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Benchmarking of data fusion algorithms in support of earth observation based Antarctic wildlife monitoring

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ABSTRACT

Remote sensing is a rapidly developing tool for mapping the abundance and distribution of Antarctic wildlife. While both panchromatic and multispectral imagery have been used in this context, image fusion techniques have received little attention. We tasked seven widely-used fusion algorithms: Ehlers fusion, hyperspherical color space fusion, high-pass fusion, principal component analysis (PCA) fusion, University of New Brunswick fusion, and wavelet-PCA fusion to resolution enhance a series of single-date QuickBird-2 and Worldview-2 image scenes comprising penguin guano, seals, and vegetation. Fused images were assessed for spectral and spatial fidelity using a variety of quantitative quality indicators and visual inspection methods. Our visual evaluation elected the high-pass fusion algorithm and the University of New Brunswick fusion algorithm as best for manual wildlife detection while the quantitative assessment suggested the Gram-Schmidt fusion algorithm and the University of New Brunswick fusion algorithm as best for automated classification. The hyperspherical color space fusion algorithm exhibited mediocre results in terms of spectral and spatial fidelities. The PCA fusion algorithm showed spatial superiority at the expense of spectral inconsistencies. The Ehlers fusion algorithm and the wavelet-PCA algorithm showed the weakest performances. As remote sensing becomes a more routine method of surveying Antarctic wildlife, these benchmarks will provide guidance for image fusion and pave the way for more standardized products for specific types of wildlife surveys.

1. Introduction

1.1. Remote sensing for Antarctic wildlife

Since its discovery, the Antarctic has been plagued by data scarcity, as geological and biological surveys have been largely confined to easily-accessed coastal regions, or to the areas surrounding permanent Antarctic stations capable of providing logistical support to survey operations. However, the Antarctic is quickly becoming a model system for the use of remote sensing for the physical and biological sciences because the costs of field access are high, the landscape is simple (e.g., rock, snow, ice, water) and free of woody vegetation, and polar orbiting satellites provide extensive regular coverage of the region. Increased access to sub-meter commercial satellite imagery, which rivals aerial imagery in terms of spatial resolution, has sparked a number of developments in geology, glaciology, geography, oceanography, and biology. Very high spatial resolution (VHSR) satellite sensors like IKONOS, QuickBird, GeoEye, Pléiades, Worldview-2, and Worldview-3 provide very high resolution multi-spectral imagery that can capture the detail needed for an array of applications, e.g. individual houses on a city street, individual animals standing on the ground, or individual tree canopies within a forest stand (Ardila et al., 2012; Kurtz et al., 2012; Lynch et al., 2012; Beguet et al., 2014; Huang et al., 2014; Karlson et al., 2014). Due to shorter revisit times of these sensors, it is also possible to acquire near real-time imagery over the area of interest (Kim et al., 2011).

While remote sensing has a long and fruitful history of use mapping environmental layers such as land cover type, which can be used as an indirect measure of biodiversity, the use of remote sensing imagery to directly survey animals (either individual animals, or groups of animals) is, with a few notable exceptions (Schwaller et al., 1984; Schwaller et al., 1989), a much more recent phenomenon (Barber-Meyer et al., 2007; Fretwell and Trathan,

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2009; LaRue et al., 2011; Lynch et al., 2012). Recent satellite-supported surveys of wildlife in the Antarctic have included penguins (*Pygoscelis* spp. and Emperor Penguin, *Aptenodytes forsteri*; Barber-Meyer et al., 2007; Fretwell and Trathan, 2009; Fretwell et al., 2012; Lynch et al., 2012; Schwaller et al., 2013; LaRue et al., 2014; Lynch and LaRue, 2014; Fretwell et al., 2015), seals (Weddell seal, *Leptonychotes weddellii*, LaRue et al., 2011; Ainley et al. 2015; elephant seal, *Mirounga leonina*, McMahon et al., 2014), and whales (Abileah, 2002; southern right whale, *Eubalaena australis*; Fretwell et al., 2014).

VHSR satellite sensors typically record image data in a low resolution multispectral (MS) mode and high resolution panchromatic (PAN) mode. High spatial resolution is needed to accurately describe feature shapes and textural patterns, while high spectral resolution is needed to classify detailed land-use and land-cover types (Wald, 2000; Ranchin et al., 2003; Ehlers et al., 2010; Myint et al., 2011; Yuhendra et al., 2012). Fusing PAN and MS images with complementary characteristics can provide a better representation of the observed area (Wald, 2000; Ranchin et al., 2003). In this respect, data fusion serves as an integral step in the processing of remotely sensed imagery for ecological applications. This is particularly true in surveys of wildlife, where classification hinges on both spectral and spatial information.

The increasing availability of VHSR imagery has resulted in the need for more sophisticated image processing techniques (Gamba, 2014; Pohl and van Genderen, 2014; Xu et al., 2014; Zhang, 2014). Over the years, many image fusion methods have been developed and tested (Hallada and Cox, 1983; De Bethune et al., 1998; Zhang, 2002; Ehlers et al., 2010). A fusion algorithm that preserves the spectral properties of the MS data and the spatial properties of the PAN data would be ideal, but there is always a compromise between these two elements (Civco et al., 2009). The choice of fusion algorithm depends on the application domain because the reflectance varies with different environmental features. Data fusion algorithms introduce spectral and spatial distortions to the resulting fused product that depend on the scene content; therefore, a careful selection of fusion method is required. For example, a fusion algorithm designed to address high-frequency edge information in urban landscapes might not produce satisfactory results when applied to a relatively homogenous agricultural or forested landscape (Witharana et al., 2013b). In this respect, it is challenging to transfer the knowledge on the performances of fusion algorithms that have been tested in one application domain to another application domain. There is a plethora of literature on fusion-quality assessments addressing general context (Vijayaraj et al., 2006; Karathanassi et al., 2007; Ling et al., 2007; Ling et al., 2008; Nikolakopoulos, 2008; Ehlers et al., 2010) and focusing on specific remote sensing applications (Ashraf et al., 2012; Yang et al., 2014; Witharana et al., 2013a; Witharana et al., 2013b), but nothing that would address the needs of Antarctic biology.

The utility of VHSR imagery in Antarctic wildlife detection is new and actively evolving owing to the availability of data and the ever increasing demand for ecological information. It is necessary to revisit best available remote sensing image processing tools, gauge their potential use, and understand the degree of transferability to support accurate and timely wildlife surveys. The study described below reports the first comprehensive work on pansharpening techniques in support of remote-sensing-based wildlife monitoring in Antarctica. The central objective of this research is to investigate how well different fusion algorithms perform when applied to single-sensor single-date VHSR images comprising key wildlife elements (penguin guano, seals, and vegetation); benchmarking these image fusion approaches will provide specific guidance for ongoing wildlife mapping efforts in Antarctica and general guidance for highly similar applications in other high latitude or alpine environments.

1.2. Image fusion and quality assessment

Pohl and van Genderen (1998) defined image fusion as a tool to combine multisource imagery using advanced image processing techniques that can be performed at three different processing levels (pixel, feature, and decision) depending on the stage at which the fusion takes place. Image fusion can occur in different ways such as inter-sensor, intra-sensor, single-date, and multi-date. Pansharpening, also called resolution merge (Gangkofner et al., 2008) is a pixel-level fusion technique used to increase the spatial resolution of the multispectral image while preserving the spectral information (Vijayaraj et al., 2006). Many studies report the problems and limitations associated with different fusion techniques (Chavez et al., 1991; Wald and Ranchin, 1997; Zhang, 2002). The most frequently encountered problem in fusion algorithms is that the fused image exhibits a notable deviation in visual appearance and spectral values from the original MS image (Ling et al., 2007; Kalpoma and Kudoh, 2007). Spectral distortions including spatial artifacts affect both manual and automated classifications because any error in the synthesis of the spectral signatures at the highest spatial resolution incurs an error in the decision (Ranchin et al., 2003). Thus, it is necessary to evaluate the quality of fused images in terms of qualitative and quantitative indices. Qualitative comparison of the fused image and the original MS and PAN images for color preservation and spatial improvements is the most simple but effective way of benchmarking different fusion algorithms (Nikolakopoulos, 2008); on the other hand, visual inspection methods are also subjective and largely depend on the experience of the interpreter (Klonus and Ehlers, 2007; Ehlers et al., 2010).

A number of objective metrics have been proposed to quantify spectral and spatial distortions incurred during the fusion process. Li et al. (2010) document a comprehensive survey on spectral quality indices. The most widely used metrics for evaluating spectral fidelity are the two-dimensional correlation coefficient (CC), root mean squared error (RMSE), relative difference of means, relative variation, deviation index, and band discrepancy. Research by Vijayaraj et al. (2006), Karathanassi et al. (2007), and Yakhdani and Azizi (2010) used peak-signal-to-noise ratio (PSNR) and entropy as spectral quality metrics in addition to common indicators. Wald (2000) proposed the ERGAS metric, which aims to provide a quick but accurate measure of the overall quality of a fused product. Samadzadegan et al. (2012), Witharana et al. (2013b), and Liu et al. (2014) used the spectral angle mapper (SAM) to assess the overall spectral quality of fused images. The universal image quality index (Q-average) is a global metric that models any distortions as a combination of loss of correlation, luminance distortion, and contrast distortion (Wang and Bovik, 2002). Alparone et al. (2004) generalized the Q-average as the Q-4 index, which Alparone et al. (2007) applied to assess fusion quality along with SAM and ERGAS. Alparone et al. (2006) proposed a new index called QNR based on the findings of Wang and Bovik (2002) and Xydeas and Petrovic (2000). The correlation of the gradient information, a combined quantity to evaluate spectral consistency and information content, was developed by Weidner (2010) based on the findings of Wang and Bovik (2002) and Xydeas and Petrovic (2000). Wang et al. (2004) proposed another metric called mean structure similarity index (MSSIM), which is an enhanced version of the Q-average. Ling et al. (2007) and Ehlers et al. (2010) adopted the MSSIM to evaluate the spectral fidelity of fused images. Compared to spectral quality indicators, only a few metrics are available to evaluate the spatial fidelity of fused images (Makarau et al., 2012). Ehlers et al. (2010), Gangkofner et al. (2008), Klonus and Ehlers (2007), and Yakhdani and Azizi (2010) used high-pass correlation and edge detection using filters like Canny, Sobel, and Perwitte. In contrast, Civco et al. (2009), Civco and Witharana