A Practical Deformation Monitoring Procedure and Software System for CORS Coordinate Monitoring (6838)

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Contents

• Introduction
• System Development Approach:
  o GPS processing...Bernese
  o Deformation analysis...ConDAS [IWST & S-Transformation]
• Test Results
• Conclusions
Introduction

- GNSS/GPS is capable of detecting significant deformations...to mm-level
- However, a rigorous deformation analysis technique is still required
- Recent research works: Continuous deformation monitoring systems [SCIGN, GOCA, DDS]
- This study...
Introduction.

- This study...GPS processing strategy and deformation analysis to monitor the positional changes [3D coordinates] of local Continuous Operating Reference Station (CORS) network: ISKANDARnet, MyRTKnet.
- Investigation of the quality of published coordinates through daily GPS solution was performed [Bernese 5.0].
- Window-based software system for GPS deformation analysis, called Continuous Deformation Analysis System [ConDAS], developed at UTM.

Introduction.

- Deformation detection & analysis: this study combines a robust method [known as Iteratively Weighted Similarity Transformation or IWST] and final S-Transformation.
System development approach

• Overview: CORS...GPS...Bernese...ConDAS
System development approach.

The coordinate monitoring [2 parts/stages...2 steps analysis]:

- (i) GPS data processing using Bernese [high precision GPS processing software]...Independent LSE of each epoch.
- (ii) Deformation analysis between epochs using ConDAS.

ConDAS is designed to work with Bernese.

Work flow:

- Bernese
- ConDAS
GPS data processing strategy

- ...

GPS data processing

- GPS baselines are thousands of kilometers in length...requires sophisticated data processing software to achieve high precision results for long baselines.
- Bernese v. 5.0 software is employed for GPS data processing [Bernese...also used in other studies]
- Bernese capability: data cleaning, cycle slip detection, ambiguity resolution and network adjustment of GPS data [Bernese allows user to control processing strategies].
- Double difference GPS data processing using Bernese...3 parts: Preparation, Pre-processing and Processing.
Double difference GPS processing step, 3 parts: preparation, pre-processing and processing.

### Table 1: Parameters and models used in GPS data processing

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input data</td>
<td>Daily</td>
</tr>
<tr>
<td>Network design</td>
<td>DEFINED</td>
</tr>
<tr>
<td>Elevation cut-off angle</td>
<td>5°</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>30 seconds</td>
</tr>
<tr>
<td>Orbits/ EOP</td>
<td>IGS final orbits (SP3) and EOP</td>
</tr>
<tr>
<td>Ocean-loading model</td>
<td>FES2004</td>
</tr>
<tr>
<td>Ambiguities solution</td>
<td>Fixed, resolved using QIF strategy</td>
</tr>
<tr>
<td>Differencing level</td>
<td>Double</td>
</tr>
</tbody>
</table>
Double Difference GPS Data Processing using Bernese

• Deformation analysis...input/deformation files for ConDAS.

• 5 parameters (priori coords, estimated coords, degree of freedom, a posteriori variance factor and variance-covariance matrices) are required to carry out the deformation analysis.

• Some processing scripts in Bernese are slightly changed to well fit the requirement of deformation analysis...to generate 3 deformation files [for every 24h epoch]: priori coordinates, estimated coordinates, covariance matrix.

Deformation analysis

• ...
Deformation analysis

- The developed deformation analysis strategy combines robust method and Similarity Transformation (S-transformation).
- Procedure for Deformation analysis between epochs... 2 stages: i) Stability analysis of reference stations using IWST and single point test; and ii) Final S-transformation of all stations with respect to stable reference stations & deformation analysis of all stations using single point test.
- The single point test: reject any point [i.e. unstable] with its displacement extends beyond the confidence region.

IWST/robust

- Displacement vectors & cov matrix: $d = X_2 - X_1$, $R = R_0 + R_1$
  - Start $W=I$, apply S-transformations
    $S=I-G(G^TW_jG)^{-1}G^TW_j$, $d_j=Sd_i$
  - Weight matrix $W$ changed: $W^{(k+1)}(i,i) = \text{diag}(1/d^{(k)})$
  - Iterative procedure continues until: $|d^{(k+1)} - d^{(k)}| < \delta$
    - Transform: $Q_{ij} = SQ_{ij}S^T$
    - Check stability using single point test: $T_i = \frac{d_i^TQ_{ii}^{-1}d_i}{m \sigma_i^2} \sim F(m,df_x,\alpha)$
Final S-transformation

- Final S-transformation of all stations with respect to stable reference stations...
- \( S = I - G (G^T W_j G)^{-1} G^T W_j; d_j = S d_i; Q_{xj} = S Q_{xi} S^T \)
- \( W = 1 \) for stable reference stations, \( W = 0 \) for other stations [similar to Congruency testing]
- Stability/The single point test

IWST & final S-Transformation
ConDAS

- ConDAS: In-house Deformation Analysis software
- ConDAS is designed to work with Bernese.
- The main components of ConDAS: parameter extraction (from Bernese output), deformation detection and graphical visualisation.
- All these components are integrated in one environment using MATLAB.
Module 1: Parameters extraction

- To extract the required parameters according to the format of Bernese results files.
- 3 types of result files were used for extraction.
- GUI of parameters extraction module & deformation input file.
Module 2: Deformation detection

- Two-epoch deformation analysis: 2 deformation input files.
- GUI of Deformation detection module & deformation output file.

Module 3: Visualization

- 2 functions of the visualization module: i) to view the stability results of every two-epoch analysis; ii) to generate the deformation trend over a selected period.
- GUI of visualisation module.
In order to fully implement the method, ConDAS was designed to cooperate with Bernese.

**Bernese**

- **Bernese processing (24 hrs GPS data-daily solution):**
  - Prepare relevant parameters and files.
  - Daily solution (Sampling rate= 30s).
  - Bernese processing Engine.

**ConDAS**

- **Two-epoch deformation analysis (displacement detection):**
  - Extract required parameters from Bernese output.
  - Execute in-house deformation analysis software.
  - Compare epoch by epoch using rigorous deformation analysis.

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**More info**

- Raw GPS data in RINEX format.
- Size of 24hrs data=4-5 MB, sampling rate of 30 s.
- Main output from BPE [daily solution]: approx coords, estimated coords, covariance matrix...in 3D X, Y, Z WGS84 system; transform to local coord system when visualisation.
- How fast to get results? Bernese= few mins (daily solution), deformation analysis= few mins. Total 10 – 15mins.
Test Results

- 2 test results
- Test results 1: Malaysia Real Time Kinematic GNSS Network (MyRTKnet)...system validation, Aceh earthquake
- Test results 2: Iskandar Malaysia CORS Network (ISKANDARnet)...deformation monitoring
Test Results 1

• Validation of the entire system: using the existing GPS data set from MyRTKnet.

• The processed data set started from 4\textsuperscript{th} until 31\textsuperscript{st} Dec 2004 (i.e. before and after the Aceh earthquake incident on 26\textsuperscript{th} Dec 2004).

• Control points: 6 IGS stations (ALIC, DARW, DGAR, HYDE, KARR and KUNM)

• Object points: two stations from MyRTKnet [JHJY and LGKW]
Test Results 1

• All stations were stable before the earthquake.
• JHJY station: stable
• LGKW station: moved/unstable from 26th Dec 2004 and onwards...similar with findings from Jhonny (2010).

![Graphs of station movements over time]

Table 2: The displacement vectors of station JHJY and LGKW

<table>
<thead>
<tr>
<th>Date[D/M/Y] / Day of Year</th>
<th>Displ. Vector [m]</th>
<th>Status</th>
<th>Displ. Vector [m]</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>22-12-2004/ 357</td>
<td>0.0108</td>
<td>Stable</td>
<td>0.0108</td>
<td>Stable</td>
</tr>
<tr>
<td>23-12-2004/ 358</td>
<td>0.0085</td>
<td>Stable</td>
<td>0.0206</td>
<td>Stable</td>
</tr>
<tr>
<td>24-12-2004/ 359</td>
<td>0.0111</td>
<td>Stable</td>
<td>0.0138</td>
<td>Stable</td>
</tr>
<tr>
<td>25-12-2004/ 360</td>
<td>0.0115</td>
<td>Stable</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>26-12-2004/ 361</td>
<td>0.0119</td>
<td>Stable</td>
<td>0.1439</td>
<td>Moved</td>
</tr>
<tr>
<td>27-12-2004/ 362</td>
<td>0.0221</td>
<td>Stable</td>
<td>0.1609</td>
<td>Moved</td>
</tr>
<tr>
<td>28-12-2004/ 363</td>
<td>0.0234</td>
<td>Stable</td>
<td>0.1644</td>
<td>Moved</td>
</tr>
<tr>
<td>29-12-2004/ 364</td>
<td>0.0209</td>
<td>Stable</td>
<td>0.1665</td>
<td>Moved</td>
</tr>
<tr>
<td>30-12-2004/ 365</td>
<td>0.0153</td>
<td>Stable</td>
<td>0.1657</td>
<td>Moved</td>
</tr>
<tr>
<td>31-12-2004/ 366</td>
<td>0.0191</td>
<td>Stable</td>
<td>0.1629</td>
<td>Moved</td>
</tr>
</tbody>
</table>

n/a = data not available
Test Results 2

• Deformation Trend of ISKANDARnet

Test Results

• The deformation monitoring network: 7 stations.
• Reference points...4 IGS stations (i.e. COCO, NTUS, PIMO, XMIS).
• Object points...3 stations from local ISKANDARnet (ISK1, ISK2, ISK3).
Test Results

• 2 days...ISKANDARnet [4/1/2010-5/1/2010].
• 2 years...ISKANDARnet [4/1/2010-31/12/2011]
• Stability analysis of reference stations [via IWST]: all stable.

<table>
<thead>
<tr>
<th>Station</th>
<th>$D_x$ [m]</th>
<th>$D_y$ [m]</th>
<th>$D_z$ [m]</th>
<th>$\text{Disp. Vect}$ [m]</th>
<th>Test statistic vs critical value</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>COCO</td>
<td>-0.0017</td>
<td>-0.0021</td>
<td>0.0040</td>
<td>0.0048</td>
<td>0.0066 &lt; 2.60547</td>
<td>stable</td>
</tr>
<tr>
<td>NTUS</td>
<td>0.0005</td>
<td>0.0001</td>
<td>0.0001</td>
<td>0.0005</td>
<td>0.0012 &lt; 2.60547</td>
<td>stable</td>
</tr>
<tr>
<td>XMIS</td>
<td>-0.0038</td>
<td>0.0116</td>
<td>-0.0011</td>
<td>0.0122</td>
<td>0.0043 &lt; 2.60547</td>
<td>stable</td>
</tr>
<tr>
<td>PIMO</td>
<td>0.0051</td>
<td>-0.0030</td>
<td>-0.0029</td>
<td>0.0066</td>
<td>0.0015 &lt; 2.60547</td>
<td>stable</td>
</tr>
</tbody>
</table>

• Stability analysis of all stations [via final S-transformation]: stable.

<table>
<thead>
<tr>
<th>Station</th>
<th>$D_x$ [m]</th>
<th>$D_y$ [m]</th>
<th>$D_z$ [m]</th>
<th>$\text{Disp. Vect}$ [m]</th>
<th>Test statistic vs critical value</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>COCO</td>
<td>-0.0007</td>
<td>-0.0025</td>
<td>0.0023</td>
<td>0.0034</td>
<td>0.0026 &lt; 2.60521</td>
<td>stable</td>
</tr>
<tr>
<td>NTUS</td>
<td>0.0026</td>
<td>-0.0038</td>
<td>-0.0005</td>
<td>0.0046</td>
<td>0.0021 &lt; 2.60521</td>
<td>stable</td>
</tr>
<tr>
<td>XMIS</td>
<td>-0.0002</td>
<td>0.0029</td>
<td>-0.0006</td>
<td>0.0030</td>
<td>0.0005 &lt; 2.60521</td>
<td>stable</td>
</tr>
<tr>
<td>ISK3</td>
<td>-0.0023</td>
<td>0.0036</td>
<td>-0.0010</td>
<td>0.0044</td>
<td>0.0018 &lt; 2.60521</td>
<td>stable</td>
</tr>
<tr>
<td>ISK2</td>
<td>-0.0016</td>
<td>0.0023</td>
<td>-0.0013</td>
<td>0.0031</td>
<td>0.0017 &lt; 2.60521</td>
<td>stable</td>
</tr>
<tr>
<td>ISK1</td>
<td>0.0002</td>
<td>0.0054</td>
<td>-0.0008</td>
<td>0.0055</td>
<td>0.0022 &lt; 2.60521</td>
<td>stable</td>
</tr>
<tr>
<td>PIMO</td>
<td>-0.0018</td>
<td>0.0033</td>
<td>-0.0012</td>
<td>0.0040</td>
<td>0.0016 &lt; 2.60521</td>
<td>stable</td>
</tr>
</tbody>
</table>
Test Results 2: 2 years

- 2 years...ISKANDARnet [4/1/2010-31/12/2011]
- Gaps in GPS data...due to on-site maintenance [2010-Mar, Jul, Aug; 2011-Apr, Mei, Jun]
- Similar analysis procedure
- Results: Fluctuations in cm level, all stations are stable

Deformation Trend of ISKANDARnet at 2010 – ISK1
Deformation Trend of ISKANDARnet at 2010 – ISK2

Deformation Trend of ISKANDARnet at 2010 – ISK3
Deformation Trend of ISKANDARnet: 2010

Table 5: Statistical analysis of ISK1, ISK2 and ISK3 for year 2010

<table>
<thead>
<tr>
<th></th>
<th>Delta Easting [m]</th>
<th>Delta Northing [m]</th>
<th>Delta Up [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>-0.0376</td>
<td>-0.0112</td>
<td>-0.0325</td>
</tr>
<tr>
<td>ISK1 Max</td>
<td>0.0036</td>
<td>0.0135</td>
<td>0.0392</td>
</tr>
<tr>
<td>ISK1 Std</td>
<td>0.0114</td>
<td>0.0037</td>
<td>0.0094</td>
</tr>
<tr>
<td>ISK1 Min</td>
<td>-0.0352</td>
<td>-0.0145</td>
<td>-0.0268</td>
</tr>
<tr>
<td>ISK2 Max</td>
<td>0.0017</td>
<td>0.0134</td>
<td>0.0183</td>
</tr>
<tr>
<td>ISK2 Std</td>
<td>0.0110</td>
<td>0.0041</td>
<td>0.0078</td>
</tr>
<tr>
<td>ISK2 Min</td>
<td>-0.0427</td>
<td>-0.0100</td>
<td>-0.0333</td>
</tr>
<tr>
<td>ISK3 Max</td>
<td>0.0006</td>
<td>0.0138</td>
<td>0.0190</td>
</tr>
<tr>
<td>ISK3 Std</td>
<td>0.0132</td>
<td>0.0040</td>
<td>0.0092</td>
</tr>
</tbody>
</table>

Deformation Trend of ISKANDARnet at 2011 – ISK1

Min: -0.0336m
Max: 0.0029m
Std: 0.0080m

Min: -0.0265m
Max: 0.0166m
Std: 0.0086m

Min: -0.0441m
Max: 0.0122m
Std: 0.0153m
Deformation Trend of ISKANDARnet at 2011 – ISK2

Min: -0.0330m
Max: 0.0026m
Std: 0.0092m

Min: -0.0391m
Max: 0.0152m
Std: 0.0114m

Min: -0.0441m
Max: 0.0085m
Std: 0.0131m

Deformation Trend of ISKANDARnet at 2011 – ISK3

Min: -0.0158m
Max: 0.0058m
Std: 0.0043m

Min: -0.0279m
Max: 0.0137m
Std: 0.0082m

Min: 0.0085m
Max: 0.0185m
Std: 0.0125m
Table 6: Statistical analysis of ISK1, ISK2 and ISK3 for year 2011

<table>
<thead>
<tr>
<th></th>
<th>Delta Easting [m]</th>
<th>Delta Northing [m]</th>
<th>Delta Up [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISK1</td>
<td>Min   -0.0336</td>
<td>-0.0265</td>
<td>-0.0441</td>
</tr>
<tr>
<td></td>
<td>Max    0.0029</td>
<td>0.0166</td>
<td>0.0122</td>
</tr>
<tr>
<td></td>
<td>Std    0.0080</td>
<td>0.0086</td>
<td>0.01525</td>
</tr>
<tr>
<td></td>
<td>Min    -0.0330</td>
<td>-0.0391</td>
<td>-0.0441</td>
</tr>
<tr>
<td>ISK2</td>
<td>Max    0.0026</td>
<td>0.0152</td>
<td>0.0085</td>
</tr>
<tr>
<td></td>
<td>Std    0.0092</td>
<td>0.0114</td>
<td>0.0131</td>
</tr>
<tr>
<td></td>
<td>Min    -0.0158</td>
<td>-0.0279</td>
<td>-0.0350</td>
</tr>
<tr>
<td>ISK3</td>
<td>Max    0.0058</td>
<td>0.0137</td>
<td>0.0185</td>
</tr>
<tr>
<td></td>
<td>Std    0.0043</td>
<td>0.0082</td>
<td>0.0125</td>
</tr>
</tbody>
</table>

CONCLUSIONS

• ...
Conclusions

- This study: coordinate monitoring of local GPS CORS network using Bernese & ConDAS.
- Bernese GPS software: special processing strategies; 3 types of output files from Bernese were extracted for deformation detection/analysis.
- ConDAS: a windows-based software system for GPS deformation detection via IWST and final S-transformation methods.

Conclusions

- ConDAS has been proven to have potential for providing high-quality stability information of CORS network.
- The test results show the suitability of the approach/software system for practical applications such as local CORS coordinate monitoring.
- Future works: to improve the flexibility of this software system in data searching, loading and code embedding.
Acknowledgements

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• Research facility/ISKANDARnet: GNSS & Geodynamics Research Group, FGRE, UTM.

Thank you for your attention!

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Double Difference GPS Data Processing using Bernese

- The preparation part: computing a priori coordinate file, preparing the orbit and earth orientation files in Bernese formats, converting RINEX files to Bernese format, synchronising the receiver clocks to GPS time and producing an easy to read overview of available data.

- The pre-processing part: creation of single difference files, editing of the cycle slips and removal of suspect observation.

- The processing part: to resolve the ambiguity. After computing a solution with real valued ambiguities the Quasi Ionosphere Free (QIF) strategy is used to resolve ambiguities to their integer numbers. Subsequently, compute and provide the fixed ambiguity solution using double differencing strategy.

- A summary results file is saved and dispensable output files are removed at the final stage of processing.