Optimizing Refractivity from Clutter (RFC) for Surface-Based Ducts

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LONG TERM GOALS

Develop electromagnetic propagation models, and refractivity inversion algorithms, that perform equally well over land and sea and in the presence of anomalous propagation conditions for both surface and airborne emitters, for use in operational or engineering propagation assessment systems.

OBJECTIVES

Develop an advanced unified hybrid radio propagation model based on parabolic equation and ray-optics methods for both surface-based and airborne applications. This model is named the Advanced Propagation Model (APM) and is the primary model used in the Advanced Refractive Effects Prediction System (AREPS). The specific technical objectives are to develop algorithms to extract surface clutter only from weather files provided by the Hazardous Weather Detection and Display Capability (HWDDC); and to improve, refine, and optimize the current state-of-the-art Refractivity From Clutter (RFC) algorithms to infer and characterize surface-based ducts (SBD).

APPROACH

In RFC, the duct-strength (range and height-dependent atmospheric index of refraction) is statistically estimated from the sea-surface reflected radar clutter. Genetic algorithms (GA) [1], importance sampler [2], and Markov chain Monte Carlo (MCMC) [3] samplers have been used to calculate the atmospheric refractivity from returned radar clutter. Although GA is fast and does well in estimating the maximum a posteriori solution, it gives poor results in calculating the multi-dimensional integrals required to obtain means, variances and underlying probability distribution functions of the estimated parameters. Accurate distributions can be obtained using MCMC samplers, such as the Metropolis-Hastings and Gibbs sampling algorithms. Their drawback is that they require a large number of samples relative to techniques such as GA and become impractical with increasing number of unknowns. The most recent work by Yardim, et. al. [4] demonstrates that the use of particle filters in RFC show much promise in tracking the spatial and temporal variations in the lower atmosphere over a maritime environment. We will continue this area of work in refining the RFC algorithms.

The RFC methods described in [1-4] consistently use an obsolete propagation model called the Terrain Parabolic Equation Model (TPEM) [5]. The TPEM is the predecessor to the Advanced Propagation Model (APM), currently integrated in the Advanced Refractive Effects Prediction System (AREPS) and included in the Oceanographic and Atmospheric Master Library (OAML) [6]. The current APM contains many improvements and modifications specifically to compute the grazing angle, and subsequently the forward scatter rough surface. This will affect the overall clutter predictions as well, although to the extent they significantly affect the already-published SBD inversion results is still an unknown. Therefore, the current RFC algorithms for SBDs will incorporate the latest APM version to ensure RFC results between the two propagation models remain consistent.

Surface clutter extraction algorithms have already been developed using the tactical scans of the SPY-1 radar under the Tactical Environmental Processor (TEP) effort. We have investigated extending the algorithms to extract surface clutter from the SPS-48 weather data files. Due to the differences in range sampling, and modes of operation between the SPS-48 and SPY-1 radars, we expect to perform some modifications to the SPY-1 clutter extraction algorithms.

WORK COMPLETED

A comparison of APM and TPEM results on synthetic data has been performed, as well as comparisons using the Space Range Radar (SPANDAR) data set [7]. We also compared the performance of different error measures using both propagation models. All results, for both synthetic and measured data comparisons will be documented in an in-house report.

In extraction of surface clutter from radar returns, the radar data currently being analyzed and tested was taken from SPS-48 radar universal format (UF) files generated in 2006, from the U.S.S. Peleliu. The purpose of this analysis has been to search for detectable patterns contained within the data of these files in order to categorize various atmospheric conditions that will ultimately provide real-time feedback to characterize the environment for subsequent use in a tactical decision aid (TDA). The first step in doing this is to remove any and all echo returns from point targets not categorized as surface clutter. Initial work on developing a point target removal algorithm for the SPS-48 data has been performed.

RESULTS

APM vs. TPEM Comparisons

Modeling clutter signals from the refractivity profile of the environment is a crucial step in RFC. The clutter power can be computed as:

$$P_c(r) = \frac{P_t G^2 \sigma \lambda^2 F^4}{(4\pi)^3 r^4 L}, \tag{1}$$

where σ is the surface clutter cross section in meters^2, P_t is the transmitter power, G is the antenna gain (assumed equal for both transmit and receive), λ is the wavelength in m, F is the propagation factor, r is range, and L is the total assumed system losses. The clutter cross section is a function of the reflectivity, σ_0, and the area of the clutter cell, which is also a function of range, antenna beamwidth, pulsewidth, and the grazing angle, ψ. Substituting these quantities into eq. 1 gives

$$P_c(r) = \frac{B_c \sigma_0 \sec(\psi)}{r^3} F^4. \tag{2}$$

Here, we've simplified the equation by using the variable B_c to represents all of the system specific parameters.

It has previously been assumed in [3,4,7] that beyond 10 km from the emitter the grazing angle is constant. Previous work showed that the assumption of range independence of grazing angles is a valid assumption after approximately 5 km from the antenna in an evaporation duct. However, in the presence of surface-based ducts, grazing angle is very much a function of range and we cannot simply neglect the grazing angle.

The difference in the clutter calculations from the APM and TPEM comes from two sources:

1. TPEM does not calculate grazing angle and it was assumed previously that it could be approximated by a constant value. In previous RFC analyses using TPEM, F was computed with a smooth sea surface, perfect conductor, assumption. On the other hand, APM calculates the maximum grazing angle in order to obtain the "worst-case" clutter, which enables us to use the modified Georgia Institute of Technology (GIT) model [8,9] to determine the range dependent surface reflectivity. The APM also considers a rough sea surface and finite conducting boundaries.
2. The propagation factors obtained by the APM and TPEM are computed with different algorithms used to solve the PE. The difference in the internal PE algorithms is that TPEM uses the wide-angle split-step Fourier algorithm whereas the APM uses the discrete mixed Fourier transform algorithm [10].

This results in different propagated fields, not only due to the difference of handling the boundaries, but also in approximations involved in the solution.

The GA searches for the best set of unknown parameters in the feasible space to minimize the difference between the observed and modeled clutter power. We have used the data from the Wallops Island 1998 experiment, conducted by the Naval Surface Warfare Center, Dahlgren Division. These data are obtained using a SPANDAR, operating at 2.84 GHz, located 30.78 meters above mean sea level. This radar has a half power beamwidth of 0.39°, with an elevation angle of 0°, and vertical polarization. We have only used the clutter data in the range between 10.2 and 60.6 km.

The l^2 norm difference of two vectors is the summation of squared of element-wise subtraction of the vectors:

$$\|x-y\|_2^2=\sum_{i=1}^{n}(x_i-y_i)^2 \tag{3}$$

We can expect that with the low resolution radar, we should get an unbiased estimation of the underlying parameters by the l^2 norm. Since the probability distribution of the clutter is close to a log-normal distribution, we can expect the clutter to have a Gaussian distribution in the dB domain. Figure 1 shows the best modeled clutter when we use l^2 norm as the error measure, and TPEM (Fig. 1a) and the APM (Fig.1b) as the propagation models. Figure 1a is reproduced from [3]. The comparison of these figures demonstrates that we get better results when we model the propagation with the APM. The APM was better able to capture the variation in observed clutter beyond 35 km but did not qualitatively perform as well as TPEM between 10 and 25 km. A more detailed and quantitative analysis will be documented in an open journal publication.

Point Target Removal

The structure of the SPS-48 UF files is similar to that of the SPY-1 radar data files, though certain adjustments were made in the point target removal algorithms original developed for the SPY-1. Both SPS-48 and SPY-1 radar data contain several spectral moment data fields, most importantly the reflectivity and the signal-to-noise ratio (SNR). Using these two data sets it is possible to determine the location of point targets within the range of the radar. The current algorithm is still under development, but has shown a considerable amount of success in properly detecting point targets in a single quadrant using these two data elements. Further meticulous analysis is underway to eliminate the minor remaining errors currently produced by the filtering algorithm.

For the SPS-48 data, both the reflectivity and SNR data sets contain 360 azimuth points and 301 range points, which result in a 360-by-301 matrix for each of the two data sets. This data is converted from rectangular to polar coordinates for the purposes of this study. At each coordinate point (represented by an azimuth index and a range index) there exists a corresponding reflectivity and SNR value. This essentially means that the plots produced will yield a polar graph with a third dimension represented by intensity values (reflectivity or SNR). These values are displayed using a gradually shifting color bin, where red represents a higher intensity and blue represents lower values. An example of this graph is shown in Figure 2 for one UF file from 2006. The square boxes shown in magenta indicate high intensity areas due to point targets that must be filtered, or removed, in order to obtain surface clutter produced strictly as a result of the surrounding atmospheric conditions.

The current method for filtering through the large amount of data available within a given UF file primarily involves the manipulation of threshold values. Both reflectivity and SNR values are normalized and then sorted into a more precise group of data points. The general equation for normalization is shown below, where $a_{i,j}$ represents the entire 360-by-301 matrix (either reflectivity or SNR) and $a_{n,m}$ represents a single non-normalized data point within this data set.

$$A_{n,m} = \frac{a_{n,m}}{\max(a_{i,j})} \tag{4}$$

Once normalized, fine-tuning of the initially large data set is performed by requiring the filtering algorithm to eliminate all data points below a simple predetermined threshold. As a result, it becomes easier and quicker to sort through the remaining data points and identify any point targets that may exist. This process comprises the bulk of the sorting and is performed on this reduced set of data points. Several requirements must be met in order to qualify a group of data points as a point target, and the filtering algorithm performs a multi-step process to identify these areas. Once complete, the algorithm returns all detected point targets as an *x-y-z* matrix.

The high intensity areas highlighted by the areas in magenta, in Fig. 2, illustrates the detection of apparent point targets by this filtering algorithm. However, after numerous tests were performed it was observed that not all apparent point targets were detected by the filtering algorithm. Currently we have focused on the data from the first quadrant only of each UF file. In future tests, the entire 360 degrees of radar data will be analyzed. In some cases, every single visible point target was detected by the program (Fig. 2), and in other cases some point targets went undetected while other apparent false detections were made. Despite the relatively straightforward task of detecting groups of data points above a specified threshold, designing an efficient, and robust, filtering algorithm proved to be much more complicated than expected.

Further effort will be required in order to improve the detection success rate of this algorithm. This process has required careful study of the SPS-48 radar return data, to the extent of defining what constitutes a point target and what does not. Point targets do not affect the actual weather, but can alter the analysis of the atmosphere if taken into account in the process—thus the need to develop a more robust algorithm to identify and remove such data. Figure 3 shows the success rates of eight separate UF files taken from the SPS-48 radar. Each radar return file was created from data recorded on April 8, 2006 at consecutive five minute intervals.

IMPACT/APPLICATIONS

The impact of this effort is that it will provide the U.S. Navy the capability to use through-the-sensor (TTS) technology to estimate low altitude refractive information in near real-time, and with sufficient spatial resolution, to provide timely and accurate radar performance assessment for naval operations. The propagation models and algorithms developed under this task will significantly aid in the overarching capability under the Weather-Radar-Through-the-Sensor (WRTTS) program to provide a completely integrated end-to-end "system of systems".

The overall goal of this work is to produce operational RF propagation models for incorporation into U.S. Navy assessment systems. Current plans call for the APM to be the single model for all tropospheric radiowave propagation applications. As APM is developed it will be properly documented for delivery to the OAML, from which it will be available for incorporation into Navy assessment systems. Recent optimizations and enhancements of APM not only benefits the U.S. Navy but also **unifies** the overall military EM performance assessment capability by having a single high-fidelity propagation model that performs equally well over land and sea and in the presence of anomalous propagation conditions.

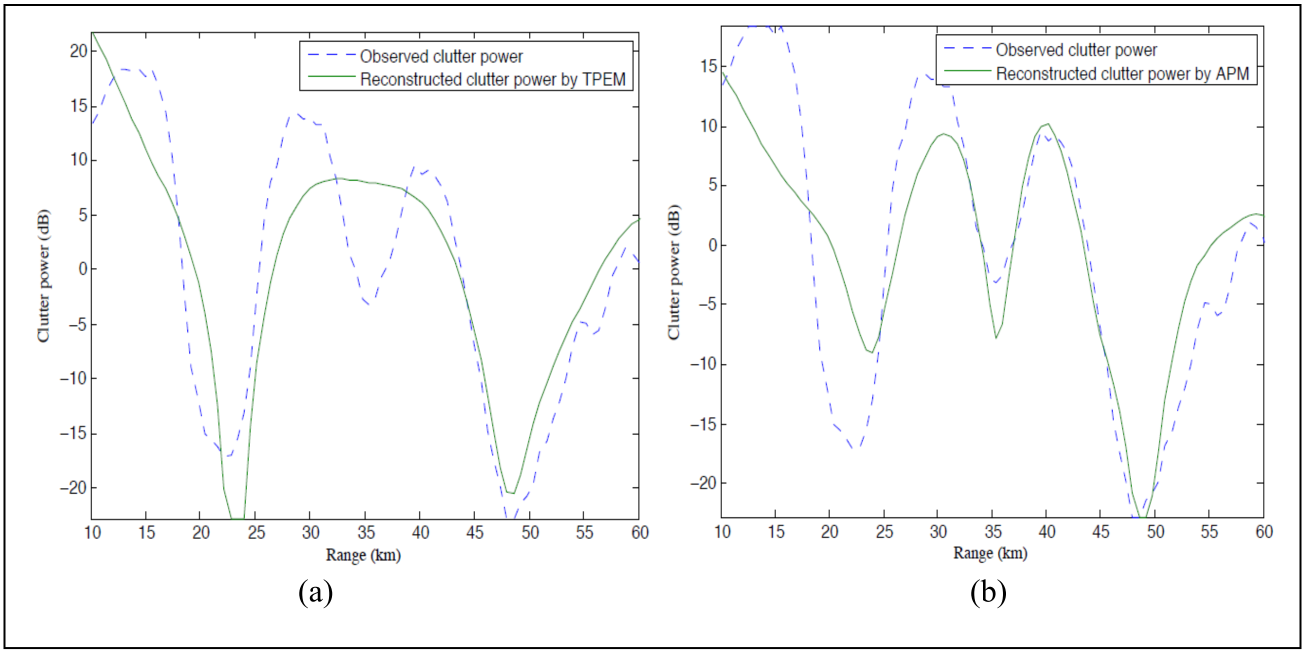

Figure 1. The observed clutter from the SPANDAR and the best modeled clutter, when using l-2 norm as the error measure, for (a)TPEM and (b) APM.

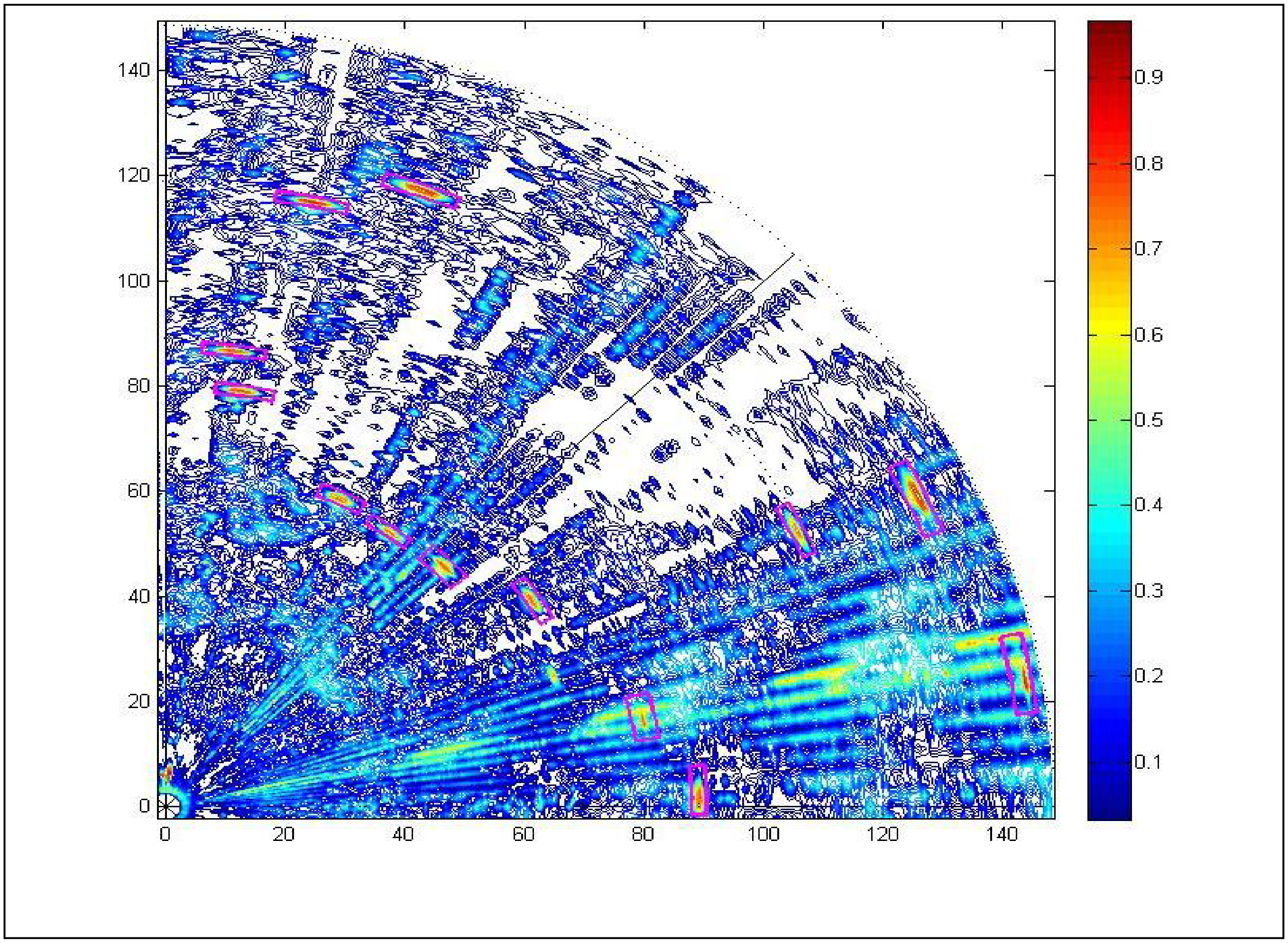

Figure 2. Reflectivity plot for first quadrant of one UF file with point targets indicated by the magenta boxes. Axes represent range in km.

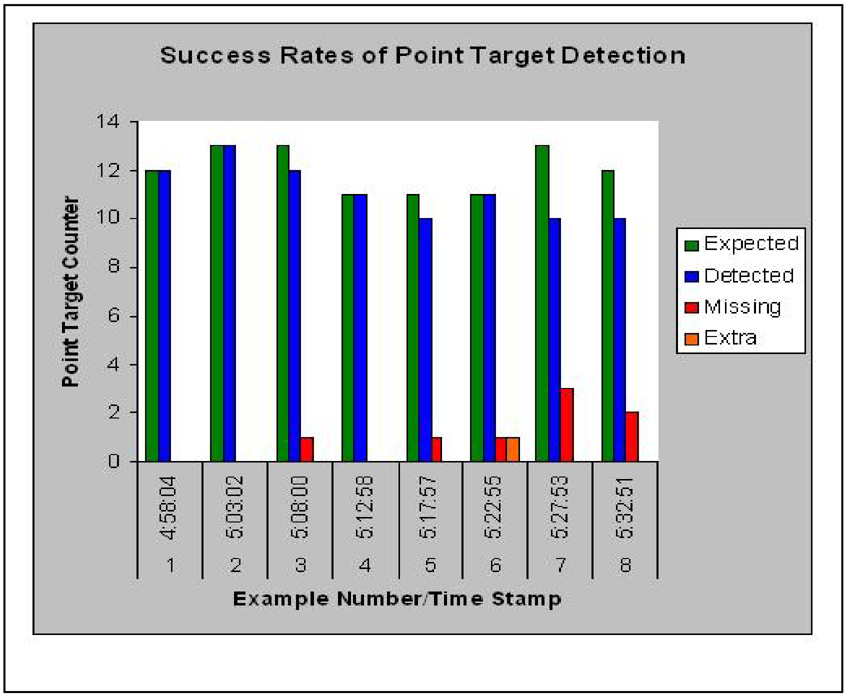

Figure 3. Success rate of point target detection for eight UF files.

TRANSITIONS

All APM modifications and added capabilities transition into the Tactical EM/EO Propagation Models Project (PE 0603207N) under PMW 120 which has produced the Advanced Refractive Effects Prediction System (AREPS). Current and new software, along with information displays will also transition to PMW 120 and/or software projects for inclusion in the Naval Integrated Tactical Environmental Subsystem (NITES)-Next. Propagation modeling capabilities can also be transitioned to the Hazardous Weather Detection Display Capability (HWDDC) for use in future refractivity from clutter (RFC) integration plans.

Academia and other U.S. government are also utilizing APM/AREPS. The APM is currently being used by foreign agencies as the underlying propagation model within their own assessment software packages. The APM has also been adopted as the preferred propagation model in the Ship Air Defence Model (SADM), which is an operational analysis software tool developed to simulate the defense of a naval task group against multiple attacking anti-ship missiles and aircraft. BAE Systems, Australia are the developers of SADM and some of their customers include U.S. DoD agencies.

RELATED PROJECTS

Efforts under this task are related to the Joint Tactical Radio System (JTRS) program and the Communication Assets Survey and Mapping (CASM) Tool. CASM is used Nationwide for planning and gap analysis of communications interoperability between state, local and Government agencies. It has been deployed to 77 urban areas across the Nation, and is expanding to statewide use. This tool was used during Operation Golden Phoenix for DoD and first responder communications planning and is currently being investigated for use by the Navy Expeditionary Combat Command, the National Communications System, First Naval Construction Division, and the Naval Coastal Warfare Squadron, as well as other military components in Hawaii and Alaska.

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PUBLICATIONS

Open journal submission for RFC optimization using the APM – in press.

HONORS/AWARDS/PRIZES

1. A. Barrios, SSC Pacific Lauritsen-Bennett award for Excellence in Science, 2010.

2. A. Barrios, Women of Color in Science, Technology, Engineering, and Mathematics for Professional Achievement - Government award, 2009