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The dangers of underestimating the importance of data adjustments in band ratioing

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Abstract. The practical importance of simple data adjustments for path (atmospheric) radiance and sensor calibration offsets prior to band ratioing has often been overlooked or misjudged. This paper describes and demonstrates the critical nature of data adjustments for the production of useful ratio images, including ratio images derived solely from long wavelength bands. A simple bispectral graphic model is used for illustrating and evaluating the impact of data offsets upon ratio images. Orthogonal indices, used as alternatives to band ratios, are shown to be sometimes less sensitive to topographic influences than ratios of unadjusted data but not less sensitive than ratios of properly adjusted data.

1. Introduction

Band ratioing is a standard image processing routine that suppresses spatial radiance variations that are proportionally constant between bands and are generally attributable to terrain illumination, ground albedo and look angle effects. Band ratioing commonly thereby enhances spatial radiance variations that are not proportionally constant between bands and are generally more informative in terms of surface composition. Although the theoretical need for data adjustments prior to ratioing to compensate for path radiance and sensor calibration offsets (collectively termed 'data offsets') has been widely acknowledged, too often the practical importance of the adjustments has been overlooked or misjudged and adjustments have not been implemented. The purpose of this paper is to clarify the importance of data adjustments by presenting (1) examples of image data for which adjustments are clearly critical and (2) a simple bispectral graphic explanation of the role of data adjustments in band ratioing.

2. Image example: short wavelength bands

Figures 1 (*a*) and (*b*) are from band 1 and band 4, respectively, of a Landsat Thematic Mapper (TM) subscene of the Eagle Mountains in southern California (scene 40149-17443, 12 December 1982). The area is rugged (local relief up to 700 m) and consists largely of well-exposed crystalline rocks. An open pit mine is located within the mountainous terrain and mine tailings are located at the eastern mountain front. Although there are reflectance differences between the unweathered bedrock of the mine and tailings and the weathered, undisturbed surface materials in surrounding areas, these differences are not easily detected as brightness variations in the single-band imagery due to their convolution with more-prominent brightness variations that result from topographic modulation of surface irradiance (topographic shading).

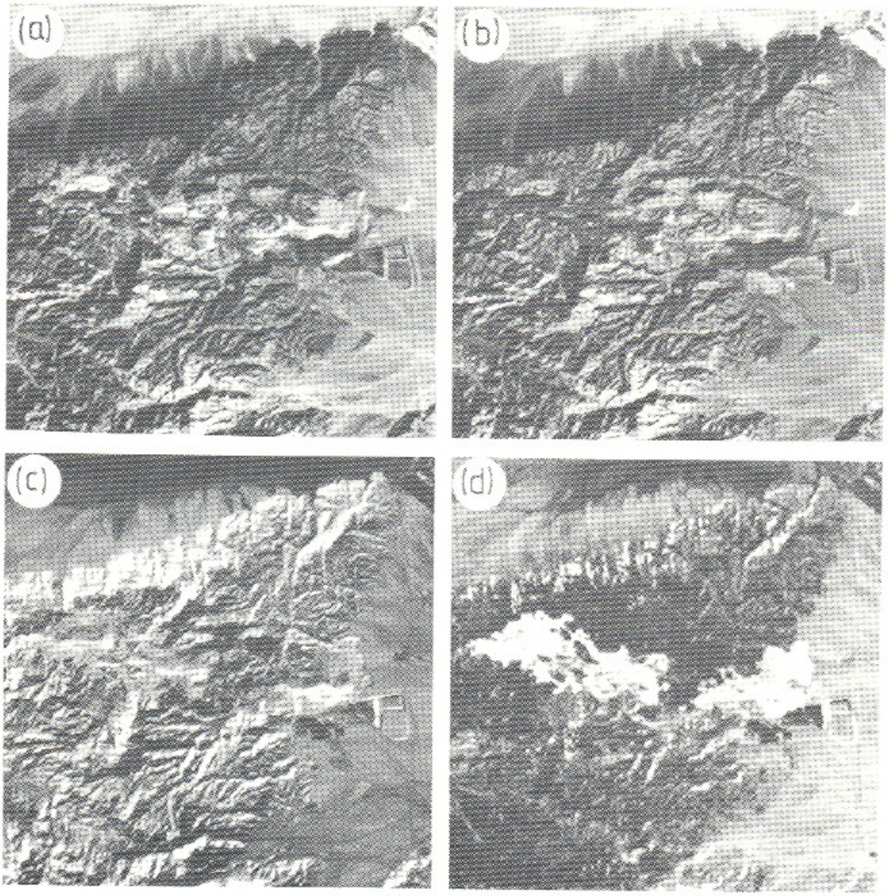

Figure 1. Landsat-4 TM subscene of the Eagle Mountains Iron Mine in southern California. (*a*) Band 1. (*b*) Band 4. (*c*) Band 1/band 4 ratio without data adjustments—topographic expression is retained with reversal. (*d*) Band 1/band 4 ratio with data adjustments—topographic expression is largely removed and the mine and tailings are easily distinguished as anomalously bright (high ratio value) areas.

Figure 1 (*c*) is a ratio image produced by dividing band 1 by band 4 without data adjustments. Topographic expression is not significantly suppressed, but is instead reversed, and the mine remains masked by the topographic expression.

Figure 1 (*d*) is a ratio image produced by dividing band 1 by band 4 after data adjustments were applied (subtractions of 44 DN for band 1 and 6 DN for band 4, derived by Crippen (1987)). Topographic expression is almost completely removed, and the mine and tailings are clearly distinguishable from undisturbed ground.

Figures 1 (*a*)–(*d*) demonstrate that the common practice of not making data adjustments can lead to an unnecessary failure of the band ratioing process. Assertions that data adjustments do not need to be made because such adjustments do not significantly change the ratio image information content are demonstrably incorrect for this image and are certainly incorrect for many other images as well.

3. The role of data adjustments in band ratioing

The general concept of band ratioing is that ratio values should be constant for pixels representing materials of homogeneous spectral properties and should vary for some (not necessarily all) pixels representing materials of differing spectral properties. Utilization of band ratioing to discriminate materials by their spectral properties therefore has the prerequisite that surface materials of uniform reflectance properties plot as approximately straight lines emanating from the origin of a bispectral graph, since these lines trace the trends of constant ratio values. Although, to the first order, pixels of variably-illuminated homogeneous materials commonly plot as approximately straight lines (termed 'data lines'), they usually do not emanate from the bispectral graph origin (figure 2 (*a*)) due to additive path radiance and sensor calibration offsets (Kriegler *et al.* 1969).

Fortunately, to the extent that the atmospheric effects and sensor calibration offsets are uniform across the scene, they can be largely removed by subtraction of an appropriate constant value from each band. These constants are band-specific and can change with scene location, acquisition time and sensor. When the correct adjustments are made, the original bispectral data distribution in figure 2 (*a*) shifts to that of figure 2 (*b*), and ratio values of each surface material become largely independent of topographic modulation of irradiance and thus relatively constant. Note that in figure 2 (*a*), prior to data adjustments, variably-illuminated, spectrally homogeneous materials can have a wide range of ratio values, and spectrally differing materials can have identical ratio values. As a result, discrimination of the differing materials and recognition of uniform materials is largely impossible in the ratio image. As shown here, in cases where the data lines are less steep than the lines of constant ratio values that intersect them (figure 2 (*a*)), brighter (more intensely illuminated) pixels have lower ratio values than darker (shaded) pixels, resulting in a reversal of topographic expression (figure 1 (*c*)). This usually occurs when the data offsets are greater in the numerator band than in the denominator band. Conversely, when the data lines are

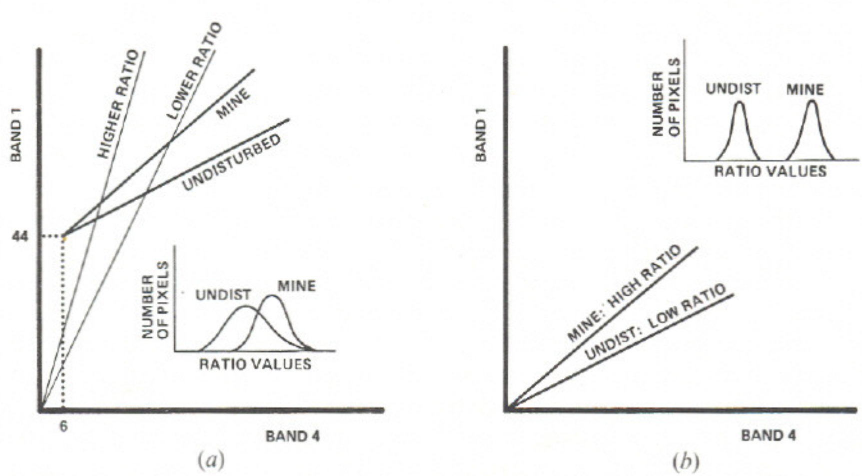

Figure 2. Simplified bispectral plots corresponding to the ratio images of figure 1. (*a*) Unadjusted data used in figure 1 (*c*). (*b*) Adjusted data used in figure 1 (*d*). Insets show the relative distinctiveness of ratio values for the differing surface materials.

steeper than the lines of constant ratio values that intersect them, topographic expression is retained without reversal.

As can be inferred from figure 2 (*a*)), a worst-case scenario for retaining topographic information in ratio images is one in which one of the ratioed bands has a large data offset and a relatively small data variance, and the other band has a small data offset and a relatively large data variance (e.g. the commonly used combination of Landsat TM bands 1 and 5, respectively, for scenes of rugged, well-exposed lithology). Such a situation results in a maximal incongruence of the data lines and the lines of constant ratio values. Only when data adjustments are made so that the intersection of the data lines is situated near the bispectral graph origin (figure 2 (*b*)) will there be an approximate coincidence of the data lines and constant-ratio lines such that each material has its own distinct (range of) ratio value(s) and can be easily recognized in the ratio image (as in figure 1 (*d*)).

4. Image example: long wavelength bands

Clearly, data adjustments can be critical for the production of useful ratio images that incorporate at least one band in which the atmospheric and/or sensor calibration effects are large (atmospheric effects are commonly large for the visible wavelength bands). However, virtually unrecognized in the literature is the fact that data adjustments can also be very important for bands in which path radiance and sensor offsets are *minor*. This is especially true for scenes that have a significant number of very dark pixels, due to the extreme ratio value variability near the bispectral graph origin. Data offsets as small as a few (5 or less) digital numbers can determine whether dark pixels have extremely low ratio values (and remain depicted as dark) or extremely high ratio values (and are consequently depicted as bright). Although the dark (e.g. deep shadow) pixels themselves may not be of interest (because of a poor signal-to-noise relationship), it can be important to direct their ratio values so as not to interfere statistically or perceptually with the interpretation of the pixels that *are* of interest. For example, if relatively high values of a TM band 5/band 7 ratio generally indicate the presence of carbonates, then data adjustments should be made to ensure that very dark pixels have intermediate or low values. This will prevent errors of acceptance in searching for carbonates (high ratio values will indicate just carbonate instead of carbonate and/or shadow), and errors of rejection will not be substantially increased since dark pixels should already be omitted from the search due to their unreliable, low signal strength. In short, the dark pixels may be largely noise in the ratio image, but they can be adjusted to be statistically and perceptually unobstructive.

As an example, figures 3 (*a*) and (*b*) are images of bands 5 and 7, respectively, of an area near to that shown in figure 1. Figure 3 (*c*) is a band 5/band 7 ratio image produced with a simulated data-offset combination of 5 DN for band 5 and 0 DN for band 7 (i.e. equal to or less than the actual offsets determined by Crippen (1987)). Note that areas of deep shadow are anomalously bright (have high ratio values) and are readily confused with the brightly-depicted rock units, in this case quartzites (Powell 1981), that likewise have relatively high band 5/band 7 ratio values at this site. A density slice of this image or use of this image as an input to a statistical classifier would produce very unsatisfactory results. Figure 3 (*d*) is a band 5/band 7 ratio image produced with data adjusted to have no offset in either band. Here the shadows are no longer anomalously bright and the quartzite can be easily distinguished from the surrounding terrain. Thus, a minor adjustment of only 5 DN for band 5 resulted in a significantly different and much more useful ratio image result. Figure 4 illustrates the slight but significant bispectral differences of these ratio images.

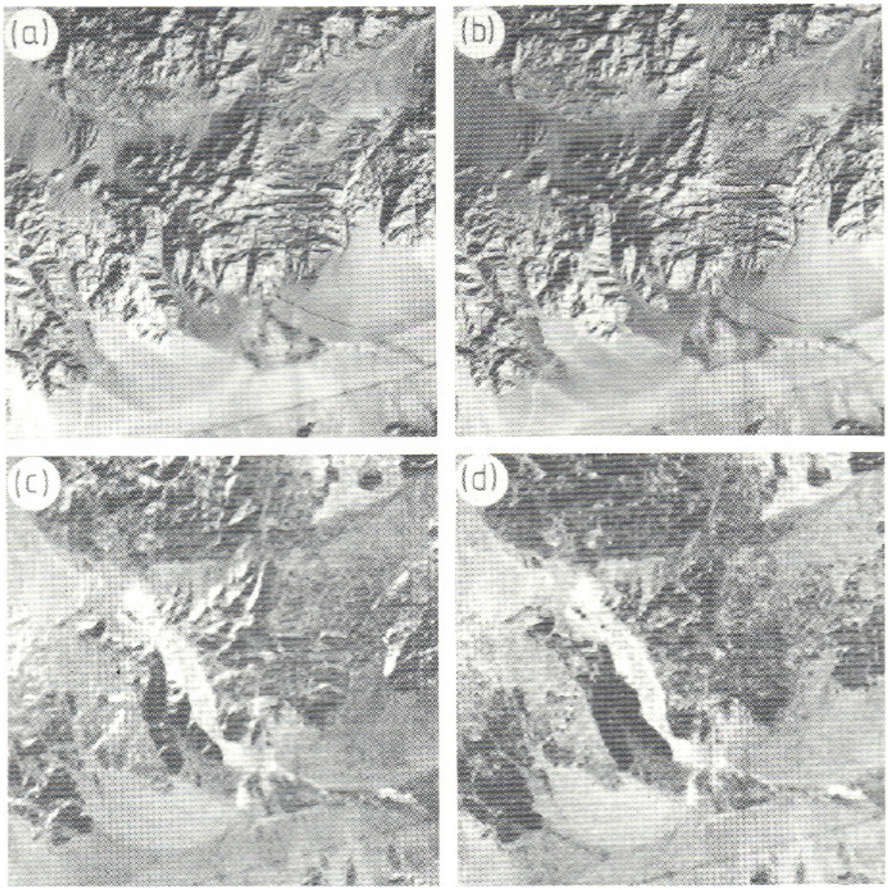

Figure 3. Landsat-4 TM subscene of an area southwest of that shown in figure 1. (*a*) Band 5. (*b*) Band 7. (*c*) Band 5/band 7 ratio with a data offset of 5 DN for band 5 and no offset for band 7. The bright (high ratio value) bedrock areas are quartzite and/or topographic shadows retained with reversal. (*d*) Band 5/band 7 ratio with proper data adjustments. Shadowed areas no longer have ratio values that can be confused with those of the quartzite.

For standard colour ratio composites, ratio image sensitivity to data adjustments can be even more extreme. Data adjustments as small as 1 DN in one band of just one of the three ratio inputs can cause prominent alterations in the colour coding of dark pixels. This is because a 1 DN change is proportionally large for dark pixels, and the colour of a displayed pixel is a function of the proportions of the three primary colour (blue, green, red) display input channels. Attention to this effect is important because if shadows are depicted in a locally anomalous colour, then they can easily be confused with other ground cover units that are also depicted by that colour.

5. Beneficial retention of data offsets: possibilities and risks

An exception to the need for removal of data offsets (but not for their adjustment) is presented by Crippen *et al.* (1988), who describe a ratio-based technique of colour composite chromaticity enhancement. In that technique, topographic variability is prominently retained (without reversal) in each ratio in a consistent manner. Subsequently, topographic variability is distinguished from reflectance variability in

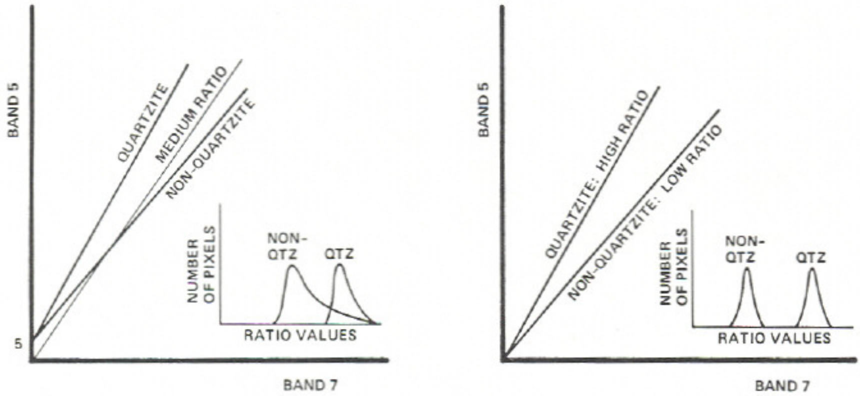

Figure 4. Simplified bispectral plot corresponding to the ratio images of figure 3. (*a*) Data used in figure 3 (*c*). All quartzite pixels *and* dark pixels of other materials have the same (high) range of ratio values. (*b*) Data adjusted to eliminate offsets. Nearly all pixels of quartzite have higher ratio values than nearly all pixels of other materials such that quartzite is distinctive in the ratio image.

the colour composite by its depiction as variations in image intensity, while most reflectance features vary non-proportionally between ratios and are thus depicted as variations in colour. The more conventional methods of band ratioing lack this means of differentiating topographic and reflectance features and, if data adjustments are not made, can result in ineffective black and white images (such as figure 1 (*c*)) or perceptually convolved colour coding of reflectance *and* topographic features in colour ratio composites, as discussed above.

In achromatic ratio images, there is no situation in which data offsets can be retained without introducing or retaining obstacles to image interpretation. Topographic expression in ratio images presents problems similar to those found in single-band images. In single-band imagery, topographically-modulated illumination is indistinguishable from ground reflectance variations for any given pixel viewed individually. A decrease in pixel brightness can be attributed either to a decrease in ground illumination or to a decrease in ground reflectivity. The only clue as to which factor is the more likely one for that pixel is obtained by the experienced image interpreter who recognizes the spatial patterns of image brightness that are reasonably associated with geomorphic (or botanic or cultural) features. Proper data adjustments leading to topography-free ratio images, can remove this uncertainty so that the interpreter can clearly see patterns that are attributable solely to ground reflectance.

It may be reasonable in some cases to leave a minor amount of topographic expression in a ratio image while necessarily sacrificing part of the ratio-enhanced information. For some purposes, this may adequately enhance the features of interest while retaining some useful reference landmarks. In these cases, the interpreter should be highly cognizant of the pattern of topographic shading (as better seen in the original bands) and should be aware of its potential for deception. Unfortunately, the data offsets inherent in the band data can, in some cases, be too substantial to allow any utility of a ratio image that is produced without data adjustments (as was seen in figure 1 (*c*)). Also, it is usually difficult to determine *a priori* how much topographic expression will be retained with data offsets of any given size since the retained expression also varies with terrain ruggedness and the relative band variances. Similarly, it is difficult to estimate *a priori* what the critical threshold of topographic effects suppression is for exposing a previously unrecognized reflectance pattern. These problems point to the need for topography-free (or topography maximally-removed) ratio images, even if topography-retained versions are also used.

It is unlikely that retention of topographic expression in ratio images is ever beneficial in statistical analyses. Studies that have found ratios of unadjusted band data to be superior to ratios of adjusted band data in statistically isolating a designated target have likely only shown that ratioing was the wrong method to use in searching for that target. Such cases occur for targets that are primarily distinctive in terms of albedo or their geographic concentration in areas of anomalously high or anomalously low insolation (as determined by topographic shading and as represented only by that shading present at the time of data acquisition). Band data should be at least as useful as ratios in these cases, since the retention of albedo and topographic expression in ratios of unadjusted data is unreliably dependent upon sensor gains (affecting data variance and therefore data-line slopes), sensor offsets and temporally-variant path radiance.

6. Orthogonal indices: substitutes for data adjustments?

As previously stated, band ratios are used to measure radiance variations that are not proportionally constant between bands. Alternatives to band ratios have also been used for this general purpose. These include principal components, the 'greenness index' (Kauth and Thomas 1976), the 'perpendicular vegetation index' (Richardson and Wiegand 1977) and other 'orthogonal' indices (e.g. Collins 1978, Miller and Elvidge 1985). The following discussion will show how some studies which have favourably compared orthogonal indices to band ratios may have been biased because of inattention to data adjustments when implementing the ratios.

Orthogonal indices are measured through spectral space along straight lines that are perpendicular to a multispectral reference line or 'baseline' (e.g. in a variety of studies, perpendicular to the first principal component or, in vegetation studies, perpendicular to a line delineating the albedo variations of the soil background). In contrast, ratios are measured through bispectral space along a circular path that is centred at the bispectral graph origin (the point of zero data numbers). A significant aspect of this difference is that the orthogonal indices are inherently independent of data offsets because the data lines and the baseline move in unison with such offsets. However, another significant aspect is that the orthogonal indices are not independent of radiance variations that are radial from the point representing zero ground radiance. Data variations attributable to topographic shading generally trend along such radial lines. Thus, the orthogonal indices are not optimally insensitive to topographic effects.

Band ratios *are* optimally insensitive to topographic effects (to the first order) if the point of zero ground radiance is approximately located at the bispectral graph origin, as is the case when proper data adjustments have been made. However, band ratios *are not* insensitive to topographic effects if the point of zero ground radiance is significantly displaced from the bispectral graph origin. In fact, ratio images produced from unadjusted data or incorrectly adjusted data can be severely affected by these effects, as demonstrated above. Thus, while band ratios are potentially superior to the orthogonal indices in suppressing topographic effects, they can actually be inferior to the orthogonal methods if improperly applied (i.e. applied without the necessary data

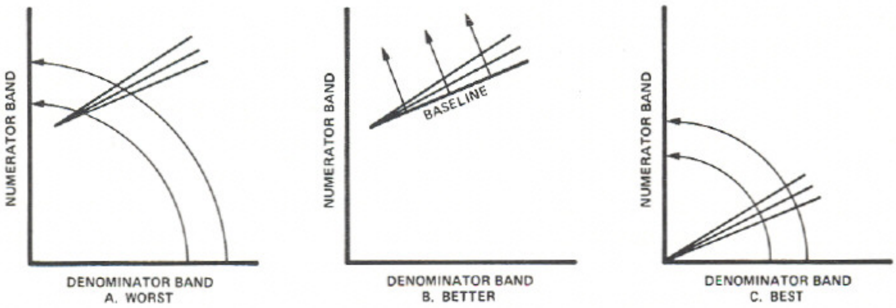

Figure 5. Comparative sensitivities of bispectral indices to topographic shading and other proportionally-constant ground radiance variations. Sensitivity is inversely related to the acute angle between the data lines (radial) and the path of index measurement (arrows). (*a*) Band ratio of data with offsets; (*b*) orthogonal index and (*c*) band ratio of adjusted data.

adjustments). This is illustrated in figure 5. Stated another way, the right method used wrongly can be worse than the wrong method used correctly. Of course, the right method used correctly is the best choice. Band ratioing of properly adjusted data is clearly the right method for minimizing image effects attributable to topographic modulation of irradiance (topographic shading). It may also be the right method for minimizing look angle, soil albedo and vegetation shadowing effects, even in areas lacking significant topographic relief, although this is the subject of continuing controversy and research (e.g. Pinter *et al.* 1983, 1987, Wardley 1984, Huete *et al.* 1985, Hatfield *et al.* 1985).

7. Conclusion

The discussions and examples given above demonstrate the importance of accurate adjustments of image data prior to band ratioing. Data adjustments do not consist only of atmospheric corrections. They can also consist of corrections for even minor sensor calibration offsets, especially for scenes containing deep shadows. The need for proper data adjustments should be assumed to be significant for each image until proven otherwise.

Practical methods of estimating the data offset values for each band include dark pixel subtraction (Crane 1971), an iterative ratioing procedure (Crippen 1987), radiance-to-reflectance conversion (Honey *et al.* 1974), the regression method (Potter and Mendlowitz 1975), the covariance matrix method (Switzer *et al.* 1981) and the regression intersection method (Crippen 1987). Choice of method (or methods) is dependent upon scene characteristics.

The simplified bispectral model used here is very effective for conceptual and illustrative purposes. However, four sources of inaccuracies of the model should be noted. First, the calibrations can differ for individual detectors for a given band. Secondly, path radiance can vary across a scene. Thirdly, skylight irradiance can be proportionally large for dark shaded pixels relative to brightly illuminated pixels, such that dark pixels tend to shift off the data lines toward the axis of the shorter wavelength band (probably accounting for the remnant topographic expression in the deepest shadows in figure 1 (*d*)). Fourthly, terrain-reflected irradiance can be proportionally large for shaded pixels and can distort the data lines in either direction. In most images, for most purposes, these effects are relatively minor. If needed, the detector-specific calibration problem can be largely (and fairly easily) solved by use of a destriping routine applied to the band data (Goetz *et al.* 1975, Sabins 1987), as long as the data have not been resampled. Compensation for spatially variable path radiance may be possible by determining a spatially gradiational data adjustment. More difficult to handle are skylight variations and other terrain-related effects that are highly pixel-specific and require detailed terrain modelling (Sjoberg and Horn 1983, Woodham and Lee 1985).

In summary, the important points of this paper are that data adjustments can be indispensable in the production of useful ratio images and that, in most cases, the most significant data adjustments are those that are easiest to determine and implement; namely, those that compensate for scene-average path radiance and calibration effects. While the effort required for implementation of the more-complicated data adjustments (for spatially varying effects) can be justified only in the most exacting studies, the images shown here demonstrate that implementation of the relatively simple adjustments (only involving subtraction of a constant from each band) should be considered an essential part of the band ratioing process.

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