JWG 3: Improved understanding of space weather events and their monitoring by satellite missions

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(Joint with IAG Commission 4, Sub-Commission 4.3)

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Activities during the period 2019-2023

JWG3 aims at gaining a better understanding of space weather events and their effect on Earth's atmosphere and near-Earth environment. In particular, by analyzing the correlation between Space Weather data from different sources (including observations from spacecraft and radio telescopes) and perturbed ionospheric/plasmaspheric conditions derived from different space geodetic techniques (e.g. GNSS, DORIS, RO, VLBI, satellite altimetry) and identifying the main parameters that could be useful to improve their real time determination and their forecasts in extreme conditions.

For this purpose, a multidisciplinary team has been assembled. In fact, the members of the WG provide access to complementary models as well as operational products/services linked to: ionospheric Total Electron Content determination, ionospheric electron density, geomagnetic disturbances from the Sun to Earth, DORIS ionospheric products, TIDs and scintillations, solar flares detection/prediction, EUV flux-rate, CMEs and SEPs, solar corona electron density, dimmings and coronal holes, solar wind, polar depletions, among others. Combination of such measurements and estimates can pave the way for a better understanding of space weather events.

At first, an online survey form to gather feedback from JWG 3 members was carried out to have a better understanding of the complementarity within the team, which was helpful to identify the existing background in both geodetic and space weather domains.

In particular, we identified potential useful data sources to broaden our analysis, as well as the existing models and operational products/services being provided or accessible by the members. Furthermore, applications that could impact positively to end users were listed, complementing the initial considered ones. In addition, it was a way to interchange ideas on the objectives and expectations of what the JWG should be.

At first, a set of three historical representative space weather events were selected. Given these were coincident with the ones selected within JWG 1, we have finally extended the events to be analyzed adding a fourth case which was also considered by JWG 1. Thus, we will analyze storm-related periods in 2013, 2015, 2017 and 2018. Also note that the connection between both joint working groups was considered a key objective from the beginning.

Fig 4: Capture of the online survey form

We are currently working on the correlation between SW products and perturbed ionospheric electron density/Total Electron Content, jointly with JWG 1. In particular, we are compiling and/or generating data and plots from different sources (see few plots below) that could be linked to the selected events useful to understand perturbed conditions and features found within JWG 1 analysis. The possibility to provide insights of these correlations could be helpful for JWG 1 and may also be highlighted through their website and database, as part of the coordination process we are conducting with them. We also keep in mind that for the monitoring and prediction of space weather events and their impact on geodetic measurements, low latency data availability would be of great importance, ideally in real time (RT) or near real time (NRT), also to enable triggering alerts.

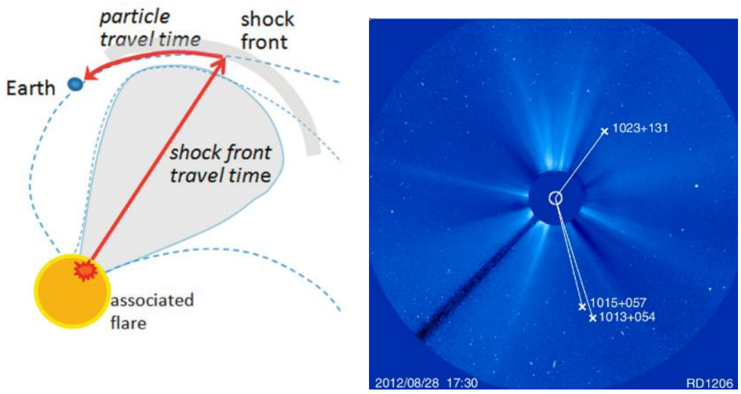

Fig. 5: Left: Shock interaction with the interplanetary magnetic field of SEP events associated to eastern events (Garcia-Rigo et al., 2016). Right: Radio source geometry and coronagraph images for VLBI experiment to assess the electron density of the solar corona (Soja et al., 2014)

The conducted analyses and the combination of measurements and estimates, derived from space geodetic techniques and from solar spacecraft missions, shall lead us to a better understanding of the main parameters that could be useful to improve real time determination as well as predictions derived from geodetic techniques, in case of extreme solar weather conditions. In fact, there is the interest within the team on how well models can reproduce changes during storms, understanding the interactions with the solar wind and magnetosphere, and how correlation of data from different available techniques could be key in this regard.

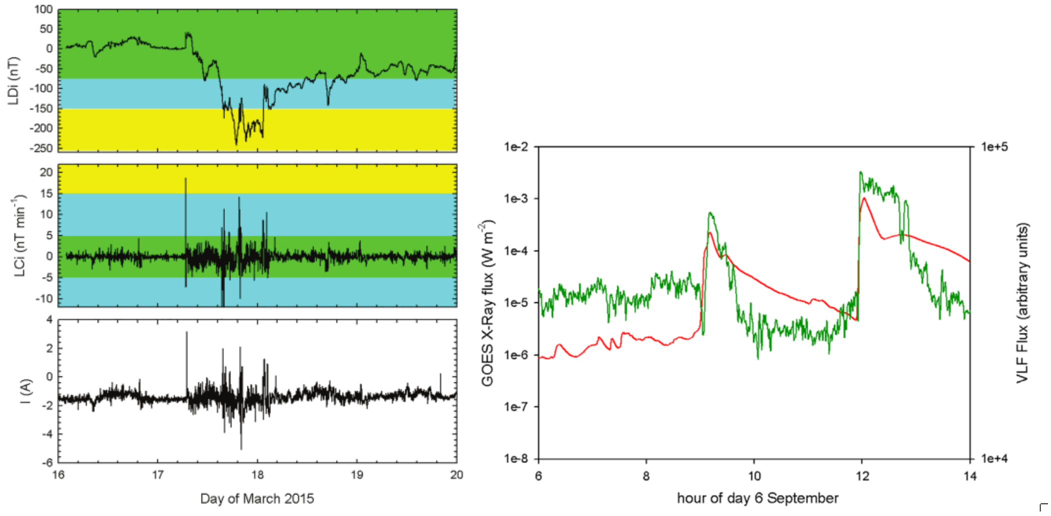

Fig. 6: Left: (from top to bottom) the LDi and LCi geomagnetic indices, and the geomagnetically induced current measured at a substation in the northwest of Spain by REE during the period from 16 to 20 March 2015. Colored areas in panels correspond to the five-level scale introduced to help decision makers in an operational environment (Cid et al., 2020). Right: Superposed plot of the GOES X-ray flux (red) and the amplitude of GQD recorded at UAH receiver (green) from 6 to 14 UT on 6 September 2017 (Guerrero, Cid et al., 2021).

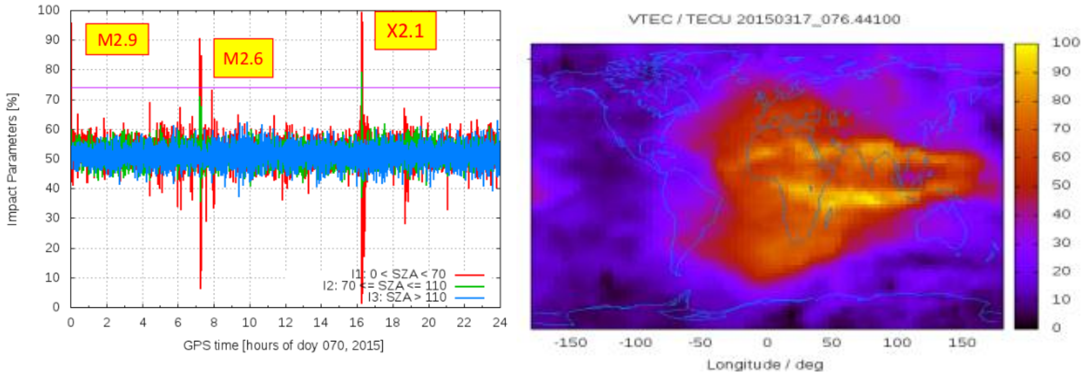

Fig. 7: Left: Detected solar flares prior to St. Patrick's day 2015 Geomagnetic Storm by means of SISTED detector, which relies on GNSS-based ionosphere monitoring (Garcia-Rigo et al., 2017; Borries et al. 2020). Right: UPC-IonSAT ionospheric TEC GIMs perturbed conditions during St. Patrick's day 2015.

In order to foster interdisciplinary cooperation, Session AS52 "Ionospheric Space Weather Monitoring and Forecasting" at AOGS 2023 was convened and 19 abstracts were attracted. Researchers from Geodesy and Space Physics will meet and exchange knowledge during this event.

AOGS 2023 20th Annual Meeting | Session AS52 "Ionospheric Space Weather Monitoring and Forecasting"

The Asia Oceania Geosciences Society (AOGS) 2023, the 20th annual meeting, will take place in **Singapore between 30 July and 04 August 2023**.

The following session is organized: **AS52 - Ionospheric Space Weather Monitoring and Forecasting**

Conveners:

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Session Description:

The Earth's ionosphere is highly variable due to the complex interaction in the solar wind-magnetosphere-ionosphere system, and the atmosphere-mesosphere-ionosphere coupling. It exhibits variation in different time scales and in different forms, e.g. gradients, disturbances, storms, etc. These abnormal or irregular behaviors of the ionosphere can adversely affect satellite navigation and communication systems on which nowadays human activities rely, thus the importance of ionosphere state monitoring and forecasting. Presently more and more observation instruments, networks, and satellite missions are built and launched for a better and deeper understanding of ionospheric climate features and space weather events. Benefiting from these observation plans, whether by state and/or commercial initiatives from different countries or by international collaboration, the impact of the ionosphere on GNSS positioning, telecommunication, and other techniques can be analyzed and evaluated. This session will cover the advancements in ionosphere modeling, forecasting, and validation, both globally and regionally. Analysis of the ionospheric space weather impact on the GNSS application and service is also welcome.

Please visit the conference website https://www.asiaoceania.org/aogs2023/public.asp?page=home.asp and submit your abstract to AS52 session by 14 February 2023.

Fig. 8: AOGS 2023 Session AS52 News released by the PITHIA-NRF project website

Among the fruitful research indicated in the publications, a new 3D ionosphere model based on characterizing shape function is constructed (Lyu et al. 2023), which deepens our understanding of the spatial variability of the ionosphere, thus with better prediction of the ionospheric state. This model will be further refined and shared with the JWG1 for assessment in order to facilitate the collaboration between JWG1 and JWG3.

It is worth mentioning that the newly built Chashan Broadband Solar millimeter spectrometer (CBS) has begun its routine observation from 35 to 40 GHz since 2020 and the first solar flare observation was reported by Yan et al. (2022). The CBS provides a new data source for space weather events and more synergy will be done in the future.

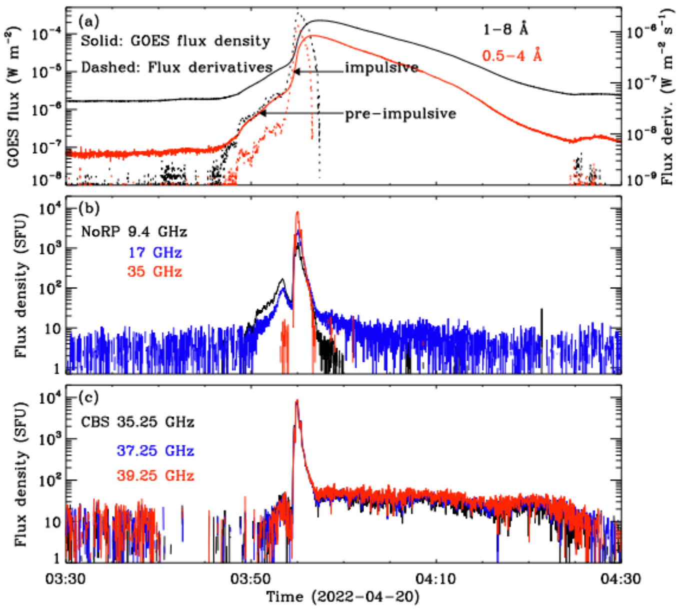

Fig. 9: Overview of the X2.2 flare observed by GOES, NoRP, and CBS on 2022 April 20 (Yan et al., 2022)

In a collaboration between IAG Working Group 4.3.2. “Ionosphere Prediction” and this Joint Working Group, predictions of global ionospheric maps (GIMs) have been investigated. ETH Zurich provided predictions of one-day ahead forecasts that were then compared with those of other institutions. Three different types of predictions were computed, with one of them including data related to space weather and geomagnetic activity (“auxiliary data”). Comparisons of the results for quiet days in terms of ionospheric activity are given in Fig. 10, whereas the results for storm days are depicted in Fig. 11. The model that included auxiliary data did not result in improved predictive performance during quiet days, but delivered the best performance during the storm days.

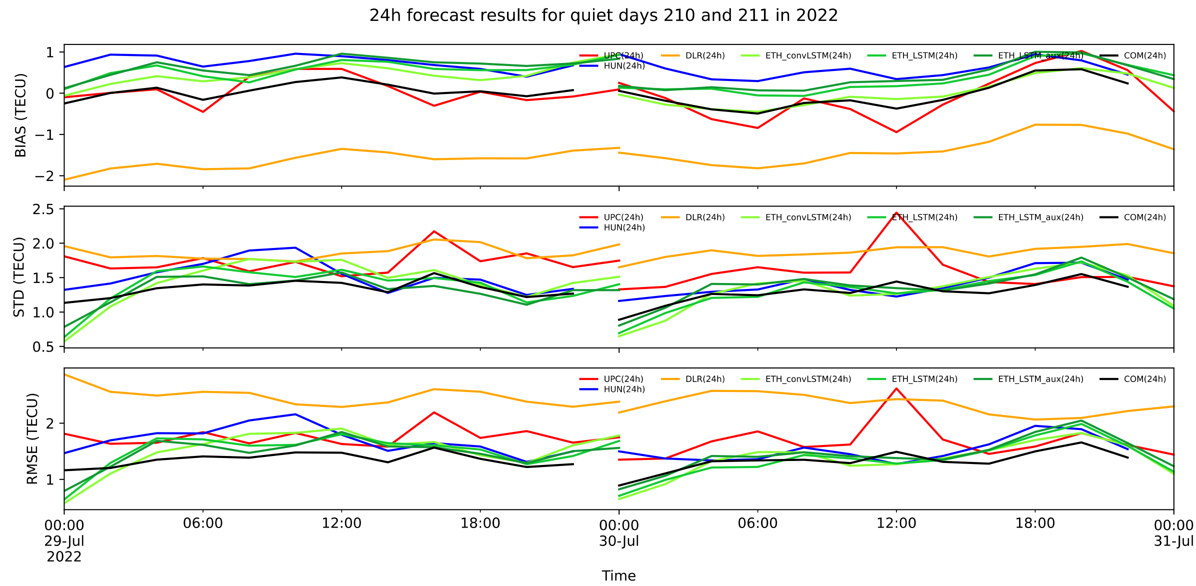

Fig. 10: One day ahead forecast errors of UPC (red), HUN (blue), DLR (orange), ETH models (shades of green; the model with space weather data is in dark green) and COM(black) with respect to IGS final maps on quiet days of 210 and 211 in 2022.

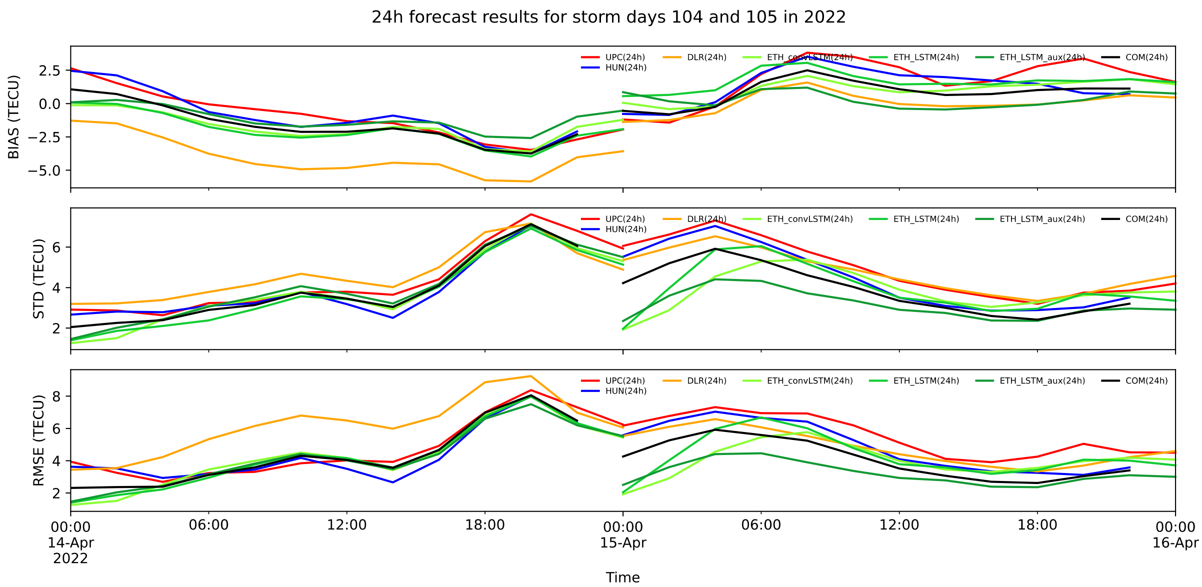

Fig. 11: One day ahead forecast errors of UPC (red), HUN (blue), DLR (orange), ETH models (shades of green; the model with space weather data is in dark green) and COM (black) and COM(black) with respect to IGS final maps on storm days of 104 and 105 in 2022.

In several publications and presentations by Natras et al. (2022a,b,c,d,e,f, 2023), space weather and geomagnetic data were used as input to machine learning models to predict VTEC at different latitudes. As shown in Fig. 12, in certain cases significant feature importance is attributed to the solar and geomagnetic data. This means that they have an impact on the prediction of VTEC. The physical relationship between VTEC and these parameters does not have to be exactly known as the machine learning algorithms learn the relationship between these variables.

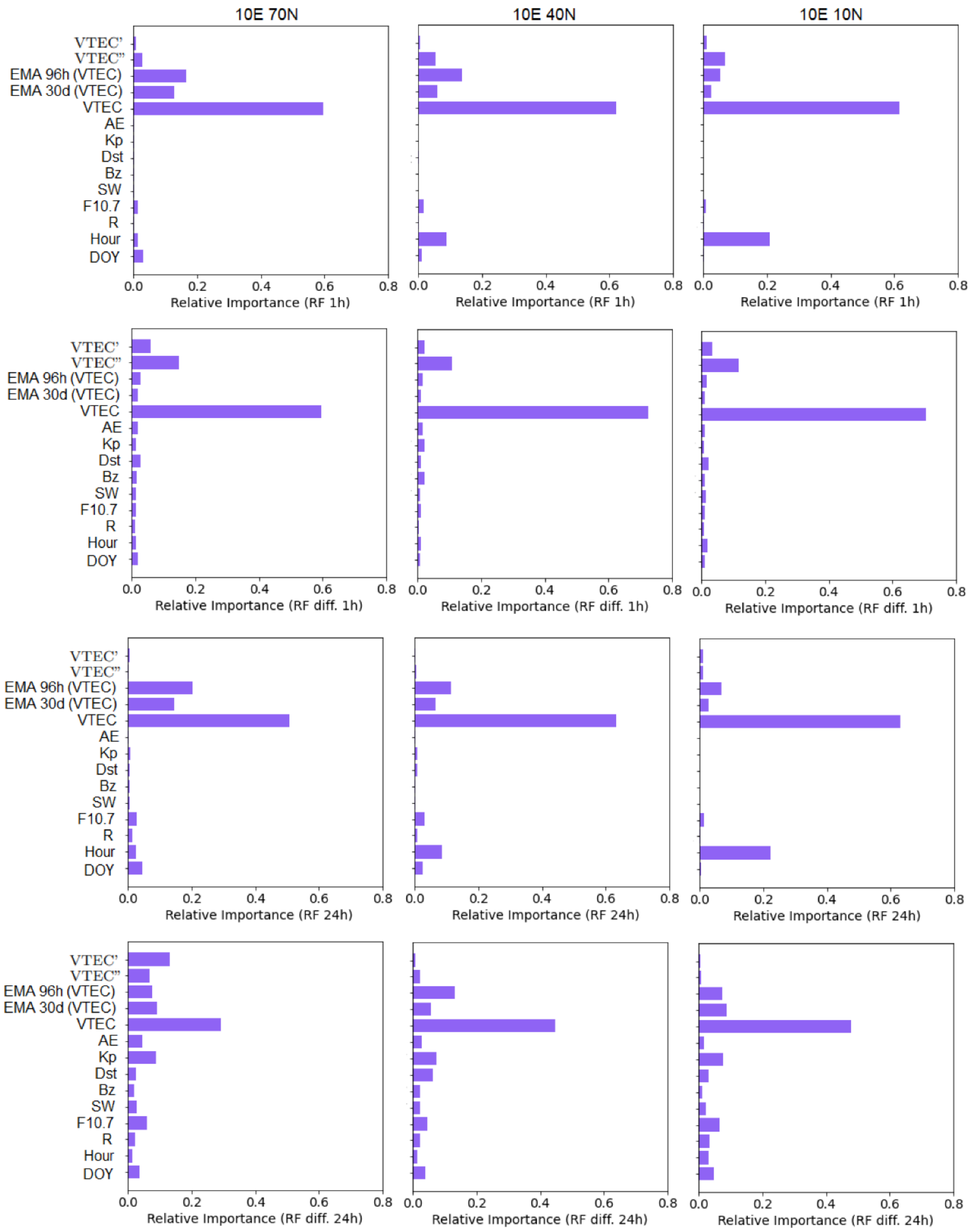

Fig. 12: Relative importance of input variables to VTEC forecast estimated from the Random Forest models. Results are presented for 1 h forecast with non-differenced data (first row) and differenced data (second row), and for 24 h forecast with non-differenced data (third row) and differenced data (fourth row) for high-latitude (left), mid-latitude (middle) and low-latitude (right) VTEC (Natras et al., 2022a).

In Awadaljeed et al. (2022), solar flux data from the Soil Moisture and Ocean Salinity (SMOS) mission was considered for improving predictions of ionospheric VTEC. The inclusion of the highly resolved solar flux data generally had a positive impact on the predictive performance, when included as input to most types of machine learning algorithms (Fig. 13). The work was presented at the "SMOS for Space Weather" workshop organized by ESA and shows how missions that were not originally intended for space weather monitoring can still make an important contribution.

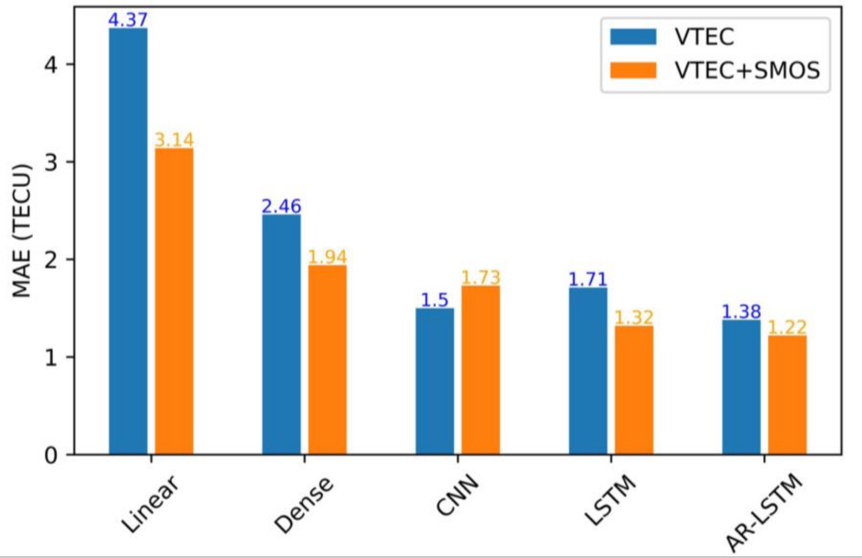

Fig. 13: VTEC prediction errors (in terms of Mean Absolute Error, MAE) of different machine learning algorithms. Blue bars indicate models that have only been trained on VTEC data. Orange bars represent models that include solar flux data from SMOS (Awadeljeed et al., 2022)

Additional next steps include the possibility to conduct extensive simulations, combining different datasets and testing different algorithms, carry out comparisons and validation against external data, as well as deriving impact on end user' applications (such as in the case of HF communications, GNSS positioning and EGNOS performance degradation, influence on ground and space-based infrastructures, etc.).

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