Target Height Estimation using Multipath Over Land

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Abstract—**Airborne radars often receive more than one report on airborne targets due to what is called multipath. Multipath is merely a second, and sometimes third, radar report at a greater range than the actual target. The multipath reports are due to reflections from the earth, and if the location and altitude of the point of reflection is known, the altitude of the target can usually be estimated with good accuracy. This concept is nothing new, and it is believed it may already be employed for operation over water by other systems. The Airborne Warning and Control System (AWACS) radar has never utilized multipath for height finding because it operates a substantial part of the time over land, and no algorithms for multipath height finding over land were available. More recently, availability of Digital Terrain Elevation Data (DTED) and improvements to the AWACS radar have prompted an investigation into the possibility of adding this capability. The result of this work, we believe, is the first known solution for using multipath radar reports over land to determine target altitude.**

I. Introduction

During the Airborne Warning and Control (AWACS) Radar System Improvement Program (RSIP) flight test program, recorded data over water were used to demonstrate that the altitude of most targets could be calculated an order of magnitude more accurately with multipath than by using the AWACS measured elevation angle. The RSIP program made this process easy because the RSIP upgrade greatly improved the range resolution and range measurement accuracy, and because algorithms were added to tag reports thought to be multipath.

However, as simple and as accurate as the above was shown to be, it was not accepted as a potential AWACS upgrade because it had not been shown to work over land as well as water.

In 2002, Felcyn analyzed additional AWACS recorded flight data from orbits over land to see if multipath reports are prevalent, and if so can they be used to calculate target height. His results showed that AWACS does indeed obtain numerous multipath reports over land, and that the accuracy and resolution of the AWACS radar are good enough to allow consistent height estimation.

However, although multipath over land is available and we can measure it accurately, the exact reflection point on the earth along with its altitude was not known and this introduced bias errors into the process. It was apparent that we needed to refine the algorithms to utilize terrain data.

In 2005, Latimer investigated the use of Digital Terrain Elevation Data (DTED) to remove the bias errors in multipath height estimation over land. The challenge was to derive iteration techniques that converge rapidly to accurate solutions over a variety of terrain types. This effort resulted in an approach that is not only feasible and reliable, but yields reasonable accuracy as well. To our knowledge, no one else has successfully solved this problem, and while our approach is not yet optimized, it answers the question “is it possible?”

II. Performance over Water

A simple model for multipath geometry is depicted in Fig. 1. Radar signals from the AWACS can follow four distinct paths: the direct path is from the radar to the target and back again; a single bounce path from the AWACS to the ground, then to the target, and then back to the radar on the direct path; another single bounce path following the opposite direction; and a double bounce path from the radar, to the ground, to the target, back to the ground a second time, and finally to the radar. The direct path range is shortest, the ranges for the second and third instances of single bounce multipath are equal but greater, and the range for the double bounce multipath is greater still. Assuming equal angles, Θ, of incidence and reflection, a simple spherical earth model can be used to solve for the target altitude given radar altitude, and measured ranges for the direct path and single or double bounce multipath. An effective earth radius is assumed to correct for atmospheric refraction.

The AWACS radar has always experienced multipath radar reports, and for many years they were considered a nuisance and a source of unwanted data on the operator’s screens. So, during the AWACS Radar System Improvement Program (RSIP) in the early 1990s, provisions were made to tag radar reports thought to be from multipath and to link such reports to the actual skin reports for each target. This, plus greatly improved range measurement accuracy, and finer range resolution, led us to speculate if these multipath reports could be used to calculate target altitude. The concept is simple, and requires only knowledge of the altitude of the radar, the range to the skin report, and the range(s) to the multipath report(s).

During qualification testing for RSIP, the MITRE Corporation was employed to analyze all flight data and to prepare flight test reports. Consequently, we possessed a large quantity of data useful for answering this question about

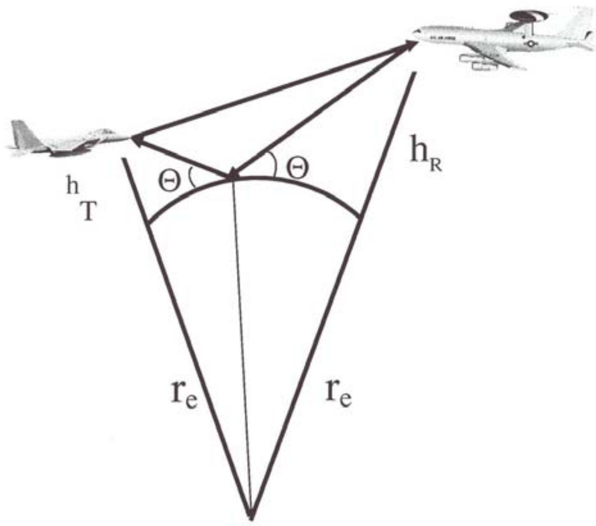

Fig. 1. Simple geometric model for multipath over a spherical earth.

multipath. Felcyn identified target tracks over water taken with one of the radar's height finding modes, and Swanay used these data to estimate target height with a simple algorithm that assumed a spherical earth. The result was an estimate of target height an order of magnitude better than was obtained using the radar's own height finding technique.

Because AWACS does not always operate over water, our findings were not considered to have broad enough application for AWACS. We then needed to investigate if it could be made to work over land.

III. PERFORMANCE OVER LAND

One effect of improved detection sensitivity in the RSIP radar was the increased frequency of occurrence of detected multipath on airborne targets. Further, the precision of measuring range on targets and their ground bounce appeared to be adequate to geometrically solve for target altitude. Although many factors influence the generation of multipath (e.g. terrain reflectivity and radar-to-target geometry), the radar has sufficient range resolution to distinguish the direct path from multipath signals for many targets. Thus, recorded flight data were used to quantify how frequently multipath could be detected and used to measure target altitude over various terrain types.

The objective of the flight data survey was to analyze how frequently and how accurately the single bounce multipath could be used to determine target altitude. Lacking absolute knowledge of the true altitude for targets of opportunity, reported altitude information from the Identify Friend or Foe (IFF) System was used as a reference for assessing height errors. Radar report data were first correlated in time and position to IFF reports to form a base set of data for analysis. Then, the individual radar reports were used to determine if additional detections could be found at the same Doppler frequency but farther range. When this occurred, the farther range detection was assumed to be single bounce multipath. The difference in measured range from the initial radar report to the assumed multipath was then used to geometrically solve for the target altitude as described above. Statistics were accumulated on the errors in IFF reported altitude and target altitude determined using multipath. Although the double bounce multipath could conceptually be used to do the same, there were occurrences where the double bounce path was detected but the single bounce was not. This would result in erroneous height measurements as the difference in second bounce multipath range and direct path range is twice as great as for single bounce. To mitigate this, the range difference was hard limited prior to calculating target height.

Anomalous height errors could occur for a variety of reasons. The IFF altitude is not always reported accurately and could lead to very large height errors. Sometimes the decision to declare a detection as multipath was incorrect, not only for the second bounce instances mentioned earlier, but also due to false alarms. Some of the limitations could potentially be circumvented with a refined multipath declaration scheme or also with kinematical tracking and smoothing, but this was outside of the scope of the intended survey.

The survey included radar data from multiple days and multiple geographic locales. Table 1 summarizes the two major findings of the analysis. The second column shows how often target height was successfully measured using multipath, as a percentage of the total base data set. This percentage varied depending upon the locale. The data set over the sea was limited in size, primarily to inter-continental commercial air traffic. Coastal Oregon and Los Angeles Basin data were limited to aircraft flying over land. This yielded a low percentage of multipath presumably due to the proximity of mountain ranges and irregular terrain at the typical multipath bounce point. The data collected over Nevada was in a region of a military training exercise under operationally representative conditions. It provided the most frequent source of useful multipath detection.

TABLE 1
Summary Height Estimation Errors

Terrain	Occurrence (%)	Mean Error (Kft)
Sea	26	-0.8
Coastal Oregon	11	-0.9
Los Angeles Basin	14	-1.5
New Mexico High Desert	26	8.3
Nevada	47	3.8

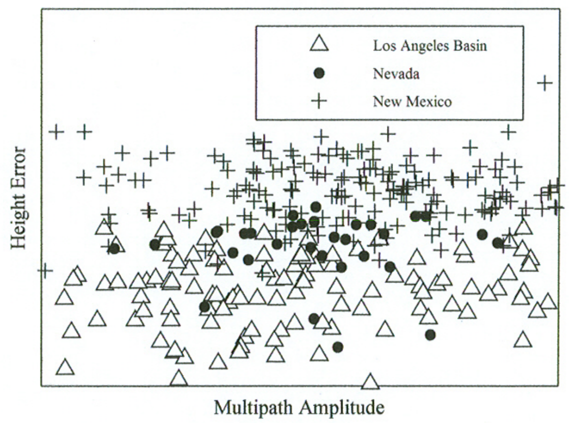

Fig. 2. Comparison of height error bias for various terrain locations.

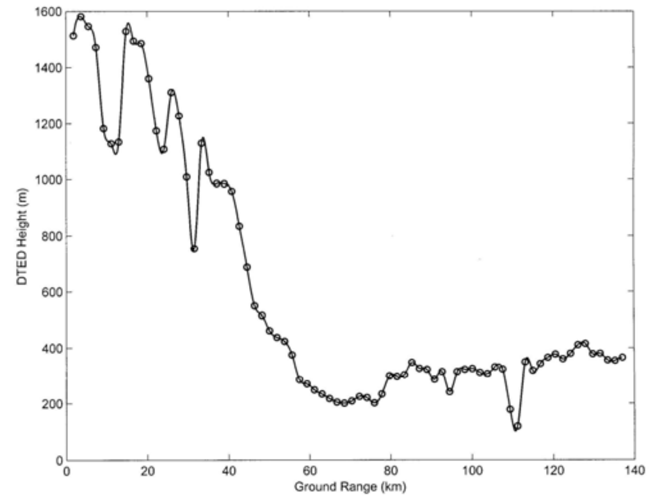

Fig. 3. An example of a cubic spline approximation of the terrain height from DTED. The sensor platform is at zero, the target at the right. The circles are sampled points from the DTED data base, in this case at 1 nautical mile intervals.

The second major finding was that the measured target height was biased for conditions over land terrain. This was due to the initial assumption that the height of the bounce point for multipath is constant, which is typically not the case over land. The accuracy achieved in terms of the random component of the height error achieved using multipath was better than could be realized through elevation measurement techniques. This is due to the fact that the accuracy of estimating height with multipath is determined by the range measurement accuracy of the RSIP radar. Fig. 2 shows a plot of height errors versus the signal strength of the return multipath. Errors in height were typically independent of signal strength. Although the frequency of occurrence of multipath is limited, when it does occur, the height estimation is particularly accurate and therefore, useful in the operational arena, provided that the bias can be properly accounted for when over terrain.

IV. MULTIPATH HEIGHT ALGORITHM USING DIGITAL TERRAIN ELEVATION DATA (DTED)

The sensor platform (AWACS E-3) records its position and attitude, together with the epoch of the observation, the range and the azimuth to the target. That, together with a coupled record when multipath returns are detected, plus terrain knowledge, in the form of Digital Terrain and Elevation Data (DTED) can be sufficient to estimate the height of the target independently from use of the radar's target elevation angle data. This paper documents the algorithm we successfully used on an actual case with real data. Parameters revealing the performance of the radar are classified; however the basic algorithm we employed is unclassified

An observation couplet is a linked pair of records as described above with the property that one is a direct path radar range measurement and the other is a multipath range measurement, either a hybrid return with one bounce off the surface or a pure multipath return with both transmitted and returned paths bouncing off the terrain. The algorithm processes couplets serially. The platform position and the azimuth and range to the target constitute the classic first geodetic problem: given a latitude and longitude on the earth's ellipsoid and the azimuth and normal section (range) to a second point, determine the latitude and longitude of the second point. There are several satisfactory algorithms that do this; we used the Rudoe algorithm. By repeatedly applying the Rudoe algorithm with increasing normal sections, we obtain an evenly spaced sequence of positions (latitudes and longitudes) along the geodesic from the sensor to the target. We expect the true bounce point to lie somewhere in this sequence.

The sequence of positions between the sensor and the target are candidate bounce points for multipath propagation. We make the simplifying assumption that the terrain does not slope left-right across the path from the sensor to the target. We use the sequence of positions along this path to enter the DTED data base and retrieve the terrain height above mean sea level for each position. This constitutes a profile of the terrain. In order to establish a continuous approximation to the actual terrain height from the sensor to the target, we fit a cubic spline through the sequence of heights. Fig. 3 is an example of a spline fit through the heights for one case. We note that the 1st derivative of the cubic spline is trivially available at any point also, so that the slope of the terrain between the sensor and the target is thus known approximately for any desired point. Fig. 4 is an example of the slope for the same terrain. Since the direct path range to the target is known, and the sensor's position is known, then in the vertical plane containing the sensor and the target, there is a vertical arc that is the locus of all points in the vertical plane at the measured range from the sensor.

To determine the target height, we search over combinations of target height and multipath bounce point ground range from the sensor for a minimal cost solution. The cost function is calculated as follows: we calculate for a given target height and a given bounce point position, the path length difference between the direct path from the sensor to the target, and the longer path between the sensor and the

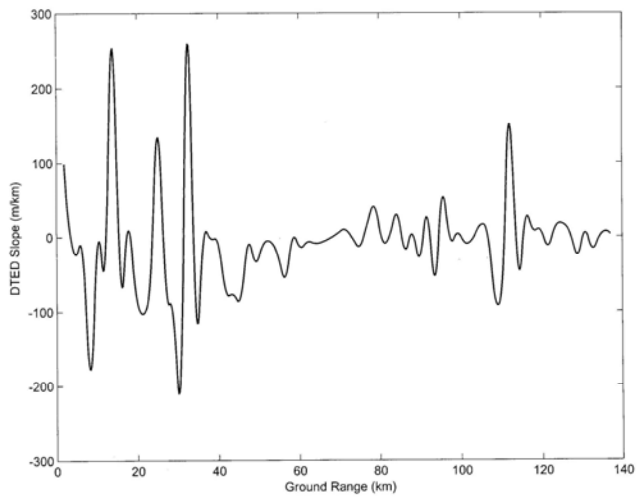

Fig. 4. The cubic spline approximation of the terrain slope from DTED. The case is the same as in Fig. 2.

target via the ground bounce point. We compare the "postulated" path length difference with the measured path length difference and a component of the cost function is the square of this difference between the postulated and observed path lengths.

Consider the triangle formed by the sensor, the target, and the multipath bounce point, *d* is the direct propagation path, s1 is the path between the sensor and the ground point, and s2 is the path between the ground point and the target. The path length difference z is

$$z = s1 + s2 - d \tag{1}$$

For generating the cost function *J*, there is an observed z and a postulated z. The contribution to the cost from the path length difference error is

$$J_{PLD} = \left(z_{observed} - z_{postulated}\right)^2 \tag{2}$$

There is a second component of the cost function: For the given target height and the given bounce point position, we calculate the incident and reflected grazing angles of the multipath rays relative to the sloping terrain (from the cubic spline approximation) and form the square of their difference from equality, as Snell's law requires. Denote the postulated incident grazing angle of s1 by η, and the postulated reflected grazing angle of s2 by ξ. Then the contribution to the cost from the postulated geometry's violation of Snell's law is

$$J_{Snell} = \left(\eta - \xi\right)^2 \tag{3}$$

We compute J_{PLD} in square meters and J_{Snell} in square degrees. The total cost, *J*, is

$$J = J_{PLD} + J_{Snell} \tag{4}$$

This cost function assumes an equivalence between meters and degrees.

Having defined a cost function, we perform a two-dimensional search for a minimum cost. We used the Nelder-Mead Simplex method contained in the MATLAB fminsearch function to seek the minimum cost location of the bounce point and the target height. This algorithm requires an initial two-dimensional point to begin the search, but does not require gradients. The algorithm searches for a minimum by constructing figures that have points numbering one greater than the dimensionality of the problem -in this case, triangles in our two-dimensional state-space. As the algorithm proceeds, it generates positions for which we must evaluate the cost. Eventually the triangles generated begin to shrink, and when the triangle areas become less than a pre-determined threshold, the algorithm terminates at a minimum cost function. Note that there is no guarantee that the minimum cost is a global minimum, but it will be at least a local minimum. We have noted that generally we are able to obtain minimum costs that are equivalent to discrepancies of a few thousandths of a degree and a few centimeters. We believe that the quality of our results is limited by the bandwidth of the AWACS radar, not the numerical precision of our mathematical algorithm.

The algorithm sometimes fails, yielding ridiculously high or low heights, but it more often succeeds, When the results are very bad, our experience with actual data has been that it is easy to spot outliers. As long as we know that we are aggregating data from a single target, and that the target's height is constant or known, we can use standard statistical techniques to automate outlier rejection. We have found between 10 and 15% of the cases to be outliers. We have results from an event involving a target that was instrumented with GPS. Although the quantification of these results is classified, we can report that the level of performance convinces us that the phenomenon is real and could be exploited.

We found only slight differences in results with various spacing of DTED samples from 0.04 nautical miles to 2 nautical miles. Fig. 5 shows the variability of the dispersion of the results from our test case when the sampling interval was varied over several values. When the terrain is not too rugged, one would not expect the spatial sampling interval to be critical. There is no reason to use an interval smaller than the DTED interval of about 70 m. in longitude at intermediate latitudes.

For similar reasons, we did not perform interpolation of DTED grid point heights to furnish the DTED heights for the intermediate latitude and longitude positions - we used the height of the closest "corner" of the DTED grid to the desired position.

We noted that the spacing had an indirect effect on the results in that the ratio of points failing the statistical test after each editing cycle varied slightly. There is a strong correlation between the quantity of data surviving editing and the standard deviation of the edits, with more data tending to

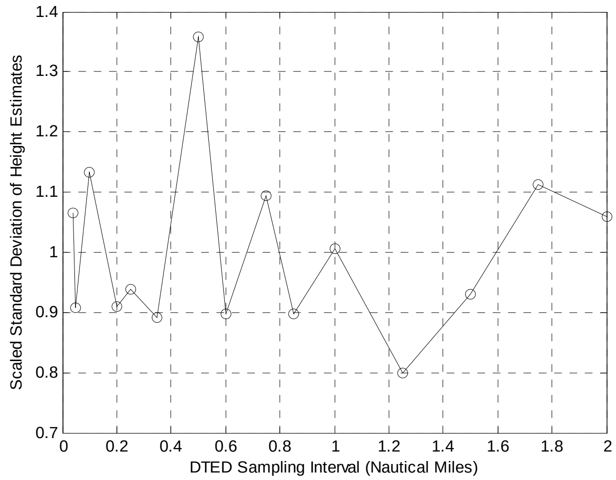

Fig. 5. Variability of height estimate dispersion as a function of DTED intermediate point spacing.

increase the dispersion.

The simple model used for modeling terrain using DTED data appears to work well in many cases. There are undoubtedly some instances of geometries where the multipath propagation is more complicated than our simple model will allow. There are from 10% to 15% failures but they are easily recognized and discarded.

V. CONCLUSIONS

By using actual flight data from the AWACS radar, we have found that multipath reports occur over all types of terrain with more frequency than we expected, and that the identification of such reports as multipath is not difficult. We also found that the target height estimates from multipath are nearly always more accurate than the elevation angle measurement method currently used with the AWACS radar.

The algorithms for eliminating height bias errors over land are, to our knowledge, the first to be developed, and demonstrate that height estimation using multipath is a viable supplement to elevation angle measurement height finding for AWACS.