TAT.py: Tropospheric Analysis Tools in Python

Marco Zennaro
STI Unit
ICTP
Trieste, Italy
mzennaro@ictp.it

Marco Rainone
STI Unit
ICTP
Trieste, Italy
mrainone@ictp.it

Ermanno Pietrosemoli
STI Unit
ICTP
Trieste, Italy
epietros@ictp.it

***Abstract*—Wireless links extending beyond the horizon at frequencies of 868 MHz cannot be attributed to ionospheric reflections, since those only happen at much lower frequencies. For very long links the propagation can be attributed to the bending of the radio waves due to anomalies in the atmospheric refractivity index. These anomalies are caused by abnormal variations in temperature and humidity versus elevation that result in tropospheric ducts that can reach thousands of kilometers. Leveraging available data from radiosondes that are periodically launched worldwide, it is possible to determine the refractivity index profile and from this the conditions for the existence of a tropospheric duct. We developed a series of Python tools to analyze such links and applied them to assess the propagation mechanism in three cases, reported by other users, that overcome the earth's curvature obstruction. These tools can be used to determine the presence of ducting conditions at any place in the vicinity of a radiosonde launching site and results are valid at other frequencies as well. They can also be used by people not versed in Python by using the Jupyter Notebook hosted in Google Colab.**

***Index Terms*—Software tools, propagation, tropospheric, internet of things**

I. Introduction

TROPOSPHERIC propagation beyond the horizon is a well known field of research since WW II [12]. Oftentimes people have experienced abnormal reception of FM radio channels or TV broadcasts, especially in the summer. With the exponential growth of Internet of Things (IoT) networks, some users have documented very long links happening on the ISM bands (868 MHz in Europe) used by such devices. It is worth noting that beyond the horizon transmission is also a source of interference to other users, which might be unaware of the origin of the spurious signals [1]. Shedding light on the anomalous propagation mechanism involved is a first and important step in the mitigation efforts. Given the ever increasing use of the radioelectric spectrum it is worthwhile to investigate real world propagation based on experimental results, since the numerous models, like the Cost-231 Hata [11], the Stanford University Interim (SUI) and the Ericsson [8] that have been developed to estimate the path loss show significant variations with respect to the measurements. Even the irregular terrain model (ITM, or Longley-Rice) [9], which relies on digital elevation maps and ray tracing, fails to incorporate the anomalous propagation effects.

In a previous study [2], we focussed on the use of the crowd sourced initiative TheThingsNetwork (TTN), since it allowed leveraging the openness of that system and the great number of TTN gateways deployed globally, to check the reach of a simple IoT node that we have installed on the roof of our institute. TTN is currently undergoing transformations that might jeopardize its accessibility as an open tool, so we have developed a solution that no longer depends on TTN. Presently, we generalize the analysis to cover any wireless link for which the transmitter and receiver sites are specified, as well as the date on which the very long distance link was observed.

Anomalous tropospheric propagation is defined [3] as a transmission that extends beyond the geographical horizon. Normally, signals start to decay rapidly beyond the geographical horizon. Viewers living in such a "deep fringe" reception area will notice that during certain conditions signals from distant broadcasters, normally masked by noise, increase their strength to the point of allowing normal reception. Furthermore, in special conditions related to the state of the troposphere at a given time along the trajectory, the signals can reach extremely long distances [4], [7], [5], [15]. Tropospheric propagated waves travel in the part of the atmosphere adjacent to the surface and extending to some 12000 m. Such signals are thus directly affected by weather conditions extending over hundreds of kilometers.

Although the maximum transmitted power of 14 dBm in LPWAN networks in Europe [6] is much lower than that of FM or TV transmissions, the advantage in terms of receiver sensitivity of both LoRa (thanks to the processing gain offered by spread spectrum modulation) and Sigfox (thanks to the ultra narrowband employed), explains why such long distance paths can be spanned, provided that the anomalous propagation conditions exist.

In this paper we present a set of software tools that allow the analysis of any radio link making use of the publicly available IGRA (Integrated Global Radiosonde Archive) database [10] of meteorological radiosondes that are periodically launched all over the globe.

These tools facilitate the analysis of beyond the horizon propagation by automating the process of identifying the nearest radiosonde launch site to any pair of points at a specific date.

The data gathered by the identified radiosonde are then used to graph the refractivity gradient versus height, the information needed to assess the possible presence of the

978-1-6654-2854-5/21/$31.00 ©2021 IEEE

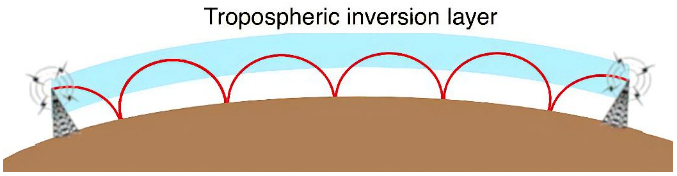

Fig. 1. Tropospheric duct propagation: Wave reflection on the surface (water or ground) is sharp, while in the tropospheric layer a succession of gradual bends emulates a softer reflection. Happens more frequently in paths over water, which is a better reflector than ground, while its evaporation favors the formation of inversion layers,

Fig. 2. Jupyter Notebook hosted by Google Colab

conditions for the existence of super-refraction (which can extend the propagation moderately beyond the line of sight) or tropospheric ducts, which can explain transmissions over distances of thousands of kilometers. Figure 1 depicts the latter case, which is more frequent in paths over seawater, since it is a very good reflector. It is worth noting that the reduction of the path loss with respect to that in free space can be attributed to the fact that the duct acts as a sort of waveguide, confining the spreading of the signal in the vertical direction.

II. Python Tools

We built a series of software tools to analyze anomalous tropospheric propagation links. They are available on Github[1] under an MIT License and also as a Jupyter Notebook hosted by Google Colab[2] as shown in Figure 2. Sharing the code using Google Colab facilitates the usage of these tools by researchers, practitioners, or anyone interested, since there is no need to install any software (Colab runs in a browser). While the complete set of tools include more than 20 separate pieces of code (to parse data from online databases and find long links, to gather data from TTN, etc), in this paper we will focus on the tools that are part of the workflow shown in Figure 3 . All the code is compatible with Python 3 and runs on Windows, OSX and Linux devices.

[1]https://github.com/marcorainone/TropPOLoRaTools
[2]https://colab.research.google.com/drive/1cF3Ge2zFBydOPTaOSzhlsK4mHYmzkoNf

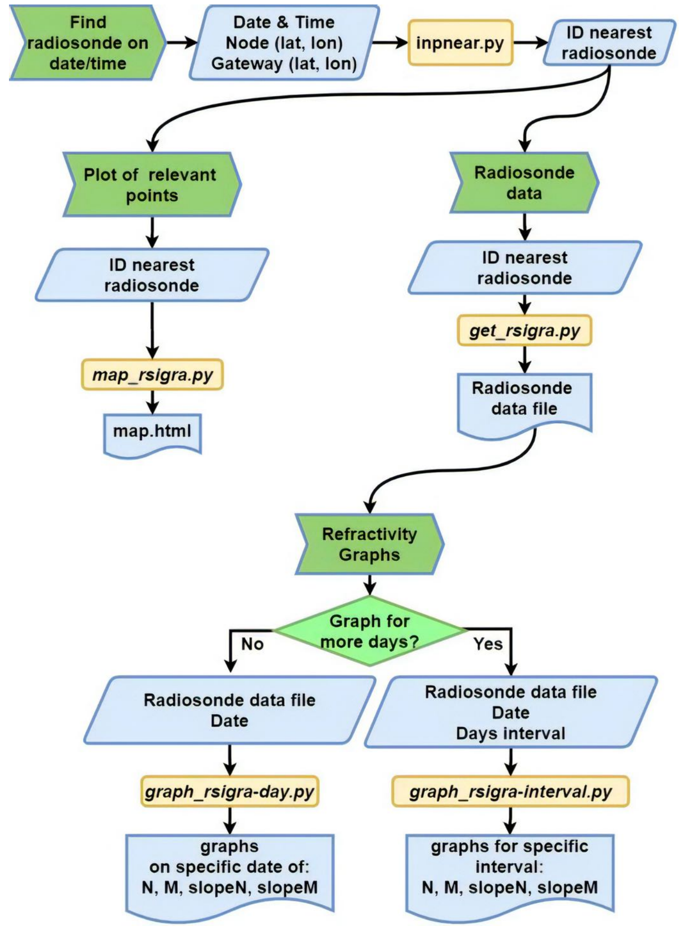

Fig. 3. Workflow using the Python tools developed.

Following is a description of the workflow to analyze a specific link.

1) the user launches the *ipnear.py* script and enters the geographical coordinates of the two extremes of the link, the transmitter and the receiver, or the node and the gateway using LPWAN's naming convention. Next the date and time when the link has been observed must be supplied. The output is the name of the radiosonde closest to the midpoint between the two ends which has measurements available for that specific date. To determine its location we use the IGRA database, which contains radiosonde and pilot balloon observations from over 2700 globally distributed stations.
2) to visualize the location of the radiosonde, launch the script called *map-rsigra.py*. This will produce a map similar to the one shown in Figure 5. This is not a mandatory step in the workflow, but gives an idea of where the nearest radiosonde is located.
3) after the closest radiosonde has been determined, data for the specific date and time has to be downloaded from IGRA. This is done using the *get-rsigra.py* script. No further input is needed as the necessary information has been inserted earlier. As output, the file from the

nearest radiosonde for the specific date and time is downloaded in idx format. From this file the refractivity index N, the refractivity module M, and their respective gradients (slopes) ΔN/Δh and ΔM/Δh, are obtained at each measurement height h. They will be used to check if the conditions for a tropospheric duct are met (some publications use the refractivity lapse-rate instead of the slope, which has the same value but opposite sign).

4) it is now possible to generate the graph of the refractivity gradient ΔN/Δh in N units per km by calling the *graph-rsigra-day.py* script. Whenever the gradient is between -79 and -157 the conditions for super-refractivity are in place, meaning that the curvature of the wave is much greater than that of the earth, and the radio horizon will be considerably greater than the geographical horizon. If the gradient falls below the -157 threshold, the possibility of the existence of a tropospheric duct is present [3], [5]. If the duct is confirmed, the wave will encounter a heavily perturbed layer that will reflect it back to the surface (either ground or water), where it undergoes another reflection upward. This process can repeat itself a number of times, depending on the reflectivity of the surface, which is very high in the case of seawater and the intensity of tropospheric layer inversion. So in essence, between the surface and the perturbed layer a sort of waveguide will be formed that can extend the transmission to very long distances. The trapping of the wave in the vertical plane accounts for the fact that the attenuation increases linearly with the distance, instead of quadratically as is the case in normal propagation conditions [7], so the received signal level could be higher than that of free space propagation. Figure 6 is an example of the output of the script showing the threshold for ducting conditions.
There is also the option to gather data for multiple dates, and this is done via the *graph-rsigra-interval.py* script. Figure 7 shows an interesting case in which only one of the launches from the site surpassed the -157 threshold that indicates the condition for the possibility of a tropospheric duct. These launches were made at the Rivolto site in Italy, which is the closest to the beyond the horizon links reported in [2] and is shown here only to demonstrate the variability of the refractivity index gradient over 4 consecutive days.

III. Use Cases

A. LoRaWAN link in Germany

Using TTNMapper, a popular application to check LoRaWAN coverage using TTN, we identified a 280 km long link crossing over Munich in Germany. Data about the link is provided in Table I. Leveraging our BotRF tool [13], that uses the ITM model and digital elevation maps, we obtained the corresponding terrain profile shown in Figure 4, evidencing that the line of sight is completely blocked and therefore the transmission must be attributed to anomalous tropospheric propagation. Launching the scripts produced Figures 5 and 6. Figure 5 shows that the radiosonde in the IGRA database which is closest to the center of the link lies at a distance of 25 km. Data collected by this radiosonde on the same day in which the anomalous propagation was reported, processed by the *graph-rsigra-day.py* script produced Figure 6. The -157 ΔN/Δh gradient in N units per km is shown to be crossed at an altitude of 1800 m, confirming the probable presence of a tropospheric duct. It is worth noting that anyone can perform this kind of analysis, even without command of the Python language, since it relies on openly available data, and the Colab tool is straightforward to use, opening many possibilities for Citizen Science initiatives.

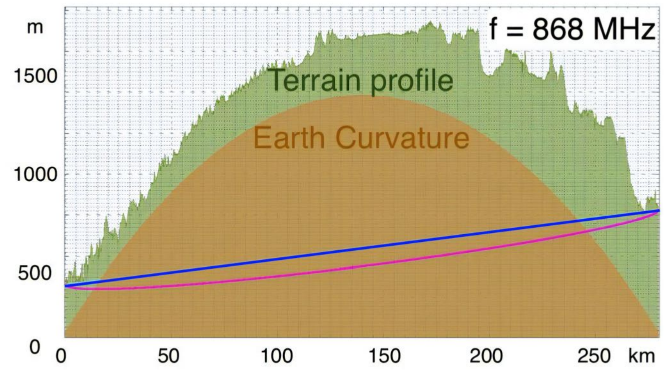

Fig. 4. Terrain profile obtained with the BotRF tool of the 280 km link in Germany, showing a completely blocked line of sight

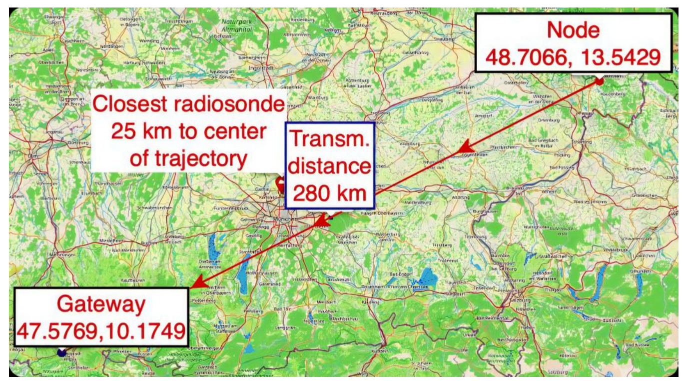

Fig. 5. Map of a 280 km tropospheric duct link in Germany showing the positions of the node, gateway and the closest radiosonde launch site.

TABLE I
Data for the link in Germany.

Node	48.7066, 13.5429
Gateway	47.5769, 10.1749
Date and Time	13/9/2020 at 10:46 GMT
Technology	LoRaWAN

B. LoRaWAN link Netherlands - UK

In the TTN forum there have been discussions about a long LoRaWAN link between the UK and the Netherlands. The link spanned 354 km, from Leusden, Netherlands to Northfleet,

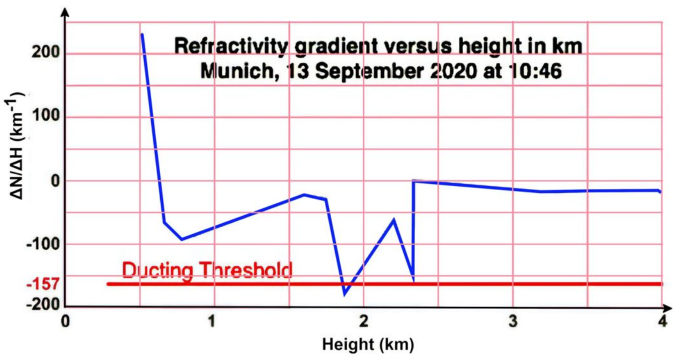

Fig. 6. Refractivity gradient ΔN/Δh versus height in Munich. The -157 threshold is crossed at the height of 1800 m denoting a tropospheric duct.

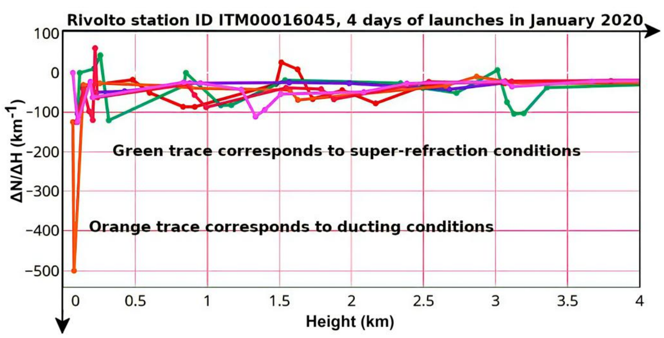

Fig. 7. Refractivity gradient ΔN/Δh versus height corresponding to 4 days launches from the ITM 00016045 station in Italy. Conditions for tropospheric duct were present at a height of 100 m on 12 January 2020.

UK. Data about this link are in Table II. Launching the bespoken scripts produced Figures 8 and 9. Figure 8 shows that the radiosonde in the IGRA database which is closest to the center of the link lies at a distance of 162 km from the center of the trajectory, but very close to the node in the Netherlands. Data collected by this radiosonde on the same day in which the anomalous propagation was reported, processed by the *graph-rsigra-day.py* script produced Figure 9. The -157 ΔN/Δh gradient in N units per km is shown to be crossed, confirming the probable presence of a tropospheric duct.

TABLE II
DATA FOR THE LINK UK - NETHERLANDS.

Node	52.1577,5.3729
Gateway	51.4661,0.3599
Date and Time	23/7/2019 at 23:24 GMT
Technology	LoRaWAN

C. Sigfox link between Portugal and Grand Canary Island

On social media some extremely long links have been documented using Sigfox [14]. As this is an LPWAN technology using a much narrower band than that of LoRaWAN, it is understandable that longer links can also be established, since the amount of noise entering the receiver is much lower.

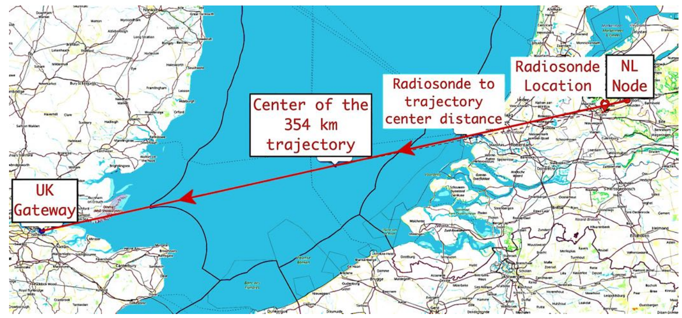

Fig. 8. Map of a 354 km tropospheric duct link from the UK to the Netherlands

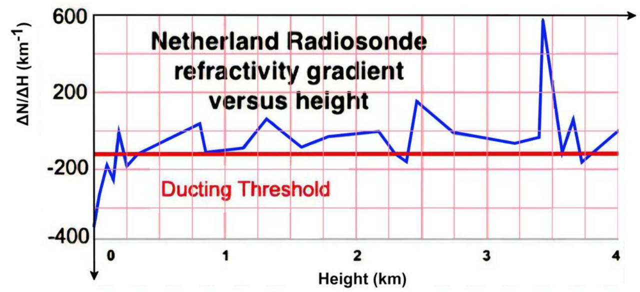

Fig. 9. Refractivity gradient ΔN/Δh versus height. The -157 threshold crossing indicates a tropospheric duct.

Thanks to the collaboration with the Sigfox operator we were able to get the exact positions and time of such long links. One of them spanned 1204 km, with the end node in Portugal and the gateway (base station) on Grand Canary Island, Spain. Data about the link is provided in Table III. Given the extremely long distance, only tropospheric ducting propagation can explain this link, entirely over sea water, which is a strong reflecting medium.

Launching the scripts we obtained Figures 10 and 11. Figure 10 shows that the nearest radiosonde is in Casablanca, Morocco, 400 km away from the center of the trajectory. In Figure 11 we see that the ΔN/Δh value drops below the threshold value of -157, so a tropospheric duct is clearly the propagation mechanism since the earth curvature is blocking the line of sight.

TABLE III
SIGFOX PORTUGAL TO SPAIN (GRAND CANARY) LINK.

Node	37.0858, -8.2352
Gateway	28.1464, -15.5376
Date and Time	8/8/2017 at 15:36 GMT
Technology	Sigfox

IV. CONCLUSIONS AND FUTURE WORK

We have presented a series of Python open source tools that can be used in an automated fashion to analyze wireless links that extend well beyond the geographical horizon. They were applied to explain the propagation mechanism in three

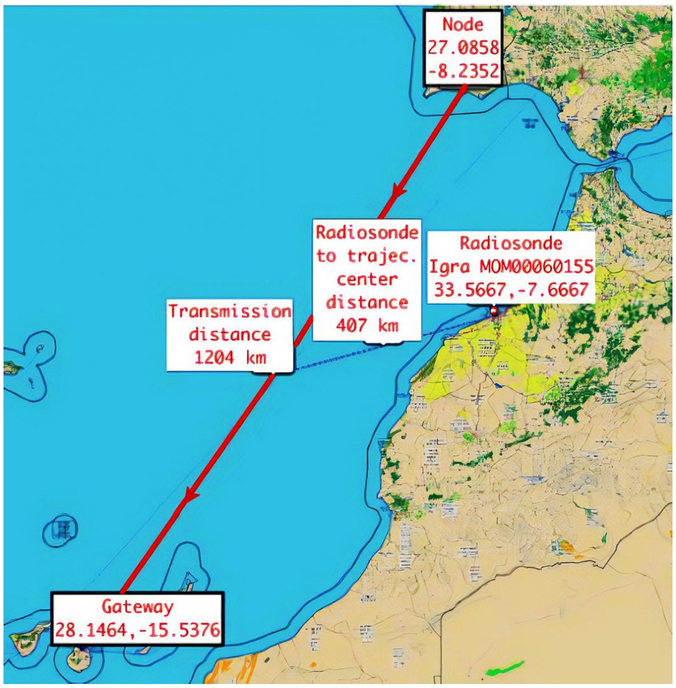

Fig. 10. Map of the node in Albufeira (PT), the gateawy in Grand Canary (ES) and the launching site of the closest radiosonde in Casablanca, Morocco.

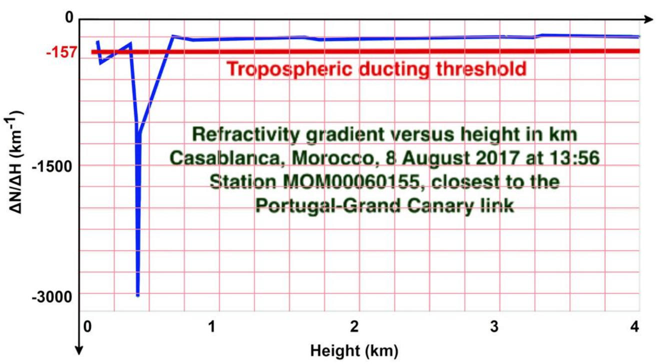

Fig. 11. Refractivity gradient $\Delta N/\Delta h$. The -157 N units per km threshold is crossed very close to the surface in this link between Portugal and Spain, as revealed by the tropspheric data gathered by the radiosonde in Morocco.

representative examples. One was over land and the other two over seawater, in which the reflections very often can negatively affect radio links. As an exercise of citizen science, these tools can be used by anyone to assess the existing tropospheric conditions in many places, in order to determine the type of anomalous radio propagation at a given date, leveraging publicly available radiosonde derived data. The Google Colab notebook can be used by any interested person (the only requirement being access to an Internet browser). Students,for instance, can acquire knowledge about real life propagation issues by exploiting open data and tools. Further details about the profile of the terrain between two points and the expected received signal strength under different refractivity conditions can be obtained by means of the RfBot tool mentioned, which uses the irregular terrain model (ITM) and digital elevation maps. Anomalous propagation is essentially independent of the signal's bandwidth, over a wide range of frequencies that extend from VHF to microwaves. There is the possibility that the identified radiosonde does not evidence the presence of a duct, due to the fact that even being the closest to the center of the trajectory it might miss local anomalies. In future work we will extend the tool to examine several radiosondes data in the proximity of the path of interest to address this situation.

Acknowledgment

The authors would like to thank Mr.Stéphane Driussi of HidnSeek for his kind collaboration. This research would have not been possible without the TTN community.

References

[1] Prediction procedure for the evaluation of interference between stations on the surface of the Earth at frequencies above about 0.1 GHz, Recommendation ITU-R P.452-16, p. (07/2015)

[2] Marco Zennaro, Ermanno Pietrosemoli, Marco Rainone, Daniele Trinchero, Mattia Poletti, and Giovanni Colucci. 2020. TROPPO LoRa: TROPospheric Personal Observatory using LoRa signals. In Proceedings of the 1st Workshop on Experiences with the Design and Implementation of Frugal Smart Objects (FRUGALTHINGS'20). Association for Computing Machinery, New York, NY, USA, 24–29. DOI:https://doi.org/10.1145/3410670.3410856

[3] Effects of tropospheric refraction on radiowave propagation, Recommendation ITU-R P.834-9, p.13 (12/2017)

[4] H. W. Ko et al., ANOMALOUS MICROWAVE PROPAGATION THROUGH ATMOSPHERIC DUCTS, Johns Hopkins APL Technical Digest, Volume 4, Number 1, 1983

[5] E. Dinc and O. B. Akan, "Channel Model for the Surface Ducts: Large-Scale Path-Loss, Delay Spread, and AOA," in IEEE Transactions on Antennas and Propagation, vol. 63, no. 6, pp. 2728-2738, June 2015, doi: 10.1109/TAP.2015.2418788.

[6] Short Range Devices (SRD) operating in the frequency range 25 MHz to 1 000 MHz; Part 2: Harmonised Standard for access to radio spectrum for non specific radio equipment, ETSI EN 300 220-2 V3.2.1 (2018-06)

[7] HANDBOOK ON RADIOMETEOROLOGY, Radiocommunication Bureau, 2013 edition https://www.itu.int/pub/R-HDB-26

[8] Zreikat, Aymen Djordjevic, Milan. (2017). Performance Analysis of Path loss Prediction Models in Wireless Mobile Networks in Different Propagation Environments. 10.11159/vmw17.103.

[9] Hufford, G.A., A.G Longley and W.A. Kissick (1982), A guide to the use of the ITM Irregular Terrain Model in the area prediction mode, NTIA Report 82-100.

[10] https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive

[11] Y. Singh, Comparison of Okumura, Hata and COST-231 Models on the Basis of Path Loss and Signal Strength, International Journal of Computer Applications, vol. 59, no. 11, pp. 37–41, 2012.

[12] Crawford, A. B., Hogg, D. C., & Kummer, W. H. (1959). Studies in tropospheric propagation beyond the horizon. Bell System Technical Journal, 38(5), 1067-1178.

[13] Zennaro, M., Rainone, M., & Pietrosemoli, E. (2016, November). Radio link planning made easy with a telegram bot. In International Conference on Smart Objects and Technologies for Social Good (pp. 295-304). Springer

[14] https://twitter.com/xtorrest/status/1088193472929189888?s=20

[15] J.-P. Zhang and Z.-S. Wu, A FOUR-PARAMETER M-PROFILE MODEL FOR THE EVAPORATION DUCT ESTIMATION FROM RADAR CLUTTER, Progress In Electromagnetics Research, Vol. 114, pp. 353-368, 2011