The relationship between signal intensity and maximum observed frequency in long-distance propagation of VHF radio waves based on the reflection from the ionosphere

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Abstract. Observation of VHF radio waves with high frequency resolution has been carried out at Tateyama, Japan. 48.25 MHz radio waves transmitted from Bangkok, Thailand, located in the distance of 4500 km from Tateyama were frequently received in 2001. These radio waves have a carrier of TV broadcast used in Thailand and vestigial side band whose bandwidth is 6 MHz. It is found that, simultaneously with the reception of the radio wave, maximum observed frequency (MOF) increased in spring, autumn, and winter. Since the electron density in the ionosphere was large in these seasons in 2001, the reception of the radio wave is obviously due to one-hop F_2 reflection. Simultaneous observations of both the reception of the radio wave and the enhancement of MOF have never been reported in the previous studies. Using ray tracing calculation, it is confirmed that this reception is due to the reflection from the ionosphere. The increase of the signal intensity corresponds to the crossing of the skip distance at Tateyama.

Keywords: VHF wave, Long-distance propagation, Skip distance, Maximum observed frequency, Ray-trace.

1 Introduction

It is well known that VHF radio waves are frequently received over thousands kilometers from a transmitter due to the reflection from the ionosphere. Ujigawa et al. (2009) have reported that 48.25 MHz radio waves transmitted from Bangkok (geographic coordinates: 14.0°N, 101.0°E; geomagnetic latitude: 6.0°N) were observed at Tateyama observatory (geographic coordinates: 35.0°N, 139.9°E; geomagnetic latitude: 28.0°N) in 2001. The reception mainly occurred in the afternoon in spring, autumn, and winter. In these periods, f_oF_2 at Guangzhou and Okinawa exceeded 15 MHz and one-hop reflection condition between Bangkok and Tateyama is achieved.

As for the propagation of VHF radio waves due to the reflection from the ionosphere, the frequency for transmission between two points is limited. This frequency is characterized by maximum usable frequency (abbreviated as MUF), which is calculated from the distribution of the ionospheric electron density under consideration. Historically, the prediction of MUF is very important for the operation of HF sky-wave telecommunication. Many papers have contributed to the theoretical and/or numerical studies of determination of MUF (e.g. Bremmer, 1949; Warren and Muldrew, 1961; Croft 1967; Davis and Rush, 1985). As for the experimental study, on the other hand, the maximum observed frequency (abbreviated as MOF) has been observed using ionospheric sounding equipments, such as ionosondes, chirp sounders, digizondes, and so on (e.g. Reckwith and Narayana Rao, 1975; Cherkashin et al., 2003; Eremenko et al., 2007; Maltseva et al., 2007). Since these equipments use a single modulated frequency, however they are not able to observe the wideband spectrogram. In this study, the signal intensity at 48.25 ± 2.5 MHz has been observed with the frequency resolution of 0.025 MHz and the

time resolution of 10 s at Tateyama observatory. The 48.25 MHz radio wave is suitable for observation of the enhancement of the MOF because this radio wave is used for TV broadcast and the 6-MHz vestigial side band is associated.

In this paper, we report not only the time variation of signal intensity of 48.25 MHz but also the variation of MOF. In addition, the observational result is verified by the ray tracing technique.

2 Observation

Using a horizontally polarized 5-element Yagi antenna, VHF radio waves (47.5 – 52.5 MHz) have been observed at Tateyama Observatory since October, 2001 (Takano *et al.*, 2002). In this study, the propagation of 48.25 MHz radio wave transmitted from Bangkok is examined. The locations of Tateyama and Bangkok are shown in Figure 1 and the distance between them is 4500 km. Figure 2 shows the dynamic spectra (bottom panel) and the signal intensity of 48.25 MHz radio waves (middle panel) observed on a particular day of October 08, 2001. As described before, the 48.25-MHz radio wave is used for TV broadcast in Thailand. This is confirmed by the sound signal demodulated from the radio waves. To study the reflection condition in the ionosphere, f_oF_2 observed at Guangzhou which is located near the mid-point between Bangkok and Tateyama, is plotted on the top panel of Figure 2. From this figure, it is found that the signal intensity of 48.25 MHz starts to increase rapidly at about 13 JST (Japanese Standard Time = UT + 9 hours). The intensity is varied from -100 dBm/Hz which corresponds to the background noise level, to -50 dBm/Hz in several tens of minutes as f_oF_2 at Guangzhou increases slightly. After this rapid increase of the signal intensity, the intensity decreases slowly to -80 dBm. Then the intensity keeps the moderate level up to 24 JST.

Figure 1: Locations of Bangkok, Tateyama, and Guangzhou. A solid line shows a great circle path between Bangkok and Tateyama.

In association with the increase of the signal intensity, MOF also increased as shown in the bottom panel of Figure 2. At 13:00 JST, the signal intensity at 47.5 MHz starts to increase and then the signal intensity at high frequency also increases continuously. The

Figure 2: The diurnal variations of f_oF_2 at Guangzhou (top), the signal intensity at 48.25 MHz (middle), and the dynamic spectrum observed at Tateyama (bottom) on 2001/10/08

Figure 3: The same figure as Figure 2 except on 2001/06/19

Figure 4: The variations of signal intensities at 47.0, 48.25, and 49.5 MHz determined by ray tracing calculation. The electron density for 2001/10/08 is used. Vertical dotted lines show the position of Tateyama, which is 4500 km from the Bangkok

start time of the enhancement at each frequency implies the variation of MOF, which varies from 47.5 MHz to 52.5 MHz in one and a half hours. As described before, the 48.25 MHz radio wave is assigned for video signal in TV broadcast. As concerns with the analog video format of TV broadcast, the vestigial sideband modulation is used and the upper and lower sidebands of bandwidth are 4 MHz and 1.25 MHz along with a carrier, respectively. Therefore, the radio waves which show the MOF variation are transmitted from the same transmitter (Bangkok).

Besides the reception of 48.25 MHz, the signal intensity at 49.75 MHz was also enhanced from 14 JST. This frequency is used as video carrier of 1 Ch in China channel assignment. We do not discuss the behavior of this radio wave because it is out of the topic in this paper.

The result as shown in Figure 2 is a typical case observed in 2001. The other type of reception is shown in Figure 3. In this event, the signal intensity gradually increased up to -80dBm/Hz , and there is no MOF variation. On this day, sporadic-E layer was intensely developed in the daytime and the value of f_oF_2 was missing. Therefore, the condition for one-hop propagation was not achieved.

Considering all types of receptions, the receptions of the 48.25 MHz radio wave are observed all the year. To examine the occurrence of the reception which is associated with the enhancement of MOF, we determine the seasonal variation of the occurrence ratio of the reception in 2001 as shown in Table 1. In determining the occurrence rate, the number of events is counted by day in which the reception occurs at least once. Even when the receptions occur twice a day, the number of event is counted as one day. This table shows that this type of the observation of the radio wave is frequently observed in spring, autumn, and winter. In December, the 48.25 MHz radio wave observed every day and all the receptions of the radio wave are associated with the enhancement of MOF. In July, on the other hand, the 48.25 radio waves were observed 10 days but all the receptions were the other type of receptions. This result is consistent with Ujigawa et al (2009). In the afternoon in winter, spring, and autumn, f_oF_2 at Guangzhou is so high that the radio wave transmitted from Bangkok can propagate to Tateyama due to the reflection effect in the ionosphere.

Figure 5: The MUF for 48.25 MHz radio wave at the distance of 4500 km from Bangkok determined by ray tracing calculation. The electron density is the same as Figure 4.

3 Discussion

From the observation of VHF radio waves with high frequency resolution, it is confirmed that the reception of the radio wave due to the reflection in the ionosphere is associated with the increase of the MOF. Here, we examine the characteristics of the reception by a two-dimensional ray tracing calculation which was also used by Ujigawa et al (2009). The basic equation of the calculation is described by Maeda and Kimura (1984). In this calculation, the electron density distribution is determined by IRI model (Bilitza, 2001). The ray paths are determined for any inclinations of the emitted waves, frequencies, and local times. The results are shown in Figure 4 where the histograms show the number of the rays filling a fixed range bin from 15 to 20 JST, at the frequencies of 47.0, 48.25, and 49.5 MHz. The ray tracing calculation is carried out in 2-dimensional plane under the assumption that off great-circle path propagation is ignored. Only the elevation angle is varying in the ray tracing calculation and the rays are emitted in every 0.01° of inclination. The power of each ray is supposed to be constant although it must be dependent on the inclination as the beam pattern of the transmission antenna. However, the inclination at which the rays can propagate to Tateyama is about $86\text{--}90$ degrees. Since the range of the inclination is very narrow, the power of ray propagated to Tateyama is assumed to be almost constant. Therefore, it allowed us to estimate the signal intensity by the number of rays (e.g. Stocker et al., 2000).

As an alternative to the ray tracing calculation for determining the signal intensity, a wave theory can also be performed. In the wave theory, the wave interference between low and high angle rays is considered, resulting that the signal amplitude is fluctuated just further from the skip distance. Bremner (1949) showed the signal intensity in the neighborhood of skip distance ($=907$ km). In this case, the interference pattern is about 1 km. Since the skip point moves with 100 km/s, the time resolution must be less than 10 seconds to observe the interference pattern. In the present observation, the time resolution of the observation in this study is 30 seconds. However, Warren and Muldrew (1961) shows that the ray tracing calculation derives the average values obtained in terms of the wave theory and that the ray theory is available for examining the macroscopic features of the wave propagation. Since the observation in this study can detect the macroscopic

Figure 6: The signal intensity for 48.25 MHz radio wave at Tateyama determined by ray tracing calculation. It is estimated by the logarithm of the number of ray (N) which is propagated to the distance of 4500 km from Bangkok. The electron density is the same as Figure 4.

variation of the signal intensity. Not the wave theory but the ray path calculation is carried out in this study.

It is found from Figure 4 that the radio waves are received in the evening and that the skip distance is shortest around 17:30 JST. The skip distances for 47.0 MHz, 48.25 MHz, and 49.0 MHz are crossing Tateyama at 15:10, 15:50, and 16:30 JST, respectively. In crossing the skip distance, each radio wave starts to be received at Tateyama. Simultaneously, MUF at Tateyama increases as shown in Figure 5. (In this paper, MUF is distinguished from MOF. It is assumed that MUF is theoretically or numerically determined and that MOF is experimentally observed.) After MUF reaches the maximum frequency ($\sim 17:20$ JST), the skip distance becomes longer and MOF decreases. In Figure 4, the reception of the radio wave at 48.25 MHz is terminated at 19:30 JST. At this moment, there is no ray which reaches the ground. This termination of the reception does not depend on the crossing of the skip distance but the rays at 48.25 MHz are not reflected by the ionosphere.

The ray tracing calculation also shows the temporal variation of the signal intensity at Tateyama as shown in Figure 6. It is worth noting that the signal intensity reaches maximum at the start of the reception because the signal intensity is maximum at the skip distance. This variation is quite similar to that of observational results of 48.25 MHz signal intensity as shown in Figure 2. In the end of the reception, on the other hand, the signal intensity determined by the ray tracing calculation decreases stepwisely. As described before, the reception is terminated because the ray is not reflected from the ionosphere. The step-like variation of the signal intensity is affected not only by the decrease of skip distance but also by the total number of the rays which reach the ground. During 19:10–19:30 JST, only 3 rays propagate to Tateyama. This seems to be a numerical error. Just before the rapid decrease ($\sim 19:10$ JST), on the other hand, the signal intensity is slightly increased. This variation also appeared in the observation. In Figure 2, just before the end of the reception at 23:30 JST, the signal intensity increased, and this increase is the same as the start of the reception, which is decrease of the skip distance.

Month	Occurrence [days]	by reflection [days]	ratio [%]
Jan	25	19	76
Feb	5	4	80
Mar	29	27	93
Apr	13	10	77
May	9	4	44
Jun	17	2	12
Jul	10	0	0
Aug	5	2	40
Sep	11	11	100
Oct	31	31	100
Nov	29	28	97
Dec	30	30	100

Table 1: Occurrences of the reception of 48.25 MHz radio wave and that by the reflection from the ionosphere in 2001. The right column is the ratio of the reception by reflection to all the receptions.

Even though the ray tracing calculation explains the observational results qualitatively, there is a clear difference in the time of reception between the observation and the ray calculation. One of the main reasons for this discrepancy is that IRI model is adapted to the state of the ionosphere using median values. This means that IRI is not suitable for the actual day-to-day variation of the phenomena. In addition, the distance between Bangkok and Tateyama is 4500 km, which exceeds the limit of one hop propagation. The equatorial anomaly located above Guangzhou enables the radio waves transmitted from Bangkok to propagate to Tateyama. As described in Ujigawa et al. (2009), the propagation between them is very sensitive to behavior of the equatorial anomaly, which easily breaks the horizontal homogeneity of the ionosphere. To determine the actual propagation of the radio wave is very difficult and then more observational equipments would be required to identify many features of the propagations of the radio waves.

4 Conclusion

We have carried out the observation of VHF radio waves with high frequency resolution at Tateyama observatory. By observing radio waves used as a carrier of TV broadcast, it is firstly found that both the enhancement of MOF and the increase of the signal intensity are observed in the reception of the radio wave due to the reflection from the ionosphere. In the propagation between Tateyama and Bangkok, this type of the propagation occurred in spring, autumn, and winter in solar maximum period. Most of the receptions in these seasons are due to 1-hop reflection from the ionosphere. The main features of the reception are qualitatively explained by the result of the ray tracing calculation.

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