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Towards a common definition of the Signal-to-Noise Ratio

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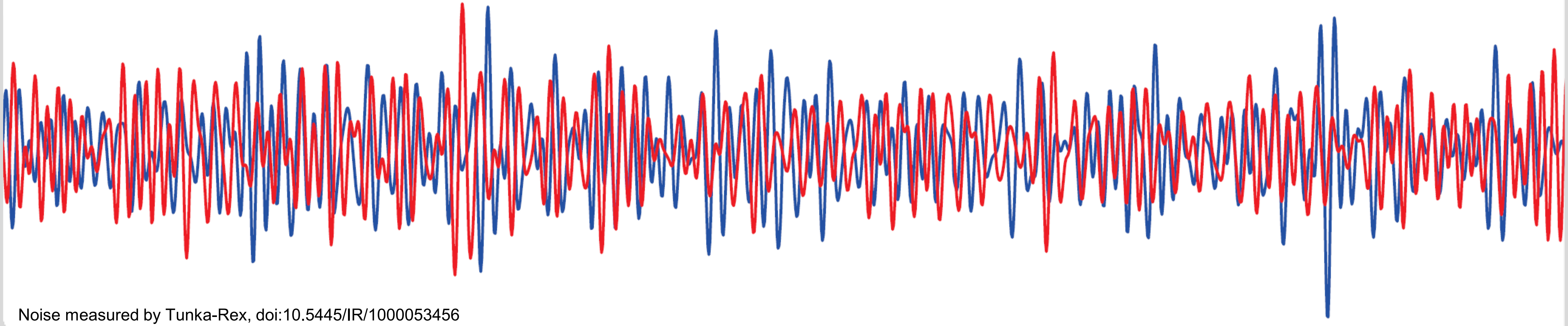

Noise measured by Tunka-Rex, doi:10.5445/IR/1000053456

Current situation

- Every collaboration has their own definition of SNR, sometimes every analysis
- This is partly useful because 'signal' depends on the analysis, and the impact of noise can be different for different analyses and experiments.
- Yet it is very confusing and lead to misunderstandings and wrong interpretations

  "Why do you use an SNR cut of 10, this is a pretty large signal?" – But pure noise in that analysis turned out to have an SNR > 10, so this was not large at all

Can we improve on this situation? Can we agree on common standards?

Many advantages:

- interpretation of other analyses or simulation studies when reading/reviewing papers
- software can be exchanged more easily between experiments
- people are less confused when switching experiments

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Decisions to make about the Signal-To-Noise Ratio

- How to measure **signal**?
  - many methods around, and no consensus of a universally best method
    - **energy fluence** = power integrated over certain integration window preferred when possible? (depends on integration window)
    - alternatives are maximum of Hilbert envelope, E-field vector vs. channel voltage, …
    - system properties like bandwidth and dispersion, analysis pipelines like filters, de-dispersion, beamforming, …
  - independent of method, we can still agree on *amplitude vs. power definitions*

  → **power**, to be consistent with noise measurements

- How to measure **noise**?

  → average **power**
  - used in engineering (often expressed in dB)
  - easy to measure or calculate when long traces are available
  - details may still vary by experiment, e.g., local RFI and filters applied against RFI

- Disfavored: an alternative approach is to apply the signal definition on many noise samples and get the statistical average. However, often recorded traces are too short, and this approach is not feasible for all experiments. It therefore, is not suitable as a standard.

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Should we subtract the noise from the signal for calculating SNR?

- Pro
  - easy for high signals, when power of noise and signal add linearly
  - consistent with naive understanding of ‘signal’ in SNR
- Contra
  - non-trivial for low signals as the interference of signal and noise is usually nonlinear:
    upward fluctuations, signal peak shifts with noise, pulse shape changes with noise, …
  - can potentially yield negative SNR values for low signals with upward noise fluctuation
  - for high signals with clear linear behavior, the impact is anyway small
- My suggestion: Use S + N for the SNR, and in any case clearly indicate what is done

$$SNR = const\ \frac{S+N}{N} = const\,\frac{P_{S+N}}{P_N} = const\,\frac{\int V_{S+N}^2\,dt}{\int V_N^2\,dt} \quad or \quad const\,\frac{\int \vec{E}_{S+N}^2\,dt}{\int \vec{E}_N^2\,dt}$$

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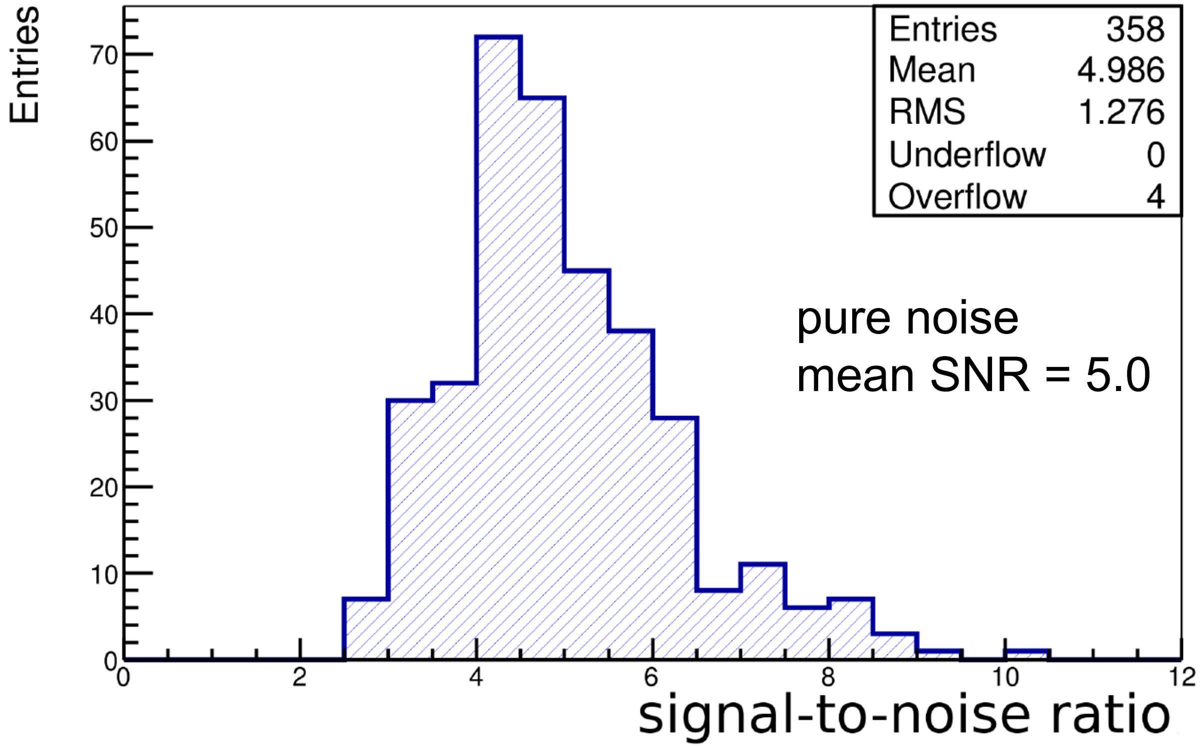
Why do we need a constant coefficient in the SNR definition?

SNR of pure noise can be large, depending on the definition, experiment, procedure,

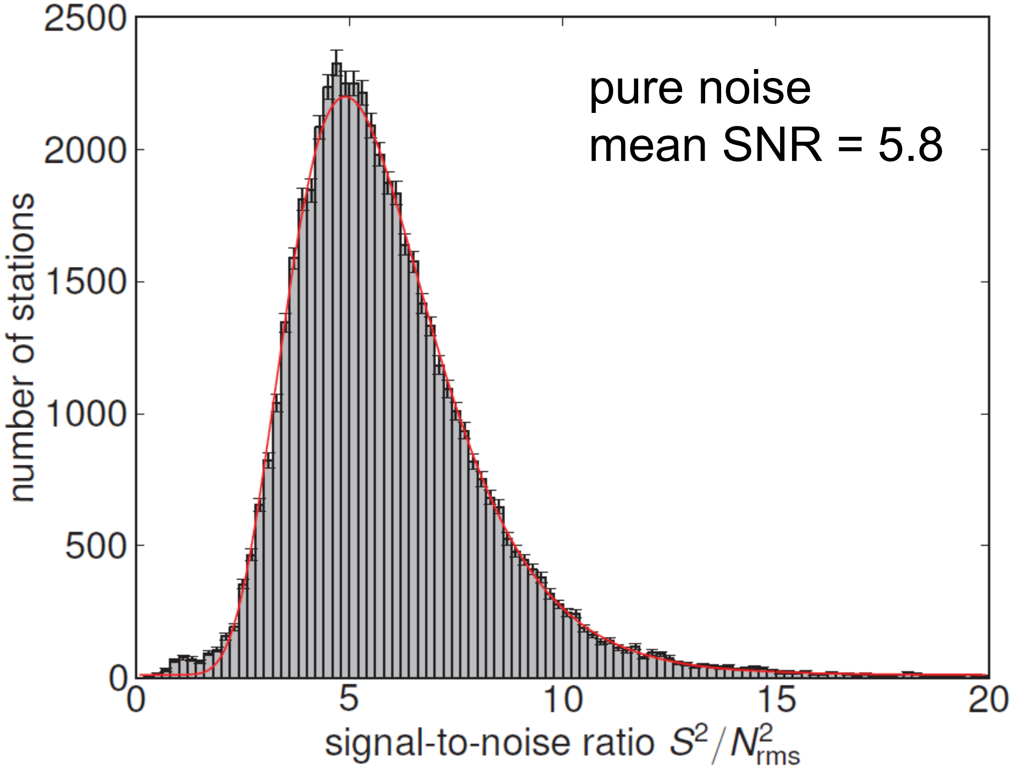
AERA



Noise = RMS of Hilbert envelope
(within few percent the same as RMS of the trace)
Signal = Maximum of Hilbert envelope

C. Glaser, PhD Thesis, 2016

Tunka-Rex



Noise = RMS of 500 ns long window
Signal = Maximum of Hilbert envolpe

Tunka-Rex, doi:10.5445/IR/1000053456

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Similar definition used for Prototype Surface Station at IceCube

- Same definition as at AERA and Tunka-Rex used with the goal to have comparable results

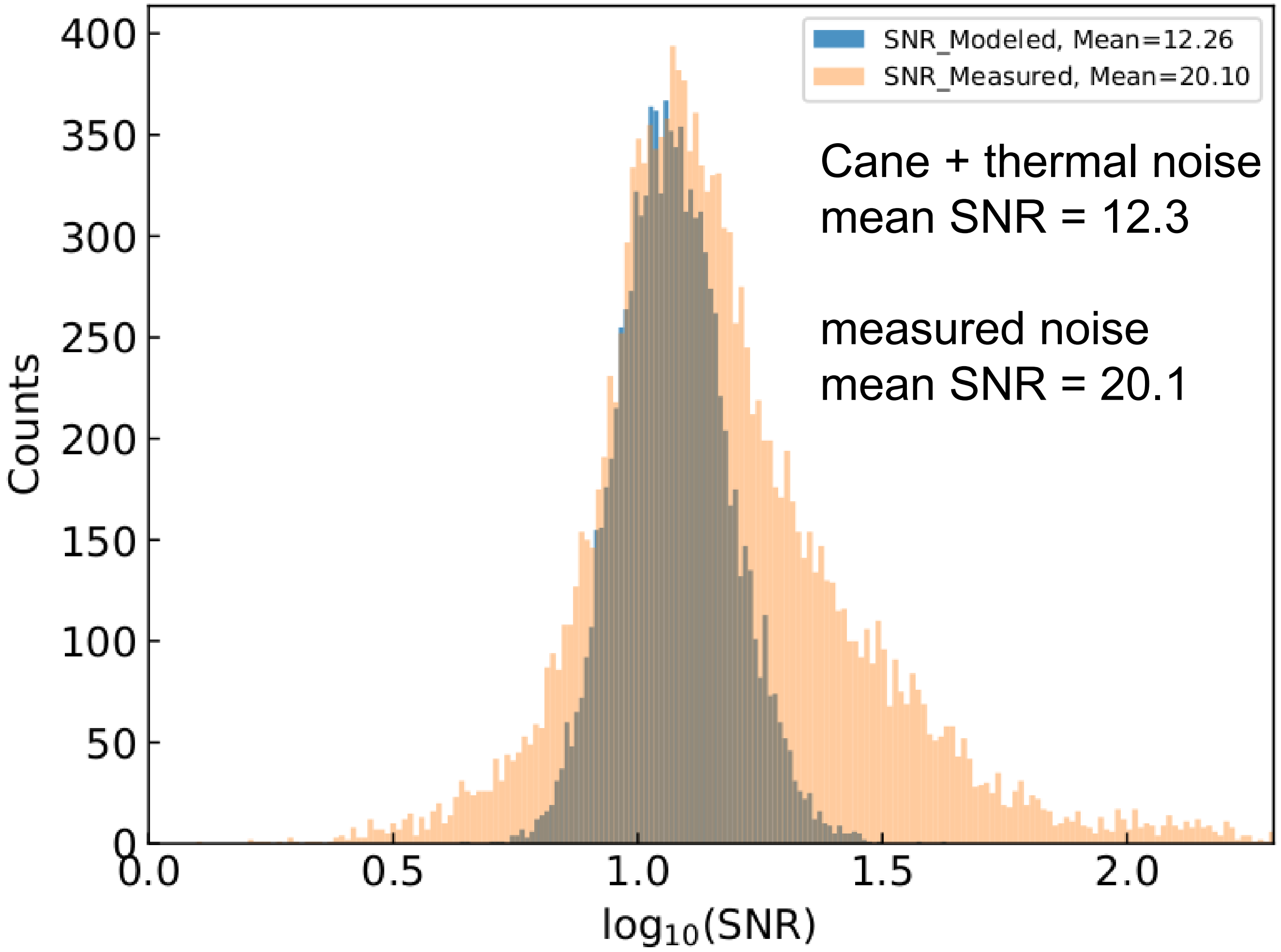
$$\mathrm{SNR} = \left(\frac{\mathrm{Signal}_{\mathrm{Peak}}}{\mathrm{Noise}_{\mathrm{RMS}}}\right)^2$$

- Approach failed by a factor of ~3

- Different antennas, different band, different RFI, different procedures

→ **SNR is still not comparable if the formula is the same.**

→ **Can be fixed by an experiment specific constant.**



A. Rehman et al. for the IceCube Coll, talk on Tuesday

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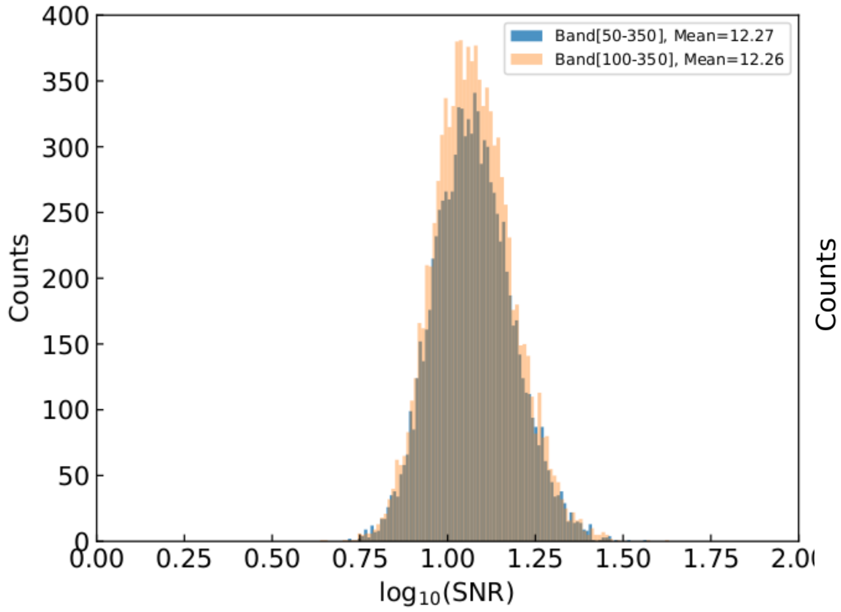
Dependencies of the SNR

Some procedural parameters have almost no impact, others are critical

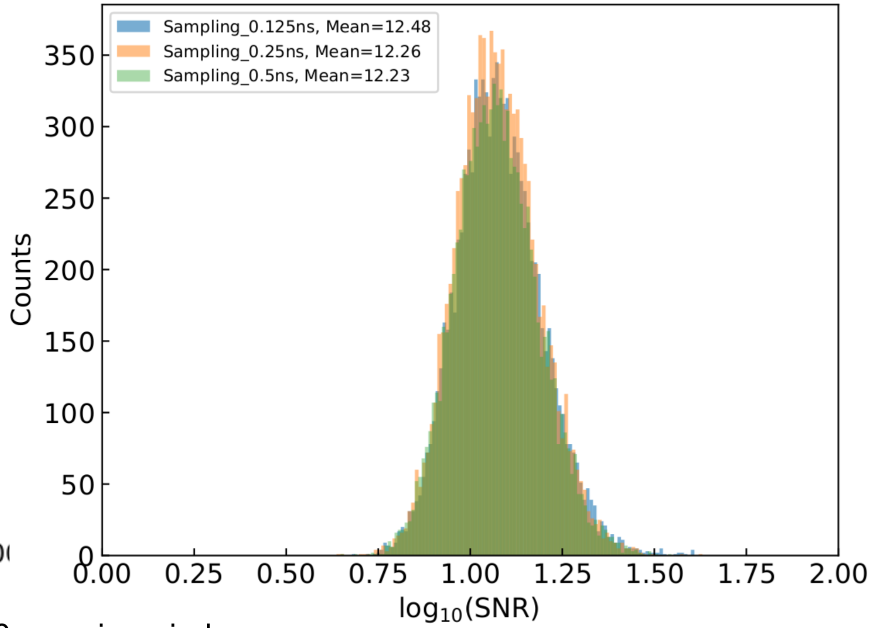
- Large impact by size of signal search window
- Hypothesis: signal search procedure introduces bias (upward fluctuations) for small signals

→ **Need to correct for this by a normalization constant or give SNR of pure noise as a reference**

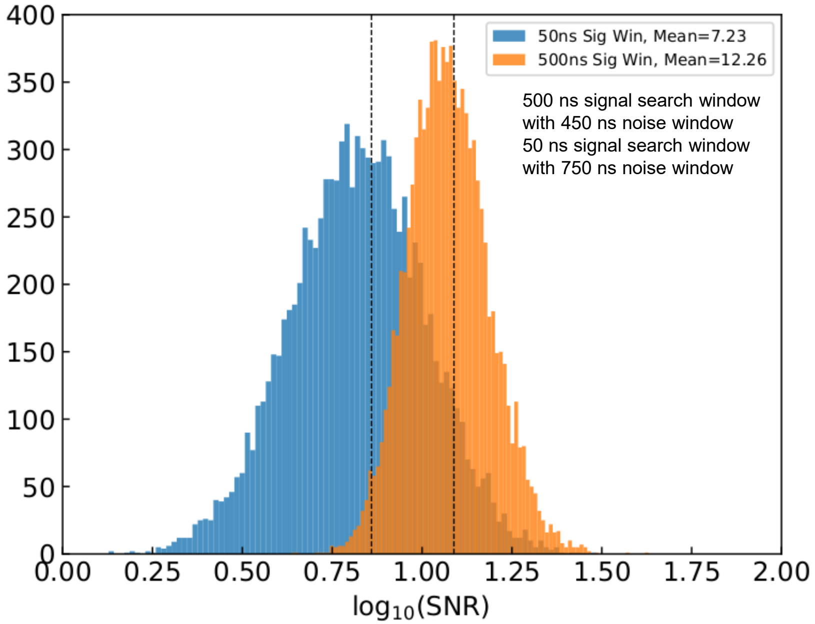
different frequency band



different upsampling



size of signal search window



trace lengths: 1024 ns; 500 ns signal search window, 450 ns noise window

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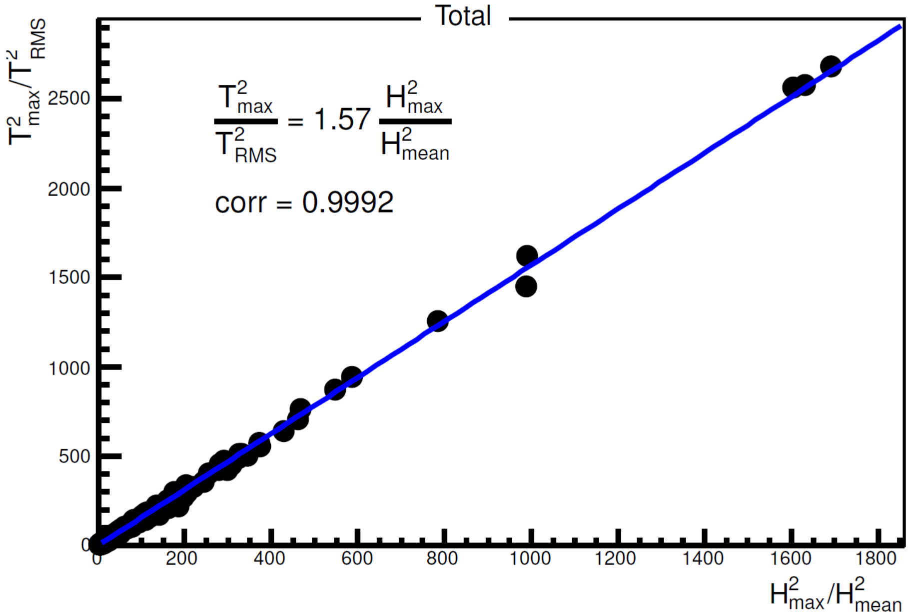
Different SNR definitions scale linearly: normalize them?

- Pro normalization constant
  - fixes naive understanding that the SNR of pure noise should be 1 (or 0 when subtracting noise)
  - easiest way to make different SNR definitions comparable

- Contra normalization constant
  - this could make the SNR incomparable for large signals which are not impacted by noise



Example for linear correlation
of different SNR definitions
C. Glaser et al.

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Suggestions for a SNR standard

1) Signal-to-noise ratios should be ratios of *power* (or energy). Average noise power is easy to measure, *energy fluence* is a possibility to measure signal.
2) It must be clearly indicated whether and how noise is subtracted from the signal. Personal preference: *not subtract it for the SNR value* (but of course in the analysis)
3) The SNR needs to be *normalized* to an average value of 1 for no signal (or 0 if noise is subtracted). Otherwise, the average *SNR of pure noise* must be stated.
4) The *definition of signal and noise* must be given *including procedures*, such as search and integration windows, band, filters, dispersion, RFI mitigation, etc.

$$SNR = const\,\frac{S+N}{N} = const\,\frac{P_{S+N}}{P_N} = const\,\frac{\int V_{S+N}^2\,dt}{\int V_N^2\,dt} \quad or \quad const\,\frac{\int \vec{E}_{S+N}^2\,dt}{\int \vec{E}_N^2\,dt}$$

$$const = \frac{1}{< SNR\,(pure\ noise) >} \Rightarrow \quad SNR = 1 \quad \text{for} \quad S \longrightarrow 0$$

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