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# The *foF2* depression over pameungpeuk during solar minimum and its application on HF radio communication

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Abstract — The ionospheric *foF2* depression is a reference for determining the maximum usable frequency depression for an HF communication circuit, which usually occurs several hours after a geomagnetic storm. This paper discusses the *foF2* depression observed at the Pameungpeuk (7.65°S, 107.96°E; inclination 32.38°S) from 2018 to 2021, when solar activity is minimum. The result shows that even though the solar activity is minimal, the *foF2* depression still occurs to *Severe*. Likewise, geomagnetic disturbances also occur to a *Moderate* level, so geomagnetic disturbances should be suspected as one of the causes of the *foF2* depression. Other results suggest that the temporal variation of the occurrence of *foF2* depression is unclear, and consequently, statistical models cannot be constructed for its occurrence. The correlation between the number of monthly occurrences of *foF2* depression and the number of geomagnetic disturbances is relatively weak. There were several months without geomagnetic disturbances, but *foF2* depression still occurred. This indicates that the geomagnetic disturbance is not the only cause of *foF2* depression. Another possibility, the cause of the *foF2* depression, is a solar eclipse. The prediction of the *foF2* depression that will occur can be used in HF frequency management, such that the ionosphere supports selected frequency during operation. The level of solar activity and geomagnetic disturbances can be used as inputs in predicting the *foF2* depression.

Keywords – *foF2* depression, maximum usable frequency, geomagnetic disturbances, frequency management, ionospheric layer



## I. INTRODUCTION

The critical frequency of the ionosphere layer (*foF2*) is the highest frequency of radio waves that the ionosphere layer can reflect in the vertical direction of propagation. The ionosphere is a part of outer space that occupies about 60 km to 1000 km above the Earth's surface. The ionosphere layer contains charged particles that cause the reflection and refraction of radio waves that propagate through it. Radio waves in the HF band (High Frequency: 3 – 30 MHz) that propagate through this layer will be reflected, while waves in the VHF (Very High Frequency: 30 – 300 MHz) band and UHF (Ultra High Frequency: 300 – 3000 MHz) band will be refracted. Regarding that ability, the ionosphere has been used as a medium for reflecting radio waves in HF radio communications for a long time. Therefore, *foF2* becomes important information, and it is an indicator of the reflectivity of the ionosphere layer.

The ionosphere is a dynamic layer, so the *foF2* is always changing. The decreasing of *foF2* (*foF2* depression) will fail the reflection of HF radio waves by the ionosphere layer so that HF radio communication will be disrupted. The *foF2* depression is an indicator of the ionospheric storm. The ionospheric storm is one of the space weather information that has been established by the (International Civil Aviation Organization) as one of the information/ advisory for air navigation purposes [1].

Meteorological services for aviation require information about the timing of ionospheric storms [2], so a method is needed to estimate the time of occurrence of ionospheric storms and the level of disruption of HF radio communications used for air navigation. The method to predict ionospheric storms has been developed, but it still needs to be developed further. An example is an IRI2016 model [3], a collaboration between NASA and the National Science Foundation. In particular, for the ionosphere above Indonesia, ionospheric storms have not been widely carried out, and the model has not been developed. Therefore, it is necessary to conduct a research series n foF2 depression and develop the models to predict the ionospheric storm. One of these series is research on *foF2* depression over the Pameungpeuk station (7.65°S, 107.96°E; inclination 32, 38°S) needs to be done, which is one of the stations of the ionosphere observation network in Indonesia.

This research aims to understand the behavior of the occurrence of *foF2* depression over Pameungpeuk during minimum solar activity (2018-2021), which is important to answer the following questions:

a. Does *foF2* depression also occur during minimum solar activity?

b. Does the temporal variation of *foF2* depression have a clear pattern?

c. Does the *foF2* depression correlate with geomagnetic disturbances, the geomagnetic level disturbance can be used as an indicator of the occurrence of *foF2* depression?

d. How is the application of *foF2* depression information to optimize HF radio communication operations?

This paper was organized as follows. In section 2, we try to explain the *foF2* depression and MUF, also, illustrate ionosphere observations. Then, there will be some explanation about ionogram, geomagnetic storm level, and index of *Dst*. In section 3, we described the measurement results, and we discussed each resulting graphic of *foF2* depression, geomagnetic disturbance, and the correlation between them. Finally, in section 5, the conclusion will be given.

## II. RESEARCH METHOD

### A. foF2 depression and MUF

Depression *foF2* is derived from the ratio $(r)$ of *foF2* to the monthly median value at a certain time. If the value of $r$ is less than 1, then *foF2* is depressed, and otherwise, there is no depression. The *foF2* depression indicates ionospheric storm events, which is one of space weather information.

$$r_j = \frac{foF2_j}{< foF2_j >} \tag{2}$$

Maximum Usable Frequency (MUF) is the highest frequency of HF radio waves reflected by the ionosphere layer such that HF radio communication between Tx and Rx stations is opened. The formulation for MUF is as follows [4].

$R_B$ is the radius of the Earth, and $d$ is the distance between Tx and Rx, while $h$ is the height of the ionosphere layer, reflecting HF radio waves. The unit of MUF and *foF2* is in MHz, $R_B$, *d*, and *h* are in kilometers.

Based on (1), if *foF2* is depressed by $r$ value, then MUF will be depressed by the same value. Therefore, the ratio r can be used as an indicator of MUF depression.

A geomagnetic storm is a condition when there is a strong disturbance to the Earth's magnetic field, which responds to the high energy flux carried by the solar wind. Geomagnetic storms cause changes in charged particle composition in the ionosphere, which changes the electron density in that layer. Changes in the electron density of the ionosphere layer will cause changes in the *foF2* and MUF values. In addition, geomagnetic storms also induce electric currents in the ionosphere. This change in electric current will also affect the ionization in the ionosphere layer and will change the values of *foF2* and MUF.

Geomagnetic storms are associated with the *foF2* depression. In general, during the main and recovery phases of geomagnetic storms, the *foF2* depression is more intense, has a longer duration, and covers a large area [2]. So, geomagnetic storms will result in changes in ionization in the ionosphere layer and changes in the reflectivity of the layer.

### B. Ionosphere Observations

Ionosphere was observed at the Pameungpeuk observation station (7.65°S, 107.96°E; inclination 32.38°S) using HF radar or CADI (Canadian Advanced Digital Ionosonde) ionosonde. This ionosonde transmits radio wave signals from a frequency of about 2 MHz to 22 MHz in a vertical direction and receives signals reflected by the ionosphere layer. Observations or sounding are done every 15 minutes for 24 hours continuously.

In every observation (sounding), we obtained one ionogram (Fig. 1), an image of the ionospheric traces in a plane with the horizontal axis representing the frequency in the MHz unit. The vertical axis is virtual height in kilometers. The ionogram obtained is then interpreted by a scaling process, a dedicated method based on the UAG-23A Report [5]. One of the parameters resulting from the scaling is the value of *foF2*. In one month of observation, we obtain a median value of *foF2* $(< foF2_j >)$ for a certain time, for example for 12:15 WIB. Then, the median $< foF2_j >$ is used to determine the ratio between *foF2* and $< foF2_j >$ observed each value of *foF2* for 24 hours using equation (2).

$$MUF = foF2 \frac{\sqrt{\frac{1}{4}\left(2R_B \sin\left(\frac{d}{2R_B}\right)\right)^2 + \left(h + \left(1 - \cos\left(\frac{d}{2R_B}\right)\right) R_B\right)^2}}{h + \left(1 - \cos\left(\frac{d}{2R_B}\right)\right) R_B} \tag{1}$$

Where $r_j$ is ratio of $foF2_j$ to the monthly median value, for an hour of *j*.

Based on the value of $r_j$, then we determined the level of depression *foF2* refers to ICAO provisions, namely the ***Moderate*** (MOD) level if $0.5 \leq r_j \leq 0.7$ and the ***Severe*** (SEV) level if $r_j \leq 0.5$ . The number of foF2 depression events for each level can be calculated in one day observation. Because observations were made every 15 minutes, one depression event could be considered the representation of 15-minute time frame.

The ionospheric data used results from observations from January 2018 until December 2021, when solar activity is low, as seen in Figure 2.

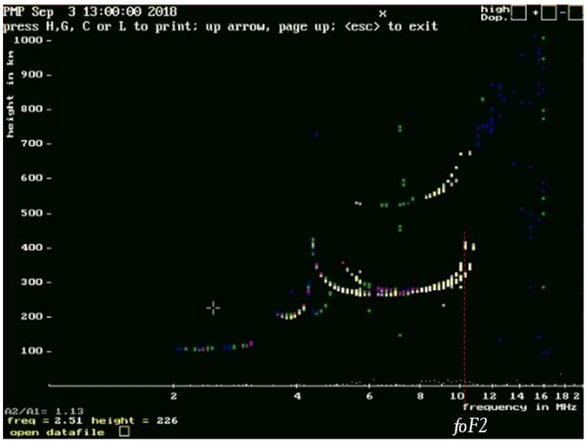



Fig.1. Example of an ionogram observed using CADI ionosonde at Pameungpeuk station, September 3, 208, at 13.00 WIB

Geomagnetic storms can be identified using several indices. One of them is the *Dst* (*disturbance storm time*), which is determined based on the results of the network observatory of the Earth's magnetic field at low latitudes near the geomagnetic equator. $Dst$ is an index of the disturbance of the Earth's magnetic field in the equatorial region, which is derived from the hourly variation of the horizontal magnetic field.

The geomagnetic storm level was determined by using the hourly *Dst* index and the level division, as shown in Table 1. This level division is used for the SWIFTS information service (http://swifts.sains.lapan.go.id/).

Table 1. The level of geomagnetic disturbance and the range of *Dst* index values used in the SWIFtS service.

| Level of Disturbance | *DST* Index in Nano Tesla (nT) |
|---|---|
| Quiet | -25.4 nT < $Dst$ |
| *Active* | -44.9 nT < $Dst$ < -25.4 nT |
| *Minor* | -79.2 nT < $Dst$ < -44.9 nT |
| Moderate | -139.6 nT < $Dst$ < -79.2 nT |
| Major | -245.9 nT < *Dst* < -139.6 nT |
| Severe | $Dst$ < -245.9 nT |

Many previous studies [6]–[8] show that the geomagnetic disturbance index causes a decrease in *foF2*. So, the *Dst* index can be used to indicate *foF2* Depression. Therefore, the next step is to calculate the correlation between the occurrence of *foF2* depression, $r_j$ , with $Dst$ index. If the correlation between the two is strong or very strong, then a statistical model can be developed and used to predict the occurrence of *foF2* depression. On the other hand, if the correlation is weak, then statistical models cannot be used, and it needs another model such as artificial neural networks, machine learning, or others. In this research, the *Dst* were obtained from the World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/kp/index.html ).

## III. RESULT & DISCUSSION

### A. *foF2 Depression Events*

As shown in Figure 2, solar activity during 2018-2021 is quiet, with solar flux values at a wave length of 10.7 cm (F10.7), which are between 60 and 100 s.f.u. (*solar flux unit*). Even though solar activity is quiet, the observations still obtained *foF2* depression data for as much as 38% of the total observations. Number of *foF2* depression level *Moderate* (0.5 < $r_j$ < 0.7) per year from 2018 to 2021 were 918, 1128, 1147, and 1031 events, respectively, and the total number was 4187 events (approximately 3% of total observations). The number of *foF2* depression events is *Severe* ($r_j$ < 0.5) level were 19, 17, 19, and 6 events, respectively, or the total number to 61 events (0.04% of total observations).

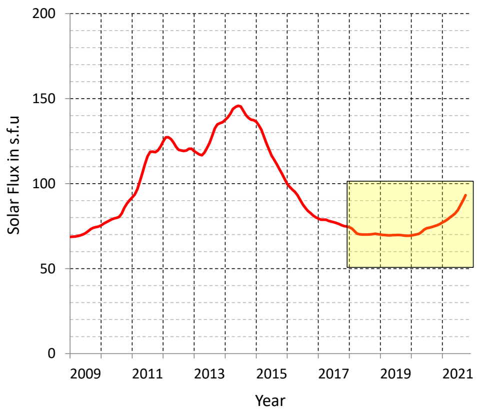



Fig.2. The monthly average value of the 10.7 cm solar flux (F10.7) during cycle 24 (2009-2021), which shows that in the 2018-2021, solar activity is quiet (Source: https://spaceweather.gc.ca/forecast-prevision/ solar-Solaire/solar flux)

Events of *foF2* depression per month during the observation period are shown in Figure 3. Based on the months with *foF2* depression occurrences, it was found that during the period 2018-2021, there was foF2 depression in Moderate levels during all of the month (48 months), while the Severe levels occur only in certain months (22 months). This shows that even though solar activity is low/minimum, *foF2* depression still occurs.

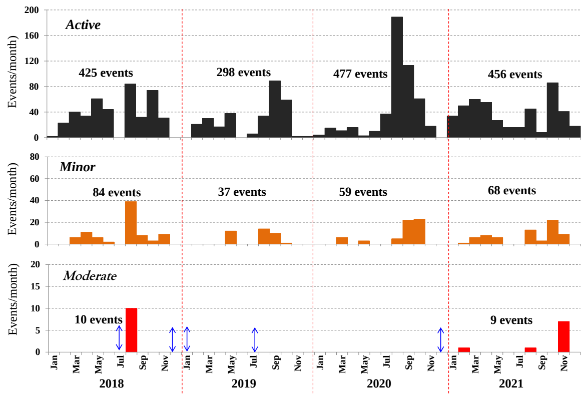



Fig.3. Graph of the number of *foF2* depression events per month with *Moderate* (top panel) and *Severe* (bottom panel) levels observed at Pameungpeuk station from January 2018 to December 2021.

The result obtained are that during the period 2018-2021, the number of *foF2* depression events ($r_j$ < 1) was 53265 events or about 38% of the total observations from January 2018 until December 2021 (140256 observations). The other events (62%) were *foF2* values equal to or higher than the median. In the total of *foF2* depression events, there are 4187 events (about 3%) in the *Minor* level and 61 events (0.04%) at the *Severe.*

From the diagram in Figure 3, the Moderate level pattern looks like an increase in the number of events around July - October, but the pattern is unclear. For the *Severe* level, the chart pattern is very unclear. This indicates that the *foF2 depression* does not have a certain pattern of variation. The result also indicates that the *foF2* depression model cannot be constructed using statistical methods.

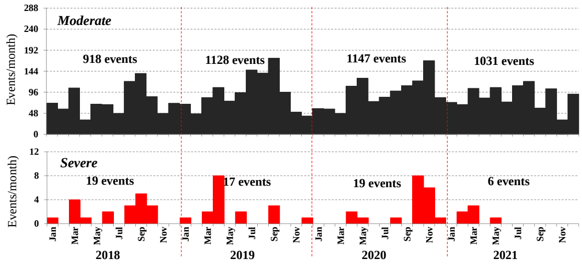
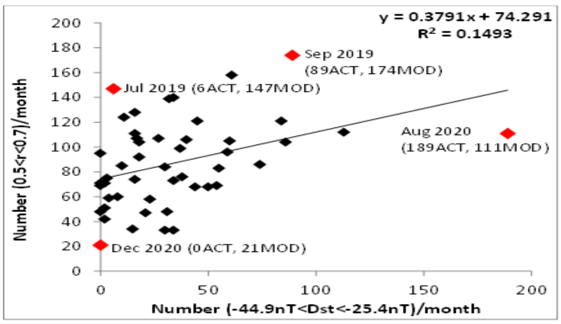


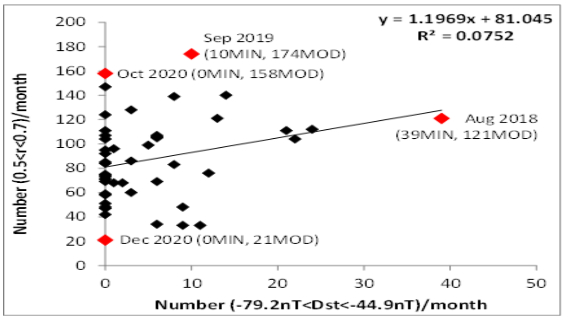

Fig.4. Distribution of the number of geomagnetic disturbances at *Active* (top panel), *Minor* (middle panel), and *Moderate* (bottom panel) levels, from 2018 to 2021 (Source: World Data Center for Geomagnetism, Kyoto http://wdc.kugi.kyoto- u.ac.jp/dstdir/ )

During the 2018-2021 observation period, the number of geomagnetic disturbances per month is shown in Figure 4. The number of geomagnetic disturbances in *Active* (-44.9 nT < *Dst* < -25.4 nT) level during 2018 until 2021 were 425, 298, 477, and 456 events, respectively. Furthermore, the number of *Minor* (-79.2 nT < *Dst* < -44.9 nT) level for 2018, 2019, 2020, and2021 were 84, 37, 59, and 68 events, respectively. Then the *Moderate* (-139.6 nT < *Dst* < -79.2 nT) level only occurred in 2018 (10 events) and in 2021 (9 events). Meanwhile, Major (245.9 nT < *Dst* < -139.6 nT) and *Severe* (*Dst* < -245.9 nT) levels of geomagnetic disturbances did not occur during this period. In the 96 months of observation, there were 5 months in which geomagnetic disturbances did not occur (↕), there are on July & December 2018, January & June 2019, and December 2020. The datashows that although the solar activity was quiet during the observation period, and there were still many geomagnetic disturbances occurred.

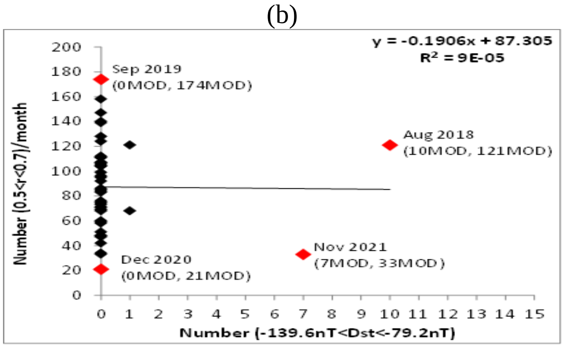
There are still many occurrences of geomagnetic disturbances during the period from 2018 to 2021, and it is indicates that geomagnetic disturbances are one of the causes of the *foF2* depression during minimum solar activity. There is a lot of research on the relationship between geomagnetic disturbances and the *foF2* depression, but the discussion is mostly based on incidental cases of geomagnetic storms. This is shown by research conducted by [7], [9]–[11]. Therefore, we discuss the correlation between these events statistically to know the relationship quantitatively.




(a)




(b)




(c)

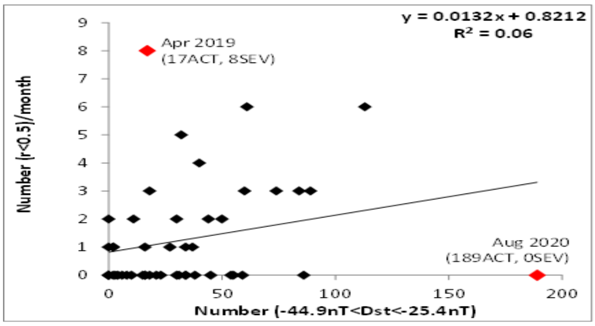
Fig.5. Linear correlation between *foF2* depression events at the *Moderate* level per month. And the geomagnetic disturbances at *Active* (left panel)(a), *Minor* (middle panel)(b), and *Moderate* (right panel) levels (c).

*Scatter plots* between the event of *foF2* depression and the occurrence of geomagnetic disturbances are presented in Figure 5 and Figure 6. First, the horizontal axis shows the number of geomagnetic disturbances in *Active* (left), *Minor* (middle), and *Moderate* (right) levels. Then the vertical axis represents the number of *foF2* depression events at *Moderate* level for Figure 5 and *Severe* level for Figure 6. The given point are the month and year initials, the number of geomagnetic disturbances,the initials of the month and year, the number of geomagnetic disturbances, and the number of *foF2* and the number in brackets. For example, a dot labeled Aug 2020 (189ACT, 111MOD) indicates that in August 2020, there were 189 geomagnetic disturbances in *Active* level (ACT) and 111 *foF2* depression in *Moderate* level (MOD).

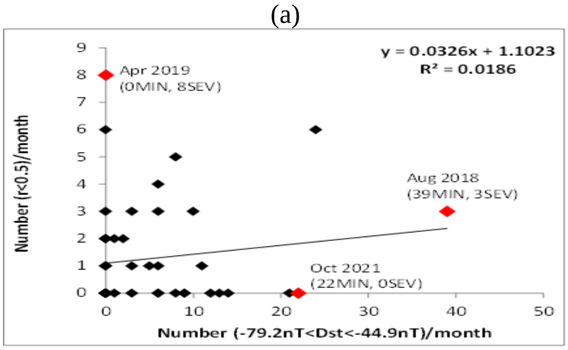
From Figure 5, it is known that the correlation coefficient (R) between the number of *Moderate* levels of *foF2* depression *and* the number of geomagnetic disturbances in the *Active* level is R = 0.39 ($R^2$ = 0.1493). Then, the correlation coefficient of this *foF2* depression with the number of *Minor* geomagnetic disturbance levels is 0.27 ($R^2$ = 0.0752), and the level of geomagnetic disturbances *Moderate* is 0.01 (R2 = 0.0009). This shows that *foF2* depression *Moderate* correlates between *Active* and *Minor*. Although the correlation is not strong, the *Active* and *Minor* level geomagnetic disturbances are sufficient to affect the *Moderate* level of *foF2* depression. Whereas the correlation of *Moderate* level geomagnetic disturbance is very weak.

The correlation between *foF2* depression *Moderate* and geomagnetic disturbance is relatively weak, as shown more clearly by the number of points on the vertical axis or close to the vertical axis of Figure 5. These points indicate that there was no geomagnetic disturbance during this month, but the *foF2* depression still occurred. For example, in December 2020, there was no geomagnetic disturbance (0ACT), but there was a *moderate* depression of *foF2* (*21MOD*) or equal to a time duration of 5 hours 15 minutes. In July 2019, there were only 6 *Active* levels of geomagnetic disturbances (6ACT). However, there is 147 *Moderate levels* of *foF2* depression or 36 hours 45 minutes duration.

Furthermore, in August 2018 and September 2019, there were many geomagnetic disturbances and many *foF2 depression* events. In August 2018, geomagnetic disturbances that occurred were *Active* (84 events), *Minor* (39 events), and *Moderate* (10 events), whereas the *foF2 depression* occurred was *Moderate* (121 events) and *Severe* (3 events). In September 2019, the geomagnetic disturbances occurred in *Active* (89 events) and *Minor* (10 events) levels with *foF2 depression* in *Moderate* (174 events) and *Severe* (3 events) levels. This result causes the correlation between *Moderate* level *foF2* depression and *Active* and *Minor* level geomagnetic disturbances to exist, although this correlation is not strong.




(a)

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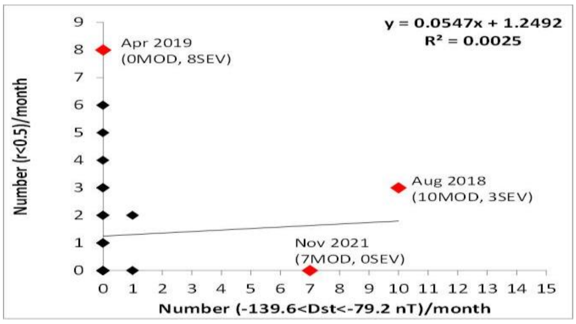


(c)

Fig.6. Linear correlation between *Severe foF2* depression events per month. And *Active* geomagnetic disturbances (a), *Minor* (b), and *Moderate* (c).

Figure 6 shows *the scatter plot* between the *Severe* level of *foF2* depression with the *Active*, *Minor*, and *Moderate* levels of geomagnetic disturbances. The correlation coefficient between the number of *foF2* depression occurrences in *Severe* level with the number of *Active* level of geomagnetic disturbances is R = 0.24 ($R^2$ = 0.06); then R = 0.14 ($R^2$ = 0.0186) for *Minor* level of geomagnetic disturbance; and R = 0.05 ($R^2$ = 0.0025) for *Moderate* level. These results indicate that the correlation between the occurrence of *foF2* depression (*Severe*) with *Active* and *Minor* level geomagnetic disturbances, still exists, although the correlation is weak. This data also indicates that the Active and Minor level of geomagnetic disturbance during minimum solar activity contributes to the *foF2* depression occurrences.

The scatter plot in Figure 6 shows the reverse of the scatter plot for the *foF2* depression at the *Moderate* level (Fig. 5). From the picture, we know that there are months when geomagnetic disturbances occur, but there is no *foF2* depression. This information can be seen from the dots are close to the horizontal axis of Figure 6. For example, in August 2020 (189ACT, 0SEV), there were 189 Active events of geomagnetic disturbance, but there were no *foF2* depression in *Severe*. Then in October 2011 (22MIN, 0SEV), although there were 22 Minor events of geomagnetic disturbance,there was no *Severe* level of *foF2* depression. Similarly, in November 2021 (7MOD, 0SEV), the 7 *Moderate* geomagnetic disturbance events *were* not followed by a *Severe* level of *foF2 depression*. The next result, in April 2019, there was 17 *Active* levels of geomagnetic disturbances and 8 *Severe* events of *foF2* depression (17ACT, 8SEV), whereas geomagnetic disturbances in *Minor* and *Moderate* did not occur.

This discussion of the correlation between the *foF2* depression and the level of geomagnetic disturbance during minimum solar activity shows that geomagnetic disturbances are not the only cause of the *foF2* depression. Although there is no geomagnetic disturbance, both moderate and severe, the foF2 depression still *occurs*. Another possibility that causes *foF2* depression is a solar eclipse, either a total eclipse or a partial eclipse. This conclusion is supported by the results of previous research regarding the decrease of *foF2* during a total solar eclipse [6], [12] and a partial solar eclipse [13].

### B. APPLICATIONS

In general, the application of information on the condition of the ionosphere is for frequency management in the HF radio communication circuit. There are three stages of frequency management. **Stage-1**: Selecting several usable frequencies based on the predicted monthly median of ionosphere parameters. **Stage-2**: Determine several frequencies supported by the ionosphere layer's ability to reflect HF radio waves during the time of operations. And **Step-3**: Determine the best frequency at the time of operation.

In stage-1, the usable frequency range is predicted, that is, the frequency range between the minimum frequency (LUF) and the maximum frequency (MUF). The MUF value is obtained from calculations using equation (1) with *foF2* used as the monthly median predicted values. Likewise, the LUF value is determined by one method not discussed in this paper. The MUF value is obtained by running the prediction software, such as ASAPS (Advanced Stand-Alone Prediction System). The LUF-MUF frequency range is used as reference to determain frequency, which has been permitted to be used, will be used for a month of operation. Suppose the operational frequencies are $f_1$ and $f_2$ which the $f_1$ the channel is lower.

Stage-2 requires information on the solar activity as the main cause of changes in the ionosphere layer. Then, the EEarth's magnetic field was used as an intermediate indicator of the impact of solar activity on changes in the ionosphere layer. Changes in *foF2* will affect the usable frequency range during HF radio communication operations. If the change is a decrease or depression of *foF2*, it allows one or all of the operational frequencies to be higher than the upper limit of the usable frequency. Consequently, the operational frequency cannot be used when the *foF2* depression occurs. Therefore, if the forecast for *foF2 depression* can be determined one or several days in advance, then the HF radio communication operator can mitigate and anticipate the possibility of radio communication failure.

As an illustration, we review the occurrence of *foF2* depression during 1 - 2 September 2019 and its application for correction of the MUF predictions for the circuit of Merak (5.94°S, 106.00°E) - Teluk Penyu (7.94°S, 109.09°E), with a distance of 394 km as seen on Figure 7. For example, the operational frequency channel used is $f_1$ = 6 MHz and $f_2$ = 10 MHz. Based on the LUF-MUF range as a result of the frequency prediction, $f_1$ is open from 6.45 UT+7 to 21.45 UT+7, while $f_2$ is open from 10.30 UT+7 to 17.15 UT+7.

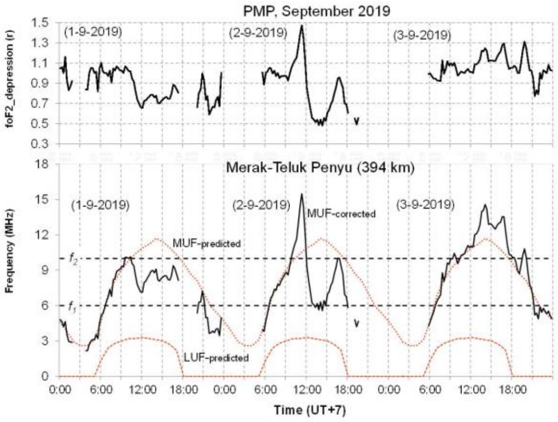

Fig.7. The graph of *foF2* depression (r) above Pameungpeuk from September 1 to 3, 2019 (top panel) and the correction results for MUF predicted using ASAPS software, for the Merak - Teluk Penyu communication circuit.

On September 1, 2019 *foF2* was depressed to the *Moderate* level (0.5 < $r_j$ < 0.7), so that the MUF is corrected. As a result, the channel $f_2$ which should be open from 10.30 UT+7 to 17.15 UT+7, becomes closed and cannot be used at all because its frequency is higher than MUF-corrected. Meanwhile, the $f_1$ the channel still can be used due to predictions.

Furthermore, on September 2, 2019, their *foF2* was an increased ($r_j$ > 1) during 9.45 UT+7 until 11.45 UT+7, and $f_2$ was opened. After that, *foF2* was depressed, even reaching the *Severe* ($r_j$ < 0.5). As a result, the channel $f_2$ is closed from 12.00 UT+7 until midnight. Meanwhile, channel $f_1$ failed at 13.15 UT+7 until 14.15 UT+7 because it was slightly lower than MUF-corrected.

Referring to the discussion on the occurrence of *foF2* depression on September 1 and 2, 2019, if the time of *foF2* depression can be estimated a day or several days before, radio communication operators can mitigate and anticipate the impact of this disturbance. In this case, solar activity and geomagnetic disturbances can be used to determine the forecast for *foF2* depression.

## IV. CONCLUSION

Based on the results and discussion, several points can be concluded as follows. Even though solar activity is low, the *foF2* depression still occurs in *Severe*. Likewise, geomagnetic disturbances also continue to occur up to the *Moderate* level, so geomagnetic disturbances are a potential cause of *foF2* depression. The pattern of temporal variation of the incidence of *foF2* depression is unclear, and then statistical models cannot be used; The correlation between the number of *foF2* depression per month and the number of geomagnetic disturbances is relatively weak, and there are several months without the geomagnetic disturbances, but *foF2* depression still occurs, which suggests that geomagnetic disturbances are not the only cause of *foF2* depression.

Another possibility that causes *foF2* depression is a solar eclipse. The prediction of the *foF2* depression that will occur can be used in HF frequency management, such that the ionosphere supports selected frequency during operation. In addition, solar activity and geomagnetic disturbances can be used to predict the *foF2* depression.

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