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RETRIEVING EVAPORATION DUCT HEIGHTS FROM POWER OF GROUND-BASED GPS OCCULTATION SIGNAL

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Abstract—Evaporation duct is a manifest phenomenon that can affect microwave propagation seriously with low elevation angles near the sea surface. As an important parameter to describe the characteristic of the evaporation duct, duct height can be estimated from radar sea echo using a technique called as "refractivity from clutter". In this study, we proposed a novel approach to estimating the evaporation duct height. The signal power received by a ground-based GPS receiver is used when the GPS satellites rise or set at the local horizon over the sea. A forward propagation model and genetic algorithm are adopted to implement this method. The performance is evaluated via numerical simulation for inferring evaporation duct with different height. The results showed that the proposed method is well effective, especially for the conditions with higher evaporation duct height.

1. INTRODUCTION

Evaporation duct results from the rapid decrease of atmospheric moisture in the first few meters above sea level, which is quasi-permanent present and can increase signals above diffraction levels significantly for near surface propagation at frequencies of 1 GHz and above [1-3]. The evaporation duct height (EDH) has been shown to be a good parameter to describe the profile of the modified refractivity versus height. The EDH varies depending on the region, the time and

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the atmospheric dynamic processes [4]. Generally, models based on Monin-Obukhov similarity theory are used to calculate EDH from in situ measurements such as air temperature, humidity, wind speed, and sea surface temperature [5, 6]. These models are sensitive to input bulk measurements, especially under stable condition. Therefore, research on alternative means for remotely sensing evaporation duct heights continues [7–9]. Considering that the effects of evaporation ducts are manifested in radiowave propagation, it might be feasible to infer the structure of duct from the propagation measurements. Accordingly, a technique named as "refractivity from clutter" (RFC) is presented and developed which can be used to estimate the lower atmospheric refractivity using radar clutter [10–15].

Previous work shows the feasibility of retrieving the lower marine atmospheric refractivity from very low angle GPS signal power collected by a single ground-based receiver near the sea surface [16]. Attempts to retrieve the lower refractivity from ground-based GPS measurements are relatively rare compared with space-based ones, primarily because of the geometry of the source-receiver which invalidates the Abel transform based on the phase delay measurements [17]. On the other hand, satellite to ground propagation loss is affected by evaporation duct at very low angles, provoking significant enhancements of signal power at negative angles corresponding to the spot beyond the horizon. In this paper, a novel method to remotely sense the height of evaporation duct is proposed using ground-based GPS radio occultation signal power as the satellite rises or sets on the horizon. Deterministic models can be founded to calculate the received power under tropospheric ducting conditions, which could be used in the approach to estimating EDH [18, 19]. The concept of using GPS received signal for the EDH estimation has many advantages, such as the integrated refractive effects can be obtained, low cost, easily automated and extended to other GNSS systems. Exploring an alternative method to remotely sense the EDH is the motivation of the study.

In the following Section 2, the forward propagation model and the inversion algorithm are introduced, including the evaporation duct model, the propagation model, the objective function and the inversion steps. In Section 3, implementation of the forward model and inversion algorithm for ground-based GPS occultation signals is simulated and discussed assuming that the evaporation duct environment is range-independent. A conclusion is drawn in Section 4 for the preliminary study.

2. FORWARD MODELING AND INVERSION ALGORITHM

2.1. Forward Modeling

A forward propagation model was founded for the exploitation of the ground-based GPS signal power. The received GPS signal power can be expressed by the ratio of the power of carrier frequency to that of base noise (CN0) as follows (in dB/Hz)

$$P_r = P_t + G_t - L + G_r - kT_0 \tag{1}$$

where P_t is the GPS transmitter power, G_t the transmitter antenna gain, G_r the receiver antenna gain, k the Boltzmann's constant, T_0 the absolute noise temperature (K), and L the path loss. The path loss L is defined as the ratio of the equivalent isotropic radiated power of the transmitter system to the power available from an isotropic receiving antenna taking the propagation effects into account.

As shown in Equation (1), the key factor for predicting the received signal power depends on the calculation of the path loss L. For satellite-to-ground propagation path, serious refraction effects occur only at low angle, which means that the ground-based signal power in GPS occultation events are mainly affected by the lower atmosphere. Then it is reasonable to use the parabolic equation (PE) to model the evaporation duct effects on satellite-to-ground radio links near the horizon. The region above the top of the PE region is regarded as free space. Assuming $\exp(-i\omega t)$ as time-dependence of the fields, where ω is the angular frequency, the form of PE is

$$\frac{\partial^2 u(x,z)}{\partial z^2} + 2ik\frac{\partial u(x,z)}{\partial x} + k^2\left(n^2(x,z) - 1 + \frac{2z}{a_e}\right) = 0 \tag{2}$$

where $u(x,z)$ is the electromagnetic field component at range x and height z in Cartesian coordinates, k the wave number in free-space, n the refractive index, and a_e the radius of the Earth.

The solution is given by

$$\begin{aligned} u(x_0+\delta x, z) = e^{ikm\delta x/2}\Big\{ & e^{i\alpha^2\delta x/2k} e^{-\alpha z} K(x_0) \\ & + \frac{2}{\pi}\int_0^\infty \frac{\alpha \sin pz - p\cos pz}{\alpha^2+p^2} e^{-ip^2\delta x/2k} \cdot \int_0^\infty u(x_0, z') \\ & \left[\alpha \sin pz' - p \cos pz'\right] dz' dp \Big\} \end{aligned} \tag{3}$$

with

$$K(x) = \begin{cases} 2\alpha \int_0^\infty u(x,z) e^{-\alpha z} & \text{for } \mathrm{Re}(\alpha) \geq 0 \\ 0 & \text{for } \mathrm{Re}(\alpha) \leq 0 \end{cases}$$

where $m = n^2 - 1 + 2z/a_e$, p is the transform variable. The solution at $x_0 + \delta x$ in terms of the solution at x_0 is calculated numerically using the split-step discrete mixed Fourier transform (DMFT) algorithm [20]. One should begin with an field at the initial range in order to propagate the field forwardly. The initial field is synthesized by the direct and reflected GPS signals. The propagation factor F is the field relative to free space, which can be expressed in dB as

$$F(x,z) = 20\log|u(x,z)| - 10\log(R) - 10\log(\lambda) \tag{4}$$

where R is the distance from the point (x,z) in the computing region to the position of the ground-based receiver, and λ is the wavelength. Finally, the path loss in dB can be written as

$$L = 32.4 + 20\log R_s + 20\log f - F \tag{5}$$

where R_s is the slant range from the GPS receiver to the satellite in km, f is the frequency in MHz.

2.2. Evaporation Duct Model

The atmospheric refractive index can be computed by the following formula [21]

$$n = 1 + N \times 10^{-6} \tag{6}$$

where N is the refractivity expressed as

$$N = \frac{77.6}{T}\left(P + 4810\frac{e}{T}\right) \tag{7}$$

where P is the atmospheric pressure (hPa), e the water vapour pressure (hPa), and T the absolute temperature (K). The modified refractivity is used considering the flat earth, which is related to the refractivity by

$$M = N + \frac{z}{a_e} \times 10^6 \tag{8}$$

The evaporation duct can be denoted by a single parameter exponent model as [13]

$$M(z) = M_0 + 0.125 \cdot z - 0.125 \cdot z_e \cdot \ln[(z + z_0)/z_0] \tag{9}$$

where z is the height, z_e the estimated EDH, and the roughness factor $z_0 = 1.5 \times 10^{-4}$. M_0 is the modified refractivity at sea surface, taken as as 350 M-units in this study. The refractivity model adopted in the following study consists of an evaporation duct profile and line segments corresponding to the mixed layer. The value of modified refractivity is given by

$$M(z) = M_0 + \begin{cases} 0.125 \cdot z - 0.125 \cdot z_e \cdot \ln[(z + z_0)/z_0] & \text{for } z \le z_e \\ c_1 z & \text{for } z > z_e \end{cases} \tag{10}$$

where c_1 is the slope in the mixed layer. The typical range of EDH is [0, 40] m. The parameter c_1 is chosen to vary from 0.079 to 0.157 M-units/m as normal gradients.

2.3. Inversion Algorithm

Retrieving the refractivity parameters from signal amplitude of ground-based GPS occultation is a nonlinear inverse problem. The problem can be solved using an optimization method and a forward propagation model. An objective is performed to provide the difference between the observed signals and the simulated signals taking the candidate refractivity profile as input. The candidate EDH that yields the minimum difference is prescribed as the retrieving parameter. It is assumed that the EDH is unvaried with a range in the simulation to get a mean EDH along the range-height path. Efficient global optimization methods such as simulated annealing (SA) and genetic algorithms (GA) may be used to accelerate the inversion process.

It is assumed that the difference power (in dB) between the observed and modeled signals is in Gaussian distribution. This leads to a simple least squares objective function as follows

$$\phi(\mathbf{z}_e) = \mathbf{e}^T\mathbf{e} \tag{11}$$

$$\mathbf{e} = \mathbf{P}_{obs} - \mathbf{P}(\mathbf{z}_e) - \widehat{T} \tag{12}$$

$$\widehat{T} = \bar{\mathbf{P}}_{obs} - \bar{\mathbf{P}}(\mathbf{z}_e) \tag{13}$$

where $\mathbf{P}_{obs}$ is the observed signal power, $\mathbf{P}(\mathbf{z}_e)$ is the simulated signal power, $\bar{\mathbf{P}}_{obs}$ and $\bar{\mathbf{P}}(\mathbf{z}_e)$ are the mean values of the observed and simulated signal power, respectively. $\widehat{T}$ is an estimated normalization constant such that the objective function only depends on the variation of the signal power but not on its absolute level. According to the technique of RFC, the retrieving steps are given as follows

1. A vector of GPS occultation signal power $\mathbf{P}_{obs}$ at discrete elevation angle $(\theta_1, \theta_2, \ldots, \theta_n)$ is measured by a ground-based receiver, which is used as the input data to the proposed technique.
2. Getting candidate refractivity profiles with the parameters of the EDH and the slope in the mixed layer.
3. Using the forward model and the candidate M profiles, the replica field $\mathbf{P}(\mathbf{z}_e)$ is calculated.
4. An objective function ϕ is used to evaluate the difference between $\mathbf{P}_{obs}$ and $\mathbf{P}(\mathbf{z}_e)$.
5. A global optimization procedure is used to search over all $\mathbf{z}_e$ and c_1 to find the optimal estimation parameters of the objective function.

6. An assessment is made for the quality of the retrieving results by examining the forward model solutions or the parameter error estimates/distributions.

3. SIMULATION RESULTS

3.1. Propagation Simulation Results

In this section, two examples of the GPS signal power strength near the Earth surface in maritime evaporation duct environments are presented. The power strength contour for a normal refractive environment is also illustrated for comparison. Considering the EDH (m) alway exists in the interval [0, 40], three typical refractivity profiles are selected, namely the standard atmosphere with refractive gradient of −0.118 M-units/m, the evaporation duct with EDH of 10 m, and the evaporation duct with EDH of 30 m, which indicate the presence of normal atmosphere, weak and strong evaporation duct, respectively. The refractive gradient above the EDH (slope in the mixed layer) is set as −0.118 M-units/m. These modified refractivity versus height profiles are shown in Fig. 1. The equivalent isotropic radiated power (EIRP) is 28.6 dBW, and the receiver antenna gain is simulated as 0 dB in the simulations.

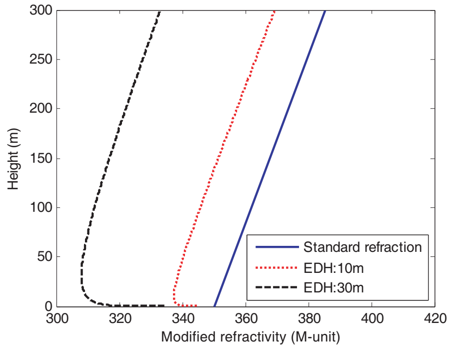
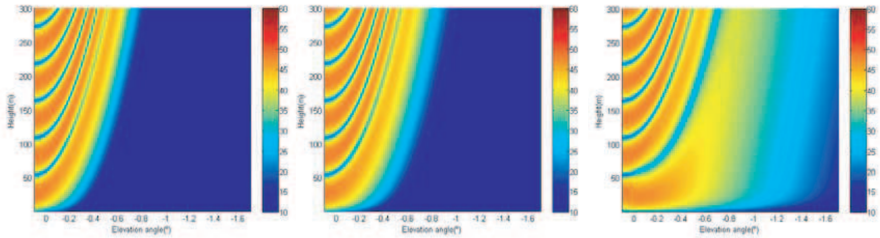


Figure 1. Modified refractivity profiles.

The power strength (dB/Hz) contours for the GPS L1 signals within the selected refractive environments are shown in Fig. 2. Generally, signals exceeding about 30 dB/Hz could be captured and tracked by a GPS receiver. As shown in Fig. 2, the minimum observed elevation angle of the satellite is negative due to the refraction of the lower atmosphere and the altitude of the receiver. It can be seen the multipath interference effect produced by the path length



(a) (b) (c)

Figure 2. Power contours (dB/Hz) of the GPS L1 signals propagating in (a) standard atmosphere, (b) evaporation duct with duct height of 10 m and (c) duct height of 30 m.

difference between the direct and reflected rays. Additional important phenomenon should be noticed by comparing the power contour results for different refractive environments. Firstly, evaporation ducts can extend to very low angle region with high signal power. Secondly, as shown in Fig. 2(b) and Fig. 2(c), different evaporation duct height leads to different distribution of the signal power. Evaporation duct with higher EDH can extend the region remarkably and have obviously trans-horizon propagation effects. Conversely, the EDH depends on the variation of the GPS received power when a GPS satellite rises or sets on the horizon. A Higher EDH usually corresponds to a small absolute value of received power gradient with respect to elevation angle, and a lower EDH corresponds to a relatively large gradient.

Since the evaporation ducts can affect the propagation characteristics of GPS signals at very low angles and the extent of this effect varies with different EDH, inferring evaporation duct height from the ground-based GPS occultation signals is possible.

3.2. Inversion Simulation Results

Supposing a GPS receiver located at the altitude of 15 m above mean sea level, the simulation occultation signals received by a ground-based receiver are illustrated in Fig. 3, with $c_1 = -0.118$ M-units/m and EDH of 10 m, 20 m and 30 m, respectively. The ground-based occultation signals are the sum of the received GPS signal power and the noise power, which will be unlocked when the GPS signal power below 30 dB/Hz in our simulations.

These simulated signals are utilized to retrieve the evaporation duct heights as input. The inversion problem of retrieving EDH from ground-based GPS receiver power is solved by the forward propagation

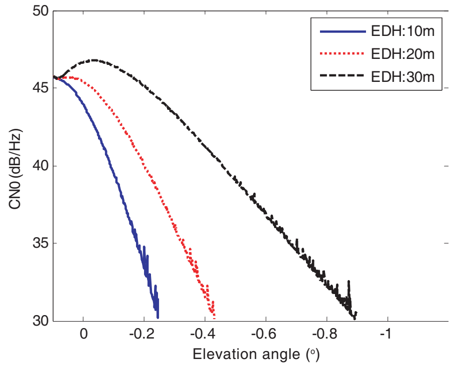


Figure 3. Simulated ground-based occultation signal power.

model and an optimization method. The Matlab GA toolbox is adopted as the requisite global optimization method for retrieving the duct height in the inversion process. The GA search parameters were: parameter quantization of 1024 values, population number of 20, rate of selected individuals of 0.9, cross-over probability of 0.7, mutation probability of 0.035, generation of populations of 10. Thus totally 200 forward modeling runs were executed for one inversion.

Objective function is used to evaluate the fitness of the input GPS signals and the signals generated by the forward model according to the candidate evaporation duct. Fig. 4 illustrates that all the three inversion cases are converged at relatively small objective function values. The convergence results of the objective function illuminate the validity of the method and the accuracy of the signals calculated from the retrieving results. The two retrieved parameters are the EDH and the slope in the mixed layer. Multiple simulations are implemented to analyze the statistic characteristics of the retrieving results. The number of the simulations for each EDH is 100. The retrieving results are shown in Fig. 5 and Table 1. Fig. 4 shows the probability distributions of the estimated EDHs, which indicates that better results can be obtained for higher EDH. For the cases of target EDH 20 m and 30 m, the EDH mean error is about 0.2 m, and the Standard deviation (STD) is less than 0.4 m. For the case of target EDH 10 m, the EDH mean error is 1.19 m, and the STD is 2.19 m. Worse result in the case of low EDH may be attributed to the insensitivity of weak evaporation duct for the GPS L1 frequency and the supposed receiver altitude which is greater than the EDH of 10 m. Compared with the RFC technique, many of which work at X band, the inversion results may be worse for the proposed method under low EDH environment because of relatively low work frequency, but as good results could be obtained under higher EDH environment because of their similar theory based on point-to-point microwave propagation measurements.

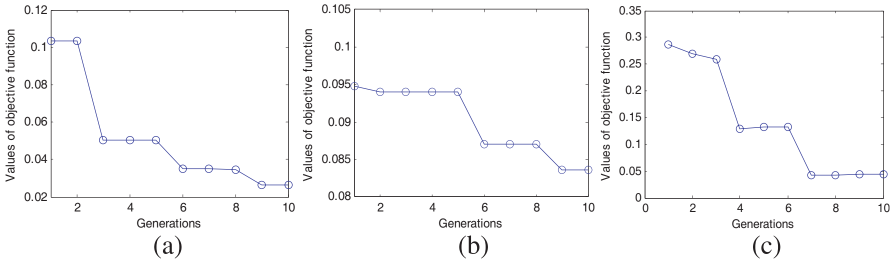


Figure 4. Values of objective function in cases of evaporation duct height of (a) 10 m, (b) 20 m, and (c) 30 m.

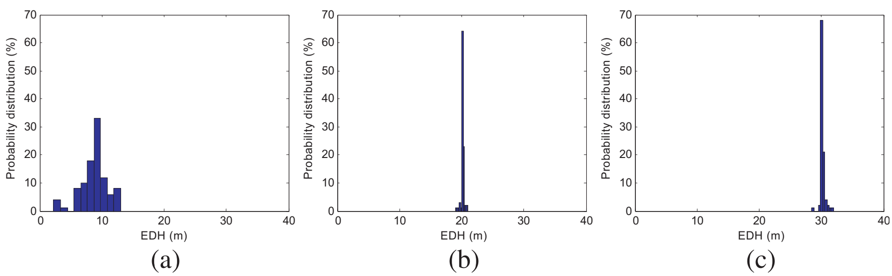


Figure 5. Probability distribution of estimated evaporation duct height of (a) 10 m, (b) 20 m, and (c) 30 m.

Table 1. Inversion results.

Target EDH (m)		10.00	20.00	30.00
Inversion EDH (m)	mean	8.81	20.19	30.20
	std	2.19	0.251	0.356
Inversion c_1 (M-units/m)	mean	0.115	0.124	0.128
	std	0.011	0.015	0.009

4. CONCLUSIONS

A novel method for inferring the evaporation duct height (EDH) from ground-based occultation GPS signal power has been presented. Being nonlinear optimization problem, the inversion method is based on the evaporation duct model, the parabolic equation propagation model, the genetic algorithms, and the objective function, which relied on the fact that the evaporation manifests itself in signal variation by a ground-based GPS receiver. It has been shown though three case examples that the ground-based GPS occultation signals can be used to retrieve the evaporation duct by the proposed method, especially for evaporation duct with higher EDH.

Although the results show much feasibility of the new method, it should be mentioned that all the received GPS signals and the evaporation ducts are simulated in ideal conditions. The refraction effects from the maximum PE region height to the GPS satellite height are ignored in the forward propagation model. Further work is necessary to improve the method and to validate the forward model and the inversion algorithm using experimental data in order to approve its operational usage.

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