**Title:** Assessment/Forecasting of Anomalous Microwave Propagation in the Troposphere Using Model Output

**Author:** Wayne Sweet

**Abstract:**
A method for forecasting microwave propagation conditions below the 850 mb level is described and evaluated using radiosonde data in the eastern North Pacific Ocean. The method demonstrates good skill in assessing the existence of ducting or normal propagation conditions below the 850 mb level. Duct altitudes are not provided in the assessment, nor are the probabilities of occurrence. The categorical assessment is based on an 850 mb parameter derivable from model output fields, and can be used in ocean regions characterized by a marine...
Block 20, Abstract, Continued

inversion below the 850 mb level. The method does not seem useful in ocean regions at high latitudes or in those characterized by warm surface currents.
Enclosure (1) examines a method by means of which the existence or nonexistence of microwave ducts below the 850 mb level can be assessed and predicted. The 850 mb parameter used in the calculations can be derived from either the analysis fields or the forecast fields of the Fleet Numerical Oceanography Center's hemispherical model.
A method for forecasting microwave propagation conditions below the 850 mb level is described and evaluated using radiosonde data in the eastern North Pacific Ocean. The method demonstrates good skill in assessing the existence of ducting or normal propagation conditions below the 850 mb level. Duct altitudes are not provided in the assessment, nor are the probabilities of occurrence. The categorical assessment is based on an 850 mb parameter derivable from model output fields, and can be used in ocean regions characterized by a marine inversion below the 850 mb level. The method does not seem useful in ocean regions at high latitudes or in those characterized by warm surface currents. (Author)
ASSESSMENT/FORECASTING OF ANOMALOUS MICROWAVE PROPAGATION IN THE TROPOSPHERE USING MODEL OUTPUT

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1. **INTRODUCTION**

The Navy uses refractometer or radiosonde data to assess microwave* refractive conditions over the oceans. The refractometer procedure, which takes 2-3 hours, requires that aircraft tape recordings of refractometer data be recovered and then processed on a small programmable calculator. Radiosonde data can be processed as soon as they are received, in an hour or less.

If radiosonde data at the task force location are not available, Fleet Numerical Oceanography Center (FLENUMOCEANCEN) in Monterey, California, can be requested to select the nearest radiosonde data available, compute the refractive structure, and send this information to the task force in coded graphical form via the message circuits; this procedure can take up to 3 hours.

The disadvantages of these techniques are obvious; (1) radiosonde/refractometer data are needed, but not usually available; (2) time delays may invalidate assessments due to changes in ships' positions; (3) no forecast capability is provided; and (4) unrepresentative soundings may be used. The single advantage is that assessments based on refractometer or radiosonde data provide information on ducts' altitudes and strengths.

This report examines a method by which the existence/non-existence of microwave ducts below the 850 mb level can be assessed and predicted. The method uses an 850 mb parameter which is derivable from either the analysis fields or forecast fields of the FLENUMOCEANCEN hemispherical model. This method is advantageous because it can be used for forecasting occurrence of elevated ducts and any naval ship can receive the information. The forecast of ducting would use FLENUMOCEANCEN forecast fields and therefore the skill of the forecast would be less--exactly how much is yet to be determined.

*Generally 0.01-100 cm wavelengths.*
The method evolved from work of Gjessing and Moene (1967) in which an 850 mb parameter, $\Delta N$, was correlated to the received signal data of an L-band radar and a 1-GHz radio link. By using an empirically determined threshold value for $\Delta N$, the investigators were able to forecast the occurrence of anomalous propagation with an 80% accuracy.

This present method uses a similar 850 mb predictor parameter and shows very good correlation to the existence of microwave ducts below the 850 mb level. Radiosonde data from an ocean region off the U.S. west coast for the period 1960-65 were analyzed for ducts below the 850 mb level. The predictor parameter, $\Delta e$, was calculated for each of the radiosonde observations using 850 mb data, and a file was compiled with these data. Discriminant analyses was used to find the critical value of $\Delta e$, and this critical $\Delta e$ was used to generate contingency tables and skill scores.

This study is a follow-on to work reported in Sweet, 1980, NAVENVPREDRSCHFAC TR 80-01, which used Gjessing's and Moene's $\Delta N$ parameter and considered three classes of refractive conditions based on an $N$ gradient criteria: (1) ducts, $\frac{dN}{dz} < -0.157 \text{ N/km}$; (2) ducts and superrefraction, $\frac{dN}{dz} < -0.10 \text{ N/km}$; and (3) normal, $\frac{dN}{dz} > -0.10 \text{ N/km}$. TR 80-01 examined only data from zone 2 of the five geographical zones of data established for the EASTPAC area. The critical value of $\Delta N$ in TR 80-01 was chosen by optimizing Heidke skill scores.

In this present report the classification functions are solved to find the critical $\Delta e$. Two classes of refractive conditions, ducting and normal, are considered; a third class considered in TR 80-01, ducting and superrefraction, was not included here since ducting conditions are believed to be more important than superrefraction (which to some extent is defined by agreement rather than by physics). The EASTPAC geographical zones defined for this study, and the numbers of radiosonde soundings that contributed data to the analysis, are shown in Figure 1.
2. PHYSICAL RATIONALE FOR $\Delta e$ METHOD AND DATA

Over a cool ocean surface, which provides a water vapor source as well as a heat sink (regions of upwelling offshore of continents, for example), a temperature inversion usually occurs. Water vapor trapped within the marine layer by this temperature inversion normally causes microwave ducting conditions. Dry air aloft, at the 850 mb level, for example, would signify a temperature inversion somewhere below that level, since synoptic conditions which cause inversions are usually anticyclonic with accompanying subsidence. In the region examined in this study, the inversion heights were generally below the 850 mb level (~1500 m) as shown in Figure 2.

A parameter that measures the dryness of the air aloft and is calculated at a level above the inversions would then indicate the likelihood of ducting below. Gjessing and Moene used a parameter $\Delta N$, calculated at the 850 mb level, which indicates the dryness of the air using the wet term of the refractivity equation.
Figure 2. Cumulative distributions of inversion heights (m).
\[ N = N_w(T_a) - N_w(T_d) \]  \hspace{1cm} (1)

where

\[ N_w(T) = \frac{Be(T)}{T^2} \]

and

\[ T_a = \text{air temperature} \]
\[ T_d = \text{dew point temperature} \]
\[ B = 3.73 \times 10^5 \]
\[ e(T) = \text{water vapor pressure at temperature } T. \]

This parameter measures the dryness of the air aloft, since

\[ \Delta N = B\left[\frac{e(T_a)}{T_a^2} - \frac{e(T_a)}{T_a^2} - \frac{e(T_d)}{T_d^2}\right] \approx \frac{B\Delta e}{T_a^2} \]  \hspace{1cm} (2)

where

\[ \Delta e = e(T_a) - e(T_d) \]  \hspace{1cm} (3)

For normal 850 mb temperature and dew points, the approximation in Eq. (2) is in error by no more than 10-15\%. The linear correlation between \( \Delta N \) and \( \Delta e \), using actual radiosonde data, is better than 0.999. Thus \( \Delta e \) can and will be used in this present analysis to classify ducting conditions.

Gjessing and Moene (1967) used a critical value of \( \Delta N \) equal to 15N units; a \( \Delta N \) above 15N was assessed as ducting. The critical \( \Delta N \) was chosen by inspecting received signal data from L-band radar and relating signal strength to \( \Delta N \) values. The critical value was applied to three years of radar data obtained off the coast of southern Norway. The linear correlation coefficient between signal intensity and \( \Delta N \) values was 0.76, and the total correct for 36 hr forecasts was about 80%.

With Gjessing and Moene's work as a guide, the pilot study reported in TR 80-01 (Sweet, 1980) used a sample of radiosonde data from the EASTPAC picket ship data to examine the skill of the \( \Delta N \) predictor. The results obtained in this sample analysis
for one geographical zone were sufficiently encouraging to warrant analysis of the remaining picket ship data for all five EASTPAC zones, as reported herein; this study, at present however, uses the $\Delta e$ parameter in place of the Gjessing and Moene $\Delta N$.

The anticipated use of the $\Delta e$ method is in assessing and forecasting ducting and normal propagation conditions based on FLENUMOCEANCEN analysis and forecast fields. Such uniform distribution of forecasts is not possible otherwise.

2.1 Limitations of the $\Delta e$ Method

The forecasts/assessments of propagation conditions using the $\Delta e$ method are limited to the vertical region below the 850 mb level. The method does not specify the expected altitudes of ducts, or whether there is more than one duct.

Ideally, forecasts developed by this $\Delta e$ method would be issued as probabilities of ducting. For ocean areas where radiosonde data are available, this is possible and future efforts could be made to compile such information. Most ocean areas have sparse radiosonde coverage, however, and to extrapolate available data to such regions is risky, although some of this risk can be removed by careful synoptic comparisons between regions. In regions where ducting occurrences are relatively infrequent, ducting forecasts have a much lower confidence level since overforecasting is the rule. Forecasts of normal conditions (since this condition is more prevalent) will be more accurate and thus have higher confidence values.

2.2 Data

Only radiosonde data were used in this analysis of the $\Delta e$ method, in contrast to the work of Gjessing and Moene which used received signal data. The radiosonde is a useful instrument for determining upper air characteristics, but its near-surface (0-100 m) accuracy can be misleading. Helvey (1979), reported that surface temperature biases produced inaccurate relative humidity profiles near the surface; surface duct statistics obtained from radiosonde data are biased toward greater percentages of surface ducts. Some of these biases were removed in this
study (see following section), but no attempt was made to correct the lag inherent in radiosonde data.

Radiosondes were launched from radar picket ships stationed about 200 n mi off the west coast of the U.S. Variations in the positions of the ships while they were on station caused considerable scatter in the geographical locations of soundings. The 6402 soundings used in this study were divided among the five zones shown earlier in Figure 1. The determination of the boundaries of these zones was guided by a need to (1) include the intended station locations, (2) minimize the number of reports on the lines of demarcation, (3) minimize the movement of ships across the selected lines, and (4) avoid concentration of data near the boundaries.

Data were obtained from the National Climatic Center, Asheville, NC, in two forms: WBAN-31A adiabatic charts, and CDF-645 and CDF-505 computer tapes. The adiabatic charts were processed by a digitizer whose card output was then input to a CDC-6500 computer for processing. Quality control checks removed all soundings with coding errors and made reasonable corrections to obvious bad data points.

3. ANALYSIS PROCEDURE

3.1 Data Editing

The soundings were checked for coding errors, missing levels, erroneous readings of relative humidity, temperature, pressure and height, and surface superadiabatic layers. If the latter layers were found, the lapse rate was adjusted to adiabatic (dew point lapse rates were unchanged).

The superadiabatic lapse rates were adjusted for two reasons: (1) there is no reasonable physical process over the oceans, whereby surface superadiabatic lapse rates can be maintained under clear skies; and (2) the time of occurrence of 2500 superadiabatic surface lapse rates was biased, heavily favoring the afternoon soundings by a margin of 59% to 41%. (An afternoon sounding is affected by biased surface temperatures due to insolation.
heating of the ship and subsequent heating of the radiosonde. Some soundings reported autoconvective layers at the surface; this phenomenon can be expected within a few meters of a desert floor, but clearly is not likely over the ocean.)

After editing, the soundings were examined for ducts between the surface and 850 mb and the value of $\Delta e$ at 850 mb was calculated. A file of this information was then used as input data to the P7M group multiple discriminant analysis program of the University of California at Los Angeles BMDP statistical package (Dixon, 1977).

3.2 Critical $\Delta e$ Value

The P7M program uses a stepwise procedure for multiple predictor variables to compute linear classification functions. For a single predictor, the classification functions are a pair of linear equations relating the predictor to the classification groups.

As an illustration of this relationship, let $a$, $b$, $c$, and $d$ be the constants determined by the discriminant analysis program, and let $X$, $Y$, be real valued numbers. Then,

\[
X = a \Delta e + b \quad \text{(ducting)}
\]
\[
Y = c \Delta e + d \quad \text{(normal)}
\]

If $\Delta e$ is the 850 mb value of $\Delta e$, then $X \geq Y$ assesses ducting and $Y > X$ assesses normal conditions. This procedure involves several computations; a simpler method in the case of simple discrimination is to classify according to a critical value of $\Delta e$, whose value is found by equating $X = Y$ and solving for $\Delta e$:

\[
\Delta e_c = \frac{b-d}{c-a}.
\]

If $\Delta e_c$ is exceeded, ducting is assessed; and if it is not, normal conditions are assessed.

The pilot study (Sweet, 1980; TR 80-01) which used only the data in zone 2 of Figure 1, found the critical value of the predictor, actually $\Delta N$, by optimizing the Heidke skill scores. This
method was found to be inadequate for the present study because of the variation in $\Delta e_c$ among independent data samples taken from the same zone. The variation resulted from the ambiguity of the optimum value of $\Delta e_c$. Figure 3 shows that the maximum in the skill versus $\Delta e$ curve is not distinct; in fact, several near maximum occur, leaving the selection of one true optimum value of $\Delta e$ unclear.

![Figure 3. Heidke skill scores versus $\Delta e_c$, zone 2.](image)

3.3 Analysis Procedure

Contingency tables were computed from both dependent and independent data, using the $\Delta e_c$ value for each zone. Tables 1-5 are for the dependent data sample (50% of the total available soundings in each zone).

The columns are the observed (actual) groupings and the rows are the classified groups. For example, in Table 1, of the 197 total soundings classified as ducts, 151 soundings were observed to be ducting and were classified correctly. The 46 soundings observed to be normal, but classified as ducting, were incorrectly
<table>
<thead>
<tr>
<th>Assessed</th>
<th>Observed</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ducts</td>
<td>Normal</td>
<td>Total</td>
</tr>
<tr>
<td>Ducts</td>
<td>151</td>
<td>46</td>
<td>197</td>
</tr>
<tr>
<td>Normal</td>
<td>44</td>
<td>128</td>
<td>172</td>
</tr>
<tr>
<td>Total</td>
<td>195</td>
<td>174</td>
<td>369</td>
</tr>
</tbody>
</table>

Total % correct - 76%

Duct prefigurance - 76%
Normal prefigurance - 75%

Duct postagreement - 77%
Normal postagreement - 74%

Climatology (ducting below 850 mb) - .53

Critical $\Delta e = 10.4$ mb

Heidke skill - .51
Table 2

Zone 2

<table>
<thead>
<tr>
<th>Assessed</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ducts</td>
</tr>
<tr>
<td>Ducts</td>
<td>208</td>
</tr>
<tr>
<td>Normal</td>
<td>55</td>
</tr>
<tr>
<td>Total</td>
<td>263</td>
</tr>
</tbody>
</table>

Total % correct - 78%

Duct prefigurance - 64%
Normal prefigurance - 88%

Duct postagreement - 79%
Normal postagreement - 77%

Climatology (ducts) - .37

Critical $\Delta e = 7.8$ mb

Heidke skill = .53
Table 3

Zone 3

<table>
<thead>
<tr>
<th>Assessed</th>
<th>Ducts</th>
<th>Normal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ducts</td>
<td>118</td>
<td>95</td>
<td>213</td>
</tr>
<tr>
<td>Normal</td>
<td>36</td>
<td>449</td>
<td>485</td>
</tr>
<tr>
<td>Total</td>
<td>154</td>
<td>544</td>
<td>698</td>
</tr>
</tbody>
</table>

Total percent correct - 81%

Duct prefigure - 55%
Normal prefigure - 93%

Duct postagreement - 76%
Normal postagreement - 83%

Climatology (ducts) - .22

Critical $\Delta e$ - 6.3 mb

Heidke skill - .52
Table 4

Zone 4

<table>
<thead>
<tr>
<th>Assessed</th>
<th>Observed</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ducts</td>
<td>Normal</td>
<td>Total</td>
</tr>
<tr>
<td>Ducts</td>
<td>77</td>
<td>119</td>
<td>196</td>
</tr>
<tr>
<td>Normal</td>
<td>29</td>
<td>516</td>
<td>545</td>
</tr>
<tr>
<td>Total</td>
<td>106</td>
<td>635</td>
<td>741</td>
</tr>
</tbody>
</table>

Total percent correct - 80%

Duct prefigurance - 39%
Normal prefigurance - 95%

Duct postagreement - 72%
Normal postagreement - 82%

Climatology - .15

Critical $\Delta e$ - 5.3 mb

Heidkie skill - .40
### Table 5

#### Zone 5

<table>
<thead>
<tr>
<th>Assessed</th>
<th>Ducts</th>
<th>Normal</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ducts</td>
<td>41</td>
<td>68</td>
<td>109</td>
</tr>
<tr>
<td>Normal</td>
<td>21</td>
<td>376</td>
<td>397</td>
</tr>
<tr>
<td>Total</td>
<td>62</td>
<td>444</td>
<td>506</td>
</tr>
</tbody>
</table>

Total percent correct - 82%

Duct prefiguration - 37%
Normal prefiguration - 95%

Duct postagreement - 66%
Normal postagreement - 85%

Climatology - .12

Critical $\Delta e$ - 5.1 mb

Heidke skill - .38
classified. The sum of the diagonal elements in Table 1 is the number of total correct classification. The total percentage correct is this sum divided by the total number of soundings used, 369. This same design is applied to the remaining tables.

The accuracy and the false alarm rate of the procedure can be examined using two percentages: prefigurance and postagreement. Duct prefigurance is the percentage of the number of correct duct assessments. Postagreement is the percentage of actual ducts correctly assessed. The sample space of prefigurance is the total number of ducts assessed; the sample space of postagreement is the total number of ducts.

The critical value of \( \Delta e \) could have been chosen by maximizing either of these percentages. For example, the optimum \( \Delta e_c \) could have been selected by maximizing the duct prefigurance, thereby reducing the false alarm rate. Maximizing postagreement would increase the accuracy of the procedure, i.e., increase the number of ducts correctly assessed. The operational aspects of prefigurance and postagreement and the difference in emphasis depending on which of these is stressed, are discussed below.

3.4 **Prefigurance and Postagreement**

A low duct prefigurance percentage indicates that a large percentage of assessed ducts were actually normal conditions; this is a high false alarm rate. The nature of the intended operation would determine whether a high false alarm rate is less objectionable than a lower rate that misses many ducts altogether.

In actual operations, the forecast often generates the action: ships' tactics are planned, particular ordnance is loaded, electromagnetic emission operations are chosen based on the "forecast." Once a decision is made and a tactic is chosen, the outcome of such decisions depends on the correctness of the "forecast" used to make that decision. Prefigurance, therefore becomes the more important factor under the assumptions just stated.

Postagreement is meaningful mainly in hindsight. If a commander wanted to assess an operation during which the accuracies of several different forecast procedures were compared, for example, then the postagreement percentages would be useful.
A concern only with postagreement, however, could lead to choice of a procedure that forecasts ducting conditions 100% of the time, since every ducting day that occurred would then have been predicted. Conversely, those days that actually had normal propagation conditions would have been forecasted as ducting a 0% normal postagreement. If cost/loss factors allow such percentages to be acceptable, then such a procedure might well be chosen as the optimum.

Without cost/loss factors and other pertinent operational considerations, the only reasonable choice is to emphasize the forecast accuracy, prefigurance. (The assumption here is that the method would be applied to 850 mb forecast fields, producing a direct forecast.)

4. DISCUSSION OF RESULTS

4.1 Critical Δe - Discriminant Analysis

The table given below shows the zone-to-zone variation of the critical Δe and the variation between independent data sets. The two data sets are simply complimentary sets, the first one chosen by a reproducible random process. The stability of $\Delta e_c$ is indicated by the small variations of $\Delta e_c$ between the dependent (the first data set chosen) and the independent data. The variation of the zonal $\Delta e_c$ values follows the climatological variation of duct occurrence extremely closely: the linear correlation coefficients are .996 and .993 for independent and dependent samples, respectively. The larger values of $\Delta e_c$ are related to the regions with more frequent ducting. The variations of the skill scores between data sets are less than 0.05 (see Sweet, 1980, TR 80-0, for an explanation of Heidke skill scores). The small variation is an indicator that the selection criterion is a good one.
There is an unusual linear relationship between $\Delta e_c$ and the relative frequency of ducting. The following table is helpful in examining possible reasons for this relationship:

<table>
<thead>
<tr>
<th>Zone No.</th>
<th>Dep.</th>
<th>$\Delta e_c$ (mbs)</th>
<th>Indep.</th>
<th>Skill</th>
<th>Relative Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.4</td>
<td>10.5</td>
<td>.51 - .53</td>
<td>.53</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>7.8</td>
<td>8.0</td>
<td>.53 - .51</td>
<td>.37</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>6.3</td>
<td>6.1</td>
<td>.52 - .47</td>
<td>.22</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>5.6</td>
<td>5.3</td>
<td>.40 - .40</td>
<td>.15</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>5.1</td>
<td>5.2</td>
<td>.38 - .36</td>
<td>.12</td>
<td></td>
</tr>
</tbody>
</table>

The elevated-to-total duct ratio decreases with climatology, whereas the surface-to-total duct ratio does not. The climatology then is correlated to the number of elevated ducts. This correlation may be explained by the relative dryness of the air at the 850 mb level needed to indicate ducting due to the marine inversion. The generally cooler temperature of northern latitudes, compared to more southern latitudes, would cause the specific humidity to be less; therefore, the difference between saturation and ambient vapor pressure values would, on the average, be smaller. This smaller mean value of $\Delta e$ would nevertheless still be an indicator of an inversion below and of the accompanying ducting conditions. The lack of correlation between the relative frequency of surface ducts and the $\Delta e_c$ implies the lack of a real physical link between these two events.
Another possible meteorological factor is the height of the temperature inversion -- a higher mean inversion height would probably correlate with a smaller $\Delta e_c$. The cumulative height distribution for each of the five zones, as shown in Figure 2, are very similar: the 50% point varies from 750 m for zone 5 to 925 m for zone 3, but at the 75% point the variation is only 75 m. The distributions do not show any systematic variation from zone 1 to zone 5; the variation of inversion heights with zone therefore is not a significant factor, and has no effect here on the critical $\Delta e$ interzonal variations.

4.2 Contingency Tables

Contingency tables, developed by applying the critical $\Delta e$ to the independent data set and analyzing by discriminant analysis, show a gradual increase in the total percent correct with increasing latitude (refer to Tables 1-5). The reason for this increase in percent correct is the gain in reliability of assessing the normal conditions, even though the duct assessment becomes less reliable. The prefigurance percentages for ducting and normal propagation by zones (hence by climatology) are shown in Figure 4. In zone 1 the climatology for ducting is essentially the same as for normal conditions; the prefigurance percentages of 76% and 75% respectively reflect the nearly equal occurrence frequencies.

The variation in postagreement of ducting and normal conditions follow less spectacularly the same general zonal trends as the prefigurance percentages. In zone 5 the difference between ducting and normal postagreement (Figure 5) is less than 20%, compared to almost 60% for zone 5 prefigurance. Ducting is relatively infrequent for zone 5, and hence difficult to assess. Over-assessing (over-forecasting) causes the accompanying low prefigurance, but the ducting postagreement is relatively high because of this overassessing.

4.3 Critical $\Delta e$ - Heidke Skill Score

Choosing the critical $\Delta e$ with an intent to optimize the skill score causes greater variation in $\Delta e_c$ between samples in
Figure 4. Prefigurance percentages for ducting and normal propagation.

Figure 5. Postagreement percentages for ducting and normal propagation.
the same zone. This variation results from the criteria for the \( \Delta e_c \) selection: \( \Delta e_c \) is the first "maximum" on the skill versus \( \Delta e_c \) curve. This first apparent maximum may indeed be only a local maximum, as was shown in Figure 3; the relative flatness of the maximum region of the curve in Figure 3 indicates that this method of selecting \( \Delta e_c \) is not stable. The variation in \( \Delta e_c \) for two samples of zone 3 (see Para. 4.4) exemplify that instability; sample sizes are large enough to preclude an unrepresentative sample with at least a 95% confidence. The following table gives the \( \Delta e_c \) found by Heidke skill scores, and the skill values:

<table>
<thead>
<tr>
<th>Zone No.</th>
<th>( \Delta e_c ) Dep.</th>
<th>Indep.</th>
<th>Skill</th>
<th>Relative Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9.0</td>
<td>8.6</td>
<td>0.51 - 0.56</td>
<td>0.53</td>
</tr>
<tr>
<td>2</td>
<td>7.8</td>
<td>7.0</td>
<td>0.52 - 0.51</td>
<td>0.37</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>8.0</td>
<td>0.53 - 0.54</td>
<td>0.22</td>
</tr>
<tr>
<td>4</td>
<td>7.0</td>
<td>7.6</td>
<td>0.42 - 0.38</td>
<td>0.15</td>
</tr>
<tr>
<td>5</td>
<td>6.8</td>
<td>7.6</td>
<td>0.36 - 0.36</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The zonal variation of \( \Delta e_c \) varies with the relative frequency of duct occurrence in a nearly linear relationship. The linear correlation coefficient for the relation is a high 0.968. This high correlation substantiates the even higher correlation found previously, and reinforces the climatology versus \( \Delta e_c \) relationship.

The interzone variation of skill scores for the discriminant analysis and the maximum skill method are very similar. The intrazonal-sample dependent variations are of the same magnitude as found earlier, with the largest .05.

4.4 Critical \( \Delta e \) Other Methods

There are other possible methods for selecting \( \Delta e_c \), depending on the intended use of the assessment/forecast.

The plots of ducting and normal prefigurances and postagreement for zone 3 are shown in Figure 6. The curves for the total
percent correct, normal prefigurances and postagreement do not vary greatly with changing $\Delta e_c$. The ducting prefigurance steadily increases throughout the range of $\Delta e_c$ plotted, and presumably would continue up to the point where the criteria were met by only a few soundings. Then the percentage may rapidly fluctuate as the $\Delta e_c$ increases, because of a too-small sample size. This would occur well beyond the point of forecast distribution matching climatology. Therefore choosing an optimum $\Delta e_c$ is not benefitted based on examination of such plots as Figure 6.

Figure 6. Plots of ducting and normal-propagation prefigurance and postagreement for geographical zone 3.

An upper limit of $\Delta e_c$ could be set, however, at the point at which the ratio of ducting forecasts to total forecasts matches climatology (the number of predicted "ducting events" matches the numbers of observed "ducting events"). These values are given in the following table under climatology. The rightmost column gives the ranges of $\Delta e_c$ for each zone, i.e., the difference between $\Delta e_c$ chosen by discriminant analysis and by climatology.
The values established by climatology minimize the false alarm rate for ducting. These ranges are useful for selecting the optimum $\Delta e_c$ depending on the tactical application of the forecast. For example, if false alarms are to be minimized even at the expense of increased inaccuracy of the normal forecasts, then the upper value of the $\Delta e_c$ range would be used. If the cost for not forecasting ducting when ducting occurred was of greatest significance (with a parallel desire not to over-forecast to an extreme), then the $\Delta e_c$ found by discriminant analysis would be used. The range of $\Delta e_c$ offers some flexibility that will enable the user to adjust the $\Delta e_c$ based on experience gained in specific ocean regions.

The preferred value obviously is the $\Delta e_c$ found from discriminant analysis. Flexibility is added through using a range of $\Delta e_c$ limited at the upper boundary by climatology.

### 4.5 Characteristics of Soundings Incorrectly Classified

The $\Delta e_c$ procedure is based on the assumption that if the air at 850 mb is very dry, and is over a body of water, a temperature inversion exists at some elevation between the surface and the 850 mb level. These temperature inversions produce water vapor gradients that usually are steep enough to cause microwave ducting. (The correlation between these two situations has been established at least for the North Sea and the eastern North Pacific.) Certain modifying factors of this relationship, however, should be noted.
Some surface ducts, maybe most, apparently are not related to dry air at 850 mb. Figure 7 shows a sounding that indicates a temperature inversion above the 850 mb level, but the inversion does not appear to be related to the surface duct. The modified refractivity profile indicates a duct whenever the M values decrease with height. The reason for such ducts cannot be ascertained solely from radiosonde analysis; a synoptic analysis also must be performed.

Sometimes weak inversions that produce ducts occur below or near 500 m, while the air above the inversion is not dry enough to meet the $\Delta e_c$ criteria. Figure 8 depicts such a case with a sounding that appears unusual in two areas: the dew point inversion between 100 and 300 m seems suspect, and the parallel drop-off of both temperature and dew point above 1500 m is similarly so. This sounding actually shows a slight surface duct up to about 80 m (slight decrease in M with height) with an elevated duct just below 500 m. The indications of either of these ducts may in fact be the result of radiosonde errors due to the instrument's ascension through stratus tops.

Surface ducts occasionally have the appearance of extremely thick evaporation ducts. Figure 9 shows a sounding with a surface duct over 200 m thick, with multiple, weak temperature inversions above 1000 m. A surface pressure of 1025 mb suggests that these inversions were caused by subsidence aloft. At the 850 mb level, the cool air temperature (4.0°C) causes the $\Delta e$ value to be less than $\Delta e_c$, even though the temperature-dew point difference is a surprising 25.9°C.

The soundings in Figures 7, 8 and 9 illustrate cases that indicated ducting, but were classified as normal. Figure 10 shows a non-ducting M profile that was classified as ducting; a strong temperature inversion over a nearly 300 m vertical extent is depicted. The decrease in dew point temperature shown in Figure 10 was not steep enough to produce a duct, even though $\Delta e$ was calculated to be 16.1 mb, well above the $\Delta e_c$. This large value was due primarily to the warm air temperature at 850 mb.
Figure 7. Sounding with $\Delta e = 2.8$.

Figure 8. Sounding with $\Delta e = 7.7$. 
Figure 9. Sounding with $\Delta e = 7.1$.

Figure 10. Sounding with $\Delta e = 16.1$. 
Figure 11 illustrates a similar case: the air at 850 mb is dry, but the dew point gradient is not strong enough to produce ducting. Figure 11 shows an almost linear M profile in which the temperature dew point difference slowly increases with altitude. For zone 2 the value of $\Delta e$ is above the critical value, primarily because of the warm 850 mb temperature.

Figure 12 depicts a case in which an elevated duct results from a very weak temperature inversion and an accompanying steep dew point gradient. The value of $\Delta e$ is not large enough to classify the sounding as ducting because of an apparent dew point increase in the region of 850 mb, an increase that could have been caused by the radiosonde ascending through a layer of cloud (the dew point does drop off just below a second small temperature inversion).

The examples just discussed (Figures 7-12) were selected to illustrate the various problems that can occur in incorrectly classified soundings: some show weaknesses in basic assumptions, while others demonstrate the results of weaknesses of radiosonde data.

5. FUTURE WORK

Recent work done by researchers at Pacific Missile Test Center, Pt. Mugu, CA has shown that there is considerable skill to be derived from an additional parameter that allows development of probability statements about the vertical location of the inversion duct (R. Helvey, private conversation). Future work will combine this $\Delta e$ discriminator with Helvey's "equivalent altitude" parameter (Helvey, 1979); the combination will be examined using the data set developed for this present report.

If this combination is found to have value, other ocean areas characterized by cold currents with resulting marine layer inversions will be examined to determine the universality of the method.

After the validity and operational usefulness of the method are established, the next logical step would be to examine carefully the skill of the procedure under operational conditions.
Figure 11. Sounding with $\Delta e = 9.9$.

Figure 12. Sounding with $\Delta e = 8.1$. 
using data fields from FNOC's forecast model to provide the input. The forecast of refractive conditions would be verified by using available radiosonde data nearest the time and location of the forecast. Given ample data, regional guidelines then could be established.

6. SUMMARY

A method that assesses (and could forecast) the occurrence of ducting within 1500 m above the ocean has been described. The method was examined using radiosonde data from five latitude zones of the eastern Pacific Ocean. The skill of the method was found to equal or exceed that of standard weather forecasts.

The parameter \((\Delta e)\) used to assess/forecast ducting or normal conditions is calculated using only 850 mb level data. Therefore the method can be applied using FNOC 850 mb field output from the hemispherical model, thereby providing a forecast capability in open ocean regions void of radiosonde data.

The critical value of \(\Delta e\) used for the assessment/forecast is selected using discriminant analysis. The value of \(\Delta e_c\) shows a strong linear correlation to the relative frequency of ducting. This linear relationship results from the method skill in assessment/forecasting of elevated ducts, since their latitudinal variation of relative frequency accounts for all of the total latitudinal variation in critical \(\Delta e\).

The variation of \(\Delta e_c\) for different samples of data within any zone is small, indicating good stability in the method of choosing \(\Delta e_c\).
REFERENCES


APPENDIX A

Comparison of $\Delta e$ and $\Delta \theta$

Consider a parameter defined as the difference between the 850 mb level and the surface level potential temperature, $\Delta \theta = \theta_{850} - \theta_{surf}$. If this parameter is positive, then the air aloft is warmer than that which would occur by adiabatic convection. Over a body of water, warm air aloft implies a temperature inversion, which usually leads to a strong water vapor gradient, hence microwave ducting. Studies have shown this parameter to correlate well with ducting conditions (R. Helvey, private conversations).

The discriminant analysis program, P7M of the UCLA BMDP statistical package (Dixon, 1977), was used to generate the classification functions for this correlation. The critical value of $\Delta \theta$ was found from the classification functions (see Sec. 3 of the main report). The results are summarized in the following tables and compared to the $\Delta e$ method.

<table>
<thead>
<tr>
<th>Zone</th>
<th>$\Delta e_c$</th>
<th>Duct</th>
<th>Normal</th>
<th>Postagreement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.4</td>
<td>78</td>
<td>77</td>
<td>Duct: 79</td>
</tr>
<tr>
<td>2</td>
<td>7.8</td>
<td>66</td>
<td>84</td>
<td>Duct: 75</td>
</tr>
<tr>
<td>3</td>
<td>6.3</td>
<td>53</td>
<td>91</td>
<td>Duct: 72</td>
</tr>
<tr>
<td>4</td>
<td>5.6</td>
<td>40</td>
<td>93</td>
<td>Duct: 69</td>
</tr>
<tr>
<td>5</td>
<td>5.1</td>
<td>32</td>
<td>97</td>
<td>Duct: 72</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zone</th>
<th>$\Delta \theta_c$</th>
<th>Duct</th>
<th>Normal</th>
<th>Postagreement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.4</td>
<td>73</td>
<td>75</td>
<td>Duct: 78</td>
</tr>
<tr>
<td>2</td>
<td>9.7</td>
<td>60</td>
<td>88</td>
<td>Duct: 80</td>
</tr>
<tr>
<td>3</td>
<td>9.2</td>
<td>45</td>
<td>93</td>
<td>Duct: 72</td>
</tr>
<tr>
<td>4</td>
<td>9.0</td>
<td>30</td>
<td>95</td>
<td>Duct: 74</td>
</tr>
<tr>
<td>5</td>
<td>8.7</td>
<td>23</td>
<td>97</td>
<td>Duct: 74</td>
</tr>
</tbody>
</table>
The prefigurance percentages for the \( \Delta e \) method and the \( \Delta \theta \) method are similar, with the \( \Delta e \) method having the higher duct percentages. The only significant difference in postagreement percentages is in the normal category. The zonal variations of \( \Delta \theta \) is not as much as that for \( \Delta e \), indicating less dependence on climatology.

The following two tables compare the total percent correct and the difference between percentage of ducts forecasted and climatology ("obs." column is percentage of ducts observed, hence climatology).

### \( \Delta e \)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Total % Correct</th>
<th>Ducts (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Obs.</td>
</tr>
<tr>
<td>1</td>
<td>77</td>
<td>52</td>
</tr>
<tr>
<td>2</td>
<td>76</td>
<td>37</td>
</tr>
<tr>
<td>3</td>
<td>78</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>78</td>
<td>17</td>
</tr>
<tr>
<td>5</td>
<td>83</td>
<td>10</td>
</tr>
</tbody>
</table>

### \( \Delta \theta \)

<table>
<thead>
<tr>
<th>Zone</th>
<th>Total % Correct</th>
<th>Ducts (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Obs.</td>
</tr>
<tr>
<td>1</td>
<td>74</td>
<td>53</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>75</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>72</td>
<td>14</td>
</tr>
<tr>
<td>5</td>
<td>73</td>
<td>12</td>
</tr>
</tbody>
</table>

The \( \Delta e \) method shows a general increase in total percent correct with latitude zone (see Section 4 for discussion); the \( \Delta \theta \) shows only a minor fluctuation, with about a 74% overall average. The average for \( \Delta e \) is 78%, over 4% higher than the \( \Delta \theta \) method.
The last column in each of these two tables is the difference between observed and forecast number of ducts. A positive value for "difference" means that the method forecast more ducts than observed - a large positive value means a high false alarm rate. The $\Delta \theta$ method consistently had a higher false alarm rate than the $\Delta e$ method. This high rate implies a procedure which is less responsive to climatology and, in many tactical applications, one that is misleading.

**Summary**

Both methods show good skill in assessing ducting conditions below the 850 mb level. The $\Delta e$ method shows somewhat more response to change in ducting climatology, both in the $\Delta e_c$ zonal variation and in the false alarm rate. The primary advantage to the $\Delta e$ method is the requirement for only one level of data. In the foreseen application of the methods, large-scale model output fields will be used to calculate the value of the predictor. The surface values of temperature in some cases may be inaccurate due to the method of determining this parameter in the model.
APPENDIX B

Other Parameters Tested

The following additional variables and combinations of variables were tried using the multivariate discriminant analysis program:

\[ \Delta \theta = \theta_{850} - \theta_s; \quad \theta = \text{potential temperature} \]

TVS - surface virtual temperature

T850 - temperature at 850 mb

TV850 - virtual temperature at 850 mb

H850 - height of 850 mb level

DESURF - \((e_s - e)\) at the surface

DIFE - \((\text{DESURG} - \Delta e)\)

DIFTV - \((\text{TVS} - \text{TV850})\)

DT2 - \((\Delta \theta)^2\)

The following table shows the three best combinations, along with the percentages for \(\Delta e\).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total Correct (%)</th>
<th>Prefigurance (%)</th>
<th>Postagreement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Duct</td>
</tr>
<tr>
<td>(\Delta e)</td>
<td>77</td>
<td></td>
<td>78</td>
</tr>
<tr>
<td>{\Delta e, T850}</td>
<td>77</td>
<td></td>
<td>76</td>
</tr>
<tr>
<td>{\Delta e, T850, \Delta \theta}</td>
<td>78</td>
<td></td>
<td>78</td>
</tr>
<tr>
<td>{\Delta e, TVS, DIFF, DTZ}</td>
<td>76</td>
<td></td>
<td>76</td>
</tr>
</tbody>
</table>

35
Postagreement percentages showed slight improvements for the set of three; no improvements in prefigurance or total correct percentages resulted. The other parameters tested yielded results which were slightly worse than the $\Delta e$ percentages above.

In every case where the multivariate discriminant analysis program was given several variables (including $\Delta e$) to select, the first variable selected was always $\Delta e$. This means that $\Delta e$ had the best discrimination characteristics of any of the variables.
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