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Spectral and spatial artifacts from the use of desktop scanners for remote sensing

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Abstract. Inexpensive desktop scanners are frequently used for the scanning of small format aerial photographic images. However, these scanners do not always conform to the spectral and spatial quality required for subsequent image analysis. This Letter outlines simple tests that can be conducted to characterize the properties of desktop scanners and illustrates the performance of a specific instrument. Spectral and spatial artifacts introduced by this scanner are outlined. It is important for image analysts to be aware of these scanner properties, and decide in each case whether the use of these instruments is warranted for quantitative applications.

1. Introduction

Advancement in consumer electronics products has led to widely available and relatively inexpensive desktop scanners. This proliferation of desktop scanners has resulted in the use of these instruments in remote sensing research as an inexpensive means of digitally converting aerial photography for analysis. Consumer products are the result of a series of design and engineering trade-offs. A device must perform to a standard while also meeting the demands of production cost. The majority of scanners are designed for desktop publishing without any information regarding their suitability in an analytical context (Glasbey *et al.* 1994).

Small and medium (35 to 70 mm) format aerial photography can supply valuable data for scientific and resource management purposes. For example, Gao and O'Leary (1997) conducted a study on estimation of suspended sediment concentrations from airborne remote sensing data and used a Hewlett-Packard ScanJet to scan their aerial photographs. Baker *et al.* (1995) used scanned aerial photographs to map ecotones.

Few studies have addressed the spectral and spatial properties of these scanners and the effects they have on scanned images used for image analysis. Glasbey *et al.* (1994) evaluated a HP ScanJet and issued a set of recommendations for quantitative use. Kölbl and Bach (1996) tested radiometric performance of scanners used in the printing industry and photogrammetry. They examined issues such as image resolution, noise, sensitivity of the scanner and visual appearance of the scanned images.

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The authors concluded that the scanners tested did not allow them to adequately reproduce the high image quality of modern aerial photographs.

This Letter reports the results of tests characterizing the performance and properties of a Polaroid SprintScan 35/LE, a slide scanner representative of the mid-cost ($1000 USD) 35-mm slide scanners. The tests were designed to provide a simple evaluation of scanners with respect to selected spectral and spatial properties.

2. Spectral properties

2.1. *Dark-current measurement*

Dark-current, also called the dark signal non-uniformity (DSNU), is a form of additive noise that represents the pixel-to-pixel variation in a CCD's voltage when the sensor is not illuminated (Gann 1998). The DSNU is important because it represents a measure of the base-level noise. The signal of the DSNU will be present in scanned images and can affect image quality (Jähne 1997). The DSNU is measured by analysing an image recorded with all sources of illumination removed from the CCD sensor.

The SprintScan 35/LE calibrates the CCD before each scan by imaging the light source without obstruction. This calibration establishes the upper limit of the intensity scale. The procedure used to generate a dark-current signal with this scanner was to calibrate the scanner to the light source, then remove the light source prior to the scan. If the light source is removed prior to the calibration, the non-illuminated light condition is treated as the highest intensity, preventing an accurate analysis of the dark-current. To ensure the scanner was not recording any stray light from inside the device all sources of illumination were removed from around and within the scanner, including monitors and onboard LED displays.

Figure 1 shows the resulting dark current for the SprintScan as recorded for the red band. Ideally, without the presence of light, all DN values should be 0—however, in this case, the DN range was 0 to 27. Therefore, roughly 10% of DN variations in an 8-bit image might be caused by dark current signal alone and are unrelated to variations in actual signal.

2.2. *Photo response non-uniformity*

Photo response non-uniformity (PRNU) is a form of random or systematic noise that is detected as the pixel-to-pixel variations in a CCD's array response to a light with fixed intensity (Gann 1998). We tested the scanner's PRNU by scanning Wratten filters #94 A (blue), #93 (green) and #92 (red). Pixel values were recorded along transects from the scanned filters (figure 2(*a*)). Densitometric measurements were taken using the same transects and were used to compare the pixel values with the measured optical counts (figure 2(*b*)). While the densitometry measurements yielded consistent results, the corresponding DNs on the scans had variations within tens of DNs; these variations are solely related to scanner properties rather than to actual signal.

Although difficult to isolate, the sources of error from the final image would include the dark-current and the procedure used to produce colour. A single CCD with a striped filter is the most commonly available colour scanning technology. It has the advantage of being able to produce colour images in a single pass. The main problem with this technology is that colour is generated using an algorithm that interpolates the gaps left by offset of the striped filter causing colour misalignment and interpolation errors (Gann 1998).

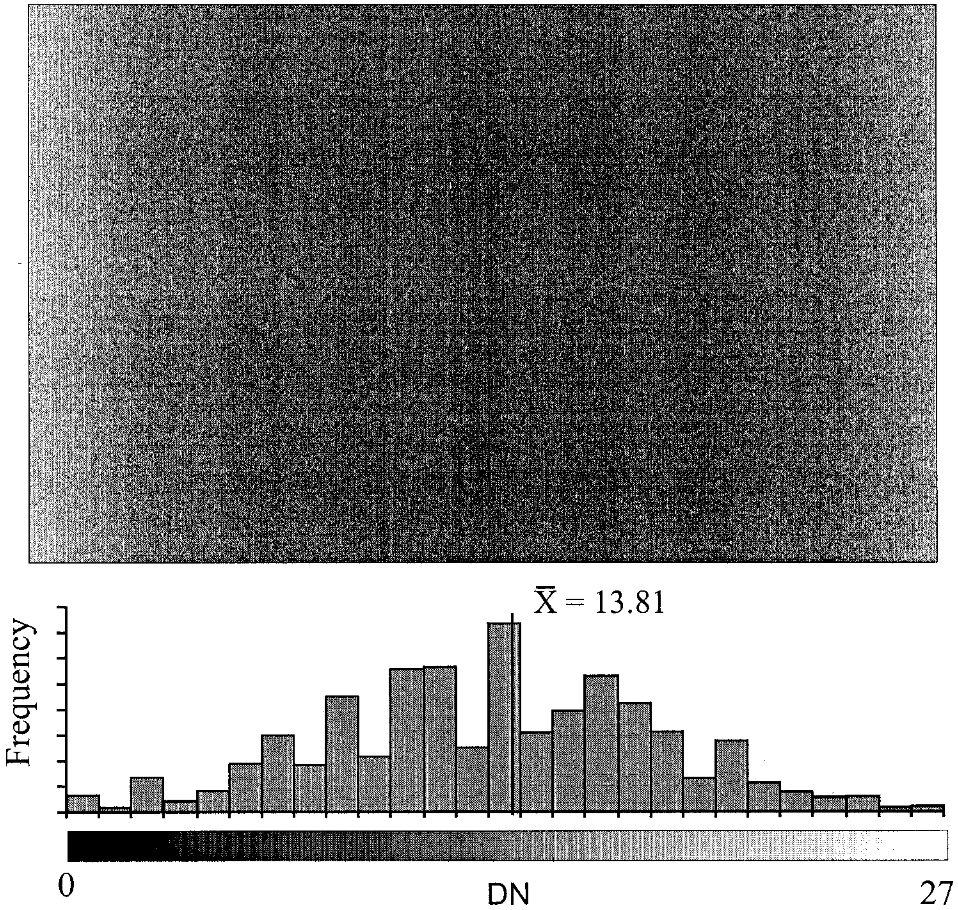


Figure 1. Dark-current (red image band) of the Polaroid Sprint Scan 35/LE. The observed DN range was 0–27, or approximately 10% of the dynamic range of the scanner.

3. Spatial properties

Any scanning instrument is a sampling device. In the case of the Polaroid SprintScan 35/LE, the optical resolution is 1950 dpi. The optical resolution is a theoretical ideal that represents the ratio of the number of CCD elements to the width of the scan. Optical resolutions, therefore, represent the sampling rate of the scanner and are not a measure performance (Gann 1998).

Sampling theorem states that for a periodic function to be accurately reproduced it must be sampled at twice the rate of the highest frequency of the input signal, or the Nyquist rate (Pratt 1991). Given the optical sampling rate of the Polaroid SprintScan 35/LE is 1950 dpi the scanner should be able to reproduce spatial detail with a frequency of 38 line pairs per mm. While theoretically possible, most scanners are unable to resolve detail at their Nyquist rate (Gann 1998).

The standard test of scanner resolution is to measure the scanner's modulation transfer function (MTF). The MTF measures the scanner's optical frequency response when scanning a target with different spatial frequencies. Providing that the input spatial frequencies are within the capabilities of the scanner, the MTF gives a measure of the performance of the scanners electro-optical system.

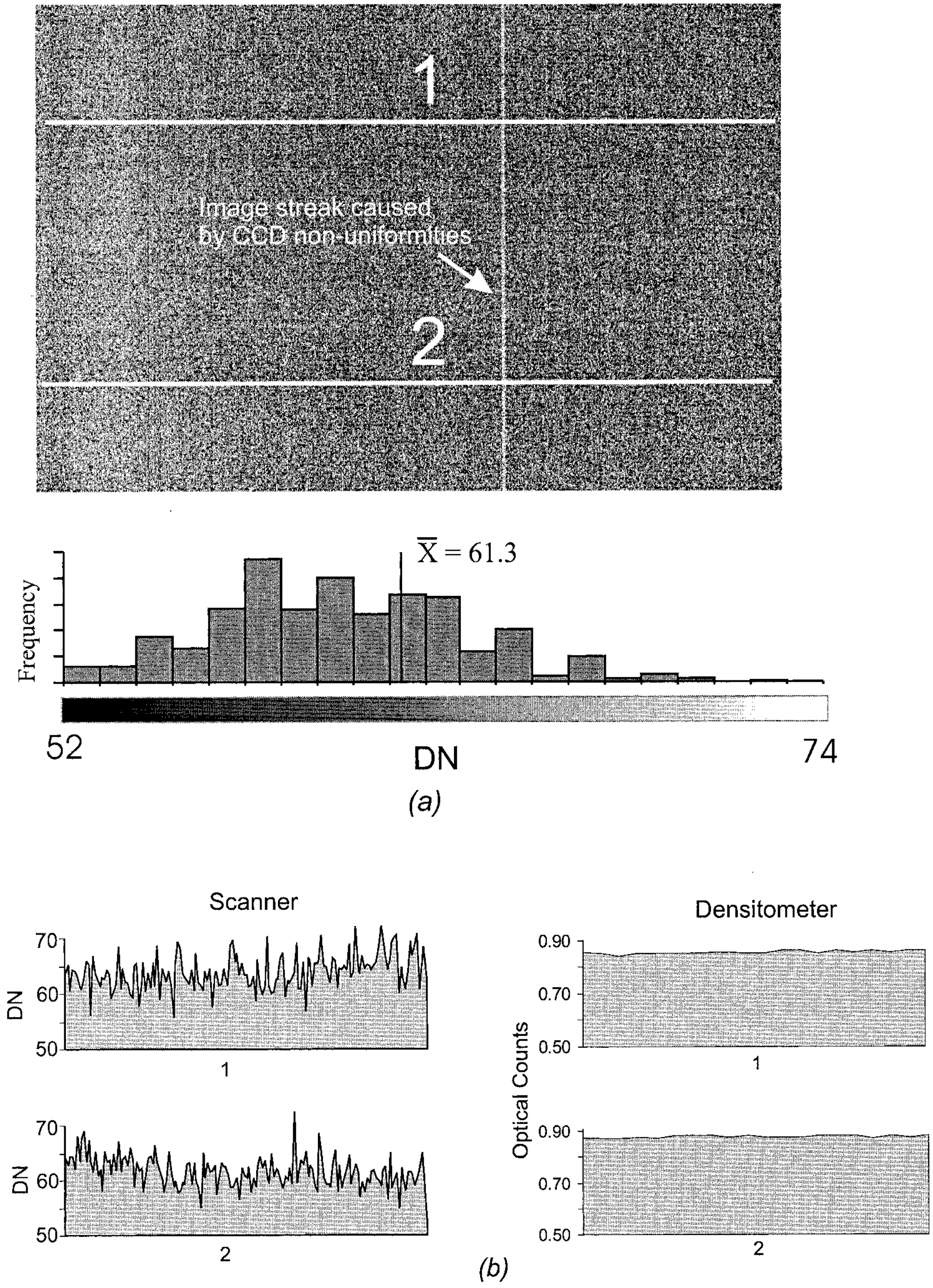


Figure 2. Comparison between scanning and densitometry of a consistent colour (Wratten #93 (green) filter) demonstrates the variation in DN values which occur as a result of pixel non-uniformity and the presence of dark-signal non-uniformities. (*a*) Green image band from Wratten #93 filter (green) with the data transects. (*b*) Variation in DN values recorded by the scanner and the optical counts recorded from the densitometer.

The basic test of a scanner's MTF involves scanning a target with alternating back and white lines at different spatial frequencies. In theory, the maximum value for the MTF is 1, where the modulation of a spatial frequency is identical to that of the reference pattern. In practice, the modulation of the reference pattern is not ideal given the limitations in the production of the resolution target.

For practical purposes the MTF is measured using the modulation of the lowest spatial frequency pattern to represent the reference pattern. The other spatial frequencies from the test target are then compared to the reference pattern. The MTF is then calculated by dividing the maximum difference in DN values for each frequency by the maximum difference in DN values recorded for the reference pattern.

Figure 3 is a graph of the DN values recorded for spatial frequencies of 4, 10, and 16 lp mm^{-1}. It is important that the exposure settings on the scanner are set so that saturation at either extreme of the DN range (0 or 255) does not occur as this will lead to an overestimation of the MTF. The MTF for the Polaroid SprintScan was calculated by comparing seven different spatial frequencies from a NTSC resolution target (figure 4). This test revealed that this instrument is capable of resolving detail with a spatial frequency of 16 cycles mm^{-1} with a modulation transfer of 45%. The calculation of a MTF for this instrument gives information on the resolution of the instrument and provides a means of comparing scanners.

3.1. *Spatial resolution*

The optical resolution of a scanner is the ratio of the number of CCD elements in the array and the width of the scanning area in the X dimension. Most scanning software allows the user to change interactively the resolution of the scan by specifying a spatial resolution. The scanning software then produces an image using one of two techniques. The first technique is known as native resolution. Native resolutions are those resolutions that result by the division of the optical resolution by integer

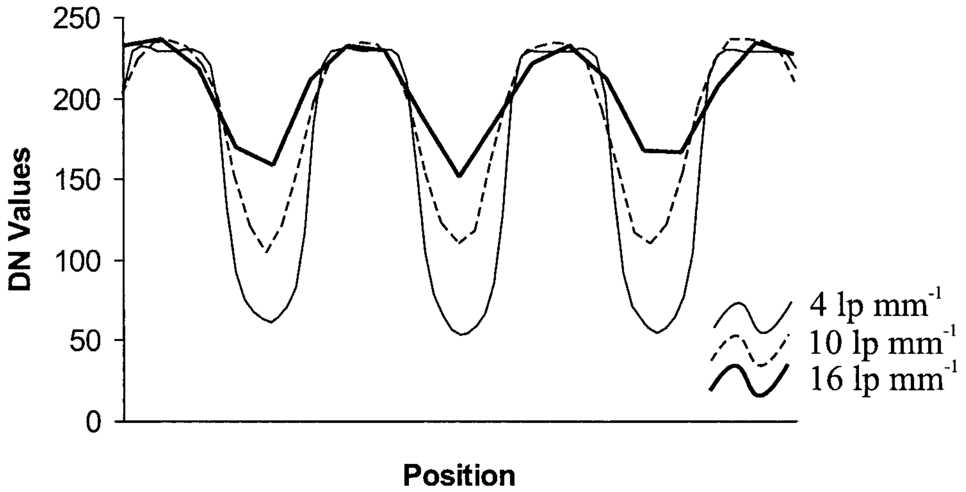


Figure 3. A graphical representation of the data used to calculate the MTF. This graph shows how well the pattern of alternating light and dark lines is formed by the scanner at different spatial frequencies. As the spatial frequency increases the modulation of the signal decreases. The attenuation of the signal is strongest for the dark lines, while the lighter lines are all within the same range but not saturated.

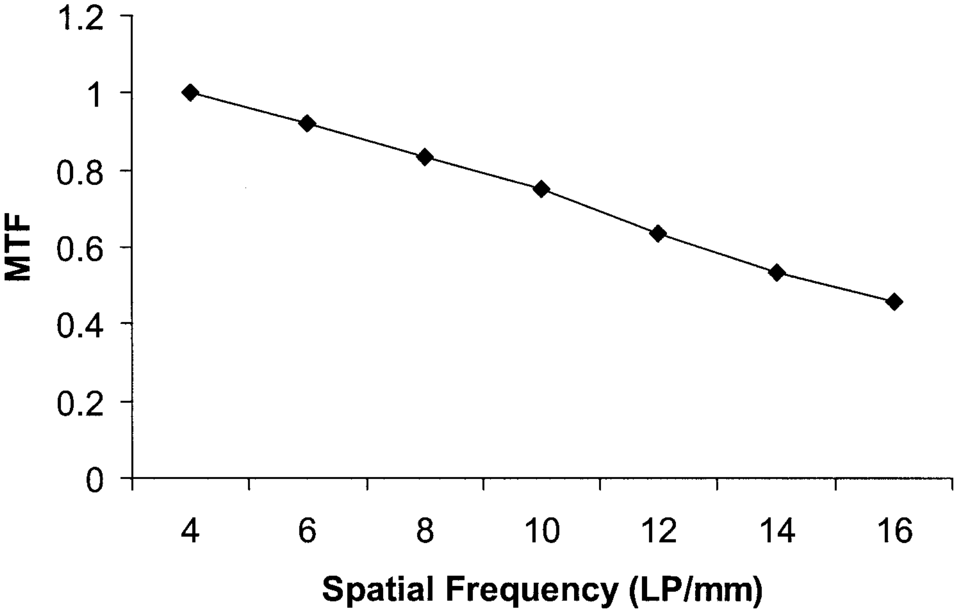


Figure 4. The calculated modulation transfer function (MTF) for the Polaroid SprintScan 35LE. The MTF is generated by taking the ratio of the maximum difference in DN values for each spatial frequency by the maximum difference in DN values from the reference pattern.

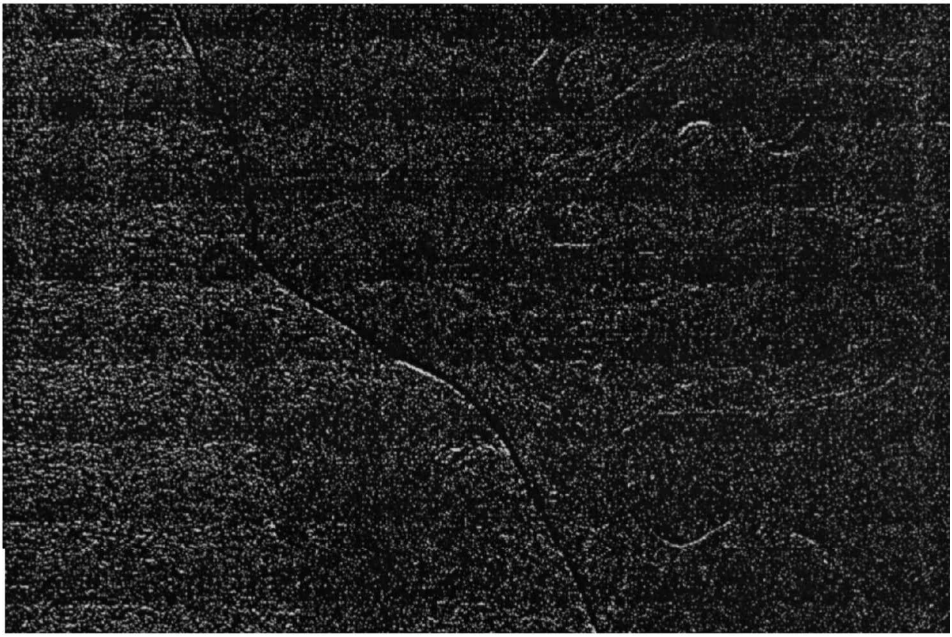
values. For example if the optical resolution is 1950 dpi then the next lowest native resolution is 1950/2, or 975 dpi. The native resolutions for this instrument are 975, 650 and 390 dpi if every second, third or fifth pixel is used to create an image.

All non-native resolutions are achieved by a scanner-performed resampling of the image. This resampling procedure acquires a buffer of data and resamples these data, a new buffer is then scanned and the image is built by combining these buffers. The end result of this resampling procedure is different from an image created by scanning at the optical resolution of the scanner and resampling the image. Figure 5, a scanned aerial photograph of the Horsefly River, British Columbia, Canada, shows the difference between scanner-performed resampling and software resampling. The horizontal striping pattern (figure 5(*b*)) is an artifact of the buffering procedure.

In summary, while all scanning software allows the user to vary the resolution of the scan produced the sampling rate of the scanner can not be varied. The selection of resolutions other than the optical resolution of the scanner results in interpolation either by using a resampling algorithm or by only reading selected photo-sites from the CCD sensor. If lower image resolutions are required for analysis, resampling an optical resolution scan produced the most accurate results.

Figure 5. (*a*) A scanned aerial photograph of the Horsefly River, British Columbia, Canada. (*b*) Non-native resolutions are achieved by resampling the image. This technique involves the collection of a buffer of data and a resampling operation. Figure 5(*b*) is the difference between the scanner-performed resampling and (*a*) an image created using software performed resampling. The horizontal striping pattern is a result of the image buffering process.

(a)



(b)

3. Conclusions

Digital conversion of photographs by desktop scanners might be sufficient for most applications, because any scanner-induced effects are not strong enough to mask the actual signal. However, just as radiometric calibrations are especially important for the use of remotely sensed images in the estimation of subtle biophysical variables, for example from water bodies (chlorophyll, suspended sediment, temperature) or vegetated surfaces (Jensen 1996), the effect of the scanning process needs to be evaluated for such applications. There is a danger that both spectral and spatial artifacts generated by the scanning process might obscure subtle differences in parameters, or even lead to inaccurate parameter estimation. Given the trend to use consumer electronics for scientific applications, it is important to keep the properties of desktop scanners in mind when using scanned imagery for analytical purposes. Scanner properties can be identified by simple tests such as the ones outlined in this paper before desktop scanners are considered for analytical applications.

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