VARION extension to GEO satellites: application to recent tsunami induced TIDs events

Michela Ravanelli, Giorgio Savastano, Augusto Mazzoni and Mattia Crespi

Geodesy and Geomatics Division, DICEA, Sapienza University of Rome

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Outline

1 Introduction
   - Aim of the work
   - Travelling Ionospheric Disturbances

2 The VARION algorithm
   - VARION fundamentals
   - GEO satellites: pros and cons

3 Mw 7.5 - 165km ESE of Tadine, New Caledonia
   - Dataset
   - VARION processing
   - Summary

4 Conclusions and prospects
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Aim of the work

To show the benefit of combined application of MEO and GEO satellites for detecting and analysing Travelling Ionospheric Disturbances (TIDs) through the VARION algorithm.

MEO satellites
- Medium Earth Orbit satellites (GNSS)
- height of \( \approx 20200 \text{ km} \)
- orbital period of \( \approx 12 \text{ hours} \)

GEO satellites
- Geostationary Earth Orbit satellites
- height of \( \approx 35800 \text{ km} \)
- orbital period equal to the Earth rotation period
Travelling Ionospheric Disturbances (TIDs)

- **TIDs related to gravity waves**
  - Atmosphere as **low-pass filter**: only waves with **frequency lower than buoyancy frequency** (about 3.3 mHz at sea level) reach the ionosphere.
  - **Strong amplification** during the upward propagation (density decreasing, momentum conservation).
  - Ionosphere perturbations detectable with GNSS.

*(Figure from Giovanni Occhipinti)*
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VARION fundamentals

Variometric Approach for Real-time Ionosphere Observation

Features

- derived from VADASE (real-time ground velocity and displacement)
- sTEC variation estimation from the observations of a stand-alone GNSS receiver (single station approach) in real time
- advantages: no infrastructure, no post-processing, no initialization needed

Realization

- designed in 2015 at Sapienza University of Rome
- developed and validated in 2016 in collaboration with the Jet Propulsion Laboratory, Ionospheric and Atmospheric Remote Sensing Group

Reference

**VARION fundamentals**

**Methodology**

\[
\frac{L_{4R}^S(t+1) - L_{4R}^S(t)}{\Delta m_R + \Delta \epsilon_R^S} = f_1^2 - f_2^2 \left[ I_{1R}^S(t+1) - I_{1R}^S(t) \right] + f_1^2 - f_2^2 \left[ I_{1R}^S(t+1) - I_{1R}^S(t) \right]
\]

unknown term, sTEC variation

time single difference geometry free observation

\[
\delta sTEC(t+1, t) = \frac{f_1^2 f_2^2}{A(f_1^2 - f_2^2)} \left[ L_{4R}^S(t+1) - L_{4R}^S(t) \right]
\]

note: (this is a total space-time variation)
VARION Algorithm for MEO vs. GEO satellites

**MEO satellites**

\[
\frac{ds\text{TEC}}{dt} = \frac{\partial s\text{TEC}(t, s)}{\partial t} + \frac{\partial s\text{TEC}(t, s)}{\partial s} \frac{\partial s}{\partial t} \tag{2}
\]

**GEO satellites**

\[
\frac{ds\text{TEC}}{dt} = \frac{\partial s\text{TEC}(t, s)}{\partial t} + \frac{\partial s\text{TEC}(t, s)}{\partial s} \frac{\partial s}{\partial t} \tag{3}
\]

(Figure from Hoffman et al., 2008)
**GEO satellites: pros and cons**

### Pros
- **determination of the sTEC time variation**
- **elimination of all the effects** due to satellite motion in sTEC time series (i.e. increasing observational noise, IPP velocity and trends for elevation decrease)
- **continuous sTEC time series**

### Cons
- **still low spatial coverage:**
  - few dual frequency GEO satellites
  - few stations observing GEO satellites
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4. **Conclusions and prospects**
Mw 7.5 New Caledonia earthquake and tsunami

On September 5, 2018, at 04:08:18 UTC, a Mw 7.5 earthquake occurred 165 km ESE of Tadine, New Caledonia, (21.950° S, 169.427° E, depth = 10.0 km)
Mw 7.5 New Caledonia earthquake and tsunami

On September 5, 2018, at 04:08:18 UTC, a Mw 7.5 earthquake occurred 165 km ESE of Tadine, New Caledonia, (21.950°S, 169.427°E, depth = 10.0 km).

Tsunami

- Waves 2 meters high damaged a school and several homes at Anelghowhat and Oumetch, Vanuatu.
- Waves 72 cm high were observed at Tanna, Vanuatu and at Loyalty Islands.

Dataset

<table>
<thead>
<tr>
<th>Gauge Location</th>
<th>Coordinates (LAT, LON)</th>
<th>Time of Measure (UTC)</th>
<th>Maximum Tsunami Height (M/FT)</th>
<th>Wave Period (MIN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUVA VITI LEVU FJ</td>
<td>18.1S 178.4E</td>
<td>0652</td>
<td>0.03M/0.1FT</td>
<td>38</td>
</tr>
<tr>
<td>NUMBO NEW CALEDONIA</td>
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<td>0613</td>
<td>0.04M/0.1FT</td>
<td>06</td>
</tr>
<tr>
<td>THIO NEW CALEDONIA</td>
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<td>0631</td>
<td>0.23M/0.8FT</td>
<td>12</td>
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<tr>
<td>VANUATU</td>
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<td>10</td>
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<td>0505</td>
<td>0.72M/2.4FT</td>
<td>06</td>
</tr>
</tbody>
</table>
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On September 5, 2018, at 04:08:18 UTC, a Mw 7.5 earthquake occurred 165km ESE of Tadine, New Caledonia, (21.950°S, 169.427°E, depth = 10.0 km)

Dataset

- stations from BANIAN GNSS network
- 20 GNSS stations, located over the territory of New Caledonia
VARION processing

**Analysis**

- VARION was applied to both MEO and GEO GNSS data
- sTEC variations filtered with **bandpass filter** (0.1-1 mHz)

![Graph showing sTEC variations over time](image)
VARION processing

GPS satellite G19
VARION processing

GPS satellites G19 and G02
VARION processing

Beidou GEO satellite C04 and GPS satellite G12

C04 observed from KOUC, LPIL, NRMG and NMEA
VARION processing

Beidou GEO satellite C04 and GPS satellite G12

![Graph showing distance from epicenter vs. time with TECU values]
VARION processing

Summary of results

- GPS satellite G19 and G02 well highlight the TIDs connected to the tsunami
- Beidou GEO satellite C04 show a good sTEC signature
  unfortunately
- still few GNSS stations can observe GEO satellites nowadays
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VARION combined application of MEO and GEO satellites

GEO satellites

- **no geometric effects** $\Rightarrow$ potentially better TIDs detection
- **continuous sTEC solutions** $\Rightarrow$ ionosphere activity monitoring

Mutual benefits of GEO and MEO satellites for **ionosphere monitoring** and **enhancement of tsunami early warning system**

Outlook I

- application to more intense tsunami events such as **January 23, 2018, Mw 7.9 Gulf of Alaska earthquake and tsunami**
- application to other kinds of ionospheric disturbances
A challenge for societal benefits

Outlook II

- **hoped increase** of the number of stations observing GEO satellites

- VARION-GEO as a contributing tool to reliably confirm tsunami alert and to prevent casualties as in case of Palu (Indonesia)

- in this background, Indonesia/Philippines area can already benefit of dual frequency GEO satellites from Beidou constellation

This research and its outlook have been/will be developed under the umbrella of **GETWS initiative, within GGOS Geohazards Focus Area**
Thank you very much for your kind attention