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A Comparative Investigation of Different Ionospheric Models to Predict the MUF Parameter During Severe Geomagnetic Storm on 17th March 2015.

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Abstract

The present work aimed to make a comparative investigation between three different ionospheric models: IRI-2020, ASAPS and VOACAP. The purpose of the comparative study is to investigate the compatibility of predicting the Maximum Usable Frequency parameter (MUF) over mid-latitude region during the severe geomagnetic storm on 17 March 2015. Three stations distributed in the mid-latitudes were selected for study; these are (Athens (23.50° E, 38.00° N), Jeju (124.53° E, 33.6° N) and Pt. Arguello (239.50° W, 34.80° N). The daily MUF outcomes were calculated using the tested models for the three adopted sites, for a span of five-day (the day of the event and two days preceding and following the event day). The calculated datasets were compared for each location with the observed daily MUF values. In general, the findings show that the three investigated models gave good outcomes compared to the observed values for all selected stations. The comparative investigation results of the three tested models corresponding to the observed MUF values during the storm event revealed that the IRI -2020 Model indicate a clear impact of the geomagnetic storm on the predicted MUF values during the day of event. Similarly, for ASAPS Model, the storm's impact is clear on both the day of the event and the subsequent day, in contrast, the VOACAP model showed almost no impact of the geomagnetic storm on the observed MUF values throughout the entire study period for event 17 March 2015.

Keywords: Ionosphere Parameters, Maximum Usable Frequency, ASAPS, IRI-2020, and VOACAP Models.

تحقيق مقارن لنماذج الأيونوسفير المختلفة للتنبؤ بمعامل MUF أثناء العاصفة الجيومغناطيسية الشديدة في 17 مارس 2015

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الخلاصة

يهدف العمل الحالي إلى إجراء دراسة مقارنة بين ثلاثة نماذج أيونوسفيرمختلفة: IRI–2020 و ASAPS و VOACAP. هدفت الدراسة المقارنة إلى التحقيق في مدى توافق التنبؤ بمعامل التردد الأقصى القابل للاستخدام (MUF) فوق منطقة خطوط العرض الوسطى أثناء العاصفة الجيومغناطيسية الشديدة في 17 مارس 2015. لأغراض البحث، تم اختيار ثلاث محطات موزعة على منطقة خطوط العرض الوسطى؛ وهي

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(23.50 شرقًا، 38.00 شمالًا)، جي جو (124.53 شرقًا، 33.6 شمالًا) وبي تي أرجويلو (239.50 غربًا، 34.80 شمالًا). تم إجراء الحسابات اليومية لمعامل التردد الأقصى القابل للاستخدام (MUF) لمدة خمسة أيام (يوم الحدث و واليومين السابقين واللاحقين ليوم الحدث) باستخدام النماذج الثلاثة المختبرة للمحطات الثلاث المعتمدة. تمت مقارنة مجموعات البيانات المحسوبة مع قيم MUF المرصودة لكل موقع من المواقع الثلاثة المختارة . بشكل عام، أظهرت نتائج الدراسة التي أجريت أن النماذج الثلاثة التي تم اختبارها قد أعطت نتائج جيدة مقارنة بالبيانات المرصودة لجميع المحطات المختارة، كشفت نتائج التحقيق المقارن للنماذج الثلاثة المختبرة المقابلة لقيم MUF المرصودة أثناء حدث العاصفة أن نموذج IRI -2020 يشير إلى تأثير واضح للعاصفة المغنطيسية الأرضية على قيم MUF المتوقعة خلال يوم الحدث. وبالمثل، بالنسبة لنموذج ASAPS، حيث يكون تأثير العاصفة واضحًا في كل من يوم الحدث واليوم التالي ، في المقابل، أظهر نموذج VOACAP عدم وجود أي تأثير تقريبًا للعاصفة المغنطيسية الأرضية على قيم MUF المرصودة طوال فترة الدراسة لحدث يوم 2015\3\17.

1. Introduction

The ionosphere is the upper part of the Earth's atmosphere above 50 km, it constitutes less than 1% of the atmosphere mass [1]. By absorbing the incoming solar radiation, the ionosphere is formed in the upper part of the atmosphere and creating the ion-electron pairs [2]. The ionosphere extends from about 50 km to 1000 km, and it merges with near-terrestrial space at its highest limit. Although most of the atmosphere is electrically neutral, it contains an ionosphere that forms as a result of the interaction of solar radiation with atmospheric components. In this process, electrons are departed from atoms and molecules, forming the ionosphere [3]. The structure of the ionosphere is closely related to the electron density [4], which leads to the division of the ionosphere into four layers: D, E and F layers. D layer (60 to 90) km, E and E_S layer (90 to 140) km, F1 and F2 layer (140 to 420) km and topside layer (420 to 1000) km [5] [6]. These layers change during day and night, affecting their ability to refract or reflect electromagnetic waves depending on their frequency. Each layer has the capability to reflect a certain band of frequencies. It is worth noting that high-frequency (HF) radio waves operating in the range of 3-30 MHz are the key of long-distance communication, by reflecting the transmitted HF signals back to the Earth [7]. Ionospheric parameters such as the lowest usable frequency (LUF), optimum workable frequency (OWF), and maximum usable frequency (MUF) can play an important role in defining the operational frequency for HF radio communication between certain terminals. These parameters can be changed due to various factors; electron density being one of the main factors. These parameters increase as the electron density increases and decrease as the ionization density decreases [8]. The aim of this research is to conduct a comparative study of three different ionospheric models (IRI-2020, ASAPS and VOACAP) on the prediction of the MUF parameter in mid-latitudes during the severe geomagnetic storm on 17 March 2015.

2. Maximum Usable Frequency (MUF) Parameter.

The Maximum Usable Frequency, often abbreviated as MUF, holds significance as an essential ionospheric parameter. It determines the highest frequency that can rely on in high-frequency (HF) radio communication between two terminals over long distances due to ionospheric refraction. It plays an important role in determining the workable frequencies for long-range radio communications [9]. Long-term observations have revealed that changes in the ionosphere exhibit a stochastic nature, making it challenging to predict variations in all ionospheric parameters [10]. This parameter is subject to major influences, with ionization density being the main factor. It follows that higher ionization density causes an increase in these parameters, while lower ionization density results in a decrease [11]. There exist two distinct definitions for "MUF" The International Telecommunications Union ITU-R has put forth these definitions: Operational MUF, often referred to as just MUF, signifies the highest frequency at which acceptable operation of a radio service between specified terminals at specified time, considering particular working conditions. Basic MUF, on the other hand, MUF represents the highest frequency at which radio waves propagate through the ionosphere between specific terminals, regardless of power [12]. Therefore, frequencies above the MUF tend to penetrate the ionosphere and continue into space, while frequencies below the MUF tend to refract within the ionosphere and return to Earth's surface [2]. Numerous studies have examined the variability of ionospheric parameters during the geomagnetic storm including, C. Mudzingwa and A. Chawanda, 2018 [13], J. Niu, et al., 2019 [14], Persai, S.K. et al., 2019 [15], A. A. Hamied and K. A. Hadi, 2021 [1].

3. Geomagnetic Storm

A geomagnetic storm refers to a substantial disturbance in the Earth's magnetosphere, occurring when energy from the solar wind is efficiently transferred into the surrounding space environment. These storms are brought on by fluctuations in the solar wind, causing significant changes in the plasmas, currents, and fields within the Earth's magnetosphere [16]. There are many geomagnetic indices, some of which are: (Dst) which represents the intensity of a geomagnetic storm, (AE) characterizes auroral Electrojet activity and (PC) describes geomagnetic activity on Polar Caps [17,18]. The intensity of geomagnetic storms is measured using the Disturbance Storm Time (Dst) index. This index has been expressed in nano Tesla (nT) which has been derived from average value of horizontal component of the magnetic field of the Earth’s and measured in an hour-by-hour basis at a 4 near equatorial geomagnetic observatories network. According to the Dst value, geomagnetic storms can be divided into the following categories: weak (Dst < -20 nT), medium (Dst < -50 nT), strong (Dst < -100 nT), strong (Dst < -200 nT)) and Great (Dst < -320 nT) [19].

4. International Ionospheric Models

In this study, three international models, namely the Advanced Stand-Alone Prediction System (ASAPS6), the International Reference Ionosphere (IRI-2020), and the Voice of America Ionospheric Communication Analysis and Prediction (VOACAP) model were chosen to assess their accuracy in predicting the ionospheric Maximum Usable Frequency (MUF) parameter generated using these adopted models [20]. Monthly averages of critical F2 layer frequency within 50-1500 km altitude range in the ionosphere are estimated by the IRI model [21]. ASAPS specializes in forecasting the performance of sky-wave communication systems within the High-Frequency (HF) radio spectrum (1 to 30 MHz) [22]. Meanwhile, the Voice of America Coverage Analysis Program (VOACAP) lies in it is ability to predict how high-frequency (HF) broadcast systems, proving valuable for planning and operating HF transmissions across different seasons [23].

5. Test and Results

In this research, a comparative analysis to examine compatibility of the ASAPS, IRI-2020, and VOACAP models of predicting the ionospheric Maximum Usable Frequency (MUF) parameter during a severe geomagnetic storm on 17 March 2015. The investigation involved evaluating the compatibility of the predictions made by these three models for three distinct stations. the geographical coordinates and locations of these stations were documented in Table (1) and visually represented in Figure (1).

Table 1: Distribute geographical coordinates of selected sites

#	Station Name	Country	Geo. Location	
			Lat. (N)	long. (E)
1	Athens	Greece	38	23.5
2	Je Ju	South Korea	33.43	126.3
3	Pt. Arguello	USA	34.8	353.3
				-6.73

The implementation of the IRI-2020 and VOACAP models necessitates the utilization of multiple input parameters, one of which is the daily sunspot number (SSN) for the event. On the other hand, the ASAPS model requires the daily T-index of the geomagnetic storm event as input. In this study, the daily sunspot numbers and T-index were employed to compute the daily alterations in the maximum usable frequency.
Table (1) provides the daily values of the sunspot numbers and T-index for the event day, as well as the two days preceding and succeeding the event, which were adopted for the study.

Table 2: Daily Sunspot Numbers (SSN) and T-index during the storm event

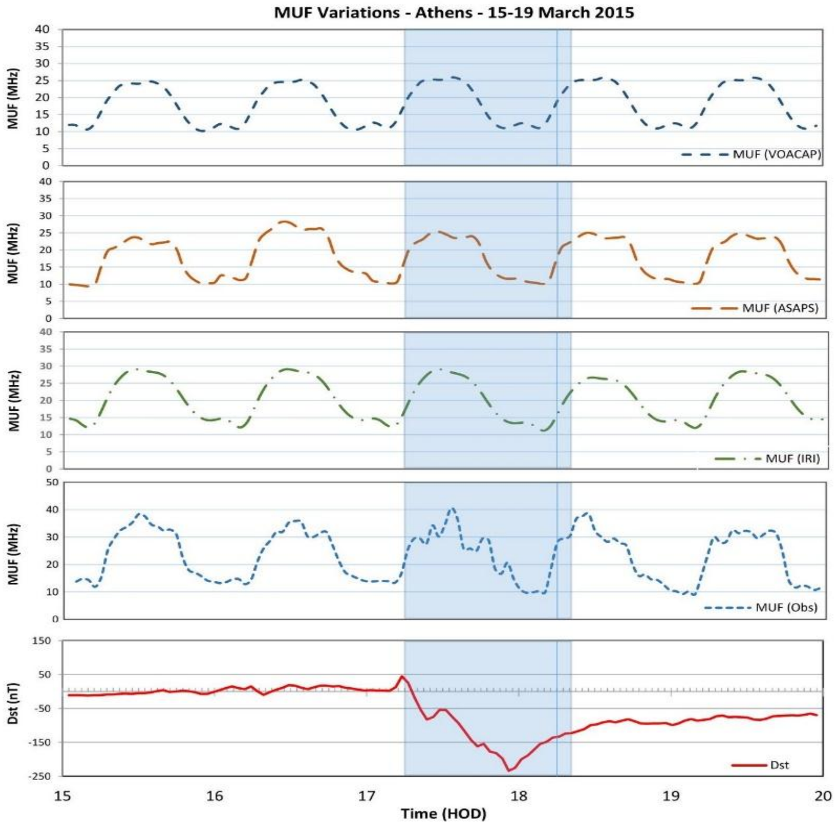
Date	SSN	T-index
15-March	11	101
16-March	15	101
17-March	22	84
18-March	20	25
19-March	19	91

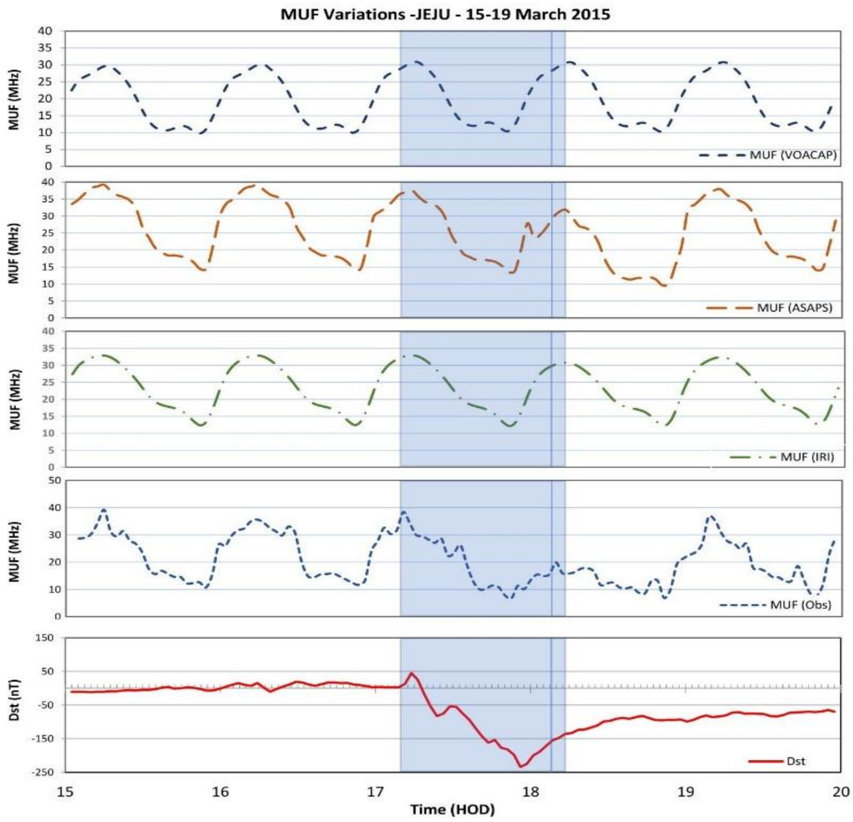
The MUF outcomes were computed directly using ASAPS and VOACAP models, whereas the calculations of IRI-2020 model was involved converting the ionospheric critical frequency (foF2) values into a MUF-values. This conversion for the IRI-2020 outcomes were made using the following equation [21].

$$MUF = \frac{\sqrt{1-\left(\frac{R}{R+h}\right)^2}}{f_{\circ}F_2}$$

The radius of the earth, denoted by (R=6372 km), ionosphere height (h) (typically 400 km for F2 ionosphere), critical frequency (f_o), and maximum usable frequency (MUF).

The generated MUF values for the three different stations from the IRI-2020, ASAPS and VOACAP test models were contrasted to the observed data over a five-day interval the day of event and two days before and after the event day. This period corresponds to the severe geomagnetic storm that occurred on 17 March 2015. Daily calculations of the maximum usable frequency parameter (theoretical) were conducted for the chosen sites utilizing the available observational data during the study duration. Figure 2 displays the outcomes depicting the day-to-day variations in the MUF ionospheric parameter. A comparison was made between the calculated values and the observed data along with the DST values all corresponding to the same time period.





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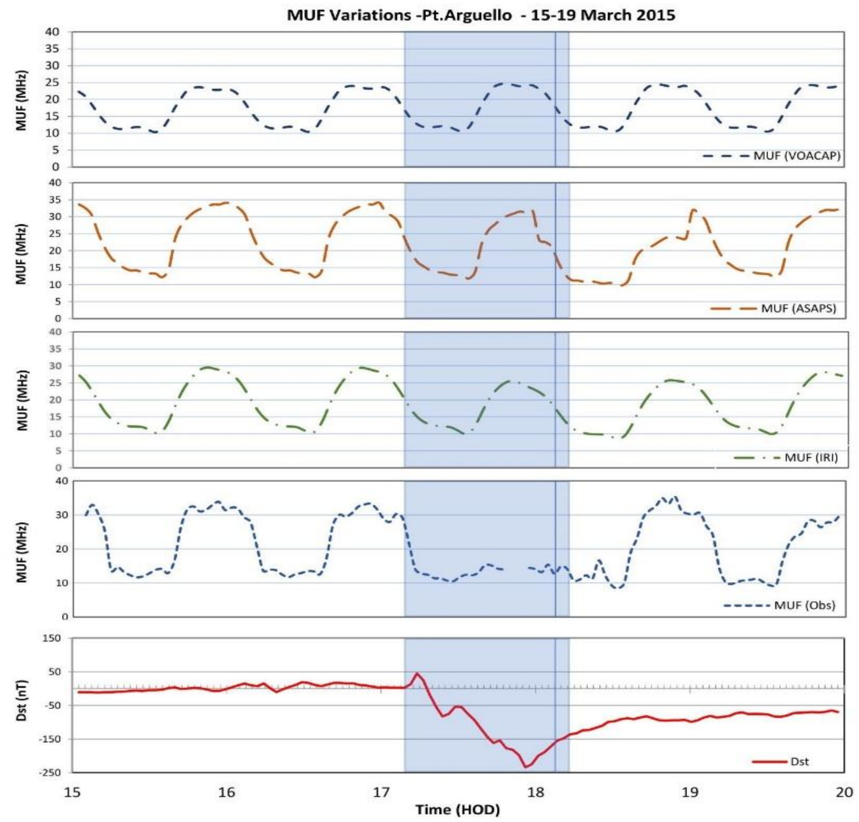
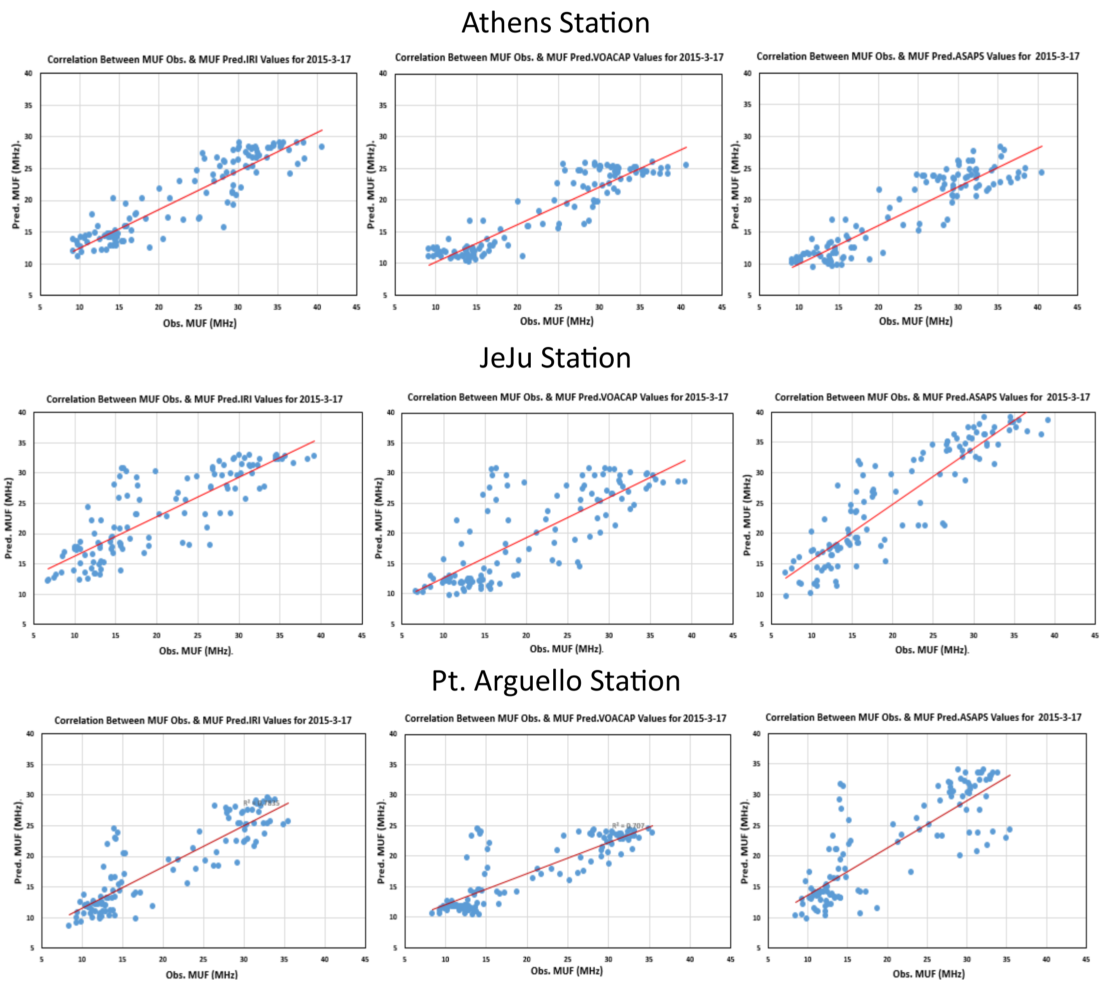


Figure 2: Variations of the predicted MUF values generated using the three tested models for Athens, Jeju and Pt. Arguello stations correspond to the observed MUF and Dst-index values during the storm event time.

Based on the results illustrated in Figure 2, for Athens station, we can notice that the results of IRI model showed that the effect of the selected geomagnetic storm (Severe) was on the day following the event causing a reduction in the predicted MUF values comparing with the observed MUF values. Conversely, the ASAPS model demonstrates that the effect of the geomagnetic storm indicates an opposite impact for the day preceding the day of the event through an increase of the predicted MUF values compared to the observed one. The impact of geomagnetic storms on the MUF outcomes predicted by the VOACAP model showed almost no impact during the entire study period. As for Jeju station, prediction results of IRI Model indicate a clear impact of the geomagnetic storm on the predicted MUF values during the day of event. Similarly, for ASAPS Model, the storm's impact is clear on both the day of the event and the subsequent day, caused a decrease in the predicted MUF values compared to the observed values. In contrast, the VOACAP model's predicted MUF values remain relatively unchanged across all tested days compared to the observed values. For the third station (Pt. Arguello), the results of IRI model showed that there is a distinct decline in the predicted MUF values during the storm event day compared to the observed values of the station. While for ASAPS model, a slight impact is evident on the predicted MUF values during the event day, with a noticeable dip occurring on the day following the event. For VOACAP model, no significant impact of the geomagnetic storm on the predicted MUF values was observed comparing to the observed MUF values during the entire testing period.

In this work, the statistical-correlation between the predicted and observed ionospheric MUF outcomes generated using IRI-2020, VOACAP and ASAPS models were examined. Figure 3 shows the examination findings of the correlation between the observed and predicted MUF values for the three tested stations (Athens, JeJu and Pt. Arguello).



Figures 3: Statistical-correlation between the predicted and observed MUF outcomes generated by the IRI-2020, VOACAP and ASAPS models at three test stations (Athens, Jeju, and Pt. Arguello) during the 17 March 2015 storm event.

In this research, statistical calculations were also performed for the observed and predicted MUF datasets generated using IRI-2020, VOACAP and ASAPS models. The calculations were carried out using various statistical techniques, including the Normalized Root Mean Square Error (NRMSE), Determination Coefficient (R^2), Correlation Coefficient (R), Mean Difference (Mean Diff.) and Mean Deviation (MD) statistical methods. Table 3 demonstrate samples of the outcomes of the conducted statistical methods for the three tested stations during geomagnetic storm event on 17 March 2015.

Table 3 Samples of statistical-calculation outcomes between the observed and predicted MUF datasets for Athens, Jeju and Pt. Arguello stations during Severe geomagnetic storm on 17 March 2015.

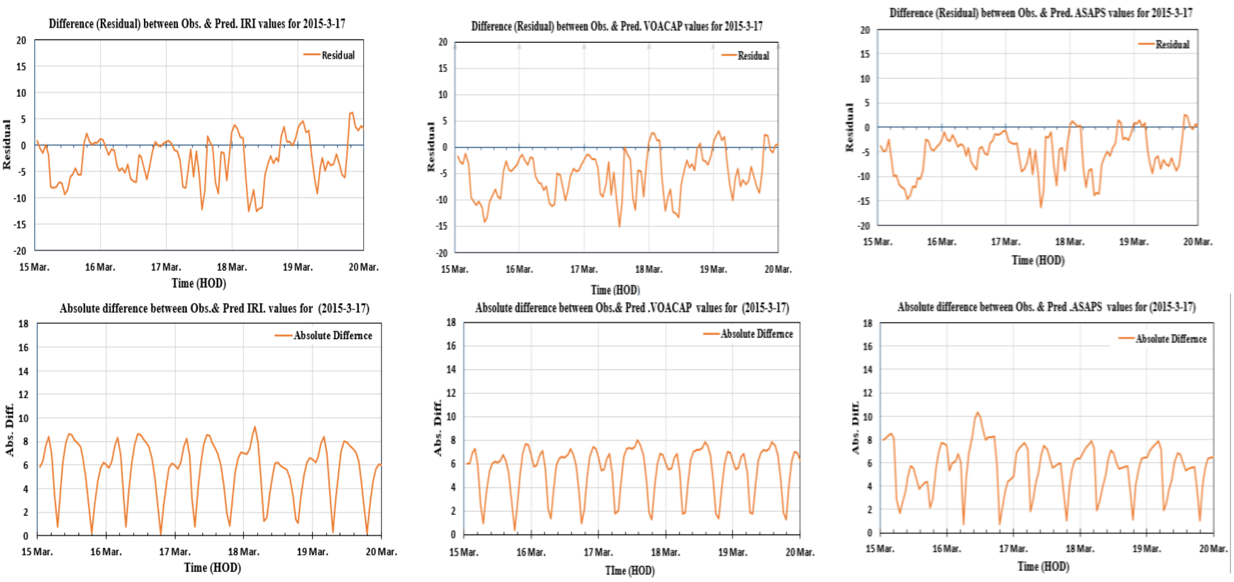
	Athens Station		
Statistical Method	**IRI**	**VOACAP**	**ASAPS**
NRMSE	0.217	0.288	0.290
Det. Coeff. (R^2)	0.843	0.859	0.843
Corr. Coeff. (R)	0.918	0.927	0.918
Mean Diff.	0.169	0.239	0.234
NMAE.	0.217	0.288	0.290

	JeJu Station		
Statistical Method	**IRI**	**VOACAP**	**ASAPS**
NRMSE	0.271	0.271	0.306
Det. Coeff. (R^2)	0.693	0.606	0.805
Corr. Coeff. (R)	0.832	0.779	0.897
Mean Diff.	0.213	0.211	0.258
NMAE.	0.271	0.271	0.306

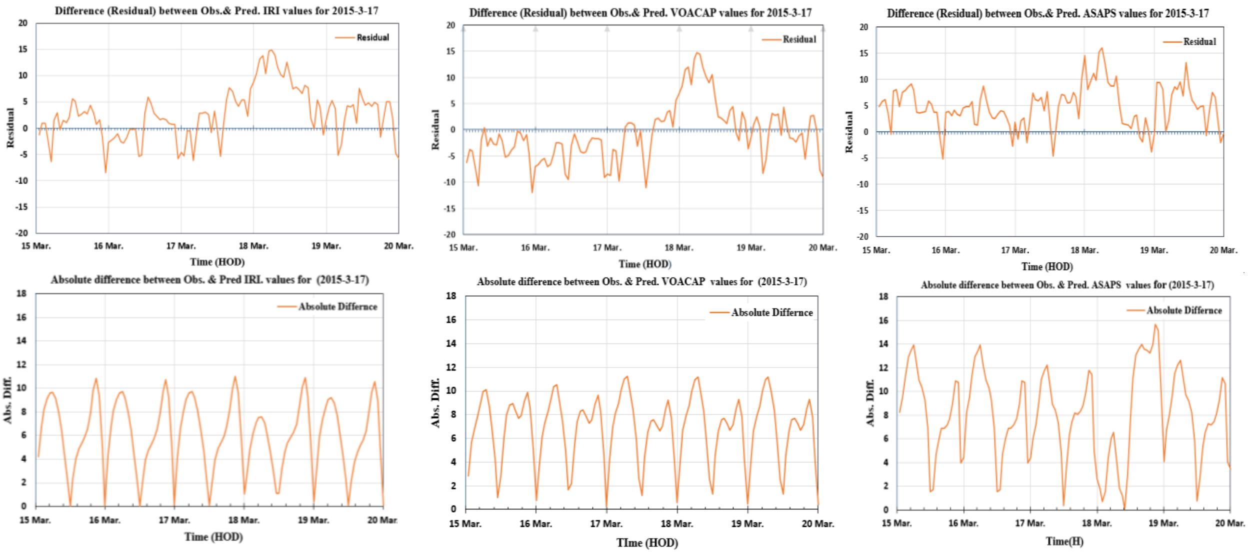
	Pt. Arguello Station		
Statistical Method	**IRI**	**VOACAP**	**ASAPS**
NRMSE	0.298	0.347	0.348
Det. Coeff. (R^2)	0.783	0.707	0.689
Corr. Coeff. (R)	0.885	0.841	0.830
Mean Diff.	0.203	0.262	0.216
NMAE.	0.298	0.347	0.348

As well as, the statistical analysis outcomes encompassing residuals and absolute differences methods between the predicted and observed MUF datasets for the three stations during the day of event (hour of the day (HOD)) were shown in Figure 4.

Athens-Station



Jeju-Station



Pt. Arguello –Station

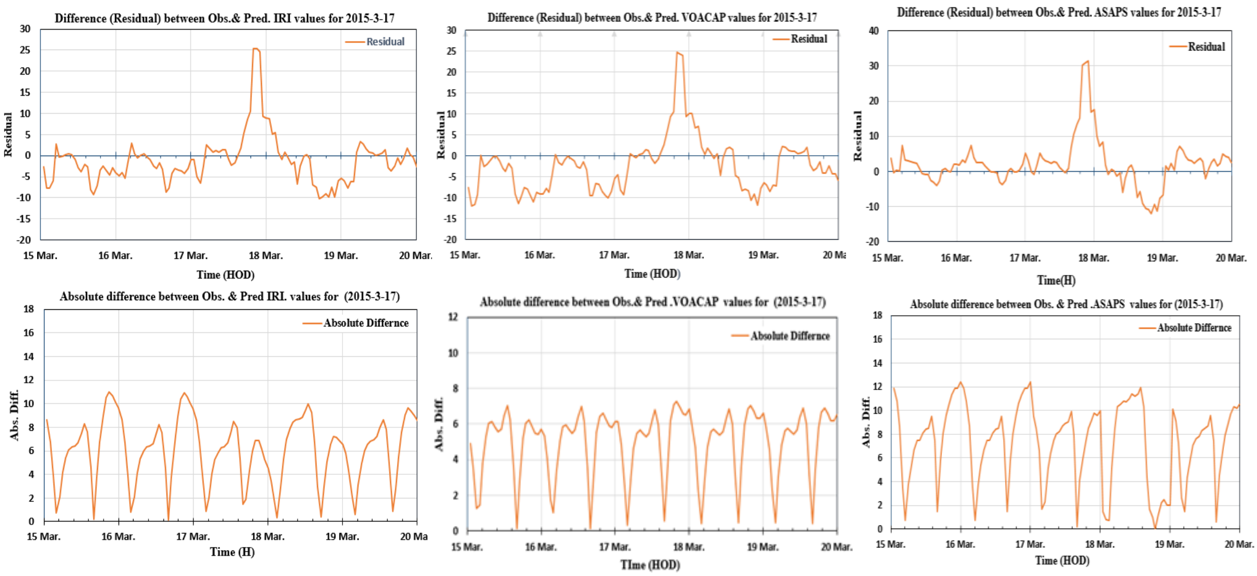


Figure 4: Statistical analysis results for the Difference (Residual) and Absolute Difference statistical methods between predicted and observed MUF outcomes using IRI, VOACAP, and ASAPS models for Athens, Jeju, and Pt. Arguello locations during geomagnetic storm event.

Based on the calculation outcomes of the statistical-correlations between predicted and observed MUF values generated using IRI-2020, VOACAP and ASAPS models, as well as the outcomes of the conducted statistical methods (mainly, the coefficient of determination (R2) and the correlation coefficient (R)) performed for the three tested stations during 17 March 2015 geomagnetic storm event, which illustrated in Figure 3 and Table 3, respectively, the predicted ionosphere parameter values for Athens station using VOACAP model showed relatively a better and closer results with observed data than those results generated using the IRI-2020 and ASAPs models. Conversely, at Jeju station, the ASAPS model demonstrated better results than IRI-2020 model and VOACAP model. Whereas the correlation results of Pt. Arguello station showed that the IRI-2020 model gave better result compared to the outcomes generated using VOACAP and ASAPS models during the Severe geomagnetic storm. Also, according to the statistical analysis results for the difference (residual) statistical methods between observed and predicted MUF values that illustrated in Figure 4, the predicted ionosphere parameter values for Athens station using IRI-2020 model exhibited a slightly better results compared to the predictions calculated using VOACAP and ASAPS models. Similarly, for Jeju station, the IRI-2020 model showed better results than the other two models, but conversely, for Pt. Arguello station, ASAPS model presented better results compared to those obtained from the IRI-2020 and VOACAP models. It's worth noting that in Figure 4, for all stations (Athens, Jeju and pt. Arguello), the difference (residual) statistical method between observed and predicted MUF values exhibits a significant peak on the day right after the geomagnetic storm (18 March 2015). This peak is attributed to the impact of the geomagnetic storm. Furthermore, the absolute difference statistical methods, depicted in Figure 4, showed that the ionospheric parameter outcomes for Athens station predicted using VOACAP model were relatively better than those produced by the IRI-2020 and ASAPs models. While, for Jeju and Pt. Arguello stations, the IRI-2020 model exhibited better results than both VOACAP and ASAPS models.

6. Conclusions

According to the findings that were achieved and the discussion that was conducted, several key points can be concluded as follows:

- In general, the study's findings indicate that the three models tested gave good outcomes for all three adopted stations compared to the observed data along the whole study period.
- The finding of a comparative investigation study of the three tested models corresponding to the observed MUF values during the storm event revealed that the IRI Model indicate a clear impact of the geomagnetic storm on the predicted MUF values during the day of event. Similarly, for ASAPS Model, the storm's impact is clear on both the day of the event and the subsequent day, in contrast, the VOACAP model showed almost no impact of the geomagnetic storm on the observed MUF values throughout the entire study period.
- The calculation results of the statistical determination and correlation coefficients showed that the three tested models displayed variable results for each of the selected stations.
- The calculations of the difference (residual) statistical method showed that the IRI-2020 model exhibited better variance than the other models compared to the observed values for Athens and Jeju stations, except for Pt. Arguello station, which revealed, ASAPS-model performs better behavior and is closer to the observed values than the other models.
- The absolute difference statistical method showed that the IRI-2020 model showed better results than VOACAP and ASAPS models in Jeju and Pt. Arguello stations, whereas VOACAP model showed relatively better results than the other two models in Athens station.

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