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Spatial Frequency Pseudocolor Filters

The pseudocolored image, using attenuated cumulative filters, gives good image quality and color saturation.

Abstract: *In this paper, pseudocolor encoding of the spatial frequency information of black-and-white transparencies is performed through color filters and sequential spatial filtering. The influence of different types of spatial filters with respect to the resulting color saturation and image quality in partially coherent light is investigated and applied for identification purposes in aerial photographs.*

Introduction

Different methods of image analysis based on optical techniques have been used for years. Among them Fourier Transformation by optical lenses has received significant impetus in a large number of fields. Using this technique, land-use classification has been tested with reasonable success through power spectrum measurements.[1–4] Commercial measuring systems of power spectra are now available[5] and have been applied to a variety of tasks such as diagnosis of lung disease from chest radiographs[6] and cloud typing from aerial photographs.[7,8] The introduction of different kinds of filters in the Fourier plane can be employed to suppress artifacts or to enhance the detectability of features.[9,10]

Pseudocoloring or color encoding of black-and-white images is now also well accepted as a means to enhance images or increase detectability by using the greater sensitivity of the human eye to color changes. The color encoding can be done as a function of the gray levels, the spatial frequency information, or a combination of both, and this by digital[11,12] or optical methods.[13–21] For the special case of textured images, pseudocolor methods of spatial frequency information are more appropriate because of the recognized connection between the texture and the spatial frequency content of a given image segment.[22] A simple optical method of pseudocoloring of spatial frequency information based on the introduction of color filters in the Fourier plane of a spatial filtering setup has been recently proposed.[18] This method has been adapted for texture identification[23] and, combined with a digital system,[24] has been applied to identify distinct cloud types from satellite photographs. In this case, the optical pseudocolor encoding provides a quick preprocessing that otherwise would be cumbersome and slow to be done digitally. A different pseudocolor method of spatial frequency information has been proposed[19] based on rainbow holographic recording in connection with spatial filtering and then reconstruction with a white light source. Another alternative method[20] allows for interaction of spectrum of the object in contact with a Ronchi grid, with distinct bandpass filters on different diffraction orders, and then uses color filters in the demodulation set-up.

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The last two methods require two steps for the pseudocolor encoding as well as more complex systems without clear advantages from the point of view of practical results. However, in all reported methods a loss of image quality is observed, due in part to the spatial filtering process.

This paper addresses the improvement of the quality of the encoded image. With this purpose, amplitude spatial filters for the different spatial spectral bands are used in a sequential way in order to increase the flexibility and capability of the pseudocoloring method. Diverse shapes of spatial filters are considered and applied to aerial photographs. The introduction of colors for different tree species or features is expected to improve the photo interpretation by a human observer or a second image device, so enabling more objective methods for analysis and inventory at regular time periods.

Optical Pseudocolor System and Spatial Frequency Filters

The basic processing system previously used for pseudocolor encoding of the spatial frequency content of images is a conventional white light filtering system, where spatial color filters of the shape described in Figure 1 are introduced in the Fourier plane . When the object is illuminated with spatially coherent white light, all monochromatic spatial spectra spread over the Fourier plane but the filter only allows low spatial frequencies of blue wavelengths, intermediate spatial frequencies of green wavelengths, and high spatial frequencies of red wavelengths to pass. In this way the image is formed by incoherent addition of these three spectral bands so that every detail of the object will get a color that will depend upon its spatial frequency content. However, spurious effects appear in the image due to the noncoherent addition of the three spatial frequency regions, and mainly due to the fact that the central blue filter is opaque for the green and red wavelengths, so behaving as a central obscuration for the intermediate (green) and high (red) spatial frequencies. This central filter blocks out the zero order component, or d.c. term, of the green and red spatial spectra, and after squaring to get the intensity in the detection step, the intermediate and high frequency components appear with doubled spatial frequency.[25] In fact, if $i(x)$ is the amplitude transmittance of a sinusoidal object of frequency ν,

$$i\ (x) = 1 + \cos 2\pi\nu x = 1 + ½\ e^{i2\pi\nu}x + ½\ e^{-i2\pi\nu x}$$

and the d.c. term is eliminated, the image intensity becomes

$$I(x) = /\cos 2\pi\nu x/^2 = ½ + ½ \cos 2\pi\ 2\nu x$$

which is a grating of frequency 2 ν.

Although these effects may not be important in many applications in which only a mapping of frequencies to color is desired, they can be disturbing in certain applications in which a good pseudocolored image quality is still needed. The false effects, although essentially due to the structure of the spatial filter, would be very difficult to remove using the same filtering system; otherwise, a very complicated spatial filter would be required. For this reason, a modified version of the pseudocoloring scheme is introduced here and described in Figure 2. Pseudocolored images are now obtained by sequential exposures: in each exposure a specific spatial frequency band is selected by an appropriate amplitude filter and encoded to color by a color filter. Different amplitude filters associated to color filters will encode through sequential exposures the spatial frequency information to color. This modified system enlarges the flexibility of the method not only to allow more appropriate design of the spatial filters but also for an easy change of the encoded colors. On the other hand, the construction of the spatial filters is highly simplified because they are now restricted to neutral density filters. Four filter configurations, each composed of three successive amplitude filters associated with three corresponding color filters, are described in Figure 3.

Separate Frequency Bands Filtering

This operation is performed by the three filters represented in Figure 3a for the one-dimensional case. They are essentially a lowpass filter, a bandpass filter, and a highpass filter, respectively. The selection of separate bands of spatial frequencies by these filters is expected to produce the same effects described for the previous method by the filter of Figure 1, with the advantage that relative exposures among the selected bands are not fixed and can be easily changed.

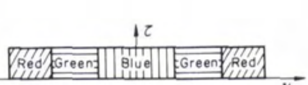


FIG. 1. Color spatial filter for pseudocolor encoding of spatial frequency information.

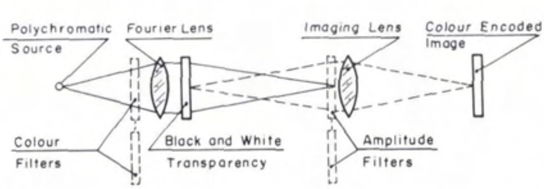


FIG. 2. White light optical set-up for sequential pseudocolor encoding.

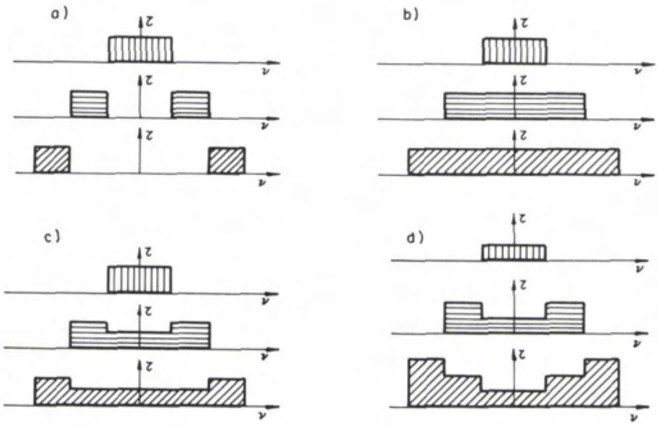


FIG. 3. One-dimensional filter transmittances for sequential pseudocoloring: (a) Separate frequency bands filters; (b) Cumulative frequency bands filters; (c) Attenuated cumulative frequency bands filters; (d) Attenuated cumulative frequency bands filter.

CUMULATIVE FREQUENCY BANDS FILTERING

Figure 3b shows these cumulative bands filters, which have the shape of three lowpass filters with different cut-off frequencies. In this case, high frequencies are mapped to the color of the third color filter, intermediate frequencies to the color obtained with the second plus the third color filter, and low frequencies to the color obtained with the three color filters. Because the zero order frequency and low frequencies are here also transferred in the color coding of high frequencies, a mapping of spatial frequencies to color without change of frequency values is expected. However, the addition of colors for the low and intermediate frequencies can result in a decreasing saturation of color in these ranges.

ATTENUATED CUMULATIVE FREQUENCY BANDS FILTERING

In order to avoid false imaging effects and to obtain good saturation of images, the spatial filters depicted in Figure 3c are proposed. They are an intermediate case of filters 3a and 3b; in the encoding for the intermediate frequency range, the zero order frequency and low frequencies are attenuated as much as possible without introducing contrast reversal effects, and for the high frequency range all lower frequencies are also attenuated. The attenuation values will obviously depend on the contrast of the original image, and it can be determined by simple visual inspection. Finally, the filters of Figure 3d are similar to those of Figure 3c, but with different attenuations for the low and intermediate frequency ranges and with the additional advantage that only one filter is needed (Figure 3d, bottom), the two others being derived from that by reducing the aperture.

APPLICATION TO AERIAL PHOTOGRAPHS

EXPERIMENTAL SET-UP AND FILTERS

The experimental set-up for pseudocolor encoding (Figure 2) is a white light filtering system where a Xenon arc lamp has been used because of its high luminance and color rendering. The amplitude filters have been constructed by photographic techniques and are sequentially introduced in the Fourier plane, associated with the corresponding color filters. Figure 4 shows two sets of filters for encoding through selection of frequency bands, for two bands instead of three as was represented in Figure 3a. The cut-off spatial frequency for the lowpass filter of the first set (Figure 4a) corresponds to 3 cycles/mm and the lowest frequency for the highpass one of the same set to 4.5 cycles/mm ($\lambda = 0.55\ \mu m$). Filters of the following figures are represented at the same frequency scale. Figure 5 shows the actual filters for encoding by cumulative frequency bands filtering. Figure 6 shows two sets of filters for the attenuation case (type of Figure 3c) in which the edges have been smoothed to decrease diffraction effects, and Figure 7 corresponds to the case represented in Figure 3d, whose transmittance increasing from the center, enables pseudocolor encoding through successive exposures without change of spatial filter. This is particularly interesting to avoid possible decenterings in the position of the spatial filters. The sizes of the filters have been adjusted in accordance with the selected frequency bands for pseudocolor, and different transmittances have been obtained for the attenuated filters.

Filters of Figure 8 have also been used to get color encoded images, but because both filters attenuate low frequencies, the high ones will be

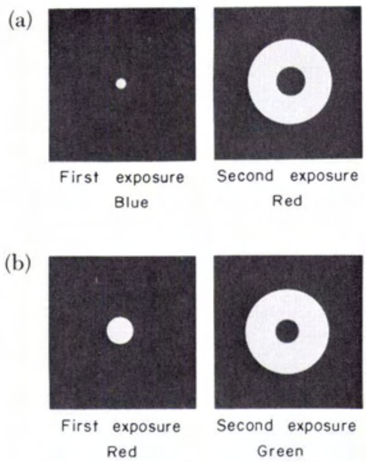


FIG. 4. Two sets of filters for pseudocolor encoding through selection of frequency bands.

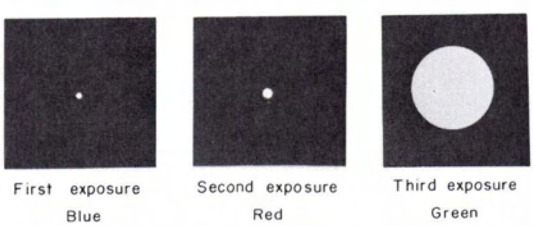


FIG. 5. Set of filters for encoding by cumulative frequency bands filtering.

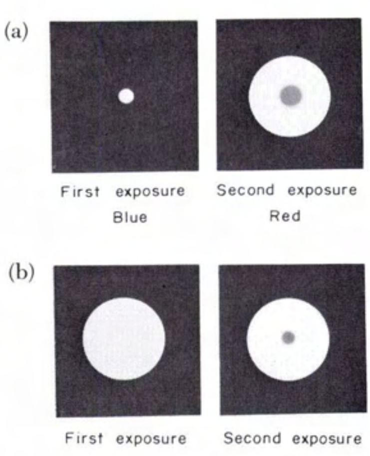


FIG. 6. Two sets of filters for encoding by attenuated cumulative frequency bands filtering.

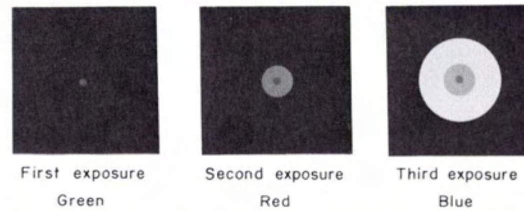


FIG. 7. Filter for attenuated cumulative frequency bands filtering. Different spatial bands are selected from the filter on the right by an iris diaphragm.

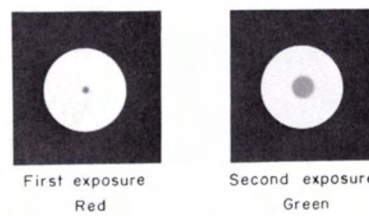


FIG. 8. Attenuated cumulative frequency bands filters. In both filters low frequencies are attenuated.

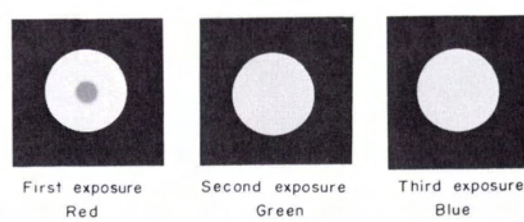


FIG. 9. Filters for encoding by attenuated cumulative frequency bands filtering.

emphasized. Finally, Figure 9 shows another case of attenuated cumulative filters used in a second image test.

RESULTS

We have applied the referred pseudocolor filters to several aerial scenes and will present here some color results for two of these scenes. The images have been selected with respect to two possible applications: land-use classification and tree species identification. The first test image (Figure 10) is an aerial image of a village, Almazán (Spain), at 1:15,000 scale with a few major regions (forest area, pasture and agricultural areas, rural area, and linear features). The second image (Figure 11) is an aerial image at 1:10,000 scale, where two main

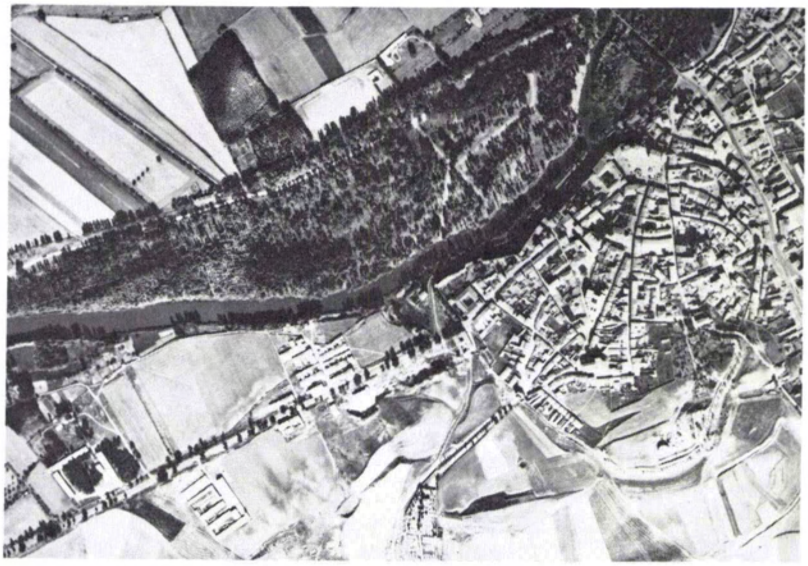


FIG. 10. Aerial image as input for pseudocoloring.

tree species, "Eucaliptus globulus" and "Pinus pinea," can be observed. The spectrum of both images has been studied by placing successive apertures in the Fourier plane, in order to know the spectral components of the different features.

Plates 1 and 2 show some color encoded images obtained with the described system and filters. The image of Plate 1a has been registered through the filters of Figure 4a. Pasture and agricultural areas are encoded in blue, and forest and rural areas in red. Plate 1b has also been obtained with two separate frequency filters, in this case those of Figure 4b. In both encoded pictures the loss of image quality is manifest in the small details, although good color saturation is achieved. Plate 1c shows the results obtained with the set of three spatial filters of cumulative frequency bands represented in Figure 5. Low frequencies are here not colored while high frequencies are most encoded to green and intermediate frequencies to purple. Although the image quality in this case is improved, pseudocolor for frequency bands is also depending on the gray levels. Plates 1d and 2a show the images obtained with attenuated cumulative frequency band filters of Figures 6a and 6b, respectively. The resolution of both pseudocolored images is highly improved with respect to the images of Plates 1a and 1b, and the

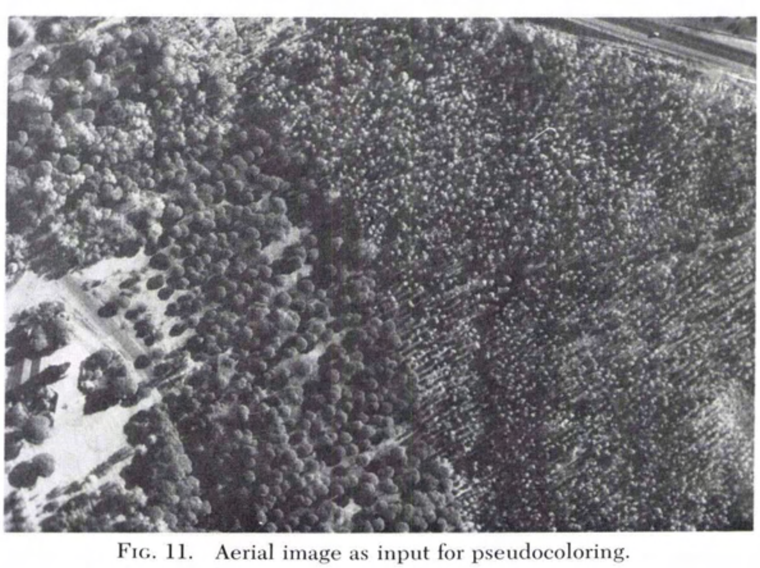
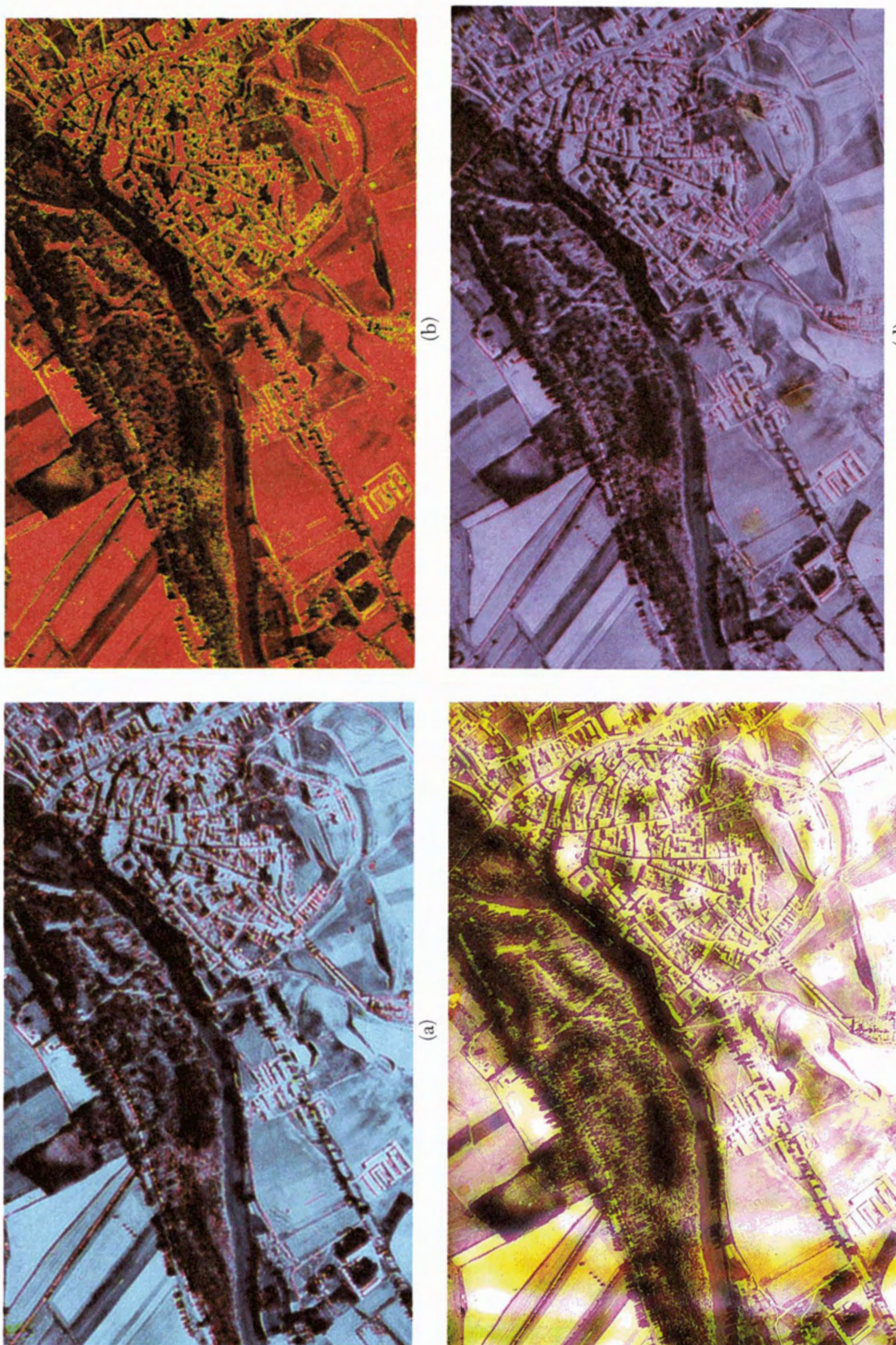


FIG. 11. Aerial image as input for pseudocoloring.



(a) (b) (c) (d)

PLATE 1. Pseudocolored images of Figure 10: (a) with the filters of Figure 4a; (b) with the filters of Figure 4b; (c) with the filters of Figure 5; (d) with the filters of Figure 6a.

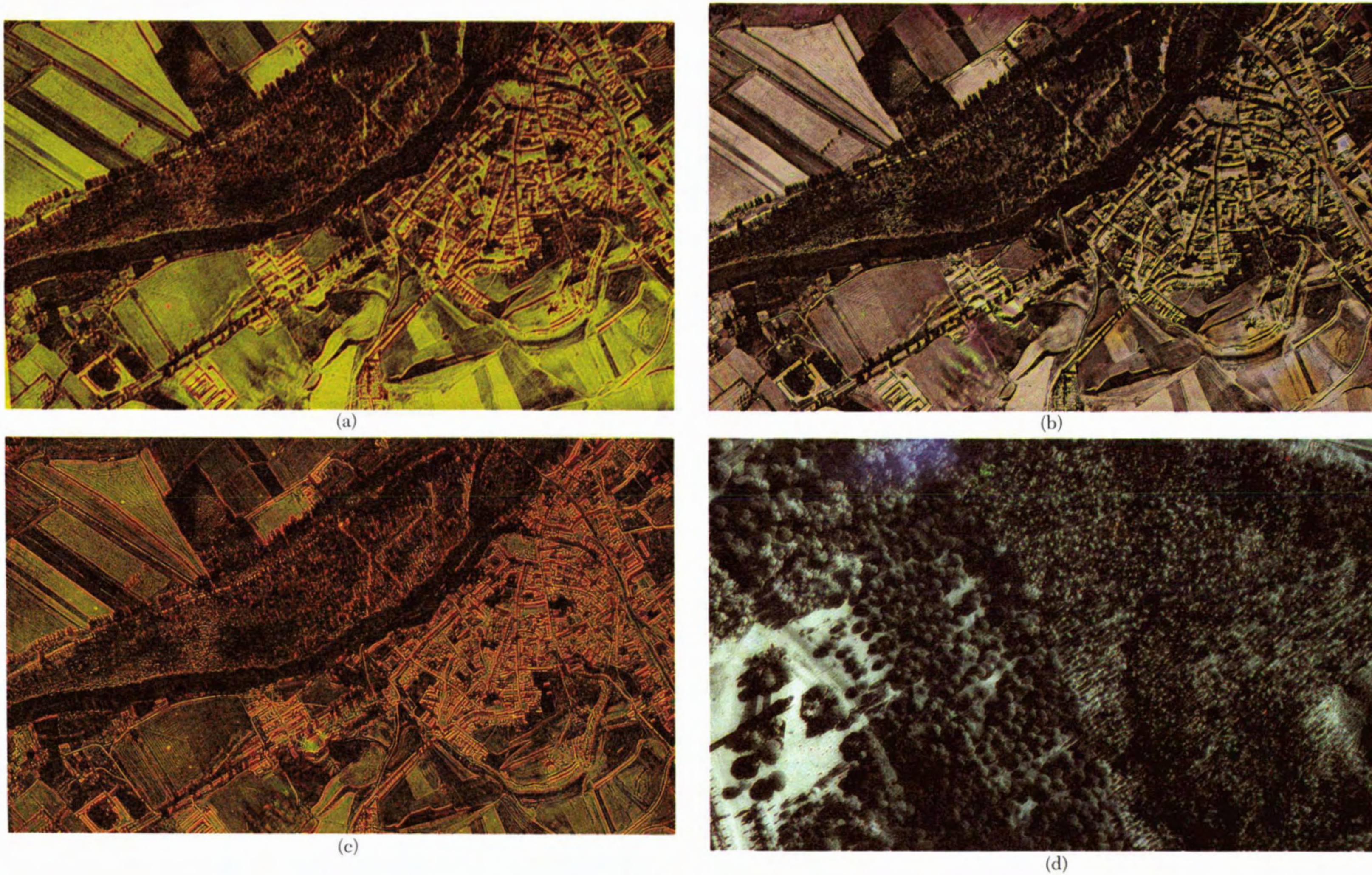


PLATE 2. Pseudocolored images of Figures 10 and 11: (a) with the filters of Figure 6b; (b) with the filters of Figure 7; (c) with the filters of Figure 8; (d) with the filters of Figure 9.

mapping of frequency bands to different colors is also kept. The saturation of some colors decreases as they are now obtained from addition of colors; however, the difference of color for the forest and agricultural areas is large enough to be distinguished by any further color based processing system or human observer. Plate 2b shows the image obtained through the filter of Figure 7, which does not need to be replaced for successive exposures. Plate 2c has been made with the two attenuated cumulative filters of Figure 8. In the pseudocolor encoded image high frequencies are emphasized because in this case both spatial filters attenuate low frequencies. Finally, Plate 2d shows the pseudocolor encoded image for the picture of Figure 11 through the attenuated cumulative filters of Figure 9, and where "Eucaliptus globulus" are encoded in yellow and "pinus Pinea" in cyan.

Conclusions

A new system for optical pseudocolor encoding of spatial frequency information in black-and-white transparencies is presented. Color encoded images are obtained by applying sequential amplitude filtering through color filters in a white light processing system. From the high flexibility of the method, diverse types of amplitude spatial filters have been designed and applied to distinguish features in aerial photographs. Separate frequency band filters provide good color saturation in the encoded images, but the image quality is deteriorated by the filtering. Cumulative filters give better image quality, but the color saturation in the image for some spatial bands and the general mapping are poor. The pseudocolored image using attenuated cumulative filters still gives good image quality and better color saturation.

The application of the method to aerial photographs shows that tree species or land uses with different power spectra can be encoded in color to enhance their detectability for a human observer. On the other hand, the system provides a quick preprocessing, preserving the image quality, and is suitable to further processing systems for other analysis or inventory purposes.

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