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Research paper

Comparison of maximum usable frequency (MUF) variability over Peninsular Malaysia with IRI model during the rise of solar cycle 24

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ABSTRACT

The aim of this paper is to study maximum usable frequency (MUF) variability over Peninsular Malaysia (112.5°E, 2.5°N) which is located in the equatorial region during the rise of Solar Cycle 24 (2009–2011). The MUF Test data was obtained from high frequency (HF) transmission tests that were conducted from April 2009 to September 2011. Relative variability VR was used to compute the relative variability of MUF. Variability of diurnal, seasonal and sunspot effect on MUF of test was compared to International Reference Ionosphere (IRI) version of 2012. The results show that: (a) MUF from the IRI model is higher than the MUF Test but the magnitude for the MUF Test and IRI are similar; (b) from the diurnal analysis, MUF is more vulnerable to variability during the nighttime than the daytime where the variability range for MUF Test and IRI during daytime is 4–12% compared to the nighttime range of 10–30%; (c) seasonal variability for MUF Test in 2011 indicates no clear trend for all seasons, and the seasonal and monthly variability for both MUF VR in 2011 is lower compared to 2009 and 2010; and (d) when sunspot number increases, MUF VR decreases. This result complements the variability in the equatorial and low latitude regions in that when solar activity increases, variability decreases.

1. Introduction

Maximum useable frequency (MUF) refers to the highest possible frequency for high frequency (HF) communications that can be used to transmit over a particular path under given ionospheric conditions (Harris, 2005; Freeman, 2006; Hadi and Aziz, 2012; Mudzingwa et al., 2013) which fluctuate continuously due to temporal variations of the ionosphere (Maslin, 1987). MUF is the product of F2-layer critical frequency *fo*F2 and propagation factor *M*(3000)F2 and is defined by the relation:

$$MUF(3000)\mathrm{F2} = fo\mathrm{F2} \times M(3000)\mathrm{F2} \quad (1)$$

where *M*(3000)F2 is the propagation factor of F2 layer of which its influence is significantly less than *fo*F2 (Kouris et al. 2000; Fotiadis et al., 2004; Chen et al., 2008), and *MUF*(3000)F2 is a usable frequency that can be received at a distance of 3000 km when reflected by the ionosphere (Bradley, 1973; Kouris et al., 2000; Adeniyi et al., 2003).

The biggest problem in HF radio communication is the rapid change in the ionospheric characteristics, resulting in the need for the operating frequencies to be changed from time to time to get satisfactory performance (Lakshmi, 1994). Therefore, MUF is important for HF radio users to achieve better frequency management (Fotiadis et al., 2004). Kennedy and Davis (1993) reported that tremendous increases of MUF variability are observed after unusual solar activities such as solar radio bursts and sudden ionospheric disturbances (SID), while Rishbeth (1993) pointed out that the impact of space weather effects can be assessed by investigating the variability of MUF in 1979, which is a year of high solar activity, because X-ray and extreme ultraviolet radiation (EUV) flux were high and variable during that year. The variation of MUF is maximum near local noon and minimum at night until pre-dawn (Milan et al., 1997).

There are several studies on MUF variability based on solar activities and ionospheric properties. Studies on MUF variability include those of Kouris et al. (2000) and Chen et al. (2008) who investigated MUF variability in Europe such as Rome and Slough and low latitude stations, i.e. at Haikou, China respectively. Whilst Zolesi et al. (2001) studied the variability of *MUF*(3000)F2 within

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the hour by 5 min using the vertical sounding campaigns, and revealed the variability of *MUF*(3000)F2 is not constant during the day. Kouris and Fotiadis (2002) revealed that the variability of ionospheric parameters including day-to-day *MUF*(3000)F2 is greater than the hour-to-hour variability. Fotiadis et al. (2004) later produced new reference deciles for MUF of every longitude sector and hemisphere and obtained a significant dependence of MUF VR on longitude. Somoye and Akala (2011) found that the effect of solar activities on MUF variability is latitudinally dependent, which is due to more variable F region dynamics at the equator than at higher latitudes. Maltseva et al. (2012) studied the characteristics of radio wave propagation in the ionosphere in conditions of very low solar activity and observed the changes of MUF using total electron content (TEC).

Nevertheless, the study of MUF and its variability is scarce, unlike that of *fo*F2 or *Nm*F2 which has been studied more often because it is the more easily accessible characteristic of the ionosphere (Mansilla et al., 2004). Due to these circumstances, there is a lack of MUF variability study over Southeast Asia or the surrounding Malaysian region which is located in the equatorial area. Equatorial ionosphere has several characteristic features like the Equatorial Electrojet, Equatorial Sporadic-E, Equatorial Anomaly and Equatorial Spread-F. Therefore, there is a need to study HF frequencies in the equatorial region (Dabas et al. 2006; Wichaipanich and Supnithi, 2009; Liu et al. 2012) where the diurnal and monthly variations may perform differently in the mid-latitude region. As the equatorial ionosphere has special features, it may consequently pose serious threats to communications and navigation systems compared to the ionosphere over the temperate region (Akala et al. 2011; Chao et al. 2011). This is because radiation from the sun falls directly over the equatorial region, causing the strongest ionisation. Thus, ionospheric variations in the equatorial region is well correlated to solar activities (Xue and Boon, 2004). Moreover, Wen and Xun-jie (1999) stated that the ionosphere over the South China Sea is complex because its ionospheric conditions vary considerably with time and location.

Hence, the aim of this study is to (i) contribute to the study of MUF variability from the Southeast Asia/equatorial region by providing the data of these characteristics for the development of global ionospheric models, (ii) compare MUF variability over Peninsular Malaysia (112.5°E, 2.5°N) during the rise of Solar Cycle 24 with MUF variability from the IRI model with a view to determining similarities and/or differences and (iii) find the effect of diurnal propagation, seasonal propagation, and sunspots in the analysis of MUF variability on diurnal, seasonal, and sunspot variability.

2. Data and method of analysis

The MUF Test data were obtained from actual HF transmissions from the Science and Technology Research Institute for Defence (STRIDE), Malaysia. The HF Telefunken Radio, which complies with the world's strictest standards for radio communications equipment, including MIL-STD-810 and ALE per MIL-STD-188-141B (Racoms, 2015), was used as the transceiver system to perform actual transmission to obtain MUF data. The locations of the transmission tests are between Kajang (101.8°E, 2.98°N) and Lumut (100.6°E, 4.22°N). The transmission tests were conducted from April 2009 to September 2011, during the increase of Solar Cycle 24, where the yearly average sunspot number R_z values rose from low levels in 2009 (4.2) and 2010 (17.5) to much higher levels in 2011 (50.4) (Malik et al., 2010). This cycle has risen much more slowly than any other space age solar cycle, with the solar activity in 2013 being the weakest peak in 100 years (Komitov et al., 2011; Gopalswamy, 2012; Komitov and Kaftan, 2013; Hao et al., 2014; Kilpua et al., 2014). Several predicted MUF from STRIDE's database were selected for the transmission tests, which were based on predicted frequencies from the Advanced Stand Alone Prediction System (ASAPS) software (IPS, 2008). The predicted frequencies were transmitted using HF radio transceivers between the two locations.

For comparison purposes, ionosonde measurement of MUF with predictions of the International Reference Ionosphere (IRI) 2012 model was used to compare the MUF variability during the rise of Cycle 24. The IRI is produced by a joint COSPAR/URSI Working Group. It is an empirical standard model that provides a basis for the simulation and prediction of the ionospheric radio wave propagation. The model takes into account daily and seasonal variations, perturbed and quiet conditions as well as the impact of the solar activity on the ionospheric plasma. MUF was obtained from the IRI model by using Eq. (1), via predicted *fo*F2 and *M*(3000)F2 from the IRI 2012 model.

In this study, relative variability VR (Bilitza et al., 2004; Somoye et al., 2011; Somoye and Akala, 2011; Somoye et al., 2013b) or coefficient of variability (CV) (Akala et al., 2011) was used to obtain the relative variability of MUF. Somoye et al. (2013a) have reviewed the merit of this formula in that the deviation of all the daily values from the means is considered to indicate that the whole data is used. VR is statistically defined as:

$$VR(\%) = (\sigma/\mu) \times 100 \quad (2)$$

where μ is the mean of MUF and σ is the standard deviation of MUF.

3. Results and discussion

It has been highlighted that HF propagation is extremely varied and the simplest and shortest propagation cycle is the diurnal cycle. Fig. 1(a–c) shows the monthly hourly median MUF for 2009 to 2011 plotted against local time (LT). Observations from the plots clearly indicate diurnal trend for all the years: lower MUF in the morning, increasing MUF in the afternoon until pre-sunset and decreasing MUF at post-sunset until pre-sunrise. This is consistent with the statement in Harris (2005) and Harden (2005) where MUF is lower at night and higher during the day. Rais (2012) highlighted that the time-of-day has the greatest impact on HF sky wave propagation, when there is more radiation from the Sun that

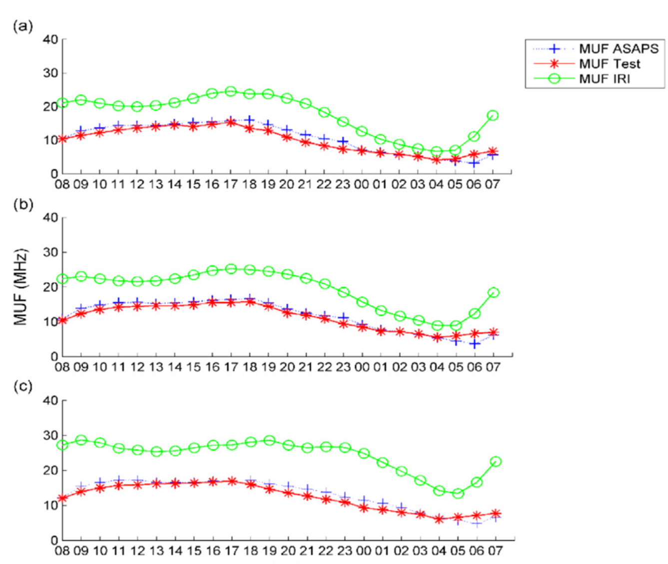

Fig. 1. Hourly monthly median of MUF for (a) 2009, (b) 2010 and (c) 2011.