Over-the-Horizon Skywave Radar Target Localization

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Remote Sensing in Multipath Propagation Channels

WHAT WE DO: Develop statistical signal and array processing techniques for electromagnetic and acoustic remote sensing which exploit complex multipath propagation to achieve enhanced performance.

BACKGROUND:

• Radar and sonar signal processing methods have historically relied on plane-wave propagation models because of their analytic and computational simplicity.

• Methods for mitigating multipath propagation have been developed but typically exhibit performance which is upper bounded by their behavior when multipath is absent.

• The idea of exploiting, rather than undoing, the effects of multipath propagation to achieve improved localization performance by use of a computational propagation model is the essence of matched-field processing (MFP).

• Our current projects involve multipath signal processing for passive and active sonar, over-the-horizon skywave radar, and tropospheric refractivity estimation using microwave clutter from the sea surface.
Matched-field Altitude Estimation for OTH Radar

OBJECTIVE: To estimate aircraft target altitude to within 3000 feet using a limited number of dwells by matched-field processing of unresolved multipath returns in complex delay-Doppler space.

BACKGROUND:

- Previous attempts at altitude estimation with OTH radar have required either excessive signal bandwidth or revisits to resolve micro-multipaths in slant range or Doppler.
- Matched-field processing consists of correlated the observed data with predictions of the unresolved multipath signal as a function of hypothesized target position.
- Our approach to altitude estimation is aimed at precisely modeling the changes in the micro-multipath signal from revisit to revisit in complex delay-Doppler space.

ALTITUDE ESTIMATION CURRENT STATUS:

- Initiated by ONR in 1996 and transitioned to OSD Counter-Drug Program in 1997.
- Currently implemented on a real-time demonstration system attached to the Navy’s Relocatable OTH Radar (ROTHR).
Micro-multipath Returns in Delay-Doppler Space

- Overlapping micro-multipaths consist of a coherent sum of direct and surface-reflected returns which are unresolved in log-amplitude delay-Doppler space.

- Within and across revisits, delay and Doppler differences between micro-multipaths result in complex target peak shape changes and fading which is altitude dependent.
Multi-dwell Matched-field Altitude Estimation

- Multi-dwell maximum likelihood altitude estimates exploit shape changes in complex delay-Doppler return without requiring knowledge of target backscatter characteristics.
- Slow fluctuations due to target aspect changes and Faraday rotation are handled using a first-order Markov model for unknown aircraft reflection coefficients.
- Ionospheric model and estimated target ground track can be obtained from current radar.

![Flowchart for Multi-dwell Matched-field Altitude Estimation](chart.png)
A Markov Model for Complex Delay-Doppler Data

- Let vector $x_k$ denote the delay-Doppler neighborhood around a target at altitude, $z$, and slant range, $\tau_k$, and Doppler $\omega_k$, during the $k^{th}$ revisit:

$$x_k = e^{j\theta_k} H_k(\tau_k, \omega_k, z)d_k + n_k$$

where the matrix $H_k(\tau_k, \omega_k, z)$ contains the predicted post-compression micro-multipath waveforms, $d_k$, is the unknown reflection coefficient vector, $\theta_k$ is the unknown phase path, and $n_k$ is uncorrelated complex Gaussian noise.

- To handle Faraday rotation and slow aspect-dependent changes in the target backscatter, the unknown complex reflection coefficient vector, $d_k$, is modeled as a first-order zero-mean complex Gaussian Markov process.

- Thus $x_k$ is a time-evolving complex random process with unknown nonrandom parameters, $z, \tau_k, \omega_k, k=0,...,K$, and $\theta_k, k = 1,...,K$. 
Maximum Likelihood Matched-field Altitude Estimation

- Using a Markov model for the time-dependent target reflection coefficients, the maximum likelihood estimate of altitude is given by:

\[
\text{arg max} \left\{ \log p(x_o | z, \tau_o, \omega_o) + \sum_{k=1}^{K} \log p(x_k | x_{k-1}, z, \tau_k, \omega_k, \theta_k) \right\}
\]

where \( p(x) \) is the multivariate complex Gaussian density function.

- ML estimates of \( \tau_k \) and \( \omega_k \) can be approximated by using the radar’s slant tracker output.

- ML estimates of \( \theta_k \) may be solved analytically for this model so that only numerical evaluation of the time-evolving likelihood function accumulation over altitude is required.
MFAE Results for High and Low Flying Targets

- Time-evolving log-likelihood functions of aircraft altitude obtained using ROTH data.

- Commercial flight at range of 1200 km. FAA ground-truth is 35 kft. Estimated altitude is **35.2 kft**.

- Small aircraft at range of 2300 km. GPS ground-truth is 5.2 kft. Estimated altitude is **4.9 kft**.
MFAE Altitude Error Probability Distributions

- Simulation results indicate that errors are typically within 3000 ft. for low, medium, and high altitude aircraft.

- Simulation results indicate that MFAE can be performed using a radar bandwidth as low as 8 kHz with a possible SNR trade-off.
Estimation of Aircraft Altitude in Ascent or Descent

- Target altitude rate adds different Doppler shift components to each micro-multipath, depending on the target range rate and altitude.
- Modification of the micro-multipath model permits joint estimation of altitude and altitude rate to discriminate aircraft in ascent, descent, or level flight.

Simulated log-likelihood surface for an aircraft ascending from 5000 feet at 3.3 ft/s after 5 min.

Simulated log-likelihood surface for an aircraft descending to 3700 feet at -3.3 ft/s after 5 min.
Altitude Rate Estimation Results with Aztec Data

- ROTH-VA data collected 11/97 of a GPS ground-truthed Aztec flight SW of Puerto Rico had both ascending and descending legs.

- Time-evolving log-likelihood of initial altitude (left) and altitude rate (right) of descent from 10 kft. at approximately -5 ft/s.

- Correct altitude rate obtained when initiated with previous MFAE altitude estimate. Currently working on approaches for resolving possible altitude-rate ambiguities.
• In contrast to line-of-sight microwave radars, skywave HF radars require a propagation model to convert multipath delays to a target location estimate.

• The process of making slant-track-to-raymode and slant-track-to-target assignments and determining target ground locations is called mode linking and coordinate registration (CR).

• Conventional CR methods assume perfect knowledge of the down-range ionosphere and are prone to large localization errors when the ionospheric model is uncertain.
Target Localization with an Uncertain Ionospheric Model

- Ionosonde measurements provide spatially and temporally *incomplete* information about the downrange ionosphere.

- A statistical ionospheric model is obtained by treating plasma frequency profile parameters as random variables with mean and covariance derived from sounder data.

- Monte Carlo raytracing through a random ionospheric model gives the probability distribution function (PDF) of slant-coordinates for each ground location.
Deterministic versus Statistical CR and Mode Linking

- **Deterministic CR/mode linker block diagram**

- Ionospheric model realization → Compute CR Table → CR → Clustering in Ground Space → Hypothesize Slant-Track-to-Raymode-to-Target Assignments → Evaluate Chi-square Hypothesis Test

  Possible raymodes from previous dwell for current hypothesis

- **Statistical CR/mode linker block diagram**

  - Ionospheric model statistics → Compute PDF of Raymodes

  - Clustering in Slant Space → Hypothesize Slant-Track-to-Target Assignments → ML Mode Assignment and CR → Evaluate MAP Hypothesis Sequence

  Possible raymodes from previous dwell for each hypothesis
Maximum Likelihood Mode Assignment and CR

- Each slant observation is modeled as a doubly-stochastic random variable whose distribution is determined by both the probability that it corresponds to a particular raymode type and its variability conditioned on its raymode family.

\[ x_{j,k} = F_{s_{j,k}}(r_k) + n_{s_{j,k}} \]

- Given the Doppler-ordered observations, \( x_{j,k} \), the MLE of target ground position, \( r_k \), and associated raymodes, \( s_{j,k} \), in the presence of slant track jitter, \( n_{s_{j,k}} \) is obtained by:

\[
\arg\max \sum_{j=1}^{K} \left\{ \log p(x_{j,k}|x_{j-1,k}, s_{j,k}, s_{j-1,k}, r_k) + \log \Pr(s_{j,k}|s_{j-1,k}, r_k) \right\}
\]

where raymode transition probabilities, \( \Pr(s_{j,k}|s_{j,k-1}, r_k) \), and the output probability distribution parameters are estimated from Monte Carlo raytracing through a statistical ionospheric model.

- A fast recursive dynamic programming method is used to compute this ML estimate.
MLCR Results with the Puerto Rico Beacon Data

- Ground range error histograms from ROTH-VA, minimum variance (MV) CR with 3-D raytracing, and MLCR for Puerto Rico beacon at 2193 km range using real data. Average absolute miss distance (AVMD) reported in normalized coordinates.

![Histograms showing AVMD and BIAS for different methods.](image)
Statistical CR and Mode Linking Features

- Statistically models the ionosphere to achieve greater robustness to uncertainty in downrange environmental conditions. In contrast, for example, current deterministic approach may lead to large errors if strongest raymode incorrectly predicted.

- Estimates the correlation between slant tracks due to ionospheric variability under different hypothesized raymode assignments to improve mode linking. In contrast, for example, current approach assumes independence among bistatic EE, EF, and FF raymodes which during an F-layer TID could prevent tracks from being linked.

- Uses Doppler ordering of slant tracks to assist in raymode assignments. This exploits raymode elevation angle information useful for slant-track-to-raymode assignment.

- Maximum a posteriori probability (MAP) decision criteria based on estimated PDF’s of slant-track observations under different hypotheses. This extends conventional minimum variance test to provide a more accurate criteria for mode linking decisions.

- Chooses mode linking decision which optimally weights time history of decisions with current slant track data. In contrast, existing mode linker makes a hard decision after a limited observation time.
Scenario for Multi-Target Multi-Mode Mode Linking

- Typical QVI and WSBI with prediction from CREDO ionospheric model for 9/22/98 data.

- Slant tracks from DIR 200 from 1946 to 2110 Z used to evaluate mode linker performance. Note several occurrences of possible multipath arrivals.
MAP vs. ROTHHR Geographical Displays

- MAP ground tracks vs. FAA data for 1946-2110 Z.
- Current ROTHHR ground tracks versus FAA data for 1946 to 2110 Z.

- Observe that MAP ground tracks exhibit smoothness comparable to ROTHHR without a “hard-wired” ground track jump limit and while retaining the ability to revise mode linking decisions as more slant-track data becomes available.
Multi-Target Multi-Track Mode Linking Example

• NASA806 and NASA817 flights from 9/22/98 where MAP assigns the four tracks to the two targets to gives as much as a 3:1 accuracy improvement over ROTH.

Flights NASA806 and NASA817 DIR 200

<table>
<thead>
<tr>
<th>Slant ID</th>
<th>MAP Ground ID</th>
<th>MAP Mode</th>
<th>MAP Miss Distance (median nm)</th>
<th>ROTH Ground ID</th>
<th>ROTH Mode</th>
<th>ROTH Miss Distance (median nm)</th>
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<tr>
<td>28817</td>
<td>28817</td>
<td>F2L-F2L</td>
<td>6.2</td>
<td>28846</td>
<td>F2L-F2L</td>
<td>15.0</td>
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<tr>
<td>28846</td>
<td>28817</td>
<td>E-F2L</td>
<td>6.2</td>
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<td>F2L-F2L</td>
<td>15.0</td>
</tr>
<tr>
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<td>28856</td>
<td>F2L-F2L</td>
<td>6</td>
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<tr>
<td>28895</td>
<td>28856</td>
<td>EL-F2L</td>
<td>9.9</td>
<td>not put to ground</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Multi-Mode Single Target Example

- FWL774 flight from 9/22/98 where MAP correctly links two tracks to give a 2:1 accuracy improvement over ROTH.

<table>
<thead>
<tr>
<th>Slant ID</th>
<th>MAP Ground ID</th>
<th>MAP Mode</th>
<th>MAP Miss Distance (median nmi)</th>
<th>ROTH Ground ID</th>
<th>ROTH Mode</th>
<th>ROTH Miss Distance (median nmi)</th>
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<td>29281 (from DIR 199)</td>
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<tr>
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<td>29284</td>
<td>F1L-F2L</td>
<td>10.0</td>
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<td>F2L-F2L</td>
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</tbody>
</table>
Conclusions

- Complex multipath propagation conditions can be modeled and exploited to provide new capabilities, such as altitude estimation, to existing radars.

- Matched-field altitude estimation (MFAE) exploits the complex fading characteristic of unresolved multipath to achieve a median absolute error of less than 3000 feet with typically no more than 10 revisits on the target.

- Our current extensions of MFAE include target depth estimation with active sonar.

- Statistical modeling of the ionosphere facilitates target ground localization which is more robust to uncertainties in the down-range electron density profile.

- Comparison of statistical mode linking/CR with conventional methods using large datasets will by facilitated by near-term ionospheric modeling upgrades to ROTHR.