PANCHROMATIC ENHANCED SUPER-RESOLUTION OF MULTI-SPECTRAL IMAGERY

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ABSTRACT

Using high-resolution Panchromatic (Pan) imagery to sharpen Multi-Spectral Imagery (MSI) has been an active area of research for a number of years. The primary innovations of our approach is casting the problem as a super-resolution of the MSI to the sampling geometry of the Pan, using the Pan as a template for object boundaries and cross-calibrating the Pan/MSI spatially and spectrally. This perspective leads us to a fused image with the sampling geometry (high spatial resolution) of the Pan which preserves the radiometric calibration (high spectral resolution) of the MSI. The Pan and MSI do not provide sufficient information for this fused product; additional constrains must be imposed to obtain a unique solution. Preserving the radiometric calibration of the MSI, and our choice of additional constraints are motivated by our ultimate goal of material classification of the MSI at the Pan resolution.

Key Words: Data Fusion, Image Fusion, Pan Sharpened, Super-resolution, Registration, Material Classification, Atmospheric Characterization

INTRODUCTION

Material classification of MSI at Pan resolution can be broken down into the following steps: 1) Collection of Pan and MSI of the same scene, at nearly the same time (within 1 minute), and from nearly the same perspective (same sensor,) 2) register Pan pixels to MSI pixels and estimate spatial/spectral cross-calibration, 3) atmospheric characterization of the MSI overlapping the Pan, 4) data fusion of Pan and MSI, 5) atmospheric correction of fused image, 6) convert corrected image to surface reflectance, 7) segment the multi-band reflectance image, 8) classify segmented image based on material reflectance spectral library.

Image Collection

We specifically define the output fused image to have the same geometry (spatial resolution) of the input Pan image. In addition, we mask out of the fused product all pixels that do not map to valid MSI data. The resolution of the MSI will not be improved except in regions overlapping the Pan.

Between the collection of the Pan and of the MSI, moving objects such as vehicles and ocean waves are not likely to be registered correctly between the two images, leading to error in spatial registration and spectral calibration. If the time between collects is more than a few minutes, the change in position of the sun will result in significant changes in shadows and variations in the illumination of the surface based on how well the surfaces are aligned with the sun. This can result in significant calibration and registration errors. If days pass between the collection of Pan and MSI, there can be significant changes in atmospheric conditions. If months pass, there can be significant changes in the surface properties due to ice, snow, rain, leaves falling from the trees, new growth.

Collecting the Pan and MSI from nearly the same position reduces the impact of parallax of the 3D shape of the scene imaged. This significantly simplifies the registration to little more than shift, scale, and rotation such as an affine transform. For simplicity we limit our discussion to same-sensor collection of Pan and MSI within a minute, although that we acknowledge that our methods can be extended to cross-sensor collection with degraded results.

IMAGE REGISTRATION AND CALIBRATION FROM PAN TO MSI

Fusing the Pan and MSI requires knowing how each pixel in the Pan image maps onto the MSI image with an accuracy of less than 0.1 Pan pixel. The standard approach involves selecting a number of points in one image, finding where they map to in the other image, and optimizing the coefficients of an affine or projection transform between the images. Our novel approach to registration is to derive it as a by-product of spatial/spectral calibration of the Pan and MSI.

We chose to model the transform from Pan to MSI coordinates as a bilinear interpolation. In its most basic form, we estimate where the four corners of the Pan image map to in MSI coordinates. We estimate the mapping of each pan pixel as a bilinear interpolation of the mapping of the corner points

$$\begin{aligned} x_M(i_p, j_p) &= x_M(0,0) + i_p \frac{x_M(m-1,0) - x_M(0,0)}{m-1} + j_p \frac{x_M(0,n-1) - x_M(0,0)}{n-1} \\ &+ i_p j_p \frac{x_M(m-1,n-1) - x_M(m-1,0) - x_M(0,n-1) + x_M(0,0)}{(m-1)(n-1)} \end{aligned},$$

where x_M is the position in MSI coordinates, i_p/j_p are the row/column of the Pan and m/n are the number of rows/columns in the Pan. In registering the Pan to the MSI, we seek to place the four corners of the Pan image onto the MSI to minimize the spatial/spectral calibration error.

Spatial/Spectral Calibration

Based on an estimated mapping between the Pan and MSI pixel coordinates, we propose a method to simultaneously calibrate the radiance values of the MSI bands spectrally to the Pan values and to calibrate the Pan pixels spatially to the lower resolution MSI pixels. The Pan responds to light over a broad spectral range spanning a number of the response of a number of the MSI bands as illustrated in Figure 1 and the footprint of MSI pixels are large enough to spatially span several Pan pixels.

Specifically, we propose to down-sample both images to the same low-resolution Pan image. This image will be the result of spectrally down-sampling the MSI as a linear combination of the bands. It will also be the result of spatially down-sampling the original high-resolution Pan to the MSI by convolving the Pan with a point-spread function (PSF.)

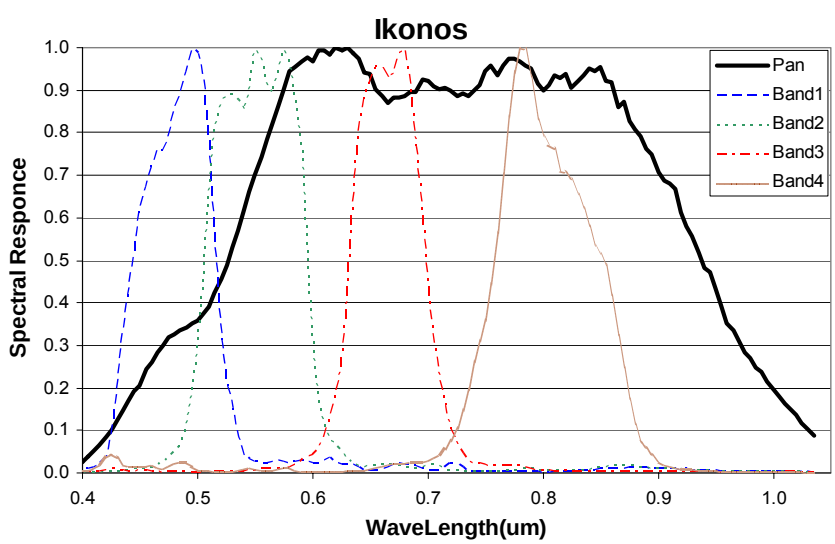

Figure 1. Spectral response curves for IKONOS.

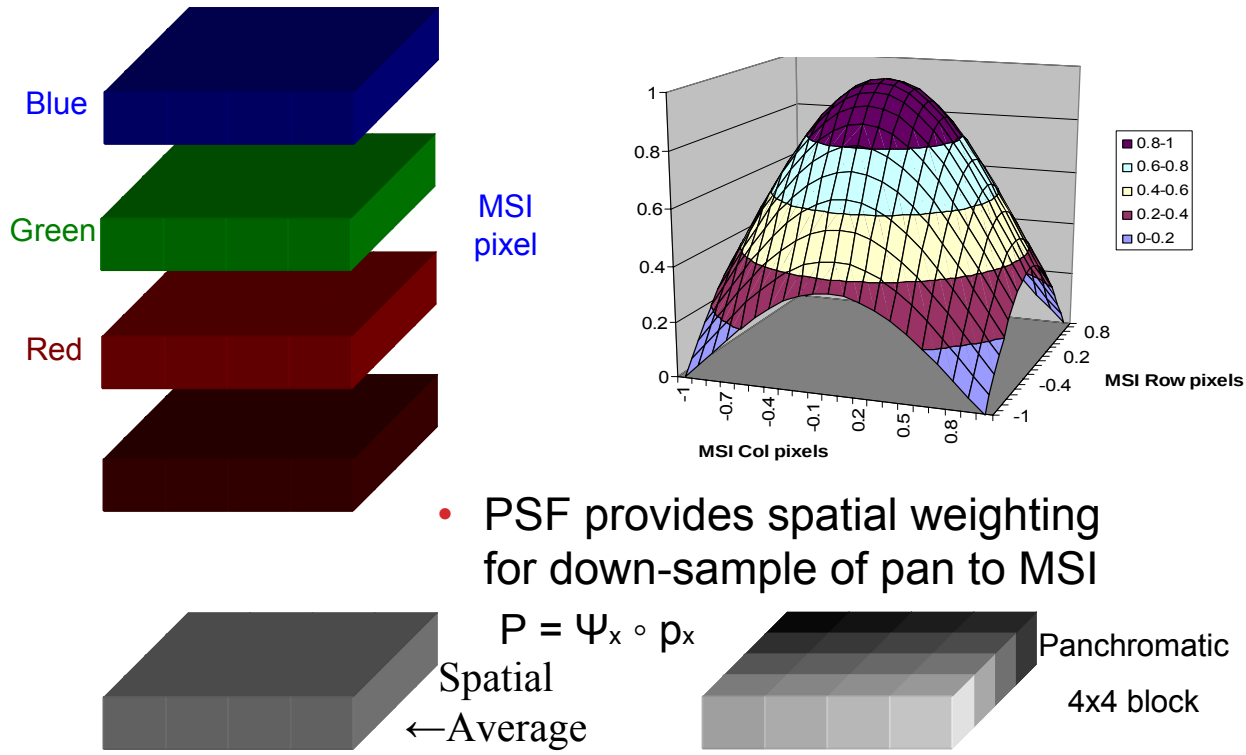

Figure 2. Spectral Calibration Method.

For each MSI pixel, we have

$$\sum_{i,j} p_{i,j}\Psi_{i,j} = P = \sum_{\lambda} W_{\lambda} M_{\lambda} + P_0$$

where P is the Pan radiance of the MSI pixel, W are the unknown spectral weights of the MSI bands, Ψ is the unknown point-spread function, and p is the high-resolution pan image re-sampled to the PSF. In general, the PSF is estimated as a set of weights on a 2D spatial mesh of points in MSI coordinates at roughly the resolution of the Pan image. The PSF mesh should cover about twice the height and width of the MSI pixel.

Since we have a similar equation for each pixel in the MSI image[1], we can write this as an over-determined system of linear equations for the unknown PSF and spectral weights

$$\begin{vmatrix} 1 & \cdots & 1 & 0 & \cdots & 0 & 0 \\ p_{0,0} & \cdots & p_{n,n} & -M_0 & \cdots & -M_b & -1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \end{vmatrix} * \begin{vmatrix} \Psi \\ W \\ P_0 \end{vmatrix} = \begin{vmatrix} 1 \\ 0 \\ \vdots \end{vmatrix}$$

where the first row requires the sum of the PSF to be 1. To make this equation significant, it is weighted to be comparable to the impact of all of the MSI pixels.

In general, the Pan and MSI may have been re-sampled before fusion possibly leading to the PSF being under-determined at this desired resolution. In these cases, the computed PSF can have significant non-physical oscillations. We add regularization terms to this matrix equation to obtain the PSF with the smallest RMS values to minimize the number of negative numbers;

$$\Psi_{i,j} \approx 0 .$$

[1] In general, not all pixels of the Pan and MSI are populated with valid data. Only MSI pixels that have valid data for all bands and all Pan pixels in its PSF footprint are used to compute the calibration and error. We avoid using the brightest 10% of the Pan and MSI to reduce the impact of clouds and saturated pixels.

These regularization constraints are imposed with a (~0.001) smaller weight than the sum to 1.0 constraint since they are added to provide a unique solution to an otherwise underdetermined system of equations.

The degeneracy of the system of equations is also be reduced by explicitly setting peripheral values of the PSF to zero by removing them from the matrix equations and solving again for a more compact PSF.

Atmospheric Characterization of the MSI

We construct a model of how the atmosphere affects the MSI radiance image collected by the sensor and optimize the model based on the MSI and meta-data about the atmospheric conditions and the solar/scene geometry. MSI imaging the visible to near-infra-red spectrum are dominated by solar radiance reflected by the surface materials. The basic radiation transfer equation is

$$\begin{aligned} L_{x,b} &= \Delta_{b,\lambda}\left\{L_\lambda^\uparrow + \left[\cos(\theta_{sol})_x Lsol_\lambda^\downarrow + Lscat_\lambda^\downarrow\right]\rho_{x,\lambda}\right\} \\ &\cong L_b^\uparrow + \left[\cos(\theta_{sol})_x Lsol_b^\downarrow + Lscat_b^\downarrow\right]\rho_{x,b} \end{aligned},$$

where $\Delta_{b,\lambda}$ is the sensor spectral band sampling operator, $L^\uparrow$ is the path radiance spectrum (µf) and $L^\downarrow$ is the at-sensor downwelling radiance (µf). Based on this atmospheric model, atmospheric characterization consists of optimizing the three vectors, $L^\uparrow$, $Lscat^\downarrow$, and $Lsol^\downarrow$.

Atmospheric correction is the process of converting the image radiance to reflectance as

$$\rho_{x,b} \cong \frac{L_b - L_b^\uparrow}{\cos(\theta_{sol})_x Lsol_b^\downarrow + Lscat_b^\downarrow} .$$

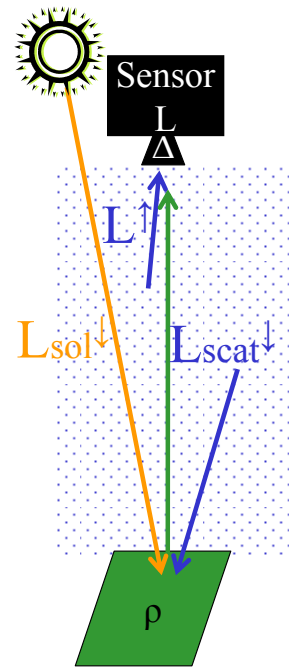

Figure 3. Atm. Radiative Transfer Model.

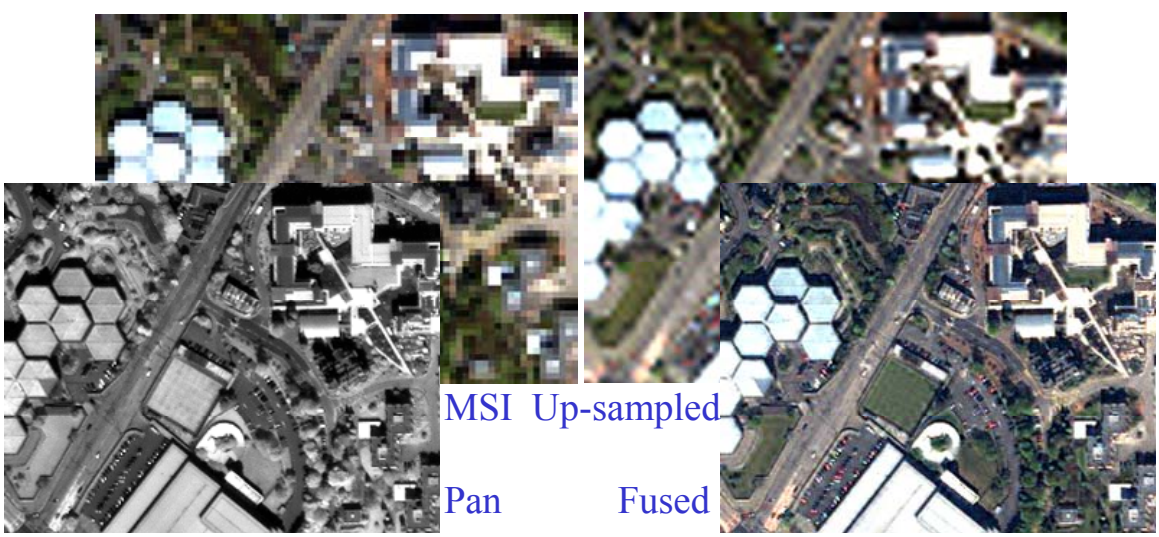

Figure 4. Pan/MSI fusion of IKONOS imagery.

Figure 5. Fusion results for symmetric blur and structured blur.

RESULTS

In the sample results shown in Figure 4, you can see that the resolution of the MSI is improved to the Pan resolution while preserving the spectral calibration (no color artifacts).

CONCLUSIONS

Our method for Pan/MSI fusion 1) preserves the color distribution of the original MSI, 2) is automated requires only a registered pair of pan/MSI, 3) does not introduce ringing artifacts at region boundaries, 4) smoothes fused bands within regions defined by pan, but not across material boundaries, and 5) correctly sharpens bands outside the spectral range of the pan.

We have tested on imagery from IKONOS, Landsat, QuickBird, and Spot.