An experimental study of the effects of the evaporation duct on microwave propagation

An Experimental Study of the Effects of the Evaporation Duct on Microwave Propagation

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***Abstract*—This paper presents the results of a study on the effects of the evaporation duct on microwave propagation in the Irish Sea. The evaporation duct is a phenomenon that occurs almost permanently over the earth's oceans and can be exploited to enable over the horizon communications in the marine environment. The study consisted of an experimental test, where signal strength from a shore-based transmitter was recorded at a number of distances. The results of this experiment were compared to simulated values. Atmospheric data used to simulate the signal propagation was taken from weather buoys in the Irish Sea. It was found that the evaporation duct does have an effect on microwave signals and can be used to extend microwave communications beyond the horizon. This could be useful in enabling high bandwidth communications links to or between offshore assets and equipment including navigation buoys, ships, renewable energy infrastructure and lighthouses which are often situated beyond line of sight of land.**

Keywords—Evaporation duct, microwave propagation, marine communications, marine boundary layer, remote presence, high bandwidth

I. INTRODUCTION

One of the biggest challenges in the maritime and offshore renewable energy sectors is the inspection and maintenance of infrastructure/assets and equipment at sea. To ensure these are operating successfully a ship must often be sent at regular intervals so that maintenance teams can be deployed. To reduce the cost of this, remote presence where the operators of Remotely Operated Vehicles (ROVs) are based onshore is being investigated [1]. A major part of this remote presence system involves transmitting a live video feed from the ROV back to the operator onshore. In order for the remote presence system to work successfully, a high bandwidth, low-latency link between the vessel and shore is necessary.

Achieving high bandwidth communication once a ship goes beyond the visual horizon has always been a challenge. Traditional microwave links used in terrestrial communications systems cease to work beyond line of sight, and satellite communications can be prohibitively expensive for extended use. Using a phenomenon known as the evaporation duct to extend microwave communications beyond the horizon is a possible solution to this problem [2]. The evaporation duct occurs when water evaporates off the sea surface, creating a layer of humid air. Above this layer the air is less humid, and the rapid change from humid to less humid air causes a change in the refractive index. This sharp change in refractive index creates the evaporation duct, which can act like a leaky waveguide and cause signals to refract around the curve of the earth [3].

A major drawback to using the evaporation duct to extend communications is the high variability in its strength. The possibility of being able to use the evaporation duct for communications varies widely with the weather and seasons, sometimes changing from strong to non-existent in a single day. The strength of the evaporation duct is commonly quantified using a measurement known as the evaporation duct height (EDH) [4]. While the EDH can be determined by direct measurement of the refractivity of the air, this method is difficult and impractical so it is recommended to calculate the EDH using bulk meteorological measurements [5]. In this paper, these measurements are taken from weather buoys in the Irish Sea. The EDH can then be calculated using a mathematical model. There are several that can be used, but the most popular is the Paulus-Jeske model [5], [6]. This model takes the air temperature, sea temperature, wind speed and relative humidity, and uses them to calculate a value for the evaporation duct height.

Past research on the evaporation duct has been conducted by the United States Navy to examine its effect on marine radar [7], [8]. They showed that the evaporation duct could be exploited to more than double the detection range of some radar systems. As well as experimental studies, the United States Navy has developed several models for calculating the evaporation duct height, and for simulating the propagation of electromagnetic waves in the evaporation duct [9]. Recently, attention has focused on the prospect of using the evaporation duct to extend communication links. Some research on this has been done in Australia, where a 78 km link was set up over the ocean. This study used a commercially available 10.5 GHz microwave communication system, and used the evaporation duct to extend it beyond the horizon [10]. A similar study was done in Malaysia, where a 64 km link between shore and a moving vessel was set up [11].

The main difference between the research presented in this paper and previous research is that the others were in tropical waters with very different atmospheric conditions to the Irish Sea. While the Irish Sea is not as conducive to the formation of evaporation ducts as more tropical areas, this paper will show that evaporation ducts do occur there and can be used for extending communications beyond the horizon.

This paper consists of three parts. First, the methods used to get both simulated and experimental results are discussed. Then

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the results from these are discussed and summarized. Finally, the paper concludes with a discussion on the implications of this study and recommendations for future research.

II. Methods

A. Simulation

In order to simulate the effects of the evaporation duct on microwave signals, it was necessary to find values for the evaporation duct height in the Irish Sea. Values for sea temperature, air temperature, wind speed and humidity over the past 17 years were taken from the Marine Institute network of weather buoys [12]. Using data from the M2 buoy in the Irish Sea, the EDH was calculated using the Paulus-Jeske method and averaged over the time period. The distribution of evaporation duct heights can be seen in the figure below. While the mean EDH was 6.87 m, it is clear that the EDH is highly variable.

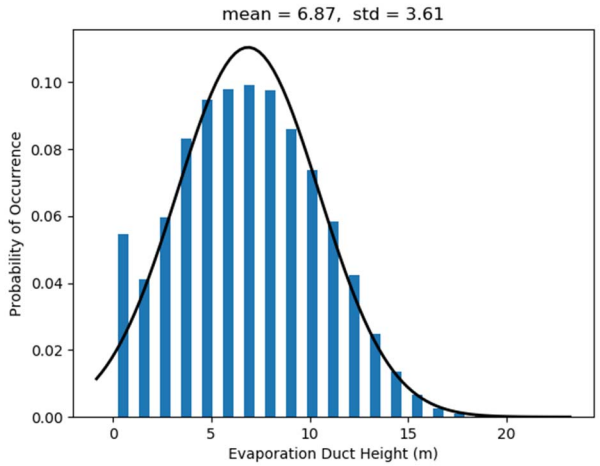

Figure 1: Distribution of evaporation duct heights at M2 buoy

For comparison, the average global EDH is 13.1 m [13]. While the evaporation duct in the Irish Sea may not be as strong as in other areas of the world, an evaporation duct does exist more than 94% of the time. As well as the average over the entire year, the average EDH for each month was found. It can be seen in the figure below that the evaporation duct is the strongest in late autumn and early winter, and weakest in late spring and early summer. For December, when the experiment took place, the average EDH was calculated to be 8.82 m.

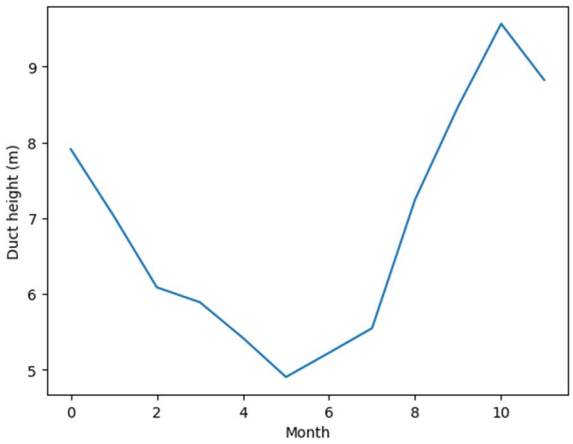

Figure 2: Average monthly evaporation duct height

Once expected values for the EDH had been found, it was then possible to simulate the effects of the evaporation duct on microwave signals. Several signal propagation simulation packages that take into account the evaporation duct are available. The Advanced Refractive Effects Prediction System (AREPS), developed by the US Navy for simulating radar performance over water, is a popular software package [14]. However, AREPS is no longer available to the public so an older version of the software, the Engineers Refractive Effects Prediction System (EREPS), was used [13]. While EREPS was developed for simulating radar propagation, it also works well for simulating microwave communications due to the similar range of frequencies. EREPS was used to simulate the planned experiment over a range of frequencies and antenna heights. An assumption made during these simulations was that the EDH was homogenous over the course of the whole link. While this is unlikely to be the case in reality, the lack of atmospheric data for each point in the route means that assuming a homogenous atmosphere is the only viable way to model it.

B. Equipment

To choose the best frequency for propagation in the evaporation duct, simulations were run over a range of different frequencies from 1 to 20 GHz. The EDH was set to the average EDH for December. From these simulations, it was found that the best frequency to use would be in the 15-18 GHz range. The ideal antenna height was found in a similar manner, by simulating signal propagation at a range of different heights. It was found that the ideal antenna height for the expected conditions would be approximately 4-6 m above sea level.

Two commercially available 17GHz radios with parabolic antennas were chosen [15]. The radios are capable of 22 dBm power output, and the 2 foot parabolic antennas have a gain of 39 dBi. One was mounted on a building onshore and the other mounted on a moving vessel. The antenna onshore was mounted on the roof of a building approximately 12 m above the sea surface, and the antenna on the vessel was mounted on a railing approximately 6 m above the sea surface. While physical limitations meant the shore antenna was above the ideal height for the expected conditions, it was still expected to provide adequate performance. The building the shore antenna was mounted on was approximately 50 m from the water's edge and

the vessel antenna was placed less than 10 m from the water, so the over land component of the link would be negligible.

C. Antenna Stabilization

As the antenna used on the vessel had a beamwidth of just 1.8°, it was necessary to implement a stabilisation system to counteract the movement of the vessel. A pan/tilt positioner was used to adjust the elevation and azimuth of the antenna [16]. The antenna was mounted on the top of the positioner, as can be seen in Figure 3 below. The vessel's position, heading, pitch and roll data were taken from a feed from the vessel's reference system. This data was then used along with the shore location to calculate the ideal pan and tilt angles to point the vessel antenna at the shore antenna. As the positioner was only a two-axis system and the motion of the vessel was in three axes, a certain amount of control over the position of the antenna was lost. However, it was found that the most vessel movement during this experiment was along the y-axis, or pitching, so with the antenna pointing over the stern of the vessel it was possible to counteract most of the vessel motion. Further accuracy could be gained in the future by using a three-axis positioner system.

Figure 3: Antenna and positioner mounted to vessel railing

D. Experimental Procedure

The vessel started at a point 12 km from the shore antenna. Once the stabilisation system was started and the antennas were fully aligned, the vessel moved away from shore at a steady speed of 6.5 kts. As the shore antenna was fixed in one position, the vessel could only move in one dimension. The figure below shows the path of the vessel as it moved away from shore. The locations of the buoys used to record atmospheric data during the experiment are also shown on the map.

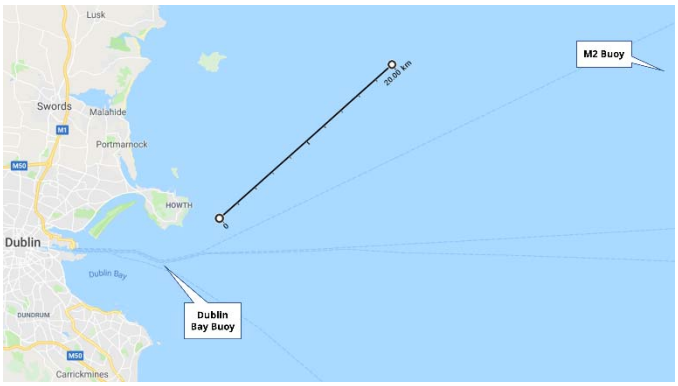

Figure 4: Survey path and buoy locations

Measurements of the signal strength received by the antenna on the vessel were taken every 500 m until the signal was lost, approximately 32 km from shore.

E. Comparison to Simulations

Atmospheric conditions during the experiment were taken from both the Marine Institute M2 buoy and the Irish Lights Dublin Bay Buoy. Due to no sea temperature measurement on the M2 buoy at this time, the sea temperature was taken from the Dublin Bay Buoy [17]. These measurements were then used to calculate the evaporation duct height. As atmospheric measurements on the buoy were only taken once per hour, this leaves some uncertainty about the exact EDH at all times during the experiment. For the purposes of simulation, the EDH between the known points was interpolated using the Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) method. The results of this can be seen in the figure below.

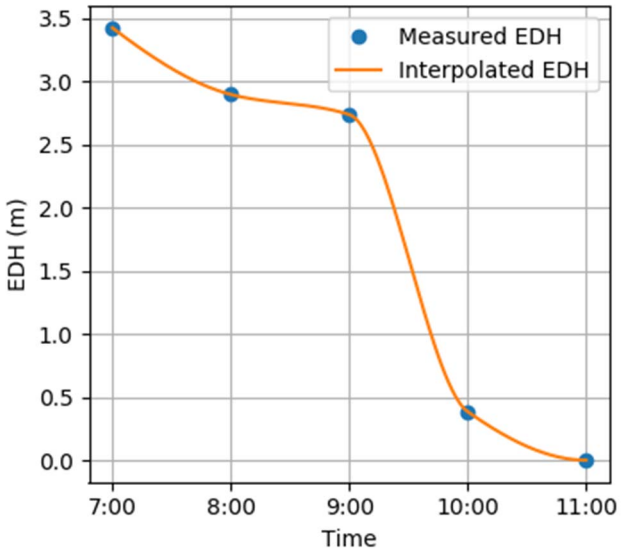

Figure 5: EDH vs. time during the experiment

Taking into account the EDH at each point in time during the experiment, the signal propagation was simulated in EREPS for each of the distances from shore. The atmospheric conditions during the experiment were relatively poor. The evaporation

duct height calculated varied from approximately 2.8 m down to less than 0.4 m. This EDH is below the average for December, and well below the ideal conditions for over the horizon communications. However, it can be seen from both the experimental and simulated results that some signal was received beyond the horizon.

III. Results

The received signal strength (RSS) measured in dBm was recorded from the radio on board the vessel. The radio used on shore had a power output (P) of 22 dBm, and both antennas had a gain (G_{TX}, G_{RX}) of 39 dB. Using these values, the total path loss (PL) between the antennas could be calculated in the formula below.

$$PL = RSS - P_{TX} - G_{TX} - G_{RX}$$

$$PL = RSS - 22 - 39 - 39$$

The experimental and simulated path loss versus distance from shore can be seen in the graph below. It is clear that while they both appear to follow the same downward curve, the experimental results stay approximately 30-40 dBm below the simulated results. This may be explained due to losses not taken into account in the simulation such as antenna alignment, precipitation, cable losses etc.

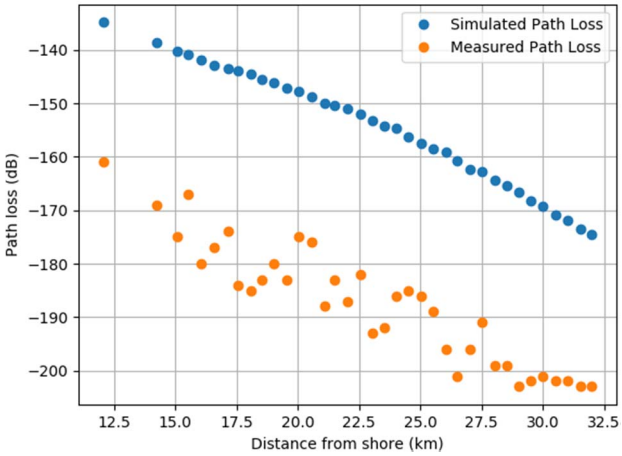

Figure 6: Path loss (simulated and measured) vs. distance

With the shore antenna at 12 m above the sea surface, and the vessel antenna at 6 m, the two antennas will still be in line of sight up to 21.1 km. Beyond this distance, the main propagation mode for the link is the evaporation duct. As signals were received well beyond this distance, it shows that the evaporation duct in the Irish Sea effects microwave signals and guides them beyond the horizon.

IV. Conclusion

In conclusion, it was seen that when using the right equipment and setup, the evaporation duct can be used to extend the range of microwave communications. While it may not be possible to rely on the evaporation duct for communications all the time, it could be used in conjunction with satellite or other communications methods to reduce the cost and increase the availability of high bandwidth marine communications. When the evaporation duct height is low and the data speed over the link is low or non-existent, the link could automatically switch over to use satellite communications. Also, as the system used in this experiment is an off the shelf microwave link, it could be used to provide line of sight communications when the vessel is closer to shore.

In addition to its use in remote presence systems mentioned at the start of this paper, the evaporation duct could also be used to provide high bandwidth communications to a number of maritime users. Remote observation stations such as weather buoys and lighthouses beyond the horizon could make use of it to send environmental and monitoring data back to shore [18]. If the data to be sent is not time critical it could be stored at the station when a weak evaporation duct makes communications impossible, and sent when the duct is stronger.

Further research in this area is needed to investigate the potential amount of time a communications link using the evaporation duct would be operational due to changes in the EDH. Such an experiment could use historical data for theoretical analysis from the Marine Institute Weather Buoy and the Irish Lights MetOcean Buoy networks. The equipment used in this experiment could be set up at a suitable location and left running for a year or more to determine annual variation in availability due to EDH variations. Another area that may be worth investigating is the effects of both antenna height and frequency on signal propagation in the evaporation duct. While the values chosen worked well for this experiment, being able to vary these factors as the EDH changes may result in more performance gains.

References

[1] E. Omerdic, D. Toal, G. Dooly, and A. Kaknjo, ‘Remote presence: Long endurance robotic systems for routine inspection of offshore subsea oil and gas installations and marine renewable energy devices’, in *2014 Oceans - St. John’s*, 2014, pp. 1–9.

[2] L. Robinson, T. Newe, J. Burke, G. Dooly, J. Coleman, and D. Toal, ‘High Bandwidth Maritime Communication Systems - Review of Existing Solutions and New Proposals’, presented at the 2nd URSI AT-RASC, Gran Canaria, 2018.

[3] A. Kukushkin, *Radio Wave Propagation in the Marine Boundary Layer*. Wiley-VCH, 2004.

[4] Y. Shi, Q. Zhang, Y. Yang, K. Yang, B. Lei, and Y. Ma, ‘Frequency response of evaporation duct channel for electromagnetic wave propagation’, in *OCEANS 2016 MTS/IEEE Monterey*, 2016, pp. 1–5.

[5] R. A. Paulus, ‘Specification for Evaporation Duct Height Calculations’, p. 35, Jul. 1989.

[6] S. M. Babin, G. S. Young, and J. A. Carton, ‘A New Model of the Oceanic Evaporation Duct’, *J. Appl. Meteorol.*, vol. 36, no. 3, pp. 193–204, Mar. 1997.

[7] K. D. Anderson, ‘Radar measurements at 16.5 GHz in the oceanic evaporation duct’, *IEEE Trans. Antennas Propag.*, vol. 37, no. 1, pp. 100–106, Jan. 1989.

[8] H. Hitney and R. Vieth, ‘Statistical Assessment of Evaporation Duct Propagation’, *IEEE Trans. Antennas Propag.*, vol. 38, no. 6, pp. 794–799, Jun. 1990.

[9] A. E. Barrios, 'Considerations in the development of the advanced propagation model (APM) for U.S. Navy applications', in *2003 Proceedings of the International Conference on Radar (IEEE Cat. No.03EX695)*, 2003, pp. 77–82.

[10] G. S. Woods, A. Ruxton, C. Huddlestone-Holmes, and G. Gigan, 'High-Capacity, Long-Range, Over Ocean Microwave Link Using the Evaporation Duct', *IEEE J. Ocean. Eng.*, vol. 34, no. 3, pp. 323–330, Jul. 2009.

[11] K. S. Zaidi, V. Jeoti, M. Drieberg, A. Awang, and A. Iqbal, 'Long-range mobile communication over sea utilizing evaporation duct', in *2017 Progress in Electromagnetics Research Symposium - Fall (PIERS - FALL)*, 2017, pp. 846–850.

[12] 'Irish Weather Buoy Network | Marine Institute'. [Online]. Available: http://www.marine.ie/Home/site-area/data-services/real-time-observations/irish-weather-buoy-network. [Accessed: 01-Aug-2018].

[13] W. L. Patterson *et al.*, 'Engineer's Refractive Effects Prediction System (EREPS) Version 3.0'. 1994.

[14] W. L. Patterson, 'Advanced Refractive Effects Prediction System (AREPS)', in *2007 IEEE Radar Conference*, 2007, pp. 891–895.

[15] 'ALFO Plus'. [Online]. Available: https://www.siaemic.com/index.php/products-services/telecommunication-systems/microwave-product-portfolio/alfo-plus. [Accessed: 20-Dec-2018].

[16] 'FLIR PTU-D48E Pan/Tilt Unit for side-mounted payloads up to 15 lbs | FLIR Systems'. [Online]. Available: https://www.flir.com/products/ptu-d48e/. [Accessed: 20-Aug-2019].

[17] 'MetOcean Charts'. [Online]. Available: https://www.irishlights.ie/technology-data-services/metocean-charts.aspx. [Accessed: 06-Sep-2019].

[18] 'Data services'. [Online]. Available: https://www.irishlights.ie/technology-data-services/data-services.aspx. [Accessed: 13-Sep-2019].