Cascade Model of Noise Formation in Electron Detectors

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Abstract: Signal and noise evolution in electron detectors are analysed using a cascade model. For each cascade, the required parameters can be obtained experimentally or by simulation. The model allows predicting the noise properties of a detector, in order to identify and improve the most important stages in the signal formation chain, or in return to evaluate the performance of unknown stage. Experimental results from Raith ionLINE tool are presented, demonstrating good agreement with the model.

1. Background
Signal to Noise Ratio (SNR) is one of the most critical properties of any imaging system. In electron microscopy, it is governed by probe beam shot noise and by statistical nature of signal formation within the electron detector. The image formation is a chain of stochastic transformations of the primary beam: Secondary Electron (SE) or Backscattered Electron (BSE) emission from the sample, detection of part of the emitted electrons, and conversion of the detected electrons to electronics signal. The later can be either direct multiplication of the collected electrons, as in solid state detectors, or transforming the electrons to light using scintillator, use a light guiding system and then convert it back to electronic signal which is multiplied. All detectors use additional stage of electronics which is not taken into account in this analysis.

Due to the statistical nature of the transformations in the chain, each step adds noise to the previous stage. In this paper we present an analysis for the most common scintillator-based chamber detector, but the model can be used for analyzing practically any detection system. The treatment presented here is an improvement over previous ones[1][2], by providing a detailed and universal calculating method, taking into account more factors in the noise formation.

2. Noise factor calculation
The detector Noise Factor NF is the measure of SNR deterioration along the signal formation chain, and is defined as the ratio between input SNR to output SNR. Each transformation is considered as cascades with statistical gain, which has mean value \( m \) and standard deviation \( s \). Denoting \( \gamma = m / s \) the formula for NF calculation can be expressed as:

\[
NF = \sqrt{1 + \frac{1}{\gamma_1^2} + \frac{1}{m_1 \gamma_2^2} + \frac{1}{m_1 m_2 \gamma_3^2} + ...}
\]
This formula is derived from a common expression for the noise of multi-cascade systems [3] assuming shot noise (Poisson process) in the input of the first cascade. In the electron detection system, this would be the probe beam shot noise.

Signal formation chain includes Poisson processes for which \( \gamma^2 = m \), binary processes for which \( \gamma^2 = \frac{m}{1 - m} \), and more complex processes for which \( \gamma \) is more complicated and in some cases, should be obtained experimentally.

Applying the model to signal formation in Everhart-Thornley (ET) chamber detector in an ion beam tool, we consider the following cascades:

- Secondary electron (SE) emission from sample
- Collection of electrons emitted from sample to scintillator
- Photon generation within scintillator
- Light transmission from scintillator to Photo-Multiplier Tube (PMT)
- Photoelectron generation on PMT photocathode
- Electron multiplication in PMT

SE emission from sample and electron multiplication on each PMT dynode are Poisson processes, for which \( m_i = \sigma_i \), where \( \sigma_i \) is SE yield for each stage. Electron collection, light transmission and photoelectron generation are binary processes since in these cases, the electron, photon or photo-electron either reaches the next stage in the chain or not. These stages satisfy \( m_i = \eta_i \), where \( \eta_i \) is electron detection efficiency, light collection efficiency and photocathode QE respectively. Photon generation within scintillator is a more complicated process since it involves the location of light formation, its distribution, light propagation in scintillating material and in the substrate, and light extraction from the substrate. While it can be readily calculated for crystal scintillators, it becomes model dependent for granulated phosphorous materials, which are most commonly used. Therefore, for our analysis, we obtained the \( m \) and \( \gamma \) parameters experimentally.

3. NF calculation for ionLINE tool

The NF calculation was employed for the ETD detector developed by El-Mul for Raith ionLINE tools in order to evaluate and optimize the detector performance. The cascade stages with their \( m \)-values are shown in Table 1. SE yield on sample was taken from literature[4].

The electron collection efficiency was calculated by 3D electron trajectories simulation under the electric field which is calculated from the actual electrodes construction and their voltages. Light transmission efficiency was simulated by El-Mul, \( \gamma \) for the phosphor was obtained experimentally from its cathodoluminescence image taken in a SEM, and PMT manufacturer’s QE and gain data were used.

| Stage | Parameter | \( m \)-Value |
|-------|-----------|--------------|
| 1     | SE from sample (for 35keV Ga ion beam on Al sample)| 1.5          |
| 2     | Electron collection efficiency | 0.2          |
| 3     | Photon generation in P47 scintillator | 110          |
| 4     | Light collection from scintillator to PMT | 0.66         |
| 5     | Photoelectron generation in PMT | 0.13         |
| 6     | SE from PMT dynodes | 3.4          |

Table 1: \( m \) values for ETD process steps
The NF calculation results are shown in Figure 1. It can be seen that the SE generation and the electron collection efficiency to the detector are the most dominant NF contributors.

The images of a flat uniform Silicon sample were taken with both the original Raith and new El-Mul detectors, and their SNR were obtained by image processing. As Ga+ ion beam does not give backscattered particles from Si, only SE generated by ion beam are detected. For both detectors the NF calculated by the presented formula and obtained by image processing are in good agreement.

| Detector           | NF Calculation | Experimental NF |
|--------------------|----------------|-----------------|
| Original Raith detector | 4.81           | 4.76            |
| El-Mul detector    | 2.14           | 2.25            |

Table 2: comparison of calculated and measured NF values

4. Electron and light collection efficiency effect

Since the electron collection efficiency is the most contributing part for the detector simulated here, the NF was calculated for various values in order to evaluate the possibility for improvement. The calculation results, shown in Figure 2 (left side), demonstrate that increasing the collection efficiency from 20% to 50% will result in SNR improvement by ~20%. Generally, the electron collection efficiency is limited by the available space around the pole piece, limited by various elements in the chamber, and such improvement in
collection efficiency is not possible. However, in some cases, it is possible to add another detector that may almost double the efficiency. Figure 2 also shows that also in the case of low SE yield from the sample, the CE plays a major role in determining the SNR.

Although in the ETD case, the influence of the cascade stages following the electron detection are negligible, in some cases they can become major factor. For example, for In-Lens detectors or when space is very limited and the light guide becomes complicated, the light transmission efficiency might become a dominating factor. Figure 3 demonstrates that when light collection efficiency becomes of the order of 15% or lower, it starts to play an important role in the noise factor. Only a small fraction of the photons reach the PMT and the number of photo-electrons at the PMT photocathode becomes very small with poor statistics. The contribution of the photo-electron generation then becomes a major factor. This in turn, can be improved by using a more efficient PMT.

![Figure 3: NF for various light collection efficiency values](image)

5. Summary
A general model for deriving output SNR of electron detectors in electron or ion beam imaging tools was presented. The SNR calculated by the model was compared with experimental SNR for the case of ETD in a Ga+ beam tool and the results were in good agreement which also confirms the accuracy of the electron collection efficiency simulations. The model can be extended to many types of electron/ion detecting systems e.g. detectors with ion/electron convertor, with MCP or SSD based. Applying the model during detector design enables to identify the critical stages where noise formation should be reduced.

References
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