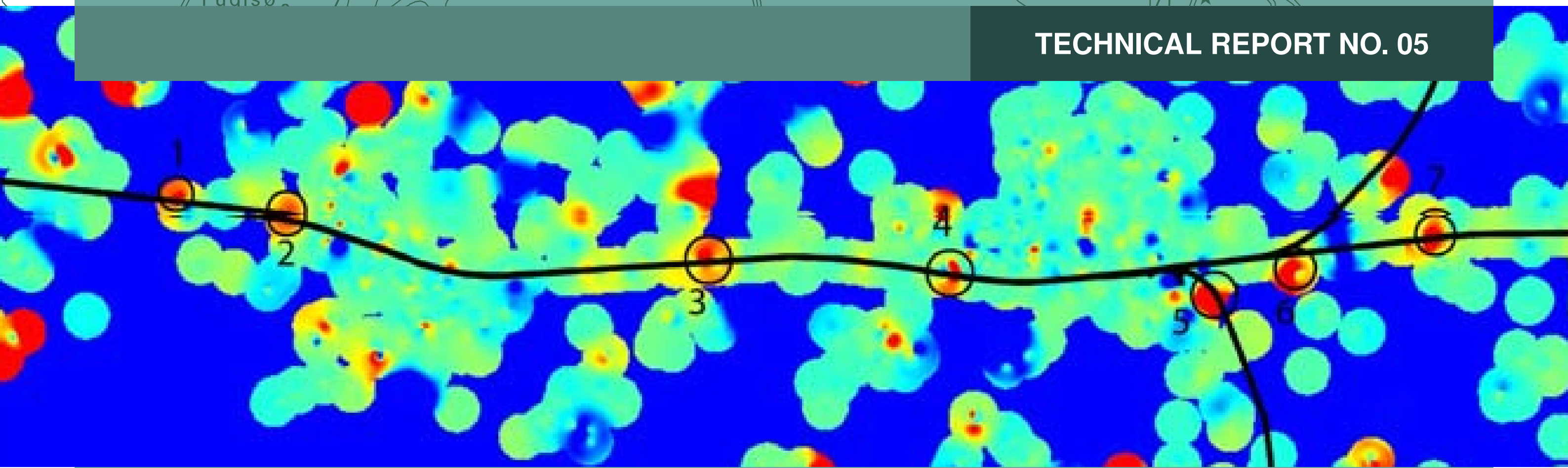
TECHNICAL REPORT NO. 05



ABSRATE – absolute subsidence rates from persistent scatterer interferometry data. Final report.

Thomas Knudsen, Nynne Sole Dalå, Per Knudsen, and Peter Roll Jakobsen

DANISH MINISTRY OF THE ENVIRONMENT
National Survey and Cadastre

Contents

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ABSRATE – absolute subsidence rates from persistent scatterer interferometry data. Final report.

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Introduction

The ABSRATE project

This is the final report of the ABSRATE project. ABSRATE – the ABsolute Subsidence RATEs project, was initiated in order to derive absolute (i.e. geodetically tied) subsidence rates from relative measurements based on persistent scatterer interferometry (PSI).

ABSRATE is a collaborative project between the Danish National Space Center (DTU-space) and the National Survey and Cadastre (KMS), with additional input from the geological survey of Denmark and Greenland (GEUS). The project is financed by ESA through Terrafirma – the pan-european ground motion hazard information service.

Terrafirma

Terrafirma is one of a number of services being run by the European Space Agency under the GMES Service Element Program as part of the Global Monitoring for Environment and Security (GMES) initiative of the European Union. Terrafirma started in 2003. ABSRATE joined the Terrafirma activities in 2007. Terrafirma harnesses the unique power of satellite radar interferometry to detect and measure Earth-surface terrain motion. These data, in combination with geophysical expertise, are used to save lives, improve safety and reduce economic loss.

Terrain motion can be related to subsidence, landslides, earthquake activity, flooding, coastal erosion, volcanoes, unstable buildings and infrastructure, and even poor engineeering standards. Many of these phenomena and their associated hazards are made worse by the effects of rapid climate change. The socio-economic cost of terrain motion across Europe runs into tens of billions of euros a year, and is becoming higher as populations increase, cities become larger, resources become scarcer, and the climate becomes more unstable.

Persistent scatterer interferometry (PSI) in the ABSRATE project

PSI is a radar satellite based technique, providing very precise information on vertical motion rates. Raw PSI data are, however, relative, in the sense that all motion rates are measured relative to a local reference, which is assigned a vertical motion rate of zero.

The goal of the ABSRATE project is to combine PSI data with additional data from three different sources: [1] motion rates from permanent GPS stations, [2] sea level measurements from tide gauges, and [3] long wavelength motion data from regional geodetic models. Properly handled, such data can take us from the locally referenced, relative vertical motion rates, to motion rates including regional effects, and tied to global geodetic reference systems.

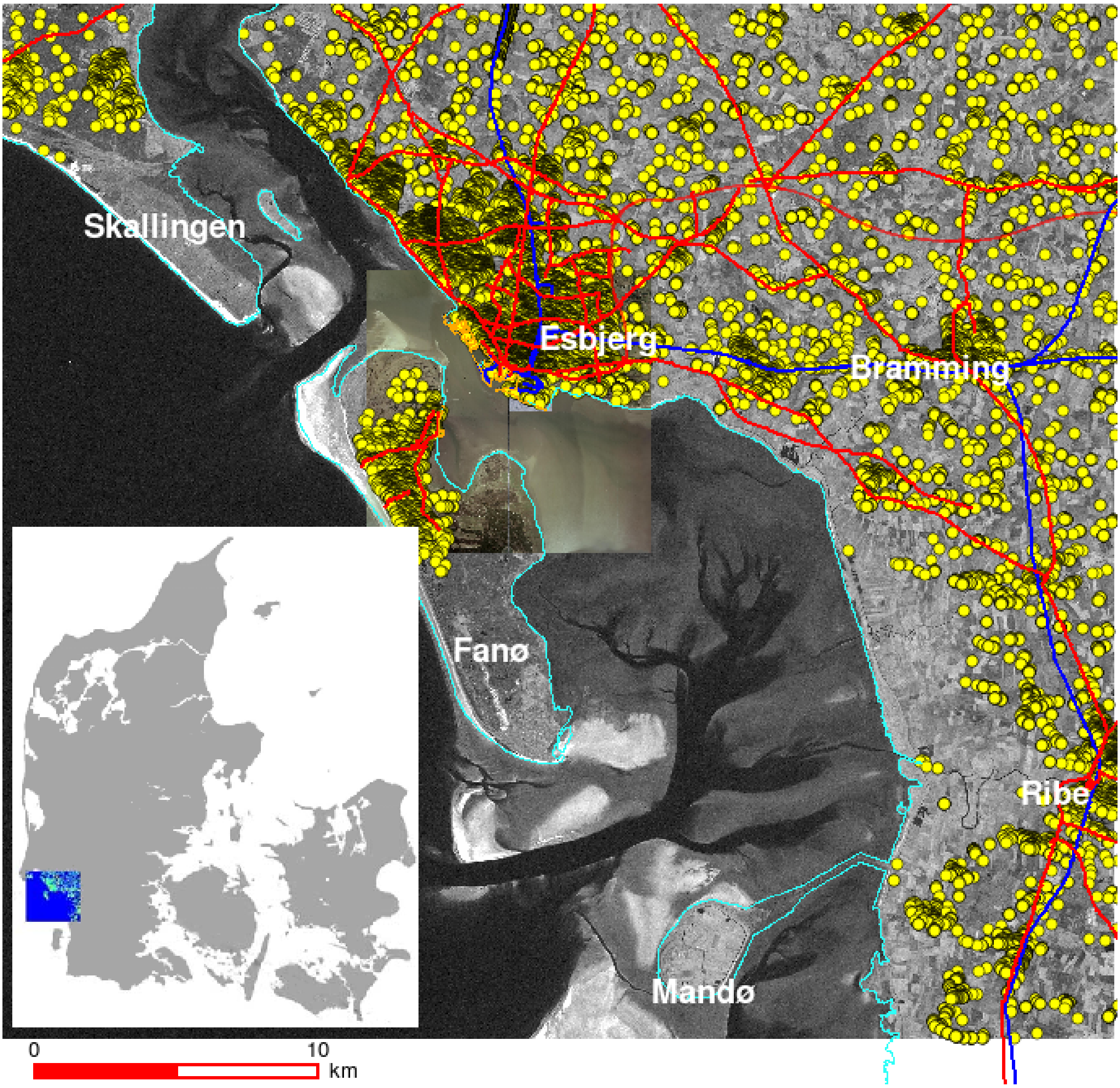
Results/reports

This final report of the ABSRATE project consists of a collection of summary papers written during the 18 months of project activity, and a wrap up in the form of an Activity Report.

The primary interpretations and results of the project are given in the Activity Report, by project lead Per Knudsen, and in the paper about the implementation and production of the ABSRATE Relative Subsidence Rates (RSR) product, by Thomas Knudsen. The important geological interpretation of the Esbjerg test field is given in a paper by Peter Roll Jakobsen (GEUS). It should be noted that the two latter papers use different visualizations and colour codings. Confusion is possible, but not expected. Note, however, that in a few cases (most evident on figure 1, page 19), persistent scatterer points are offset slightly southwards. This is due to a mismatch in the plot only: it does not affect our computations and conclusions.

As part of the work with the Relative Subsidence Rates product, a new gridding program, PINGPONG, was written, as a test bed for alternative gridding methods. While being used for the RSR product, PINGPONG had its public debut, and received much additional care during its tenure as a tool for quality control of height models. As a supplement to the RSR paper, the paper describing PINGPONG is reprinted here for completeness, despite being demonstrated using an entirely different kind of data. Again: confusion is possible, but not expected.

Most of the ABSRATE activities are centered around our Esbjerg test field. Hence, the reader is encouraged to read the description of the Esbjerg area on the following page, before proceeding to the main contents of the report.



The Esbjerg PSI test field of the ABSRATE project.

The insert in the figure above shows the location of the area around Esbjerg used in the ABSRATE project, for testing Persistent Scatterer Interferometry (PSI). The test field comprises a 40 km by 40 km area (Northing 6 120 000 m . . . 6 160 000 m and easting 447 000 m . . . 487 000 m, in ETRS89/UTM zone 32). It is situated in the southeastern part of Denmark on the North Sea coast of Jutland, the Danish mainland.

The main figure shows the coast of Jutland from north-west towards south-east, shielded by the Skallingen peninsula, and the islands of Fanø and Mandø (the latter connected to the mainland through a characteristic ebb tide road). Mainroads are shown in red, railroads in blue. Esbjerg and Ribe are the main cities in the area, while the town of Bramming hosts a major railroad junction.

Economically, Esbjerg was built on fisheries and bacon export during the 1870s, but geotechnically it was built on landfill and dredging. Geologically, the surface layers in the area are primarily built from Quaternary glacial deposits and postglacial freshwater deposits.

All in all, this combination of landfill, soft surface deposits, recent urban development, and heavy railroads, should provide a large number of interesting PSI targets (our current data set comprises 27113 PSI targets, shown as yellow dots—clearly delineating the urban areas, as well as the railroad tracks). But the main reason for the selection of this area is its location close to the margin of the the Weichselian glaciation (120 000–10 000 BP). Hence, we may expect a discernible effect from the shift of the isostatic compensation (*postglacial rebound*, etc.) in the area.

These geotechnical, geological, and geodetic factors, combined with climatological effects, means that vertical velocities measured in the area, results from a complex superposition of effects from [1] subsidence due to consolidation of soft layers, [2] gravity driven regional scale (*geodetic*) changes, and [3] sea level rise. Evidently, PSI can contribute immensely towards the understanding of this.

Activity Report

Per Knudsen

The work has been structures in workpackages as follows:

WP1000 Service Provision, Qualification and Evolution
- WP1100 Generate and deliver services
- WP1200 Service validation and qualification
- WP1300 Documentation of service utility
- WP1400 Test and integrate new and improved methods

WP2000 User Federation and Promotion
- WP2100 Establish the Potential User Group (PUG)
- WP2200 Generate promotion material and packages for the services proposed
- WP2300 Deliver service related training
- WP2400 Gather requirements from new users

WP3000 Management

A detailed description of the work carried out in each workpackage is found below:

WP1000 Service Provision, Qualification and Evolution

The overall goal of WP1000 with its sub-workpackages was to derive the Absolute Subsidence Rates (ASR) product. As the main input from the existing Terrafirma service a test H-1 product was used and combined with regional subsidence information derived from historic precise levelling, tide gauges and GPS. The provision of the H-1 product is in accordance with the SLA that was agreed.

WP1100 Generate and deliver services

<u>Acquire all necessary EO and in-situ data required for each SLA</u>
The basic product from the Geo-hazards information service Terrafirma is the Historical Subsidence Motion Measurements denoted H-1. According to the SLA the product covering an area around Esbjerg on the West coast of Denmark was acquired (Figure 1).

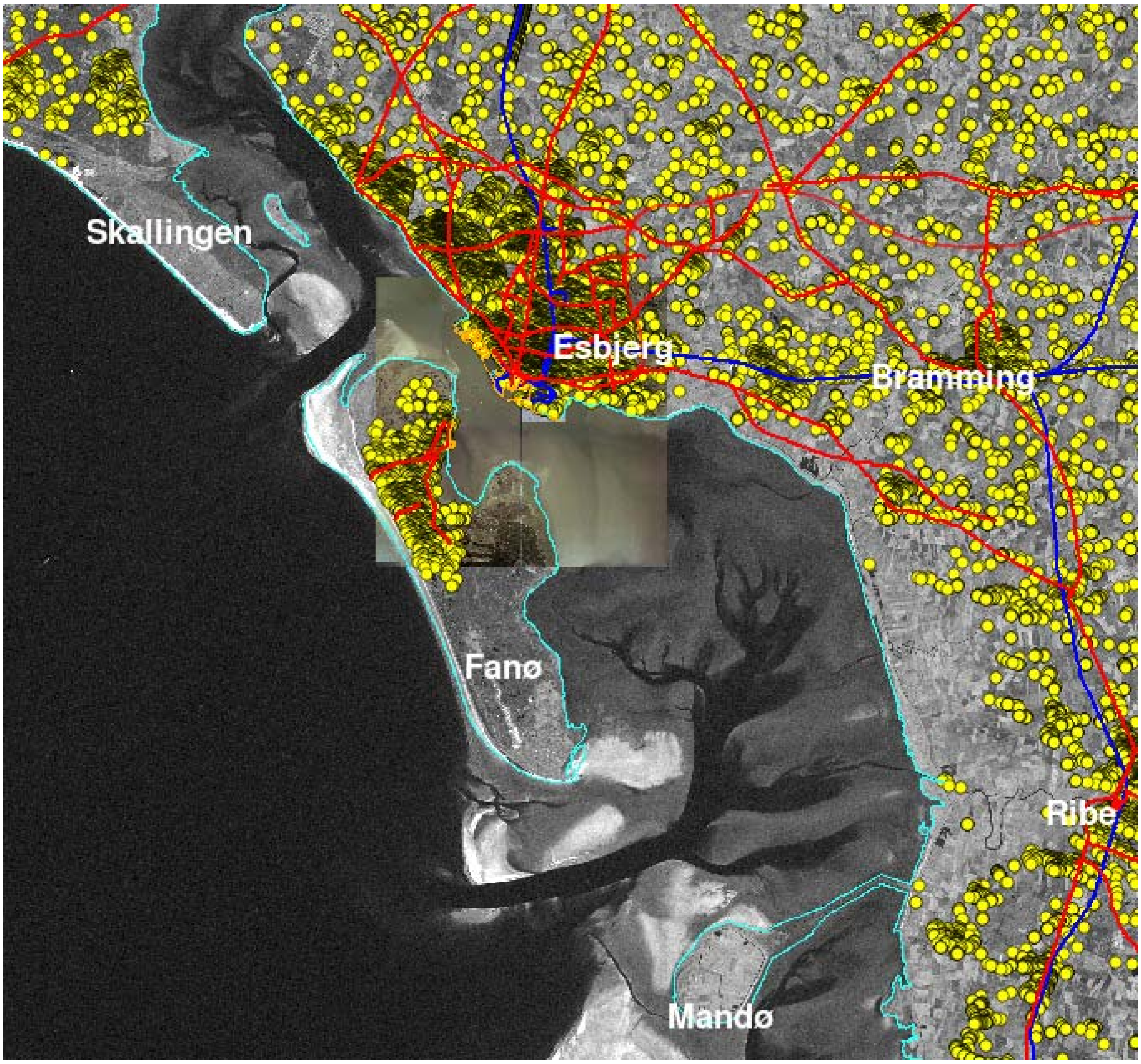


Figure 1. The Esbjerg study region. PSI values locations are shown with yellow dots.

Additional information was acquired to perform an assessment of the H-1 subsidence rates and to determine the regional characteristics of the subsidence. The most important information for the direct assessment is precise levelling carried out in three campaigns spanning about 100 years (Figure 2). Furthermore, for the absolute fixing in a global geodetic reference frame GPS data from two permanent GPS sites and sea level data from one Tide Gauge in Esbjerg was collected.

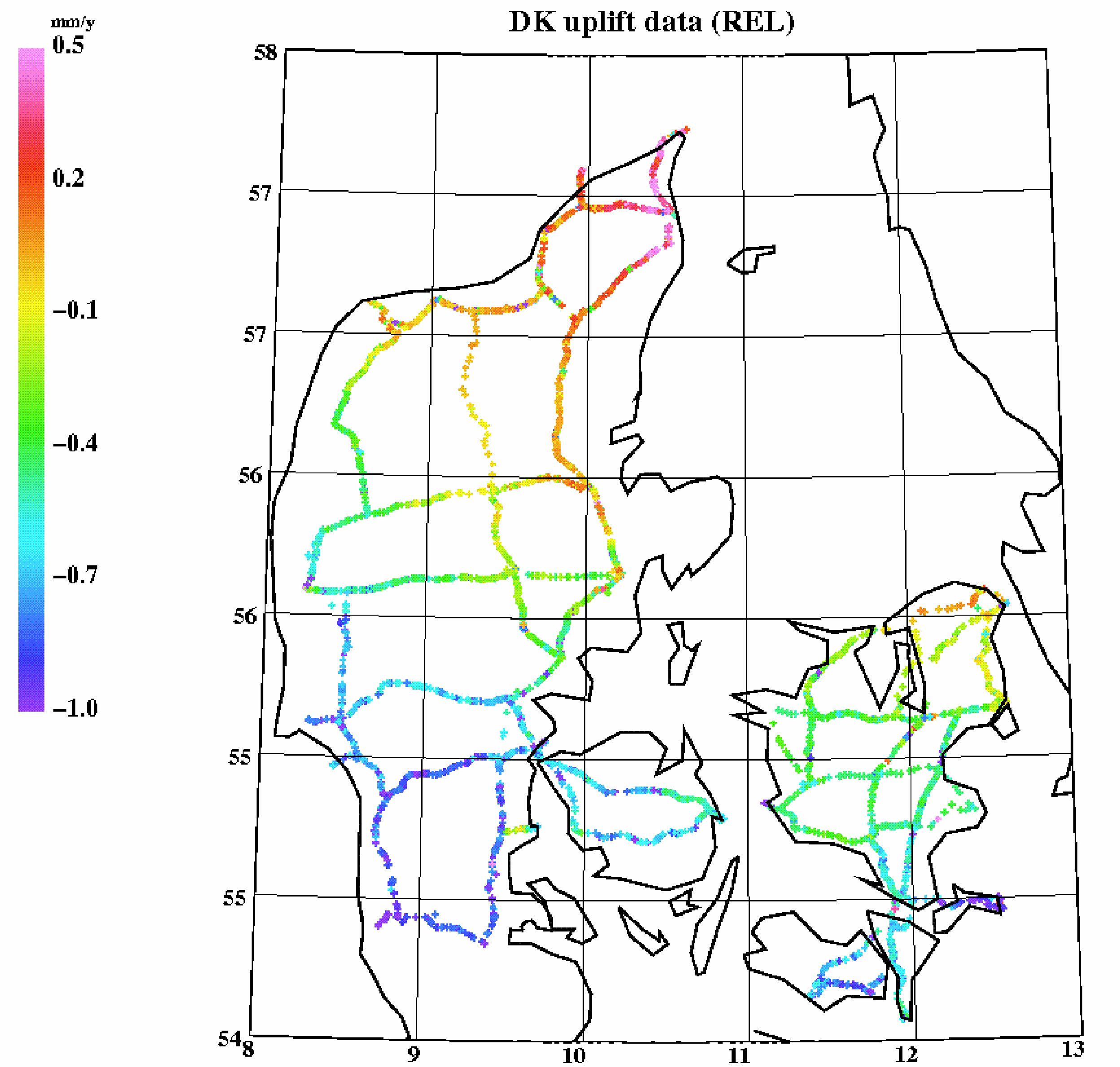


Figure 2. Uplift rates derived from precise levelling data from three campaigns spanning about 100 years and each adjusted to fit mean sea level. Hence, the rates are relative to a common sea level rise.

Finally, regional uplift/subsidence models from the Nordic Commission of Geodesy (NKG) were acquired (Figure 3). Such models compile historic precise levelling data combined with mean sea levels at tide gauges from the Nordic region. To evaluate currently available GPS rates the information available at the EUREF European GPS analysis centre was acquired as well.

To summarise the data that was acquired is:

- Historical subsidence motion measurements - H-1
- Precise levelling carried out in three campaigns spanning about 100 years
- GPS data from two permanent GPS sites
- Tide Gauge data from Esbjerg
- Regional uplift/subsidence models from NKG and
- GPS rates from EUREF.

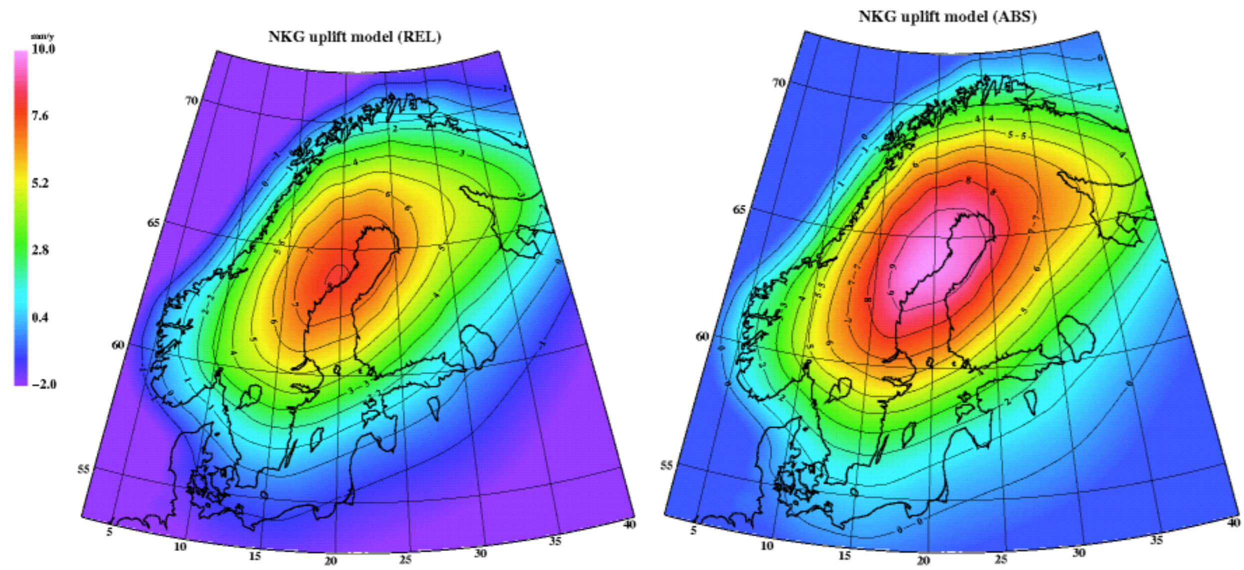


Figure 3. The NKG uplift model derived from GPS data and tide gauge data. Model on the left is relative to sea level and the model on the right is relative to the centre of the Earth.

<u>Execute data ingestion, processing, assimilation, modelling processes</u>

An initial processing of data was carried out to derive the sub-products that will be used to process the ASR product and to evaluate this product subsequently. To provide the absolute reference in a global geodetic reference frame vertical GPS positions were computed using GIPSY/OASIS as Precise Point Positioning in ITRF2000. Based on those vertical positions uplift/subsidence rates for the GPS stations are computed. Furthermore, to provide information on the sea level rise the tide gauge data were used to compute the rate of the sea level relative to land (the tide gauge bench mark).

Tabel 1. Sea level rise at tide gauges.

Tide Gauge	Sea level rise mm/y
Esbjerg	1.08
Hirtshals	-0.41
Frederikshavn	-0.51
Århus	0.46
Fredericia	0.95
Hornbæk	0.06
Københ	0.23
Slipshavn	0.79
Korsør	0.63
Gedser	0.93

Tabel 2. Land uplift from GPS data in mm/year from GPS stations in Denmark. DTU values are obtained using GIPSY/OASIS. EUREF values are obtained from their website. Corrected values are relative to Potsdam (POTS).

GPS station	DTU Mm/y	EUREF ITRF2005	EUREF corrected
Esbjerg C	0.2		
Hirtshals	1.8		
SMID	1.9	1.9	0.9
SULD	1.7	2.7	1.8
BUDP	1.2	2.4	1.5
Gedser	0.8		

For the evaluation of the H-1 product, the NKG uplift/subsidence model as well as the ASR product data from the precise levelling lines located with the H-1 product was extracted. The associated heights were used to determine subsidence rates in the common points.

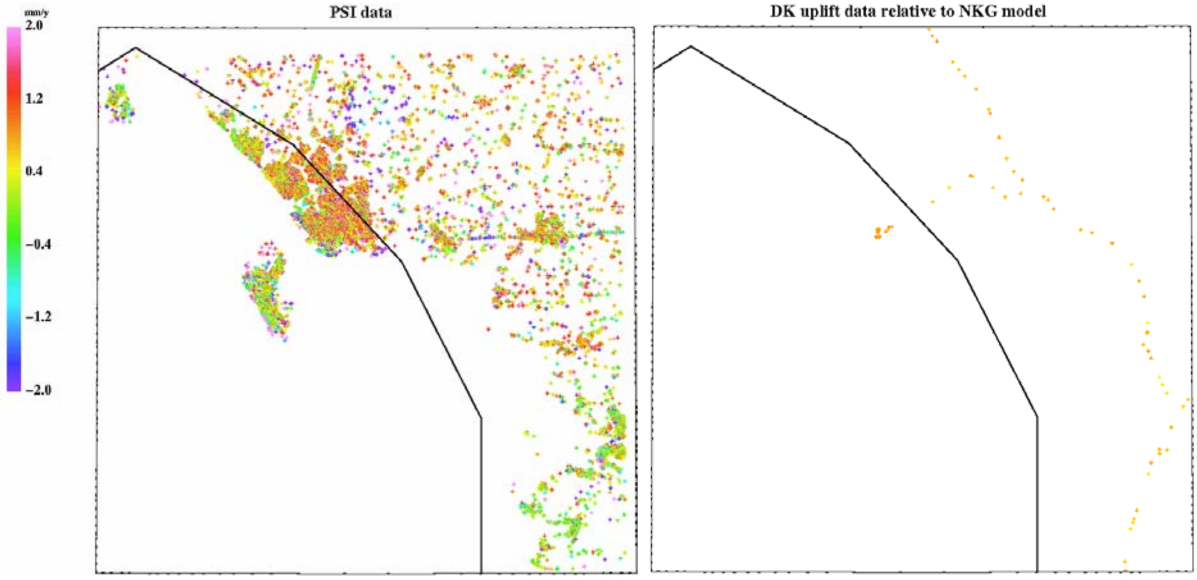


Figure 4. PSI uplift values are shown on the left and values from levelling on the right.

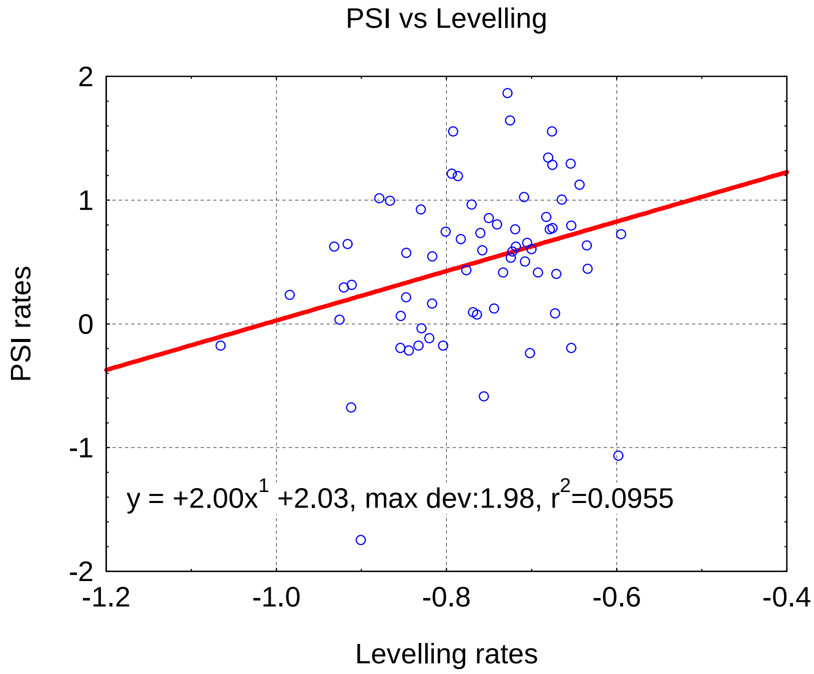


Figure 5. Plot of common uplift values from levelling (x-axis) and PSI (y-axis) in mm/y. Values may be separated up to 1 km in distance.

A preliminary subsidence product (Relative Subsidence Rates - RSR) was derived by draping the H-1 subsidence rates on to the NKG model. The draping technique combined the products, so that the NKG model defines the regional patterns that are unresolved in the H-1 product. The local and precise subsidence information in the H-1 product is kept. Those relative subsidence rates were compared and referenced to sea level rate at tide gauge locations. This preliminary product expresses subsidence relative to sea level.

A comparison of the NKG model with the uplift values from levelling revealed large differences between the two data sets. The NKG model was interpolated to the levelling point and residuals were formed by subtracting those values from the original levelling values. The mean of the differences is 0.51 mm/y and the std.dev. 0.35 mm/y. Large residual of -1.37 and 2.47 mm/y were found (see Table 3). The Figure 6 show that the differences are quite large in the Western part of Denmark. In the Esbjerg region a systematic offset of about 0.8 mm/y is found. Hence it was decided to redo the computation using the direct comparicon at common PSI and levelling points (see Figure 5). Using those pairs of values an offset between the two data sets of -1.26 mm/y was found. The poor spatial distribution of the levelling points did not alow for a computation of regional trends. Subsequently the new RSR product was derived by removing the offset.

Table 3. Statistics of comparison of NKG model (grid interpolated values) and levelling point values.

points predicted: 3290, skipped points: 0					
statistics:	mean	std.dev.	min	max	unknown
original data (pointfile) :	-0.38	0.36	-1.36	1.16	0
Grid interpolation results:	-0.89	0.47	-1.69	0.64	0
predicted values output :	0.51	0.35	-1.37	2.47	0

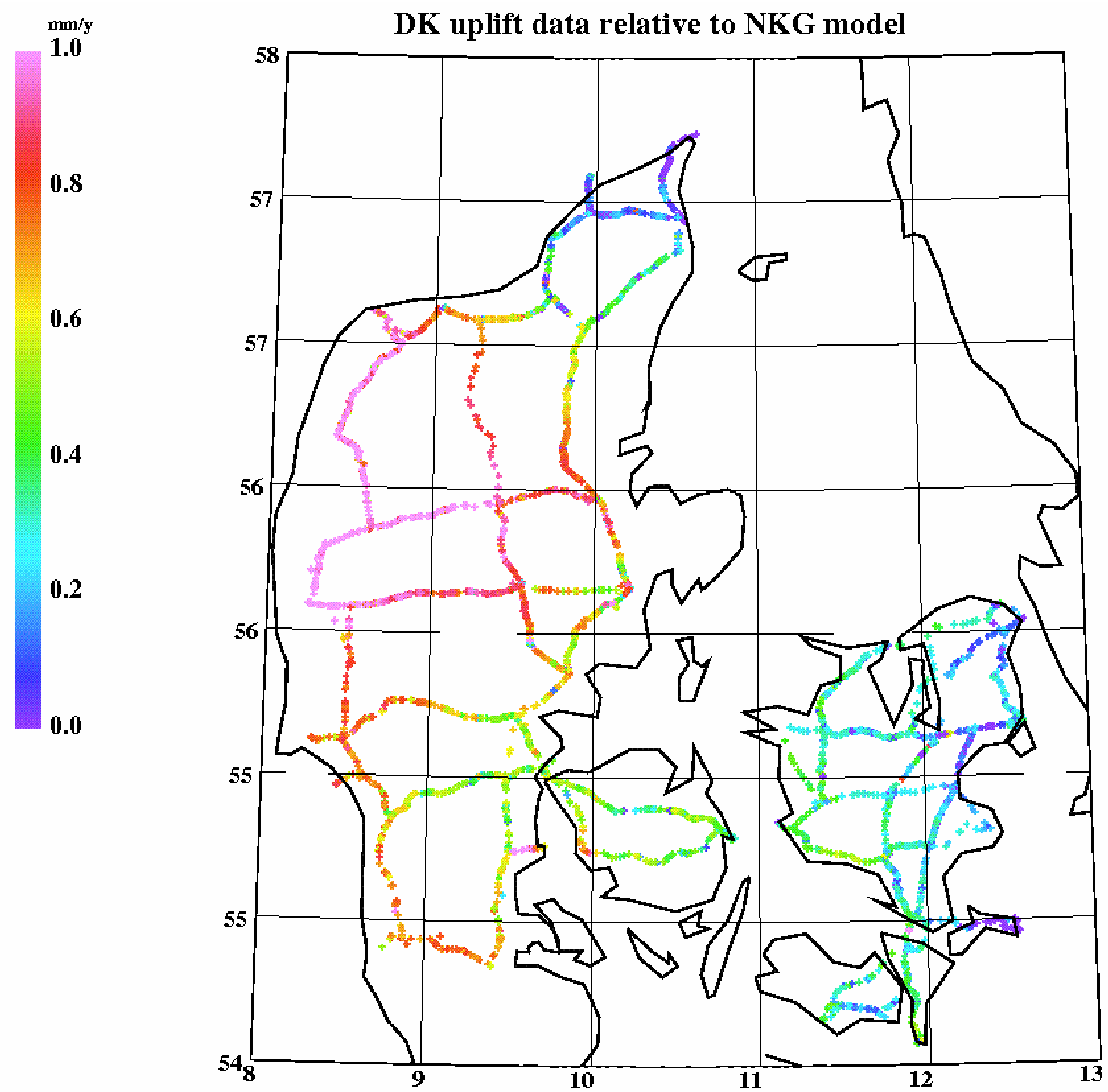


Figure 6. Residuals between levelling uplift values and the NKG model.

Table 4. Statistics of result of draping psi values onto levelling rates to obtain RSR

points predicted: 27113, skipped points: 0					
statistics:	mean	std.dev.	min	max	unknown
Original data (pointfile) :	0.54	1.95	-29.72	32.46	0
grid interpolation results:	-1.26	0.00	-1.26	-1.26	0
predicted values output :	-0.71	1.95	-30.97	31.20	0

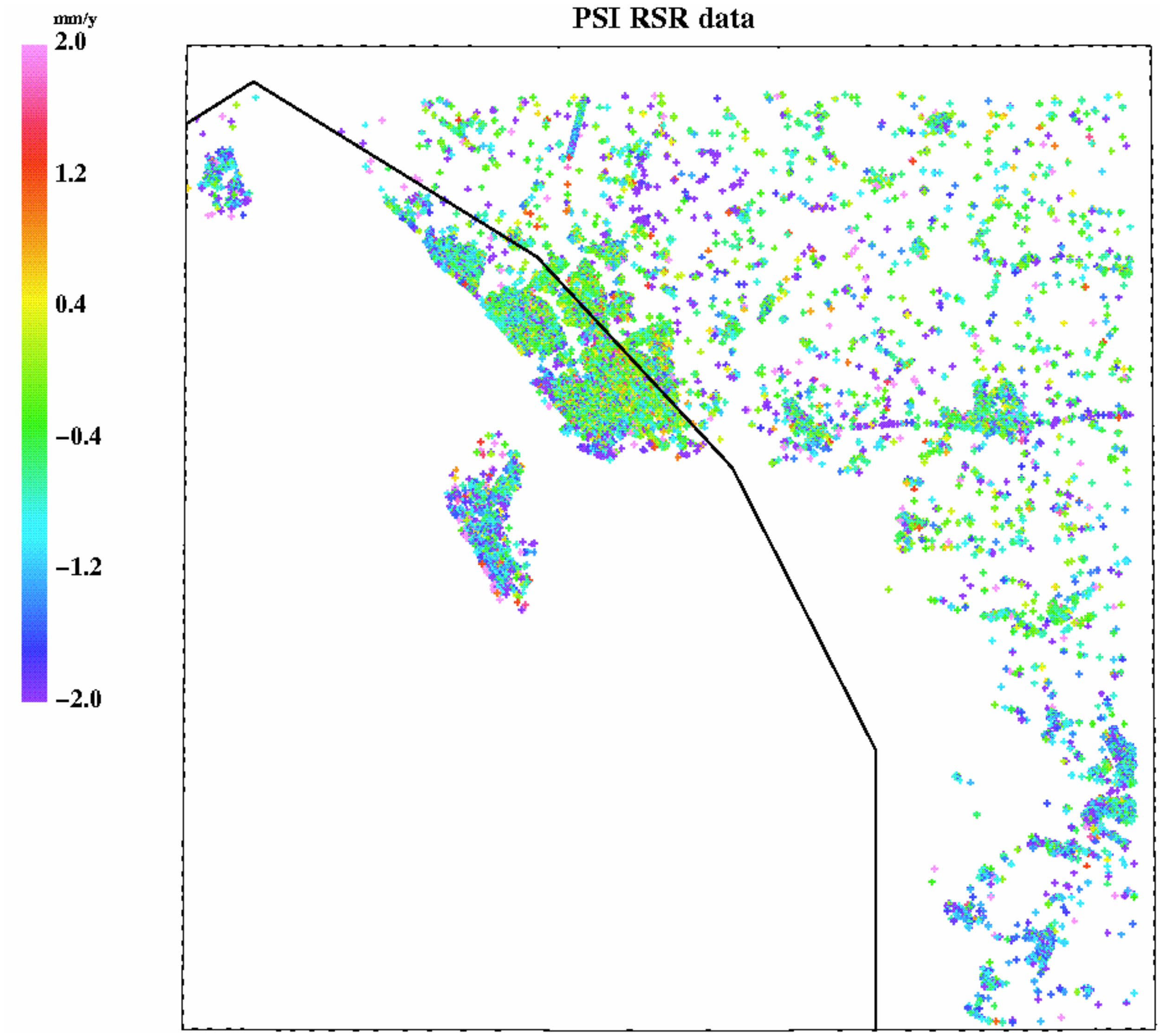


Figure 7. RSR values obtained by referencing PSI values to sea level usinglevelling data and tide gauge data.

The final ASR product was derived using the GPS vertical rates. For each GPS station a regional vertical land motion relative to the global geodetic reference frame was compared to the uplift rates computed from levelling and references to sea level to give information about the regional rate of sea level relative to the global geodetic reference frame. This value was found to be be close to the common value of sea level rise of 1.8 mm per year. Subsequently, the final ASR product was obtained from the RSR product by adding this rate of sea level rise. Hence, the ASR product expresses subsidence rates relative to the global geodetic reference frame.

Table 4. Statistics of result of draping psi values onto levelling rates to obtain ASR

points predicted: 27113, skipped points: 0					
Statistics:	mean	std.dev.	min	max	unknown
original data (pointfile) :	-0.71	1.95	-30.97	31.20	0
grid interpolation results:	1.80	NaN	1.80	1.80	0
Predicted values output :	1.09	1.95	-29.17	33.00	0

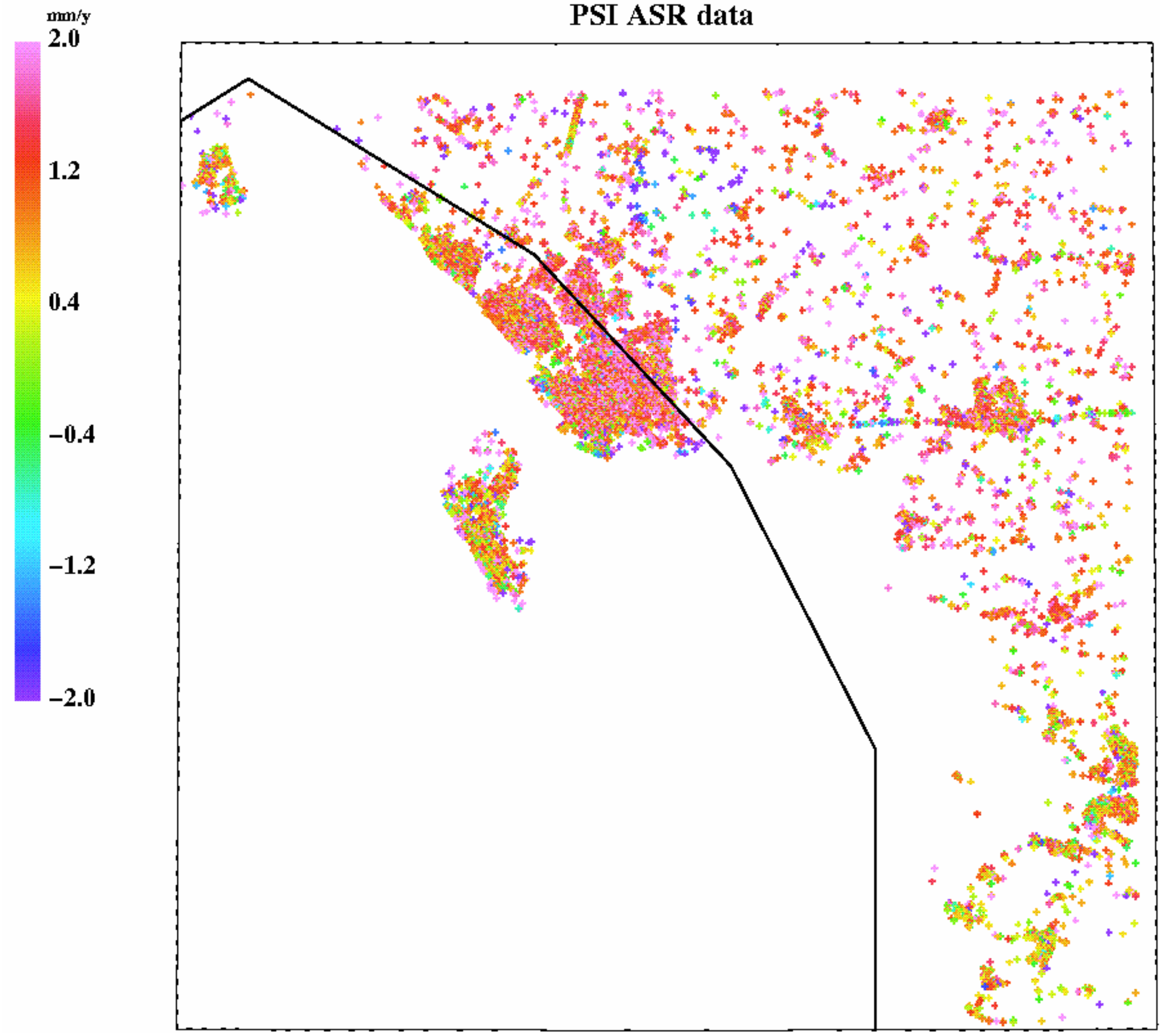


Figure 8. ASR values obtained from the RSR values byadding the sea level rise.

Conduct standard quality-control procedures
The H-1 product is quality controlled by the Terrafirma service. The NKG uplift/subsidence model was evaluated as described above. Both products were assessed in this project using the precise levelling rates.

The GPS data was quality controlled using state-of-the-art procedures (as at EUREF http://www.epncb.oma.be/) (see Table 2). The tide gauge data are quality controlled using state-of-the-art procedures.

Perform all required routine calibration and validation procedures
Required routines for calibration and validation of the ASR products were based on the procedures used in Terrafirma on H-1 and value added products. As a special activity the H-1, the RSR, the ASR products were evaluated using the precise levelling rates. This assessment was carried out in order to get insight in the quality of those products and to derive documentation for the future users of those products.

The results showed that a direct comparison of PSI and levelling values are hampered by the fact that only a few levelling values are available in the region. Only 74 levelling points are situated within one kilometre from the PSI points. The comparison the pairs of values showed that there is no correlation between them (the correlation coefficient is 0.1) (see Figure 5). Furthermore, the variation of the PSI values are twice as big as for the levelling values. Hence, such a comparison cannot give useful results.

Detect and rectify all operational production anomalies
The production procedures were evaluated considering a production of ASR products covering the entire country. That was done using present locations of GPS and tide gauge stations. The levelling data cover the country well and they are well connected to both the GPS and the tide gauge stations. No problematic regions were identified. However the regions should be large enough to overlab with the precise levelling lines – see Figure 2.

Generate, format and distribute service packages to end-users
No standard product description of the NKG uplift/subsidence model compliant with the H-1 descriptions exists. This is also the case for the GPS and the sea level rise rates. The NKG model has been described by its authors recently.

Promotional materials were compiled. Then the PUG got the opportunity to get hands-on experience with the product. Subsequently, their feedback was acquired as described in the Utility Report.

Monitor and respond to user feedback on service deliveries
When the Potential User Group (PUG) received the materials and made hands-on experiences, their feedback was acquired and compiled into a set of recommendations for enhancing the product and the service delivery associated with it. This is reported in the Utility Report as well.

WP1200 Service validation and qualification

Conduct regular validation of service information content
Procedures for validation of service information content and how the validation was conducted were based on the existing procedures used in the Terrafirma service. A few new validation procedures may be needed to evaluate the absolute level and its consistency with the GPS and tide gauge information. More experince with the data may be needed to describe those procedures.

Generate validation reports in compliance with the agreed service validation protocol
Again the procedures were based on the existing procedures used in the Terrafirma service. A few new reporting items associated with the absolute level and its consistency with the GPS and tide gauge information may be needed. More experince with the data may be needed to describe those new items.

Monitor service information content and delivery performance compliance with applicable user domain standards and rectify non-conformance events
Again the procedures were based on the existing procedures used in the Terrafirma service. A few new items associated with the absolute level and its consistency with the GPS and tide gauge information may be needed. More experince with the data may be needed to describe those procedures.

Analyze consistency and interfaces to relevant fast track services
As an extension to Terrafirma the developed product contribute to the implementation of the Land Fast Track Service and to the Emergency Management Fast Track. Sufficient information to do such an assessment were not available.

WP1300 Documentation of service utility

Assess utility, impact and benefit of services provided with respect to user needs
Based on the user requirements that have been compiled and revised through feedback from the users represented in the PUG the provided service package. This has been reported in the Utility Report. The users showed more interest in the H-1 product than the ASR product and wished to have more flexibility with respect to the selection of reference points.

Provide user feedback on service quality, fitness-for-purpose, required improvements to service provided, requirements for new services to be included in portfolio needs
Based on the user requirements that have been compiled and revised through feedback from the users represented in the PUG the quality of the provided service package and its usage as well as requirements for new services were assessed. As reported in the utility report the potential users were not able to provide feedback without information on costs of the products.

Synthesise user feedback, service validation and operational production experience into service portfolio upgrade objectives
No further feedback from the PUG has been collected.

Specify needs for enhancement of service network throughput and performance
No further feedback from the PUG has been collected.

WP1400 Test and integrate new and improved methods

Test and integrate improved algorithms and models
During this activity alternative draping techniques were tested to improve the algorithms that are used. For this purpose, the PINGPONG program for inverse distance weighted interpolation was tested. Also the use of levelling data for direct draping onto sea level referenced uplift rates were tested. Subsequently, the improved algorithms and models were integrated in the production flow as described above.

Investigate new products to extend the portfolio
Potential new products were suggested though the work in PUG.

Verify new EO data and in-situ data sources as they become available
The main task was to follow the developments in geographical infrastructure to integrate GALILEO and make full use of its ground station network and associated services. More work and GALILEO experience are needed for this verification.

Integrate automated methods to improve supply chain efficiency
The algorithms were designed for automated production as far as possible. Especially, the experiences made in this workpackage were used to evaluate how far the supply chain efficiency could be improved.

WP2000 User Federation and Promotion

The main goals of WP2000 and its sub-workpackages were to consolidate the requirements of the users of the new ASR product and to preliminary Service Level Agreements that support those requirements and simultaneously involve relevant public and private service providers in Denmark. A fundamental task was to establish the Potential User Group to involve a variety of users of the proposed ASR service product.

WP2100 Establish the Potential User Group (PUG)

A Potential User Group (PUG) was formed at the beginning of the project to facilitate communication and feedback from the relevant users. PUG included representatives from the main relevant national authorities and companies. Those are:

- The National Authority for Mapping and Cadastre,
- The Danish Coastal Authority,
- The Geological Survey of Denmark and Greenland,
- Rail Net Denmark, and
- COWI.

WP2200 Generate promotion material and packages for the services proposed

<u>Provide material to the prime for integration into overall promotion packages</u>
Based on the results in WP1000 the documentation material will be provided to the prime for inclusion into the overall promotion packages.

<u>Support users to make press & media briefings on results & benefits of GMES Services</u>
Based on the results of WP1000 the documentation material as well as materials coming out of the user evaluation and assessments will be made available as a report to the users so that they may make press and media briefings.

WP2300 Deliver service related training

<u>Prepare and distribute training packages for main user segments</u>
Based on the results in WP1000 and in WP2100 the documentation material will be used to prepare a training package for the main users. Subsequently, it will be distributed to the PUG for feedback. Based on the feedback, the training package will be revised and sent to the main user segment. This has been reported in the Utility Report.

<u>Deliver training and briefings to existing users and stakeholders</u>
The promotion materials and the training package will be used to develop a training programme that together with the promotion material will be provided to the existing users and stakeholders. More experience and a better understanding of the applications of the new products are needed to further develop the training programmes.

WP2400 Gather requirements from new users

<u>Document and analyze needs of new user organizations for the relevant services</u>

A common requirement from the new users is that all geographical registration should be done in a uniform geodetic reference system. Furthermore, in order to strengthen the infrastructure the registration should be consistent with the reference frame used for GNSS (GPS and GALILEO).

In the ABSRATE project the members of the Potential User Group (PUG) did not identify a need for further requirements on the geographical registration.

<u>Conduct a limited number of trial cases with new users</u>
More experience and a better understanding of the applications of the new products are needed to further develop the service package to facilitate further trial cases.

<u>Define terms of preliminary Service Level Agreements with new users</u>
The ABSRATE project has involved potential Danish service providers in the consolidation of the GMES services in Denmark. In this case relevant service providers are National authorities responsible for the geodetic reference network and for the topographic mapping. Other important service providers are companies in the field of surveying and geoinfomatics. Again,more experience is needed as well as more information on costs are needed before Service Level Agreements can be drafted.

The ABSRATE Relative Subsidence Rates product: implementation details and case study of the Esbjerg test site

Thomas Knudsen

1 Introduction

The framework and rationale leading to the ABSRATE *Relative Subsidence Rates* product (RSR) was presented in the ABSRATE project proposal (Knudsen, 2006). This paper supplies the implementation details: how is the RSR generated in practical terms – how is it fleshed out in code, and how does its intermediate steps look. The code fragments presented are for illustration only: they are fragments, after all. Readers not natively speaking the programming languages used may safely skip the fragments.

Additionally, in order to emphasize the practicality of the implementation, the (primarily) statistical results from the processing of the ABSRATE Esbjerg test site are presented.

2 Draping

The basic idea in the generation of the RSR product is to drape the short wavelength PSI data onto a long wavelength regional subsidence model – in our case the model from the Nordic Geodetic Commision (NKG).

Draping is a classical technique in the geodetic toolbox, where it is used anywhere heterogeneous data sets are to be merged. Notable examples include the works by Ekholm (1996); Johnston and Featherstone (1998). The technique is described in some detail in Strykowski and Forsberg (1998). In outline, the idea is to correct the short wavelength data by first removing the long wavelength part (by subtraction of interpolated values from the long wavelength data set). This introduces a bias in the data. The bias is removed by adding back the local mean value of the bias which then represents the long wavelength part of the signal.

3 Software used

The entire software stack used in the production of the RSR is open source software. Not necessarily on principle, but because it was either best for the job, or most accessible – or both.

3.1 Vector processing

A fair amount of very plain vector operations are called for in the processing leading to the RSR product. To this end, we use the Octave numerical environment Eaton et al. (2008), an open source alternative to the more restricted (and vastly more expensive) Matlab system.

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3.2 Gridding

Implementing draping requires quite a lot of gridding, for which we primarily use the pingpong program (Knudsen, 2008). For occasional verification, we use the Geogrid program of the Gravsoft package Tscherning et al. (1992).

3.3 Visualization

For visualization, we use the QGIS tool, a capable, open source geodata visualization tool, that also supports very strong raster data analysis through a plug in connection to the GRASS open source GIS.

3.4 Projections/transformations

Map projection work is carried out with the proj/invproj programs originating from US Geological Survey in the 1980s.

3.5 Text reformatting

In order to fit the output format of one program to the expected input format of another program some text massaging is always necessary. To provide this indispensable glue function, we use the AWK programming language in its GAWK implementation from the Free Software Foundation.

4 Processing

The RSR processing falls in a small number of naturally separate steps. Below, each step is described using a brief description and some sample code.

4.1 Transformation into geographical coordinates

The PSI data are georeferenced using a ETRS89/UTM32 system – but the NKG regional model is a grid in latitude/longitude. Hence, in order to do the interpolation in the grid, we need to transform the point data to the grid system. AWK and invproj teams up to do the job!

```
awk '{print $2, $3}'          \
    TF_PSI.browse |            \
    invproj -f '%.7f' +proj=utm \
        +zone=32 +ellps=GRS80   \
    >pap.ll
paste -d "  " TF_PSI.browse pap.ll >TF.all
```

4.2 Remove regional model from the PSI

Doing this step in Octave is very simple!

```
% load psi data
P      =   load_psi_data('TF.all');
```

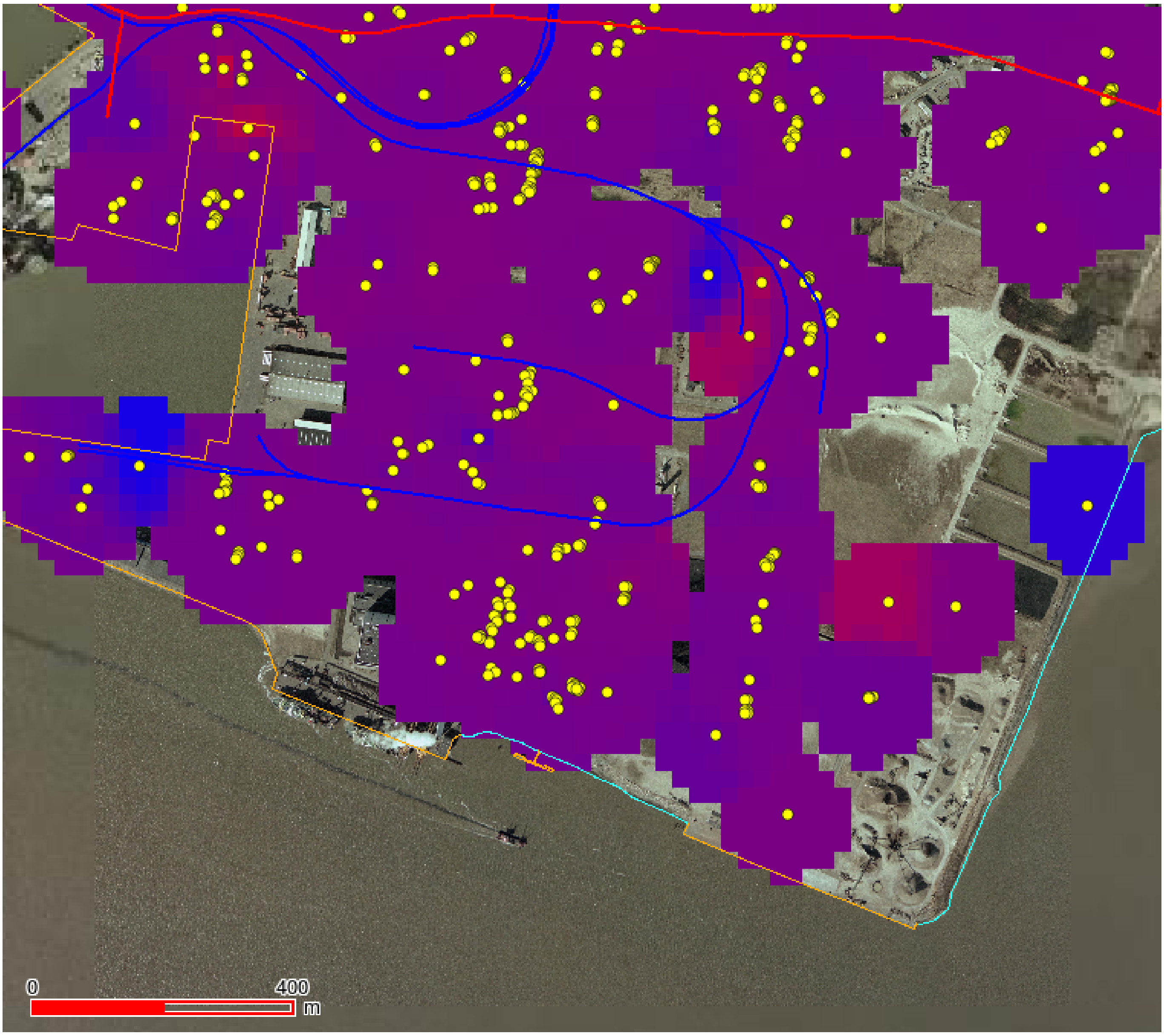

Figure 1: The ABSRATE RSR product for the Esbjerg havn area. Local displacement rates range from an uplift of approximately 30 mm/year (red) to a subsidence of -30 mm/year (blue). Yellow markers indicate the positions of the persistent scatterers. Red lines are roads, blue lines are railroad tracks.

```
% load NKG regional uplift model
[H G] =  load_gravsoft_grid('nkg.grd');

% find NKG uplift values at PSI stations
zz = interp2(H.x, H.y, G, \
        P(:,7), P(:,8),'linear');

% write interpolated and PSI-NKG "reduced"
% data to file psinkg.dat
```

4.3 Gridding the deviation

Now we need a 250 m equidistance grid of the local mean deviation between the PSI and NKG data. "Local mean" in this context means the mean value of all deviations within 5000 m from the grid node (hence the 5000/0 argument to pingpong).

```
awk '{print $1, $1, $1, $8, $7, $6}'   \
        psinkg.dat |                   \
pingpong -vvv -a idw -p 5000/0 -g     \
    G/6120000/447000/161/161/250/-999 \
    -o psinkg.grd                     \
    -e psinkg.err                     \
    -d psinkg.den
```

4.4 Drape the PSI point data

Now we are ready to interpolate the local means from the grid node positions to the actual positions of the PSI points.

```
% load PSI-NKG data
P      =  load_psi_data('psinkg.dat');

% load NKG correction grid
[H G] =  load_esri_grid('psinkg.grd');

% find NKG uplift correction values
% at PSI stations
```

data set	minimum	1st quartile	median	3rd quartile	maximum	mean	st. dev.	skewness	kurtosis
PSI	-29.71800	0.13600	0.62900	1.06300	32.45700	0.54332	1.95449	0.25905	63.04048
NKG	-0.312085	-0.210003	-0.196115	-0.163776	-0.086364	-0.189132	0.037197	0.078250	0.626135
PSI - NKG	-29.52466	0.32694	0.81904	1.25262	32.70181	0.73245	1.95400	0.26096	63.08301
Corrector	0.18942	0.60000	0.80000	0.90000	1.00000	0.73469	0.20611	-0.90632	-0.42464
Final	-29.03793	0.97353	1.56071	2.07150	33.50181	1.46715	1.98672	0.22949	59.09940

Figure 2: Basic internal statistics for the final RSR product, and each of the intermediate steps. It is evident that in our test area, the influence of the long wavelength effects are minor, with the draping correction spanning only the interval 0.18-1.00 mm/year. All statistics are given with an excessive number of decimals as they are taken directly from program output using the standard output routines.

```
zz = interp2(H.x, H.y, G, P(:,8),\
    P(:,7),'linear');

% write data to file
D = [P(:,1) P(:,2) P(:,3) \
     zz P(:,6) P(:,6)+zz   \
     P(:,7) P(:,8)];
```

4.5 Gridding of draped PSI point data

Now we are ready to generate the final gridded model of the corrected/draped PSI points:

```
awk '{print $1, $1, $1, $8, $7, $5}'  \
        psinkg.dat |                  \
pingpong -vvv -a idw -p 100/3 -g      \
    G/6120000/447000/1601/1601/25/-999\
    -o psi-full.grd                   \
    -e psi-full.err                   \
    -d psi-full.den
```

Here, we use inverse distance weighting with a comparatively large search radius of 100 m, but with a somewhat high power of 3 in the inverse radius, which will favour the nearest point. This is essential in this kind of work, since the individual scattererers may have nothing in common, and hence follow very different statistical characteristics. This is also the reason for selecting inverse distance weighting rather than an optimal interpolation technique, such as kriging: kringing (and friends) would require us to come up with a reasonable covariance function for the entire data set – which is very improbable to happen.

A subset of the final RSR data set is shown in figure 1.

4.6 Discussion/Conclusion

We have described a simple, and efficient implementation of a draping technique, which we expect will scale well to larger test areas.

The internal statistics of the intermediate (and final) results of the test run is summarized in figure 2. It is clear from this summary, that the long wavelength model has only minor influence in our test area.

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DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2008/18

Geological evaluation of observed vertical terrain movements in the Esbjerg test area

A contribution to the ABSRATE/Terrafirma project

Peter Roll Jakobsen

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF CLIMATE AND ENERGY

G E U S

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Contents

0. Resume and conclusions

The aim of this investigation was to link the observed vertical movements to the geology in the Esbjerg test area, and if possible to give a geological explanation of the movements. The evaluation is based on existing data and maps.

No recent seismic activity has been recorded in this region and the study area is considered tectonically stable. Tectonic generated movements in the area, is not likely to occur.

Along the railroad from Esbjerg and to the East, there are several locations, where vertical movements are seen. In most of these locations the rail road crosses low areas with unconsolidated postglacial deposits. It is most likely that the load of the railroad construction has caused the deposits to settle.

On the island of Fanø and in the area north of the Skallingen peninsula, sporadic vertical movements occur. In these areas the vertical movements is probably caused by settling of unconsolidated marine and aeolian deposits.

In the harbour area in Esbjerg relatively large vertical movements are seen, which probably is due to settling of the filled material, which built up the harbour area.

In the western outskirt of Esbjerg relatively strong movement are seen in an area which is a former dump. The vertical movements are most probably a consequence of settling of the filled material.

1. Introduction

In the Esbjerg area satellite data of vertical movements of the terrain has been retrieved during the ABSRATE/Terrafirma project(Figure 1.1). GEUS was asked to give a geological evaluation of the observed relative vertical movements.

The aim of this investigation was to link the observed vertical movements to the geology in the Esbjerg test area, and if possible to give a geological explanation of the movements. The evaluation is based on existing data and maps.

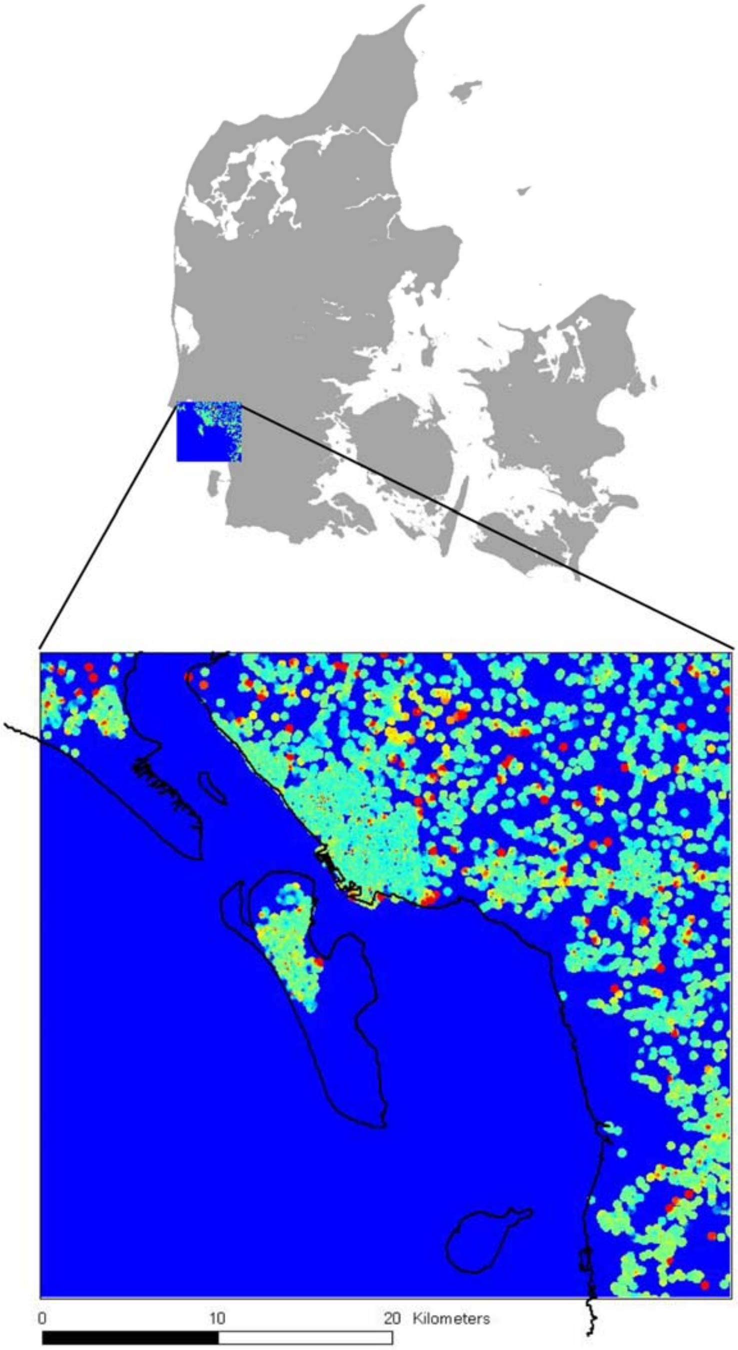

Figure 1.1. Location of the Esbjerg test site.

2. Regional geology of the Esbjerg region

2.1 Quaternary

The area in question is situated in the south-western part of Jutland. The surface deposits in the area are Quaternary glacial deposits, postglacial freshwater deposits, marine deposits and aeolean deposits. The main geological and morphological features are the hilly islands, the meltwater plains, the marine marsh foreland, the aeolean dune landscape and the barrier islands.

The hill islands consist of glacial till and meltwater sand and clay of Saalian or older age, as the glaciers of the Weichselian glaciation did not reach this area. The meltwater plains surrounding the hill islands are sandy sediments, deposited by meltwater rivers during the Weichselian glaciation.

In postglacial time freshwater sediments and peat are deposited along rivers/streams and in lake basins. Along the west coast of Jutland, marine tidal sediments are deposited and they build up the marsh flats.

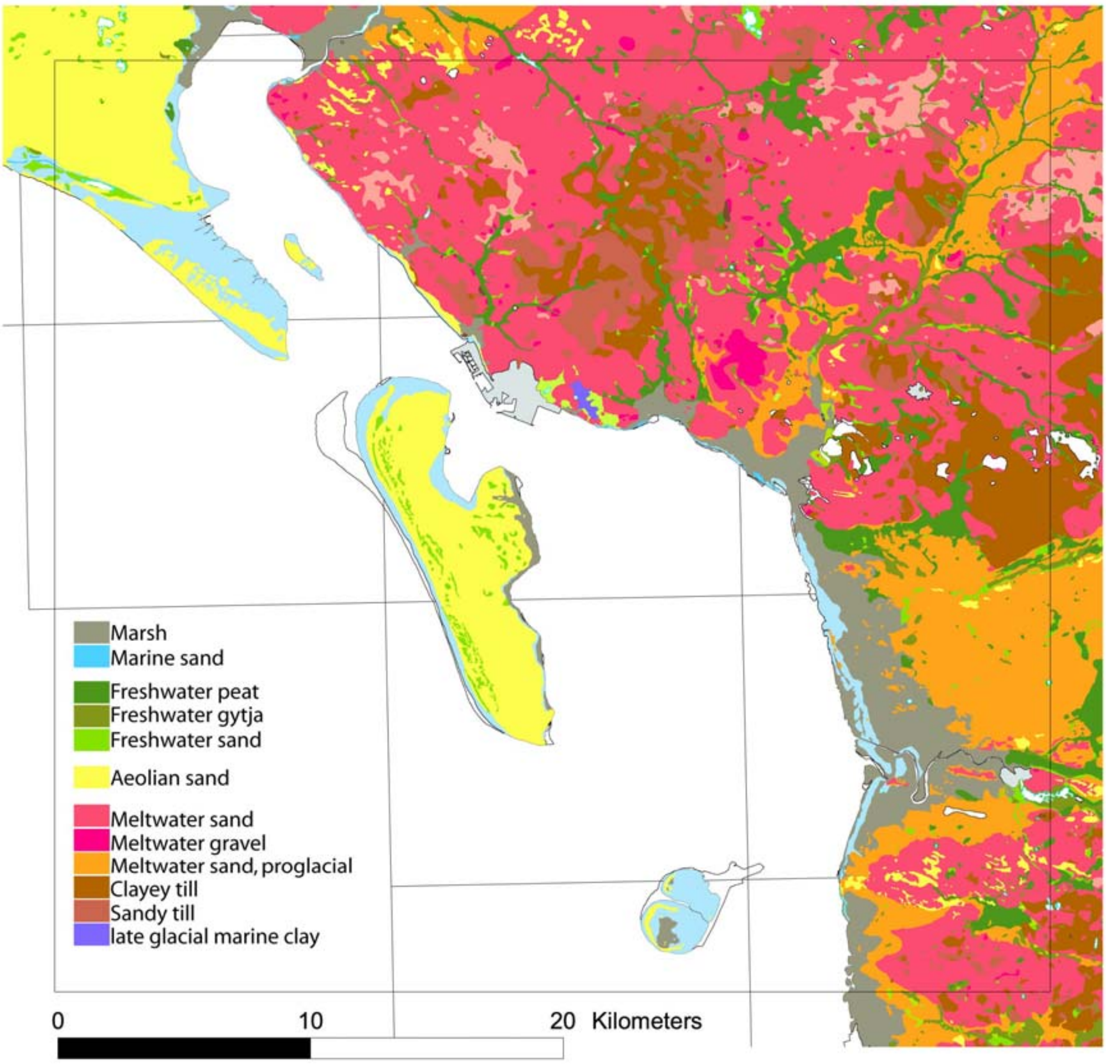

Figure 2.1. Geological map of the area (Pedersen, 1989).

2.2 Pre-Quaternary

The Pre-Quaternary deposits in the area in question are of Miocen age (Rasmussen, 1956). They consist of marine sand and clay. The level of the Pre-Quarternary surface is shown on fig. 2.2. It seems that there is no clear connection between the pattern of vertical movements and the prequaternary surface.

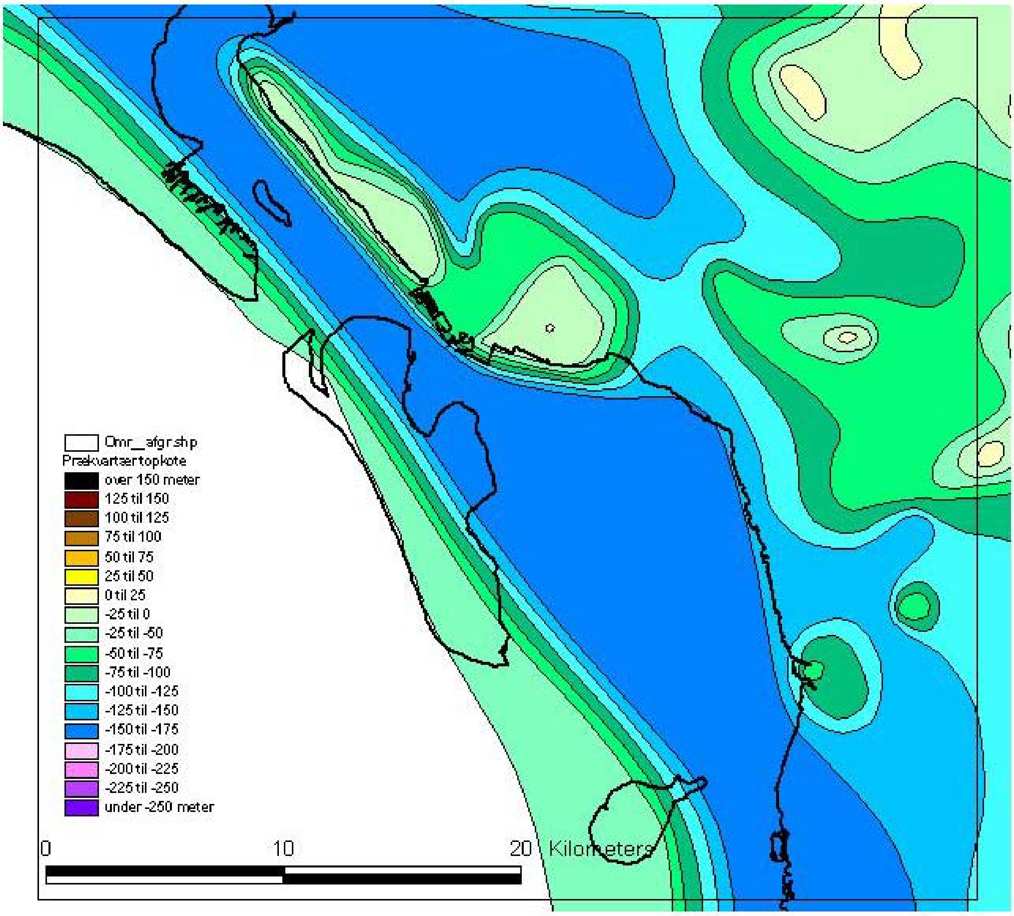

Figure 2.2. Map showing the level of the Prequaternary surface within the area (Binzer & Stockmarr, 1994).

2.3 Recent seismic activity

The seismic activity in Denmark in the period from 1929 to 2007 is shown in fig. 2.3. The major seismic activity is along the Sorgenfrei-Tornquist Zone and just south of it and in the North Sea in the central graben.

The Study area is situated on the Ringkøbing –Fyn High and on the southern edge of it. No recent seismic activity has been recorded in this region and the study area is considered tectonically stable, which means that tectonic generated movements in the area, is not likely to occur.

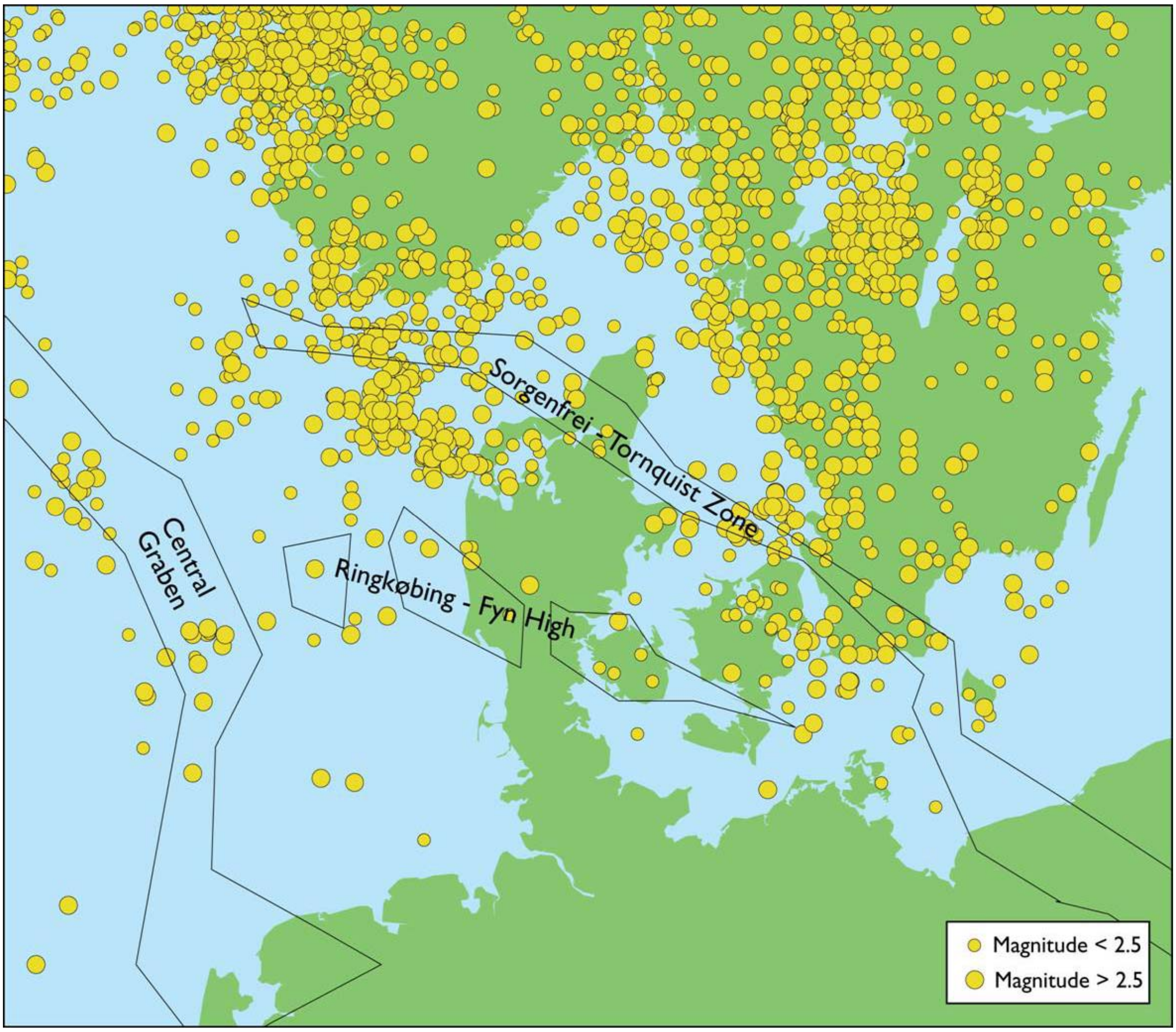

Figure 2.3. Earthquakes in Denmark, and adjacent areas. Location and magnitude of earthquakes are indicated. (modified from Gregersen et al., 1998).

3. Interpretations of some of the vertical movements

3.1 Vertical movements along the railroad

Along the railroad from Esbjerg and to the East, there are several locations, where vertical movements are seen (Figure 1.1 and 3.1). On figure 3.1 7 locations are outlined. The location numbers 1, 2, 5 and 7 are situated in areas with postglacial freshwater deposits. Location 3 is situated in an area with postglacial marine deposits.

Both postglacial freshwater deposits and postglacial marine deposits are unconsolidated, and it is very likely that the load of the railrod construction has caused the deposits to settle.

There is no immediate explanation of the vertical movements at locations 4 and 6.

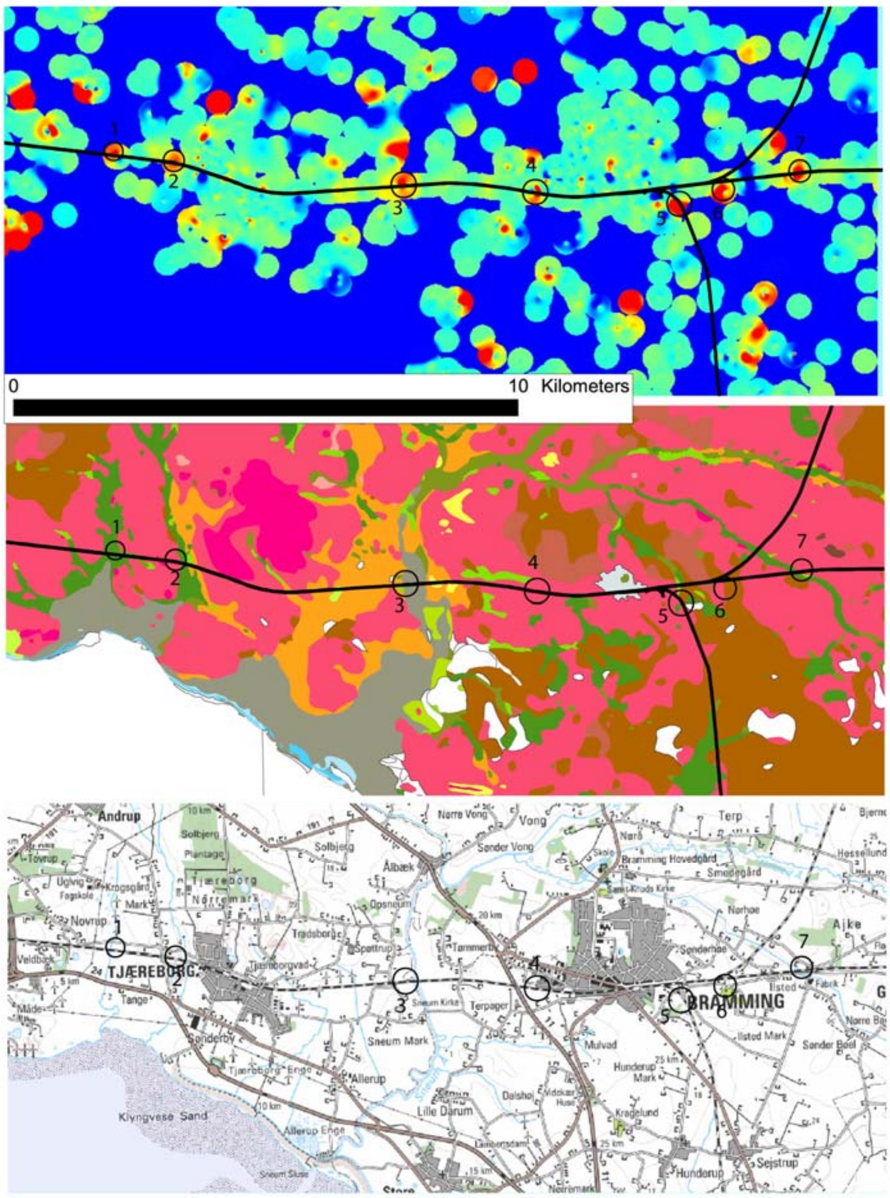

Figure 3.1. Uppermost: location of vertical movements along the railrod. Middle: Geological map with the located points (same legend as fig. 2.1). Lowermost: Map of the are with the located points.

3.2 Vertical movements on Fanø and north of Skallingen

On the island of Fanø and in the area north of the Skallingen peninsula, sporadic vertical movements occur.

In both regions the geology consists of postglacial marine deposits overlain by eolian dunes and cover sand. The postglacial marine and eolian deposits are unconsolidated. It is therefore likely that the vertical movements are caused by settling of the unconsolidated deposits.

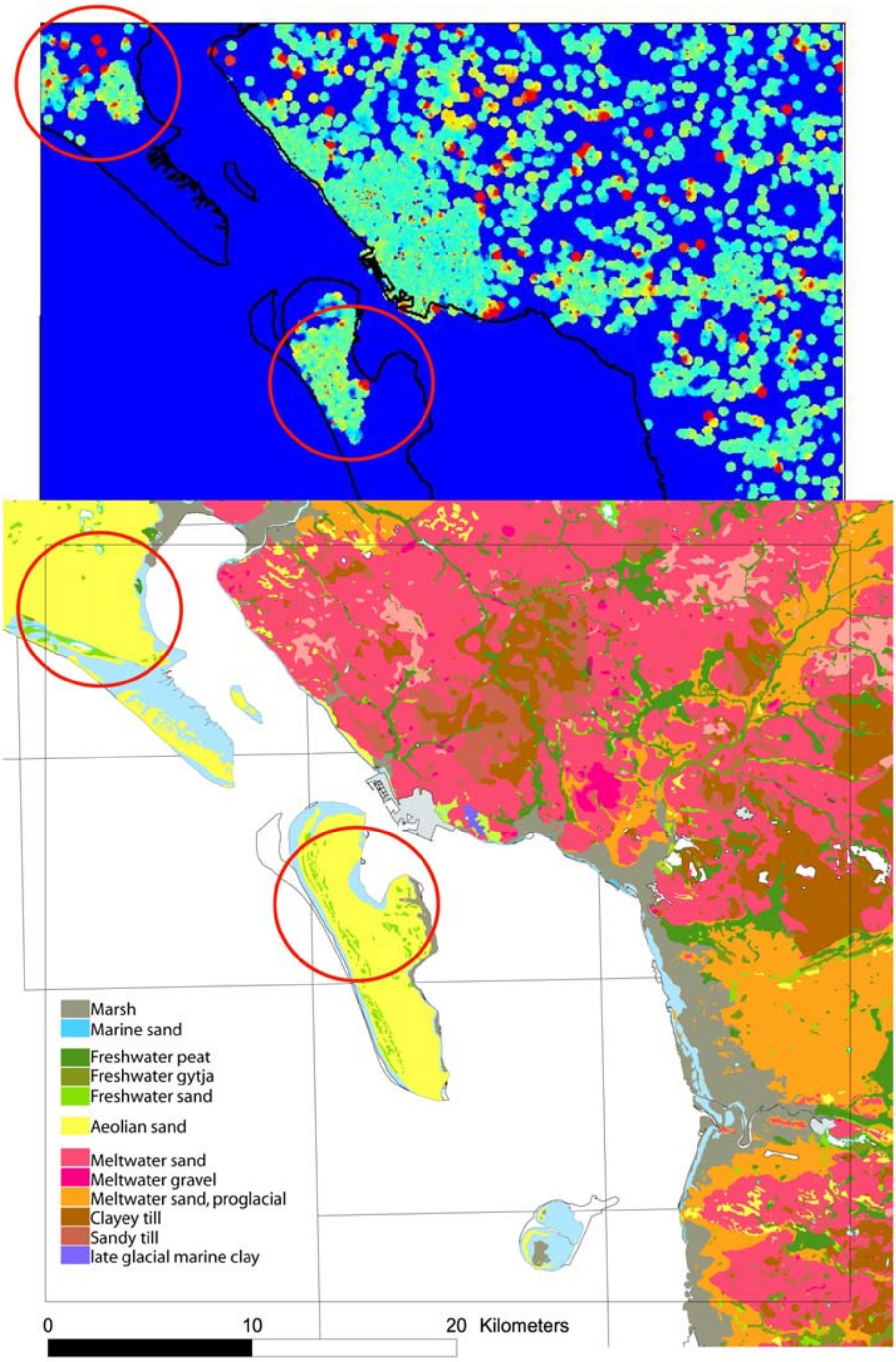

Figure 3.2. The vertical movements on Fanø and North of Skallingen (indicated with red circles) occur in areas with postglacial marine deposits overlain with eolian deposits.

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3.3 Vertical movements in the habour

In the habour area in Esbjerg relatively large vertical movements are seen. The habour area consists largely of filled material.

The vertical movements seen in the harbour area are probably due to settling of the filled matarial which built up the habour area (Figure 3.3).

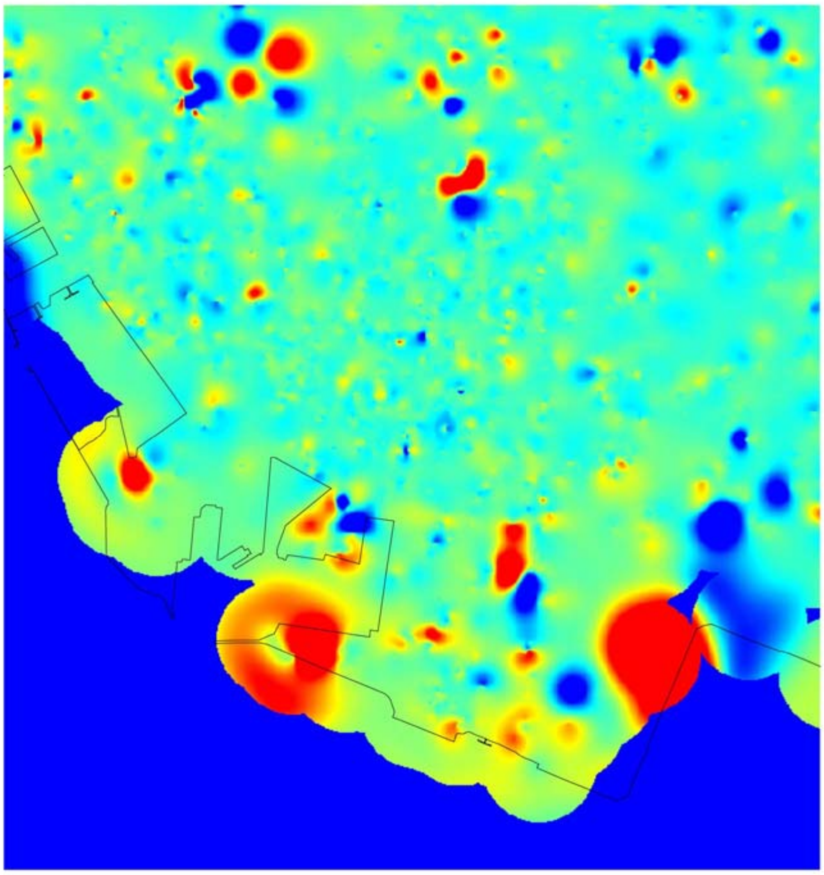

Figure 3.3. Vertical movements in the habour area in Esbjerg.

3.4 Vertical movements in the dump area at Måde

Måde is situated in the western outskirt of Esbjerg (Fig. 3.4). In this area a former clay pit has subsequently been used as a dump. The former clay pit is now filled and covered with soil. Within this area relatively strong movement are seen, and it is most probably a consequence of settling of the filled material.

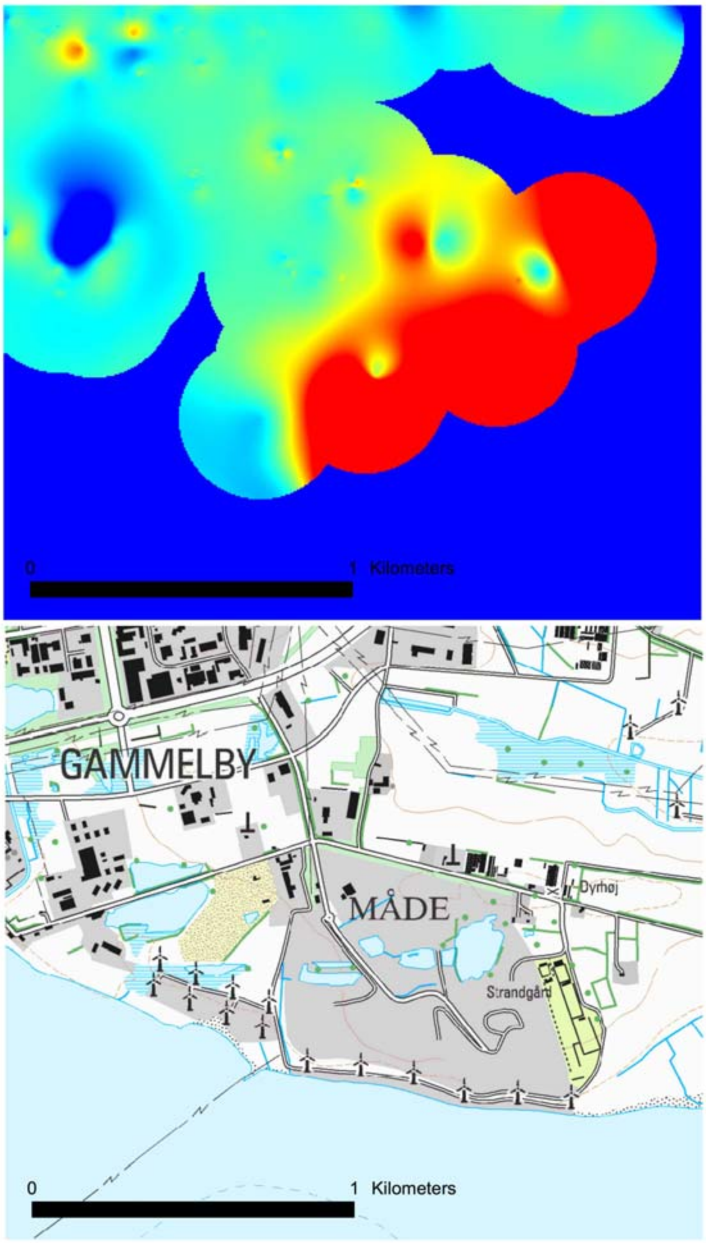

Figure 3.4. The upper and the lower picture have the same delimitation. The upper picture shows vertical movements in the Måde area, and the lower picture is a map of the area. The grey area is a former clay pit, which subsequently has been used as a dump.

4. References

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PINGPONG: a program for height model gridding and quality control

Thomas Knudsen

Abstract

Pingpong is a simple inverse distance weighting (i.e. low pass filter) gridding program. It does, however, implement a highly efficient, data organization and data selection scheme, running in $O(n \log n)$ time (where n denotes the number of raw point observations).

This makes PINGPONG very efficient for initial explorative gridding of laser scanner data. Providing actual operational height models is, however, explicitly *not* the intention with PINGPONG.

In this paper, the basics of the program is outlined, and demonstrated by a sample run, providing a digital surface model (DSM), a grid of variance estimates for the DSM, and a corresponding grid of the local point density.

In a companion paper (Rosenkranz and Knudsen, 2008), we show how the efficient explorative gridding allows us to check the quality of laser scanning strip adjustment procedures, without any access to GPS or INS data.

1 PINGPONG—the name and the aim.

PINGPONG is a self-referring, recursive acronym meaning PINGPONG Is Not Geogrid, PINGPONG's an Ordinary New Gridding program (where the *geogrid* referred to is the name of a classical gridding program, widely used by geodesists).

The primary aim of PINGPONG is to aid in the initial exploration of a laser scanned point cloud, by providing rough gridded estimates of

1. elevation,
2. elevation estimation variance and
3. local point observation density.

The distance from each grid node to the nearest observed point is used as a proxy for the estimation variance. This definitely is a coarse approximation, but for a dense data set (as is typical for laser scanning) this proxy gives a good insight of how the scanning geometry interacts with the grid geometry, and hence helps diagnose potentially intricate aliasing effects.

2 Example

Figures 1–2 show output from a test session with PINGPONG. The test was run on a fairly modest portable PC: 1.6 GHz Intel Centrino with 1GB RAM, running Ubuntu 8.04, Linux kernel 2.6.24. The input data set consisted of approximately 500 000 data points. The output grid dimensions were 1000×1000 nodes (i.e. 1 000 000 height, variance, and density estimates). It ran in slightly less than 10 seconds, which in our case is approximately as fast as we can push the output back onto the backing storage. Hence, motivation for additional speed optimization is minor.

3 Method

For nation wide height models, we will have to handle a very large amount of data. So even though it is common practice to operate within smaller rectangular zones (as the 1 km by 1 km grid example above), we do need a fairly efficient data organization structure in order to complete the gridding task in a reasonable amount of time: searching through all 500 000 input data items for each of the 1 000 000 grid points in the example, is simply not feasible.

The data organization structure used is outlined in figure 3. The primary design consideration is that for any grid node, we need only consider point observations that are within a certain search radius, R_0, ideally determined in terms of the autocorrelation of the physical phenomenon observed.

As a first step in utilizing this (before doing any gridding at all), we sort all point data according to their northing coordinate, in north $\rightarrow$ south collating order.

Now, since we do the gridding row-wise, we may utilize the fact that each node in row number i has the same northing coordinate N_i. Hence, at the start of the row, we may bracket the

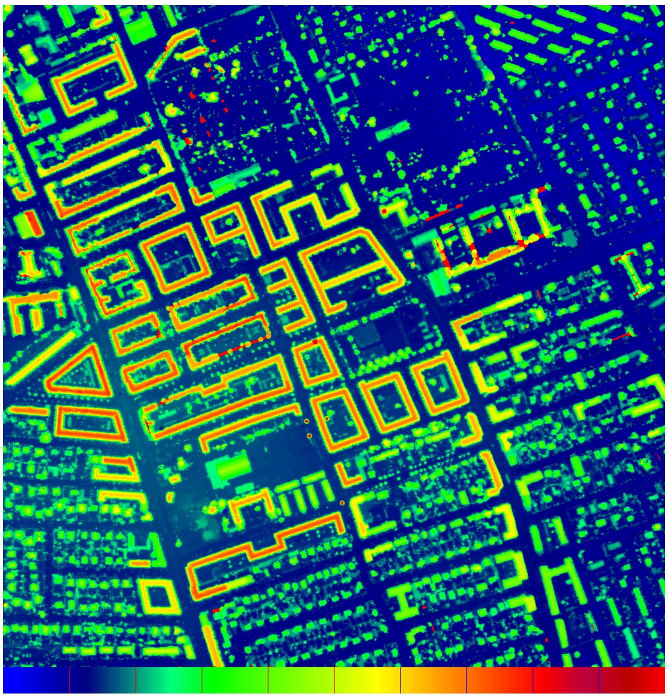

Figure 1: Digital Surface Model (DSM), from a sample run of PINGPONG(range $0\,m$–$35\,m$).

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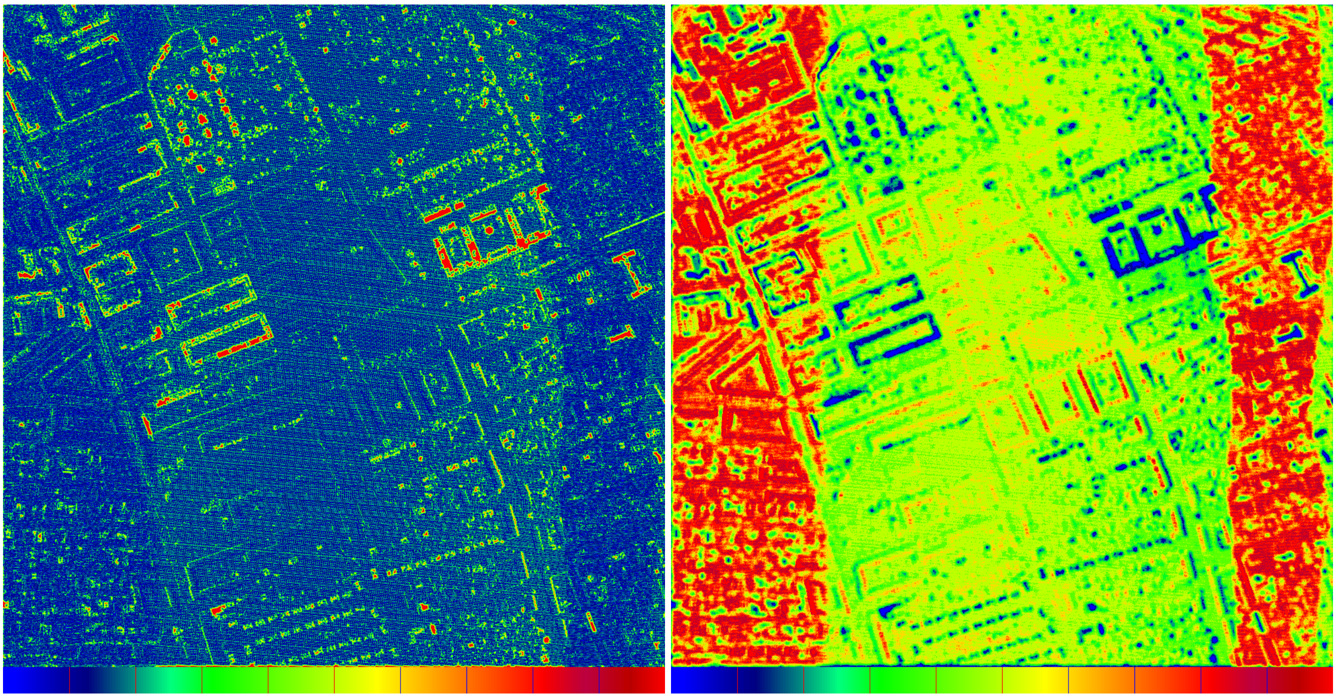


Figure 2: The quality parameters computed by PINGPONG (same sample run as in figure 1). *Left:* Variance estimate proxy (range $0m$–$4m$), computed as the distance from the grid node to its nearest point observation. For uniform input data sets, this gives a fairly good estimate of the relative quality of the grid node height estimates. It also gives a warning of potential aliasing effects, through the intensity of the moire pattern between the laser scanner swath and the grid lines. *Right:* Point density (range $0/m^2$–$1/m^2$), estimated as $D = n/\pi {R_0}^2$, where n is the number of points falling within a search radius of R_0 from the grid node. Note the clear delineation of the overlap zones between the flight strips, where the data density is very high. Also note the cases of very low data density typical of very dark roofs. This problem is described in more detail in Knudsen et al. (2008).

input data, leaving only the data points falling within a narrow zone $N \in [N_i + R_0 \dots N_i - R_0]$.

After this bracketing, we have a small data set which is much faster to run a search through. But knowing that we do the gridding systematically from west to east, we speed up the process even more by sorting the bracketed data according to their easting coordinate, in west $\rightarrow$ east collating order. Now, we have a small, and very well organized set of data, and can do the combined gridding, variance estimation, and density determination with minimal search effort.

To reiterate, the overall idea of the algorithm is to gain efficiency by avoiding repeated work: The entire data set is only sorted once, at the start of the process. Then smaller subsets are sorted once at the start of each grid row. Only linear search and no sorting, is carried out during the actual estimation of grid node values. Here the only computation not directly used in the estimation process is related to the rejection of points being outside of the search radius, R_0, but within the box defined by the coordinate ranges $N \in [N_i + R_0 \dots N_i - R_0] \wedge E \in [E_j + R_0 \dots E_j - R_0]$, where (N_i, E_j) represent the northing and easting coordinate of the current grid node, respectively.

4 Discussion and future work

Currently, PINGPONG runs sufficiently fast, and handles sufficiently large data sets for our needs. Algorithms for faster handling of larger datasets exist (it is, for example one of the core research areas of the Massive Data Algorithmics center at Aarhus University—http://www.madalgo.au.dk/).

Hence, speeding up operations is not a priority in future work with PINGPONG. However, the algorithm for checking of strip adjustment, presented in (Rosenkranz and Knudsen, 2008), will gain a significant speed up and a much simplified operation if implemented directly in PINGPONG. This, as well as an extended amount of documentation are priority items for the future work on PINGPONG. It should be noted, however, that PINGPONG is distributed under the terms of the GNU general public license, which ensures that any user has full rights to modify and improve the software as she sees fit.

References

Thomas Knudsen and Brian Pilemann Olsen, editors. *Proceedings of the 2nd NKG workshop on national DEMs*, Copenhagen, Denmark, 2008. National Survey and Cadastre.

Thomas Knudsen, Andrew Flatman, Brian Pilemann Olsen, and Rune Carbuhn Andersen. A priori land use information for improvement of digital surface models through fine grained selection of surface model gridding parameters. In Knudsen and Olsen (2008).

Stephen Lacey and Richard Box. A fast, easy sort. *BYTE*, 16 (4):315ff, April 1991.

Brigitte Christine Rosenkranz and Thomas Knudsen. Checking strip adjustment without access to navigation records. In Knudsen and Olsen (2008).

Acknowledgement: Scankort A/S (through inimitable laser scanner magician par excellence, Andrew C. Flatman), provided the laser point cloud used in the example.

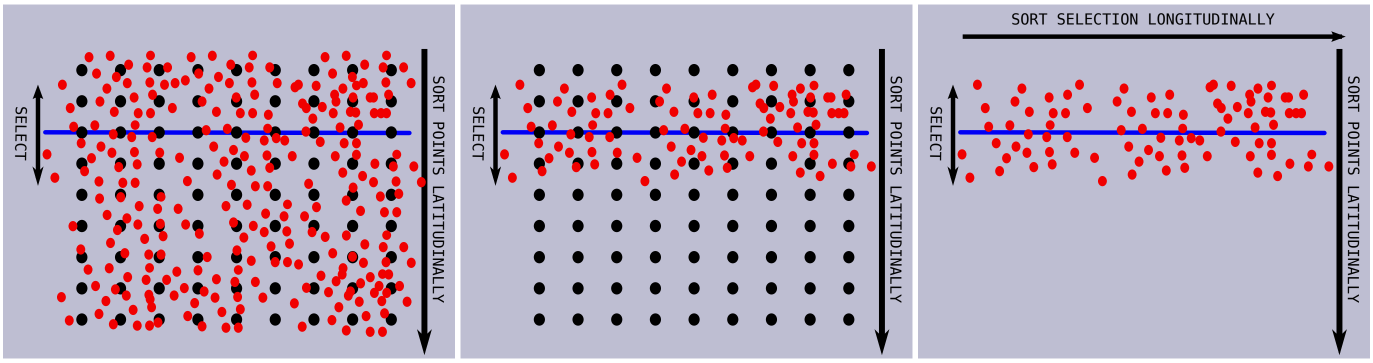


Figure 3: The data sorting algorithm: point data are shown as red dots, grid nodes as black dots, and the grid row currently worked at as a blue line. *Left:* Prior to any gridding, the full data set is sorted from north to south. *Center:* We bracket the data relevant for the current grid row, by ignoring point data too far north or south of the current grid row to make a difference (in a statistical sense). *Left:* Before starting the gridding, we sort the bracketed data from west to east, then do the gridding in the same direction.

Appendix

A Sort algorithm

PINGPONG uses the combsort algorithm for sorting observations into a fast access order. Combsort (Lacey and Box, 1991) is a modification of the classical, simplistic bubble sort—but where bubble sort works in time proportional to the square of the number of elements to be sorted, i.e. $O(n^2)$, combsort reduces this to $O(n \log n)$.

$O(n \log n)$ is comparable to the average quicksort time—but while quicksort may work very slowly in pathological cases (most notably when applied to an already sorted array), combsort does not appear to suffer from such maladities.

A.1 Bubble sort

Bubble sort operates by striding through the input array, comparing neighbouring points, and swapping them if out of sequence. When reaching the end, the process is repeated from the beginning until all elements have been bubbled into place. This means that large elements near the beginning of the input array are bubbled all the way to the end during just one pass (although with O(n) comparisons under way). By allegorical analogy, these elements are called *rabbits*. Small values near the end of the array are, however, more problematic, since they bubble only one position backwards for every pass through the array, i.e. they reach their final position only after O(n) passes. By a related analogy, such elements are known as *turtles*.

A.2 Combsort

Combsort repairs this problem by varying a gap parameter from an initial value of approximately gap $= 0.77 \times$ array length down to 1, by setting gap $= 0.77 \times$ gap at the beginning of each pass through the input array.

The gap parameter specifies the gap between the two array elements being compared in the sorting process. So initially, we have a very large gap—which means that turtles are quickly eliminated.

Eventually, the gap will reach the fixed value 1, where the algorithm will degenerate to bubble sort. But at this stage, the array will typically be "almost sorted" meaning that only a few bubble steps will be needed to get the final elements into order.

Evidently combsort is highly related to bubble sort, and may share its conceptual clarity and coding economy (as can be seen from the "bare basics" implementation in appendix B). It is less evident that the speed of combsort rivals that of quicksort - this is however an empirical fact, and the reason it has been selected as "the work horse" here.

A.3 Implementation details

The original analysis by Lacey and Box revealed that should the gap parameter at any time reach 10 or 9, a more optimum last steps route will be obtained by forcing gap to 11 and proceeding from there. This variant of the combsort algorithm is widely referred to as "combsort11".

PINGPONG needs to sort the array of observations according to two different criteria: first a descending (i.e. smallest values last) sort along the northing parameter, then an ascending sort along the easting parameter.

Implementing both kinds of sorting in a shared function would imply a time penalty through the need for an extra comparison during each pass through the central loop. To avoid this, the two different sort strategies (using the same algorithm) are implemented as two different functions.

B Combsort sample implementation

A simplified implementation of combsort11: sort n integers stored in T

```
void combsort11(int *T, int n) {
    int i, f, gap=n;
    do {
        gap = (gap*10)/13;
        if (gap==0)  gap=1;
        if ((gap==9) || (gap==10))
            gap = 11;
        for (i=0, f=0; i < n-gap; i++) {
            if (T[i] > T[i+gap]) {
                int temp = T[i];
                T[i] = T[i+gap];
                T[i+gap] = temp;
                f = 1;
            }
        }
    } while(f || (gap>1));
}
```

ABSRATE promotion leaflet

Thomas Knudsen, Nynne Sole Dalå

In the following two pages, we reprint the contents of the ABSRATE promotion leaflet. The folder was designed as a three panel leaflet, so reprinting in plain A4 results in a slightly odd page ordering: cover page is the upper third of the following page; back cover is the middle third of the following page. Main text runs through the three columns of the 2nd following page, and concludes on the lower third of the following page.

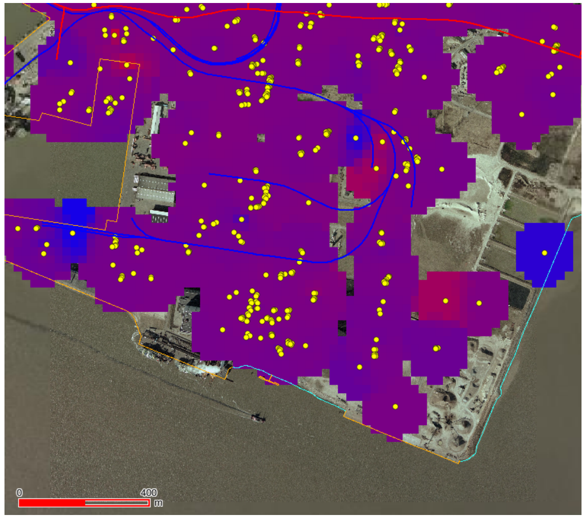


Figure 3: The ABSRATE RSR product for the area shown in figure 1. Local displacement rates range from an uplift of approximately 30 mm/year (red) to a subsidence of -30 mm/year (blue)

The additive constant is computed from a combination of time series data from local permanent GPS observation stations, and from sea level rate data from local tide gauges, tied to GPS stations through high precision levelling.

Additional information

DTU-space http://www.space.dtu.dk/

KMS http://www.kms.dk/

Terrafirma http://www.terrafirma.eu.com/

Contact

ABSRATE: State Geodesist Per Knudsen, Danish National Space Center, pk@space.dtu.dk, http://www.space.dtu.dk/

Terrafirma: Ren Capes, Terrafirma Project Manager, NPA group, ren@npagroup.com

ABSRATE is a collaboration between the Danish National Space Center (DTU-space), the National Survey and Cadastre (KMS), and Terrafirma, the pan-european ground motion hazard information service.

ABSRATE (ABsolute Subsidence RATEs) provides land motion information tied to global geodetic systems (hence “absolute”), from locally tied land motion data. The locally tied data is provided through Terrafirma, and is based on observations from satellite borne radar instruments.

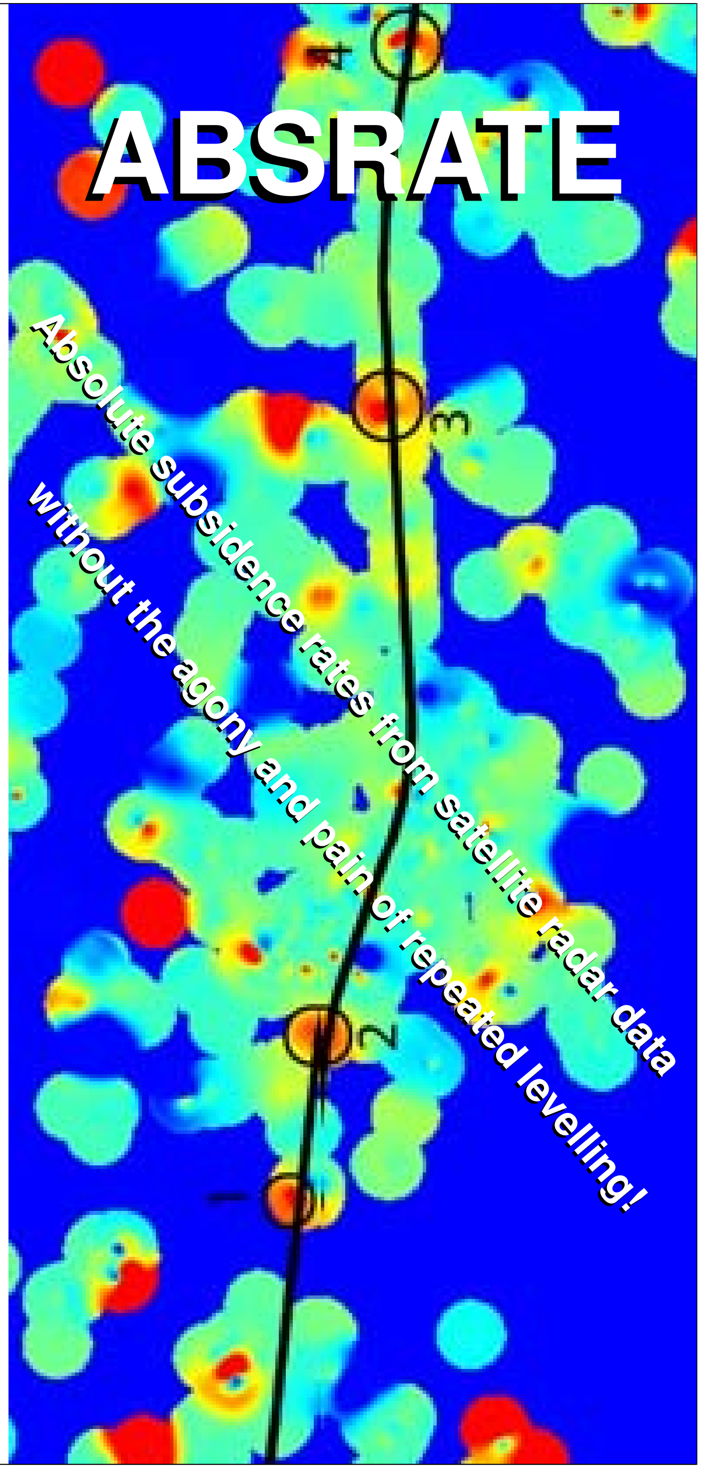
DTU Space
Institut for Rumforskning og -teknologi

DTU

DANISH MINISTRY OF THE ENVIRONMENT
National Survey and Cadastre

GMES TERRAFIRMA

The illustration on the front cover shows subsidence along the railroad tracks between Esbjerg and Bramming (southwestern Denmark). Most of the subsidence effects are due to well known unconsolidated deposits, which are here reconfirmed by independent satellite observations.



ABSRATE

ABSRATE – the ABsolute Subsidence RATEs project, was initiated in order to derive absolute (i.e. geodetically tied) subsidence rates from relative measurements based on persistent scatterer interferometry (PSI).

ABSRATE is a collaborative project between the Danish National Space Center (DTU-space) and the National Survey and Cadastre (KMS). The project is financed by ESA through Terrafirma – the pan-european ground motion hazard information service.

Terrafirma

Terrafirma is one of a number of services being run by the European Space Agency under the GMES Service Element Program as part of the Global Monitoring for Environment and Security initiative of the European Union. Terrafirma started in 2003. ABSRATE joined the Terrafirma activities in 2007.

Terrafirma harnesses the unique power of satellite radar interferometry to detect and measure Earth-surface terrain motion. These data, in combination with geophysical expertise, are used to save lives, improve safety and reduce economic loss.

Terrain motion can be related to subsidence, landslides, earthquake activity, flooding, coastal erosion, volcanoes, unstable buildings and infrastructure, and even poor engineering standards. Many of these phenomena and their associated hazards are made worse by the effects of rapid climate change.

The socio-economic cost of terrain motion across Europe runs into tens of billions of euros a year, and is becoming higher as populations increase, cities become larger, resources become scarcer, and the climate becomes more unstable.

Persistent Scatterer Interferometry

ABSRATE is based on persistent scatterer interferometry (PSI) data from Terrafirma.

Figure 1: Persistent scatterers in Esbjerg harbour

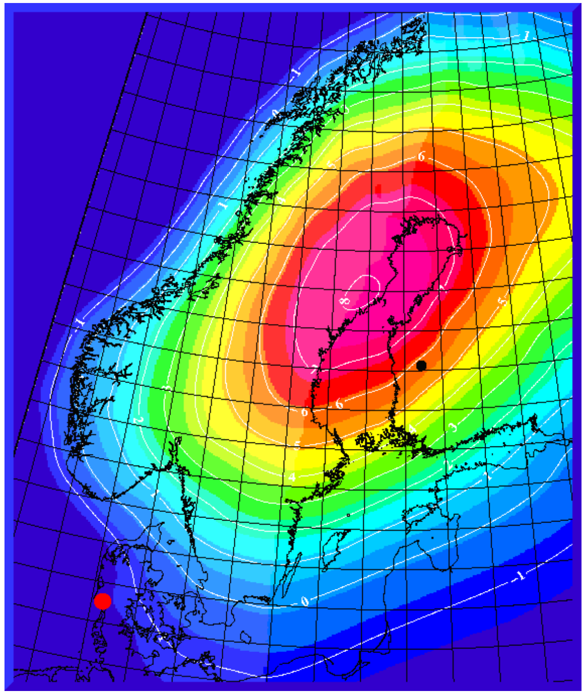


Figure 2: NKG regional ground motion model.

PSI is a radar satellite based technique, providing very precise information on vertical motion rates.

Raw PSI data are, however, relative, in the sense that all motion rates are measured relative to a local reference, which is assigned a vertical motion rate of zero.

The goal of the ABSRATE project is to combine PSI data with additional data from three different sources:

1. motion rates from permanent GPS stations.
2. sea level measurements from tide gauges.
3. long wavelength motion data from regional geodetic models.

Properly handled, such data can take us from the locally referenced, relative vertical motion rates, to motion rates including regional effects, and tied to global geodetic reference systems.

Figure 1 shows an area in Esbjerg Harbour (a subset of the ABSRATE test field). Yellow dots indicate locations of the persistent scatterers used in the interferometric processing.

The red dot in figure 2 indicates the approximate position of the test field in its regional context.

Absolute rates from PSI

The first step in generating absolute rates from PSI is to drape the PSI data onto a regional ground motion model. We use the model from the *Nordic Geodetic Commission* (NKG), shown in figure 2. The NKG model is founded on geodetic measurements, and resolves the long wavelength effects of vertical movement variations, with very high accuracy.

In the draping process we combine the long wavelength data from the regional model, with the very short wavelength data from PSI, to get an overall high precision at both short and long wavelengths.

The result of the draping process is known as the *relative subsidence rates* (RSR) product (shown in figure 3). It differs from the *absolute subsidence rates* (ASR) only by an additive constant fitting it to the local sea level rise rate.

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