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The variometric approach for the monitoring of natural hazard-induced ionospheric perturbations

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Abstract

This work shows how the VARION (Variometric Approach for Real-Time Ionosphere Observation) algorithm, able to estimate the TEC variations in real-time, can be used to shed the light on the mechanism of Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) and thus to be used for ionospheric monitoring of natural hazards events.

In particular, we present the methodology of Total Variometric Approach (TVA) was developed to estimate the tsunami genesis and to support classic methods for tsunami warning system. TVA is based on the joint application of VADASE (Variometric Approach for Displacements Analysis Standalone Engine) and VARION to estimate ground shaking, co-seismic displacements and TEC disturbances, using the same real-time GNSS data stream.

Furthermore, we present an oceanic-ionospheric joint analysis after the 2022 Tonga eruption. We report on the reversed amplitude of the two phenomena in the oceans and in the ionosphere. The sea-surface perturbation caused by the Lamb wave was not significant, while ionospheric perturbation was considerable. In contrast, the regular tsunami waves manuscript reached ∼1m around New Caledonia-New Zealand and ∼2m along the Chilean coastline; however, the associated ionospheric perturbation was quite small, half the size of the Lamb wave perturbation.

We finally explore the possibility to increase the amount of available data for a denser ionospheric monitoring, applying VARION also to observations coming from geostationary satellites, from ship-based GNSS receivers and from smartphones.

1 Introduction

The GNSS (Global Navigation Satellite System) Ionospheric Seismology studies the ionospheric response to natural hazards, such as earthquakes, tsunamis and volcanic eruptions, by means of the GNSS signal [1]. Indeed, these events trigger acoustic and gravity waves (AGW) that can disturb the total electron content (TEC) of the ionosphere, causing the so-called Traveling Ionospheric Disturbances (TIDs). In detail, we can distinguish earthquake and tsunami induced ionospheric perturbations in AGW_{epi}, $AW_{Rayleigh}$ and IGW_{tsuna} [2].

The acoustic-gravity waves generated by the vertical displacement at the source are indicated as AGW_{epi}. They are detectable near the epicenter (within about 1000 km), but the earthquake rupture and the consequent ground displacement at the source area have a rich spectral signature: consequently, both acoustic and gravity waves are simultaneously generated. They are connected with the uplift at the source, a key parameter in the genesis of a tsunami.

The acoustic waves triggered by the propagation of the Rayleigh waves are called $AW_{Rayleigh}$. They are observable only in the far field and move horizontally at the speed of around 3.5 km/s, imposed by the forcing source, nominally the Rayleigh wave. They are connected to earthquake magnitude.

Finally, tsunamis can trigger internal gravity waves (IGW_{tsuna}). The IGW_{tsuna} are governed primarily by buoyancy, the transverse oscillations of an air parcel when it is displaced by its equilibrium position; in this case it is due to the earthquake induced slow rise and fall of the ocean surface. They are connected to the amplitude of the tsunami offshore.

In this background, the VARION (Variometric Approach for Real-Time Ionosphere Observation) algorithm, able to estimate the TEC variations in real-time, was developed. In detail, the VARION approach is based on single time differences of geometry-free combination of GNSS carrier-phase measurements, using a standalone GNSS receiver and standard GNSS broadcast products (orbits and clocks corrections) that are available in real time.

In this work, we present how the VARION algorithm can be used as a useful tool to better understanding of Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) and, hence, to the detection and the monitoring of ionospheric perturbations induced by natural hazard events.

2 Total Variometric Approach

Specifically, a novel methodology named Total Variometric Approach (TVA) was developed to estimate the tsunami genesis and to support classic methods for tsunami warning system [1]. It is called total, since it allows a complete monitoring of a seismic event: from the ground to the ionosphere. TVA includes the term variometric, because the two algorithms, VADASE and VARION, leverage the same variometric principle (Figure 1). TVA is based on the joint application of VADASE (Variometric Approach for Displacements Analysis Standalone Engine) [4] and VARION to estimate ground shaking, co-seismic displacements and TEC disturbances, using the same real-time GNSS data stream [3].

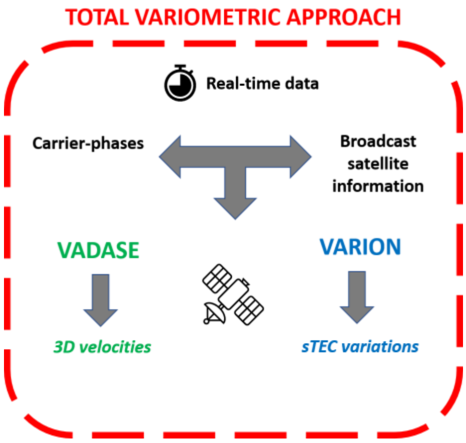

Figure 1. TVA methodology layout.

We analysed the cosemeisc displacements and the ionospheric perturbation induce by the 2015 Mw 8.3 Illapel (Chile) earthquake. In detail, this earthquake also caused a tsunami.
The 2015 Illapel earthquake was used as a benchmark to prove the feasibility and reliability of the TVA methodology [1].
In detail, benefiting of the well-known robustness against saturation of the GNSS receivers, TVA allowed to estimate significant ground shaking at only 30 seconds after the rupture as well as to evaluate the released energy associated to the earthquake ground shaking, highlighting a north-south asymmetry. Additionally, the anomalous TEC perturbation related to the propagation of the AGWepi, is detected at 9.5 minutes after the rupture and it also displays and very well matches the north-south asymmetry previously recognized through the GNSS ground-motion measurements. The high spatial resolution of the GNSS-TEC observations (number of GNSS stations multiply by the number of satellites-in-view) enables to map the earthquake source extent in real-time, that is the key point of tsunami genesis estimation.
GNSS-TEC data are today the only and unique technique to image the source extent (not achievable with standard techniques).

3 Tonga eruption

We also investigated the oceanic and the ionospheric response to the January 2022 Hunga-Tonga volcanic eruption near the source, New Caledonia-New Zealand, and far from the source, Chile-Argentina.
At the sea surface, we observe both the air-sea wave, i.e., the tsunami-like wave of atmospheric origin caused by the Lamb wave propagation, and the "regular" tsunami.
At ionospheric heights, we identify the corresponding ionospheric perturbations, by means of the VARION algorithm, due to the Lamb wave and the regular tsunami.
We report on the reversed amplitude of the two phenomena in the oceans and in the ionosphere. The sea-surface perturbation caused by the Lamb wave was not significant, while ionospheric perturbation was considerable.
In contrast, the regular tsunami waves manuscript reached ~1m around New Caledonia-New Zealand and ~2m along the Chilean coastline; however, the associated ionospheric perturbation was quite small, half the size of the Lamb wave perturbation.

4 Increasing the ionospheric information

Then, the inclusion in the VARION processing of new observations coming from geostationary satellites (GEOs), ship-based GNSS receivers and GNSS dual-frequency smartphones proved how to effectively increase the information available for a denser and more accurate ionospheric monitoring.
To prove the feasibility of TEC estimations coming from GEOs, we evaluated the VARION computed TEC variations coming both from standard GNSS satellites (i.e, satellites placed in Medium Earth Orbit, MEO) and GEOs to analyse the TIDs connected to the 2018 New Caledonia earthquake and tsunami.
The possibility to provide continuous time series, to remove all the geometry effects and to keep the observation noise level constant are among the greatest advantages.
Furthermore, an analysis of ionospheric data from a Xiaomi Mi8 dual-frequency smartphone was carried out. Thanks to the opportunity for Android 7.0+ smartphones to access GNSS raw measurements, it was possible to process GNSS data with VARION. Despite the high level of noise in the measurements, the application of a moving median filtering technique allowed for noise reduction, making it comparable to what is achievable with geodetic class receivers. This first study aims at paving the way for the use of smartphones to increase the amount of available data.
VARION basic principle, i.e., the single time differences of geometry-free combination, allows to leverage observations coming from moving receivers. The receiver motion, hence, does not affect the TEC estimation. Therefore, we demonstrated the VARION feasibility of using ship-based GNSS receivers to detect the TIDs connected to the 2010 Maule earthquake and tsunami. Using GNSS receivers already onboard of ships can represent a cost-effective tool useful to improve already existing TEWS and to densify ionospheric monitoring.

3 Conclusions

In this work, we summarized some of the VARION application in the field of the natural hazard events.
In detail, we described the TVA methodology to simultaneously estimate ground shaking, co-seismic displacements and TEC disturbances, using the same real-time GNSS data stream. In this respect, we demonstrated how TVA can support traditional instruments (e.g., seismometers, accelerometers, buoys and tide gauges) to improve the quick estimation of the tsunami hazard.
We also investigate the oceanic and the ionospheric response to the January 2022 Hunga-Tonga volcanic eruption, showing a reverse response, in terms of associated amplitude, between oceans and ionosphere.
Furthermore, we explored the possibility to increase the amount of available data for a denser ionospheric monitoring, applying VARION also to observations coming from geostationary satellites, from ship-based GNSS receivers and from smartphones.
Finally, we aimed at demonstrating how VARION can be help scientists to better disclose the LAIC mechanisms and also to be a reliable tool for real-time ionospheric monitoring, natural hazards TIDs detection and in the near future a complementary technique to the augmentation of tsunami early warning systems.

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