Guidance for an Expert System Approach to Elevated Duct Assessment over the Northeastern Pacific Ocean

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Abstract
A knowledge base has been developed, tested and validated which relates synoptic and mesoscale weather map features, and satellite cloud patterns to the occurrence, height and intensity of elevated ducts which affect radar propagation over ocean and coastal areas. This knowledge base, together with climatology and other objective indicators, is being converted into an expert system for use operationally by users of varying levels of experience.

INTRODUCTION
An important operational need of the Navy is the ability to anticipate and exploit radar propagation conditions over ocean and coastal regions where ducting and radio 'hole' phenomena are most prominent. These phenomena, caused by elevated refractive layers resulting from 'inversion conditions' in which warm, dry air overlays cooler, moist air, are strongly influenced by both large scale air mass conditions as well as mesoscale features induced by coastlines, mountains and islands. Any attempt to assess or forecast radio propagation conditions must therefore necessarily take into account the synoptic and mesoscale variability of the lower atmosphere. Over the open ocean, it is believed that the assumption of horizontal homogeneity is valid about 80% of the time for typical radio path lengths of importance to the Navy (Glevey, 1976). However, near fronts (air and sea), and in the vicinity of islands and coastal terrain, horizontal and temporal variations can be much more prominent.

Under the Navy's electromagnetic EM/EO Propagation Assessment Program, several approaches are being explored to obtain an assessment or prediction of atmospheric conditions in sufficient detail to estimate the occurrence, height and intensity of elevated ducts (Richter, 1994). One method, underway at the Naval Research Laboratory (NRL) in Monterey involves development of a high resolution numerical forecast model and data assimilation system in which all available observations are incorporated into a model forecast for use in range-dependent assessments of refractive structure.

Another approach is represented by the Naval Air Warfare Center Point Mugu, Geophysics Division's attempts to relate refractive structure to synoptic, mesoscale and satellite data parameters by application of statistical relationships established during work under the EM/EO Program. This effort is focussed on the (generally) elevated ducts due to refractive (trapping) layers aloft; the behavior of the evaporative duct attached to the ocean surface is not considered. Implicit is a conceptual model of an elevated trapping layer associated with an inversion-dominated weather regime with low stratus or stratuscumulus clouds that are lowest and flattest in the south-eastern parts of the sub-tropical oceans, closely associated with anticyclones (high pressure regions) where the overlying inversion is lowest and strongest. This general trend in both cloud and inversion characteristics correlates well with the occurrence, height and intensity of elevated ducts as observed in extensive radiosonde data sets from the eastern and central north Pacific Ocean. An initial effort to apply these weather-refractive relationships was described in a Refractive Effects Guidebook or "REG" (Rosenthal, 1976). This guide attempted to assign specific refractive (N-Profile) types to locations within various sectors of the sub-tropical oceanic high pressure belt and peripheral regions of disturbed weather using characteristic seasonal maps for different regions of the world. This initial REG was found, however, to be overly ambitious in specifying detailed refractive profiles based on the guidance available. Subsequently, additional studies were performed (Helvey, 1981; Helvey and Rosenthal, 1983) to improve and determine additional relationships providing a more objective framework for the approach. Also, methods for inferring elevated ducting from weather satellite imagery were explored (Rosenthal et al., 1989; Rosenthal and Helvey, 1991). The improved guidelines were adapted by the Naval Oceanography Command Center at Pearl Harbor, Hawaii into a Horizontal Refractivity Depiction (HRD) procedure. In that form, an Independent Verification and Validation (IV&V) was performed (Vogel, 1992) under tasking from the Commander, Naval Oceanography Command, and the guidelines found to be statistically valid and useful. Accordingly, the (now) Commander, Naval Oceanography and Meteorology Command (CNMOC) declared the HRD technique operational for the eastern Pacific Ocean. Since it was recognized that the full implementation of the updated REG techniques requires a level of skill or experience in satellite and synoptic/mesoscale interpretation that may at times exceed the skills of the anticipated user on a ship or ashore center; and also that a less manual-intensive approach is desirable, the Geophysics Division began preparing a version for incorporation into an automated, "expert" system. Conversion into a computer implementation which will eventually reside on TESS(3) is being carried out at NRL-Monterey with the technical coordination of NAWCWPNS and sponsorship of the Navy's Environmental Systems Program Office at the Space and Naval Warfare Systems Command. Termed Experduct (Peak, 1992), this system combines information entered by the operator from a variety of sources to furnish either current estimates or short-term predictions (to 72 hours) of elevated ducting conditions.

EXPERDUCT METHODOLOGY
Initial Version
A number of rules and formulae were developed largely based on subjective or empirical considerations, to estimate duct occurrence, duct base height (of particular significance for Navy operations), and duct strength as maximum M-unit change within the duct. Input parameters were chosen which should usually be easily obtainable, and appeared from experience, meteorological reasoning, or statistical studies to correlate with duct characteristics. These included surface pressure, proximity to a center of high/low pressure, quadrant (e.g., NE, SE, SW or NW) of the high or equivalent wind directions, surface wind speed, conditions aloft, distance from the mainland, and other more subjective indicators. As an example of some of the guidance employed, a relationship for surface pressure influence on duct likelihood is shown in Figure 1, based on radiosonde data from ocean station vessel 4YN which was for many years maintained between Hawaii and California.
Revised Weighting

A new scheme was devised to resolve the problem of estimating the combined effect of the different factors on duct occurrence. The basic problem arises from an insufficient knowledge of the correlations between the various contributors utilized; in most cases the supportive statistical studies were only able to establish observed duct dependencies on independent variables taken one, or perhaps two at a time. The new method combines weighted values of duct likelihood for each of the various predictors according to the following requirements:

1. In the limit, if the probability from any single factor goes to zero, then the combined result will be zero;
2. If the probability from any single factor should go to certainty, then the combined result should be certainty;
3. In the event that a contradiction arises, i.e. one factor indicates absolutely no ducting (0.0) but another indicates absolutely certain ducting (1.0), then a mean will be used (0.5);
4. If all factors indicate the same probability, then the combined result should do likewise;
5. The result should vary smoothly and symmetrically over the entire range of individual probabilities input.

A function which conforms to the above is given by:

\[ P = \frac{C_1 W_1 P_1 + C_2 W_2 P_2 + \ldots + C_n W_n P_n}{C_1 W_1 + C_2 W_2 + \ldots + C_n W_n} \]  

(1)

where C is a confidence factor for each probability P,

\[ W = \frac{1}{[(1 - P) + \varepsilon]} \]  

(2)

and \( \varepsilon \) is a small value (0.00001, say) to preclude division by zero when the expression is evaluated.

A graph illustrating the combined effect for all possible values of two parameters is given in Figure 2. In this example both are assumed to have the same confidence, or reliability. If other parameters are considered, an additional dimension is effectively added for each, while still satisfying the requirements given above for the joint effect on the final resultant probability. Although the question of proper assessment of joint contributions of several correlated factors is still not completely resolved, this formulation at least insures a mathematical consistency in the result.

Climatology

The original version of Experduct was very sensitive to the quality and presumed effects of the various indicators used. Also, there was no explicit recognition of the degradation of the input information with time. To provide a stabilizing influence, climatology was introduced as an additional factor, in such a way that it assumes increasing importance as the quality of the other data decreases. This occurs by assigning a progressively greater confidence to the appropriate climatological estimate, corresponding to: 1) intrinsically less reliable indicators, 2) lapse of time since the indicators were observed, or 3) period of time until forecast indicators will verify. Climatology furnishes a reference towards which the estimates should approach asymptotically as the other factors degrade. For these purposes, climatology comprises variations in long-term averages of elevated duct occurrence, height and strength, according to location, season and time (local).

Currently Experduct includes consideration of variations in duct incidence by season, and a limited coverage of location. Figure 3 is a copy of an Experduct screen showing percent incidence of elevated ducts over the northeastern Pacific ocean, for October 15, adapted from statistics compiled by GTE Sylvania (Ortenburger et al, 1979). For Experduct application, the data are interpolated for each day of the year from stored monthly values, to avoid discontinuities between months.

The climatology is being revised to include time-of-day as a variable. Recent work at NAWCWPNS has established the existence of a substantial, worldwide diurnal signal in oceanic elevated duct occurrence. Figure 4 shows three-monthly overlapping average percent frequencies at ocean station vessel NAN (4YN), for the two upper-air synoptic observation times. A 10% to 20% deviation between day (00Z) and night (12Z) is clearly evident. Unlike a similar but fictitious variability in surface ducting ascribed to measurement errors (Helvey, 1983), this effect appears to be real, and is probably related to daytime dissipation and nighttime formation of marine stratocumulus clouds and attendant
deviations in the sharpness of the inversion base aloft. Evidence for a worldwide provenance is given in Figure 5, where 12-hour differences in average incidence are shown for oceanic/coastal radiosonde sites around the world, plotted by local time at 00Z. The differences have been divided by the means of the two daily observations at each site, and limited to cases with daily mean (00Z + 12Z) frequencies greater than 30%, to reduce the scatter due to overall variability between sites. Also, because of symmetry each point has been repeated, that is, a 00Z-12Z difference 12 hours later/earlier (with opposite sign). An approximate sinusoidal variation is evident, with minimum occurrence shortly after local noon and maximum after local midnight.

Climatology is an objective element which has been introduced to improve the performance of the Experduct approach. Additional indirect, but objective techniques which are promising candidates for incorporation are derived from analysis of weather satellite digital data, and gridded fields from numerical model output.

**Figures**

- Figure 3. Percent incidence of elevated ducts for mid-October, northeastern Pacific Ocean.
- Figure 4. Elevated duct occurrences for ship 4YN, day (00Z) and night (12Z).
- Figure 5. Worldwide night-day change in duct occurrence.

**Related Efforts**

**Satellite Cloud Pattern Analysis**

During the development of guidelines to relate synoptic and mesoscale features to refractive structure, it became obvious that satellite cloud patterns, particularly those evident in higher-resolution visible imagery, served as excellent signatures of marine layer depth, strength of the overlying inversion, and by implication the height and intensity of accompanying elevated ducts (Rosenthal et al., 1985). Figure 6 is a characteristic GOES visual image covering a portion of the northeastern Pacific ocean. Changes in appearance of stratus from smooth, to small granular elements and then to larger 'closed' cells have been statistically correlated to elevated duct transitions from low and strong to high and weak. Areas of open cells and frontal bands correlate with deep, well-mixed conditions and the absence of elevated ducts. The intuitive and experiential conclusions were reinforced by radiosonde refractive profiles at San Nicolas Island, about 60 miles offshore Point Mugu. The results of these studies have been incorporated into Experduct.

**Satellite-IR Duct Technique**

Early interest at the Geophysics Division in the possibility of objectively determining elevated duct heights from satellite data resulted in the so-called Satellite IR-Duct Technique (Lyons, 1985a; 1985b). It is based on the observation that 1) the tops of the ubiquitous marine stratocumulus clouds off the west coast of the USA and other regions are often co-located with the duct optimum coupling height (base of the trapping layer aloft); 2) cloud-top temperatures are related to their height, and 3) satellite IR data can provide an approximate value of that temperature. Subsequent efforts have been directed towards refining the several components of the technique so that it could be applied as an aid in mapping elevated duct heights over extended areas, using an automated or computer-assisted approach. Figure 7 illustrates an empirical fit of inversion base altitude versus temperature offset from sea-surface temperature (SST); the inversion base lies at the top of the marine layer and is the upper limit for any imbedded stratocumulus cloud tops. This relationship permits conversion of satellite-derived cloud top temperatures into duct height estimates. Complicating factors include variations in sea surface temperature (here subtracted from inversion temperatures to minimize their effect) and other factors which affect temperature lapse rates in the marine layer, and
Figure 6. GOES visual image over northeastern Pacific, for 20:15Z 29 Sep 1975. Cloud appearance correlates to duct characteristics.

Figure 7. Inversion base altitude versus temperature relative to surface (SST).

Figure 8. Optimum Coupling Height versus Equivalent Altitude.
inaccurate IR temperatures due to contamination from moisture above the marine layer, or because of partial cloud coverage.

**Equivalent-Altitude Technique**

Using the hydrostatic assumption and a simple two-layer representation of the lower atmosphere, it is possible to calculate pressure height at reference levels above and below the region of interest. Inaccurate IR temperatures due to contamination from moisture and 'equivalent' altitude obtained can be used to estimate the height of the inversion base and accompanying duct optimum coupling height. Statistical analysis of historical radiosonde data sets provides the basis for determining optimum coupling height, given Equivalent Altitude, as illustrated in Figure 8. The likelihood of a duct aloft can be estimated from climatology, reinforced by consideration of the overall stability of the 1000mb-700mb layer; ducting is favored by large stabilities (temperature increase with height). This technique is also being explored as the basis for a first guess estimate for extrapolating climatological elevated duct statistics over data-sparse ocean regions.

**FUTURE WORK**

Incorporation of the Satellite-IR Duct and Equivalent Altitude techniques into Experduct is planned, together with an improved reference climatology. In addition, a rationale is being developed to transition between conditions over the open ocean to the coastal zone. Various coastal influences can dominate the refractive environment in such locations, and wind direction (or pressure gradient) is a major factor there.

As a regional tool, subsequent versions of Experduct are planned which will focus on different geographical areas, beginning with the Persian Gulf and northern Arabian Sea; then the western Pacific including the waters bordering Korea and Japan; followed by Mediterranean, Caribbean and other theaters of interest.

Similar to the original REG, there will be an attempt to generate simplified refractive profiles suitable for input into the Navy's range-dependent Radio Physical Optics (RPO) propagation model (Hitney, 1992); in the absence of direct measurements or numerical model output products of refractive structure, it is hoped that useful estimates can be made from satellite and synoptic inferences. Guidance from the Satellite-IR Duct technique and Equivalent-Altitude will be integrated into the process.

Provision will be made for adjustments in confidence levels assigned to more subjective parameters such as derived from satellite pattern interpretation, i.e., "novice" or "expert", in recognition of the different levels of knowledge, experience and interest representative of various Experduct users.

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