The Mw 5.1 Lorca earthquake successfully recorded by GPS

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Lorca Earthquake

May 11th, 2011, 16:47 UTC

Mw 5.1 earthquake

Receiver only 5 km away from epicenter

Hypocenter between 1-2 km depth, less than 2km away from the city

Biggest foreshock, Mw 4.5

Nearly 250 injured, 9 casualties

Structural damage including the collapse of an old monastery
"Meristemum" Network

GPS Network from the Consejería de Agricultura y Agua of the Murcia Region

More Info at: http://gps.medioambiente.carm.es
GPS Data Processing

Bernese GPS Software for Double Differences (DD)

RTKLIB for Precise Point Positioning (PPP)

Filtering Process

- Modified Sidereal Filter (MSF)
- Regional Filter (RF), for PPP

To eliminate site-dependent errors

To eliminate common-mode errors
## Global Comparison

<table>
<thead>
<tr>
<th>Double Differences</th>
<th>Precise Point Positioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processes baselines</td>
<td>Processes each station separately</td>
</tr>
<tr>
<td>Relative positioning</td>
<td>Absolute positioning</td>
</tr>
<tr>
<td>High precision for the relative geometry</td>
<td>Precise site coordinates</td>
</tr>
<tr>
<td>Cancellation of both GPS receiver and satellite clock errors</td>
<td>Provides receiver clock correction</td>
</tr>
<tr>
<td></td>
<td>Clock and Orbit information quality is essential</td>
</tr>
</tbody>
</table>
### Processing Comparison

<table>
<thead>
<tr>
<th>Double Differences</th>
<th>Precise Point Positioning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bernese GPS software v. 5.0</td>
<td>RTKPOST (part of RTKLIB*)</td>
</tr>
<tr>
<td>Narrowlane-Widelane cycle-slip resolution strategy for the baseline</td>
<td>Ionosphere-free linear combination processing</td>
</tr>
<tr>
<td>Integer ambiguities introduced in a second kinematic step. Reference station’s</td>
<td>Combined Kalman filter (forwards and backwards) to eliminate</td>
</tr>
<tr>
<td>coordinates held fixed.</td>
<td>convergence effects</td>
</tr>
<tr>
<td>IGS final orbit (15 min). CODE ERP and ionosphere information.</td>
<td>IGS final orbit (15 min) and clock products (30 s)</td>
</tr>
</tbody>
</table>

*Note!! The version of RTKLIB used does not solve ambiguities. The future version does.*
## Filtering

### Modified Sidereal Filter

<table>
<thead>
<tr>
<th>Filtered Epoch</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t - 3T$</td>
<td>$t - T$</td>
</tr>
<tr>
<td>$\Delta X_{t-3T}$</td>
<td>$\Delta X_{t-2T}$</td>
</tr>
<tr>
<td>$\Delta Y_{t-3T}$</td>
<td>$\Delta Y_{t-2T}$</td>
</tr>
<tr>
<td>$\Delta Z_{t-3T}$</td>
<td>$\Delta Z_{t-2T}$</td>
</tr>
</tbody>
</table>

- $X_{t, filtered} = X_t - \bar{\Delta X}$
- $Y_{t, filtered} = Y_t - \bar{\Delta Y}$
- $Z_{t, filtered} = Z_t - \bar{\Delta Z}$

### Regional (Common Mode) Filter

- $X_{S,t, filtered} = X_s_t - \bar{\Delta X}_s$
- $Z_{S,t, filtered} = Z_{S,t} - \bar{\Delta Z}_t$
Process

Timespan considered from 15:30 to 17:30.
Earthquake occurred at 16:47 GPST, doy 131.
RINEX 1 Hertz data downloaded for GPS week 1635 (doy 128-134)

DD approach:
Medium Length baselines
(CRVC-MURC - 66.7km, MURC-LORC - 62.1km)
Ambiguities resolved: 96.4% for CRVC-MURC; 89.3% for MURC-LORC

PPP approach:
Stations in the network were processed separately.
Good convergence of the results in the first two hours of the day.
Therefore, at 16:47 GPST, the data fully converged.

A whole week of data is necessary for filtering (previous slide)
Filtered Results: DD

Blue: Raw DD
Red: DD + MSF

- NORTH [mm] EAST [mm] UP [mm]

**DD Unfiltered:** STD=12.0mm
**DD Sidereally Filtered:** STD=5.4mm

**DD Unfiltered:** STD=7.5mm
**DD Sidereally Filtered:** STD=4.3mm

**DD Unfiltered:** STD=13.6mm
**DD Sidereally Filtered:** STD=8.3mm

GPS Time
Filtered Results: PPP

- **NORTH [mm]**
  - PPP Unfiltered: STD=7.7mm
  - PPP Sidereally Filtered: STD=6.4mm
  - PPP Sidereally and Regionally Filtered: STD=3.8mm

- **EAST [mm]**
  - PPP Unfiltered: STD=5.9mm
  - PPP Sidereally Filtered: STD=6.5mm
  - PPP Sidereally and Regionally Filtered: STD=5.6mm

- **UP [mm]**
  - PPP Unfiltered: STD=14.1mm
  - PPP Sidereally Filtered: STD=13.6mm
  - PPP Sidereally and Regionally Filtered: STD=12.0mm

Blue: Raw PPP
Green: PPP + MSF
Red: PPP + MSF + RF

NORTH [mm] EAST [mm] UP [mm]

GPS Time
## Comparison of the Filters

<table>
<thead>
<tr>
<th></th>
<th>DD Raw (mm)</th>
<th>DD MSF (mm)</th>
<th>%</th>
<th>PPP Raw (mm)</th>
<th>PPP MSF (mm)</th>
<th>%</th>
<th>PPP MSF,RF (mm)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LORC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_N$ N-S</td>
<td>12.0</td>
<td>5.4</td>
<td><strong>55.0</strong></td>
<td>7.8</td>
<td>4.6</td>
<td><strong>37.0</strong></td>
<td>3.8</td>
<td><strong>51.3</strong></td>
</tr>
<tr>
<td>$S_N$ E-W</td>
<td>7.5</td>
<td>4.3</td>
<td><strong>42.7</strong></td>
<td>5.9</td>
<td>3.5</td>
<td><strong>30.2</strong></td>
<td>5.6</td>
<td><strong>5.0</strong></td>
</tr>
<tr>
<td>$S_N$ Up</td>
<td>13.6</td>
<td>8.3</td>
<td><strong>39.0</strong></td>
<td>14.1</td>
<td>13.6</td>
<td><strong>3.5</strong></td>
<td>12.0</td>
<td><strong>14.9</strong></td>
</tr>
<tr>
<td><strong>MURC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$S_N$ N-S</td>
<td>11.7</td>
<td>6.0</td>
<td><strong>48.7</strong></td>
<td>16.7</td>
<td>6.1</td>
<td><strong>63.5</strong></td>
<td>3.9</td>
<td><strong>76.6</strong></td>
</tr>
<tr>
<td>$S_N$ E-W</td>
<td>10.0</td>
<td>5.5</td>
<td><strong>45.0</strong></td>
<td>10.9</td>
<td>5.1</td>
<td><strong>33.2</strong></td>
<td>3.5</td>
<td><strong>67.9</strong></td>
</tr>
<tr>
<td>$S_N$ Up</td>
<td>14.3</td>
<td>9.9</td>
<td><strong>30.8</strong></td>
<td>44.5</td>
<td>19.7</td>
<td><strong>69.2</strong></td>
<td>9.2</td>
<td><strong>79.3</strong></td>
</tr>
</tbody>
</table>

No clear outcome, there is no “best strategy”
Graphical Comparison

- NORTH [mm]
  - PPP Sidereally Filtered: STD=13.6mm
  - DD Sidereally Filtered: STD=8.3mm
  - PPP Sidereally and Regionally Filtered: STD=12.0mm

- EAST [mm]
  - PPP Sidereally Filtered: STD=6.5mm
  - DD Sidereally Filtered: STD=4.3mm
  - PPP Sidereally and Regionally Filtered: STD=5.6mm

- UP [mm]
  - PPP Sidereally Filtered: STD=6.4mm
  - DD Sidereally Filtered: STD=5.4mm
  - PPP Sidereally and Regionally Filtered: STD=3.8mm

Green: PPP + MSF
Blue: DD + MSF
Red: PPP + MSF + RF
Lorca Earthquake: DD & PPP

**NORTH [mm]**
- PPP Sidereally Filtered: STD=6.4mm
- DD Sidereally Filtered: STD=5.4mm
- PPP Sidereally and Regionally Filtered: STD=3.8mm

**EAST [mm]**
- PPP Sidereally Filtered: STD=6.5mm
- DD Sidereally Filtered: STD=4.3mm
- PPP Sidereally and Regionally Filtered: STD=5.6mm

**UP [mm]**
- PPP Sidereally Filtered: STD=13.6mm
- DD Sidereally Filtered: STD=8.3mm
- PPP Sidereally and Regionally Filtered: STD=12.0mm

- Green: PPP + MSF
- Blue: DD + MSF
- Red: PPP + MSF + RF
Real Time Data Transmission

NTRIP standard allows the transmission of GNSS data in real-time via the Internet.

GNSS observations as well as precise orbit and clock information can be broadcasted.

1-Hz observation data from Meristemum network are available by NTRIP.

Real Time Data Processing

The processing techniques described are suite for real-time applications.

Only IGS Final products are not available for real-time.

Alternative: real-time correction streams. May decrease the accuracy of PPP positioning.

Filter: Sidereal and Regional filters are possible, but only previous data can be used.

15 seconds of observation streams latency for PPP computation.

2 minutes needed to process in Bernese, the quickest presented for GITEWS (German Indonesian Tsunami Early Warning System).
Real-Time PPP: Lorca Earthquake

Reprocess of the LORC data under real time conditions in PPP mode

Use only data available at the time of the earthquake

IGS Ultra Rapid orbits predicted part

Combination clock product from IGS-RTPP

Comparison with the previously computed data from LORC
Comparison (2 hours)

Real-Time PPP: STD=7.7mm
PPP Unfiltered: STD=32.8mm

Real-Time PPP: STD=5.9mm
PPP Unfiltered: STD=32.8mm

Blue: Post-processed PPP
Red: Real-Time PPP

GPS Time
Comparison (2 minutes)

Real-Time PPP: STD=7.7mm
PPP Unfiltered: STD=32.2mm

Real-Time PPP: STD=5.9mm
PPP Unfiltered: STD=32.8mm

Real-Time PPP: STD=14.1mm
PPP Unfiltered: STD=51.8mm

Post-processed and Real Time show identical behaviour!!

Blue: Post-processed PPP
Red: Real-Time PPP

GPS Time

NORTH [mm] EAST [mm] UP [mm]
Conclusions & Outlook

Both PPP and DD strategies are able to deliver short-term coordinate variations
Filtering reduces the noise in the position time series

MSF applied to PPP is not as good as MSF applied to DD
MSF + RF applied to PPP leads to similar results as MSF applied to DD

Dynamic peak-to-peak displacements up to 3 cm clearly visible in the time series

The rest of the stations were processed and showed no movement above noise level
Biggest foreshock (Mw 4.5) did not show movement either

PPP + filtering is less time consuming as DD + filtering
General decrease in accuracy during the whole two hours
For the timespan of the earthquake, solutions obtained by post-processing and real-time have the same quality.
Thank You

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Additional information (in English) will be published in the 24th volume of “Física de la Tierra”
http://revistas.ucm.es/index.php/FITE