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Efficiency of applying a high-pass filter cutoff frequency corrector used in the infrared focal-plane array with time delay integration mode (IR-FPA)

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The fundamental design of the readout integrated circuit (ROIC) of scanning infrared (IR) photomodules (PM) with the time delay integration mode (TDI) is considered. The role and influence of the recursive high-pass filter (HPF) in the input cells (IC) of the readout integrated circuit on the threshold characteristics of the PM are outlined. A mathematical description of the digital correction of the HPF cutoff frequency in the input cell is given. The design and operating principle of a trainable classifier capable of dividing TDI-channels into groups based on the noise power spectral density (NPSD) are described. The cutoff frequency of the HPF of the IC has been corrected for a large number of TDI-channels with different NPSD. The efficiency of applying this correction to increase the signal-to-noise ratio has been calculated, taking into account the standard intra-frame processing for scanning IR PM. It was found that threshold characteristics without window filtering improve by an average of 2.5 %, while with it, they improve by only 1 %. It was noted that with a large number of TDI-channels with low-frequency noise, the digital correction of the HPF cutoff frequency can degrade threshold characteristics by 1.5 %.

Keywords: threshold characteristics, photomodule, infrared range, time delay and integration mode, noise, signal-to-noise ratio, intra-frame processing, noise power spectral density, high-pass filter, cutoff frequency, multi-label classification.

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Introduction

Large-format infrared focal plane arrays (IR FPAs) with time delay and integration (TDI) mode are actively used as part of Earth remote sensing space systems. The key element of such IR FPAs are infrared photomodules (PMs), which are large-scale integration (LSI) readout circuits hybridized with a matrix of photosensitive elements (MPE) based on cadmium mercury telluride. A typical block diagram of the LSI readout circuit for such PMs is shown in Fig. 1.

The task of the LSI readout circuit is to receive signals from the MPE, which is connected to the LSI via microcontacts (Fig. 1, block 1), and to sum these signals in a specific time sequence, i.e., to implement the TDI mode.

When the image is uniformly moved by the scanner across the photomodule, signals are sequentially transferred from the photosensitive elements (from 1 to 6) to the input cells (IC) of the LSI readout circuit. Primary integration and high-pass filtering of the signals are performed in these cells using switched-capacitor circuits (Fig. 1, block 2). High-pass filtering increases the input dynamic range by subtracting the spread of the constant non-informative component of the signals from the MPE. These signals are then switched to each of the inputs (from 1 to 1152) of the TDI register (Fig. 1, block 3). In the TDI register, weighted summation of the terms (signals) arriving at different times is performed. The operation of the TDI register is considered complete when all 6 signals are applied to its

inputs with equal weighting coefficients of 1/6. In this case, the operation of the TDI register can be considered as an averaging operation. The purpose of this averaging is a significant

reduction in noise and interference levels, an improvement in the uniformity and stability of signals from the MPE, as well as an increase in the dynamic range at the output.

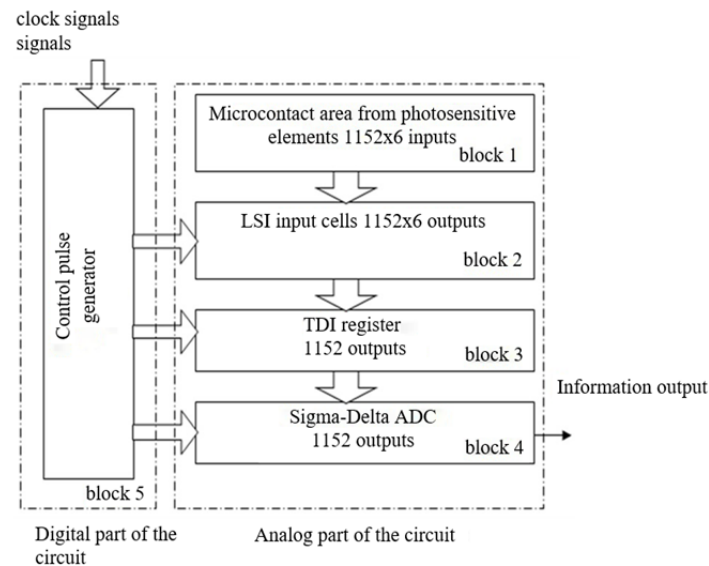


Fig. 1. Typical block diagram of the LSI readout circuit for scanning IR PMs

Further operations performed in block 4 (see Fig. 1) include:

- analog-to-digital conversion (ADC);
- switching signals to the information outputs of the LSI.

Coordination of the LSI operation and rejection of defective photosensitive elements are carried out by the digital control pulse generator block (Fig. 1, block 5) [1].

Since low-frequency noise significantly degrades the accuracy of measuring the signal obtained at the output of the IR FPA [2], given that the predominant part of the power spectral density of the signal from small-sized objects, which are the target detection objects for the considered IR FPAs, is concentrated in the low-frequency region, the idea naturally arises of the need to adjust the cutoff frequency f_{cutoff} of the high-pass filter of the LSI readout circuit input cells (hereinafter referred to as the SC filter) (Fig. 1, block 2) downwards. Conducting research on the selection of optimal parameters for a mathematical recursive filter, which ensures a reduction of the initial cutoff frequency of the SC filter from 120 Hz to 30 Hz, described in [3], showed a significant increase in the signal-to-noise ratio (up to 9 % for a first-order filter and up to 39 % for a second-order filter). However, in that study, parameter selection was carried out for

only one TDI channel, which had a noise spectrum close to "white", although it was noted in the same work [3] that a real IR FPA contains a large number of TDI channels with a non-"white" noise spectrum, for which the filtering efficiency differs significantly. In this regard, it becomes relevant to conduct a study of the dependence of the effectiveness of adjusting the cutoff frequency of the LSI readout circuit high-pass filter in the context of increasing the signal-to-noise ratio, for a large number of TDI channels with different distributions of the noise power spectral density (NPSD), which is the subject of this work.

Cutoff frequency correction

The procedure for correcting the cutoff frequency of the SC filter involves applying a combination of two first-order recursive digital filters to the output images of the IR FPA. These filters first flatten the amplitude-frequency response (F1), after which it is subjected to high-pass filtering (F2), but now with the new required cutoff frequency (Fig. 2). The frequency response of the resulting filter (F) (red curve) is calculated as the product of the frequency responses of F1 and F2. The frequency response of the SC filter corrected using Filter is shown by the purple curve ("Resulting FR" in Fig. 2).

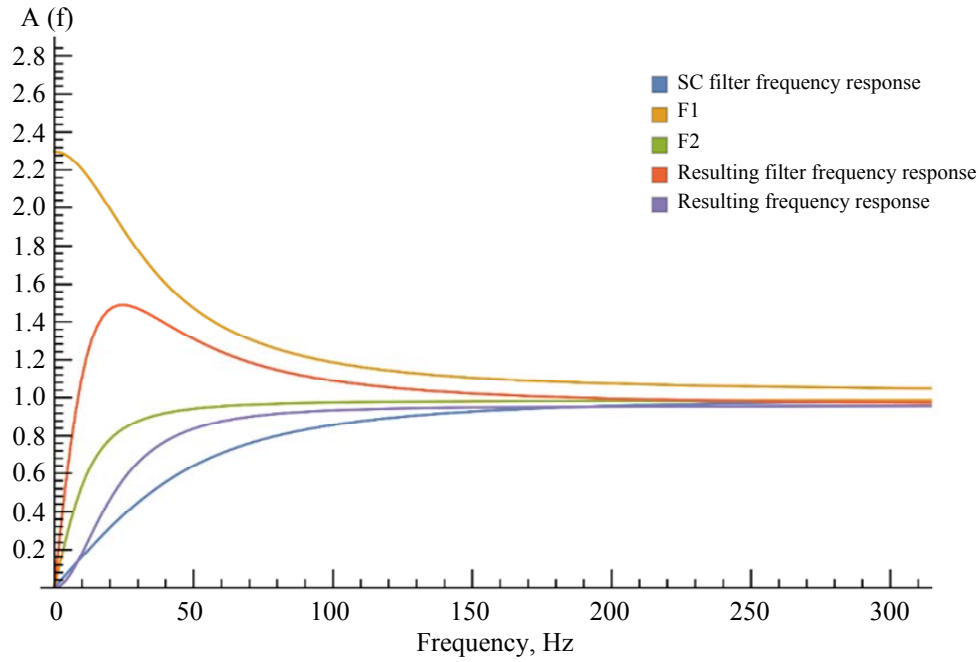


Fig. 2. Amplitude-frequency characteristics of the original SC filter, low-pass filter (F1), high-pass filter with the new cutoff frequency (F2), the resulting second-order filter (F), and the output data after the performed correction (Resulting FR)

A first-order recursive filter is described by the formula:

$$y[n] = a_0x[n] + a_1x[n-1] + b_1y[n-1], \quad (1)$$

coefficients of the low-pass filter F1:

$$a_0 = 1.061906, a_1 = -0.95238, b_1 = +0.95238;$$

coefficients of the high-pass filter F2:

$$a_0 = +\alpha, a_1 = -\alpha, b_1 = +\alpha, \alpha = 0.975.$$

The resulting second-order filter F is defined by the formula:

$$y[n] = a_0x[n] + a_1x[n-1] + a_2x[n-2] + b_1y[n-1] + b_2y[n-2] \quad (2)$$

with the following coefficients:

$$a_0 = 0.975, a_1 = -1.84944, a_2 = 0.874438, b_1 = 1.92738, b_2 = -0.928571.$$

After performing such frequency correction, the signal from a small-sized object increases, since the majority of its power spectral density is concentrated precisely in the low-frequency region. Noise also increases, however, in the case of uniform or high-frequency noise, this increase is not proportional to the increase in the signal, as a result of which the signal-to-noise ratio increases and the threshold characteristics improve. But if low-frequency noises predominate among the TDI channels, such

processing may either be ineffective or worsen the threshold characteristics.

NPSD classifier for TDI channels

To determine the effectiveness of correcting the SC filter cutoff frequency for various types of NPSD, it is necessary to classify a large number of TDI channels into four main noise classes described in [4] (elementary classes):

- 1) noise of standard TDI channels ("White");
- 2) noise with a predominant high-frequency component (high-frequency);
- 3) noise with excessive low-frequency components (low-frequency);
- 4) noise with a rise in the vicinity of 1/3 of the sampling frequency (TDI noise).

For automatic identification of the NPSD, a trainable classifier was developed, which makes it possible to determine the probability of a TDI channel belonging to one of the above groups.

The input data for the classifier are the frequency dependencies of the NPSD of the TDI channels, which have undergone preliminary digital processing carried out in 3 stages [5]:

- 1) window filtering using the median function in a window of radius 2;

2) window filtering using the arithmetic mean function in a window of radius 5;

3) normalization – ensuring that the mean value of the data is equal to one.

Based on the data obtained after preprocessing, 3 coefficients (x_1 , x_2 , x_3) are calculated, each of which characterizes the belonging of the TDI channel to one of the groups:

1) The slope coefficient in the low-frequency region is defined as the slope coefficient of a straight line constructed using the least squares method (LSM) from data in the region [50; 500] Hz.

2) The slope coefficient in the main part of the NPSD is defined as the slope coefficient of a straight line constructed using LSM from data in the regions [500; 1177] $\cup$ [1377; 1915] Hz.

3) The coefficient characterizing TDI noise is determined as follows: from the data in the region $\Delta = [1177; 1377]$ Hz, the coefficients of an approximating parabola are calculated using LSM. After that, depending on the value of the coefficient in front of the highest degree of the parabola (a), the value of the TDI noise coefficient is determined:

a) if $a > 0$, then the parameter is 0;

b) if $a < 0$ and the position of the parabola's maximum is outside the range of region Δ , then the parameter is 0;

c) otherwise, the parameter is equal to the value of the correlation coefficient of the data from region Δ with the sampled approximating parabola.

The classifier is trained by calculating the characteristic NPSD coefficients for which the class has been manually determined, and constructing probability density functions for each class based on them (Fig. 3):

1) For each elementary class C_k (white, high-frequency, low-frequency, TDI; k – parameter index) and for each characteristic coefficient x , the distribution width is estimated as the median absolute deviation, reduced to the RMS value – $\sigma_{k,x}$.

2) For each elementary class C_k and for each coefficient x , a distribution density of this coefficient is formed: the final density value $\rho_{k,x}$ is the sum of Gaussians with a mean equal to the parameter value and an RMS equal to $\sigma_{k,x} \times n$, $n = 1/4$.

3) The obtained distribution densities are normalized: $\int_{-\infty}^{\infty} \rho_{k,x}(x) dx = 1$.

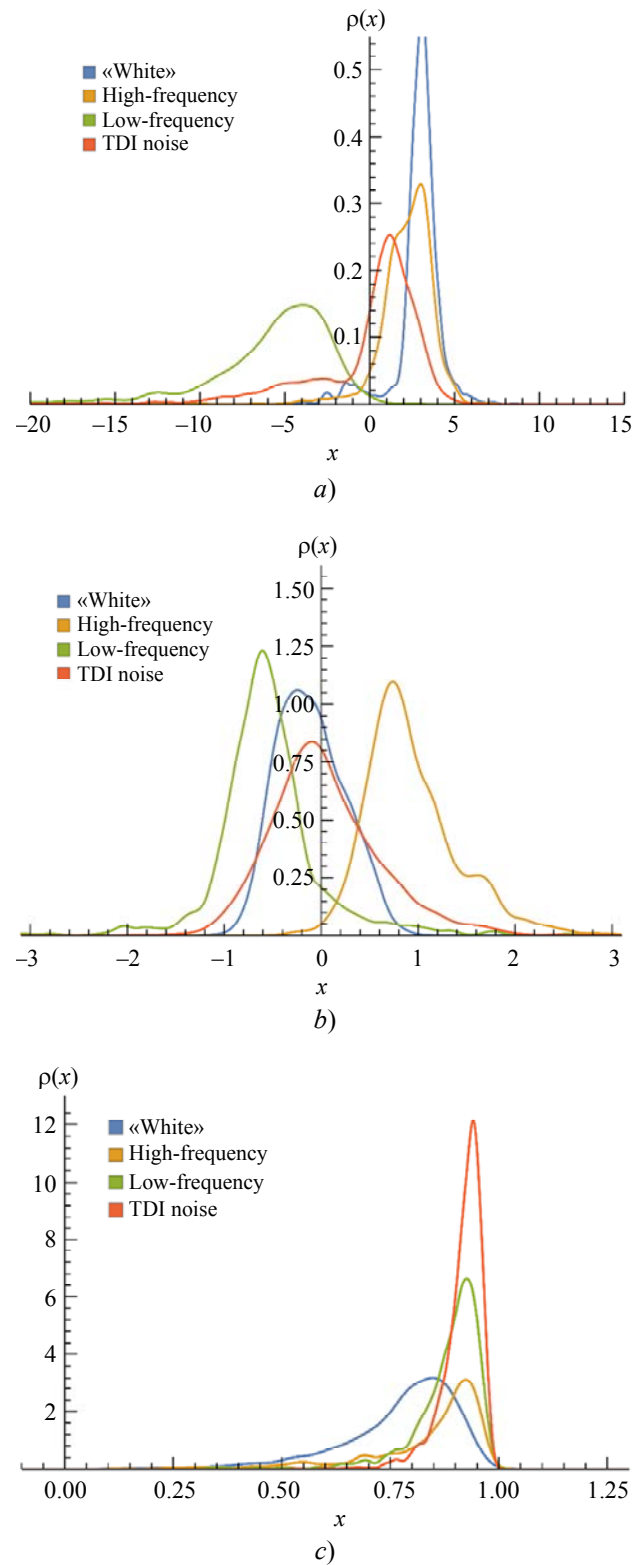


Fig. 3. Probability density functions of each elementary NPSD class: a) for the low-frequency noise slope coefficient, b) for the slope coefficient of the main part of the NPSD, c) for the correlation coefficient of the preprocessed data and the approximating parabola

After calculating the characteristic coefficients of the classified NPSD, the probability of its belonging to one of the elementary classes is calculated using the Bayes formula [6]:

$$P(C_k | \vec{x}) = \frac{P(C_k) \cdot P(\vec{x} | C_k)}{P(\vec{x})}, \quad (3)$$

where $\vec{x} = (x_1 \ x_2 \ x_3)^T$ is the vector with parameter values (coefficients);

$P(C_k)$ is the probability of encountering an elementary class C_k ;

$P(\vec{x} | C_k)$ is the probability that the value of the coefficient vector equals $\vec{x}$ given that the input data belongs to class C_k .

The prior probability of hypothesis C_k is calculated by the formula:

$$P(C_k) = N_k / N \quad (4)$$

where N_k is the number of samples in which elementary class k was observed among the training set;

N is the total number of training samples.

Due to the independence of the coefficients from each other, the conditional probability of observing the coefficients $\vec{x}$ given that they belong to the elementary class C_k is calculated by the formula:

$$P(\vec{x} | C_k) = \prod_{i=1}^3 \int_{|\xi_i - x_i| \leq \sigma_i \cdot n} \rho_k(\xi_i) d\xi_i. \quad (5)$$

The probability $P(\vec{x})$ is calculated using the formula for the total probability of an event dependent on several mutually exclusive hypotheses:

$$P(\vec{x}) = \sum_{k=1}^4 P(\vec{x} | C_k) \cdot P(C_k). \quad (6)$$

Efficiency of applying the SC filter cutoff frequency corrector for TDI channels with different NPSDs

Using the developed classifier, 5760 TDI channels from a single line of a scanning IR FPA sample were divided into groups. Using the NPSD of these TDI channels, time-domain noise realizations with a length of 1937 samples were generated for each of the channels, thus forming a frame that simulates the output low-background image of the IR FPA. Using the noise frame as a basis, a series of frames is formed, each of which represents a superposition of the time-domain noise realizations and the image of a small-sized object focused on one of the TDI channels.

The resulting series of frames is simultaneously subjected to two digital processing methods: standard processing (two-point correction and window filtering quasi-matched to the signal from the small-sized object [7]) and sequentially applied cutoff frequency correction followed by standard processing. From the processed frames, the signal-to-noise ratio (SNR) is calculated for each TDI channel, after which the ratio of the SNR values obtained from the series of frames subjected to standard processing with the cutoff frequency corrector to the SNR values obtained from the series of frames subjected only to standard processing is found. The values of these ratios characterize the effectiveness of applying the SC filter cutoff frequency correction to improve the threshold characteristics of each individual TDI channel, given their mutual arrangement in the line (due to window filtering).

Having information about which NPSD shape group each TDI channel belongs to, it is possible to correlate the effectiveness of applying the SC filter cutoff frequency correction with the noise spectrum and its prevalence in a real sample of a scanning IR FPA (Fig. 4).

The obtained results show that the application of the corrective filter:

- a) for "white" noise increases the SNR by 1 %;
- b) for high-frequency noise increases the SNR by 2 %;
- c) for low-frequency noise decreases the SNR by 1.5 %;
- d) for TDI noise increases the SNR by 1.3 %.

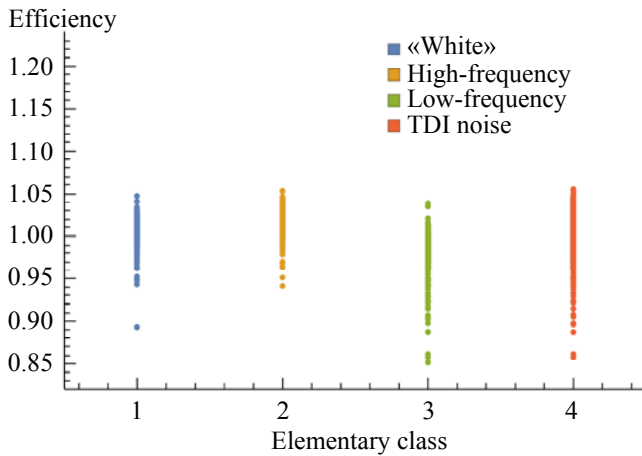


Fig. 4. Efficiency of applying SC filter cutoff frequency correction for various NPSD types considering quasi-matched window filtering

However, if window filtering of the output images is not performed, limiting standard processing to only two-point correction, then the efficiency of applying the SC filter cutoff frequency correction will be distributed as shown in Fig. 5.

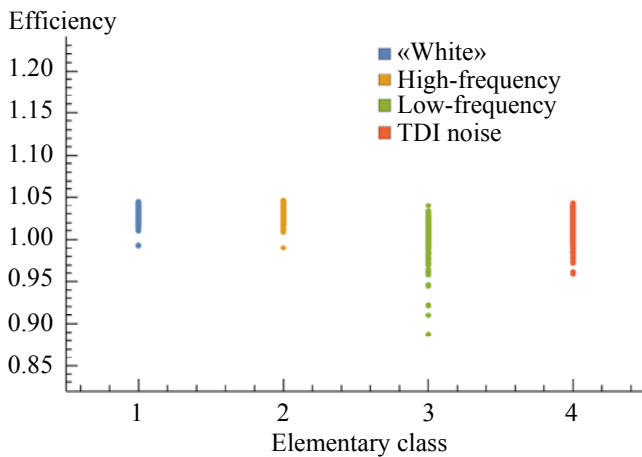


Fig. 5. Efficiency of applying SC filter cutoff frequency correction for various NPSD types without considering quasi-matched window filtering

In this case, the application of the corrective filter:

- a) for "white" noise increases the SNR by 3 %;
- b) for high-frequency noise increases the SNR by 3 %;
- c) for low-frequency noise increases the SNR by 1 %;

d) for TDI noise increases the SNR by 2.3 %.

Summarizing the obtained results, it can be concluded that the efficiency of the SC filter cutoff frequency correction on average slightly improves the threshold characteristics (up to 2.5 %), if they are evaluated from the original output images of the IR FPA. However, due to the "blurring" of time samples between TDI channels when applying window filtering, which is often used for the same purpose of improving threshold characteristics, this effect is practically negated (down to 1 %). Also, in the case of predominance of low-frequency noise in the photomodule, correction of the SC filter cutoff frequency can worsen its threshold characteristics (up to 1.5 %), which indicates the high specificity of this type of preprocessing of IR FPA output signals.

Conclusion

In this paper, a study was conducted on the influence of the shape of the noise power spectral density of IR FPA TDI channels on the efficiency of correcting the cutoff frequency of the LSI readout circuit high-pass filter in the context of increasing the signal-to-noise ratio, given the application of standard intraframe digital processing, which includes two-point correction of the sensitivity non-uniformity of the TDI channels and window filtering quasi-matched to the signal from a small-sized object. To determine whether the NPSD plots of TDI channels belong to one of the four main types, a trainable classifier was developed, which makes it possible, based on manually classified data, to calculate the probability of the classified TDI channel belonging to one or several groups at once. Using the classifier, a large number of TDI channels from a real sample of a scanning IR FPA were identified, after which, using their NPSD, a series of frames was generated containing images of a small-sized object on each of the studied TDI channels. After parallel intraframe processing of these frames with and without SC filter cutoff frequency correction, a comparison was made of the effectiveness of this correction for improving threshold characteristics for various types of TDI channels:

- a) in the case of applying window filtering,

correction of the SC filter cutoff frequency on average increases the SNR by 1 %;

b) in the case without applying window filtering, correction of the SC filter cutoff frequency on average increases the SNR by 2.5 %.

It was also shown that in the case of predominance of TDI channels with low-frequency noise in the photomodule, correction of the SC filter cutoff frequency reduces the SNR by 1.5 %, which, together with the low efficiency

when applying window filtering, indicates the high specificity of this type of preprocessing of IR FPA output signals and the impossibility of using it without a preliminary assessment of the noise characteristics of the device used. In the case of predominance of noise with a uniform or high-frequency spectrum in the device, this correction allows a slight improvement in threshold characteristics, which is nevertheless a satisfactory result for this type of IR FPA.

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