Impact assessment of Aqua MODIS band-to-band misregistration on snow index

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Abstract. The MODerate Resolution Imaging Spectroradiometer (MODIS) is a key instrument for the NASA Earth Observing System (EOS) mission. It was successfully launched onboard the Terra satellite in December 1999 and Aqua satellite in May 2002. MODIS senses the Earth's surface in thirty-six spectral bands which are distributed on four Focal Plane Assemblies (FPAs): Visible (VIS), Near-Infrared (NIR), Short-and Middle-wavelength IR (SMIR), and Long-wavelength IR (LWIR). It was found from sensor pre-launch measurements that Aqua MODIS SMIR/LWIR FPAs had a large misalignment or misregistration relative to the VIS/NIR FPAs in both along-scan and along-track directions. The misregistration of the two FPA groups has remained nearly the same during its on-orbit operation. Consequently this has been a major concern for Aqua MODIS performance since it could affect the quality of MODIS products which utilize bands from both the VIS/NIR and SMIR/LWIR FPAs, for example, the snow index. This paper focuses on investigating the impact of Aqua MODIS FPA–to-FPA or band-to-band misregistration on its snow index (NDSI) derived from measurements made by VIS band 4 and SWIR band 7. Preliminary results show that shifting one pixel (500 m) forward in the along-track direction of band 7 can improve the band-to-band registration between bands 4 and 7 and, therefore, the quality of Aqua MODIS snow mapping. This study will help MODIS data users to understand the potential impact of band-to-band misregistration on MODIS science products, and also be useful for the future sensor design.

Keyword: MODIS, Aqua, Focal Plane Assemblies, misregistration, NDSI, snow mapping.

1 INTRODUCTION

1.1 Aqua MODIS spatial characterization

The MODerate Resolution Imaging Spectroradiometer (MODIS), launched onboard the Terra satellite in December 1999 and the Aqua satellite in May 2002, contains thirty-six spectral bands spanning the visible (0.415 µm) to infrared (14.235 µm) spectrum at three different nadir spatial resolutions: 1 km (bands 8 to 36), 500 m (bands 3 to 7), and 250 m (bands 1 and 2) [1-3]. The spectral bands are located on four Focal Plane Assemblies (FPAs): Visible (VIS) for bands 3-4 and 8-12, Near Infrared (NIR) for bands 1-2 and bands 13-19, Short-and Middle-Wavelength Infrared (SMIR) for bands 5-7 and 20-26, and Long-Wavelength Infrared

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(LWIR) for bands 27-36 [4]. The band-to-band co-registration requirement (at nadir) is ±10% of a 1 km pixel or 100 m at the surface for both along-scan and along-track direction [5].

Using lessons from Terra MODIS design and characterization, the Aqua MODIS has made improvements on a number of sensor performance issues, such as system stability, crosstalk characterization, and mirror side difference [6]. However, Aqua MODIS suffers a major drawback for the band-to-band misregistration. It was found from pre-launch spatial characterization that the SMIR/LWIR FPAs had a large misalignment relative to the VIS/NIR FPAs in both along-scan and along-track directions. The SMIR/LWIR FPAs had a shift of approximately 0.2-0.35 km in the along-scan direction and 0.2-0.4 km in the along-track direction at nadir. It was clear that Aqua MODIS failed the specification of ±100 m co-registration in both directions for the bands between the two FPA groups. The alignment problem between the cooled (SMIR/LWIR) and un-cooled (VIS/NIR) FPAs can be caused by: (1) the physical shift of any optical element in the optical path mainly due to environmental temperature changes and vibrations during MODIS transportation and launch; (2) the focal planes shift due to the fragile attachment of the FPAs to the MODIS main frame to maintain thermal isolation for the cold FPAs for the SMIR/LWIR bands; (3) the difference in the signal photon integration times, crosstalk, and processing in the circuit [7]. Xiong et al. (2006) analyzed four-year trending of Aqua MODIS FPA to FPA registration for both along-scan and along-track and found that the misregistration of the two FPA groups or bands in Aqua MODIS has remained nearly the same during its on-orbit operation [8]. The Spectro-Radiometric Calibration Assembly (SRCA) is an on-board calibrator of MODIS that was designed to measure the band-to-band registration (BBR) and tracks the BBR change over time. Table 1 lists the average, at launch BBR measured by the SRCA for Aqua MODIS bands 1 to 7 (relative to band 1) in both along-track and along-scan directions. The BBR difference between Aqua MODIS band 4 and band 7 is 447 m in along-track direction [9-10].

Table 1. The average BBR measured by SRCA for Aqua MODIS bands 1-7 (relative to band 1)

Aqua/MODIS	Central Wavelength (μm)	FPA	Along-scan(m)	Along-track(m)
Band 1	0.645	NIR	0	0
Band 2	0.858	NIR	-4	0
Band 3	0.469	VIS	30	-9
Band 4	0.555	VIS	4	-38
Band 5	1.240	SMIR	-246	366
Band 6	1.640	SMIR	-285	382
Band 7	2.130	SMIR	-223	409

Using ground measurements over a carefully selected site (with high contrast scenes) to calculate the spatial deviation is one of the approaches for validating the results from the SRCA. Yong et al. (2006) have demonstrated an example showing that spatial deviation exists between different FPAs in both along-track and along-scan directions (Fig. 1). For a relatively darker target with lower reflectance than its neighboring pixels, bands 1 and 4 on the VIS/NIR FPAs scan it about one pixel (500 m) later than bands 5 and 7 on the SMIR FPA in along-track direction, and about one pixel earlier in along-scan direction. Results from comprehensive analyses of multiple overpasses of the ground targets are generally in good agreement with the BBR measured from the SRCA. The spatial deviation of Aqua MODIS is clearly out of specification for bands between VIS/NIR and SMIR/LWIR FPAs, with a maximum value approaching one pixel (500 m) at nadir in along-track direction, and over a half pixel (250 m) in along-scan direction [10].

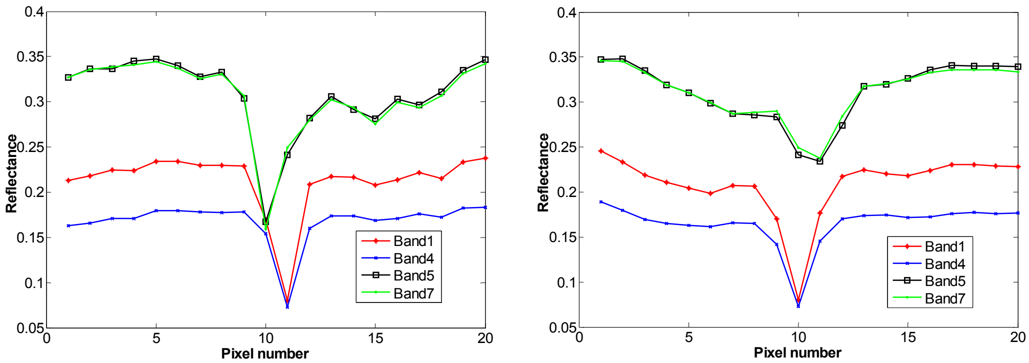


Fig. 1. Spatial deviation between VIS/NIR and SMIR FPAs in both along-track (left) and along-scan direction (right).

Obviously, the Aqua MODIS band-to-band misregistration is a significant issue that could affect the quality of MODIS products generated using measurements from different (or multiple) spectral bands. This paper focuses on the impact of the spatial alignment of Aqua MODIS on its snow index which uses VIS band 4 and SWIR band 7.

1.2 Aqua MODIS NDSI

MODIS is powerful in the remote sensing of snow because its bands cover the VIS and SWIR wavelengths. Snow has high reflectance in the VIS but low reflectance in the SWIR at about 1.6 µm, a characteristic that allows for snow detection by a normalized ratio of VIS and SWIR bands. The automated MODIS snow-mapping algorithm uses at-satellite reflectance in MODIS VIS band 4 and SWIR band 6 to calculate the Normalized Difference Snow Index (NDSI) [11].

The Aqua MODIS instrument has been performing well since its launch with the exception of band 6. Fifteen of the twenty detectors in Aqua MODIS band 6 are either non-functional or noisy (http://www.mcst.ssai.biz/mcstweb/performance/aqua/aqua-nonfunct-dets.html) [12]. Since snow has similar reflectance characteristics in MODIS bands 6 and 7 relative to other bands, the Aqua-specific snow mapping algorithm uses the Aqua MODIS band 7 instead of band 6 to compute NDSI:

$$NDSI = \frac{band4 - band7}{band4 + band7}, \tag{1}$$

where band4 and band7 are reflectances at top of atmosphere (TOA) in Aqua MODIS bands 4 and 7, respectively [13].

Spurious differences may be introduced into NDSI data when about one (447 m) or half (227 m) pixel misregistration exists between bands 4 and 7 in along-track or along-scan direction, especially for the boundary of the snow cover features. Therefore, it is necessary to investigate the impact of Aqua MODIS band-to-band misregistration on snow index NDSI. To accomplish this, three cases have been studied that run on 500m L1B granules with fixed MODIS band 4 and shifted band 7 in both along-scan and along-track directions.

2 METHODOLOGY

The impact of misregistration upon snow index is illustrated using Aqua MODIS 500 m L1B calibrated radiance and 1 km L1A geo-location data to analyze its snow mapping ability. MODIS L1B 500 m granules contain 5 minutes of radiometric calibrated and geo-located radiances at TOA for seven MODIS spectral bands (bands 1 to 7) at 500 m resolution. MODIS L1A geo-location data contain geodetic latitude and longitude, surface height above geoid, solar zenith and azimuth angles, satellite zenith and azimuth angles, and a land/sea mask at 1 km resolution.

The MODIS L1B data are first shifted in along-track and along-scan directions. Then all of the swath data are preprocessed using MODIS Reprojection Tool (MRT) Swath, a tool for re-projecting MODIS swath data to gridded products (http://edcdaac.usgs.gov/landdaac/tools/mrtswath/). Using nearest neighbor re-sampling, the data are re-sampled to grid data with an equal area at 500 m resolution. The TOA reflectances of bands 4 and 7 are generated with the gridded radiances and solar zenith angles. NDSI is produced using the equation (1). The water bodies are identified by using the land/sea mask in the L1A geo-location data. Finally the number of grids which are covered by water but have been taken as snow using snow mapping algorithm can be determined and compared.

2.1 Data used

Three Aqua MODIS granules of the same area with extensive snow cover were selected from December 30, 2003, January 15, 2004, and January 31, 2004. These granules include MODIS L1B calibrated radiance (500 m, version 4) and MODIS L1A geo-location (1 km, version 4). Each granule covers the area with latitude ranging from 35.14^{o} to 56.83^{o} and longitude ranging between -91.76^{o} and -54.95^{o} (Fig. 2).

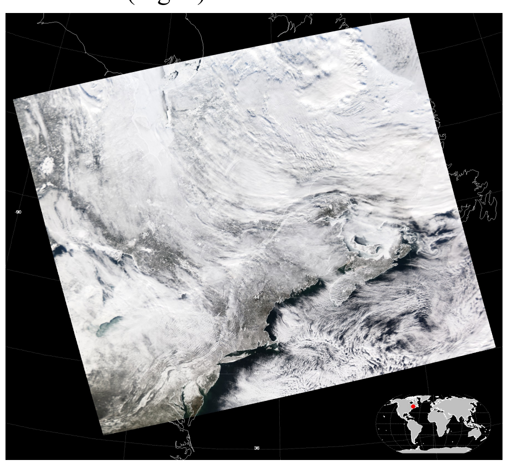


Fig. 2. True color image of the granule data on January 31, 2004.

2.2 Data processing

The L1B 500 m calibrated radiances are shifted in along-scan or along-track direction by amounts of 0, -1 (backward), and +1 (forward) pixel respectively. The original and shifted L1B data are then projected to grid data at 500 m resolution by using MRT Swath. Table 2 gives the geo-location of the input and output area in the MRT Swath by using Albers Equal Area Conic map projection. Also MODIS L1A 1 km solar zenith angle and land/sea mask are re-projected to 500 m grid data. Each re-sampled data are comprised of 2454 grids along track and 3368 grids along scan. Shown in Fig. 3 is the gridded land/sea mask, with blue color representing water, and white color representing land and ocean coastlines or land shorelines.

To reduce the impact of view angles, the study area is limited to the region in the red box with view angles less than 30 degree.

Table 2. The geo-location of input and output area in MRT Swath

	Study area	Latitude	Longitude
Input	Upper left corner	50.0^o	-82.0^o
	Lower right corner	40.0^o	-62.0^o
Output	Upper left corner	51.0^o	-82.5^o
	Lower right corner	38.8^o	-62.3^o

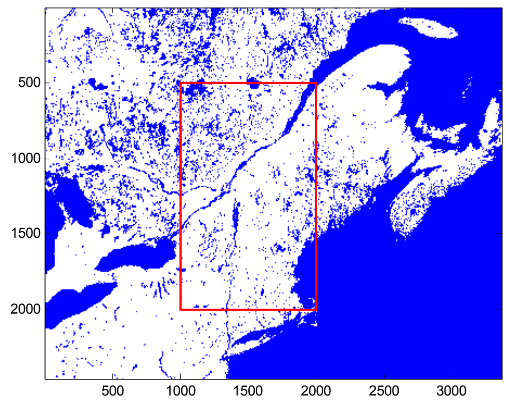


Fig. 3. Gridded land/sea mask.

2.3 Snow mapping algorithm

The approach to map snow is based on the Aqua-specific version of the L2 snow algorithm used in the MODIS Snow and Sea Ice Products. A pixel is mapped as snow if the NDSI is ≥0.54 and reflectance in MODIS band 2 (0.841-0.876 μm) and MODIS band 4 (0.545-0.565 μm) are ≥10% [14]. The threshold test of bands 2 and 4 prevents pixels from containing very dark targets such as black spruce forests, or clear water bodies from being mapped as snow because very low reflectance causes the denominator in the NDSI to be quite small, and only small increases in the visible wavelengths are required to make the NDSI value high enough to classify a pixel, erroneously, as snow [14].

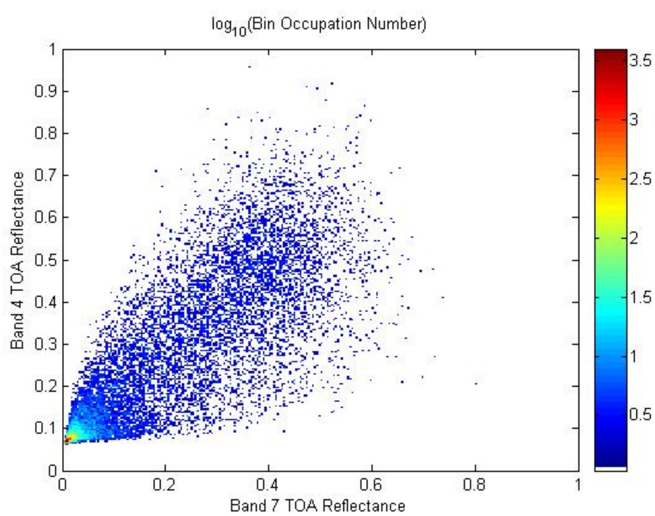
3 RESULTS

Four kinds of shifts have been performed on L1B data of MODIS band 7, including one pixel backward (-1) or forward (+1) in along-scan or along-track direction, respectively. In order to investigate the shift effects on the relationship between bands 4 and 7, cross correlations between these two bands are computed. Considering that the relations of two bands should be relatively stable and simple if the target is homogeneous, only data with the same land cover type: continental/moderate ocean in the land/sea mask are used. The results show that shifting one pixel forward for band 7 in along-track direction improves the correlation significantly, with the maximum enhancement of 13.93% from 0.8105 to 0.9234, and decreases the standard deviation by -35.74% (Table 3). The impact of shifting one pixel backward for band 7 in along-scan direction is also visible, but is not so obvious as shifting one pixel forward in along-track direction. This result might be caused by about half pixel over-shift since the spatial deviation between bands 4 and 7 in along-scan direction is 247 m: a fraction of one pixel (~1/2 pixel). On the contrary, shifting one pixel backward for band 7 in along-track direction or one pixel forward in along-scan direction worsens the correlation and increases the standard deviation compared with the original data.

Table 3. Statistic for correlation of band 4 and shifted band 7

	Shift Direction		Result			
	Along Track	Along Scan	Correlation Coefficient(R^2)	Percentage Difference (%)	Standard Deviation	Percentage Difference (%)
20031230	0	0	0.6218	0	0.1253	0
	1	0	0.6623	6.51	0.1207	-3.67
	-1	0	0.5638	-9.33	0.1317	5.11
	0	1	0.5757	-7.41	0.1304	4.07
	0	-1	0.6386	2.70	0.1235	-1.44
20040115	0	0	0.8105	0	0.1164	0
	1	0	0.9234	13.93	0.0748	-35.74
	-1	0	0.6669	-17.72	0.154	32.30
	0	1	0.6862	-15.34	0.1494	28.35
	0	-1	0.8546	5.44	0.1022	-12.20
20040131	0	0	0.8925	0	0.0728	0
	1	0	0.9504	6.49	0.0498	-31.59
	-1	0	0.8036	-9.96	0.0978	34.34
	0	1	0.8122	-9.00	0.0964	32.42
	0	-1	0.9111	2.08	0.0659	-9.48

The density plots of band 4 to band 7 on January 15, 2004 (Fig. 4) reinforce that, compared with the relationship between band 4 and un-shifted band 7, shifting one pixel forward for band 7 in along-track direction makes these two bands better correlated. Comparing these two scatter plots, the lower figure shows stronger correlation between band 4 and shifted band 7, which results in tightly clustering of data points, suggesting a stable positive linear relationship, while the upper one appears more random.



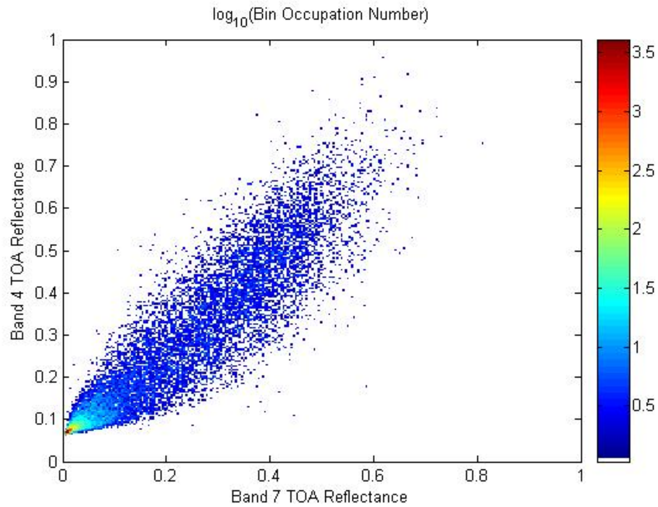


Fig. 4. a. Density plot of band 4 to band 7 on January 15, 2004. b. Density plot of band 4 to shifted band 7 (+1 pixel in along track) on January 15, 2004.

The Histograms in Fig. 5 show the distribution of NDSI in five situations for the case on January 31, 2004. It is clear that for all histograms, the majority of the NDSIs are in the 0.4 to 0.6 value category and most NDSIs appear to be within the range between 0 and 1, with a few outside these limits. With respect to distributional shape, note that all the histograms are skewed right. But in regard to variation, the spread of all the histograms appear to be somewhat different from each other in each NDSI category. For example, the bar of original NDSI appears somewhat higher than that of NDSI with one pixel forward shifting in along-track direction or backward shifting in along-scan direction, while lower than the other two shifting in the value of 0.6 to 0.8 category. Thus the histograms reveal that the shift in along-scan or along-track direction does not change the general distribution of NDSI, with respect to the data center and the distribution shape, but it does introduce slight differences in regards to variation of the NDSI value category, while determines the snow mapping results. Comparing each bar in 0.6 to 1 category, it is easy to conclude that fewer grids will be mapped as snow by NDSI with one pixel forward shifting in along-track direction or backward shifting in along-scan direction, if the criteria of NDSI>0.54 alone is used to map snow.

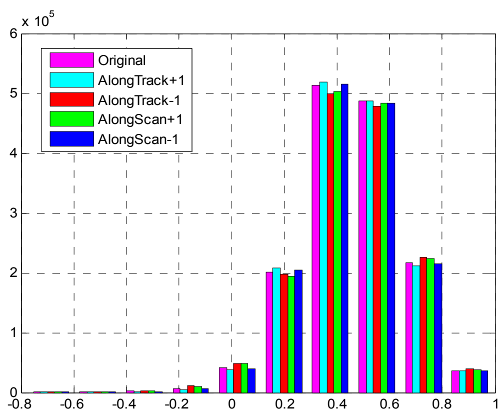


Fig. 5. Histograms of NDSI.

Snow images are obtained using the snow mapping algorithm described in section 2.3. When overlaying land/sea mask on snow mapping images, it is found that some girds of water have been classified, erroneously, as snow (Table 4). Compared with the un-shifted data, shifting one pixel forward for band 7 in along track direction decreased the number of water grids taken as snow by NDSI, and hence improves the accuracy of snow mapping, with the maximum improvement approaching 4.4%. The improvement is also visible when shifting one pixel backward in along-scan direction, although it is not so significant. The shifts in two other directions, on the contrary, take more water grids as snow and worsen the snow mapping accuracy. Listed in Table 5 is the total number of snow grids taken by different NDSI, which indicates that, compared with the original data, shifting band 7 in any direction will change the snow mapping results by 1 or 2 percent in this study.

Despite the positive results, large numbers of water grids that have been classified erroneously as snow have also been observed in this study. Re-projecting the 1 km L1A land/sea mask to 500 m grid data may cause this result. The error could also come from the fact that using 0.54 as a threshold of NDSI may not represent the real situations. The setting of 0.54 as Aqua MODIS NDSI threshold is based on analysis of twelve granules, from different regions in the Northern Hemisphere [14]. But this threshold value may vary in different situations.

Table 4. Statistic for grids of water taken as snow

	Shift Direction		Result		
	Along Track	Along Scan	Water Taken As Snow	Compared with Original Data: Difference	Compared with Original Data: Percentage Difference (%)
20031230	0	0	38584	0	0
	1	0	38045	-539	-1.4
	-1	0	39069	485	1.26
	0	1	39093	509	1.32
	0	-1	38335	-249	-0.65
20040115	0	0	54812	0	0
	1	0	53099	-1713	-3.13
	-1	0	56908	2096	3.82
	0	1	56361	1549	2.83
	0	-1	54554	-258	-0.47
20040131	0	0	28443	0	0
	1	0	27204	-1239	-4.36
	-1	0	30495	2052	7.21
	0	1	30013	1570	5.52
	0	-1	28250	-193	-0.68

Table 5. Statistic for snow mapping

	Shift Direction		Result		
	Along Track	Along Scan	Snow Grids	Compared with Original Data	
				Difference	Percentage Difference (%)
20031230	0	0	546837	0	0
	1	0	534793	-12044	-2.2
	-1	0	555591	8754	1.6
	0	1	555794	8957	1.64
	0	-1	540579	-6258	-1.14
20040115	0	0	954247	0	0
	1	0	949831	-4416	-0.46
	-1	0	947694	-6553	-0.69
	0	1	952570	-1677	-0.18
	0	-1	945738	-8509	-0.89
20040131	0	0	488368	0	0
	1	0	481983	-6385	-1.31
	-1	0	497804	9436	1.93
	0	1	498284	9916	2.03
	0	-1	486580	-1788	-0.37

Total grids: 1502501, Grids of waterbody: 121586.

4 CONCLUSION

The impact of Aqua MODIS band-to-band misregistration upon snow index NDSI has been investigated by mapping snow with different NDSIs derived from original and shifted band 7 in along-track and along-scan directions. The results demonstrated that shifting one pixel (500 m) forward in the along-track direction of band 7 can improve the band-to-band registration between bands 4 and 7 and, therefore, the quality of Aqua MODIS snow mapping. The improvement is also visible by shifting one pixel backward in the along-scan direction of band 7; however, the result might be improved by shifting a fraction of one pixel instead of one pixel. The conclusion reinforces the band-to-band misregistration measured by SRCA. Future studies will include using Point Spread Function to shift exact pixels in along-scan and along-track directions. In addition, tests for other cases in different study areas, as well as some form of ground-based snow cover "truth" in comparison with both shifted and unshifted data are planned.

This study will help MODIS data users to understand the potential impact of band-to-band misregistration on MODIS science products, and also be useful for the future sensor design.

Acknowledgments

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