uncertainties derived from the conventional method are underestimated, even for large SNR values. This work tackles these challenges by detailing a method to correctly estimate the uncertainties and lower the reconstruction bias in quantifying radio signals, thereby, ideally, eliminating the need for an SNR cut. The development of the method is based on a robust theoretical and statistical background, and the estimation of the fluence is performed in the frequency domain, allowing for the improvement of further analyses by providing access to frequency-dependent fluence estimation.

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Summary

We have recently published a method to quantify the energy fluence and its uncertainty in the presence of noise in reference [1]. In the following, we provide a short summary to document the work shown at the ARENA workshop. For details, we would like to refer the reader to the publication.

In the field of astroparticle physics, a fundamental quantity used by high-level analyses is the energy fluence, i.e., the energy per unit area deposited on the ground in the form of radio waves [2]. The energy fluence measured in the presence of noise at the antenna position is given by:

$$f_{\mathrm{tot}} = \epsilon_0 \, c \, \Delta t \sum_{\mathrm{pol}} \left(\sum_{j} E^2_{\mathrm{pol}}(t_j) \right), \tag{1}$$

where Δt is the time sampling interval and E_{pol} is the measured amplitude of a single polarisation of the observed three-dimensional electric-field vector. The measured radio pulse is either enhanced or diminished compared to the true signal depending on the random phase of the radio noise. This makes the estimation of the fluence in the presence of noise non-trivial, especially at low signal-to-noise ratios (SNR) [3]. So far, the conventional way of reconstructing the signal energy fluence consisted of estimating and subtracting the noise fluence in the time domain [4]. This method turns out to be biased at low SNR values and underestimates the uncertainties (see figure 1). To avoid the introduction of a large bias, a minimum required SNR value is typically introduced to use data from a given antenna (in many works, SNR values of at least 10, when referring to the peak electric field amplitude squared divided by the noise variance, are required [5]).

We present a novel method to estimate the energy fluence in the frequency domain that performs much better at low SNR values. The method exploits a solid statistical background based on Rice distributions [6] and allows for a consistent estimation of the uncertainties. We validated the Rice-distribution method by applying it to a data set of simulated air showers initiated by cosmic rays. To realistically simulate radio measurements, we have added the ambient background recorded at a particular site of the Pierre Auger Observatory to the radio-emission simulations. Furthermore, we simulate the antenna response of the Radio Detector [7] of the Pierre Auger Observatory, sensitive to the 30-80 MHz frequency band. Nevertheless, the results of our study are independent of the detector simulation: the method is not constrained by the frequency band, thus, any radio experiments in the field of astroparticle physics can make use of it.

In our study, we achieve an average reconstruction bias within 10% even at the lowest SNR values investigated, while the estimation of the uncertainties shows a reliable coverage of about 68% (see figure 1). At high SNR values, the method is unbiased and shows good error coverage. In conclusion, replacing the so-far-established noise subtraction method for the estimation of energy fluences by our approach will allow the use of data to lower signal-to-noise ratios, with a reliable estimation of fluence uncertainties, and lift the need to apply ad-hoc signal-to-noise ratio cuts in data analyses.

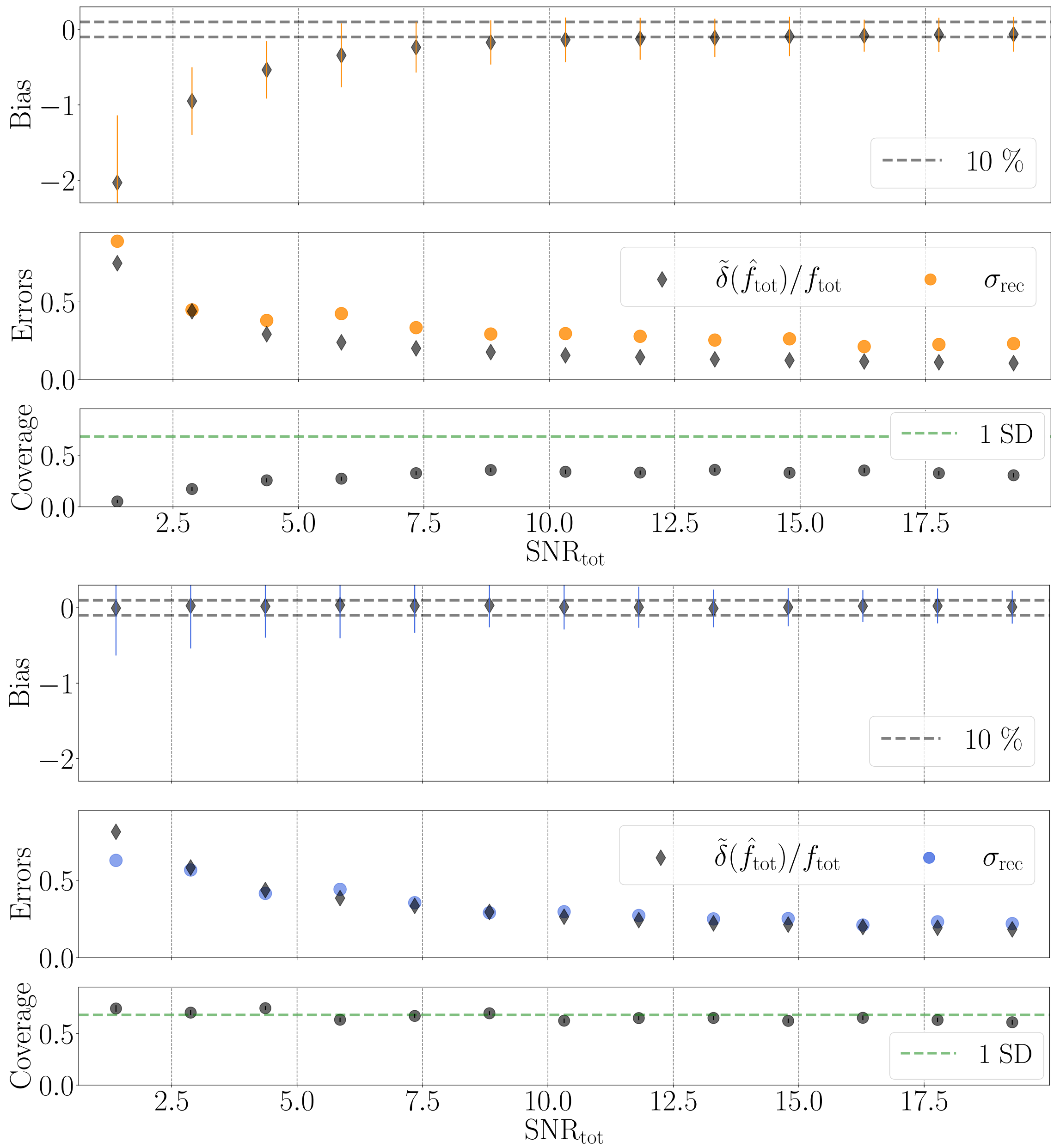

Figure 1: Estimation of f_{tot} and its uncertainty through the noise subtraction method (upper figure, orange) and the Rice-distribution method (lower figure, blue) at low signal-to-noise ratio (up to SNR=20). In the upper plots of the figures, we show the average bias together with the error bar given by the resolution of the bin as a function of the SNR. In the middle plots, the resolution of each bin is compared with the average relative fluence uncertainty of the same bin. The coverage of the uncertainties together with its error normalized to the number of entries of the bins, is shown in the lower plots of the figures.

References

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