Infrared Physics & Technology 67 (2014) 413–426

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Empirical frequency domain model for fixed-pattern noise in infrared focal plane arrays

Francisco Pérez *, Jorge E. Pezoa, Miguel Figueroa, Sergio N. Torres

Department of Electrical Engineering and The Center for Optics and Photonics, University of Concepción, Casilla 160-C, Concepción, Chile

HIGHLIGHTS

- The spatial structure of fixed-pattern noise (FPN) in infrared cameras is modeled.
- The intensity of the FPN is defined by Fourier's magnitude spectrum.
- The spatial pattern of the FPN is retained in Fourier's phase spectrum.
- A simulation tool for synthesizing meaningful samples of FPN is provided.
- Improper FPN models affect noise-compensation methods performing spatial operations.

ARTICLE INFO

Article history:
Received 16 June 2014
Available online 18 September 2014

Keywords:
Infrared focal plane arrays
Fixed-pattern noise
Spatial non-uniformity noise
Non-uniformity correction

ABSTRACT

In this paper, a new empirical model for the spatial structure of the fixed-pattern noise (FPN) observed in infrared (IR) focal-plane arrays (FPA) is presented. The model was conceived after analyzing, in the spatial frequency domain, FPN calibration data from different IR cameras and technologies. The analysis showed that the spatial patterns of the FPN are retained in the phase spectrum, while the noise intensity is determined by the magnitude spectrum. Thus, unlike traditional representations, the proposed model abstracts the FPN structure using one matrix for its magnitude spectrum and another matrix for its phase spectrum. Three applications of the model are addressed here. First, an algorithm is provided for generating random samples of the FPN with the same spatial pattern of the actual FPN. Second, the model is used to assess the performance of non-uniformity correction (NUC) algorithms in the presence of spatially correlated and uncorrelated FPN. Third, the model is used to improve the NUC capability of a method that requires, as a reference, a proper FPN sample.

1. Introduction

The response of IR imaging systems presents several disturbances that are associated to the manufacturing technology [1–3]. Specifically, the response of IR cameras based on line-scanners is corrupted with FPN, also termed as spatial non-uniformity (NU) noise, while the response of IR cameras based on staring FPA detectors is corrupted with both temporal noise and FPN, also termed as spatial NU noise [4–6]. The temporal noise varies between consecutive frames, is independent among pixels of the same frame, and is usually mitigated by averaging, along the time dimension, data in consecutive frames. Unlike the spatially uncorrelated temporal noise, when FPA-based cameras are exposed to a uniform radiation, the FPN produces fixed spatial mismatches in the rendered images. This means that spatial patterns, such as lines, stripes, grids, and even gradients, appear as artifacts laid over the ideal flat image. This phenomenon severely degrades the image quality to the extent of requiring either the camera calibration or image processing algorithms to recover the real image.

The FPN is a particular type of noise because it is spatially correlated, and its intensity remains fairly constant for minutes, or even hours, if there are no major changes in the operating temperature of the camera [7,8]. As such, researchers have modeled the FPN as a spatially uncorrelated and time-stationary process. The assumption about the time-stationary behavior of the FPN is well accepted and not restrictive at all because it is known that the FPN intensity changes only after several minutes of continuous operation of the camera. It must be noted that, in spite of the intensity changes, the spatial pattern of the FPN remains the same. For instance, Fig. 1 shows samples of FPN for a Cedip microbolometer-based camera, under both different temperature for a black-body radiator source and different operating temperature of the

* Corresponding author.
E-mail addresses: francisperez@udec.cl (F. Pérez), jpezoa@udec.cl (J.E. Pezoa), mifiguer@udec.cl (M. Figueroa), sertorre@udec.cl (S.N. Torres).

http://dx.doi.org/10.1016/j.infrared.2014.09.010
1350-4495/

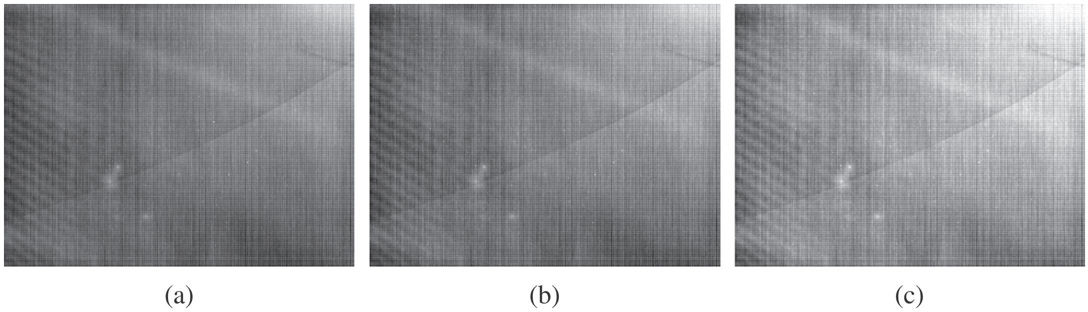

Fig. 1. FPN samples from a 14-bits Cedip JADE-UC uncooled microbolometer camera under different conditions: (a) Image of black-body radiator at 0 °C with camera housing at 25.9 °C. (b) Image of black-body radiator at 60 °C with camera housing at 31.59 °C. (c) Image of black-body radiator at 105 °C with camera housing at 33.02 °C.

camera. It can be observed from Fig. 1(a)–(c) that the spatial pattern of the FPN is the same; however, the average intensities, with respect to the maximum quantization value of the camera, are: 37.10% for Fig. 1(a), 58.24% for Fig. 1(b), and 75.54% for 1(c).

In the literature there is a vast number of studies in IR imaging in fields such as non-uniformity correction [8–13], image quality assessment [14–16], super-resolution imaging [17,18], etc. Due to the complexity in representing the spatial patterns of the FPN, in most of these works such spatial structure is totally disregarded by utilizing the aforementioned time-stationary spatially uncorrelated model for the FPN, see Fig. 2(a). This model simplifies the calculations and the development of NUC algorithms. However, it is claimed here that the spatially uncorrelated model for the FPN is not an appropriate representation because spatial patterns, such as grids, stripes and gradients, are indeed observed in the raw scenes acquired by FPA-based IR cameras. Moreover, one can think that the performance results of NUC algorithms presented in the literature may be different if an improper FPN model is used, in simulations, to generate noisy IR images.

To the best of the authors knowledge, there are a few works where the spatial structure of the FPN has been studied [18–25]. Schulz and Caldwell [19] presented an approach for modeling the FPN and its spatial structure using multiple irradiation data. Their approach considered a pixel-wise least square fitting that could lead in offset, linear, square and higher orders representations for the FPN. Through this representation they were also capable of representing bad pixels in the FPA. However, their model was not able to synthesize different FPN samples from the given spatial structure of a particular camera. El Gamal et al. [20] introduced, as far as the authors know, the first model able to synthesize FPN samples considering its spatial structure. They were particularly concerned about the FPN produced by the readout circuitry in PPS and APS CMOS sensors. In [20], the authors represented the FPN as the sum of a pixel component and a column component, which are supposed to be uncorrelated. Both of these components were modeled in terms of a first-order isotropic autoregressive random process. López-Alonso et al. [21] performed a principal component analysis of the noise present in IR images, representing the noise as real independent images that are over imposed on the scene. They decomposed the noise in spatial patterns, called eigenimages, which allowed them to classify the spatial noise into different patterns. This classification allowed them to distinguish between pure spatial and pure temporal noise components. Thus, the first eigenimage provided by López-Alonso et al. is a representation for the FPN. Zhao and Zhang [18,22] used a first-order model to represent the response of the IR FPA. In this model, the spatial structure of the FPN was considered as horizontal and vertical anisotropical lines, with uniformly distributed random intensities, which composed both, the gain and the offset components of the noise. In [23], Guadagnoli et al. developed a model that considers a combination of physical and electronics parameters, such as the optical system geometric and transmission matrices, that contribute to the FPN. Since the focus of their work was modeling FPN sources, the signal model was represented as a second-order, pixel-wise equation, regardless of the fact that the parameters implicitly capture the entire spatial structure of the noise. In an earlier work of the authors' group, Pezoa and Medina [24] used a grid-like approach based on a closed-form characterization of the FPN in the spatial frequency domain, see Fig. 2(b). They represented the FPN by the sum of Gaussian functions in the magnitude spectrum, and developed estimators for the parameters of these Gaussian functions. Even though the FPN models in these works are more appropriate than the oversimplified spatially uncorrelated noise model, the underlying assumption in all these works but in [21] is that the FPN has a regular pattern such as grids or stripes. This assumption, however, is still not realistic because the FPN exhibits also irregular patterns, like the gradients and atypical structures depicted in Fig. 2(c).

Later, in another work of the authors' group [25], a spectral analysis of FPN was performed in order to characterize its spatial

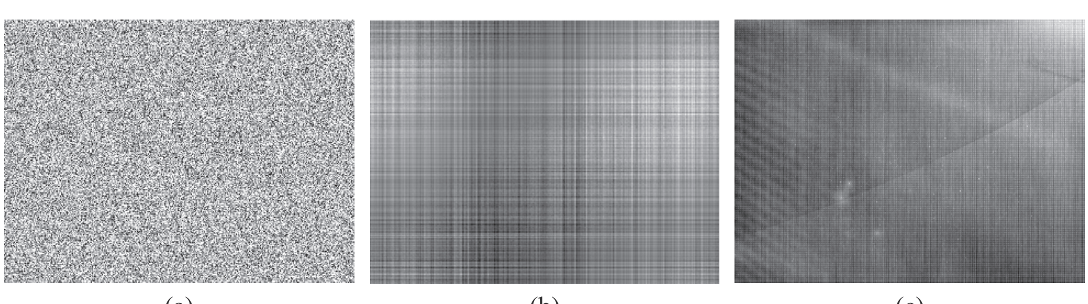

Fig. 2. Different representations for the FPN used in literature: (a) Spatially uncorrelated random noise. (b) Grid-like approach Pezoa and Medina [24]. (c) A real sample of FPN from a Cedip JADE-UC uncooled microbolometer camera.