Improved navigation of Advanced Very High Resolution Radiometer data at high latitudes

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Abstract

Uncertainties in the orbit prediction and attitude control of the NOAA spacecrafts often cause the geolocation of the AVHRR data to be in error of several kilometres. Applying the Automatic Navigation Adjustment (ANA) software developed at the Céntre de Météorologie Spatiale (CMS), Météo-France, Bordes et al. (1992) and Brunel and Marsouin (2000), in general improves AVHRR navigation significantly. ANA combines a physical image deformation model and automatic adjustment on coastal landmarks, and allows for interpreting the landmark navigation errors in terms of the satellite attitude.

However, especially at high latitudes and during nighttime and during the winter season the ANA landmark detection often fails, leaving either very few landmarks for the attitude estimation, or even worse, no valid landmarks at all, and therefore no attitude correction. For one full year (2003) of 1149 NOAA 17 overpasses received at SMHI ANA failed to derive an attitude in 19.7% of these. During wintertime (October till March) this ratio increase to 20.6%, and during nighttime (19 till 5 UTC) the rate of failure is 24.4%.

This paper presents a new landmark classification method developed mainly for nighttime. The method is based on a k-means clustering approach using all five AVHRR spectral channels. The method was tested on a large number of NOAA 15, 16 and 17 overpasses received at Norrköping during the winter months November till March of the years 2003 and 2004.

The rate of success in the landmark detection rate increases significantly when using the new method. The number of nighttime NOAA 17 overpasses for which a pitch error was derived increased from 74% using the existing histogram method to 82% with the k-means clustering method.

Introduction

In Dybbroe et al. (2003) the problem of inaccurate navigation of AVHRR data was introduced, and motivations for trying to improve navigation were given. Dybbroe et el. (2003) showed how the Automatic Navigation Adjustment tool (ANA) developed at Météo-France by Brunel and Marsouin (2002) could be used with success outside the Lannion acquisition area and at high latitudes, and without the use of the cloud mask step.

The objective of this study is to improve ANA and the navigation of AVHRR data at high latitudes. The main focus is on the difficult conditions during the high latitude wintertime with low sun elevation (no signal in the visible and near-infrared channels) and cold land and sea surfaces, known to be a particular problem with the current version of ANA (Dybbroe et al., 2003).

The Automatic Navigation Adjustment technique - ANA

The position of an AVHRR footprint depends on time, satellite position and velocity, satellite attitude (its orientation) and radiometer viewing geometry. The radiometer geometry is known prior to launch. Time is usually available, e.g. through the satellite time corrected from the satellite clock error, or from an independent clock. The satellite position and velocity may be calculated by an orbit prediction model ingesting daily bulletins (e.g. TBUS). The remaining unknown is the satellite attitude, or in fact how the actual attitude deviates from its nominal value.

The actual satellite attitude can be estimated if an adjustment is performed on the raw data (navigated using the nominal attitude) using known landmarks, as has been done operationally at CMS, Météo-France since 1990, using ANA (Brunel and Marsouin, 2000).

ANA is described in detail by Brunel and Marsouin (2000, 2002). ANA combines a physical image deformation model and automatic adjustment on coastal landmarks. The navigation adjustment is done in satellite co-ordinates allowing interpreting the landmark navigation errors in terms of satellite attitude: yaw, pitch and roll. The adjustment involves the following six steps:

1) Generation of a set of reference landmarks

2) Landmark location using deformation model and nominal attitude

3) Cloud mask generation - optional.

4) Generation of binary land-sea mask, using channel 1 and 2 at daytime and channel 4 and 5 at nighttime

5) Derivation of a similarity coefficient

6) Attitude estimation

Step 1 is done only once for a given HRPT station. Step 3, generation of a cloud mask, may be omitted, as is the case for the implementation at SMHI.

The processing steps 5 and 6 above depend on the outcome of 4. If the detection and separation of land and sea fails no correlation attempts are done in 5, and the processing proceeds with the next available landmark. Likewise, if the similarity found in 5 is lower than a threshold (presently set to 0.90) the landmark will not contribute to the attitude estimation. A set of 10 different validity codes has been defined to describe the results of the landmark identification and correlation steps, see Brunel and Marsouin (2003) or Dybbroe (2004). Only a validity of 0 is accepted in the attitude estimation step (6).

ANA nighttime detection and its deficiencies

ANA does not provide an attitude estimation when less than three valid landmarks (inside swath, cloud free, and land-sea separation successfully done) have been found. If more than five valid landmarks are found all attitude angles are retrieved, but if only three or four landmarks are valid a default yaw will be used and only the roll and pitch are retrieved.

For one full year (2003) of 1149 NOAA 17 overpasses received at SMHI ANA failed to derive an attitude in 19.7% of these. During wintertime (October till March) this ratio increase to 20.6%, and during nighttime (19 till 5 UTC) the rate of failure is 24.4%. For the same year 942 NOAA

15 overpasses were received and processed, and the rate of ANA failure was 17.4% (25.4% for wintertime). No NOAA 15 scenes were received between 19 and 5 UTC.

The number of overpasses with unsuccessful attitude estimation is not perhaps the best estimate of the performance of ANA and the landmark location algorithm. A better estimate would be to derive the ratio of valid landmarks to the number of viewed (inside the satellite swath) and cloud free landmarks, for various illuminations conditions (day, night, twilight) and to study its seasonal variation. A long-term statistic on HRPT data received and processed at CMS, Lannion, using the MAIA cloud mask has shown that the ANA landmark detection algorithm performs better during day than by night and better in summer time than during winter (Dybbroe et al., 2003).

Since no cloud mask is applied at SMHI we can only relate the number of valid landmarks to the number of viewed. On average the ratio of valid landmarks over the number of viewed before attitude estimation is 31.5% and 29.1% after attitude estimation for NOAA 17 during 2003. These same ratios are 15.7% and 13.9% during nighttime and 23.4% and 21.5% wintertime. For one year of NOAA 15 overpasses the ratio of valid over viewed landmarks before and after attitude estimation is 21.9% and 20.4%. No NOAA 15 scenes were received between 19 and 5 UTC, but the ratios during wintertime were 12.5% and 11.3%.

The landmark detection algorithm applied during nighttime is detailed in Brunel and Marsouin (2002). The algorithm calculates the histogram of brightness temperature differences between AVHRR channel 4 and 5, Tb4-Tb5, for all cloud free pixels, searches for two peaks and computes a threshold, and assigns all pixels with a Tb4-Tb5 lower than the threshold to land and all others to sea. The method is based on the fact that the Tb4-Tb5 is most often greater over sea than over land at night. This is because the cloud free lower atmosphere is most often more stable over land than over sea.

There are several weaknesses of this algorithm. Even though the Tb4-Tb5 is very rarely greater over land than over sea, it happens quite frequently that there is no clear separation of the land and sea peaks. In those cases no threshold is found and no separation is attempted, and the landmark is rejected. According to Brunel and Marsouin (2002) this is specially a problem with morning and evening passes. Also, the algorithm is based on empirical parameters tuned for mid latitude conditions only. Figure 1 shows an example where the Tb4-Tb5 is ambiguous concerning the two peaks, and the algorithm fails accordingly.

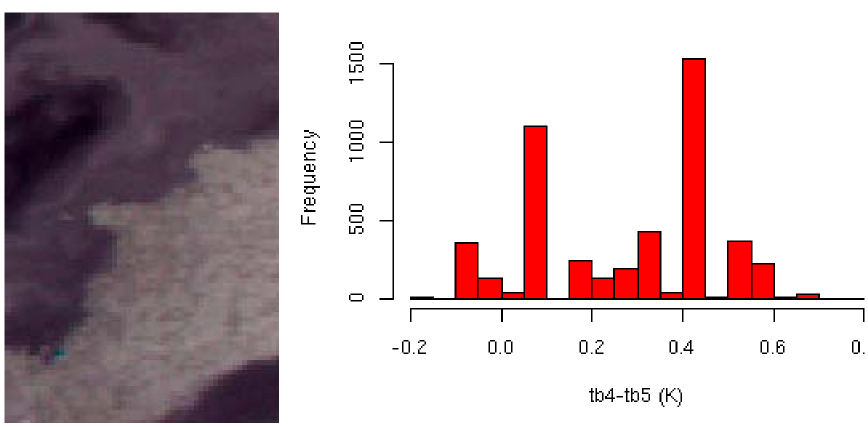

Figure 1: RGB composite using channel 3, 4, and 5 (left) and the Tb4-Tb5 histogram of all pixels (right) for the landmarks "047", Gotland, Sweden for the NOAA 17 overpass, orbit 12093, October the 21, 2004, 19:51 UTC. Though the landmark is totally or almost totally cloudfree and land and sea can be separated visually from the RGB composite image the histogram algorithm fails.

A new nighttime landmark detection algorithm using k-means clustering on all AVHRR channels

The histogram method only employs a subset of the available spectral information to separate cloudfree land from sea. As Figure 1 clearly illustrate there are cases where the utilisation of more spectral information should be able to improve the land-sea separation. For instance, the histogram method does not take advantage of the often-observed clear difference in IR skin temperature between land and sea. It is evident that the information available in the Tb4 feature should be incorporated in attempts to improve the histogram method. However, the Tb4 feature is much more variable over time of day and season than the Tb4-Tb5, so it is impossible to make the same kind of a priori assumptions on which the Tb4-Tb5 histogram algorithm is based.

Instead of extending the histogram method we have chosen to replace it with a classical automatic k-means clustering method with two clusters using all available spectral channels. Even the visible and near infrared channels are considered which makes the algorithm automatically account for a variable sun zenith angle, and thus potentially capable of also solving for twilight and daylight conditions. The method assumes two spectrally different and homogenous features and these will be separated so that all pixels in the image belong to that cluster for which the Euclidean distance (in the 5-dimensional space defined by the AVHRR channels) to its cluster mean is a minimum.

Figure 2 shows an example of a successful result of the clustering algorithm for the same landmark and overpass displayed in Figure 1. Whereas the Tb4-Tb5 histogram was ambiguous concerning two peaks the Tb4 histogram clearly indicate two separate clusters for cloudfree land and sea. Though the absolute temperature is very small indeed (< 2K) the k-means clustering algorithm successfully separate land from sea.

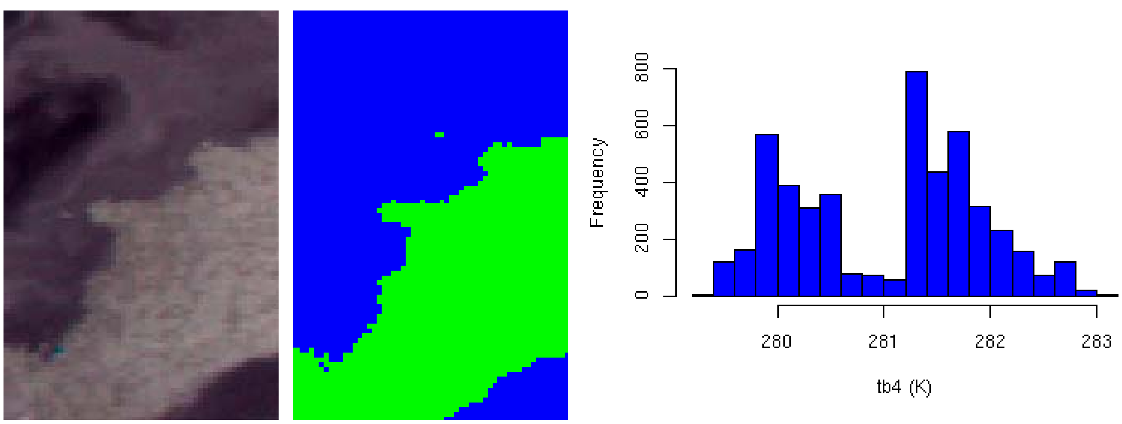

Figure 2: The result of the k-means clustering algorithm (middle panel) for the same landmark "047" (Gotland) and overpass as shown in Figure 1, together with the RGB colour composite (left) and the Tb4 histogram (right).

Contrary to the histogram method the k-means clustering method makes no assumptions of the spectral values over cloudfree land and sea. Instead it is fully adapting to the local and actual conditions at each landmark and overpass. However, this dynamical adaptation may also make the approach more vulnerable to contamination from clouds or snow/ice cover (or even sea surface features as discussed above) than what is the case with the histogram method. Therefore, it has proven necessary to precede the actual land-sea separation with a *gross cloud mask* algorithm removing the pixels where one is confident that clouds are contaminating the field of view (FOV). In addition, a quality check is performed after the cloud masking and land-sea detection steps. In this post-processing step the two clusters are being examined for possible excessive cloud contamination. The three components of the new land-sea detection algorithm are summarised below. A more detailed description can be found in Dybbroe (2004).

Algorithm step one - Cloud Mask

The purpose of the cloud masking is not to try to perform a perfect true cloud-clearing, as is the goal of e.g. the NWCSAF/PPS cloud mask (Dybbroe et al., 2005). Rather the aim is to filter out the pixels where there is severe alteration of the TOA radiance due to cloud contamination, allowing for partially filled cloud pixels and thin and highly transparent clouds. The cloud masking is more cautious than the PPS cloud mask in the sense that it takes very little or no risk of erroneously detecting cloud free pixels as clouds. The philosophy is to rather let cloudy pixels go undetected than mistake cloud free pixels for clouds.

The cloud mask is based on dynamic thresholding and is very similar to the PPS cloud mask, however using only the three IR channels. See Dybbroe et al., 2005 for details. An additional new feature of this cloud mask is that it also derives a dynamic threshold for Tb4 using statistics on the observed data. A k-means clustering with four clusters is being derived and possible cloud free clusters are then used to set the threshold. Details can be found in Dybbroe (2004).

The gross cloud mask is very cautious in the use of the tests for semi-transparent clouds, as one would like to still attempt a land-sea separation in situations with semi-transparent or broken clouds. Only the Tb4-Tb5 is used to find potentially cloud free clusters on which a Tb4 threshold may be derived.

Algorithm step two – k-means clustering

A k-means clustering is performed on all cloudfree pixels according to step one described above. The result is an image with values 0, 1, and 2, where 2 indicate cloudy, and the values 0 and 1 refer to cloudfree land and sea. The cloudfree cluster with the highest value of Tb4-Tb5 is set to be sea, and the landmark correlation coefficient is being calculated. If the resulting correlation is poor, it could be due to erroneous cluster labelling, and the two clusters will be switched and a second correlation trial will be done.

Algorithm step three – quality checking

Depending on the cloud cover, the cluster separation, and indications on the cloud contamination of the clusters, the landmark validity is evaluated. A number of new validity codes have been defined in addition to the existing 9 codes for ANA 3.1. Further processing in ANA (correlation estimation) is performed only on those landmarks which have a validity of 0.

In Table 1 the new validity codes are listed with short descriptions of the quality checks they refer to. As a measure of cluster separation we use the Jeffries-Matusita (JM) distance. The higher the JM-distance, the better the clusters are separated. A pair of well separated clusters should intuitively indicate a high level of confidence in the land-sea separation. However, as illustrated in Figure 1 and Figure 2, clusters may be close in the feature space but still result in a successful land-sea separation, if there are no or little cloudiness in the area.

Therefore we only filter out the results where the cluster distance is small if in addition significant cloud coverage is detected (see Table 1). The assumption behind this is that if clouds are detected, there is also a high risk that there are still cloudy pixels left which are undetected. If clusters are close to each other and clouds contribute to the definition of the clusters, there is also a high risk that both sea and land are mixed in both the clusters.

Validity code	Quality check	Criteria
10	High cloud cover and poor cluster separation	Cloud cover > 50%
11		Cloud cover > 20% & JM-distance < 0.3
21	Very small clusters not allowed	Relative number of pixels in one of the clusters < 5%
13	Cloud contamination according to Tb4-Tb3 Only performed if the probability of sunglint is low	At least one cluster contaminated by water clouds according to Tb4-Tb3
14		At least one of cluster contaminated by ice clouds according to Tb4-Tb3
23		Both clusters contaminated by water clouds according to Tb4-Tb3
24		Both clusters contaminated by ice clouds according to Tb4-Tb3
15	Cloud contamination according to Tb4-Tb5	At least one cluster contaminated by semi-transparent clouds according to Tb4-Tb5
25		Both clusters contaminated by semi-transparent clouds according to Tb4-Tb5
16	Cloud contamination according to Tb4	The coldest cluster cloud contaminated according to Tb4
17		The warmest cluster cloud contaminated according to Tb4
26		Both clusters cloud contaminated according to Tb4

Table 1: The various quality checks and their corresponding validity codes introduced in the k-means clustering algorithm. Detailed explanations are given in Dybbroe (2004).

Results

The 205 NOAA 17 nighttime overpasses resulted in a total of 10179 viewed landmarks, and thus on average 50 of the 111 landmarks in the database are viewed in each overpass. Of these viewed landmarks 2529 (24.8%) had the validity code 0 before attitude estimation using the k-means clustering algorithm and 1749 (17.2%) for the histogram method.

Thus, the number of valid landmarks before attitude estimation is significantly higher with the k-means clustering method. But this is not the best estimate of the quality of the landmark detection algorithms. It is important to know how big the spread in line,pixel displacements are and how much this spread is possibly increased with an increase in the landmark detection rate.

The number of landmarks with 0 validity with a displacement within 2.0 from the mean displacement is 1590 (15.6%) for the clustering algorithm and 1577 (15.5%) for the histogram method. Counting the number of landmarks with 0 validity with a displacement within 5 from the mean the result is 2294 (22.5%) for the clustering and 1728 (17.0%) for the histogram methods.

For the 36 NOAA 15 overpasses observed 2452 landmarks were viewed and inside the swath, corresponding to a landmark coverage of 68 on average.

The k-means clustering method found 526 (21.5%) landmarks to be valid and the histogram method classified 369 (15.0%) as valid. The number of landmarks with a 0 validity with a displacement within 5 from the mean was 465 (19.0 %) for the clustering method and 355 (14.5 %) for the histogram method. The number of landmarks with a 0 validity with a displacement within 2 from the mean was 259 (10.6 %) for the clustering method and 227 (9.3 %) for the histogram method.

Of the 174 NOAA 16 overpasses 11864 landmarks was viewed, corresponding to average landmark coverage of almost 68. The total number of landmarks with a 0 validity was 2934 (24.7 %) for the clustering method and 2233 (18.8 %) for the histogram method. The number of landmarks with a 0 validity with a displacement within 5 from the mean was 2691 (22.7 %) for the clustering method and 2195 (18.5 %) for the histogram method. The number of landmarks with 0 validity with a displacement within 2 from the mean was 1920 (16.2%) and 2027 (17.1 %) for the histogram method.

Figure 3 provides a clear evidence of the increase in number of successfully detected landmarks with the k-means clustering method as compared to the histogram method. A great majority of the overpasses clearly show an excess in number of landmarks for the clustering method. Only very few NOAA 16 and 17 overpasses show a negative result.

Of the 205 processed NOAA 17 overpasses a pitch error was derived in 169 of the cases using the k-means clustering method, and in 152 of the cases with the histogram method.

The NOAA 17 pitch error as estimated with the two methods agrees well. In 144 of the 205 overpasses a pitch error was derived with both methods, and this dataset shows a very high correlation of 0.98. The yaw and roll errors are in general much smaller and accordingly agree less well showing correlations of 0.56 and 0.73 respectively.

The correlations for NOAA 15 were 0.88 for the pitch error, 0.57 for the yaw error and 0.38 for the roll error. For NOAA 16 we got correlations of the attitude errors of 0.97 (pitch), 0.52 (yaw) and 0.76 (roll).

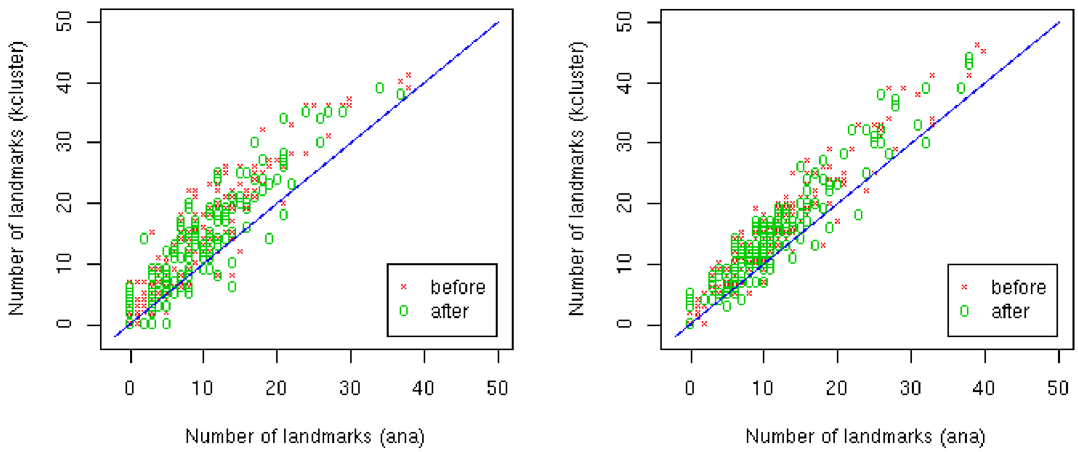

Figure 3: Comparison of the performance of the k-means clustering algorithm and the histogram method, in terms of the number of valid landmarks before and after attitude estimation, for NOAA 17 (left) and NOAA 16 (right). The blue line is y=x.

Discussion and conclusion

A new landmark classification method mainly for nighttime has been developed. The method is based on a k-means clustering approach including a cloud mask and a quality checking and filtering. The method was tested on a large number of NOAA 15, 16 and 17 overpasses received at SMHI in Norrköping during the winter months November till March of the years 2003 and 2004.

The rate of success in the landmark detection rate increases significantly when using the new method. The ratio of successfully detected landmarks over the number of viewed (cloudy and cloudfree) for NOAA 17 was 24.8% with the k-means clustering method compared to 17.2% with the current histogram based method in ANA. Similar results were obtained with NOAA 15 and 16.

A check of the line-pixel displacements derived from the valid landmarks showed that the spread is greater with the new method, and sometimes a valid landmark give rise to very big deviations from the mean displacement. However, it is natural that a higher detection rate will cause a higher spread, and such outliers will normally be filtered out in the attitude estimation step. But still, if one counts the number of valid landmarks with little or no spread the number is in general higher for the new method compared to the existing histogram method.

The number of nighttime NOAA 17 overpasses for which a pitch error was derived increased from 74% using the histogram method to 82% with the k-means clustering method. A fewer number of NOAA 16 and NOAA 15 overpasses were analysed, but also here we observed a clear improvement with the new method, though the performance was generally higher than for the NOAA 17 data for both methods. The increase in overpasses with an estimated pitch error was from 91% to 94% for NOAA 16 and 92% to 97% for NOAA 15.

In general the pitch errors estimated with the two methods agrees quite well, having high correlations coefficients of 0.97 and 0.98 for NOAA 16 and NOAA 17 respectively. During the periods studied both the roll and yaw errors were quite small, and therefore it is only natural that they correlate less well between the two methods. The NOAA 15 overpasses gave less good correlations for all attitude angles, but the pitch errors correlated still reasonable well (0.88).

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