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Spatial and temporal NEDT in the frequency domain

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ABSTRACT

It is widely accepted from noise models that the extracted performance parameters such as spatial and temporal NEDT do not depend on the number of samples, which are used to estimate the noise values. Experimental studies have determined that noise values depend on the number of sampled data because of other noise contribution or its frequency dependence. This, however, creates ambiguities since unique values NEDT cannot be established without fixing the number of frames to be utilized. However in the frequency domain, values of parameters can be easily established at certain frequency. In the frequency domain it is also easier to study the noise contribution originating from various noise sources such as from the ROIC. This presentation will present preliminary analysis of spatial and temporal noise in the frequency domain by utilizing the power of FFT analysis.

1. Introduction

It is preferred; in general, that detector is the dominant source of noise in infrared camera systems. The detector array converts the photon flux to photocurrent, and under BLIP operation, the photocurrent becomes the dominant source of noise. This is the photocurrent shot noise, and is proportional to the square root of photocurrent, and therefore the signal-to-noise ratio (SNR) is proportional to square root of the photocurrent signal [1]. In this situation, the detector limits the performance of the system. The detector array spatial and temporal noise must dominate over all other noise sources, which can originate internally or externally. It is also important to realize that the signal and noise at the detector are the dominant quantities that determine the signal-to-noise ratio for the entire system. However, in some instances it is possible that the amplifier can limit the performance of the system. This situation should be avoided. The amplifier gain also plays a role since referring the noises at the output to the input involves the amplifier gain. For the read out integrated circuit (ROIC), it is absolutely necessary that the gain on the first stage amplifier be large enough so that the input referred noises become insignificant. Another issue of interest is the dependence of the spatial and temporal noise equivalent difference temperature (NEDT) on the number of frames collected. Since temporal noise is estimated from the consecutive frames that are collected and there is a constant time interval between frames, the frequency dependence of the noise is sampled at a time interval related to the frame rate. This sampling is subjected to Nyquist sampling criterion. This means that noise can be sampled up to a maximum frequency of half the sampling frequency, which is related to frame rate. Since the collected frames are finite, the estimated noise is not a good representation of the of extended time behavior of the system. The system will be susceptible to $1/f$ noise at frequency that is very small and therefore the system behavior will drift with time. Unfortunately, this very slow drift will affect the spatial noise estimate due to temporal $1/f$ noise contamination. The spatial noise should be decoupled completely from temporal noise, and is achieved by averaging many frames. If it is not, it will affect the two-point non-uniformity correction (NUC), and in some cases this is the situation. That is, the NUC process becomes inapplicable after some finite amount of time, and recalibration is required. Essentially this means that the system is not ergodic.

When in background-limited operation, the system performance is limited by the shot noise from the photon flux. In QWIP detector the signal is related to the product of photoconductive gain g and quantum efficiency (η), and extracting η requires knowledge of the photoconductive gain [2]. In addition, the shot noise depends on noise gain, which can be approximated to be equivalent to photoconductive gain at higher detector bias. This means that the gain can be independently obtained from the shot

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noise [3]. It is reasonable to assume that photoconductive and noise gain to be comparable since the carriers are transported trough the same channel. To minimize the effect of noise from the ROIC, the detector is bias higher so that detector noise and signal are larger than the ROIC noise. Then the noise contamination from the ROIC and electronics becomes less of an issue. With this in mind, a unique noise/photoconductive gain can be extracted from the relationship of squared of noise current and photocurrent and subsequently η is obtained. However, care must be exercised not to over bias the detector since it will generate a non-linearity with large signal irradiance.

Time independent spatial noises are calibrated out using a two-point (or multi-point) non-uniformity correction (NUC). The assumption of time independent is a strong condition for the NUC process to be valid. However, time independent of spatial noises is only approximate and finite in time since this assumes that time variation in the system have been captured and represented in the NUC process. Therefore, any subsequent variation in the system will appear as drift and is not represented in the NUC process. This NUC process requires that the infrared camera system is staring at the constant blackbody surface temperatures. Using two-blackbody temperatures and collecting consecutive finite number of frames, a correction matrices, gain and offset, are constructed. These matrices are applied to the raw images data, and the results are images without the quasi-time independent spatial noises.

The dependence of temporal NEDT on number of consecutive frames collected implies that there is frequency dependence. Fourier analysis of the time series of consecutive frames should provide the frequency content in the finite amount of data collected. The spatial NEDT, on the other, is normally an average of many frames. The spatial noise frequency content can originate from: the variation on the photon flux at the detector surface, detector response non-uniformity of response and dark current, ROIC pattern noise, ADC channel, software, etc. The Fourier analysis of the spatial noise will reveal the origin of some of the spatial noise sources. Our major objective is to investigate the effect of bias on the spatial and temporal $1/f$ noise on QWIP FPA. QWIP is preferred system to experimentally measure these parameters since it is a photoconductor and bias can be externally adjusted.

2. Spatial and temporal NEDT from a large number of frames

In the two-dimensional infrared imaging system, in addition to temporal noise, spatial noise is also a major performance driver. To operate in an ideal detector limited condition, the detector spatial and temporal noise must dominate all other noise sources, internally and externally. We can estimate temporal $\mathrm{NEDT_T}$ from collected frames. This includes actual system noise and no band limiting. Temporal $\mathrm{NEDT_T}$, which derives from many consecutive frames, is estimated from [4,5]

$$\mathrm{NEDT_T} = \frac{\sigma\left(\frac{T_\mathrm{H}+T_\mathrm{L}}{2}\right)}{\mathrm{Mean}(T_\mathrm{H}) - \mathrm{Mean}(T_\mathrm{L})}\Delta T \quad (1)$$

$$\sigma^2 = \sum_{i=1}^{N} \frac{(\bar{x} - x_i)^2}{N}$$

where σ is the RMS temporal noise count collected during flat field blackbody temperature mid-point between T_H and T_L, where $T_\mathrm{H} > T_\mathrm{L}$. ΔT is the temperature difference $(T_\mathrm{H} - T_\mathrm{L})$ and is a scalar. Where $\bar{x}$ is the mean matrix and x_i is the matrix. $\mathrm{Mean}(T_\mathrm{H})$ and $\mathrm{Mean}(T_\mathrm{L})$ are the mean intensity matrices in units of counts at temperature T_H and T_L, respectively. Eq. (4) is essentially an RMS of temporal noise σ divided by the thermal responsivity $\sim\{\mathrm{Mean}(T_\mathrm{H}) - \mathrm{Mean}(T_\mathrm{L})\}/\Delta T$. Assuming that low frequency noise is negligible, the temporal $\mathrm{NEDT_T}$ is independent of the number of frames collected. $\mathrm{Mean}(T_\mathrm{H})$, $\mathrm{Mean}(T_\mathrm{L})$ and ΔT are constant in time. The σ as define in Eq. (1) above shows that if few frames deviate considerably from the mean, it can significantly affect the RMS value. Since σ is a root-sum-square of the difference between the mean and each individual frame, the frequency dependence is embedded σ. Thus we can have a finite time series of data based on $\sigma(t)$. A deviation can be defined as $\sigma_i t) = x_i(t) - \langle x \rangle$, where $\langle x \rangle$ is the mean and $x_i(t)$ instantaneous value. The $x_i(t)$ represents an image frame in a set of collected consecutive frames. We can use the Fourier analysis to investigate the frequency dependence of the time series from the deviation. The power spectral density is the absolute value squared of the Fourier transform of $\sigma_i(t)$, i.e.,

$$S(f) = |\mathrm{FT}(\sigma(t))|^2 \quad (2)$$

where FT is the Fourier transform symbol and $\sigma(t)$ represents the deviation time series. Since the frequency reconstruction of the sampled data depends on the sampling frequency, higher frequency noise requires finer time interval sampling. For very low frequency that extends to low frequency $1/f$ noise, the time series interval is increased since over sampling increases only the volume of data. Hence a longer time interval and duration of data are not required.

The non-linearity effect and $1/f$ noise, in general, affect the stability of the infrared imaging systems. The major effect is on the gain and offset matrix applicability at a longer time scale. The raw images are NUC-corrected, and any drift originating from real time image and not from the NUC matrices because it is constant. The real time images acquire offset, and therefore may require recalibration. The two-point NUC linearity assumption can breaks down when the NUC correction requires non-linear correction beyond the two-point linear correction. For example, quadratic correction may be appropriate than a two-point NUC. For well behave QWIP FPA, two-point NUC correction is more than sufficient at temperature interval of 10–20 °C. However, deviation from inapplicability of two-point NUC has been observed on some FPAs probably due to non-linear effect of the detector and pixel transistor.

Spatial noise is generally assumed to be time independent. To obtain time independent spatial noise, many frames are averaged, and preferably infinite number of frames to completely eliminate the temporal noise. Unfortunately, this is impossible since only a finite number of frames can be averaged. Hence, very low frequency $1/f$ temporal noise will affect the NUC process after a longer period of time. But, supposing that a quasi-time independent spatial noise can be removed by NUC correction, a $1/f$ temporal noise or slowly time varying temporal noises can still appear as spatial noise which can render the NUC process ineffective at longer time scale. This very low frequency $1/f$ noise is not represented in the data captured that generates the correction matrices and pixel substitution map. However, since the generation of NUC matrices is finite in time, it is usually assumed that temporal $\mathrm{NEDT_T}$ is also stable or time independent. This is true only if $\mathrm{NEDT_T}$ has no very low frequency dependence. If temporal $\mathrm{NEDT_T}$ has very low frequency dependence, spatial $\mathrm{NEDT_S}$ will have also very low frequency dependence when finite number of frames is average, and the NUC process will become less applicable at longer period of time. It will be shown later that $\mathrm{NEDT_S}$ and $\mathrm{NEDT_T}$ are intermixed at smaller interval of time, but can be probably decoupled when the number of frames collected and use to evaluated noises are increased to large number. That is, we can assume that the system is approximately ergodic when a large number of frames is time average with value approaching spatial average.

If spatial $\mathrm{NEDT_S}$ has insignificant high and low frequency temporal noise contamination as the number of frames, which are averaged, approaches a large value, then a spatial noise floor has been reached. If ROIC spatial pattern noise limits the spatial noise