gAGE/UPC GNSS Ionosphere Activities: Real-time, Galileo, EGNOS and Tomography

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Outline

• Introduction.

• Accurate Wide Area RT ionospheric corrections, the key for:
  ➢ With GPS: Wide Area RTK (WARTK)
  ➢ With Galileo: Wide Area RTK with three-frequency systems (WARTK-3).
  ➢ Accurate EGNOS real-time Ionospheric Monitoring.

• GPS ionospheric tomography.

• Conclusions
Introduction

The improvement of real-time GNSS ionospheric determination models makes now possible to fix ambiguities in real-time WADGPS networks (ref. stations separated by hundreds-thousand km).

New applications arise in such WADGPS networks:

1. cm-level real-time positioning, potentially in single-epoch with Galileo and Modernized GPS.
2. real-time instantaneous tropospheric determination.
3. real-time ionospheric integrity monitoring, i.e. for SBAS systems such as EGNOS.
Real-time iono. model

- Only carrier phase data needed
- With tomographic description: more accurate
- DCB’s no longer needed
- No affected by pseudorange multipath

\[
L_I = STEC + B_I = \int_{REC}^{SAT} N_e dl + B_I = \sum_i \sum_j \sum_k (N_e)_{i,j,k} \Delta s_{i,j,k} + B_I
\]
WARTK: Combining real-time Ionospheric & Geodetic models

Resolving the Ambiguous $\Delta$ STEC in Real Time for the Reference Stations

- Code Smoothing
- Real Time Ionospheric Model
- Geodetic Program
- Precise Orbits and Tropo
- Checking and Fixing Ambiguities
- Unambiguous $\Delta$ STEC Determination

$\Delta$: Double Difference
Lc: Ionospheric-Free Combination
Lw: Wide-Lane Combination
LI: Ionospheric Combination

$\Delta N$: STEC Differences

2004 IGS Technical Meeting, Bern, Switzerland, 5 March 2004
M.Hernández, J.M.Juan, J.Sanz, A.Aragon, M.García, R.Orus, P.Roldán
Example 1: EGNOS Test Bed vs IGS differential iono.

**RMS \( \sqrt[\Delta]{\text{STEC}_{\text{XXX}} - \sqrt[\Delta]{\text{STEC}_{\text{TRUTH}}}} \)**

**REAL CASE of use of very accurate DDSTEC reference values:** During these days of April-May 2003, the double-differenced STEC values from the IGS TEC maps (time resolution of 2 hours) are about 40% better than the ESTB values (real-time, not final configuration).
WARTK(GPS): cm-Navigation at hundreds km far

Sub-decimeter real-time positioning at more than 100 km far from the nearest GPS reference station.
Accurate STEC from fixed GPS sites thousands km far

New Experiment:
- 13 IGS stations
- Distances: 1000-3000km
- Including equator, tropics
- 4 weeks 2001 65-92
- Solar Max. conditions
- Seasonal Max.
- With high geom. activity
Real-time DDSTEC vs. truth

<table>
<thead>
<tr>
<th>Sta.</th>
<th>Ref.</th>
<th>Dist. (km)</th>
<th>% Succ.</th>
<th>RMS [TECU]</th>
<th># Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRKT</td>
<td>DAEJ</td>
<td>2507</td>
<td>93</td>
<td>1.2</td>
<td>8329</td>
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<tr>
<td>BJFS</td>
<td>DAEJ</td>
<td>1067</td>
<td>91</td>
<td>1.4</td>
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<td>KUNM</td>
<td>DAEJ</td>
<td>2640</td>
<td>95</td>
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<td>3900</td>
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<td>WUHN</td>
<td>DAEJ</td>
<td>1369</td>
<td>92</td>
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<td>6358</td>
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<tr>
<td>SAMP</td>
<td>KARR</td>
<td>3341</td>
<td>95</td>
<td>1.1</td>
<td>6441</td>
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<td>COCO</td>
<td>KARR</td>
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<td>97</td>
<td>0.9</td>
<td>9963</td>
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<td>BAKO</td>
<td>KARR</td>
<td>1939</td>
<td>90</td>
<td>1.5</td>
<td>6121</td>
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<tr>
<td>YAR2</td>
<td>KARR</td>
<td>909</td>
<td>97</td>
<td>0.8</td>
<td>12630</td>
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<tr>
<td>Exp.</td>
<td>Ionos. Activity</td>
<td>Distances (km)</td>
<td>Ref. Rover/Ref.</td>
<td>Rover Success</td>
<td>Kind Rover</td>
</tr>
<tr>
<td>------</td>
<td>----------------</td>
<td>----------------</td>
<td>----------------</td>
<td>---------------</td>
<td>------------</td>
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<tr>
<td>BelKin99</td>
<td>Quiet</td>
<td>116/286</td>
<td>97%</td>
<td>80-100%</td>
<td>Car</td>
</tr>
<tr>
<td>NWPacific</td>
<td>Active</td>
<td>400/900</td>
<td>90-100%</td>
<td>80%</td>
<td>IGS Site</td>
</tr>
<tr>
<td>(1)</td>
<td>Kp=6</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NWPacific</td>
<td>Irreg.</td>
<td>162/900</td>
<td>95-100%</td>
<td>80-90%</td>
<td>IGS Site</td>
</tr>
<tr>
<td>(2)</td>
<td>Apr30</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SolarMax</td>
<td>Solar Max.</td>
<td>130/500</td>
<td>85-95%</td>
<td>80%</td>
<td>IGS Site</td>
</tr>
<tr>
<td>(1)</td>
<td>Max.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SolarMax</td>
<td>Very Active</td>
<td>130/500</td>
<td>50-95%</td>
<td>80%</td>
<td>IGS Site</td>
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<tr>
<td>(2)</td>
<td></td>
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<tr>
<td>Baltic99</td>
<td>TID’s</td>
<td>144/285</td>
<td>97%</td>
<td>83%</td>
<td>Fixed Site</td>
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<tr>
<td>(1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equator01</td>
<td>S.Max. Equat.</td>
<td>1000-3000</td>
<td>90%</td>
<td>-</td>
<td>IGS Site</td>
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<tr>
<td>Kp:0-9</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**Prototype of the real-time ionospheric part running now in Catalonia, NE Spain, in testing mode (under contract of the Cartographical Institute of Catalonia, ICC).**

More details in:


WARTK-3 for Galileo and Modernized GPS (1)

1. The wide lane combination ambiguity is estimated from the unambiguous extra-wide lane carrier phase, obtained in step 1.

2. To solve the extra-wide lane ambiguity by adding a pseudo-range combination.

3. The L1 phase ambiguity is derived from the difference between L1 and the unambiguous wide lane obtained previously.

\[ L_1 = STEC + B_I = \sum \sum \sum (N_e)_{i,j,k} \Delta s_{i,j,k} + B_I \]

\[ \nabla \Delta \hat{N}_1 = \frac{1}{\lambda_1} \nabla \Delta (L_1 - L_w + \lambda_w N_w) = \nabla \Delta N_1 - \frac{1}{\lambda_1} \nabla \Delta (\varepsilon_w + m_w - m_1) + \frac{1}{\lambda_1} (\alpha_1 - \alpha_w) \nabla \Delta I \]

Error \( \nabla \Delta I \) < 0.26 TECU

-1.95 cycles N1/TECU
## WARTK-3 for Galileo and Modernized GPS (2)

<table>
<thead>
<tr>
<th></th>
<th>PROS</th>
<th>CONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCAR</td>
<td>Low computational load.</td>
<td>Ionospheric error limiting seriously.</td>
</tr>
<tr>
<td>ITCAR</td>
<td>Improved results by integrating TCAR in a navigation filter.</td>
<td>The ionospheric delay still limits the 3rd ambiguity fixing.</td>
</tr>
<tr>
<td>WARTK</td>
<td>Accurate RT ionospheric modelling allowing precise navigation at hundreds of kilometers far from the reference sites.</td>
<td>Computation load: need of computing a first ionospheric free navigation solution for the roving user.</td>
</tr>
<tr>
<td>WARTK-3</td>
<td>Low computation load and accurate real-time ionospheric model providing single epoch precise navigation at more than hundred km far (the best of both worlds).</td>
<td>East, Norh, Up RMS: 3cm, 5cm, 2cm (92% of the trials and 77% of the epochs: 1cm, 1cm, 2cm).</td>
</tr>
</tbody>
</table>

2. EGNOS Test Bed Monitoring activity
Collecting 24h data (1Hz) every Thursday-Friday since January 10th 2002

<table>
<thead>
<tr>
<th>Leeds, Delft, M3/ENAC, UPC1, UPC2</th>
<th>Receiver:</th>
<th>Antenna:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NovAtel (OEM3)</td>
<td>L1/L2 NovAtel 600 (Pinwheel)</td>
</tr>
</tbody>
</table>

Antenna:
- L1/L2 NovAtel 600 (Pinwheel)
- NovAtel (OEM3)

Receiver:
- NovAtel
- NovAtel (OEM3)
The existence of TIDs is the worst case scenario affecting the interpolability of accurate ionospheric corrections at mid latitudes, basic for the availability of WARTK and WARTK-3 techniques.
Example 1: ESTB vs IGS differential iono.

\[ \text{RMS (} \nabla \Delta \text{STEC}_{XXX} - \nabla \Delta \text{STEC}_{\text{TRUTH}} \text{)} \]

During these days of April-May 2003, the double-differenced STEC values from the IGS TEC maps (time resolution of 2 hours) are about 40% better than the ESTB values (real-time, not final configuration).
Example 2: ESTB during the Oct’03 Iono. Superstorm

During the 30 October ionospheric superstorm a TEC enhancement reached North Europe producing Loss of Integrity event in the EGNOS Test Bed system.
2. GPS Ionospheric Tomographic activity
Benefits of separability hypothesis

With the TEC (computed from ground GPS data) modelling the horizontal variation, the electron density at tangent point A (green) is estimated from the GPS occultation data better (red) that assuming spherical symmetry (blue).
Recent results can be found in:
Garcia-Fernandez, M., M. Hernandez-Pajas, M. Juan, and J. Sanz, Improvement of ionospheric
electron density estimation with GPS/MET occultations using Abel inversion and VTEC information,

Results with GPS/MET data during 11 days
in 1995 (Solar Cycle minimum)

Table 1. Table of foF2 Errors With Respect to Ionosonde Measurementa

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N.comp</td>
<td>RMS: MHz [%]</td>
</tr>
<tr>
<td>Quiet Ionosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low latitudes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day</td>
<td>177</td>
<td>1.2 [16.2]</td>
</tr>
<tr>
<td>D&amp;D</td>
<td>10</td>
<td>0.5 [9.7]</td>
</tr>
<tr>
<td>0° ± 30°</td>
<td>Night</td>
<td>100</td>
</tr>
<tr>
<td>Middle and high latitudes</td>
<td>Day</td>
<td>2054</td>
</tr>
<tr>
<td>D&amp;D</td>
<td>908</td>
<td>0.8 [19.1]</td>
</tr>
<tr>
<td>±30° ± 90°</td>
<td>Night</td>
<td>1122</td>
</tr>
<tr>
<td>Disturbed Ionosphere</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day</td>
<td>105</td>
<td>0.9 [17.7]</td>
</tr>
<tr>
<td>D&amp;D</td>
<td>94</td>
<td>0.7 [18.2]</td>
</tr>
<tr>
<td>Night</td>
<td>32</td>
<td>0.4 [16.1]</td>
</tr>
</tbody>
</table>

The error is Absolute RMS in MHz and Percentual relative RMS difference in brackets. The number of comparisons is also given.
Separability: improvement in E layer estimation

The improved Abel can provide reliable estimates of the NmE value as well (not just NmF2 values).

**Figure 6.** Effect of accumulative errors on the computation of the E layer electron density. The errors in the estimation of the upper layers strongly affects the lowermost layers. This particular example corresponds to an occultation of the GPSMET with the PRN20 at 11 October 1995 (day of year 284), 1000 UT (1200 LT), at E43.3 N44.9, compared with the corresponding NmF2 and NmE values obtained with the Leningrad Ionosonde.
Performance for f0E

Table 2. Table of foE Errors With Respect to Ionosonde Value\textsuperscript{a}

<table>
<thead>
<tr>
<th></th>
<th>N.comp</th>
<th>Sep. Hyp. RMS: MHz [%]</th>
<th>Sph. Symm. RMS: MHz [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E layer</td>
<td>135</td>
<td>0.4 [17.1]</td>
<td>0.7 [28.5]</td>
</tr>
<tr>
<td>Es layer</td>
<td>35</td>
<td>0.5 [16.2]</td>
<td>1.0 [30.4]</td>
</tr>
</tbody>
</table>

\textsuperscript{a}The error is Absolute RMS in MHz and Percentual relative RMS difference in brackets.

The improvement in foE estimates reaches to a reduction of 40% in E layer and near 50% in Es layer.
Thank you!