LETTER

Temperature Effects on Anomalous Radio Duct Propagation in Korean Coastal Area

Yong-Ki KWON†††, Man-Seop LEE††, Nonmembers, and Hakyong KIM††††, Member

SUMMARY Atmospheric radio ducts can trap VHF/UHF radio waves and propagate them over long distances. 284.4625 MHz Japanese radio wave signal measurements show that the radio waves are propagated to Korean coastal regions when ground temperatures exceed 10°C. This paper discusses the reasons for the existence of this critical temperature threshold.

Key words: radio duct, duct propagation, critical temperature, super refractive

1. Introduction

In the eastern coastal areas of Korea, many VHF and UHF radio wave signals from Japan are detected. Considering that Korea and Japan are more than 250 km apart, this phenomenon, called abnormal propagation, is unexpected. Referring to previous researches [1], [2], the main mechanism for long-distance abnormal propagation of VHF/UHF radio wave is estimated to be an atmospheric radio duct that is formed in the lower atmosphere.

The strength or extent of the Japanese radio wave signals detected in Korea’s coastal areas, however, varies with the months or seasons; in particular, it appears to depend on temperature.

This paper deals with the temperature effects on radio duct propagation. For this purpose, we collected and analyzed atmospheric meteorological data, and derived the atmospheric refractivity profile. The refractivity

\[ N = \frac{P}{T + 273} + 22.79 \times 10^3 \frac{RH}{(T + 273)^2} \exp \left( \frac{17.502 \times T}{T + 240.97} \right) \]

where \( P \) is atmospheric pressure in hPa, \( T \) is temperature in °C, and \( RH \) is relative humidity in %.

Considering the earth’s curvature, it is useful to convert \( N \) to the quantity of modified refractivity, \( M \), defined as

\[ M = N + 157h \]

where \( h \) is altitude in km.

Normally, \( dM/dh (= M') \) is larger than zero, and radio waves propagate upward from the earth’s surface. In the case of \( M' < 0 \) (or \( N < -157 \text{[N/km]} \)), however, radio waves bend toward the earth’s surface, which is known as a radio duct occurrence condition. Performing the derivative, \( M' \) and \( N' \) are expressed as follows:

\[ M' = N' + 157 \]

\[ N' = \frac{77.6}{(T + 273)} \times \frac{22.79 \times 10^3}{(T + 273)^2} \exp \left( \frac{17.502 \times T}{T + 240.97} \right) \times RH' \]

\[ - \left[ \frac{77.6}{(T + 273)} \times 2 \times \frac{22.79 \times 10^3 \times RH}{(T + 273)^3} \exp \left( \frac{17.502 \times T}{T + 240.97} \right) \right] + \frac{4374.98}{(T + 240.97)^2} \times \frac{22.79 \times 10^3 \times RH}{(T + 273)^3} \exp \left( \frac{17.502 \times T}{T + 240.97} \right) \times T' \]

(4)

Equation (4) shows that \( M' \) (or \( N' \)) is composed of three contributing terms: \( P' \), \( RH' \), and \( T' \) term.

In order to analyze the effects of meteorological parameters on radio duct propagation, we analyzed 608 radiosonde datasets which were collected at Pohang (35°58’8” N, 129°30’13” E), located on the eastern coastal area of Korea, during the period of Jan. 1–Oct. 31, 2004. Although one radiosonde ascent measures meteorological data from the ground to a height of 30 km at intervals of 25–30 m, we analyzed meteorological data only up to a height of 3 km, because radio ducts that trap VHF/UHF radio waves are mainly formed in the lower atmosphere [4], [5]. Meteorological data measured at 70,161 points were thus statistically analyzed.

Table 1 shows the analysis results of the radiosonde datasets. The results include statistical characteristic values of meteorological parameters: \( P' \) (hPa/km), \( T' \) (°C/km), \( RH' \) (%/km), \( M' \) (M/km), and \( M'' \) in the duct layer (M/km). The table presents the mean value, standard deviation, and cumulative distribution function (CDF) values for each meteorological parameter gradient. The 2nd column of Table 1 shows the mean values of the meteorological parameters; per 1 km, the atmospheric pressure decreases about

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108.3 hPa, the relative humidity decreases about 9.7%, and
the temperature decreases about 5.0°C; however, the modified refractivity \( M \) increases roughly 114.7M. These results
agree somewhat well with previous results [4], [6]. The last
row of the table presents the modified refractivity gradient of
the upper parts of the radio duct (refer to Fig. 1). The results
show that \( M' \) in the duct layer is −124.7 M/km. Referring
to the mean values of the last two rows of the table, we can characterize the radio duct profile of the Korea coastal area
as shown in Fig. 1.

Using Eq. (4) and Table 1, we can estimate which meteorological parameter is critical for radio duct occurrence.

When \( P' \), \( RH' \), and \( T' \) are the mean values of Table 1, the refractivity gradient \( (N') \) varies from −20 [N/km]
to −70 [N/km] under the actual temperature range (−15−35°C). Since \( N' \) is larger than −157 [N/km], a radio duct
cannot occur.

### Table 1

<table>
<thead>
<tr>
<th>Stat. Values</th>
<th>CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Std. Dev</td>
</tr>
<tr>
<td>( P' ) [hPa/km]</td>
<td>-108.3</td>
</tr>
<tr>
<td>( T' ) [°C/km]</td>
<td>-5.0</td>
</tr>
<tr>
<td>( RH' ) [%/km]</td>
<td>-9.7</td>
</tr>
<tr>
<td>( M' ) [M/km]</td>
<td>114.7</td>
</tr>
<tr>
<td>( M' ) in duct layer [M/km]</td>
<td>-124.7</td>
</tr>
</tbody>
</table>

Figure 2 represents the atmospheric refractivity gradient \( (N') \) variations with \( T' \), when \( P' \) and \( RH' \) have values of 1%, and \( T' \) is the 99% value from Table 1, which corre-
spond to optimum meteorological conditions for radio duct
occurrence.

In this case, \( N' \) may be less than −157 [N/km], and a radio duct may form. These figures also say that \( N' \) values
strongly depend on \( RH' \), but weakly depend on \( T' \) and \( P' \).
This agrees with previous research results indicating that the variation of humidity is mainly responsible for the occur-
cence of radio duct for coastal regions [4], [7].

### 3. Estimating Duct Strength Variations with \( T \)

In this section, we discuss the effect of relative humidity and estimate the radio duct strength variations. Figure 3 shows
the modified refractivity variations with \( T \). Here, the points
are the modified refractivity values measured at Pohang at
the ground, and the solid and dashed lines are the theoret-
cal modified refractivity variations with \( T \) at a pressure of
1013 hPa when the relative humidities are 0% and 100%.
This figure also shows that the modified refractivity vari-
ations increase with temperature. This means that a radio
duct can more readily occur at higher temperature than at
lower temperature.

When we define the radio duct strength as shown in
Fig. 1, the theoretical maximum values correspond to the
differences between the solid and dashed lines of Fig. 3. Al-
though the differences are only the theoretical maximum
values of the radio duct strengths, they cannot take place
in real circumstances, because the relative humidity cannot
abruptly decrease from 100% to 0%. Accordingly, it is im-
portant to determine the actual values of the duct strength
variations that can take place under real circumstances.

Figure 4 shows the duct strength variations with tem-
perature. From 608 radiosonde datasets, we found a total
of 1,069 radio ducts. Here, the points are the measured re-
sults, and the solid line is the simulation curve, which con-
tains 95% of the measured radio duct strength datasets. This
curve corresponds to relative humidity decreases of 22%.
This result is only related to the relative humidity differ-
ences; the relative humidity variations from 32% to 10%, 52% to 30%, and 72% to 50% give the same results. Relative humidity decreases of 22% can actually take place under real circumstances. Therefore, the values of the simulation curve in Fig. 4 can be considered as the actual maximum values of the radio duct strength with temperature under real circumstances.

4. Temperature Effects on Radio Duct Propagation

The existence of a radio duct does not necessarily imply that all of a radio wave will be efficiently coupled into the duct in such a way that long-range propagation will occur. The frequency of a radio wave that can be trapped by a radio duct is determined by the duct profile. Referring to a previous result [7], the minimum trapping frequency \( f_{\text{mf}} \) of a duct can be calculated as follows:

\[
f_{\text{mf}} = \frac{C}{\lambda_{\text{MAX}}} = \frac{C}{[0.66 \times A \times W \times \sqrt{S}]}
\]

where \( C \) is wave velocity in a vacuum, \( A \) is a constant (3.77 × 10^{-3} for a surface duct, 5.66 × 10^{-3} for an elevated duct), \( W \) is radio duct thickness, and \( S \) is radio duct strength.

In the previous section, we discussed the actual maximum values of radio duct strength \( (S) \). On the other hand, referring to Fig. 1, the radio duct thickness \( (W) \) can be estimated by the radio duct strength \( (S) \). Therefore, we can calculate the minimum trapping frequency by using Eq. (5).

Figure 5 shows the minimum trapping frequency with temperature. The solid line represents the minimum trapping frequency for a surface radio duct, while the dashed line is for an elevated duct. In the case of 284.4625 MHz radio wave signals, a surface radio duct that can trap the signals can be formed at a temperature of more than roughly 10°C, while an elevated radio duct can be formed at a temperature of more than approximately 7.1°C.

Here, the critical temperature for the elevated duct should be measured at the real duct heights. In the analysis of the mean height of elevated radio ducts per season, the highest value is found in autumn, and is about 600 m. This result agrees well with that of a previous study [4].

5. Comparison with Measurements

284.4625 MHz radio wave signals originating from Japan were measured at Pohang, which is located on the eastern coast of Korea, from Jan. 1 to Oct. 31, 2004. The receiving systems were composed of a directional LP antenna, a spectrum analyzer, and a computer system with an automatic measuring program. The signals were periodically measured in one-hour intervals. Occasionally, however, data were not taken because the measuring system did not work.

Figure 6 shows the measured results, which indicate that the 284.4625 MHz Japanese radio waves are mainly propagated to the Korean coastal area in the period of April to September.

Figure 7 represents the re-arranged data according to temperature from Fig. 6. This figure shows that there is a critical temperature at which the Japanese radio wave signals are mainly detected. The critical temperature is about 10°C.

A comparison of these measured results with the analyzed results from the meteorological data reveals strong agreement between the two sets.

6. Conclusions

This paper discussed the effects of temperature on radio duct propagation. It was found that there is a critical temperature above which a radio duct is formed. The reason for this is as follows: The propagation paths from Japan to Korea are mainly formed over the sea. Hence, the dominant factor of atmospheric refractivity variation is the variation of humidity (refer to Fig. 2), and the occurrence of a radio duct is mainly influenced by relative humidity variation. Since the
Fig. 6  284.4625 MHz Japanese radio wave strength variations at Pohang, Korea, from Jan. 1 to Oct. 31, 2004.

Fig. 7  284.4625 MHz radio wave signal strengths with T.

Radio duct strength and thickness depend on the temperature (refer to Fig. 4), the trapping frequency of a radio duct depends on the temperature. The temperature dependences of duct strength and thickness are estimated to be caused by the number of water vapor particles carried in the atmosphere. Warm air can carry a large amount of water vapor particles, which can lead to abrupt variation of water vapor particles at a certain height. This can create a strong radio duct. On the other hand, cold air carries a relatively small number of water vapor particles, which leads to the formation of a weak radio duct, which cannot trap 284.4625 MHz Japanese radio wave signals. That is, as the temperature increases, the duct strength and duct thickness also increase, leading to the occurrence of a strong radio duct that can trap and propagate longer wavelength (lower frequency) signals. Hence, the trapping frequency of a radio duct depends on the temperature.

However, the variation of duct strength or duct thickness with temperature is determined by the meteorological characteristics of a specific area. In a specific area between Korea and Japan, the measured and analyzed results show that radio ducts that can trap 284.4625 MHz radio wave signals are formed at a temperature of more than approximately 10°C. Since the meteorological characteristics differ from region to region, or from country to country, it is estimated that the critical temperature for a certain frequency radio wave will vary across regions of the world.

References