Technical note / Note technique

Impact of sun-surface-sensor geometry upon multitemporal high spatial resolution satellite imagery

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Abstract. Agile high spatial resolution satellites, such as QuickBird, are capable of varying their in-track and cross-track view angles, thereby reducing the time required for the satellite to revisit the same location. However, variation in these view angles can impact the structural representation of image objects, with implications for multitemporal analyses of high spatial resolution imagery. To demonstrate this, we used four QuickBird images collected annually between 2003 and 2006 over a managed forest location near Merritt, British Columbia, Canada. Selected linear features (i.e., roads) were used to assess the geometric fidelity of the images, while forest structure, characterized with image segments and local maxima stem counts, was used to assess the impact of variability in viewing geometry. Using the 2003 QuickBird panchromatic image as a base, over 80% of the selected linear features in the 2004, 2005, and 2006 images were within less than 1 m of the 2003 control, and more than 96% were within 2 m. Using pairwise *t* tests of the stem counts per segment (image-derived spatial units analogous to small groups of trees) for each year of imagery, we identified a significant difference between the stem count generated from the 2005 imagery and stem counts generated from each of the other images. The 2005 image had a markedly different in-track view angle and satellite azimuth relative to the other images considered, and therefore, although our time series of QuickBird imagery had demonstrated geometric fidelity, the forest structural information extracted from our time series was not consistent. We conclude that careful attention should be paid to these image acquisition parameters when selecting high spatial resolution images for multitemporal analyses in forested environments.

Résumé. Les satellites agiles à haute résolution, comme QuickBird, ont la capacité de varier leur angle de visée dans le sens longitudinal et transversal de la trace, réduisant ainsi le temps requis pour que le satellite puisse imager à nouveau le même site. Cependant, la variation de ces angles de visée peut influencer la représentation structurale des objets dans les images, avec des implications au niveau des analyses multitemporelles d’images à haute résolution spatiale. Pour démontrer ce phénomène, nous utilisons quatre images de QuickBird acquises annuellement, entre 2003 et 2006, au-dessus d’une forêt aménagée près de Merritt, en Colombie-britannique, au Canada. Des caractéristiques linéaires sélectionnées (c.-à-d. des routes) sont utilisées pour évaluer la fidélité géométrique des images, alors que la structure forestière, caractérisée avec des segments d’images et des maximums locaux du nombre de tiges, est utilisée pour évaluer l’impact de la variabilité dans la géométrie de visée. À l’aide de l’image panchromatique de QuickBird de 2003 comme base, plus de 80 % des caractéristiques sélectionnées dans les images de 2004, 2005 et 2006 se situaient à l’intérieur de moins de 1 m du contrôle de 2003, et plus de 96 % se trouvaient à l’intérieur de 2 m. À l’aide de tests *t* par paires du nombre de tiges par segment (unités spatiales dérivées des images analogues à des petits groupes d’arbres) pour chaque année des images, nous avons identifié une différence significative entre le nombre de tiges généré à partir des images de 2005 et les nombres de tiges générés à partir de chacune des autres images. L’image de 2005 avait un angle de visée longitudinal ainsi qu’un azimut très différents par rapport aux autres images considérées, et ainsi, quoique notre série chronologique d’images de QuickBird montrait une bonne fidélité géométrique, l’information structurale sur la forêt extraite de notre série chronologique n’était pas cohérente. Nous concluons qu’une attention particulière devrait être portée vers ces paramètres d’acquisition d’images lorsque vient le temps de sélectionner des images à haute résolution spatiale pour les analyses multitemporelles dans les environnements forestiers.
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Introduction

Until recently, aerial photography has been the primary data source for high spatial resolution change detection. Although the first commercial high spatial resolution satellite was launched in 1999 (Wulder et al., 2004), there are few instances of high spatial resolution multitemporal change detection in the literature (Desclée et al., 2006; Im and Jensen, 2005). Possible contributing factors to this apparent research gap include limited image archiving, difficulties in acquiring repeated cloud-free imagery, and the costs of tasking and purchasing imagery. Additional issues that complicate the use of high spatial resolution satellite imagery for change detection include problems in the spatial coregistration of images, and differences in viewing geometry. For example, QuickBird is capable of varying both in-track (fore and aft) and cross-track (off-nadir) view angles, and with a ±30° range in view angles, the satellite is capable of a revisit time of 1–3.5 days (depending on latitude). Although the temporal flexibility afforded by QuickBird's nimbleness can be advantageous, particularly for disaster or emergency monitoring, the variability in viewing geometry has implications for longer term monitoring of fixed objects such as forests.

Monitoring systems that incorporate remotely sensed data often utilize some form of change detection. Image-based change detection can be based on visual interpretation (Clarke et al., 2004), pixel level change (Allen and Kupfer, 2001; Im and Jensen, 2005), or object-based change (Desclée et al., 2006). Visual interpretation can be subject to bias or interpretation error. Regardless of resolution, pixel-based change detection requires that images be coregistered accurately (Townshend et al., 1992), which becomes more challenging as the spatial resolution increases. Pixel-based change detection can also produce a heterogeneous appearance due to the inherent variability of the target and variations in the sensor's response (Gong and Xu, 2003). Improvements in image segmentation have resulted in the emergence of object-based detection approaches (Möller et al., 2007). Image segmentation, which is the basis of object-based change detection, partitions an image into a set of exhaustive, non-overlapping regions that are internally uniform and distinct from adjacent regions.

Traditional pixel-based approaches to change detection are often ineffective in this context due to the off-nadir view angles and prevalence of shadows that are commonly found in high spatial resolution imagery (Im and Jensen, 2005; Smith and Wise, 2007). When there are many pixels per object, rather than many objects per pixel, then high contrast objects, such as shadows, are not subsumed within a larger pixel, but rather, form discrete objects (Wulder et al., 2004). Object-based crown delineation using high spatial resolution images from satellite (Johansen and Phinn, 2006) or airborne (Key et al., 2001) platforms has had limited success, and in a study on shadow fraction estimation, Asner and Warner (2003) concluded that variability in viewing and illumination geometries can result in notable changes in scene reflectance characteristics.

The geometric quality of an image refers to the degree to which image features correspond at the ground-surface level to true values, or those accepted as being true (typically comprising roads, lake edges, or other temporally invariant, spatially distinct features) (Janssen and van der Wel, 1994). Geometric quality is usually assessed through independent checkpoints that are not used in the image correction process (Kay et al., 2003), and is an important step in determining the information value of the results (Janssen and van der Wel, 1994).

In a high spatial resolution image, although the base of a tall object such as a tree or building may be in the correct geographic location, different view angles can cause lay-over, resulting in an appearance that the top of an object is leaning away from its base. Additionally, the surface behind a tall object will be obscured, and image statistics will be affected by the lateral exposure of an object versus the top exposure that is attained with imagery collected at nadir (Schiefer et al., 2005). The amount and direction of lean is dependant on the view angle. As a result, in an image acquired by a satellite that is capable of both in-track and cross-track viewing, a tall object could appear to lean in differing directions and magnitudes (Schiefer et al., 2005). Between two scenes, this can result in the same tree having not only a differently shaped and sized crown, but also the crown center-point being in a different location. Using scenes with different viewing geometry can therefore confound change detection approaches, since the scene structural properties can vary (Im and Jensen, 2005).

In this communication, our objective is to examine the impact of variable viewing geometry in a time series of QuickBird imagery acquired over four successive years. The geometric quality of the images in the time series will be assessed, and information on forest structure will be derived from each image year and compared. Our hypothesis is that the geometric quality of the images is sound and that the coregistration of images is not impacted by variability in viewing geometry. However, information on forest structure is expected to be different with varying viewing geometry due to related differences in tree position, crown size and shape, and shadows, among other factors.

Methods

Study area

The study area, located at Angstad Creek, 25 km south of Merritt, British Columbia, Canada, centered at approximately 49.84°N and 120.75°W, was originally part of a project on mountain pine beetle outbreak development (Carroll et al., 2006a; 2006b). Regular field surveys were conducted between 2002 and 2005 to monitor mountain pine beetle populations in selected forest stands. Three of these forest stands, identified as A, B, and C, were selected for analysis. These stands range in size from 10 to 18 ha with moderately dense stocking (800–1500 stems/ha), and are dominated by pine that are greater than 80 years of age. Mean elevations in these three stands range from 1121 to 1173 m, and average slopes are all less than 5°.

Table 1. Acquisition parameters for the QuickBird imagery.

Acquisition date	Local time (PDT)	Sun azimuth (°)	Sun elevation (°)	Satellite azimuth (°)	Satellite elevation (°)	In-track view angle (°)	Cross-track view angle (°)
2003–06–04	11:51	146.8	59.5	51.2	74.4	11.1	9.6
2004–07–17	11:59	148.0	58.3	43.5	75.3	11.6	7.5
2005–07–20	12:12	153.7	58.8	**128.5**	75.4	**–6.2**	12.0
2006–08–15	12:23	162.1	53.2	56.1	81.9	5.5	5.3

Note: Values noted in bold type indicate view parameters that are notably different.

Data

Four QuickBird-2 images were acquired during each of the 2003 to 2006 summer growing seasons (**Table 1**). The sun elevation at the time of image acquisition ranged from 53° to 58° and the off-nadir view angles ranged from 7.7° to 14.6° (**Figure 1**). QuickBird imagery contains four multispectral bands with a 2.5 m spatial resolution: 0.45–0.52 µm (blue); 0.52–0.60 µm (green); 0.63–0.69 µm (red); 0.76–0.90 µm (near-infrared); and a panchromatic band (0.45–0.90 µm), with a 0.68 m spatial resolution (Birk et al., 2003).

The QuickBird images used in this analysis were received as Standard Image products, in at-sensor radiance, from the data provider (DigitalGlobe Inc., 2007). Prior to analysis, radiometric processing was undertaken, as multitemporal analysis necessitates calibration of pixel values (Wu et al., 2005); radiance values were converted to top-of-atmosphere (TOA) reflectance using the gains and offsets provided in the

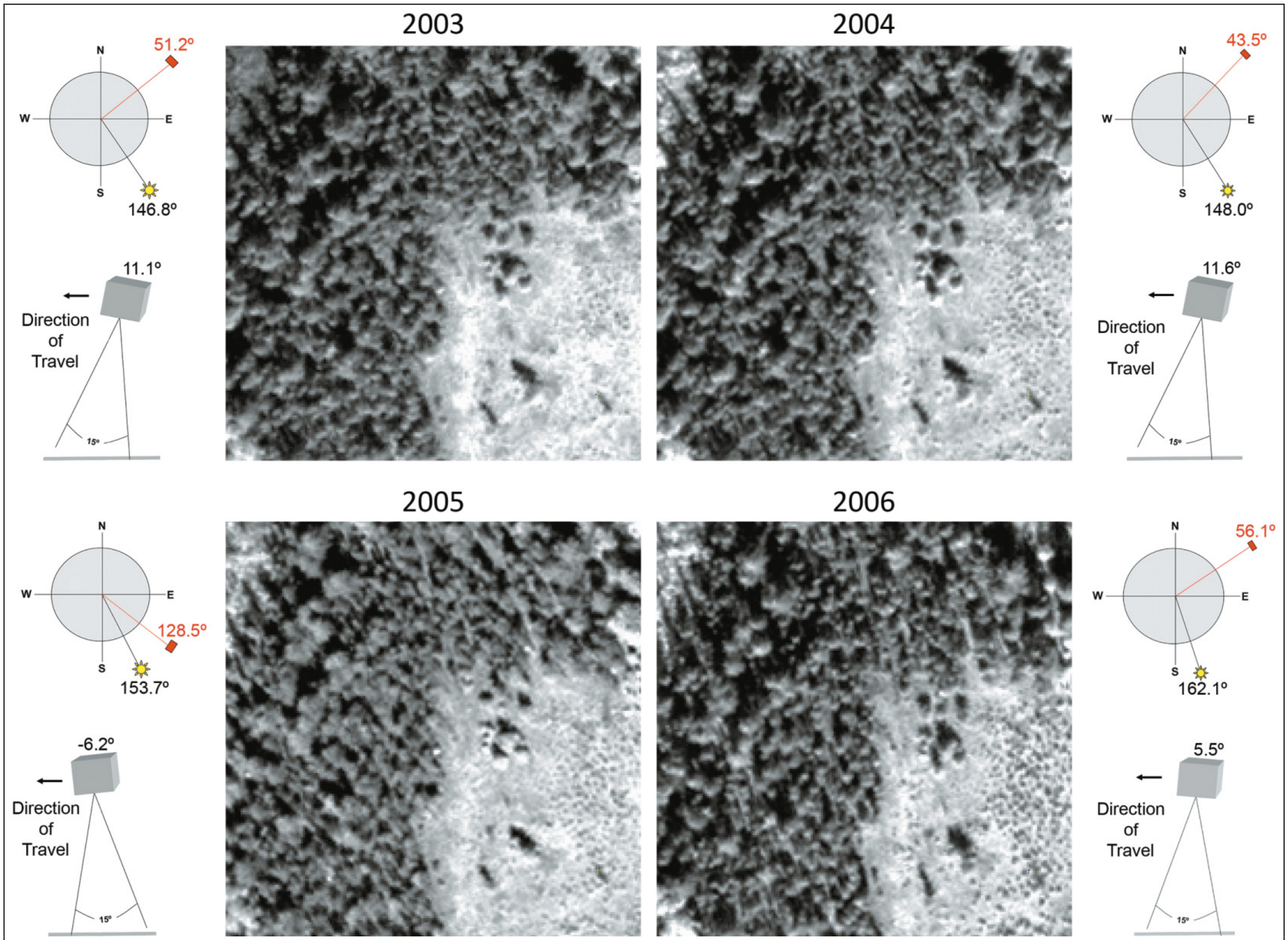

Figure 1. Comparison satellite scenes and solar and in-track satellite angle.

image header files along with solar exo-atmospheric irradiances estimated from normalized spectral response data (DigitalGlobe Inc., 2007) and a standard extraterrestrial solar spectrum reference (American Society for Testing and Materials, 2000). The 2003 image was georeferenced to Terrain Resource Information Management II (TRIM II) aerial photography (1:20 000) (British Columbia Ministry of Environment, Lands, and Parks, 1992) using a third-order polynomial and a cubic convolution resampling algorithm. The 2003 image was then used as the control image to which the 2004, 2005, and 2006 images were subsequently geometrically coregistered (also using a third-order polynomial and a cubic convolution resampling algorithm). Using a minimum of 15 ground control points, the final root mean square error (RMSE) for all three images was less than 1 pixel (0.58 m), with an average RMSE of 0.36 m for the panchromatic image band.

Geometric quality assessment

The geometric quality of the images was assessed by selecting the same sample of linear features (roads) from all of the image dates, and these same features were manually digitized from each of the images. The 2003 features were used as the control (i.e., as representing true position on the ground); these vectors were converted to point features at approximately 60 cm spacing, resulting in a total of 3800 points, each of which was treated as a separate checkpoint. The distance from each of these points to the nearest vector vertex (also at 60 cm spacing) in each of the 2004, 2005, and 2006 images was measured. This approach was used, as roads provided the only suitable checkpoint locations for the purpose of this study.

Structural analysis

With confidence in the geometric quality of the images, tree counts are selected as a means of characterizing forest structure. Stem density is commonly used as an indicator of forest structure in a range of applications such as habitat assessment (Loehle et al., 2005), forest succession (Boudreault et al., 2008), and biomass (Litton et al., 2003) The 2003 multispectral QuickBird image was segmented using eCognition software (Definiens GmbH, München, Germany); all four bands were used as input with the following parameters: equal weights for all bands; scale = 15; shape = 0.9; colour = 0.1; compactness = 1; smoothness = 0. The segmentation is performed to generate spatial units, analogous to small groups of trees, that can be used to generalize and report on the tree-level findings (Wulder et al., 2008). Segmentation is preferred over the use of a grid-based tessellation, as performed in Coops et al. (2004), to minimize edge effects and to enable temporal comparisons capturing units containing similar spatial structure. A local maximum (LM) filter was used to identify individual trees on the QuickBird panchromatic imagery independently from each year. The LM identifies tree crowns as local regions of relatively higher reflectance and has a bias towards large tree crowns, with a higher error of omission for smaller tree crowns (Wulder et al., 2000). Since the time span over which the images were collected is only four years, very few (if any) trees will grow (emerge from lower strata) sufficiently to be undetectable in the first year, and detectable in the last year. Thus, it is assumed that any changes in tree counts can be attributed to differences in viewing geometry. The results of the local maxima filter were then aggregated by segment. The LM tree counts were then used in pairwise *t* tests that compared the number of trees per segment between image years.

Results and discussion

Geometric quality assessment

The cumulative percentage of 2003 control points found within a given distance of the linear features captured from the 2004, 2005, and 2006 images are shown in **Figure 2**. For the 2004 image, 100% of roads are closer than 1 m to the 2003 control; for the 2005 image, 81.5% of roads are closer than 1 m to the 2003 control; and for the 2006 image, 86.1% of roads are closer than 1 m to the 2003 control. The maximum errors are 0.96 m for 2004, 2.47 m for 2005, and 1.27 m for 2006. Thus, the maximum geometric error that can be expected is an offset of approximately four pixels. The average offsets for each year are 0.21, 0.52, and 0.57 m for the 2004, 2005, and 2006 images, respectively. Therefore, on average, the three panchromatic QuickBird images are within one pixel of the base (2003) image, which indicates that the geometric fidelity of the QuickBird time series is sufficient to expect the absolute location of tree crowns to remain constant throughout the analysis.

Structural analysis

The total number of segments and the total stem counts for each of the three forest stands and for each image year are summarized in **Table 2**. The results of the pairwise *t* tests (**Table 3**) indicate that, for all three stands, there is a significant difference in the number of trees identified in the 2005 image compared with the 2003, 2004, and 2006 images (p-value = 1.964, $\alpha = 0.05$). The only other significant difference in stem counts was found in stand A between the 2003 and 2004 images ($\alpha = 0.05$). These results indicate that in a forested environment, varying view angles resulted in a change in the representation of forest structure sufficient to produce significantly different tree counts. Since a forest canopy can be of complex vertical structure, a change in view angle or direction can result not only in the apparent change in position of tree crowns, but also in shorter or narrower trees being concealed behind larger ones. Moreover, changes in sun angle or direction will result in a different shadow size and orientation, which can also result in smaller trees being hidden in the shadow of larger ones. Thus, the interactions of sun and sensor geometry can be quite complex, resulting in inconsistent forest structure measurements over different scenes.

Individual trees and related shadows were manually delineated in an open area to illustrate the impacts of viewing geometry on the representation of forest structure. **Figure 3**

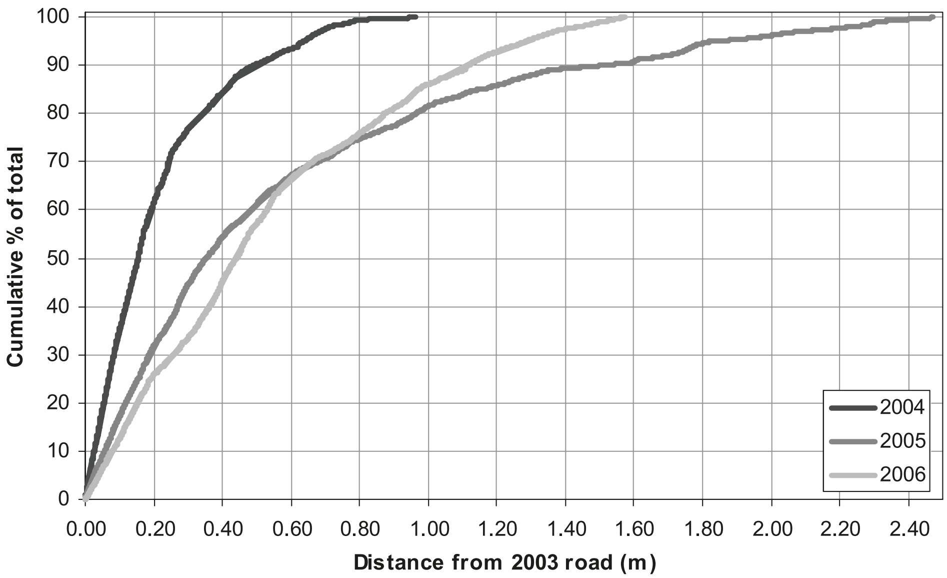

Figure 2. Using road features defined on the 2003 control image, the distance to the same features for the 2004–2006 images is presented. In the graph, we show the cumulative percent (*y*-axis) of points that are within a given distance of 2003 (*x*-axis).

Table 2. Total number of segments and total local maximum (LM) stem counts for each forest stand in the study area.

	No. of	LM identified trees			
	segments	2003	2004	2005	2006
Stand A	454	10 126	10 336	10 743	10 232
Stand B	596	10 820	10 959	11 326	10 966
Stand C	313	6 379	6 404	6 822	6 381

shows a comparison between the 2003 image and the 2005 image, with the latter having a markedly different in-track view angle and satellite azimuth relative to the other images considered. It should be noted that the shadows (blue) between these two images are very similar, as should be the case given that the solar azimuth and elevations for these two scenes are similar, as exemplified by the shadows cast from the trees in the cleared forest. Differences are apparent in the shape of the tree crowns and in the position of the trees. The trees in the opening (red) have very large crowns and show an offset between the two dates, an effect that is also observed within the closed canopy. The smaller magenta (2003) and cyan (2005) crowns outlined in the canopy are the same trees; however, two of the crowns identified in the 2003 image were not recognizable in the 2005 image. This is likely due to these trees being shorter than the surrounding ones, and either they are concealed within the shadows of larger trees or they have visually merged with the canopies of other trees.

Table 3. Pairwise t-values and p-values (in italics) by stand ($t_{crit} > 1.964$, $\alpha = 0.05$), with significant values in bold.

	2003	2004	2005	2006
Stand A				
2003	—	**–2.3595**	**–6.2293**	–0.9794
	—	***0.0187***	$\boldsymbol{1.08 \times 10^{-9}}$	*0.3279*
2004		—	**–4.6686**	1.4785
		—	$\boldsymbol{4.01 \times 10^{-6}}$	*0.1400*
2005			—	**5.7977**
			—	$\boldsymbol{1.27 \times 10^{-8}}$
Stand B				
2003	—	–1.8289	**–4.5781**	–1.9630
	—	*0.0679*	$\boldsymbol{5.72 \times 10^{-6}}$	*0.0501*
2004		—	**–3.4914**	–0.1142
		—	$\boldsymbol{5.16 \times 10^{-4}}$	*0.9091*
2005			—	**3.4472**
			—	$\boldsymbol{6.06 \times 10^{-4}}$
Stand C				
2003	—	–0.4282	**–5.2864**	–0.0355
	—	*0.6688*	$\boldsymbol{2.35 \times 10^{-7}}$	*0.9717*
2004		—	**–5.1860**	0.4655
		—	$\boldsymbol{3.87 \times 10^{-7}}$	*0.6419*
2005			—	**5.4580**
			—	$\boldsymbol{9.83 \times 10^{-8}}$

Note: Statistical comparisons were performed on the temporally varying tree counts found within the temporally invariant segments produced from the year 2003 image for stands A, B, and C.

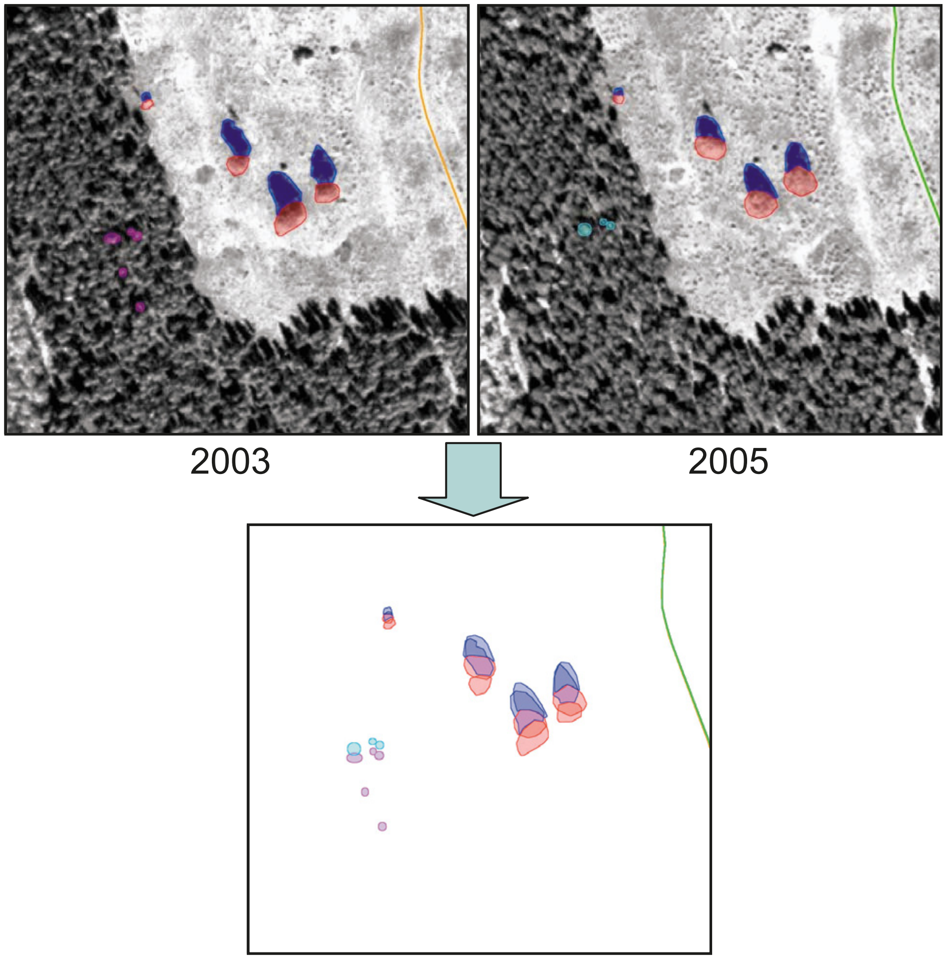

Figure 3. Comparison of the 2003 base image to the 2005 image. For the open area, vectors indicate the same tree crowns (red) and shadows (blue), as well as roads (orange and green). In the forest canopy, a selection of trees in the 2003 image (magenta) are partially identifiable in the 2005 image (cyan). The vector overlay (bottom panel) shows the comparison between the 2003 and 2005 identified objects.

Conclusions

Although we were able to verify the geometric fidelity of the time series of QuickBird imagery used in this study, significant differences in forest structure were found between the 2005 image and the other images. The 2005 image had a markedly different in-track view angle and satellite azimuth relative to the other images in our time series. With the advent of agile high spatial resolution satellites capable of acquiring imagery with a range of view angles, careful consideration must be given to these image acquisition parameters when ordering data for change detection analyses, particularly for projects in forested environments.

The small footprint and the need for pointable sensor heads to reduce revisit times will likely mean the issues identified here will persist and need to be considered for forest monitoring applications. The increasing numbers of spaceborne high spatial resolution sensors (with panchromatic spatial resolution of less than 1 m) will provide for additional acquisition options. Changes to how vendors task and capture high spatial resolution images will be required before users can take real advantage of multiple sensors. The ability to task multiple satellites for delivery of a single image that best meets acquisition requirements would be desirable from a user point of view.

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