GEOMETRIC ACCURACY INVESTIGATIONS OF AVHRR ORTHOIMAGES

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KEY WORDS: satellite sensors, AVHRR, absolute accuracy, relative accuracy, band-to-band registration accuracy, meteorology, climate variables

ABSTRACT: A joint research project on the geometric accuracy investigations of three different satellite sensors (SEVIRI, AVHRR, MODIS), which are often used to estimate climate variables, has been initiated between ETH Zurich and the Swiss GCOS Office at MeteoSwiss in 2012. This paper focuses on investigations of AVHRR/3 orthoimages. AVHRR/3 was used onboard of Metop-2, NOAA-17 and NOAA-18 satellites, with data from 2008. We have analyzed the images in terms of relative, absolute and band-to-band registration accuracy and compared results to specifications of EUMETSAT and GCOS. The methods previously developed in the project have been adapted for the AVHRR data. Firstly. the data are preprocessed. For the relative accuracy investigations, several hundreds of feature points are extracted and tracked in the Band-2 images acquired from Metop-2, NOAA-17 and NOAA-18 on the same day, using the KLT tracking extended with statistical analysis and blunder detection procedures. Systematic errors (stripes across-flight) have been observed in all NOAA-18 images. To assess the absolute accuracy in Switzerland and surroundings, major lakes in the area, digitised from Landsat orthoimages, are used as reference (GCPs). The lake boundaries are fitted to the images via 2D translations by robustly minimizing the intensity (dark) values inside the polygons. Six bands have been evaluated for the band-to-band registration accuracy using a similar procedure as for the relative accuracy. Results are presented and discussed.

1. INTRODUCTION AND DATA

The study is a part of a research project carried out at ETH Zurich and supported by the Swiss GCOS (Global Climate Observing System) office at MeteoSwiss (Seiz and Foppa, 2007; Seiz et al., 2011). The project aims at analyzing the geometric accuracy of three commonly used satellite sensors especially for meteorological applications: SEVIRI, MODIS and AVHRR/3). The test area used covers Switzerland and surroundings. In this study, we analyzed the relative, absolute and band-to-band registration (BBR) geometric accuracy of AVHRR orthoimages. The results were compared with the accuracy specifications given by the satellite operators and the GCOS specifications for map products (1/3 pixel).

AVHRR/3 is a multipurpose imaging instrument used for global monitoring of cloud cover, sea surface temperature, ice, snow and vegetation cover characteristics and has been flying on NOAA and Metop satellite series (Eumetsat, 2011). AVHRR has 6 bands (Bands 1, 2, 3A, 3B, 4, 5) simultaneously acquired with 1 km resolution at near nadir. However, only 5 bands (3A or 3B and the rest) are transmitted to the ground. In relative and absolute accuracy only Band-2 was used, in BBR all six. This choice was because Band-2 was more suitable for the first two accuracy analyses, while these results could be transferred to the other bands, using the band misregistration estimated in BBR.

We used AVHRR orthoimages with 1 km resolution for our analysis. The orthorectification procedure has been developed by Khlopenkov et al. (2010) and a geolocation accuracy better than 1/3 GSD has been achieved in their tests. The data have been acquired from 3 different satellites, NOAA17, NOAA18 and Metop-2 (called also Metop-A). In collaboration between the Canada Centre for Remote Sensing and the Remote Sensing Research Group at the Department of Geography, University of Bern, the raw AVHRR images have been georeferenced using GCPs from matching with 250 m resolution MODIS image composites, and orthorectified using a 500 m resolution SRTM DEM. Cloud masks have also been produced by the University of Bern.

We have received the data from 24 days, 2 days from each month in 2008 with minimum cloud coverage. Mainly, 3 nadir acquisitions (one per satellite) over Switzerland are available per day. However, more images have been provided for some days, i.e. off-nadir images (close to the image borders). Visual checks and preliminary investigations with off-nadir images have shown that they are heavily blurred and the GSD can reach 4km. Therefore, we have excluded from the analysis all very off-nadir images. For the absolute accuracy, 20 lakes, used as GCPs, were digitised from Landsat-5 orthoimages with 25 m GSD**.**

Figure 1 shows one full scene, its part used for the accuracy evaluation, and the corresponding cloud mask. The cloud mask used in the matching process with KLT tracking includes: a) clouds; b) water; c) cloud shadows over water, land, and snow; d) pixel adjacent to cloud over water, land, and snow; and e) no data (e.g. image borders with no information). For absolute accuracy, only cases a) and e) were used to estimate clouds. For relative accuracy, the cloud masks of the two images (satellites) were merged. For BBR accuracy, we expanded the cloud masks by 4 pixels in order to prevent selection of candidate match points very close to the cloud areas and thus reduce matching errors.

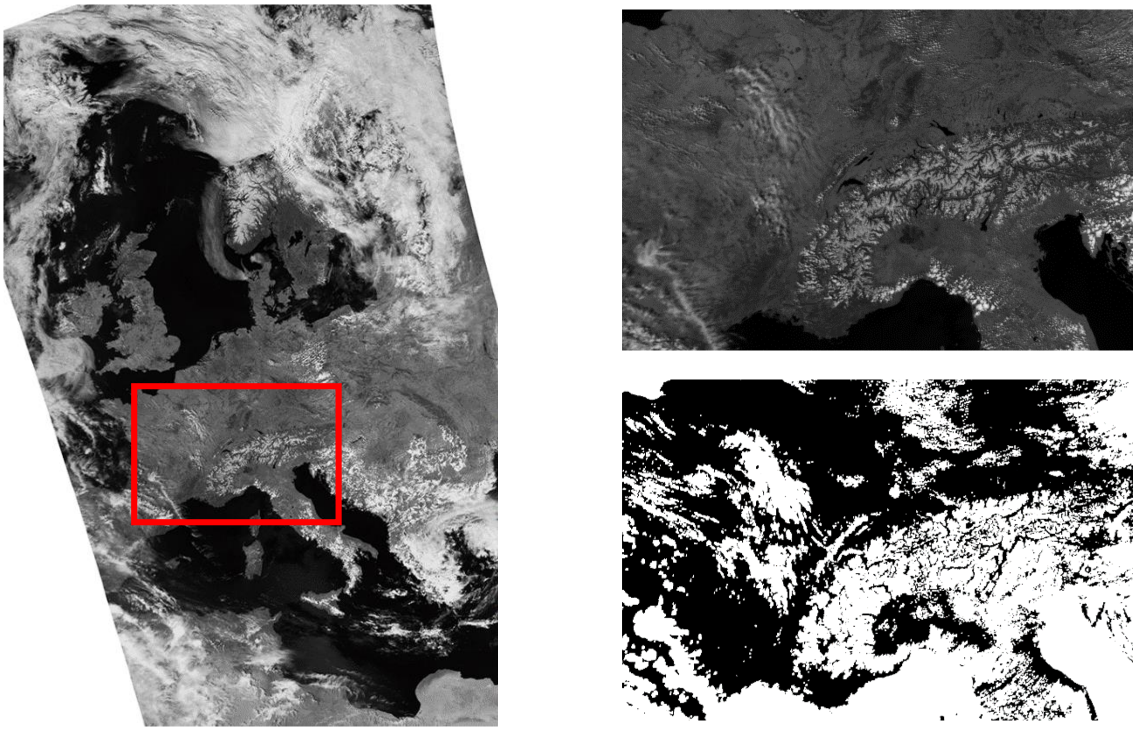

Figure 1. AVHRR Band-2 orthoimage acquired from NOAA18 on the 7th of May, 2008 at 12:08 (left). The subarea used for all accuracy tests is marked with red rectangle on the full image and shown in upper right image. The cloud mask used for relative accuracy tests is given in the lower right.

2. METHODOLOGY

The methodology has been initially developed and tested with SEVIRI images and results can be found in Aksakal (2013) and Kocaman et al. (2013a, 2013b). The tests with the MSG-SEVIRI images have shown that the accuracy of the point matching method (with KLT tracking) obtained in the tests and excluding blunders is ~0.1 pixels and for lake matching ~0.2 pixels. The same methods have been in principle used also for the AVHRR orthoimages. KLT used in relative and BBR accuracy extracts interest points and matches them (estimating two shifts) using least squares matching. Preprocessing adapted to the accuracy analysis type was always performed. Especially to reduce large radiometric differences and enhance contrast, a set of preprocessing techniques are applied (i.e. image inversion, Wallis filtering, Sobel edges, thresholding of Sobel edges). With KLT, a statistical outlier detection was used iteratively (e.g. a point is excluded if Δx or $\Delta y > 3\sigma$), with Δx or Δy, the difference between x-, y-shift of each point and the mean x-, y-shift for all image points. For BBR accuracy, a stricter threshold of 2σ was used. For relative and BBR accuracy, an additional outlier detection method using cross-correlation was employed, e.g. if after matching the cross-correlation value <0.9, the match point is rejected. The results for each image pair are evaluated via statistical analysis of point/lake shifts (i.e. minimum, maximum, mean, standard deviation, median and median absolute deviation) and additional visual checks of the shift plots.

Regarding the relative accuracy investigations, we have used the KLT tracking algorithm for matching of several hundreds of image points between two Band-2 images of the same day, even if taken by different satellites. In relative accuracy, since we observed systematic errors (stripes), we used additional data (i.e. all bands for some days, orthoimages processed with two software versions, data of one day in 2009 including the images from NOAA-19, original Level 1B reflective images, etc.). Regarding the absolute accuracy, we have evaluated the AVHRR Band-2 images based on lakes (Figure 2) by estimating the 2D shifts of the lake polygons in image space. Each lake is matched in the images based on the minimization of normalized (by the number of pixels, including partial ones) sum of pixel intensities inside the lake polygons (Aksakal (2013)). A coordinate transformation has been applied to the digitised lake polygons, to obtain the image space coordinates. Since the AVHRR images are orthorectified, only 2D shift errors for the lakes are expected in the images. Lakes having a cloud cover percentage over 60% are excluded from the process since the matching is usually not successful. The statistical parameters (i.e. Mean, σ, MED, and MAD) are derived from the shifts of all successfully matched lakes (equally weighted) within an image.

For BBR accuracy, Band-2 images are used as reference for the other 5 bands (4 bands per acquisition, since only 3A or 3B are transmitted).

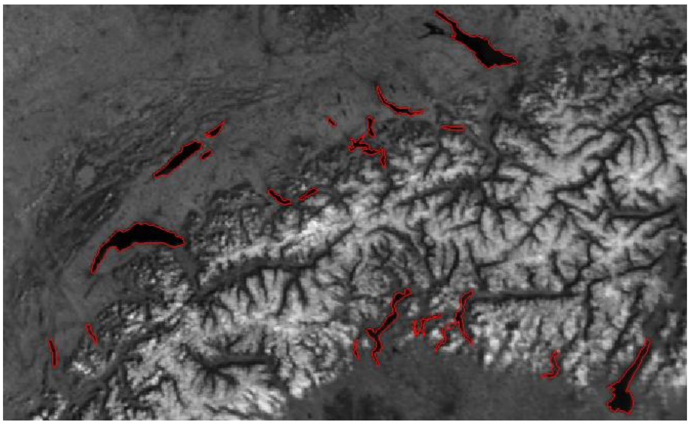

Figure 2. AVHRR Band-2 image part acquired from Metop-2 on 07.05.2008 at 10:00 and the lakes used for absolute accuracy investigations.

3. RESULTS AND DISCUSSION

3.1 Relative Accuracy Results

A total of 75 images from 24 days have been used for matching. The images acquired on the same day from different sensors are matched by pairing the images with shorter time interval in order to reduce matching errors caused by illumination differences and cloud movement. The matching results of a total of 51 image-pairs are given in Table 1 separately for different satellite combinations. The light blue colour used in some rows in this and other tables is just to visually separate the different satellite results. P0 and P1 denote the number of candidate and matched points after blunder detection. In the columns, the x- and y- Shift, MED, σ and MAD values are first computed for each image pair (or image for absolute accuracy) from all successfully matched points, so they are mean values. Then, in the 2nd column the Min, Max, Mean, MED, and σ are derived from all image pairs (or image) obtained from the respective satellites (or satellite for absolute accuracy) given in the first column. The x- and y-Shift and MED values refer to absolute shifts (not signed). The Max shifts obtained from the matching of Metop-2 and NOAA17 images are 1.8 (x) and 2.9 (y) pixels. Between the Metop-2-NOAA18 images, the Max shifts are 1.1 (x) and 0.9 (y) pixels. Between NOAA17-NOAA18, the Max shifts are 1.6 (x) and 0.6 (y) pixels. Two NOAA18 pairs are also evaluated and the Max shifts are 1.1 (x) and 0.1 (y) pixels.

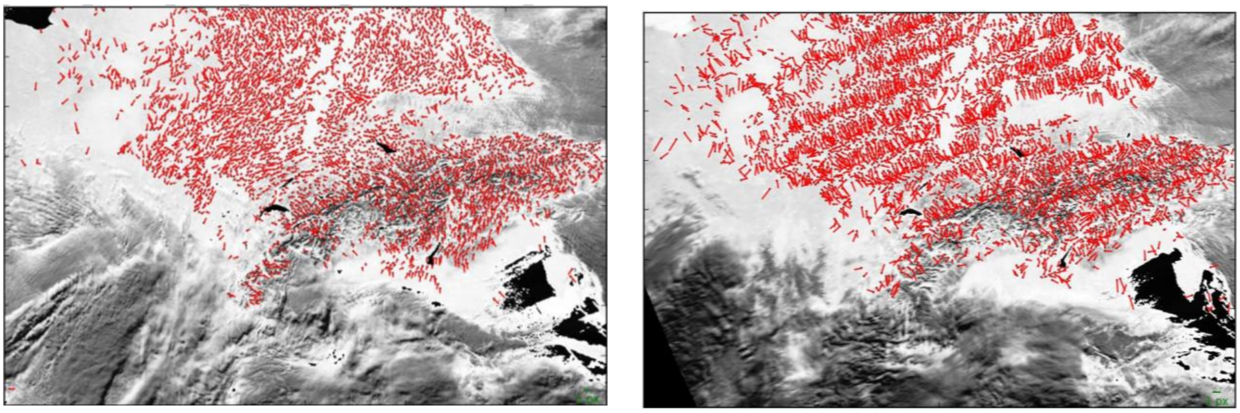

Figure 3. Image space shifts obtained from matching of NOAA17 & Metop-2 (left) and Metop-2 & NOAA18 (right) images acquired on 26.12.2008.

During the relative accuracy tests, we have observed systematic errors in stripes layout in some of the image pairs. After visual inspections on the shift plots of all pairs, we show that this effect exists in all pairs where NOAA18 images are involved (i.e. Metop-2/NOAA18, NOAA17/NOAA18, and NOAA18/NOAA18 pairs). We have investigated the systematic errors further using all bands for some days, original level 1B reflective data, and orthoimages generated by a newer version of SAPS (Canadian AVHRR Processing System) software. In addition, we have checked the images of NOAA18 and NOAA19 from one day in 2009. The stripes appear in all NOAA18 and NOAA19 images, which we have checked. Interestingly, these two satellites were imaging in ascending orbits, the rest in descending ones. The stripes appear in all spectral bands, also in the data processed with the newer version of software, and over the whole length of the images. The source of the error is currently unknown. Figure 3 show the shift plots of two image pairs from one day. The image pair which contains one NOAA18 image shows systematic errors as stripes across the flight direction, i.e. in scanning direction, of NOAA18. The stripes have a width of approximate 30 pixels. There are alternating stripes, one with mean parallax of about 1 pixel, one with a mean parallax of about 0 pixel and so on.

Table 1. Relative accuracy evaluation; statistical values of shifts (x) and (y) from 51 image pairs acquired on 24 different days in 2008. All results except the number of points are given in pixels.

Satellites	Par.	P0	P1	Shift (x)	Shift (y)	MED (x)	MED (y)	*σ* (x)	*σ* (y)	MAD (x)	MAD (y)
Metop2 & NOAA17 (25 pairs)	Min	1490	1173	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
	Max	5000	4455	1.8	2.9	1.7	2.9	1.0	1.2	0.6	0.9
	Mean	4623	3701	0.4	0.4	0.3	0.4	0.4	0.4	0.3	0.3
	MED	5000	3960	0.2	0.2	0.2	0.2	0.4	0.3	0.2	0.2
	σ	844	733	0.5	0.7	0.4	0.7	0.2	0.3	0.1	0.2
Metop2 & NOAA18 (9 pairs)	Min	2848	1979	0.0	0.0	0.1	0.1	0.3	0.5	0.2	0.4
	Max	5000	4427	1.1	0.9	1.1	0.7	0.8	1.0	0.5	0.7
	Mean	4698	3632	0.2	0.3	0.2	0.2	0.5	0.6	0.3	0.5
	MED	5000	3814	0.1	0.2	0.1	0.2	0.4	0.5	0.3	0.4
	σ	718	834	0.3	0.2	0.3	0.2	0.2	0.2	0.1	0.1
NOAA17 & NOAA18 (15 pairs)	Min	1535	372	0.0	0.0	0.0	0.0	0.3	0.5	0.2	0.3
	Max	5000	4651	1.6	0.6	1.6	0.5	1.0	0.7	0.6	0.5
	Mean	4437	2938	0.3	0.2	0.3	0.2	0.5	0.5	0.3	0.4
	MED	5000	3093	0.1	0.2	0.2	0.2	0.5	0.5	0.3	0.4
	σ	1005	1097	0.4	0.1	0.4	0.1	0.2	0.1	0.1	0.0
NOAA18 & NOAA18 (2 pairs)	Min	3989	2558	0.7	0.0	0.6	0.0	0.8	0.7	0.4	0.5
	Max	5000	3179	1.1	0.1	1.1	0.1	1.4	0.9	0.7	0.6
	Mean	4495	2869	0.9	0.1	0.8	0.1	1.1	0.8	0.6	0.5
	MED	4495	2869	0.9	0.1	0.8	0.1	1.1	0.8	0.6	0.5
	σ	715	439	0.3	0.1	0.3	0.1	0.4	0.1	0.2	0.0

3.2 Absolute Accuracy Results

We have processed a total of 72 images acquired on 23 different days using lake matching and summarized the results in Table 2. One day in April was excluded since all lakes were covered with clouds. The shift values in Table 2 show that up to 4 pixels, 1.6 pixels and 1 pixel shifts are present in Metop-2, NOAA17 and NOAA18 images, respectively. The shifts are shown with signs, where $+\Delta y$ indicates a shift to the North and $+\Delta x$ indicates a shift to the East. Accuracy of the lake matching results has been checked visually as well. Here, it should be noted that the images are acquired from different viewing angles and off-nadir images have lower GSD and inferior radiometric quality in comparison to the nadir images. The standard deviations (σx, σy) show the variability in the shifts of all lakes in an image. The larger standard deviations have been observed in the more off-nadir images. The standard deviations increase even more (up to 0.7 pixels) at the fully off-nadir images, which are excluded from the analysis (only images closer to the nadir are kept for analysis).

When the mean and σ values of Shift (x) and Shift (y) parameters are compared for all 3 satellites, it can be seen that NOAA17 and NOAA18 images have better absolute accuracy and stability. The mean values of the shifts in x and y obtained from all NOAA17 images are (0.2, -0.2) pixels with standard deviations of (0.3, 0.2) pixels, respectively. For NOAA18, the mean values of the shifts are (0.1,-0.3) pixels with standard deviations of 0.2 pixels. For Metop-2 images, although the mean values of the shifts are small (-0.1, -0.4 pixels), the standard deviations are high (0.4, 1.1 pixels), which show existence of large shifts (especially in y) in many days.

Table 2. Absolute accuracy evaluation: statistical summary from the lake shifts (equally weighted) in AVHRR images. All values are in pixels except the number of lakes. The min and max values of x and y shifts for all three sensors are shown in bold.

Satellite	Par.	Shift (x)	Shift (y)	σ (x)	σ (y)	MED (x)	MED (y)	MAD (x)	MAD (y)	No. of lakes
Metop-2	**Min**	**-1.7**	**-4.0**	0.1	0.1	-1.6	-4.2	0.1	0.0	7
	Max	**0.4**	**2.0**	0.4	0.5	0.5	1.8	0.3	0.4	20
	Mean	-0.1	-0.4	0.2	0.3	-0.1	-0.5	0.2	0.2	17.4
	MED	0.0	-0.2	0.2	0.3	0.0	-0.3	0.2	0.2	19.0
	σ	0.4	1.1	0.1	0.1	0.4	1.1	0.1	0.1	3.7
NOAA17	**Min**	**-0.3**	**-0.6**	0.1	0.1	-0.3	-0.6	0.1	0.0	9
	Max	**1.6**	**0.3**	0.5	0.4	1.6	0.3	0.3	0.4	20
	Mean	0.2	-0.2	0.3	0.2	0.1	-0.2	0.1	0.2	17.5
	MED	0.1	-0.2	0.2	0.2	0.1	-0.2	0.1	0.2	19.0
	σ	0.3	0.2	0.1	0.1	0.4	0.2	0.1	0.1	3.3
NOAA18	**Min**	**-0.2**	**-1.0**	0.1	0.2	-0.2	-1.1	0.1	0.1	8
	Max	**0.7**	**0.1**	0.4	0.5	0.6	0.1	0.3	0.5	20
	Mean	0.1	-0.3	0.2	0.4	0.1	-0.4	0.1	0.2	16.6
	MED	0.1	-0.3	0.2	0.3	0.1	-0.3	0.2	0.2	17.0
	σ	0.2	0.2	0.1	0.1	0.2	0.3	0.1	0.1	3.5

3.3 BBR Accuracy Results

We have processed the images of 63 acquisitions from 24 days for the BBR accuracy analysis. The matching results are summarized in Table 3. Given that the same georeferencing parameters and DEMs are used for all orthoimage bands of one acquisition, the test results provided here should represent the BBR accuracy of the original bands. The Shift(x) and Shift(y) values are computed using the absolute values (not signed) from all points in an image. As it can be seen in Table 3, the mean values of the Shift(x,y) are (0.07, 0.03) pixels for Metop-2, (0.04, 0.03) pixels for NOAA-17, (0.08, 0.09) pixels for NOAA-18 between Bands 2&1. For Band 3A, the mean values of the Shift(x,y) are (0.17, 0.05) pixels for Metop-2 and (0.15, 0.04) pixels for NOAA-17. For Band 3B, only the data from NOAA18 are available in the given dataset. It can be seen that the mean x shift is comparable to those of Band 3A (0.16 pixels). The mean y shift is slightly higher (0.13 pixels) than those of Band 3A. The larger shifts are observed in the more off-nadir acquisitions. Regarding Band-4, the mean Shift(x,y) are (0.30, 0.07) pixels for Metop-2, (0.26, 0.09) pixels for NOAA-17, (0.17, 0.11) pixels for NOAA-18. Regarding Band-5, the mean Shift(x,y) are (0.29, 0.09) pixels for Metop-2, (0.27, 0.09) pixels for NOAA-17, (0.13, 0.13) pixels for NOAA-18. The mean x, y shift and **σ** values get worse when matching Band-2 with 3A/B and especially 4 and 5 compared to 1, because the matching in the former case is more difficult, due to the larger radiometric and spectral differences of the matched bands.

Table 3. BBR accuracy evaluation results between AVHRR Bands.

Satellite	Bands	Mean Shift (x)	Mean Shift (y)	Mean σ (x)	Mean σ (y)
Metop-2	2&1	0.07	0.03	0.12	0.11
	2&3A	0.17	0.05	0.11	0.13
	2&4	0.30	0.07	0.15	0.15
	2&5	0.29	0.09	0.15	0.16
NOAA17	2&1	0.04	0.03	0.12	0.11
	2&3A	0.16	0.04	0.12	0.13
	2&4	0.26	0.09	0.16	0.17
	2&5	0.27	0.09	0.15	0.15
NOAA18	2&1	0.08	0.09	0.14	0.13
	2&3B	0.16	0.13	0.24	0.15
	2&4	0.17	0.11	0.20	0.16
	2&5	0.13	0.13	0.20	0.15

4. CONCLUSIONS

The proposed methods provide fully-automatic relative, absolute, and BBR accuracy assessment at sub-pixel level. Regarding the relative accuracy evaluation, images acquired from Metop-2, NOAA17 and NOAA18 acquired on the same day are matched. Significant systematic errors (stripes) have been observed in the image pairs, where one

NOAA18 (or NOAA 19) image is involved. The error source is currently unknown. Relative shifts, which are up to 2.9 pixels, have been observed between the processed image-pairs. The matching accuracy was inferior to the one previously achieved with SEVIRI HRV images. This is due to the much greater differences of the images matched (different illumination, cloud conditions, sensors, viewing angle etc.) Thus, the mean shifts and standard deviations were higher than expected. More specifically, the mean standard deviations were higher for pairs involving NOAA18 (partly due to the stripes), but for mean shifts the contrary was true, i.e. for Metop-2 and NOAA17 the mean (and max) shifts were higher than pairs with NOAA18. Note that there are no official specifications for relative accuracy.

The lake matching results show that there are 2D shift errors in the images, which are up to 4 pixels for Metop-2, 1.6 pixels in NOAA17, and 1 pixel in NOAA18 images. These values are worse than the GCOS location accuracy specifications (1/3 pixels). However, the absolute geolocation accuracy specification (not specifically for orthoimages) provided by EUMETSAT (2011) is 1 km and all NOAA-18 images stay within the specification, whereas one NOAA-17 image exceed it (1.6 km). Regarding Metop-2 images, the accuracy is worse than 1 km on several days. The mean shift values in (x,y) obtained from all 24 images of NOAA17 are (0.2,-0.2) pixels with standard deviations of (0.3,0.2) pixels in x and y, respectively. For NOAA18, the shifts values are (0.1,-0.3) pixels with standard deviations of 0.2 pixels. For Metop-2 images, although the mean shifts are small (-0.1,-0.4 pixels), the standard deviations are high (0.4,1.1 pixels), which shows the existence of large shifts, especially in y, in many days. Such large shifts were checked manually and the matching was correct, so we have no explanation for this problem.

The BBR accuracy specification for AVHRR is ~0.1 km (for original bands, not orthoimages) (EUMETSAT, 2011). The BBR accuracy investigations of AVHRR show that the mean (x,y) shifts between Band-1 and Band-2 are (0.07,0.03) pixels for Metop-2, (0.04,0.03) pixels for NOAA-17 and (0.08,0.09) pixels for NOAA-18. Bands 3A of Metop-2 and NOAA17 and Band 3B of NOAA18 also show comparable accuracy, with mean shifts of ~0.15 pixels in x and ~0.1 pixels in y. However, in some cases, shifts up to 0.4 pixels have been observed for these bands. The larger shifts are observed in the more off-nadir acquisitions. Regarding Bands 4&5, the matching results are very similar for all satellites and days. The mean (x,y) shifts for both bands for NOAA18 are ~0.15 and ~0.1 pixels. The Band-4 and Band-5 images of Metop-2 and NOAA17 show inferior BBR accuracy resulting in mean x shifts of ~0.3 pixels, which are worse than the EUMETSAT specifications. The mean y shifts of these bands are ~0.1 pixels.

Overall the absolute accuracy for all 3 satellites are often worse than the GCOS specifications and the images should be corrected for 2D shifts before their use in GCOS-related activities. The lake matching method is fully automated and can be employed easily for quality check and error correction depending on the region (e.g. availability of large water bodies). Regarding the BBR accuracy, especially the Bands 4&5 of Metop-2 and NOAA-17 fall outside the specifications, however resulting errors may be partly due to the orthorectification process. In addition, use of off-nadir images should be avoided whenever possible due to lower radiometric quality and larger GSD.

ACKNOWLEDGMENTS

The authors would like to thank the members of the Swiss GCOS Office and MeteoSwiss for providing data, their valuable inputs and financial support of the project. Also many thanks to the members of the Remote Sensing Group (Institute of Geography, University of Bern) for providing data and their continuous support and to Konstantin Khlopenkov and Alexander Trichtchenko for their feedbacks one the investigations of systematic errors.

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