Methods of Extracting a Coastline from Satellite Imagery and Assessing the Accuracy

Eva WILLERSLEV

Abstract

Greenland digital sea charts are immensely inaccurate and unsuitable for GPS navigation, hence elucidating a more general need of developing automated and reliable methods of mapping in remote areas of the world where no accurate maps exist. The current project demonstrates how coastline mapping in remote regions are made feasible by Remote Sensing methods.

Where previous researches have tended to focus on mapping the coastlines in relatively small areas from high resolution imagery, the aim of the current project is to investigate the potential of medium resolution imagery for mapping larger areas to the optimal accuracy, precision and completeness.

A high accuracy is achieved by rectifying the imagery from GPS points. A high precision and completeness is achieved by classifying the imagery at sub-pixel scale, for which purpose two different methods are compared. The uncertainties recorded are related to the source data and algorithms applied. The methods developed are shown to be effective and the resulting coastlines comparable in quality to an officially approved map of the study area, which was used as benchmark.

Apart from GPS navigation and adjustment of the existing sea charts, applications of digital coastlines include coastal management and various types of spatial analysis in GIS.

1 Introduction

Greenland digital nautical charts are unsafe for GPS navigation primarily due to a seriously displaced coastline. At the same time, the GPS system has revealed major errors in the analogue (paper) charts; a problem that has been recognized by the Danish National Survey and Cadastre, KMS, responsible for mapping the unpopulated parts of the country. In 2006, a project was initiated by KMS, endeavouring to digitize a new coastline from orthophotos and to transform the nautical charts accordingly, thereby preserving the host of information on sea depths, sunken rocks and other features, collected over the course of many years.

Unknownly of this, in 2007, a private boat trip in Greenland raised the question of the safety of the electronic navigation system. Clearly, the error of 300m registered on the screen and according to the Greenlandic sailors frequently up to 500m, could not be caused
by the GPS itself, which is known to be accurate to approximately 10m in these areas. Consequently it had to be caused by inaccuracies in the underlying maps.

The realisation gave birth to the idea of mapping a new coastline from satellite imagery. In the summer 2008, the project set out with a trip to Greenland to collect the ground control points for image rectification. The project was followed and commented upon by KMS.

The 100×100 km study area is on the edge of the inland ice with two glaciers entering the fiord, producing masses of icebergs that flow towards the ocean. Apart from the capital Nuuk, located at a peninsula where the Nuuk fiord mouths the Atlantic Ocean and housing nearly a quarter of the total population of about 57000, the study area comprises a few minor settlements and otherwise consists of mountainous wilderness.

The research aims at deriving a robust method of creating coastlines from medium resolution satellite imagery to the highest possible accuracy and precision, as well as on methods of assessing the uncertainty. For this purpose the following objectives are set:

- To achieve a high *position accuracy* of the coastline by rectifying the satellite image from field collected GCPs.
- To achieve a high *precision*, the coastline mapping should be guided by an image classification at sub-pixel scale.
- To extract a vector *coastline* from the classified imagery and to identify the problem areas and solve the problems.
- To evaluate the *error* of coastline against a reliable benchmark and to determine the uncertainty.
- To relate the *uncertainty* recorded to the uncertainty inherent in the data and algorithms applied.
2 Literature Review

(Li et al. 2001, 2002) compare various contemporary approaches to coastline mapping such as manual digitizing from scanned paper maps or aerial photos, intersecting a digital water surface model with a coastal terrain model and extraction from satellite imagery. The researchers conclude that extraction from satellite imagery is the most economic methods.

The current study is narrowed to passive Remote Sensing methods for coastline extraction. However, it is recognized that active Remote Sensing methods such as SAR and LiDAR have also been used for coastline extraction; e.g. (Pe’eri et al. 2007) and (Yu & Acton 2004).

Approaches to image rectification include image-to-image and image-to-map registration as well as registration from field measured GCPs. Most studies take one of the first two approaches, focusing on the problem of identifying homologous points, e.g. (Gianinutto et al. 2004). The method of using field collected GCPs is less explored, an exceptions being (Kardoulas et al. 1996) who both find that GPS GCPs are superior for image rectification compared to GCPs from existing maps. The researchers favour an affine (1st order) polynomial transformation for the image rectification.

Contrary to hard classification that assigns a single land cover class to each image pixel, fuzzy or soft or fuzzy classification methods estimate the composition of classes within the pixels and thus facilitate mapping at sub-pixel scale, i.e. at a higher resolution than the original imagery. Following its first introduction in Remote Sensing context in 1993, (Settle & Drake 1993), linear unmixing has become the preferred soft classification method, (Keshava et al. 2000), (Keshava & Mustard 2002). The linear unmixing problem is commonly solved by linear optimization, e.g. (Kerdiles & Grondona 1995).

Which method of coastline extraction to employ depends on whether it is completed from a discrete or continuous surface, i.e. depending on whether it follows a hard or soft image classification. Traditionally, ground features including coastlines have been extracted from discrete surfaces by image segmentation. An overview of hard classification methods that have been used for feature extraction is provided in (Armenakis & Savopol 2004).

When following a soft classification, super-resolution or sub-pixel mapping is the next step towards a map with more spatial detail than the original data. The idea is to allow the coastline to run through the pixels of the continuous fraction image. As the coastline is characterized by an abrupt change in pixel values (discontinuity property) an edge detection or contouring algorithm may be applied, which ‘floods’ the surface to a specified threshold.

Although contouring is a method with wide applications, (De Smith et a. 2007, p 298), it is rarely mentioned in connection with coastline delineation. An exception is (Verhoeve & De Wulf 2002) who sophisticatedly let a fuzzy classification follow by a rough contour extraction at sub-pixel scale, after which a pixel swapping algorithm use the first contour as a guide to predict more precisely the location of the waterline.

(Li et al. 2001) use a coastline that was digitized from aerial photos as benchmark for assessing the accuracy of an automatically extracted coastline. By creating a distance raster from the benchmark and overlaying it with the rasterized coastline, the researchers obtain a new raster in which each pixel represents the distance between the two lines, thus allowing them to calculate the total offset and standard deviation parameters. Dellepiane et al. (2004) use a similar method to calculate the RMSE and STD of a SAR generated coastline.
against a coastline extracted from aerial photos. Foody et al. (2005) apply two measures for describing the closeness of a predicted coastline to the real coastline: the percentage of predictions that are within 10% of the pixel dimension of the true, rasterized waterline; and the distance from the true waterline containing 90% of predictions, i.e. the so-called $CE_{90}$.

3 Data

Landsat imagery

The primary source of data used in the project is a Landsat 7 ETM+ multi-spectral satellite image acquired in the summer August 2002. The image consists of 7 spectral bands and a panchromatic band (with a broader spectral range). The spectral bands were re-sampled by NASA to 25m resp. 50m (the thermal band), and the panchromatic band was re-sampled to 12.5m. Apart from some icebergs, the coast is free of snow and ice. The study area is almost cloud free with only a thin cloud cover in the top left corner.

Fig. 3: The 100×100 km study area marked by a square in the Landsat satellite image

Ground control points (GCPs)

To obtain a collection of well defined GCPs for the image correction, waypoints were captured using a handheld GPS, the producer of which guarantees an accuracy better than 7m in areas like this where the GPS is not supported by a differential signal. The points were collected at 18 locations that were easily recognizable in the image and accessible by boat. Due to the risk of running aground the last bit was done by rubber boat. In each location 6-8 waypoints were captured and the spot marked in a paper copy of the imagery.

KMS data

KMS kindly permitted to use their new vector coastline, stemming from an ongoing project of manually digitizing parts of the coastline from 5m orthophotos. The orthophotos were produced from aerial photos from the 1980s. The accuracy of the digitized coastline is
assessed by KMS to 10-15m. Without doubt, this coastline is the most accurate that exist of the Nuuk fiord area and is therefore used as a benchmark in this project.

C-Map data

A private producer of GPS navigation systems, C-Map, kindly approved to use their vector coastline as collateral data in the project. This map was produced by scanning and vectorizing the old analogue nautical charts. The scale of the original charts is 1:200,000, suggesting a precision of 100m of the C-Map coastline. However, visual inspection against the corrected satellite image confirms what is known from sailing in the area: that the total uncertainty is in reality 3-4 times greater.

Fig. 4: Detail of the coastline in the current Greenland Navigation system on backdrop of the rectified satellite image, 1cm = 500m

The recorded uncertainty of the C-Map coastline is primarily due to a grave geographical bias or displacement resulting from the coarse scale of the original map and a further generalization of the vector lines. It was this particular map, currently in use in the navigation system, which initiated the idea of developing a method of producing a more accurate coastline from low-cost satellite imagery. It was thought, that this would be of interest to the producers of these systems and subsequently to the benefit of the sailors.

4 Methods and Results

The coastlines are extracted by two different methods, one using super resolution or sub-pixel mapping, resting on theories of mixed pixels and spatial dependence, and the other based on noise fragmentation.

In the first method, end-members corresponding to the four main land cover classes (water, ice, rock and vegetation) are detected, guided by a visual inspection. A linear spectral un-
mixing algorithm is applied, the output of which is a set of fraction images, containing the class ratios. The total-water fraction image is up-sampled to 5m by bilinear interpolation.

The second method starts by up-sampling the spectral bands. It employs a MNF (Minimum Noise Fraction) transformation as basis for extracting the coastline. The rationale for using MNF to detect the coastline is that it effectively separates the textural smooth areas from the textural rough areas. Even if water and ice are opposites in the way they reflect the sun energy, they are alike in having a smooth surface texture compared to other land covers.

![Fig. 5: Coastline delineation guided by water fractions (left) and image noise (right)](image)

**Mud areas**

Various interpretations may be given of the mud flats and adjacent turbid waters stemming from the melting ice. KMS captures the border between mud and land, while the automatically extracted coastline captures the border between water and mud. Depending on the purpose the map, both interpretations may be correct and no attempt was therefore made to change the coastline in these areas.

![Fig. 6: Example of mud area with the new coastline (darker) and KMS coastline (lighter)](image)
Clouded areas

The MNF method yields a surprisingly good result in the clouded areas. The MNF and KMS coastlines are shown below on backdrop of the panchromatic band. The coastlines mainly differ in the area indicated by the arrow. It is believed that the differences recorded are due, not so much to the clouds but more to low tide water in the satellite imagery. This theory is supported by the existence of many small islands, indicating a low water level, and which, in hours of low tide, may merge into a single land stripe.

![Fig. 7: Clouded area with the new MNF coastline (left) and KMS coastline (right)](image)

Shadow areas

Even at mid-day, when the satellite images are acquired, the low sun elevation angle causes the mountains at north directed coasts to create deep shadows upon land and water, thus seriously blurring the coastline (aerial photography suffers from the same problem). Due to this problem, 6 % of the coastlines had to be manually digitized on backdrop of various density sliced and coloured bands.

5 Error and Uncertainty

The error of the new coastlines relative to the benchmark is a measure of the absolute accuracy. By rasterizing the new coastlines and combining these with a distance raster based on the benchmark, two error rasters were created. The error rasters show the distance of the coastline(s) from the benchmark.

The statistics of the error rasters are compiled into RMSE (root mean square error) and CE90 (the absolute accuracy that the map is expected to hold 90% of the time). For both new coastlines a 24m RMSE (the same as the RMSE of the image rectification) and 36m CE90 is obtained.

The figure illustrates the error calculation process as well as some of the uncertainties associated with the calculation. The first close-up shows the two rasterized coastlines on top of the distance raster. The second close-up shows the error rasters with shades
indicating the distances of the two coastlines to KMS. The last two figures reveal that the error in this case is caused primarily by a displacement of the orthophoto and satellite image relative to each other and secondly to precision problems.

**Fig. 8:** Error calculations

The *precision* of the new coastlines ought to be calculated in the same manner as the accuracy while first removing the bias relative to the benchmark. However, this approach is not viable due to different interpretations of the coastline, in turn due to the different data sources and methods of creating the coastlines. Instead, a visual inspection of the coastlines against the panchromatic band confirms that the precision is around 5m RMSE for both coastlines.

By subtracting precision from accuracy, a *positional accuracy (bias)* of 19m RMSE is obtained for both new coastlines.

Based on the obtained accuracy, the *scale* of the new coastlines is 1:48000, or in round numbers 1:50000. The *generalization* of the new coastlines complies with this scale: When displayed in scale 1:50000, the coastlines appear even and uniform while capturing the shape of the coast precisely. No further details are revealed when zooming in further.

The automatically delineated coastlines capture some small islands that are missing in the KMS coastline, see figure 9. It is believed that in the KMS manual procedure, which uses an orthophoto as a background for digitizing, islands are sometimes not registered simply because they are taken for icebergs.

Following the automated coastline delineation, all small islands were double checked against a density sliced thermal band, displaying the cold and warm areas in red and blue colours. Using this method of checking, all islands resolved by the automatic methods turned out to be real and none of them were icebergs.

The smallest islands that are for sure resolved by the automatic methods are approximately 25m in diameter, thus matching the general image resolution and 24m RMSE accuracy obtained, as well as the proposed map scale.
Fig. 9: The new automated coastline (darker) and the KMS manual coastline (lighter) on backdrop of the rectified satellite image

6 Conclusion

The study successfully arrives at settling a chain of processes for the derivation of a high quality coastline from medium resolution satellite imagery. Focus is constantly on the accuracy and precision obtained; both with regard to the error relative to a set of independent control points and a coastline benchmark, and generally with regard to the expected uncertainty of the applied methods.

A satisfactory 24m RMSE absolute accuracy is achieved by correcting the satellite image from GPS points, and a 5m RMSE precision by means of a sub-pixel classification, for which two different methods, one based on spectral un-mixing and the other on noise fragmentation, are found to be equally effective. The problems of mapping the clouded areas and the shadow areas are adequately solved.

Further information may be obtained from http://emaps.dk/Dissertation_Abstract.pdf which also discusses the appliance of the new, exact coastlines to the rectification of old charts and proposes a gentle three step procedure which minimizes the distortions in the maps. The paper further discusses the tide problem and investigates the potential of high resolution satellite images for shallow water bathymetric mapping.
References