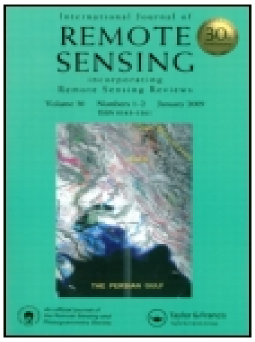

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TECHNICAL NOTE

Simple and robust removal of sun glint for mapping shallow-water benthos

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Specular reflection of solar radiation on non-flat water surfaces is a serious confounding factor for benthic remote sensing in shallow-water environments. This problem was recently overcome by Hochberg *et al.*, who provided an effective method for the removal of 'sun glint' from remotely sensed images by utilization of the brightness in a near-infrared (NIR) band. Application of the technique was shown to give an increase in the accuracy of benthic habitat classification. However, as presented, the method is sensitive to outlier pixels, requires a time-consuming masking of land and cloud, and is not formulated in a manner leading to ease of implementation. We present a revised version of the method, which is more robust, does not require masking and can be implemented very simply. The practical approach described here will hopefully expedite the routine adoption of this effective and simple technique throughout the aquatic remote sensing community.

1. Introduction

The mapping of benthic features can be seriously impeded by the state of the water surface. When skies are clear and the water surface is not flat, specular reflection of the incident radiation occludes the benthic component of the remotely sensed data with areas of bright white 'sun glint'. Unfortunately, the problem of sun glint is particularly acute under conditions at which remote sensing might otherwise be most effective: clear skies, shallow waters (which when wind-blown form waves) and when images are collected at a high spatial resolution. Typically, sun glint forms bands of white along wave edges on the windward side of near shore environments (figure 1(*a*)). These white bands confound the visual identification of bottom features, and will strongly influence image classification (typically the presence or absence of glint dominates the categorization in those areas).

Although in glint areas the recorded brightness appears almost entirely composed of the water surface specular reflectance signal, the component associated with water leaving radiance may be recoverable, providing that the sensor remains spectrally unsaturated. Whereas previous methods for sun-glint removal were designed for ocean colour applications on pixels at large physical scales (>1 km) (Fraser *et al.* 1997, Wang and Bailey 2001), a recent paper by Hochberg *et al.* (2003) presents a new and conceptually simple method of 'deglinting' applicable to benthic remote sensing at high spatial resolutions where glint effects occur at physical scales

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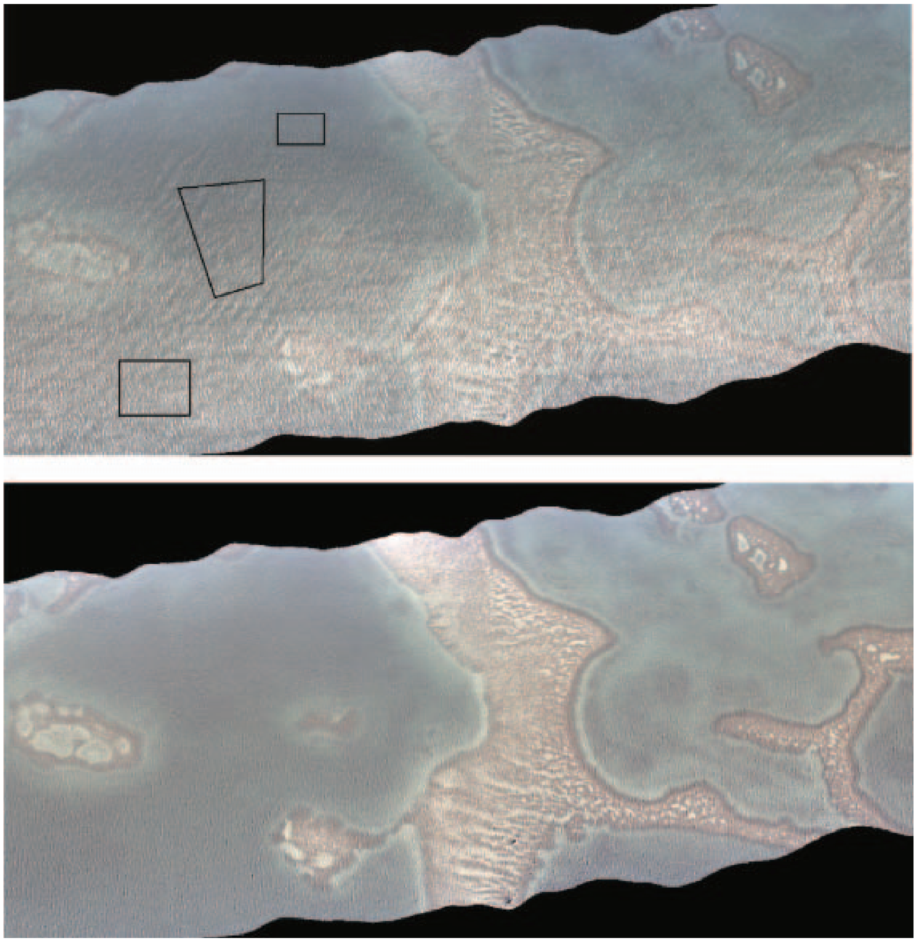
(a)



(b)

Figure 1. (a) Compact Airborne Spectrographic Imager (CASI) image of submerged coral reefs (depth over reefs 16–20 m) from St John in the US Virgin Islands. The image was collected using 19 user-selected channels between 442 and 810 nm, with 4 m^2 pixels (these images only utilize three bands: 466, 488 and 507 nm). The physical scale of the image is ≈1 km from top to bottom of the flight strip. Average wind speed at the time of image acquisition was 3.9 $m\,s^{-1}$ (8.7 mph), direction 57°. The sample pixels used for the regression are indicated by the three boxes. The image is 1157 × 581 pixels in size; ≈21 000 pixels are used for the regression sample. (b) The same image after the deglinting process.

comparable to image pixels (<10 m). In Hochberg *et al.*'s (2003) method the sunglint component of the remotely sensed signal is removed from visible wavelength spectral bands by utilization of information from a spectral band in near-infrared (NIR, ~700–910 nm). The method is therefore applicable to imagery from sensors that include an NIR band (e.g. satellites such as Ikonos or Landsat) or suitably configured multispectral and hyperspectral imagery (e.g. from airborne sensors such as CASI, Compact Airborne Spectrographic Imager). Image pixels are adjusted to remove the glint component of the recorded signal, thereby leaving only the component derived from benthic reflectance and radiative transfer processes within the water column. Hochberg *et al.* (2003) demonstrated a substantial visual improvement in one 'deglinted' image of a shallow coral reef environment, and showed a statistically significant increase in user accuracies on a maximum likelihood classification of the image based on seven habitat classes (overall accuracy showed a non-statistically significant improvement).

Although the method presented by Hochberg *et al*. (2003) is a great boon to the remote sensing community, there are several ways in which the implementation can be improved. The formulation of the deglinting method as presented by Hochberg *et al*. (2003) is unduly sensitive to outlier pixels, which is an impediment to its routine application in image analysis. Additionally, Hochberg *et al*. (2003) present the technique in a mathematically rigorous manner which may obscure the simplicity of the method's implementation for some practitioners. Further, in their formulation, the exhaustive masking out of land and cloud areas is required before deglinting can be applied. This is unduly time consuming if such masking is not required at a later stage of image processing. In this short note, we present an improvement to the deglinting method that removes the sensitivity to outlier pixels, does not require the masking out of land and cloud, and generally improves the robustness of the technique. We also describe an approach to the practical implementation of the technique that requires only a few simple processing steps. These practical improvements will assist in the routine adoption of deglinting in image processing.

2. Original method

The deglinting method as described by Hochberg *et al*. (2003) relies on two simple assumptions: (1) That the brightness in the NIR is composed only of sun glint and a spatially constant 'ambient' NIR component. In particular, there is no spatially variant benthic contribution to the NIR. (2) That the amount of sun glint in the visible bands is linearly related to the brightness in the NIR band.

The first assumption is justified by the fact that water is relatively opaque to NIR wavelengths (700–1000 nm) (Mobley 1994), so that even shallow waters (e.g. to <2 m depth) have a low water-leaving radiance in the NIR regardless of bottom type. Although a minimum NIR brightness over deep water might be expected to be zero, in practice the minimum NIR brightness in any image is greater than zero. In particular, if images are not atmospherically corrected this 'residual' or 'ambient' NIR brightness corresponds to NIR backscatter in the atmosphere. The method described by Hochberg *et al*. (2003) in effect models a constant 'ambient' NIR brightness level which is removed from all pixels during the analysis.

The assumption of a linear relationship between NIR brightness and the amount of sun glint in the visible bands holds because the real index of refraction (which governs reflection) is nearly equal for NIR and visible wavelengths (Mobley 1994). Therefore, the amount of light reflected from the water surface in the NIR is good indicator of the amount of light that will be reflected in visible wavelengths, and a linear relationship exists between the two. The deglinting method proceeds by establishing the linear relationship between NIR brightness and the amount of sun glint in each visible band. This information, combined with the NIR brightness in each image pixel, is used to ascertain how much to reduce the brightness in each visible band to remove the glint in each pixel.

The weakness in the method outlined by Hochberg *et al*. (2003) is that in order to establish the linear relationship between the NIR brightness and sun glint in the visible wavelengths, only two pixels are used. It is suggested that these should be the 'brightest and darkest' NIR pixels found across the whole image (or possibly from within a subset of it). These two pixels are used to characterize the spectral shape of sun glint in the visible bands. The implicit assumption is that if sun glint were absent, the two reference pixels would have the same spectral signature. It is for this reason that the masking out of land and cloud prior to analysis is required, otherwise there is a high probability that the brightest NIR pixel would be a land or cloud pixel, and therefore invalid. However, for a large image ($>10^6$ pixels) rigorous masking can be time consuming and difficult. Hochberg *et al.* (2003) suggest using a subset of the image, ideally with homogeneous substrate at constant depth, to ameliorate possible errors due to inconsistencies between the two pixels. However, this does not combat the principal weakness, which is the reliance on only two pixels. A single small surface object (e.g. a buoy or boat), or a mistake in the masking, can occupy a single pixel and will probably be the brightest NIR pixel in the image. In general, identifying an appropriate 'upper' pixel is problematic and can cause significant errors undermining the efficacy of the method.

3. Revised method

In order to circumvent the weakness of basing the deglinting on two isolated pixels from the whole image, we establish the linear relationships between NIR and visible bands using linear regression based on a sample of the image pixels. Following the suggestion of Hochberg *et al.* (2003), one or more regions of the image are selected where a range of sun glint is evident, but where the underlying spectral brightness would be expected to be consistent (areas of deep water are ideal for this, figure 1). For each visible band all the selected pixels are included in a linear regression of NIR brightness (x-axis) against the visible band brightness (y-axis) (figure 2). If the

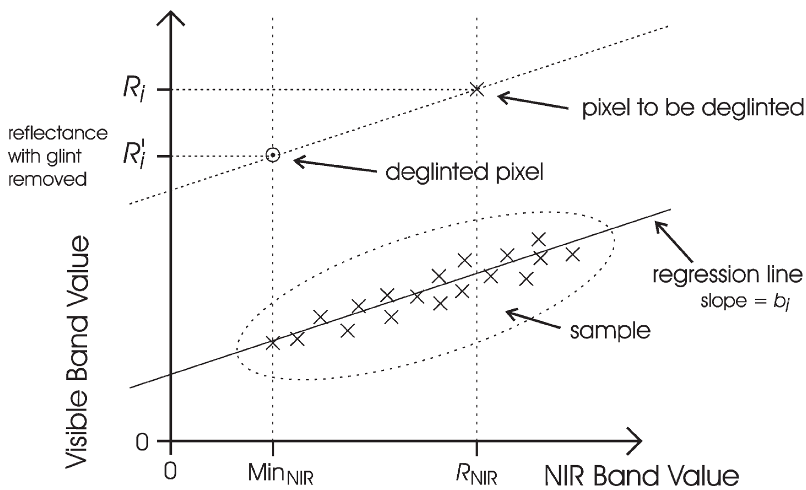


Figure 2. Graphical interpretation of the method. To deglint a visible wavelength band, a regression is performed between the NIR brightness and the brightness in the visible band using a sample set of pixels, which would be homogeneous if not for the presence of sun glint (e.g. deep water). For other pixels, the slope of the regression is then used to predict the brightness in the visible band that would be expected if those pixels had a NIR value of Min_{NIR} (equation (1)). Min_{NIR} is the NIR value expected from a pixel with no sun glint, which can be estimated by the minimum NIR value found in the sample.

slope of this line for band i is b_i, then all the pixels in the image can be deglinted in band i by the application of the following equation:

$$R'_i = R_i - b_i(R_{\mathrm{NIR}} - \mathrm{Min}_{\mathrm{NIR}}) \quad (1)$$

which simply means: reduce the pixel value in band i (R_i) by the product of regression slope (b_i) and the difference between the pixel NIR value (R_{NIR}) and the ambient NIR level ($\mathrm{Min}_{\mathrm{NIR}}$). This gives R'_i, the sun-glint corrected pixel brightness in band i. $\mathrm{Min}_{\mathrm{NIR}}$ essentially represents the NIR brightness of a pixel with no sun glint and can be estimated by the minimum NIR found in the regression sample (figure 2) or alternatively as the minimum NIR value found in the whole image. In general, the minimum NIR pixel is less prone to problematic outliers than the maximum NIR pixel.

Since this revised method relies on a user-based selection of a sample set of pixels it is not necessary to mask out non-submerged or cloud pixels prior to deglinting. It is prudent to ensure that the sample pixels do not contain any non-submerged objects, but the regression will nevertheless mitigate the impact of isolated invalid pixels. However, non-submerged areas will not contain valid data after deglinting since the algorithm is valid only for submerged pixels. Note also that as the method operates purely on the relative magnitudes of values, the absolute units of the pixel values are unimportant. Therefore, there is no need to transform pixel values into radiance and deglinting can be applied to the original image digital numbers. It is however advisable to ensure floating point arithmetic is used in order to correctly handle fractional values and possible negative numbers (see later).

The minimum sample size required is two pixels, displaying differing amounts of sun glint over similar sub-surface spectral brightness. In this case the method becomes analogous to Hochberg *et al.* 's (2003) formulation. A larger sample size is obviously desirable in order to reduce the effect of random variations. Ideally, the sample pixels should be drawn from several locations on the image including (if possible) large-scale areas with no sun glint at all (figure 1). Pixels from sun-glint free areas will ensure the lower end of the regression slope is populated (figure 2). However note that areas with no sun glint at all are not required, since sun-glint variation at small physical scales will be sufficient to establish the regression slope.

4. Step-by-step implementation

1. Radiometrically correct image using conventional method (if desired).
2. Select a sample area (or areas) of the image displaying a range of sun glint, but where the image would be expected to be more or less homogeneous if the sun glint was not present (e.g. over deep water). Determine $\mathrm{Min}_{\mathrm{NIR}}$, the minimum NIR brightness in this sample.
3. For each band to have sun glint removed, perform a linear regression of NIR brightness (x-axis) against the band signal (y-axis) using the selected pixels. The slope of the regression line is the output of interest, for band i, call it b_i.
4. To deglint band i for all pixels in the image, subtract the product of b_i and the NIR brightness of the pixel (minus $\mathrm{Min}_{\mathrm{NIR}}$) from the pixel value in band i (equation (1)).

5. Results and discussion

The result of the deglinting process on the example image is shown in the bottom part of figure 1. The deglinted image shows a clear visual improvement, similar to the figure presented in Hochberg *et al*. (2003). Previously obscured submerged reef features in the lower part of the image, such as spur and groove zones and the sand halo around the reef periphery become visible in the deglinted image. As the basis of the revised method is identical to the original, similar classification accuracy improvements in the deglinted image can also be expected.

In general, the issues and considerations in applying the revised method are identical to those raised in Hochberg *et al*. (2003) and so shall not be repeated here. One issue that should be mentioned, and which concerns both formulations of the deglinting method, is the possible creation of negative values in the deglinted image when solving equation (1). Submerged pixels should, in general, not result in out-of-range values but regions which do not conform to the deglinting model (e.g. isolated outlier pixels or shallow areas of sand where benthic NIR reflectance contributes to the water-leaving NIR brightness) may produce negative values. For many applications this is not serious (e.g. most classification algorithms) but the possibility of the existence of negative values should be considered when applying further post-processing steps.

A further question of interest may be as to whether the deglinting technique is applicable in situations where the water surface is flat and glint is restricted to a single specular sun reflection or 'hotspot'. In this case the technique can be applied, but only if the hotspot can be assumed to lie over an area of deep water (since this is required to establish the regression slope). However, if this assumption can be made then deglinting is of little advantage.

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