Restoration of Old Film Sequences*

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Abstract

Image flicker, undesirable fluctuations in image intensity not originating from the original scene, is a common artifact in old film sequences. After describing possible causes for image flicker this paper models the effects of flicker as local phenomena. Unfortunately estimation of the model parameters from the degraded sequence is hampered due to presence of noise, dirt and motion. In the latter case the model parameters can not be estimated directly from local data and are interpolated using the found model parameters of regions nearby. Once the model parameters have been estimated the film sequence can be corrected, taking care that no blocking artifacts occur. The application of this technique in combination with other restoration techniques is discussed.

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1. Introduction

Unique records of historic, artistic and cultural developments of every aspect of the 20th century are stored in huge stocks of moving picture archive material. Many of these historically significant items are in a fragile state and are in desperate need of restoration. However, the high cost and lengthy processing time required to restore archive material limit the preservation of these records on a large scale.

The aim of the AURORA project (*AUtomated Restoration of ORiginal film and video Archives*) is the development of technology that significantly reduces the cost and processing time of the restoration processes. Areas of interest within AURORA include *Noise Reduction* [1], *Blotch Detection* and *Removal* [2], *Scratch Removal* [3], *Film Unsteadiness Correction* [4], *Flicker Reduction*, *Line Registration Correction* [5] and *Color Correction*. There are several reasons why the artifacts covered by these areas are to be addressed.

The first being the explosive growth in number of broadcasters for television, in the near future the home viewer will be able to choose from a hundred or more channels and all of them require programming. The costs for creating new, high quality programs are tremendous. Recycling old programs form a good alternative, if the image (and audio) quality expectations of the modern viewer are met. The second reason for image restoration is that preservation implies storage. The presence of artifacts, and noise in particular, causes compression algorithms to dedicate many bits to irrelevant information. After processing, image sequences of higher quality can be stored using less bits.

In this paper we concentrate on the reduction of flicker artifacts. Image flicker is a common artifact in old film sequences. It is defined as unnatural temporal fluctuations in perceived image intensity (globally or locally) not originating from the original scene. Image flicker can have a great number of causes, e.g. aging of film, dust, chemical processing, copying and aliasing (e.g. when transferring film to VCR using a twin lens telecine). To our knowledge very little research has been done on this topic. Neither equalizing the intensity histograms nor equalizing the mean frame values of consecutive frames, as suggested in [6], form general solutions to the problem.

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These methods do not take changes of scene contents into account and they do not appreciate the fact that flicker can be a spatially localized effect.

2. A Model For Image Flicker

Due to the lack of detailed knowledge on how the various mechanisms mentioned above cause image flicker, it is difficult to come to models for image flicker based on these mechanisms. Even if these models are known there still is the problem of selecting one of those models for correcting the film sequence. Often only the degraded sequence is available, it is not known what mechanism caused the image flicker. What can be said about flicker is that in any case it causes unnatural changes in image intensity (locally and/or globally) in time.

Our approach models image flicker as a local effect independent of the scene contents. We want to limit fluctuations in image intensity in time by locally preserving the intensity mean and the intensity variance. The following model is assumed:

$$Y(x,y,t) = \alpha(t)\big(I(x,y,t) + \gamma(x,y,t)\big) + \beta(t) + \eta(x,y,t) \quad \begin{cases} \alpha(t) = constant \\ \beta(t) = constant \end{cases} \text{for } \; x,y \in \Omega \qquad \text{(I)}$$

where *Y(x,y,t)* and *I(x,y,t)* indicate the observed and real image intensities respectively, *α(t)* and *β(t)* are flicker gain and offset parameters and *Ω* indicates a small image region and makes that the flicker is modeled as a local effect. In the ideal case (no fading, no flicker) *α(t) = 1* and *β(t)* = 0.

Both flicker dependent noise *γ(x,y,t)* and flicker independent noise *η(x,y,t)* add to the overall amount of noise, which can be estimated, for example, as in [7]. An example of flicker dependent noise is granular noise already on the film before flicker is introduced. Flicker independent noise can be thermal noise due to electronic processing.

3. Estimation Of Flicker Parameters

Flicker correction requires estimation of the flicker parameters *α(t)* and *β(t)*. The estimates resulting from the initial approach (section 3.1) are optimal for stationary scenes. The estimation of image statistics in non-stationary scenes are usually influenced by the presence of motion. To avoid this one would like to apply some form of motion compensation.Unfortunately the presence of flicker hampers motion estimation as motion estimators usually have a *constant luminance* constraint, i.e. pel-recursive methods and all motion estimators that make use of block matching in one stage or another. For this reason we choose to merely detect the presence of motion (section 3.2). For regions in which motion was detected the flicker parameters are then interpolated using the flicker parameters of nearby regions not containing motion (section 3.3).

3.1. Flicker parameter estimation in the motion free case

For the moment a stationary scene is assumed, let *I(x,y,t) = I(x,y)*. It is also assumed that the distribution of *γ(x,y,t)* does not change in time. This is acceptable under the assumption that the physical quality of the film is constant and, as mentioned before, the scene is stationary. Taking the expected value and the variance of *Y(x,y,t)* in (I), in a spatial sense, gives for $x,y \in \Omega$:

$$E\big(Y(x,y,t)\big) = \alpha(t)E\big(I(x,y) + \gamma(x,y,t)\big) + \beta(t) + E\big(\eta(x,y,t)\big) \qquad \text{(II)}$$

$$\operatorname{var}(Y(x,y,t)) = \operatorname{var}\big(\alpha(t)(I(x,y)+\gamma(x,y,t)) + \beta(t) + \eta(x,y,t)\big)$$
$$= \alpha^2(t)\operatorname{var}(I(x,y)+\gamma(x,y,t)+\eta(x,y,t)) + \left(1-\alpha^2(t)\right)\operatorname{var}(\eta(x,y,t)) \quad \text{(III)}$$

When assuming zero mean noise, rewriting these equations give α(t) and β(t) for $x, y \in \Omega$:

$$\beta(t) = E(Y(x,y,t)) - \alpha(t)E(I(x,y)) \quad \text{(IV)}$$

$$\alpha(t) = \sqrt{\frac{\operatorname{var}(Y(x,y,t)) - \left(1-\alpha^2(t)\right)\operatorname{var}(\eta(x,y,t))}{\operatorname{var}(I(x,y)+\gamma(x,y,t)+\eta(x,y,t))}} \quad \text{(V)}$$

Following [8] it can be shown that these estimates for *α(t)* and *β(t)* are optimal in the sense that they result in the linear minimal mean squared error between real image intensity and the estimated image intensity. If the variance of the flicker-independent noise is small compared to variance of the observed signal and/or $\alpha(t) \approx 1$, (V) can be approximated by:

$$\alpha(\mathrm{t}) \approx \sqrt{\frac{\operatorname{var}(Y(x,y,t))}{\operatorname{var}(I(x,y)+\gamma(x,y,t)+\eta(x,y,t))}} \quad \text{(VI)}$$

In order to solve (IV) and (VI) in a practical situation estimates in a temporal sense of expected means and variances at frame *t* can be used:

$$E(I(x,y))_t = E_T(E(I(x,y))) = E_T\left(\frac{E(Y(x,y,t))-\beta(t)}{\alpha(t)}\right)$$
$$\approx \frac{1}{N-1}\sum_{n=t-N}^{t-1}\frac{E(Y(x,y,n))-\beta(n)}{\alpha(n)} \quad \text{(VII)}$$

$$\operatorname{var}(I(x,y)+\gamma(x,y,t)+\eta(x,y,t)) = \mathrm{E_T}\left(\operatorname{var}(I(x,y)+\gamma(x,y,t)+\eta(x,y,t))\right)$$
$$= \mathrm{E_T}\left(\frac{\operatorname{var}(Y(x,y,t))}{\alpha^2(\mathrm{t})}\right) \approx \frac{1}{N-1}\sum_{n=t-N}^{t-1}\frac{\operatorname{var}(Y(x,y,n))}{\alpha^2(\mathrm{n})} \quad \text{(VIII)}$$

To reduce memory requirements and computational load, first order *IIR* filters are used instead of (VII) and (VIII) in a practical situation:

$$E(I(x,y))_t = \kappa E(I(x,y))_{t-2} + (1-\kappa)\frac{E(Y(x,y,t-1))-\beta(t-1)}{\alpha(t-1)} \quad \text{(IX)}$$

$$\mathrm{var}\big(I(x,y)+\gamma(x,y,t)+\eta(x,y,t)\big)=\kappa\,\mathrm{var}\big(I(x,y)+\gamma(x,y,t-2)+\eta(x,y,t-2)\big)+ (1-\kappa)\frac{\mathrm{var}\big(Y(x,y,t-1)\big)}{\alpha^2(\mathrm{t}-1)} \quad \text{(X)}$$

where κ signifies the importance of the previous estimate. Depending on the value for κ this method allows the estimates of the original image mean and variance to be adapted to changes in scene lighting (e.g. during a fade or when a light is switched on). Low frequency image flicker is not removed in that case.

3.2. Motion detection in image sequences containing flicker

A number of motion detection mechanisms that can be applied to image sequences containing image flicker are described in this section. As these mechanisms rely on detecting changes in image statistics not only motion but also dirt, drop outs and scene changes trigger the motion detectors. Where motion is detected the recursive filters for estimating the mean and variance have to be reset.

3.2.1. Motion detection using the flicker parameters

Motion causes local changes in temporal statistics: significant changes in intensity variance and/or mean result in a large deviations from 1.0 for $\alpha(t)$ and/or from 0 for $\beta(t)/\alpha(t)$, respectively. Regions containing motion can be detected by comparing all $\alpha(t)$ and $\beta(t)/\alpha(t)$ to threshold values $1\pm T_\alpha$ and $\pm T_\beta$. Motion is flagged when either flicker parameter surpasses its threshold value (typical values for T_α and T_β are 0.3 and 20 respectively).

3.2.2. Motion detection using frame differences

A different method for detecting the presence of motion is the following. For each block in the current frame $\alpha(t)$ and $\beta(t)$ are estimated using (IV) and (VI). The corrected frame is generated using (XI) (see section 4). In the absence of motion the variance of local frame differences between the corrected frame and the previous frame should be twice the total noise variance. Where this is not the case motion is detected.

3.2.3. A hybrid motion detection system

The method in section 3.2.2. has the disadvantage that it is very sensitive to film unsteadiness. Slight movements of textured areas may lead to large frame differences and thus to “false” detection of motion. The method in section 3.2.1 is robust against film unsteadiness. The drawback in comparing the flicker parameters $\alpha(t)$ and $\beta(t)/\alpha(t)$ to threshold values is that it is difficult to find good threshold values: false alarms and misses will always occur.

Combining the two methods leads to a robust algorithm. First, the motion detection algorithm from section 3.2.1. is applied where T_α and T_β are chosen relatively small leading to relatively many false alarms and few misses. Second, the algorithm from section 3.2.2 is applied to those regions for which motion was detected: the correctness of the found flicker parameters is verified.

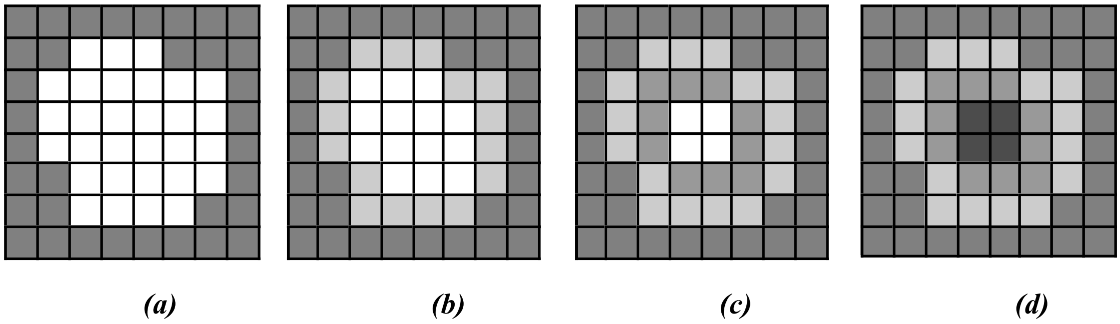

Figure 1. (a) gray indicates known parameter values, white indicates the unknown values. (b), (c) and (d) indicate what parameters have been estimated after 1, 2 and 3 steps of the dilation operation.

3.3. Interpolation of unreliable flicker parameters

Where motion is detected the flicker parameters $\alpha(t)$ and $\beta(t)$ computed according to (IV) and (VI) are unreliable. They are to be interpolated using the flicker parameters found in nearby regions. This approach leans on the assumption that the flicker parameters vary slowly (are correlated) in a spatial sense, and, as stated before, are independent of image contents.

One pitfall is to be avoided. For uniform regions corrupted by image flicker it is difficult to tell what part of the image flicker is due to variances in gain and what part is due to variances in offset. These regions should not be included in the interpolation process. Moreover, from section 4 it will become clear that that the estimated flicker parameters for these regions should be marked unreliable. In the case of the restoration of old film sequences no problems are to be expected as granular noise is always present (we implicitly assume that granular noise is affected by flicker in a similar manner as the original scene intensities).

The iterative interpolation process is as follows. Consider the matrix containing the values of all $\alpha(t)$ for a certain image. Figure 1a shows an example of such a matrix. The gray area indicates the image blocks for which $\alpha(t)$ are known, the white area indicates the image blocks in which motion was detected. For blocks in the latter region the values $\alpha(t)$ can be estimated at the boundary of the two regions, by taking the average value of the $\alpha(t)$ in adjacent blocks in the still region (fig. 1b). By repeating this dilation process an estimate for $\alpha(t)$ can be assigned to each image block in regions where motion was detected (fig. 1c,d). The procedure for estimating the unknown $\beta(t)$ is similar.

This method is not optimal in the sense that jumps might occur between the values for $\alpha(t)$ and $\beta(t)$ in adjacent image blocks near the center of the dilated region (e.g. when the values in the top-left hand side of the still region are very different from the values in the bottom right hand side). This can be resolved by smoothing the found results using, for instance, a Laplacian kernel (see section 4).

As the region containing motion becomes larger, more steps are required for the dilation process. This implies more uncertainty about the correctness of the interpolated values. Applying biases towards unity for $\alpha(t)$ and to zero for $\beta(t)$ that grow with each step reduces the probability that flicker is enhanced due to incorrect estimation of the flicker parameters.

4. Correcting Image Flicker

Once the flicker parameters have been estimated the sequence can be corrected. But first an extra step is required. As the flicker parameters are computed on a block by block basis, blocking artifacts will be introduced if the found flicker parameters are applied for correction without preprocessing. This preprocessing consists of upsampling the matrices containing the flicker parameters to full image resolution followed by smoothing using a low-pass filter. As mentioned before, when sources other than film are used the contribution to changes in gain and offset to the flicker can not be determined for uniform regions using (IV) and (VI). It is necessary that the flicker parameters in the uniform regions are estimated using the interpolation scheme in section 3.3. If not, smoothing would have the unreliable flicker parameters of these regions influence the reliable flicker parameters of neighboring regions.

Now the new flicker free image can be estimated according to:

$$\hat{I}(x,y,t) = \frac{Y(x,y,t) - \beta(x,y,t)}{\alpha(x,y,t)} \tag{XI}$$

5. Experiments And Results

In our experiments we used a test sequence of 50 frames containing image flicker and motion (introduced by a man entering the scene through a tunnel). When viewing this sequence it can clearly be seen that the amount of flicker varies locally. Also the presence of granular noise is clearly visible. The signal to noise ratio was estimated to be 21 dB. Equalizing the mean field intensities did not lead to a reduction in image flicker.

Figure 2 shows clips of frames 13 and 15, which contain excessive amounts of flicker, before and after correction. Figure 3 shows the field means and variances of the original and the processed sequence. The smoother curves resulting from the processed sequence in figure 3 imply that the amount of image flicker has been reduced. Subjective evaluation confirms this. A (very) small amount of low frequency flicker remained, which can be explained by keeping the last paragraph of section 3.1 in mind. No blocking artifacts are visible and no blurring occurred. No new artifacts were visible.

6. Discussion

In practical situations the proposed scheme for flicker correction will be applied in combination with other restoration techniques as in many old films combinations of various artifacts are present simultaneously. Two common types of artifacts are noise and image unsteadiness. An example of the place of flicker correction in an automatic restoration system is shown in figure 4. Here the flicker parameters $\alpha(t)$ and $\beta(t)$ are estimated from a noise reduced, stabilized sequence. The simultaneous image flicker correction and image stabilization is applied to the original sequence. The output of this system forms the input for subsequent stages of the restoration system where noise, dirt and dropouts are removed making use of motion estimation and motion compensation.

(a) Clip of original frame 13

(b) Clip of original frame 15

(c) Clip of corrected frame 13

(d) Clip of corrected frame 15

Figure 2. Clips of original and corrected frames.

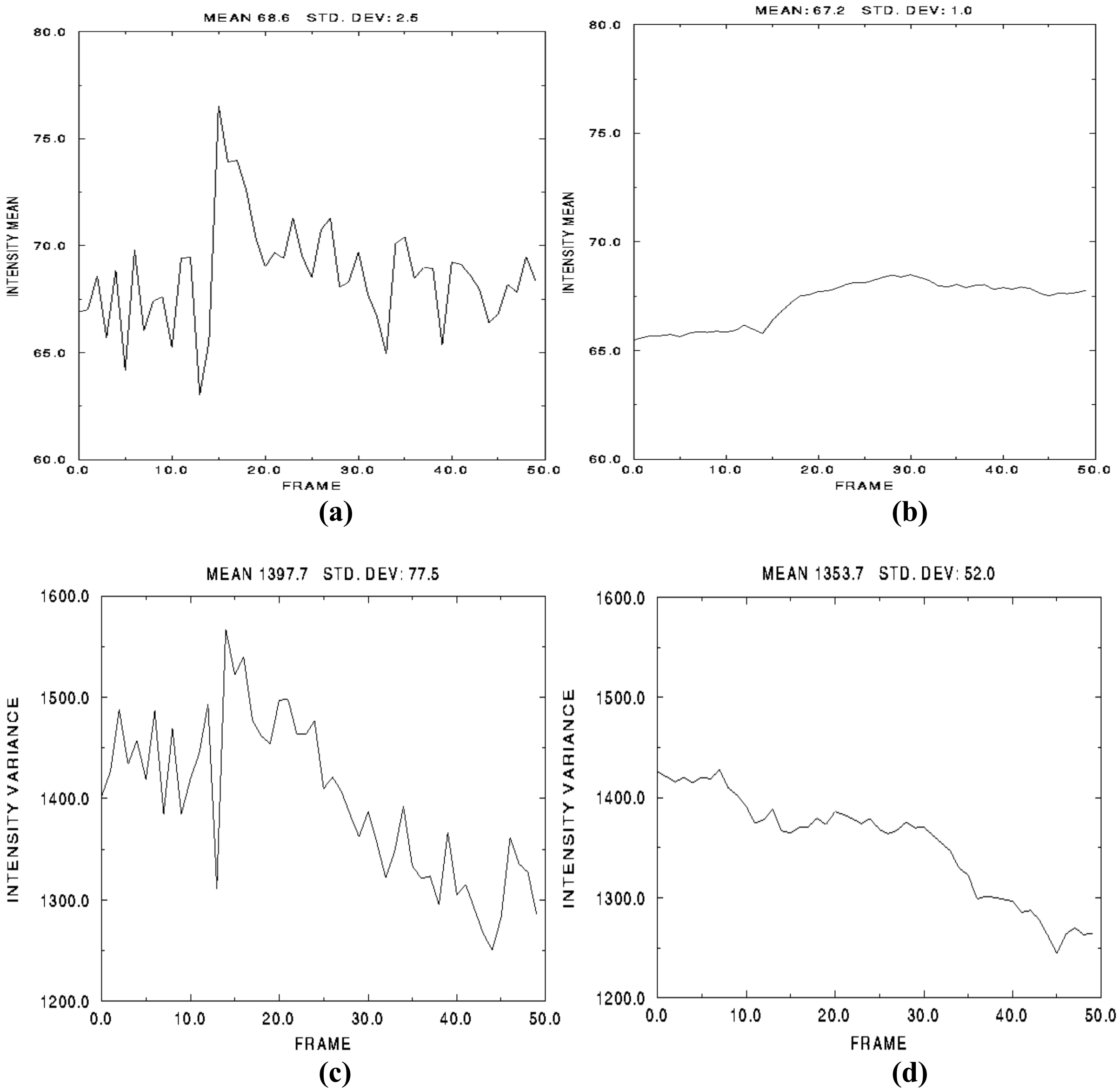

Figure 3. (a), (c) Mean frame intensities and variances of original sequence. (b), (d) Mean frame intensities and variances of corrected sequence.

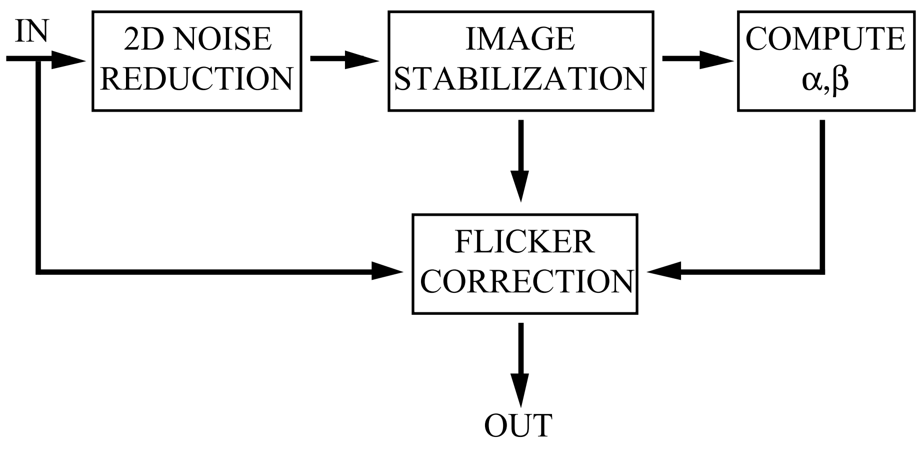

Figure 4. Flicker correction as part of an automatic image restoration system.

The flicker correction scheme can easily be extended to include camera panning, as the panning vectors can be estimated from the image stabilization vectors. Including camera zoom is more troublesome. A major problem is that the characteristics of observed texture changes depending on distance to the camera and on camera parameters such as aperture and focal point. It is difficult to adjust for these.

Including scene rotation (perpendicular to the camera) is possible. The first frame of a sequence is chosen as a reference, later frames are compensated for their rotation with respect to the reference frame. Flicker can then be corrected for and the result is rotated back again. Note that aliasing caused by correction for rotation may well influence the results. As the rotation angle becomes larger less of the frames corrected for rotation overlaps with the reference frame. It is then necessary to pick a new reference frame. This can be the current frame, with the disadvantage that the overall brightness of this frame may be noticeably different from the overall brightness of the corrected preceding frame. Another possibility is to choose the corrected preceding frame as a reference (in doing so the loop is closed and the system might become unstable).

Fortunately only old film sequences seldom contain zoom and rotation.

REFERENCES

1. P.M.B. van Roosmalen, S.J.P. Westen, R.L. Lagendijk and J. Biemond, "Noise Reduction for Image Sequences using an Oriented Pyramid Thresholding Technique", *Proceedings of ICIP-96*, Vol **I**, pp. 375-378, Lausanne Switzerland, IEEE 1996.
2. A.C. Kokaram, R.D. Morris, W.J. Fitzgerald and P.J.W. Rayner, "Interpolation of Missing Data in Image Image Sequences", *IEEE Transactions on Image Processing*, Vol.**4** no. 11, pp.1496-1508, 1995.
3. R.D. Morris, W.J. Fitzgerald and A.C. Kokaram, "A Sampling Based Approach to Line Scratch Removal from Motion Picture Frames", *Proceedings of ICIP-96*, vol. **I**, pp. 801-804, Lausanne Switzerland, IEEE 1996.
4. T. Vlachos and G. Thomas, "Motion Estimation for the Correction of Twin-Lens Telecine Flicker", *Proceedings of ICIP-96*, vol. **I**, pp. 109-111, Lausanne Switzerland, IEEE 1996.
5. A.C. Kokaram, P.M.B. van Roosmalen, P.J.W. Rayner and J. Biemond, "Line Registration of Jittered Video", submitted to ICASSP 97, Munich 1997.
6. P. Richardson and D. Suter, "Restoration of Historic Film for Digital Compression: A Case Study", *Proceedings of ICIP-95*, Vol **II**, pp. 49-52, Washington D.C. USA, IEEE 1995.
7. J.B. Martens, "Adaptive Contrast Enhancement through Residue-Image Processing", *Signal Processing* **44**, pp. 1-18, 1995.
8. K.S. Shanmugan and A.M. Breipohl, *"Random Signals",* pp. 529-534, J. Wiley & Sons, New York,1988.