Multiple Launch Angle Method-Refractivity From Clutter (MLAM-RFC) at Very-Low Grazing Angles Using Sea and Land Clutter

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Exam Date: July 7th 2023

A Ph.D. Research Proposal

Presented in partial fulfillment of the requirement for the degree Doctor of Philosophy in Electrical and Computer Engineering in the Graduate School of The Ohio State University

Content

Abstract

Electromagnetic (EM) signals traveling in the lower atmosphere are drastically affected by the propagation environment. The environment can cause events called ducting to occur which causes trapping of the transmitted wave instead of spherical spreading. Developing ways to characterize, estimate and predict when these events occur will not only help understand when and to what affect these incidents occur, but also, mitigate the error in systems that are dependent on the propagation environment.

Duct sensing can be done by sounding launches or applying numerical methods from sensor data which are usually costly and/or non-real-time processing scenarios. Refractivity-From-Clutter (RFC) allows for real-time low tropospheric refractivity profiles to be estimated. Previous RFC work only used sea clutter using the hybrid sea surface model and a single launch angle radar. The motive behind this research is to improve the RFC method by exploring the advantages of multiple launch angles as well as including land clutter.

Problem and Relevant Research

Atmospheric conditions affect electromagnetic wave propagation. These effects are more pronounced in the lower troposphere as the wave is launched parallel to the earth's surface. Changes in the moisture content in the air, temperature of the air and surface and even local pressure, can cause a phenomenon called ducting to occur. Ducting is the trapping of a signal between two planes, essentially converting the EM from spherical spreading to cylindrical spreading that can result in massive changes in signal levels. This trapping can cause a myriad of problems for a signal, specifically for radars.

For EM signals, the refractive index tends to perform as shown in equation (1) for waves traveling less than 100 GHz in the lower troposphere. In this domain, the change experienced in the index of refraction is fractional, on a sub-thousandth level, which is why most of the field uses refractivity, to magnify the small changes. When the need arises to study the refractive index over long ranges, on the order of kilometers, modified refractivity, denoted as M (M-units), is used to account for the earth’s curvature. This equation is given the term modified refractivity, shown in equation (2).

$$n(h,T,P,z) = 1 + \frac{77.6*10^{-6}P}{T} + \frac{3.73*\mathrm{e_s}}{\mathrm{T}^2} + 0.157z \qquad (1)$$

$$M = 10^6(\mathrm{n}-1) + 0.157z \qquad (2)$$

Where e_s is water vapor pressure, which is a derivative of humidity (h) and pressure (P), T is temperature and z is height.

Evaporation ducts usually occur over the ocean when there is a decrease is vapor pressure and the condition and can be accurately modeled numerically using Monin-Obukhiv Similarity Theory (MOST) when the atmosphere is unstable (meaning air sea temperature difference (ASTD<0°), while neutral (ASTD=0°)) or even gently stable(ASTD<0°). MOST can be used to extract refractivity profiles from parameters collected from environmental instruments such as temperature probes and pressure gauges. Obtaining results from this multi-variable algorithm can be tedious and cumbersome. One of the duct cases, evaporation duct, can be modeled using the Paulus-Jeske (PJ) [1] model under ideal conditions, in which, simplifies the MOST model to one equation (2).

$$M(z) = M_0 + 0.125z - 0.125\ \delta * \ln\left(\frac{z + z_0}{z_0}\right) \qquad (3)$$

Where M_0 and z_0 is the modified refractivity and height at sea level respectfully and δ is the duct height parameter. Equation (3) is of logarithmic form with the first differential with respect to height, z, being the theoretical top of the duct.

There are a wide range of different refractivity profiles with varying rates of occurrences: normal refraction, where electromagnetic wave propagates linearly, sub-refraction, where the wave curves up away from the earth's surface, super-refraction, where the wave curves down towards the earth's surface and lastly, ducting, where the wave becomes trapped between a boundary layer and the earth's surface, or another boundary layer dictated by the refractivity profile. The top of any duct acts as a leaky waveguide causing ground-based radars to extend their maximum range, increase sea surface clutter and create errors in target detection.

There are several sub-categories of ducting: evaporation, surface-based (SBD) and elevated ducts with the latter two being characterized by a tri-linear profile. The major difference between SBD and elevated duct impact on a signal is that SBD reflects off a surface and therefore can be used directly in an RFC algorithm using sea clutter, whereas elevated ducts signals are trapped between two leaky planes and therefore is intolerant of the sea surface. This is not the case for high rising terrain where the path was affected by an elevated duct. An elevated duct can be sensed by backscatter from terrain within that path as long as the terrain is high enough to include the elevated duct trapping layer. This will be discussed later in the proposal. The difference between evaporation and both surface and elevated is that the latter has a trapping layer that may allow for increased trapping, skip zones, and a higher duct height. Figure 1 is a simulation of 3 environments: evaporation duct, surface-based duct, and standard atmosphere. The right column displays the two-way path loss from the PWE. The middle column displays the M-profile, and the left column displays the power clutter return for each given scenario.

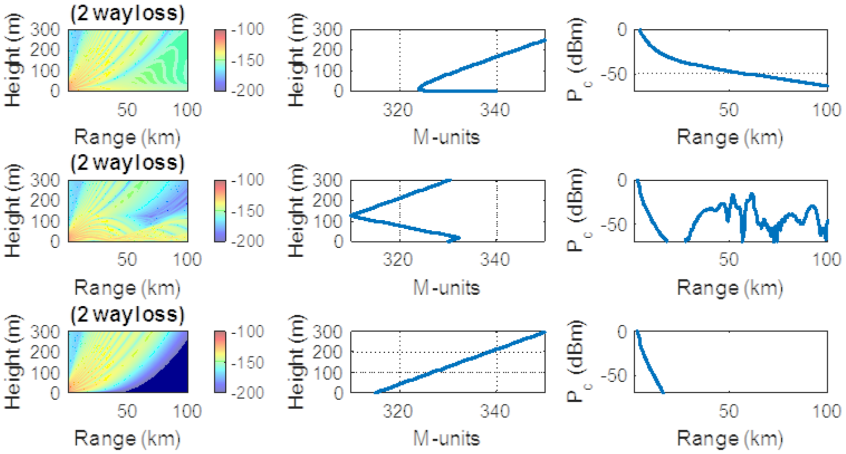


Figure 1: PWE Simulation results for evaporation duct (top row), surface-based duct (middle row), and standard atmosphere (bottom row).

Land-to-air based radars are designed to locate and/or track aircraft but under specific ducting scenarios, the radar can collect increased clutter and experience blind zones or false target location, all of which can lead to dangerous results. Developing systems that aid with understanding and predicting elements of ducting can minimize these critical errors on radars and other sensitive instruments.

There are several techniques used to find the structure of a duct, which can range from measuring refractive profile directly such as with sounding launches, to indirect measurements such as using GNSS signals in inversion techniques and even numerical methods using meteorological data such as The Navy Atmospheric Vertical Surface Layer Model (NAVSLaM) and Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS) [2] [3] [4] [5] [6] [7]. Each method has its own respective advantages and disadvantages.

[8] discussed that a duct can be estimated using these radar power returns from sea clutter by performing a best fit algorithm to a model that corresponds to a known refractivity profile thus, creating the RFC method.

Josh Compaleo dissertation [9] is a work that is heavily cited throughout this proposal due to its discussion on RFC and its use of the Lower ATmospheric PROPagation (LATPROP) radar. The RFC method used in [9] is a single launch angle inversion technique that uses sea clutter as its backscattering source.

[10] introduced the idea in “Refractivity Estimation using Multiple Elevation Angles” that uses more than one launch angle to increase the precision of RFC inversion using the sea surface as the main source for backscattering. [10] recorded power returns using two beams with data captured using SPAce and raNge raDAR (SPANDAR).

Barrios used a combination of both land and sea clutter in RFC inversion [11] where she implemented a ray trace and rank correlation technique to combat the absence of known land clutter model and accurate scattering models. She used a ray tracing density to find the proportional field strength of the backscatter return to perform the inversion technique.

An upgraded LATPROP system that can increase Clutter-to-Noise Ratio(CNR) and preform inversions using multiple launch angles was developed during this Ph.D. This system is extremely low cost due to use of commercial off the shelf (COTS) marine radar converted into a coherent-on-receive (COR) RFC-capable system compared to a system such as SPANDAR and the span of launch angles along with the data recorded will allow for a more thorough analysis of the importance of multiple launch angles using in RFC to be explored. Lastly, LATPROP was steered to a scene which covered both sea and land to which inversion using both different types of backscattering sources can be explored. These are the topics that will be discussed throughout this Ph.D. work.

Preliminary Work Summary

A list of preliminary published work that corresponds with the work that is a part of this dissertation:

- “*LATPROP Radar Modifications for CLASI Experiment”* Conference, 2021 XXXIVth General Assembly and Scientific Symposium of the International Union of Radio Science (URSI GASS) [12]
- *“LATPROP Radar Data Collection for CLASI Experiment”*, Abstract,2022 USNC-URSI National Radio Science Meeting [13]

- "*A Comparison Between Multiple Launch Angle Method (MLAM) and Single Launch Angle Refractivity-from-Clutter (RFC) Technique*", Abstract, 2022 IEEE International Symposium on Antennas and Propagation and USNC-URSI Radio Science Meeting (AP-S/URSI) [14]

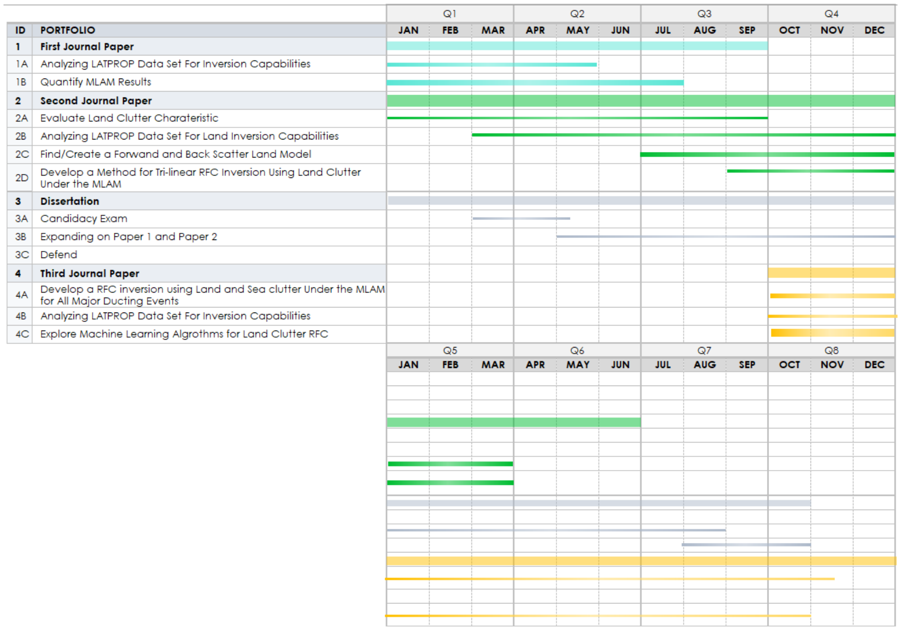
[12] [13] describes the modifications made to a commercially available marine radar and how it was retrofitted to measure Refractivity-from-Clutter (RFC) from the sea surface in order to better understand atmospheric refractivity profiles. A Koden MDS63R marine radar was updated with a horizontal and vertically polarized 3-meter dish antenna that has a 48 dB gain, two options for PRF and pulse width, both long and short, the ability to discretely step in both azimuth and elevation to study 2-D spatial mapping and grazing angle respectively and the capability to preform CoR integration. This system was upgraded to increase CNR, study sea fluctuations and perform multiple launch angles. [14] introduced improvements over the currently available RFC techniques. The duct effects on an EM signal depends on the angle that the signal is launched. Hence, using multiple launch angles might be a good way to improve the RFC inversion technique. This paper is a theoretical study of how using multiple launch angles in RFC inversion can improve duct estimation with respect to using a single launch angle. Results from each paper are detailed in the appendix.

The current journal paper will present ideals on expanding the MLAM technique by exploring not only the combination of launch angles, but also the number of critical launch angles needed to improve RFC estimation. This paper will also incorporate measured data from the LATPROP system to aid the theory.

Lastly, preliminary theory is being gathered for a second journal paper for the development of MLAM-RFC using land clutter. Early discussions will be on land clutter modeling and its grazing angle dependency.

Research Plan

The goal of this Ph.D. work is to explore the added benefit of having multiple launch angles in RFC inversion. This work will primarily use two sources of backscattering: Land and Sea clutter. The Gantt chart below shows the timeline associated with this work.



ID	PORTFOLIO
1	**First Journal Paper**
1A	Analyzing LATPROP Data Set For Inversion Capabilities
1B	Quantify MLAM Results
2	**Second Journal Paper**
2A	Evaluate Land Clutter Charateristic
2B	Analyzing LATPROP Data Set For Land Inversion Capabilities
2C	Find/Create a Forwand and Back Scatter Land Model
2D	Develop a Method for Tri-linear RFC Inversion Using Land Clutter Under the MLAM
3	**Dissertation**
3A	Candidacy Exam
3B	Expanding on Paper 1 and Paper 2
3C	Defend
4	**Third Journal Paper**
4A	Develop a RFC inversion using Land and Sea clutter Under the MLAM for All Major Ducting Events
4B	Analyzing LATPROP Data Set For Inversion Capabilities
4C	Explore Machine Learning Algrothms for Land Clutter RFC

Table 1: Projected Ghant chart for the trajectory of Ph.D. work

Below is an itemized list of topics that will be coved in thoroughly in a dissertation related to this research proposal:

- Analyze signal degradation in the last implantation of LATPROP and compared to the two channel CoR method as well as other noise suppression algorithms.
- The quantification of improvement when using MLAM than a single launch angle using sea clutter
- Exploring antenna height and launch angle dependency on duct height estimation
  - Exploration of using lower launch angles for low duct sensing at a fixed antenna height
- land clutter modeling and signal fluctuation at multiple launch angles
- Understanding stationarity as well as scattering properties of land clutter
- EDH estimation inversion using land clutter using MLAM-RFC
- Combine land and sea inversion to demonstrate that a system such as LATPROP can estimate EDH, SBD and Elevated ducts

Multiple-Launch-Angle-Method (MLAM) RFC Using Sea Clutter

The proposed research plan is to further develop the Multiple-Launch-Angle-Method (MLAM) and to quantify its benefits over the single launch angle inversion method. The first way to ensure this goal is achieved is matching the simulation to the measured data. A 3-meter dish was constructed for this project with shape imperfections. This caused the half-power beamwidth to increase. Another parameter that needed to be accounted for is the antenna height. A combination of Google Earth and the length of the allowed for height bounds to be created. With these two parameters being crucial to the correct estimation of the duct, a simulation was created that used the Navy Atmospheric Vertical Surface Layer Model (NAVSLaM) combined with CLASI (Coastal Land Air Sea Interaction) sensor data and LATPROP measured data to estimate these two nuisance parameter: the radar antenna mean sea level (MSL) height and the half-power beamwidth.

As stated before, the RFC method uses measured clutter data from radar returns and inverts it to a refractivity profile thus creating a cost and resource efficient way of obtaining an accurate refractivity profile. As defined in [15] for a single launch angle inversion, the vector of observed cutter power P_c^{obs} along with a matrix of simulated clutter power P_c^{sim} with variables associated with the modified index of refraction, m, are input variables to an objective function shown in (4).

$$\phi(m) = \sqrt{\frac{1}{N_r N_a} \sum_{\alpha} \sum_{r} \left| P_{c,dB}^{obs}(r,\alpha) - P_{c,dB}^{sim}(r,\alpha,m) \right|^2} \qquad (4)$$

Where r is the range cell, α is the launch angle, Nr is the number of range cells and Nα is the number of launch angles. The objective function calculates the error in the simulated clutter power vector ϕ(m) for any m. The minimum value of the objective is then selected as the estimate of the desired parameter which can be computed using (5).

$$\hat{m} = \arg\min_{x} \phi(m) \qquad (5)$$

Here we use a simple range-independent PJ evaporation duct to demonstrate the Multi Launch Angle Method RFC (MLAMRFC). For this simple case, the parameter vector can be given as $m = h_d$.

In theory, increasing the number of launch angles will improve RFC estimation. The data in Figures 2 - 4 are simulated data with a duct height of 15 meters, an additive noise with a log normal distribution with

2 dB standard deviation. The data in Figures 2 - 4 has a CNR of 0 dB at 5km. Figure 2 are the objective function, from equation 4, results for single angle and multiple launch angles. Figure 3 shows results of Monte Carlo simulations using 1000 runs that estimated EDH for single and MLAM. The conclusion of these results being that MLAM creates a better EDH estimate than single launch angle due to its imperviousness to gaussian additive noise. Figure 4 shows that the MLAM is better at estimating duct height than the single angle method by having more unique range values above the noise floor and is better at estimating with high additive noise fluctuations. Further details on the MLAM can be found in [14]. Further research still needs to be conducted on which angles are important to the RFC method and if those angles are independent of the different duct structures.

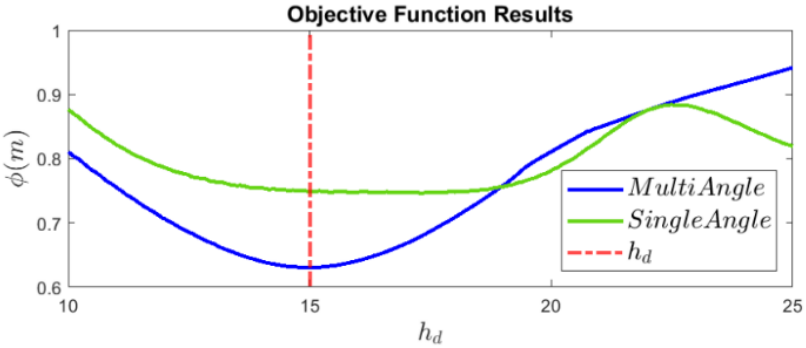


Figure 2: Objective function results for both single angle and multi-angle.

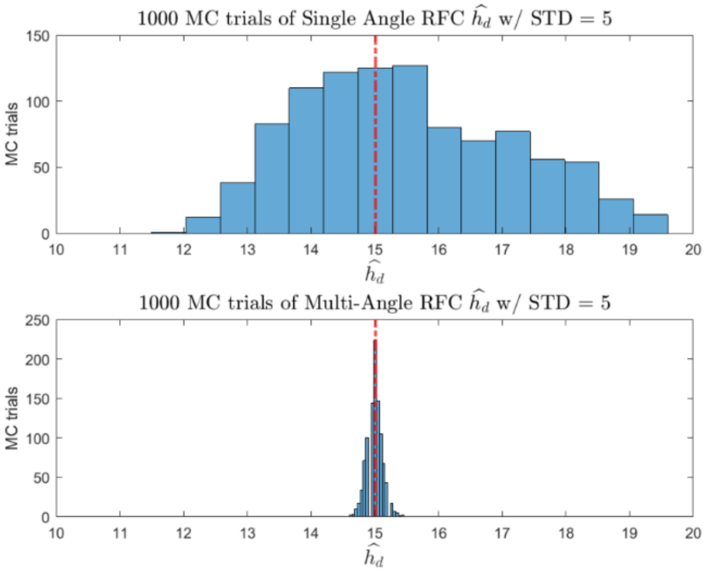


Figure 3: Top (a) is the single angle Monte Carlo Simulation Results. Bottom (b) is the MLAM Monte Carlo Simulation result.

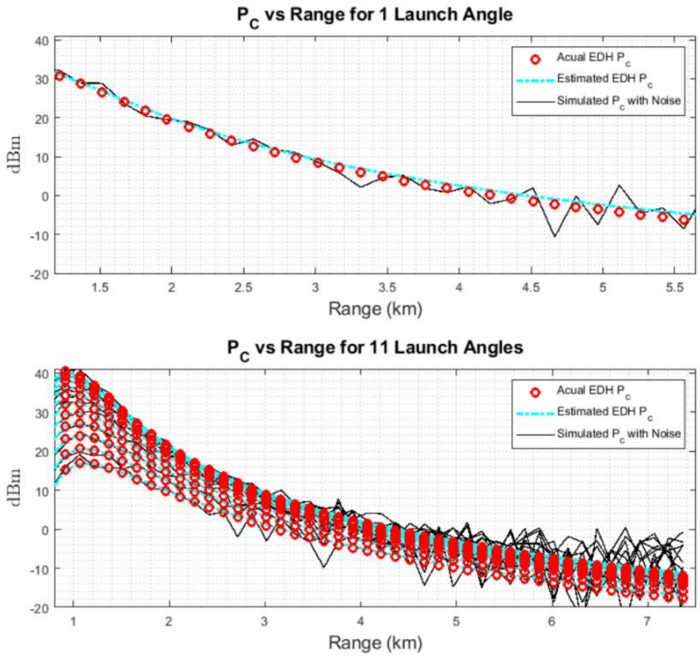


Figure 4: Top(a) is an RFC estimation for a single angle case (0°). Bottom (b) is an RFC estimation for a multiple angle case of 11 angles (-0.5° to 0.5°).

Increasing Clutter-to-Noise Level

Backscatter from the sea rapidly decreases with increased range due to 2-way propagation loss in addition to very low radar cross section due to very low grazing angle (<1 deg°), increasing the CNR is crucial in determining duct characteristics in the inversion process.

Coherent-on-Receive (CoR) is a method of signal processing that allows a radar system that is originally incoherent to recover the phase of the signal. To preform CoR processing, the transmitted leak through pulse on the receive channel is used as a match filter on the rest of the received signal to suppress the noise and, correspondingly, increase the CNR. Figure 5 shows both an example of the pre-matched and post-matched filter results. $X^n_T(t)$ is the leaked through pulse that is used as a matched filter on the signal $X_R(t)$.

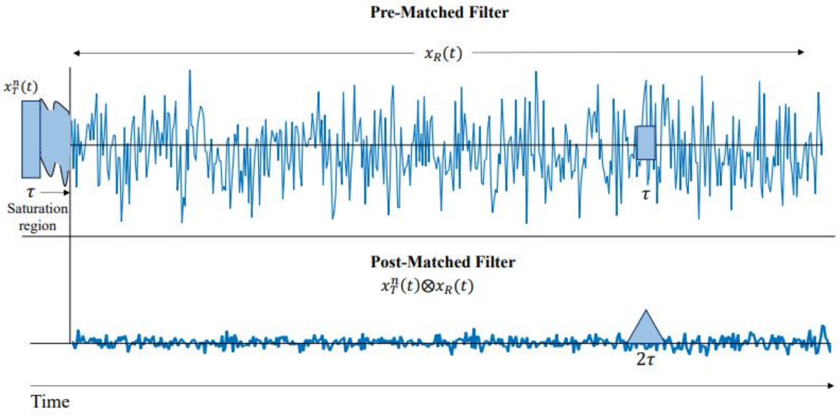


Figure 5: A diagram showing the CoR process; using the leaked through signal to perform the match filter processing.

Prior to the upgrades for the CLASI project, the transmitted signal was saturating the IF amplifiers causing distortions on the transmitted pulse thus, making the CoR method unsuitable. To combat this, two IF sections were implemented, Channel A for low power sea returns, $X_R(t)$, and Channel B for the transmitted pulse, $X^n{}_T(t)$. The length of coaxial cables is the same for both channels the leading up to an IF filter box. Any other delay in the two signals is then corrected in signal processing.

Noise calibration is an empirical procedure that can effectively lower the noise floor. Using a large number of noise-only range bins to approximate the signal's thermal noise distribution, which is a normal distribution, an effective Cutter-to-Noise Ratio (eCNR) can be obtained. This is achieved by subtracting the mean noise power from every range bin of the signal. Figure 6 shows an example of a signal that has been noise calibrated. The theory behind this is explained in [9]. Further studies need to be done to quantify the signal degradation in the previous implantation of the LATPROP radar and compared to this two channel CoR method and its theoretical value.

Currently, the noise-only range bins are empirically selected but, this process could be improved upon by using an Expectation Maximation (EM) algorithm. An EM algorithm is statistical model used to estimate the pdfs of a multi-distribution signal. Since sea clutter, noise and even land clutter all have different distributions at very-low grazing angles, the EM algorithm would be able to isolate the noise-only range bin from the entire signal thus, increasing the number of data points to characterize the noise distribution more accurately, for a better estimation of the noise power, resulting in a higher eCNR.

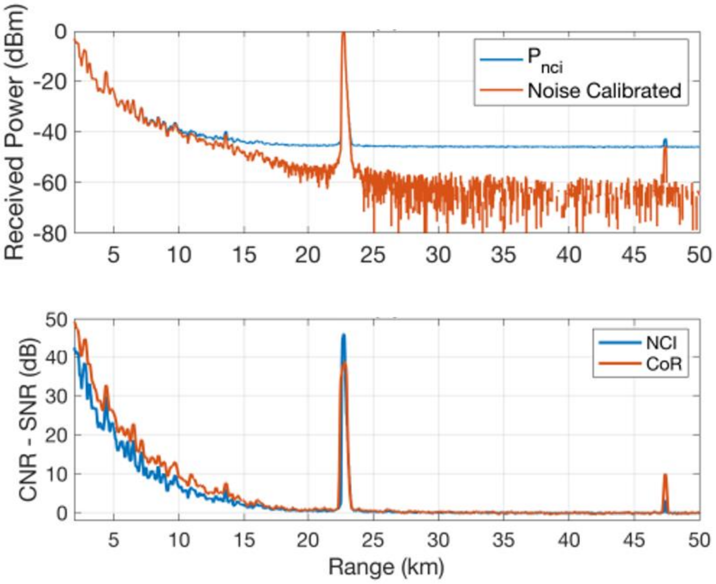


Figure 6: An example of Radar Power return noise reduction process. Top plot displays non-coherent power return with a noise calibrated reduction vs range. Bottom displays non-coherent power return vs coherent on received noise suppressed vs range.

Trade-off Between Antenna Height and Launch Angle for Optimal Clutter-Range Return

Figure 7 shows that duct characterization is not just dependent on frequency but also on antenna height [16]. The lower antenna height allows for more energy to be trapped in the ducts, allowing for a specific signature to be captured. I propose that similar dependency can be true for lower launch angles. In theory, the lower launch angles are better suited for low evaporation duct height estimation since only lower propagation angles can be trapped by the duct (typically <1 deg). This means that when the

MLAM incorporates more angles with higher launch angles there is a diminishing return and the CNR starts dropping rapidly at higher angles. If this is the case, it will be important to have a higher weight on angles that illuminate more of the duct.

Figure 8 expands on plot (f) of Figure 7 with the addition of two different launch angles, -0.5° and 0.5°. The plot for a launch angle of -0.5° shows an overall lower power return in terms of the plots for launch angles of 0°and 0.5°. For scenarios where we only have access to relative clutter signal, each clutter return is normalized with respect to the clutter power at 10km for 0° launch angle. For the evaluation of uniqueness in different launch angles, it may also be beneficial to use the clutter returns that are closer in range such as in Figures 7-9.

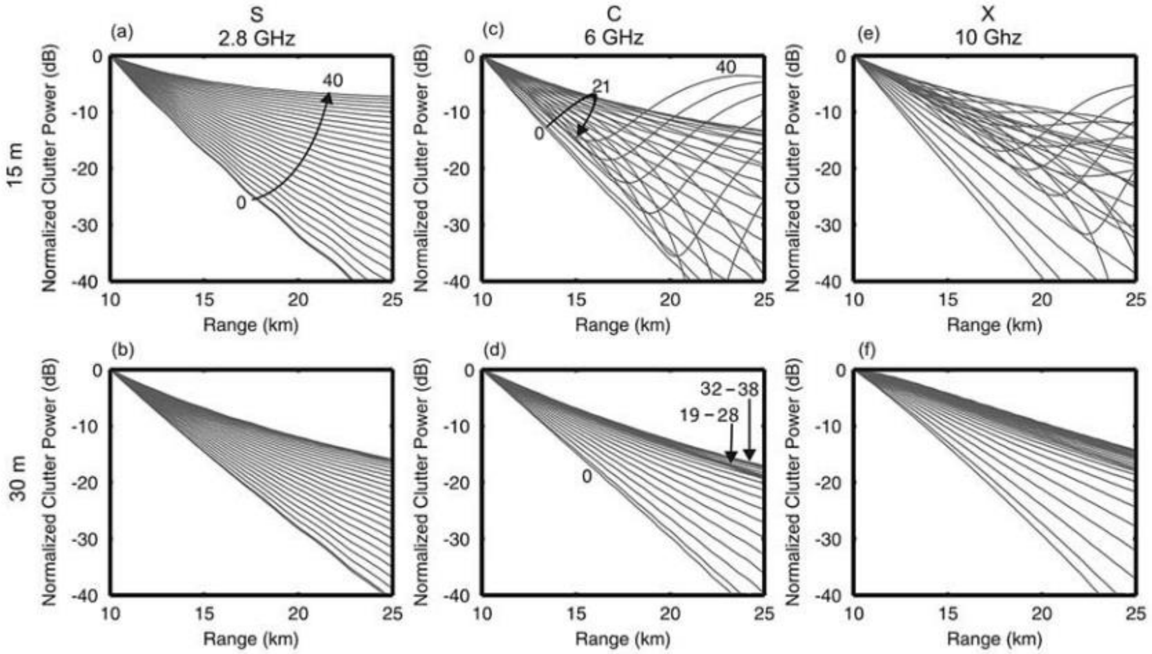


Figure 7: Normalized clutter libraries of evaporation ducts with EDH ranging from 0m to 40m for three frequencies and two antenna heights. Arrows show the evolution of the clutter patterns as EDH increases.

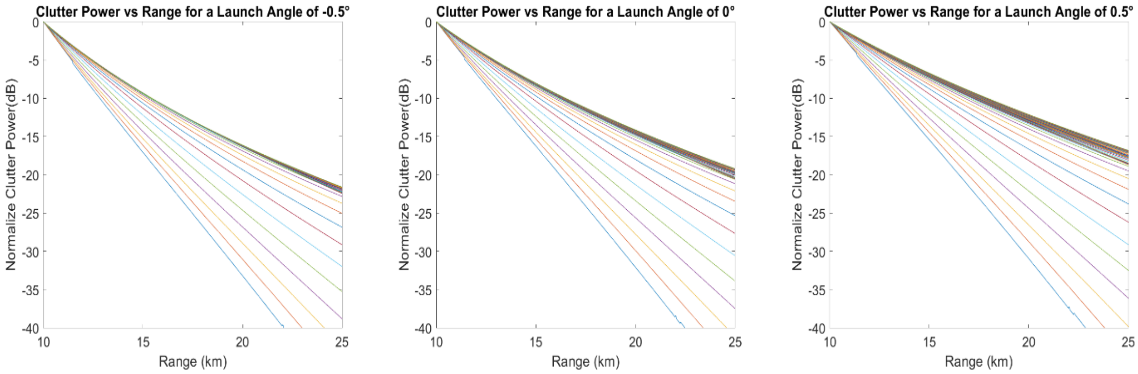


Figure 8: Normalized clutter power vs range plots for antenna height of 30 meters with EDH varying from 1m to 40 m for three different Launch angles.

Higher launches angles are known to have a limit of importance that corresponds to the energy trapped in the duct called the critical angle. Figure 9 shows four different duct heights each with a range of launch angles for an antenna height of 5m. Figure 10 shows four different duct heights each with a range of launch angles for an antenna height of 25m with Figure 11 range axis being magnified in to show the uniqueness of the clutter returns for the lower launch angles at closer ranges.

From Figures 9,10 and 11, it seems that the lower angles tend to trap more energy than their upper angles counterpart for an antenna that is relatively high compared to an ideal case for this RFC method, but not as significantly as expected. This could be because the lower angle has the same critical angle as the upper angles due to the grazing angle being higher than critical angle. Results from this simulation could mean that a multiple launch angle system such as LATPROP may be better suited for high transmitter height which makes the method more valuable being that RFC can be used in environments that were previously ill-suited. This topic will also be discussed in a later journal paper.

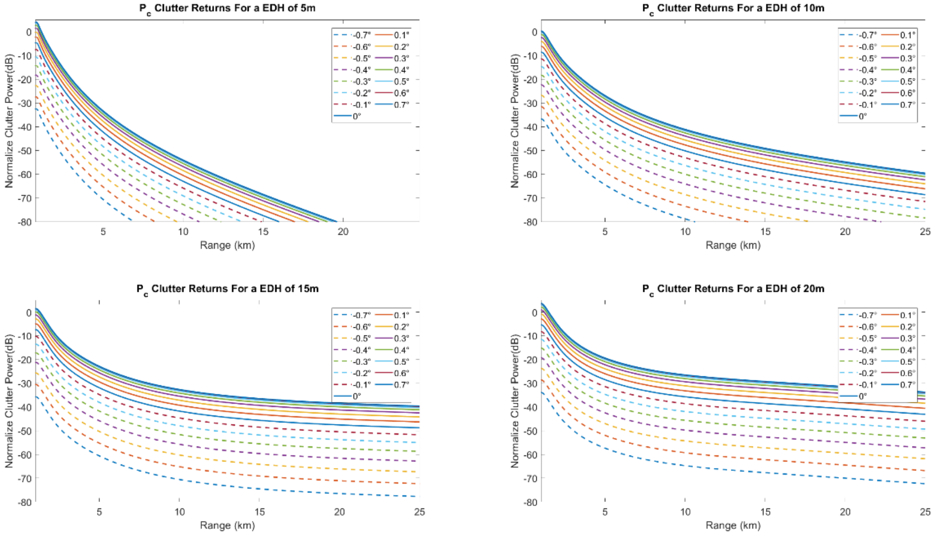


Figure 9: Launch angle Clutter vs Range plots for antenna height of 5 meters.

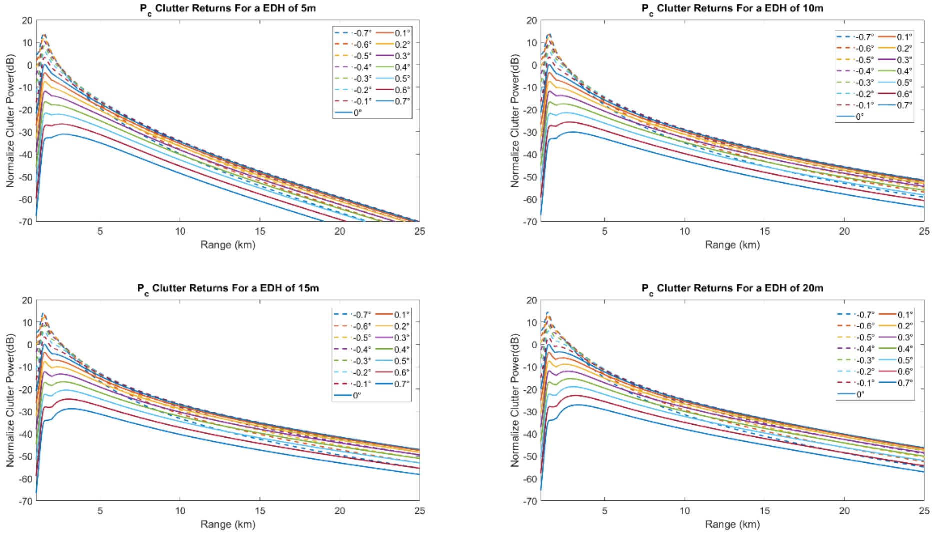


Figure 10: Launch angle Clutter vs Range plots for antenna height of 25 meters.

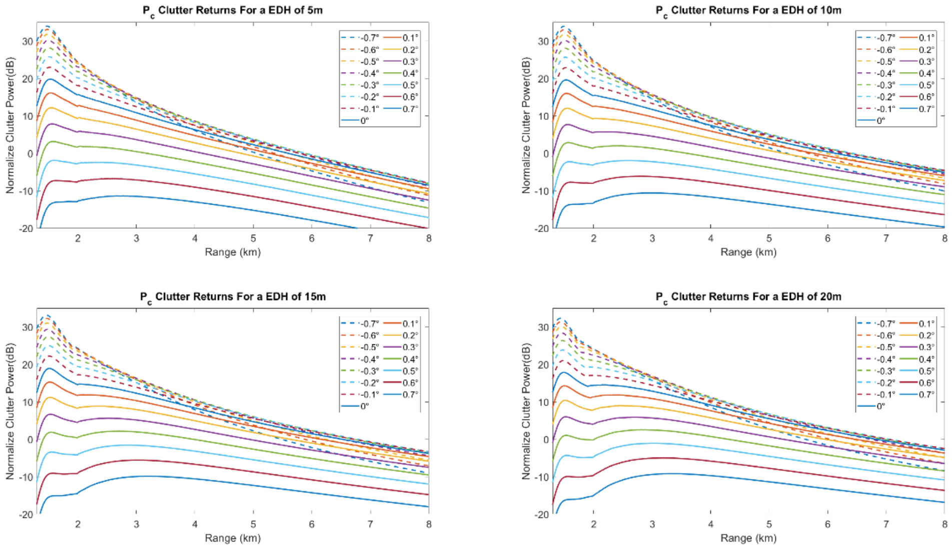


Figure 11: Enhanced launch angle clutter vs Range plots for antenna height of 25 meters.

Launch Angle Weighing Vector and Objective Function Methods

Which objective function method would produce the best results for MLAM-RFC. As stated in [14], equation (4) is a viable option but since the summation is over all angles, the inversion loses a degree of freedom allowing the estimation to be skewed by a possible outlier angle. The second option is the combination of all angles prior to the RMS error calculation, equation (6); if the summation of launch angles creates a unique power return it may be beneficial to mean all of the launch angles before the objective function for a better estimation. Lastly, the objective function, shown in equation (7) can treat each angle as its own inversion and create a distribution. This allows skewed estimation to be nulled while having a confidence bound based off the deviation of the resulting elevation duct height estimation. More research is needed to understand which objective function is best for MLAM.

$$\phi(\mathrm{m}) = \sqrt{\frac{1}{N_r}\sum_{\mathrm{r}}\left|\frac{1}{N_\alpha}\sum_{\alpha}\left(\mathrm{P}^{\mathrm{obs}}_{\mathrm{c,dB}}(\mathrm{r},\alpha) - \mathrm{P}^{\mathrm{sim}}_{\mathrm{c,dB}}(\mathrm{r},\alpha,\mathrm{m})\right)\right|^2} \qquad (6)$$

$$\phi(\alpha,\mathrm{m}) = \sqrt{\frac{1}{N_r}\sum_{\mathrm{r}}\left|\mathrm{P}^{\mathrm{obs}}_{\mathrm{c,dB}}(\mathrm{r},\alpha) - \mathrm{P}^{\mathrm{sim}}_{\mathrm{c,dB}}(\mathrm{r},\alpha,\mathrm{m})\right|^2} \qquad (7)$$

Clutter power is affected by launch angles and duct height. It is generally known that RFC performance increases with increased energy trapped from the signal. For a multiple launch angle system, it would be beneficial to create a weighing vector that can favor the launch angles that have high signal for the given EDH for a better estimation. A way that this can be explored is to perform an initial inversion to provide an initial range of EDH values to perform a statistical analysis on. Applying the results to a weighting function over the launch angles and taking a final RFC to have a more accurate estimation.

Figures 12 and 13 show normalized simulated clutter power in reference to a launch angle of 0° using specific model values for 12:30 AM GMT October 19th, 2021. Figure 12 displays that the averaged power trapped in a duct has a relationship corresponding to not only the duct height itself but also the launch angle. For evaporation duct heights less than about 4m to 7m the relationship is not as pronounced as the relationship outside of the range. In that case, the variation between clutter power and range could be used as a weighting vector. Figure 13 shows the normalized variance of the clutter power trapped in a duct and its relationship to the duct height and launch angle. One can also see that the relationship over launch angle would not be useable as a weighting vector after an EDH of 7m.

The results could be similar under different environmental conditions, but more studies need to be carried out.

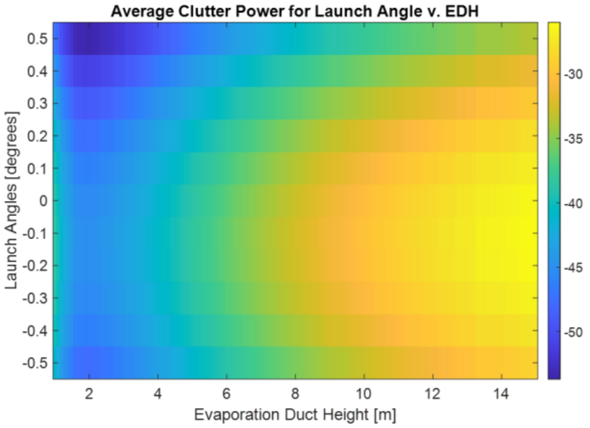


Figure 12: The averaged clutter power vs range values for every Launch angle and EDH.

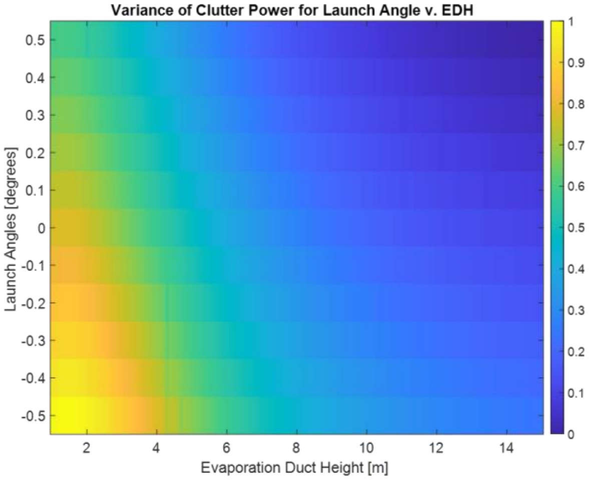


Figure 13: The variance of the clutter power vs range values for every Launch angle and EDH.

Multiple-Launch-Angle-Method (MLAM) RFC Using Land Clutter

The increased energy trapped inside the duct should be captured as an increase in backscatter to the radar, regardless of the scattering point. This research is proposing that land clutter can be a used as RFC scattering source as opposed to sea clutter; so long as the propagation path was affected by ducting. As stated above, research on this topic has been done before, but not using a dedicated low-cost RFC radar such as LATPROP.

Land clutter at very-low grazing angles is highly terrain specific with each individual range cell being impacted by the land cover features. This is important because it was theorized that at low angles, the launch angle will be the most dominant illimitation variable over the grazing angle. This means that the grazing angle is de-emphasized with terrain covered foliage in terms of the amplitude of the clutter power at low grazing angles [17]. With this knowledge it can be stated that for a given launch angle return, the only changes from land clutter will be from the propagation path and not from a change in a previously shadowed area due to a change in the grazing angle. Subsequently, changes in the launch angle could give more information for land clutter due to an illimitation of previously shadowed areas under a quasi-constant grazing angle. This means that each launch angle should contribute independent cutter signatures that could be beneficial for duct characterization.

Land Clutter Advantages and Disadvantages

With land being a high backscattering target, less processing has to be done to increase the CNR. Land clutter does not need to obtain multiple sensor-sourced data to understand its surface which is a tremendous benefit over sea clutter. Backscatter from the sea is heavily dependent on how rough the sea surface is which is dictated by wind. If there is no wind, it is virtually impossible to observe information from the sea surface even during ducting events. Another added benefit of using land clutter over the sea surface as the clutter source is that the correlation time is longer, several hundred times more as shown in Figure 14, which means that more pulses can be coherently integrated together for noise suppression. In all, using land as the backscattering surface will be a reliable reflection source due to its clutter being stationary properties and high amplitude backscatter.

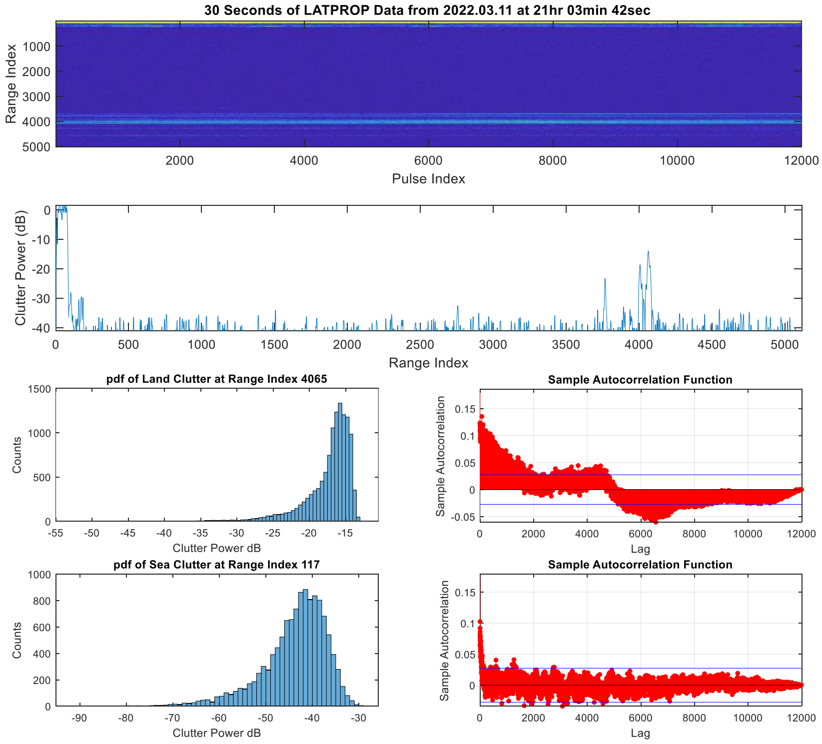


Figure 14: Stochastic results of land and sea clutter obtained by LATPROP during the CLASI experiment.

Lastly, the land profile that was captured by LATPROP in the CLASI experiment is colloquially considered a large hill, with a top height underneath 350m. This may mean that we can use the higher terrain to sense more complicated ducts that would be difficult to with the sea alone. Figure 15 shows a diagram of three different types of atmospheric conditions and its resulting effects on the clutter return that is in an environment that has land and sea clutter. The three types of atmospheric conditions are standard, evaporation duct and elevated duct. The sea and land portion of the return should be affected by the evaporation duct but the same cannot be stated for the elevated duct case. For an elevated duct, the bottom of the duct is not the sea surface and therefore no ducting information can come from sea backscatter. The land portion of the backscatter return will most likely still be affected by the duct and, therefore, information for the duct can be extracted from its return. Sea clutter for the evaporation duct case is expected to be better suited than land clutter but further studies need to be done to confirm.

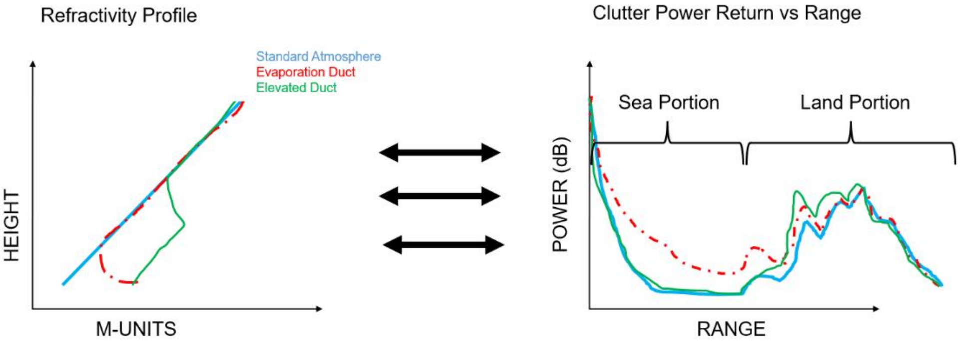


Figure 15: Diagram showing three different refractivity profiles (left) and its estimated corresponding clutter return (right).

The problem with the model is not the forward propagation model but the backscatter. The land clutter is less than 350 m in height and starts around 28 km, well within the limitations of the PWE model, which means that that the PWE will be able to accurately model the two-way loss propagation. If the backscatter cannot be modeled correctly, the next step would be to obtain measured data of a known standard atmospheric propagation scenario and use that as that to compare the amplitude difference for each range bin within the land clutter. This measured data amplitude comparison method of inversion cannot be used for sea clutter because the sea's stationaries is not long enough for this type of inversion to be reliable.

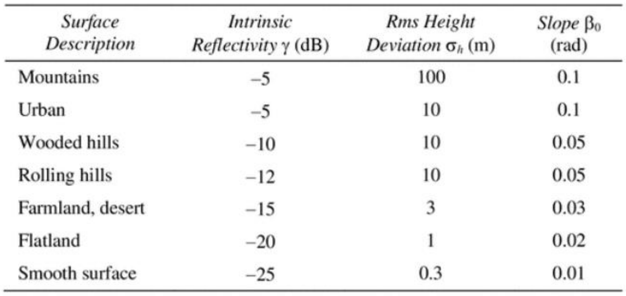
Evaluation of Land Clutter Models

Studies on combining land and sea clutter models have been done by Barrios but with key differences to the work that would be done in this dissertation. Barrios used a constant normalized clutter value to model the sea surface as well as a ray tracing method to estimate the grazing angle. Those methods have been replaced by models that perform more accurately. The hybrid model [18] uses a combination of empirical models to obtain an accurate sea surface backscatter model and the Miller-Brown model [19] for the surface roughness. Barrios attempted to use the Constant Gamma (CG) model which she stated worked well for her simulation case but needed to be adapted to minimize the error when compared to measured land clutter. [20] proposed a backscatter land model that is dependent, not only on the grazing angle, but also on frequency and other empirically based variables specific to the model.

Using the equation (8) to compute the value of which the assumption can be made to treat the surface as a smooth reflector [20]. Using the value of RMS height of 100 for he in table 2 along with the value of λ being 0.032 m the value of Ψ_c is 0.006°. The value of Ψ_c must be lower than the grazing angles for this to occur and with the grazing angle dependance on the ducting condition, even a qusi-perfectly reflecting surface cannot be assumed. This means that the land surface will have significant backscatter in order to preform RFC and higher grazing angles correlates to an increase in backscatter.

$$\sin(\Psi_c) = \frac{\lambda}{\pi h_e} \qquad (8)$$

Feng also argues against the importance of polarization, claiming that the median difference is less than 2 dB and that the max observed difference being less than 6 dB for all frequencies.



Surface Description	*Intrinsic Reflectivity* γ (dB)	*Rms Height Deviation* σ_h (m)	*Slope* β_0 (rad)
Mountains	−5	100	0.1
Urban	−5	10	0.1
Wooded hills	−10	10	0.05
Rolling hills	−12	10	0.05
Farmland, desert	−15	3	0.03
Flatland	−20	1	0.02
Smooth surface	−25	0.3	0.01

Table 2: Land surface parameters for evaluating clutter characteristics.

More research must be done to select the backscattering models for land clutter such as [20] for techniques such as the curved wave spectral estimation (CWS) [21] to be used. The CWS encompasses the spreading of the beam, which is crucial to accurately estimating grazing angle and, ultimately, ducting parameters. Other parameters such as LATPROP transmitting in X-Band, lower transmitter height, and estimating using multiple launch angles should allow for this section of the research to stand alone.

Barrios implemented a ray tracing and ranking system to do without having an accurate land clutter model. If a land clutter model cannot be made during this research, then it will be also beneficial to implement a similar model that Barrios used.

Land Clutter Profile

One of the most important variables of using land clutter for RFC at very-low grazing angles is the land profile. Using the formula for the width of the footprint of the antenna,

$$Footprint_{\ width} = \theta_B R\Delta \qquad (9)$$

with θ_B being the half-power beamwidth of the radar in radians and $R\Delta$ being the change in range in meters which is valid at very low grazing angles. For this dataset's purpose, the land clutter is between 25km and 70km, meaning that the result of using equation (9), the cross-range clutter footprint, or the width of the beam at a given range, will range from 480m to 1344m in the azimuth direction. The elevation profile will be created using data taken from the Shuttle Radar Topography Mission (SRTM). The SRTM provides a high-quality digital elevation model (DEM) in 90 m by 90 m segments. To use this data along with the data taken by LATPROP, the illimitation footprint must be the same. The DEM is averaged perpendicular to the radar to account for the beamwidth. The data is also averaged parallel to the antenna to account for the pulse width of the radar. The DEM profile is then interpolated to match the range bins of the PWE. Figure 16 shows the location of LATPROP, the scene within the antenna's beamwidth and the vegetation covering the terrain. Figure 17 shows an averaged SRTM terrain data that corresponds with LATPROP's beamwidth.

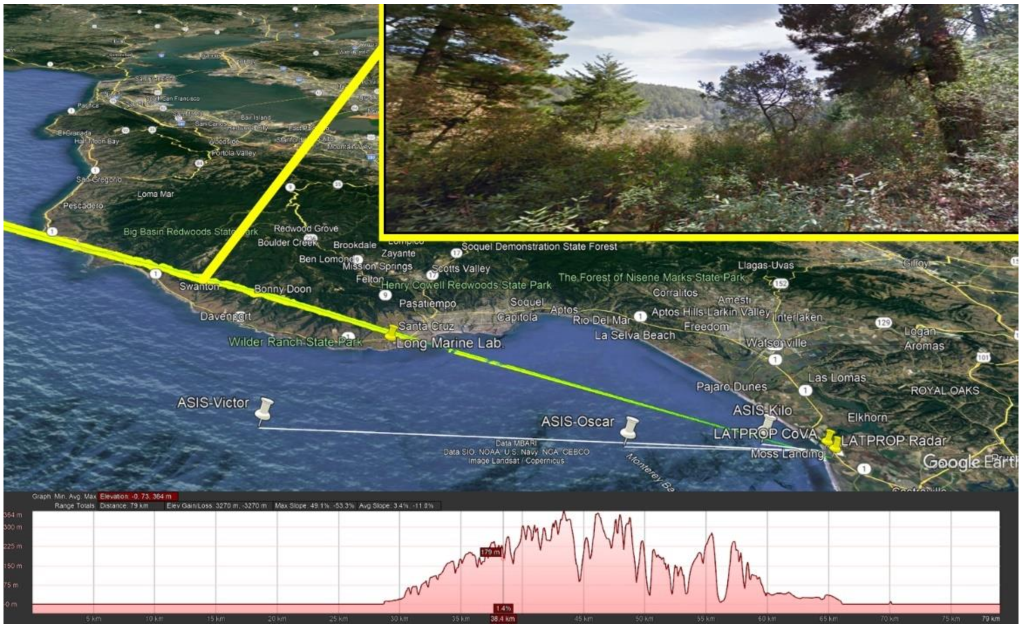


Figure 16: A google earth image of the path that is within LATPROP's Antenna beamwidth.

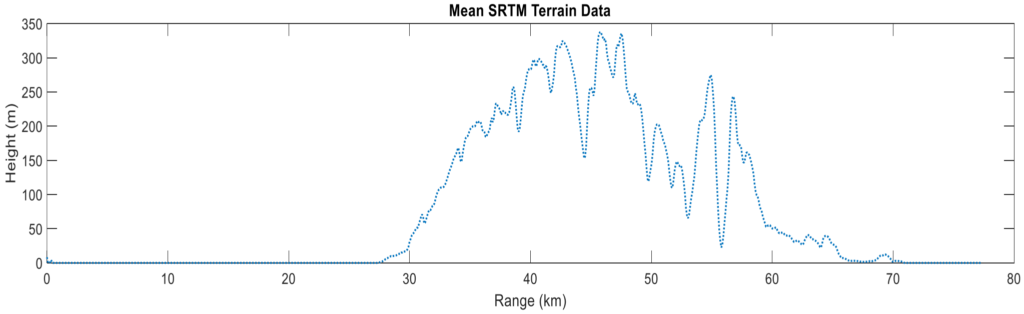


Figure 17: LATPROP specific land clutter profile.

Anticipated Results

By the end of this Ph.D. work, the study of the use of multiple launch angles in an RFC algorithm should be explored for both sea and land clutter. Along the path, the quantification of CNR and eCNR gain using CoR from previous implementations of LATPROP compared to the upgraded system and the EM algorithm should be explored. The utilization of launch angles vs antenna height for evaporation duct height estimation will also be researched. Work done for land clutter modeling and signal fluctuation will be done in tandem to the launch angle studies. Work to be done on land clutter will be to understanding its stationarity as well as scattering properties. After land clutter is characterize, then exploration on which type of duct would be best to sense with land over sea clutter and why. And finally, combine land and sea inversion to demonstrate that a system such as LATPROP can estimate Evaporation ducts and trilinear ducts such as Surface-Based and Elevated.

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