The Preliminary Investigation of Communication Characteristics Using Evaporation Duct across the Taiwan Strait

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Abstract: Affected by the Taiwan Strait Warm Current, the evaporation intensity around the Taiwan Strait is significantly higher than in other southern and eastern coastal areas of China. To explore a new and effective method for maritime communication across the Taiwan Strait, we present a preliminary investigation of wireless microwave transmission in an evaporation duct. From 9 to 14 o’clock, the percentage of the evaporation duct height exceeding 10 m reached over 90% in 2020. With the favorable channel in this period, a “straight-through propagation channel” emerged, with a serviceable ratio of 99.00% at a 300 km transmission range. The high-quality transmission with BPSK modulation occurred 98.90% of the year from 12 to 13 o’clock, with 89.89% of the signal-to-noise ratio (SNR) exceeding 90 dB. Based on the effective use of the evaporation duct, the proposed method can provide favorable support for maritime applications across the Taiwan Strait.

Keywords: evaporation duct; Taiwan Strait warm current; maritime communication

1. Introduction

The public land mobile network has been undergoing rapid development and transformation in recent decades [1], from cable to optical cable, wired to wireless network [2], analog to digital communication, and first generation to sixth generation mobile communication technology [3]. In contrast, the development of marine communication is limited due to the complicated and changeable environment. At the same time, with the continuous development and utilization of marine resources, the participation and demand for broadband wireless communication across the ocean is increasingly enhanced. The existing options for maritime communication mainly rely on HF ground waves, line-of-sight UHF/UHF, L/C band satellite, and UHF military satcom [4], which have several defects in bandwidth, coverage, and maintenance cost, etc. [5–7].

As a remarkable phenomenon in the atmosphere, the atmospheric duct may supply a favorable communication approach to the new maritime network from a different dimension [8–10]. The evaporation duct frequently occurs in the ocean, and the average occurrence in the South China Sea (SCS) is about 85% [11–13]. Due to the evaporation of the ocean, the water vapor on the surface is saturated, and the water vapor pressure decreases with the increase in altitude [14]. The corresponding refractive index decreases, resulting in a negative gradient trend, and a trapping layer of electromagnetic energy is generated. Signals can refract in the duct layers and propagate to a distance beyond line-of-sight with the befitting frequencies and angles [14], which may also serve as a supplementary means in the maritime application of the sixth generation communication network. However, the characteristics and the communication effect of the evaporation duct are limited by the temporal and spatial variation of meteorological parameters, including temperature, relative humidity, pressure, and wind speed [8,15].
In the literature [16], a regional spatiotemporal statistical database of evaporation ducts over the SCS was built, and an evaporation duct channel was found to appear at the “Golden edge”, in the northern coastal area during May–July. As an extensive piece of research literature [16], the paper explored the meteorological causes of this phenomenon and highlighted its impact on communication. As one of the major sources of the Tsushima Warm Current, the Taiwan Strait Warm Current (TSWC) is characterized by year-round high temperature and high salinity [17,18]. Therefore, stable evaporation intensity can be maintained with warm water in the TSWC. Our paper presents a communication method based on the evaporation duct, which can provide favorable support for maritime applications across the Taiwan Strait. Considering the spatiotemporal variation of the evaporation duct, meteorological datasets from the National Center for Atmospheric Research (NCAR) are introduced and verified. The rest of the article is divided as follows. First, the modeling method of the evaporation duct characteristics and the communication effect in the ducting layer are advanced, respectively. Then, we present a temporal distribution of the evaporation duct characteristics across the Taiwan Strait. At the same time, the communication effects, including the signal-to-noise ratio (SNR) and the serviceable ratio at a typical location during 2020, were analyzed. Finally, a summary of communication characteristics under evaporation ducts concludes this work.

2. Methodology

The tropospheric height extends from the Earth’s surface to 8–18 km; impacted by radiation heating on the ground, the temperature decreases with the increase in altitude. Meanwhile, the water vapor in the troposphere changes greatly, increased by the evaporation of oceans, lakes, and rivers.

The uneven distribution of meteorological parameters may lead to variation of the tropospheric structure, resulting in the refraction of the electromagnetic wave in the transmission medium. The refractive index \( n \) is used to measure the degree of refraction [14]:

\[
  n = \frac{c}{v}
\]

where \( c \) is the velocity in the free space and \( v \) is the velocity in the transmission medium.

To better reflect the degree of refraction by numerical size, the refractivity \( N \) is defined as \( N = (n - 1) \times 10^6 \) in the microwave frequency band and below [14]. The refractivity close to the Earth’s surface mainly varies in the range of 250 N-unit–400 N-unit. The relationship between the refractivity \( N \) and meteorological parameters [14], including temperature \( T \), pressure \( P \), and water vapor pressure \( e \) is:

\[
  N = \frac{77.6}{T} \left( P + \frac{4810}{T} e \right) = N_d + N_w
\]

where \( N_d \) and \( N_w \) correspond to dry air and water vapor contributions, respectively.

The refractivity structures in the lower troposphere change with the influence of weather processes, including air subsidence, advection, ground heating, and radiative cooling. As a unique phenomenon at the bottom of the troposphere, evaporation ducts arise from a sharp decrease in relative humidity near the sea surface. The electromagnetic wave refracts repeatedly in the trapped layer while signals propagate through the evaporation duct channel, and the wavefront changes from spherical to cylindrical expansion. The path loss is reduced compared with the transmission in a standard atmosphere, so that communication effects are improved.

The geographical features of the Taiwan Strait, including the low latitude, intense sunlight exposure, etc., and high sea surface temperature (SST) caused by the TSWC, creates favorable meteorological conditions for the evaporation duct. In this paper, the communication effect was modeled and analyzed according to the method in Figure 1. Meteorological parameters, including temperature, relative humidity, pressure, and wind speed, were collected for the modeling database in Section 2.1. Meanwhile, marine radiosonde datasets
were also collected to validate the modeling database. Section 2.2 analyzes the evaporation duct characteristics based on the collected meteorological parameters, and the parabolic equation method is introduced to analyze the communication effect across the Taiwan Strait.

![Diagram](image.png)

**Figure 1.** Methodology of communication effects under evaporation ducts.

### 2.1. Data Collection and Validation

To statistically analyze the characteristics of evaporation ducts in the Taiwan Strait, NCAR Climate Forecast System Reanalysis (CFSR) datasets, including pressure, temperature, relative humidity, and wind speed from NCAR datasets in 2020 at different layers, were utilized as the data source in this work [19]. The NCAR CFSR time-series datasets were produced after data assimilation processing of meteorological observation data from satellites, meteorological land stations, radiosonde, etc., [20], and were provided in hourly resolution.

In order to analyze the difference between the NCAR remote sensing datasets and ground observation data, high vertical resolution radiosonde data from the ship-based Marine ARM GCSS Pacific Cross-Section Intercomparison Investigation of Clouds (MAGIC) field campaign were collected and utilized. During the campaign, the shipboard experimental platform sailed between Los Angeles, California, and Honolulu, Hawaii. Multiple instruments were deployed to measure meteorological parameters aboard the ship, including a weather station, an infrared SST radiometer, radiosondes, etc. [21]. After data preprocessing, 476 effective datasets were selected from 799 sets of radiosonde-sounding data, with no-value and invalid data removed [21].

In Figure 2, sea surface temperature, air temperature, and sea surface pressure datasets at measured time and positions in the MAGIC were collected, and the overall trend was consistent with NCAR datasets. The tracing curve of NCAR datasets tended to be smoother, while the MAGIC datasets showed slightly discrete characteristics on their basis. Figure 2 revealed the feature of assimilated and observed data, which also verified the effectiveness of NCAR meteorological parameters datasets.
2.2. Modeling Method of the Evaporation Duct Characteristics

The modified refractive index profile at a specific position can be predicted by theoretical methods based on the Monin–Obukhov similarity theory [22–25], utilizing observed meteorological parameters at the sea surface and a specific height. Therefore, the evaporation duct height (EDH) was determined as the altitude of the minimum modified refractive index.

The Naval Postgraduate School (NPS) model was introduced in 2000 [25]. The feasibility of the NPS model was analyzed in previous studies [19,25] and it also performed well in prediction accuracy compared with measured data [25,26]. One of its specific features is that it first obtains the vertical profile of temperature \( T \) and specific humidity \( q \). During the calculation, the scale parameters and thermodynamic roughness height of the sea surface are defined by the COARE 3.0 algorithm [27], and the wind speed and temperature under stable conditions are calculated by the profile stability functions [27]:

\[
\psi_h = \frac{-b_h}{2} \ln(1 + c_h \xi + \xi^2) \left( -\frac{a_h}{b_h} + \frac{b_h c_h}{2 b_h^2} \right) \times \left( \ln \frac{2^h + c_h + b_h}{2^h} - \ln \frac{c_h - b_h}{c_h + b_h} \right)
\]

where \( a_h = b_h = 5, c_h = 3, B_h = \sqrt{3}, \xi = z/L \) is the Monin–Obukhov parameter, which is used to express the atmospheric stability; \( z \) is the altitude; and \( L \) is the similarity length.

According to the temperature profile \( T(z) \), the atmospheric pressure profile \( p(z) \) can be obtained by integrating the hydrostatic equation and the ideal gas law [28]:

\[
p(z_2) = p(z_1) \exp \left( \frac{g (z_1 - z_2)}{RT_v} \right)
\]

\[
T_v = [T_v(z_1) + T_v(z_2)]/2
\]

where \( z_1 \) and \( z_2 \) are altitudes; \( R \) is the gas constant for dry air with 287.04 J/kg/K; \( g \) is the gravitational acceleration; and \( T_v \) is the virtual temperature.

Hence, the water vapor pressure \( e \) can be obtained [24]:

\[
e = \frac{q p}{\epsilon + (1 - \epsilon) q}
\]
where ε is a constant with 0.62197 [24].

Therefore, the refractivity profile is determined according to Equation (2), and the modified refractive index can be analyzed sequentially.

### 2.3. Modeling Method of the Communication Effect

While communicating in the ducting layer, electromagnetic waves can be transmitted to a distance that is beyond line-of-sight [8,10]. However, the spatial and temporal distribution of meteorological parameters is uneven, resulting in a variation of communication effects under this mechanism [29]. Therefore, the Parabolic Equation Toolbox (PETOOL) [30] with parabolic equation (PE) method [31] was used to simulate the propagation loss under microwave channels.

For a microwave communication system, the path loss budget A can be expressed as:

\[
A = P_t + G_t + G_r - S - 10 \log 10(B)
\]

where \(P_t\) is the transmitting power; \(G_t\) and \(G_r\) are transmitting and receiving antenna gain, respectively; \(S\) is the noise level of the receiver; and \(B\) is the receiver bandwidth in Hz. The typical values of \(P_t\), \(G_t\), \(G_r\), and \(S\) in a communication system were selected as 40 dBm/10 W, 30 dBi, 30 dBi [32], and -150 dBm (1 Hz) [33], respectively. Thus, the path loss budget \(A\) could be set as 250 dB at 1 Hz, or 160 dB at 1 GHz, for the receiver to demodulate the signal.

### 3. Results and Discussion

#### 3.1. Analysis of the Evaporation Duct Characteristics

The Taiwan Strait is the confluent area between the SCS and the East China Sea, and is also one of the interaction areas of the Kuroshio Current [17]. Moreover, as one of the major sources of the Tsushima Warm Current, the TSWC exists all year round [17]. It has an overwhelming influence on the heat balance in this area, especially in summer [18]. Intense evaporation over the oceans can be maintained throughout the year, while the SST reaches nearly 30 °C in summer and 20 °C in winter, which is conducive to increasing the occurrence of the evaporation duct.

Based on NCAR datasets in 2020 and the NPS model, the average EDH in the Taiwan Strait during July 2020 is shown in Figure 3. Affected by the TSWC, the yellow area representing high EDH is distributed around the Taiwan Strait, which forms a distinct contrast with any other southern and eastern coastal area in China. The maximum height was close to 35 m, while most of the calculated region was concentrated around 10 m.

![Figure 3. The average EDH in the Taiwan Strait during July 2020.](image)

Monthly and hourly statistical results of the EDH at a typical position (23.4° N, 120.0° E) of the Taiwan Strait are shown in Figures 4 and 5, respectively. To analyze the pattern of the EDH variation with the alternation of day and night, we used local time (Beijing time) instead of Universal Time Coordinated (UTC). From 9 to 14 o’clock, the percentage of the EDH exceeding 10 m was significantly higher than in other periods, and
the proportion reached over 90%. In addition, the analyzed position could maintain high evaporation intensity as night approached, which constructed favorable communication conditions. The lowest EDHs were clustered at sunrise and sunset, affected by the transition between stable (when the air–sea temperature difference (ASTD) was greater than 0) and unstable conditions (when the ASTD was less than 0). In terms of seasonal characteristics, the EDH was significantly increased in summer. The average EDH reached 29 m in July, while the percentage of the EDH exceeding 10 m was close to 100%.

Figure 4. Temporal distribution of the EDH in the Taiwan Strait during 2020.

Figure 5. Percentage of the EDH exceeding 10 m in the Taiwan Strait during 2020.

Figure 6 displays the statistical results of the EDH in different periods and seasons with a violin chart.

For different periods, the distribution of the EDH was mainly clustered in the range of 10 m–25 m from 9 to 14 o’clock, while a large number of the EDH were lower than 10 m in other periods. Influenced by the unstable condition, partial height increased to nearly 40 m during this period.

Furthermore, the distribution of the EDH in summer also showed distinctive seasonal characteristics from 9 to 14 o’clock; the maximum EDH exceeded 32 m, while it was lower than 28 m in other seasons.
3.2. Analysis of the Communication under Evaporation Ducts

3.2.1. Propagation Effect

Based on the evaporation duct characteristics at the analyzed position \((23.4^\circ \text{ N}, 120.0^\circ \text{ E})\) in Figure 3, we investigated the communication effects across the Taiwan Strait under the evaporation duct, focusing on quality and accessibility. With a view to providing favorable support for maritime applications across the Taiwan Strait, a communication radius of 300 km was considered, which could basically cover the northeast to southwest area. The propagation effect at the receiving position 300 km away using the evaporation duct is shown in Figure 7; monthly and hourly statistical results of path loss and serviceability ratio with 8 m antenna height at 10 GHz are described. Considering the analysis results in Section 2.3, a path loss budget of 250 dB was set, in which the receiver could demodulate the signal at 1 Hz.

Figure 6. Distribution of the EDH in the Taiwan Strait in different periods and seasons during 2020: (a) statistical results from 9 to 14 o’clock; (b) statistical results in other periods.

Figure 7. Propagation effects under the evaporation duct channel at the analyzed position \((23.4^\circ \text{ N}, 120.0^\circ \text{ E})\) for a 300 km range during 2020: (a) serviceability ratio at 1 Hz at different times of the day; (b) path loss distribution at different times of the day; (c) path loss spatial distribution of transmission link in the Taiwan Strait; (d) statistical results of path loss in different months; (e) serviceability ratio at 1 Hz in different months.
Most periods are depicted in blue, representing lower path losses, in the contour map of Figure 7c. A wide contour area with a path loss below 160.0 dB from 9 to 14 o’clock emerged, which may supply efficient support for constructing a communication system using evaporation ducts. The red covered area, representing maximal losses, mainly occurred at night-time (from 19 to 4 o’clock), which may lead to serious signal interruptions.

The monthly median path losses, presented as the black line in the colorful boxes in Figure 7d, were around 150 dB. The serviceability ratio fluctuated wildly, in Figure 7e, varying from a minimum of 45.83%, to a maximum of 100.00%. A noticeable proportion of path losses exceeded the preset budget from January to April, and signal interruptions may, in the future, occur from time to time during this period. In contrast, the overall path loss was significantly reduced in summer and autumn, and the serviceability ratio continuously exceeded 80%.

3.2.2. Communication Effect

Based on the analysis of propagation characteristics, the bit-error-rate (BER) was introduced to evaluate the communication effect in the evaporation duct. According to communication theory, the BER in BPSK modulation is a function of SNR [8]:

$$\text{BER} = 0.5 \cdot \text{erfc}\left(\frac{\text{SNR}^{0.5}}{0.5}\right)$$

(8)

High-quality transmission (defined as BER < 10^{-5}) in BPSK modulation occurs when the SNR at the receiving terminal is greater than 9.6 dB [8]. In contrast, the communication system is unable to work normally (BER > 10^{-1}) when the SNR is less than –0.8 dB [8]. As shown in Figure 8, the proportion of high-quality transmission during 9–11 o’clock was 97.72%, and the percentage grew to 98.72% from 12 to 14 o’clock. Communication effects suffered a night-time off-peak, with the ratio reduced to 86.20% from 19 to 4 o’clock.

Figure 8. The percentage of high-quality transmission in the Taiwan Strait.

Communication quality could be further enhanced by using the advantageous period of the evaporation duct. The communication effect in the highest serviceable period (from 12 to 13 o’clock) is shown in Figure 9, and the communication system can be used normally without interruption (BER > 10^{-1}) during this period.
Figure 9. The SNR and BER of periods from 12 to 13 o’clock in the Taiwan Strait during 2020.

The results showed that high-quality transmission could be achieved 98.90% of the time, throughout the year, and that 89.89% of the SNR exceeded 90 dB. Therefore, the communication system across the Taiwan Strait could be feasibly improved by using evaporation ducts.

4. Conclusions

To explore a new and effective method for maritime communication across the Taiwan Strait, we presented a preliminary investigation of wireless microwave transmission in an evaporation duct. Based on the meteorological parameters drawn from NCAR datasets, the temporal characteristics of the EDH at a typical position (23.4° N, 120.0° E) of the Taiwan Strait during 2020 were analyzed with the theoretical method of the NPS model. Moreover, transmission in the ducting layer was further analyzed from the perspectives of propagation loss and communication effect.

Affected by the TSWC, the evaporation around the Taiwan Strait is significantly higher than in any other area in the SCS [16]. Our model showed that, during 2020, the percentage of EDH exceeding 10 m reached over 90% from 9 to 14 o’clock. Using the favorable channel conditions in this period, a wide contour area with a path loss below 160.0 dB emerged, with a serviceable ratio of 99.00% at a 300 km transmission range. The high-quality transmission in BPSK modulation occurred for 98.90% of the year from 12 to 13 o’clock, with 89.89% of the SNR exceeding 90 dB. The preliminary investigation in this study may provide basic support for constructing a communication system using evaporation ducts across the Taiwan Strait.

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