Statistical analysis of computer-generated thermal images based on overall modeling of line-scanning process

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Abstract

Using our previously developed computer model of line-scanner on moving platform, several synthetic thermal images of a terrain background were produced. The geometrical image deformations, spatial radiance filtration and influence of the model scene parameters on statistical properties of simple terrain image are analyzed. The change of the mean value, standard deviation, histogram and pixel-to-pixel correlation of computer-generated thermal images with a scanning angle, indicate a possibility for adaptive reduction of the data redundancy for an efficient digital image transmission.

1. Introduction

The thermal infrared image is produced by the distribution of the radiant emittance of a scene transformed through an optomechanical scanning device into a flux incident on the detector. The video signal at the detector output is proportional to the incident flux from the terrain and the atmosphere, within a specified wavelength range.

In reality the generation of an infrared thermal image is a complex process not easily modeled in a general case. An approach to one-dimensional modeling of the spatial and statistical properties of background radiance in intermediate infrared spectral region 2-14 μm was presented by Itakura [1]. The natural terrain modeling (based on a simplified heat balance equation for each image pixel) was suggested by Ben-Yosef et al [2]. Statistics of the radiance over the infrared image depends on the imaging system as well. A simulation model SENSAT-2 (Sensor-Atmosphere-Target) was presented by Richter [3]. This model was developed for remote sensing applications of passive sensors in the infrared spectral region 1-28 μm. A method for simulating of non-homogeneous sea surface images (based on modeling bottom-up processes) obtained by forward-looking infrared (FLIR) sensors in the 8-12 μm band is presented by Wilf and Manor [4]. A new computer model (based on two-dimensional terrain statistics and bottom-up process simulation) for the generation of thermal images by line-scanning from low altitude aircraft was developed by Barbaric et al [5], in the spectral range 8-12 μm.

For visual analysis, thermal images are usually recorded on film or transmitted and displayed on a video monitor. Digital signal processing techniques have important role in line-scanning systems due to the increasing need to maintain high image quality from sensor to display and efficient interface to real-time data link. Various image processing techniques can be used for sensor artifact suppression and data compression techniques for solving the enormous instantaneous data rates problem [6].

2. Computer simulation procedures for thermal image generation

The computer model used in this work has simulated a simplified real system: flat terrain with flat non-overlapping objects, homogeneous atmosphere and the scanning device moving at a constant speed-to-altitude ratio, with the scanning plane perpendicular to the terrain plane. A schematic diagram of simulation procedures is shown in *figure 1*.

The terrain is simulated as a periodic repetition of the terrain base area, made from ground and isolated square shaped hot plates of different sizes. Normal probability density

function and exponentially decreasing isotropic autocorrelation function are used to model natural fluctuation of terrain two-dimensional temperature distribution. The objects in the terrain base area are defined by their non-overlapping contours and specified statistical parameters: mean temperature distributions, the standard deviations and the correlation lengths. Desired discrete temperature distribution was achieved by filtering in the two-dimensional discrete Fourier transform domain.

We assumed that the terrain radiates as a black body following Planck's radiation law. The average temperature of the natural terrain is between 250 and 350 K, which means that the peak radiation is in the range from 11.6 to 8.3 μm, respectively. At the same time this wavelength range is convenient because of the small reflected spectral radiance, high atmospheric spectral transmittance and good spectral response of detectors. The atmosphere attenuation τ is a function of the scanning angle Θ and the average transmittance τ at the nadir $\tau = \tau^{\sec\theta}$.

The opto-mechanical scanner can be interpreted as a device collecting radiance flux from discrete elementary areas within the resolution cell on terrain and the atmosphere volume defined by the solid angle of the sensor cone. The collected radiations act on the detector, which converts it into a signal at the thermal image plane. This system is successfully modeled by the optical transfer function of the sensor and geometrical coordinate transformation from the terrain to the image plane.

The thermal images can be efficiently generated pixel-by-pixel by summation of the discrete series of spatial harmonics of the terrain radiance distribution multiplied by the optical transfer function of the sensor. The voltage at the detector output is obtained in the form of a double sum [5]:

$$V(i,k) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} K_1 \left[\tau L_C^T(m,n) + L_C^A(m,n) \right] H(m,n,\theta_k) \exp\left[2\pi j \left(\frac{m}{M}i + \frac{n}{N}k \right) \right] \qquad (1)$$

where $K_1 = A_0 k_0 R\alpha_0 \beta_0$ is a constant, i=0,1,2,... and k=0,1,2,.... The numbers M and N are selected so that all available samples of radiance over the terrain base area are included. The radiances $L_C^T(m,n)$ and $L_C^A(m,n)$ are the discrete Fourier transforms of the terrain radiance $L_C^T(i,k)$, and the atmosphere radiance $L_C^A(i,k)$. The normalized transfer function of sensor square shaped aperture is $H(m,n,\theta_k)$ where θ_k = artan($k\Delta y/H$) and H is the altitude of the moving platform. In the calculation of sinc type function $H(m,n,\theta_k)$ Hermitian symmetry with respect to m and n is taken into account.

The output signal from the detector has to be resampled and quantified. We assumed continuous scanning without overlap or underlap of adjacent scanning tracks at the nadir and resolution cells along the scan direction. Line-scanning parameters are: plane components of constant angular instantaneous field of view $\alpha_0 = \beta_0 = 1.5$ mrad, step along flight direction at the nadir $\Delta X = H\alpha_0 = 1$m and scanning angular step $\Delta\Theta = \beta_0$.

The equations describing the model have been programmed in high computer language FORTRAN. The program input data are the dimension of the terrain base area and the objects contours, statistical parameters for ground and objects areas, atmospheric conditions, flight parameters, sensor characteristics and scanning angle ranges. Computer processing procedure is very time consuming.

Several thermal images of a terrain background with square hot plates were generated by using the developed computer model. The selected image frames correspond to the scanning angle ranges: 0°<Θ<5.5°, 15°<Θ<20.5°, 30°<Θ<35.5°, 40°<Θ<45.5° and 55°<Θ<60.5°. The dimensions of each frame are 64x64 pixels. We selected the terrain base area of 64x256 points as a compromise between computation time and good statistics. Statistical parameters of the terrain are m_G=298K, σ_G=1.25K and the correlation length d_G=2m. The dimension of

square plates are 16mx16m, 8mx8m, 4mx4m and 2mx2m with statistical parameters m_p =306K; σ_p =1K and the correlation length d_p =4m. A representative example of the three types of synthetic frames with various dimensions of square plates corresponding to the nadir $0°<\Theta<5.5°$ and scanning angle range 55°<Θ<60.5° is shown in *figure 2*. The image frames were quantified with 256 gray levels, but in this paper they are printed with limited number of gray levels.

3. Analysis of generated thermal images

In our previous works we investigated basic line-scanning effects, atmosphere radiation and attenuation role in the three characteristic cases for different ratios of average atmosphere to ground temperature[5], and isolated influence scene parameters to the statistical properties of thermal images in the two extreme cases for uncorrelated and correlated terrain background [7]. In this paper we are continuing the investigation of isolated line-scanning effects in case of simple objects on correlated terrain temperature distribution and without the influence of atmosphere. We have analyzed geometrical image deformations, spatial radiance filtration due to finite dimension of detetector aperture and image statistical parameters: mean value, standard deviation, histogram, entropy and pixel-to-pixel two-dimensional correlation as a function of the scanning angle and spatial resolution.

3.1 Geometrical image deformations

The geometrical effects of line-scanning are clearly seen on representative computer-generated thermal image frames corresponding to the scanning angle range 55°<Θ<60.5° shown in *figure 2*. Images, displayed on uniform grid with square shaped pixels, are non-linearly compressed by artan law due to *constant* instantaneous angular field of view and increasing area of scanning optics projection (resolution cell) on the terrain at various scanning angles. The area of the resolution cell increased as $\sec^3\theta$ i.e. by $\sec^2\theta$ in the along scan direction and $\sec\theta$ in the along flight direction. The use of constant angular sampling rate causes overlapping adjacent scanning tracks, seen as changes in the shape and size, and blurred edges of the plates. In practice, those sensor artifacts must be suppressed by various image processing techniques which include resampling, destriping and interpolation. Also, before applying any data compression, it is first necessary to remove all oversampled pixels from the image. Particularly, for transform coding a geometrically correct image should be created [8].

3.2 Statistical image analysis

Another effect of the line-scanning is the change of the image gray level fluctuation with the increasing scanning angle due to spatial non-invariant terrain radiance averaging on area of resolution cell i.e. decrease of spatial resolution or equivalently decrease in the bandwidth of scanning optics transfer function. The statistical parameters of selected computer-generated thermal frames are calculated.

Image histograms of representative synthetic thermal frames are shown in *figure 3*. One can see that a relative frequency occurrence of gray levels i.e. image probability density function is changed as a function of scanning angle but is still of the Gaussian type as we expected it due to system linearity. Also, its distribution is related to the line-scanning spatial resolution that approaches the normal distribution owing to the central limit theorem [2], regardless of beginning distribution. Histograms of the frames with objects at nadir have two Gaussian peaks on positions of mean values of background and hot plates. With increasing scanning angle, the plates histogram peaks disappears owing to line-scanning effects described in Section 3.1, and the background histogram peak becomes slightly asymmetric.

The mean value of three types of computer-generated thermal frames decreases as a function of the scanning angle as shown in *figure 4a*. In *figure 4b*. the standard deviation of the three types of synthetic frames gray levels as a function of the scanning angle is shown. The standard deviation also decreases with the scanning angle due to increasing area of the

resolution cell. The rates of mean value and standard deviation decay depend on the terrain type i.e. total area of plates, with expected behavior that for the scanning angles near to the horizon statistical values of all frames have the same value. Changes of mean value and standard deviation with the scanning angle can be used in selecting an optimal quantification of thermal image signal samples as a function of scanning angle.

Figure 4c. shows statistical results for the two-dimensional autocorrelation coefficients for neighboring pixels. In the along flight direction the autocorrelation coefficient (R_1^1) increases with the scanning angle because in this case we have increased overlapping of the adjacent scanning terrain tracks. The along scan direction correlation coefficient (R_2^1) decreases. It should be noticed that in spite of the assumption that the terrain is assumed isotropic, the correlation of the thermal image formed by the line-scanning is anisotropic. The local high correlation of frames can be used in selecting the weighting coefficients in the adaptive predictive coding and in analyzing the spatial frequency content of an image for transform coding techniques [8].

Figure 4d. shows the decay of first-order entropy of the three types computer-generated thermal image as a function of scanning angle. The entropy is calculated from histograms as the average value of the self-information of the selected image frames. The change of entropy with the scanning angle proves that variable word length coding can be used. The optimum entropy coding depends on image statistics and therefore must be optimized for some typical class of terrain.

4. Conclusion

Based on the analysis of statistical parameters of computer-generated thermal images of simplified terrain, we expect that the changes of parameters that were found can be advantageously used for the redundancy reduction and the selection of predictive, transform and entropy adaptive coding. The line-scanning signal is a non-standard one as compared with the standard composite television signal therefore the redundancy reduction techniques used in a television are not directly applicable to a line-scanning thermal image. In practice, image quality criteria for infrared line-scanned image differ from those used for television signal. And finally, the efficiency of the proposed techniques for data compression depends on the type of terrain and requires further study in order to arrive at an optimal solution.

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Terrain
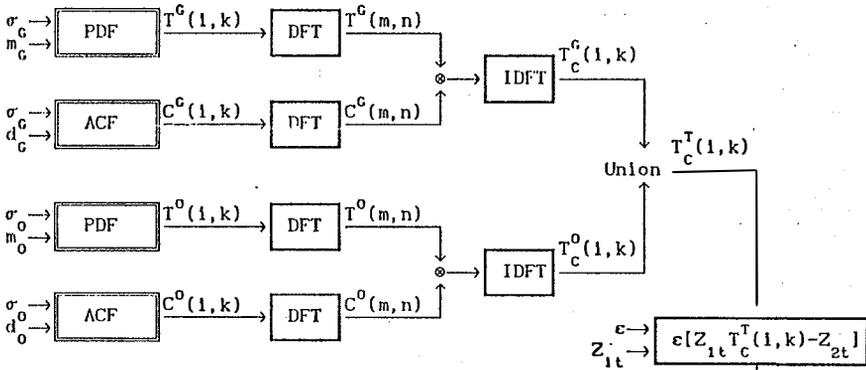
Atmosphere
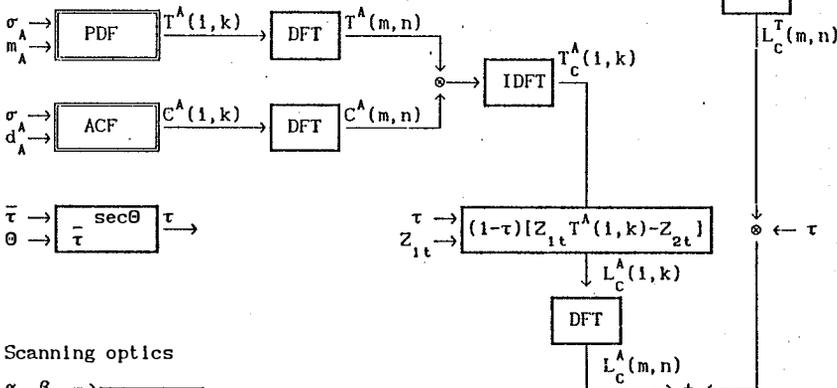
Scanning optics
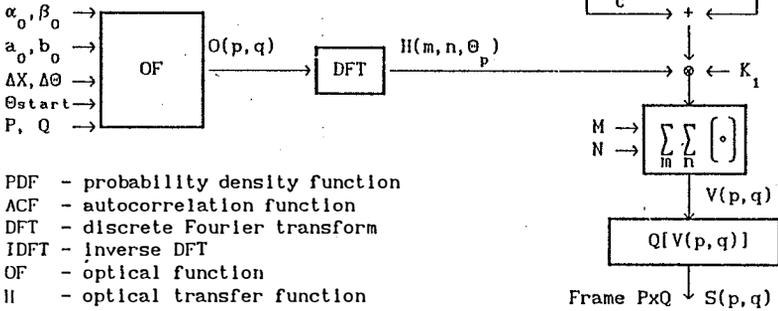
PDF - probability density function
ACF - autocorrelation function
DFT - discrete Fourier transform
IDFT - inverse DFT
OF - optical function
H - optical transfer function

Fig. 1. - Computer simulation procedures for generating an infrared thermal image.

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Scan direction →
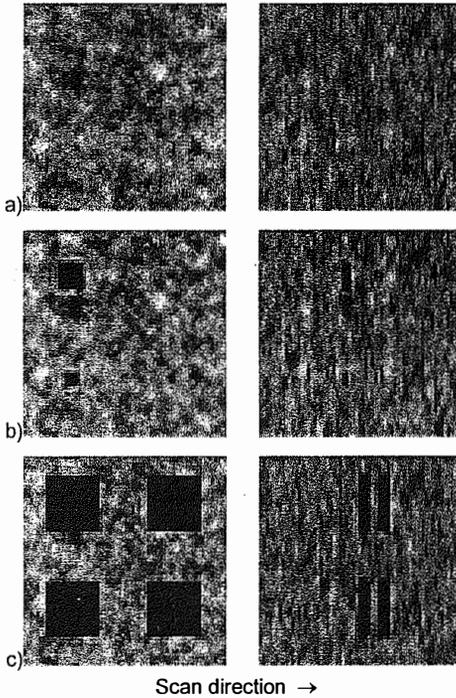
Fig.2. - Representative frames of computer-generated thermal images of three types terrain scanned in the angle ranges 0° <Θ<5.5° and 55° <Θ<60.5°: a) The terrain background; b) The four unequally sized (16mx16m, 8mx8m, 4mx4m and 2mx2m) and c) the four equally sized (16mx16m) hot plates on the background (black is hot).
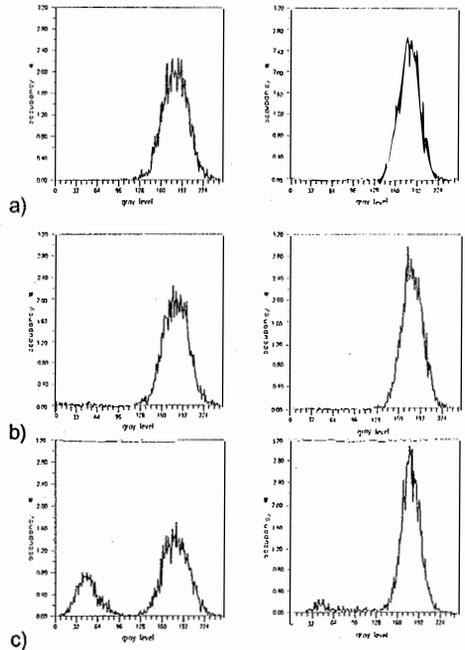
Fig.3. - Histograms of representative computer-generated thermal frames shown in: a) figure 2a; b) figure 2b and c) figure 2c.
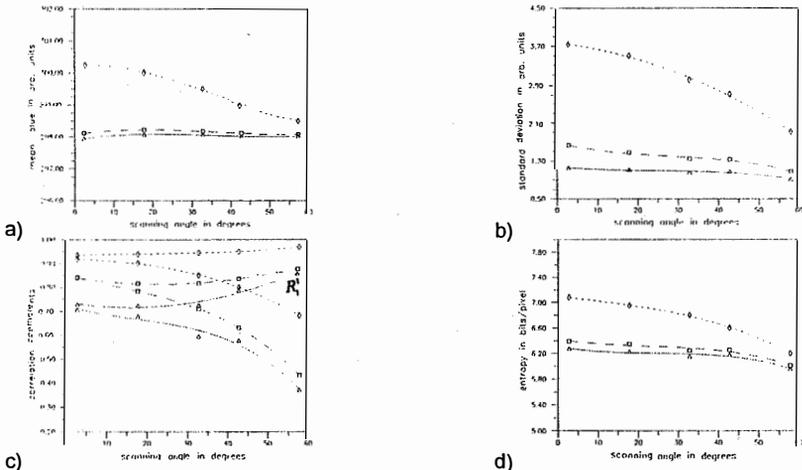
Fig.4.- The variation of statistical parameters of selected computer-generated thermal frames of three types terrain shown in figure 2 (— figure 2a, ---- figure 2b, ... figure 2c) as a function of scanning angle: a) mean value, b) standard deviation, c) autocorrelation coefficients (R_1^1 in flight direction and R_2^1 in scan direction and d) entropy.

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