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On the use of the IRI UP method to assimilate IONORING vTEC data to predict *fo*F2 over Italy for Space Weather alert purposes

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Space Weather events can have a deep negative impact on many technological systems on which our society is nowadays greatly dependent. The damages suffered by these systems, besides leading to very high costs, can also significantly affect human life. This is why in recent years the near real-time specification of the ionosphere has become more and more important to possibly mitigate the adverse consequences of severe Space Weather events.

In the framework of the ATTEMPT (integrATed sysTEm for Multi-hazard from sPace over mediTerranean) project, INGV (Istituto Nazionale di Geofisica e Vulcanologia) aims at realizing a demonstrator of an integrated system capable of collecting multi-parametric space-borne data to monitor different natural hazards, including the ones caused by Space Weather related events. Specifically, one of the project tasks concerns the development of a Space Weather real-time alert system based on *fo*F2 enhancement/depression over the Italian region.

*fo*F2 is the maximum ordinary critical frequency reflected vertically by the ionosphere and is related to the maximum ionospheric electron density. This is one of the most important ionospheric parameters for radio-communication purposes, and is routinely recorded by ground-based ionosondes. However, the current number and distribution of available ionosondes and their common sounding repetition rate, usually set to fifteen minutes, are not enough to predict the distribution of the ionospheric electron density under severe Space Weather events. Conversely, the ever growing number and distribution of ground-based GNSS (global navigation satellite system) receivers streaming data in near real-time allow to obtain very fast and reliable information on the state of the ionosphere through vertical total electron content (vTEC) measurements, i.e., the integral of the electron density from ground to GNSS altitudes.

In the light of this, we developed the IRI UP procedure [1,2] to update the International Reference Ionosphere (IRI) model by assimilating real-time vTEC measurements obtained by IONORING [3] through the RING (Rete INteGrata nazionale) permanent GNSS receivers Italian network (http://ring.gm.ingv.it/). According to this, a mathematical procedure to obtain virtual *fo*F2 values from vTEC measurements has been first developed by using analytical relationships obtained from the study of historical time series of *fo*F2 and vTEC values by co-located ionosonde and GNSS stations. These virtual *fo*F2 values are then used by the IRI UP method to calculate maps of effective values, $IG_{12\text{eff}}$, of the ionospheric index IG_{12}. $IG_{12\text{eff}}$ maps are then ingested by IRI to produce updated *fo*F2 values over the Italian region. Finally, updated *fo*F2 values are compared with median quiet-time values to evaluate off-median enhancements/depressions (i.e., anomalies), possibly related to Space Weather events.

The main steps of this prototypal data-assimilation procedure are here presented and described along with a first example of application and validation.

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2. Pignalberi, A.; Habarulema, J.B.; Pezzopane, M.; Rizzi, R. (2019) On the development of a method for updating an empirical climatological ionospheric model by means of assimilated vTEC measurements from a GNSS receiver network. *Space Weather*, 17, 1131–1164. https://doi.org/10.1029/2019SW002185

3. Cesaroni, C.; Spogli, L.; De Franceschi, G. (2021) IONORING: Real-Time Monitoring of the Total Electron Content over Italy. *Remote Sensing*, 13, 3290. https://doi.org/10.3390/rs13163290