Evaporation Duct Estimation from Clutter Using Meteorological Statistics

Caglar Yardim*, Peter Gerstoft, and William S. Hodgkiss
Marine Physical Laboratory
University of California, San Diego
La Jolla, CA 92093–0238, USA

Introduction

Many of the lower atmospheric maritime radar systems have to operate under ducting conditions. Electromagnetic ducts result in non-standard electromagnetic propagation which can fundamentally change the performance of the system that is designed to operate under standard atmospheric conditions. Therefore, it is essential to know the environment (the atmospheric refractivity) in which the radar is operating. Techniques that estimate the atmospheric refractivity profile from radar clutter returns is called Refractivity from Clutter (RFC) techniques. A typical RFC inversion would work by finding an environment whose simulated clutter pattern matches the radar measured one. This paper addresses how to incorporate meteorological statistics into evaporative duct estimation within a Bayesian framework.

1 Regional Statistics and Evaporation Duct Inversion Algorithm

Evaporation duct refractivity profiles are constructed using the log-linear evaporation duct formula following [1]. EDH defines the upper boundary of the trapping layer where $\partial M/\partial z = 0$. Hence, the M-profile is given by $M(z, h_\mathrm{d}) = M_0 + c_\mathrm{o}\left(z - h_\mathrm{d} \ln \frac{z+z_\mathrm{o}}{z_\mathrm{o}}\right)$, where h_d represents the EDH, M_0 is the refractivity at the sea surface, the constant c_o and the roughness factor z_o are taken as 0.13 and 1.5×10^{-4}, respectively.

The occurrence rates and strength of evaporation ducts vary depending on the region, season, time of the day, and regional atmospheric processes. To take these variations into account a worldwide surface meteorological observations database sponsored by the SPAWAR Systems Center, San Diego (SSC-SD) was created. This paper uses the environmental library of the Advanced Refractive Effects Prediction System (AREPS), which is a subset of this SSC-SD database. It is called DUCT63 and is obtained from 15 years of observation over 293 $10^\mathrm{o} \times 10^\mathrm{o}$ sections of the world between 80°N and 70°S latitudes called Marsden Squares (MS).

The six cases (Env-1 to Env-6) investigated here are given in Fig. 1. Selected regions, seasons, and time of day information is provided in Table 1 along with the mean EDH and surface wind speed values. They are selected such that they represent a wide spectrum of environments with different mean and statistics for the EDH, and hence different RFC performance. The cases are ranked according to their mean EDHs so they start with the North Sea with a mean EDH of only 4.8 m due to its relatively high latitude.

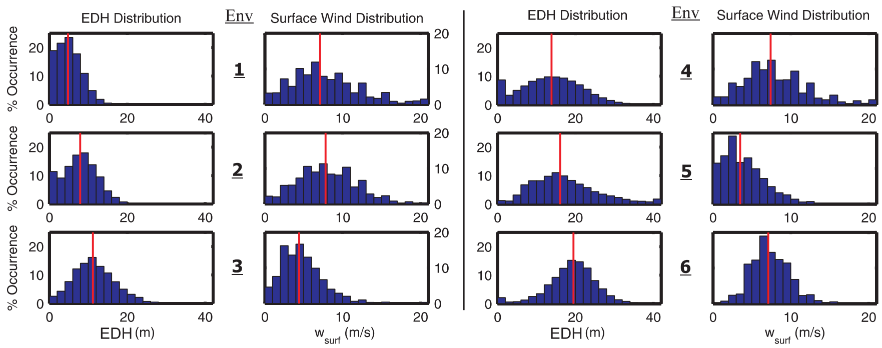

Figure 1: Regional statistics for six different regions (see Table 1) in terms of EDH and wind speed, vertical lines show the mean values.

Table 1: Regional Environmental Statistics

Env.	MS	Region	Season	Time	EDH (m)	V_w (m/s)
Env-1	MS-216	North Sea	Spring	Day	4.8	7.1
Env-2	MS-121	Coast of Calif.	Summer	Night	7.9	7.8
Env-3	MS-141	East Mediter.	Spring	Day	11.2	4.8
Env-4	MS-116	Wallops Island	Spring	Day	13.9	7.4
Env-5	MS-103	Persian Gulf	Fall	Day	16.1	3.5
Env-6	MS-303	Coast of Brazil	Fall	Day	19.5	7.1

Evaporation duct inversion consists of minimizing the RMS error $\phi(h_\mathrm{d})$ between the measured clutter $P_m(r)$ with those in a pre-computed clutter library $P_n(r, h_\mathrm{d})$ in a given range interval. The library typically consists of clutter patterns that would be encountered for EDH ranging from 0–40 m. Sea clutter in a ducted environment is obtained first by propagating the electromagnetic field in range using the recursive split-step FFT PE formula. Clutter power P_c can be calculated using $P_c(r, h_\mathrm{d}) = crL^{-2}(r, h_\mathrm{d})\sigma^\mathrm{o}$ where c is for the constant, $L(r, h_\mathrm{d})$ is the one way propagation loss obtained from FFT PE, and σ^o is the sea clutter.

The clutter library of a RFC inversion algorithm determines how well it will perform in a given environment. Six libraries are shown in Fig. 2 with different radar frequency and antenna height values. The clutter profiles are between 10–25 km and are normalized at 10 km.

Clutter libraries of S-band radars typically consist of monotonically increasing radar return profiles as EDH increases as given in Fig. 2(a)–(b). As the radar height increases the vertical spread of the library decreases, resulting in a loss of sensitivity to different EDHs. Analysis in [1] indicates that RFC is difficult for EDH > 30 m. However, this value is frequency–height dependent (can be as low as 5 m) and clutter libraries get considerably more complex in C and X–bands.

Libraries corresponding to a 6 GHz radar are provided in Fig. 3(c)–(d). For a radar height of 15 m, the clutter monotonically increases from 0–21 m EDH after which it again starts to decrease and becomes a complex pattern which no longer

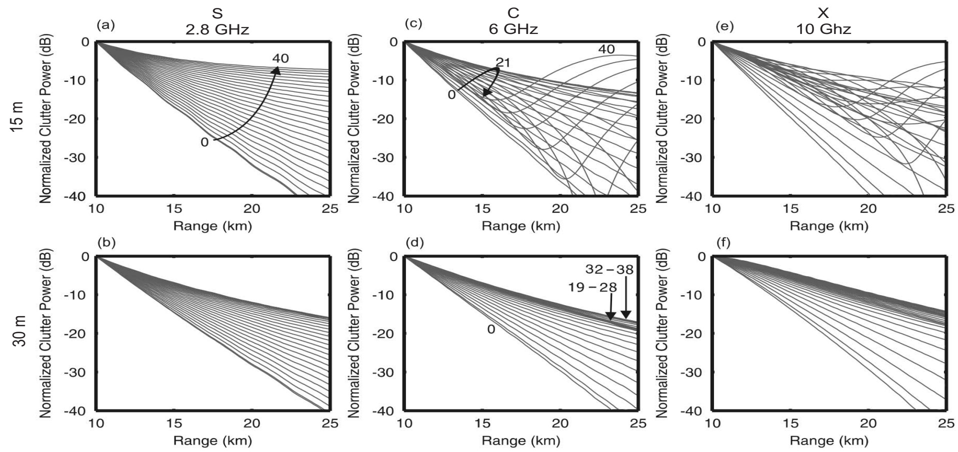

Figure 2: Normalized clutter libraries with EDH ranging from 0–40 m for three frequencies and two antenna heights.

is monotonically decreasing with range. For a radar height of 30 m, the clutter monotonically increases from 0–40 m but for EDH between 19–28 m and 32–38 m the clutter pattern is almost identical, drastically reducing the inversion quality. These effects get even more pronounced for X–band simulations.

2 A Bayesian Evaporation Duct Inversion Algorithm

A Bayesian estimator can take advantage of the regional statistics. It can use the same Bayesian RFC approach applied in [2], [3], and [4] where the posterior probability density (PPD) of EDH is obtained by multiplying the likelihood function, which carries the information obtained from clutter, by the prior density, which is the pdf of the EDH statistics encountered in that region (Fig. 1(c)). Afterwards, a maximum a posteriori (MAP) estimator which computes the peak of the PPD can be employed.

To demonstrate the advantages and drawbacks of the Bayesian approach, four cases with log-normal clutter and infinite CNR are analyzed. The MAP estimate $\widehat{h}_{\mathrm{d}}$ can be found by

$$\mathcal{L}(h_{\mathrm{d}}) = (2\pi\nu)^{-N_{\mathrm{R}}/2} \ \exp\left[-\frac{\phi(h_{\mathrm{d}})}{2\nu}\right], \quad \widehat{h}_{\mathrm{d}} = \arg\max_{h_{\mathrm{d}}} \ \mathrm{p}(h_{\mathrm{d}}|P_m), \tag{1}$$

where $\mathcal{L}(h_{\mathrm{d}})$ is the likelihood function created from the error function, N_{R} is the number of range bins in the inversion range interval, ν is the error variance, $\mathrm{p}(h_{\mathrm{d}})$ is the regional prior, and $\mathrm{p}(h_{\mathrm{d}}|P_m) \propto \mathrm{p}(h_{\mathrm{d}})\mathcal{L}(h_{\mathrm{d}})$ is the PPD.

The priors $\mathrm{p}(h_{\mathrm{d}})$ are selected from Fig. 1. The inversion results are given in Fig. 3. Due to the monotonic variation in the clutter patterns for the clutter library of the first case as given Fig. 2(b), $\phi(h_{\mathrm{d}})$ has a single minimum. The PPD is obtained by multiplying the likelihood with the prior of Env-1. Both the Bayesian and the non-Bayesian approaches work well for this case.

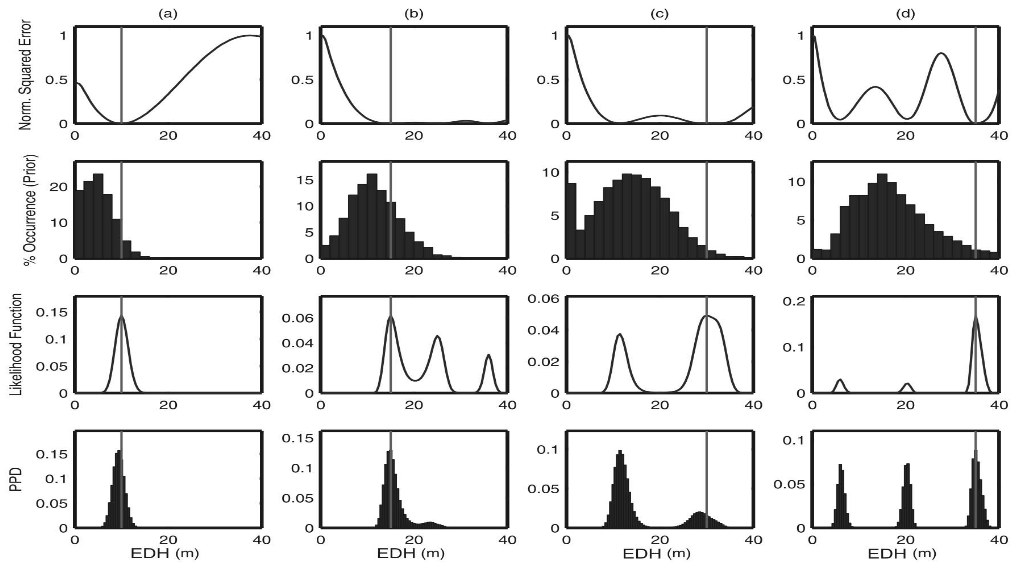

Figure 3: Evaporation duct inversion results for 4 cases. Vertical lines are EDH_{true}.

The advantage of a Bayesian approach can be observed in Fig. 3(b). A complex clutter library results in multiple possible solutions with a $\mathcal{L}(h_\text{d})$ having three local maxima. The two incorrect values are removed in the PPD due to the prior. However, the same mechanism picks a wrong value for the third case shown in Fig. 3(c). The prior results in the elimination of the peak with the true EDH value and the subsequent MAP estimation results in an incorrect estimate, whereas the non-Bayesian algorithm used in the rest of the paper would have estimated the true EDH. However, based on the priors, the probability of case (b) happening is much larger than case (c) in that environment. The final example given in Fig. 3(d) shows how both techniques may fail if the system parameters are not carefully selected. Both $\phi(h_\text{d})$ and the PPD show multiple possible solutions around 5, 21, and 35 m EDH even with an infinite CNR. Thus, the selected system parameters are not appropriate for Env-5.

References

[1] L. T. Rogers, C. P. Hattan, and J. K. Stapleton, "Estimating evaporation duct heights from radar sea echo," *Radio Science*, vol. 35 (4), pp. 955–966, 2000, doi:10.1029/1999RS002275.

[2] C. Yardim, P. Gerstoft, and W. S. Hodgkiss, "Estimation of radio refractivity from radar clutter using Bayesian Monte Carlo analysis," *IEEE Trans. Antennas Propagat.*, vol. 54(4), pp. 1318–1327, 2006.

[3] ——, "Statistical maritime radar duct estimation using a hybrid genetic algorithm – Markov chain Monte Carlo method," *Radio Science*, vol. 42, 2007, doi:10.1029/2006RS003561.

[4] ——, "Tracking refractivity from clutter using Kalman and particle filters," *IEEE Trans. Antennas Propagat.*, to appear, 2007.