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Review of the High Frequency Ionospheric Communications Enhanced Profile Analysis & Circuit (**ICEPAC**) Prediction Program

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1. INTRODUCTION

The Ionospheric Communications Enhanced Profile Analysis and Circuit (ICEPAC) program [Stewart, undated] is a full system performance model for high frequency (HF) radio communications circuits in the frequency range of 2 to 30 MHz. ICEPAC is described as being an extension of the Ionospheric Communications Analysis and Prediction (IONCAP) program [Teters, et al., 1983]. It differs in the polar region structure of the ionosphere and the low and mid latitude ionospheric structure. The model recognizes the different physical processes that exist in the different regions of the ionosphere. ICEPAC contains distinct algorithms for the sub-auroral trough, the equator-ward portion of the auroral zone, the pole-ward region of the auroral zone, and the polar cap. These changes to the IONCAP model are based in part on the ICED (ionospheric conductivity and electron density) profile model [Tascione, et al., 1988] which is a statistical model of the large-scale features of the northern hemisphere ionosphere. The purpose of this review is discuss the strengths and weaknesses of ICEPAC in comparison with IONCAP. At the present time, the IONCAP program is not available, as released in 1983. However, beginning in 1985 the Voice Of America took over the completion of the IONCAP code using technical expertise at both NTIA/ Institute for Telecommunication Sciences and the Naval Research Laboratory. Extreme care was exercised in maintaining the integrity of the IONCAP model including a final review by Donald L. Lucas, an original author of IONCAP. The result of this effort is a program now called: Voice of America Coverage Analysis Program (VOACAP) [Lane, 2001]. Consequently, the comparison in this review is between ICEPAC and VOACAP. Current versions of both programs are available for download on the Internet from the NTIA/ITS web site at: http://elbert.its.bldrdoc.gov/pc_hf/hfwin32.html

2. BACKGROUND

IONCAP was developed using over-the-horizon radar data to better determine the takeoff and arrival angles of ionospheric ray paths [Lloyd, et al., 1978]. This was accomplished using what was considered to be a better model of the ray trajectory through the electron density profile for the path. Ionospheric control points from the worldwide maps of critical frequency were used to assess the electron density at each of the layers at the points of entry. Both the low ray path and the high ray path were computed for up to 21 different layer-hop numbers. Great care was exercised in assuring that the assignment of power to each of the rays added up to the signal levels obtained from the parent model, ITSA-1 [Lucas and Haydon, 1966]. The reason for using ITSA-1 predictions for the basis of the IONCAP is that ITSA-1 had been very carefully scaled to match the existing measurements over a full solar cycle. Much of that work had been done manually at the National Bureau of Standards and the US Army Radio Propagation Agency before the advent of computers.

The original IONCAP code had numerous coding errors which resulted in unexplained propagation failure for particular circuits. These prediction anomalies made the program unacceptable for creating area coverage maps. The Voice of America undertook an 11 year development (1985 -96) project to correct coding/logic errors and modify the output of IONCAP for area coverage analyses. Every change made to the coding in VOACAP was exhaustively checked against IONCAP output to assure that no unexplained or unusual variations occurred using comparisons over hundreds of thousands of path-hour predictions. Checks were made for mode changes and for any change in a system performance factor of 2 dB or greater. For better or worse, VOACAP has retained the same degree of accuracy as the original model which was built around the largest and most comprehensive worldwide set of measurements over a full solar cycle epoch. It is known that the model had little data for the high latitude regions and in the Southern hemisphere; and that the accuracy of the predictions may be suspect in these regions of the world.

ICEPAC uses the same worldwide data maps and correction tables as does VOACAP, IONCAP and ITSA-1. Also ICEPAC appears to use the same assignment of signal power distribution amongst the various ray paths that may exist at an hour over the month. However, significant changes in the ionospheric model were made. These changes are listed as given in the ICEPAC Technical Manual [Stewart, undated]:

- **It is assumed that the ionosphere can be represented by one or more Chapman layers [Dudney, 1983], given sufficient information concerning the height of maximum ionization, semi-thickness, and electron density. Sufficient data must be available to predict an average electron density distribution with height for any possible transmission path. The current method of profile generations replaces the parabolic layer structure with a Chapman layer structure. The parabolic layer is analytically more tractable but the Chapman layer has the advantage that a layer whose process is dominated by electromagnetic ionization and chemical losses is closely described by the Chapman layer. In addition, the Chapman layer decreases exponentially with altitude above the layer peak -- this again more closely describes the ionospheric situation.**

- **The model divides the F2 region into four distinct zones: (1) normal low-latitude and mid-latitude ionosphere as described by the numerical coefficients, (2) the trough, (3) the zone of aurorally enhanced foF2's and (4) the polar cap. The key boundary for the model is the equatorward edge of the auroral oval. The resulting boundary location is parameterized by comparing it with standard Feldstein oval boundaries computed as a function of Kp or Q [Whalen, 1972]. The resulting magnetic index (Kpeff or Qe) is an effective auroral energy index because it is based on the "current" state of the high latitude ionosphere.**

- **The critical frequency of the F2 layer is obtained from world maps [Jones et al., 1966] and is the median value of that parameter. The true height of the maximum electron density of the F layer is developed in two steps. First, the M(3000)F2 factor is obtained from world maps, and then the true height of the maximum ionization hmF2 in the layer is calculated.**

- **The Auroral foE is made up of both solar ionization and auroral zone precipitating particals. The maximum auroral critical frequency (foEamax) due to precipitating particals is computed as suggested by Vondrak [Vondrak et.al., 1978] and is based on Qe, the effective geomagnetic activity index. foEamax is then adjusted for local time magnetic variations (Maximum ionizations at 0300 magnetic local time and minimum ionization at 1500 magnetic local time).**

- **A linear interpolation is done between the oval boundaries and the point of maximum ionization in the oval. The FoEa values of the polarized and equatorial boundaries of the auroral zone are set at 60% of the foEamax. The model uses linear interpolation to get values between the equatorial or polarized auroral boundaries and the geomagnetic latitude of the foEamax. FoEa, the interpolated value, is the auroral value of foE when no solar component is present (Auroral night line, Auroral sunrise, sunset).**

- **Auroral foF2 is calculated from the equations developed in the ICED model [Tascione et al, 1988].**

3. COMPARISONS OF MODELS AND MEASUREMENTS

The changes made to IONCAP to create ICEPAC do several things to the prediction model. First of all, the prediction of the circuit maximum usable frequency (MUF) will be different because of the changes in the electron density profile and the assumed shape of the profile. In general, the assumed Chapman layer in ICEPAC will generate lower MUFs due to the lower virtual height. Also ICEPAC will often return a higher order mode than IONCAP/VOACAP. Changes in mode also create large differences in the computed takeoff and arrival angles for the modes in question. Signal power prediction for a frequency and circuit-hour includes the transmit and receive antenna pattern gain values for the predicted takeoff/arrival angle. Circuit Reliability in both ICEPAC and VOACAP is used to find the most reliable mode at a given frequency and circuit hour. Therefore, the new electron density model in ICEPAC will not only change the frequency characteristics of the circuit but can also create very large differences in the system performance prediction at a given frequency and circuit-hour.

The extent to which ICEPAC will predict different MUF values than those produced by VOACAP are compared for a circuit for which there have been measurements. The test circuit had been established by Rockwell Collins from Toulouse, France to Cedar Rapids, Iowa from Jun 22 until Jul 13, 2004 which operated 24 hours per day using 20 test frequencies per hour with a 1 kW transmitter [Lane, 2005]. This test circuit data is used in making the comparison between ICEPAC and VOACAP. Ionospheric conditions during the test were quiet (Qe = 0). It would be expected that VOACAP and ICEPAC should be in close agreement for the undisturbed conditions on the test circuit.

ICEPAC was run for the mid-day of the test period (July 4, 2004). This forces the use of the URSI-88 coefficients which are also called the 'daily' predictions with Qe = 0. No guidance is given in the use of the Minimum Angle for ICEPAC. The default value is 0.1 degrees above the horizon. A more typical value as recommended for use in IONCAP [Teters, et al., 1983] is 3 degrees above the horizon. Both values of minimum angle are used in the comparison (see Fig. 1). The 'X' values shown in the figure are for the median frequency having the highest measured signal-to-noise ratio (SNR). Interestingly, the MUF predictions from ICEPAC for a horizon clearance angle of 0.1 degrees provided 2F2 mode at all hours of the day. Raising the minimum angle to 3.0 degrees changed the predominant mode to the 3F2 mode for 22 hours of the day.

Besides the great disparity in MUF values for the two very low minimum angle values, ICEPAC displays instablity in predicting the actual circuit MUF frequency when the minimum angle is set at 3 degrees. For the 0300 UTC hour which is an hour of complete darkness over the entire path just prior to the pre-dawn dip for the first hop from France toward Iowa, ICEPAC predicts a circuit MUF at 13.0 MHz for the 3F2 mode. Yet, if ICEPAC Method 20 is run for full system performance over a range of operating frequencies, we see that the probability of ionospheric support for the most reliable mode is 90% at 11 MHz and drops to 31% at 14 MHz for the 3F2 mode. But then at 15 MHz the MUFday value rises to 55% for the 2F2 mode. By definition, the circuit MUF must be above 15 MHz for the 2F2 mode. Yet, ICEPAC selects a MUF at 13 MHz for the 3F2 mode.

ICEPAC Version 031209W with minimum angle at 3 degrees

FREQ. (MHz)	11.0	12.0	**13.0 MUF**	14.0	15.0
Most Reliable Mode	3F2	3F2	**3F2**	3F2	2F2
MUFday	90%	74%	**50%**	31%	55%

Erroneous predictions of the MUF and the circuit MUF mode are seen consistently when ICEPAC is run with a minimum angle set at 3.0 degrees. Apparently the program is only valid when run for the case of no horizon blockage. This inconsistency is not seen in VOACAP for the case of minimum angles from 0.1 to 3 degrees.

VOACAP Version 03.1209W with minimum angle at 3 degrees

FREQ. (MHz)	11.0	**11.9 MUF**	**13.0**	14.0	15.0
Most Reliable Mode	3F2	**3F2**	3F2	3F2	3F2
MUFday	65%	**50%**	**4%**	1%	0%

4. ABSORPTION AND SYSTEM PERFORMANCE PREDICTIONS

The literature seems to be fairly devoid of HF system performance studies at high latitudes. One interesting study in Norway compared measurements to ICEPAC predictions [Jodalen and Trane, 1994]. Their observations showed that ICEPAC gives reasonable predictions in the daytime for transmission loss (primarily D-layer absorption) when the conditions are quiet; i.e. Qe = 0. Variations between measured absorption on a 285 km path and ICEPAC transmission loss were within ±20 dB. The values tended to fall in a range of 100 to 150 dB. However, as the conditions become moderately disturbed (Qe=3) to disturbed (Qe=8), variations between ICEPAC and measurement became very large during the late morning hours. At these times ICEPAC over predicted the loss by as much as 200 dB! A plot (Fig. 2) of VOACAP (undisturbed) and ICEPAC Qe = 0, 3 and 8, is shown for the transmission loss on the circuit from Andoya to Alta, Norway (285 km) in March 1988. VOACAP and ICEPAC agree very well for the undisturbed conditions. As Qe increases to disturbed conditions, huge losses are predicted by ICEPAC Qe =8 from 04 to 05 UTC and another period of his loss from 16 to 18 UTC. The absorption measured when Qe =8 was in the range of 150 to 280 dB over the entire day. ICEPAC predicts much lower absorption for most of the day when Qe = 8.

The Norway experiment [Jodalen and Trane, 1994] also reported that circuit reliability for this short path above 60 degrees North Latitude fell in the range of 20 to 60% for the month of March 1988. Reliability predictions were made for this path. Unfortunately, the circuit parameters were unknown to the author so these predictions are just relative estimates. However, the input to VOACAP and ICEPAC is identical. In Fig. 3, reliability predictions are shown for VOACAP (undisturbed condtions) and ICEPAC for Qe = 0, 3 and 8. For undisturbed conditions the reliability values shown to fall within 39% and 71% with VOACAP being slightly higher than ICEPAC Qe = 0. A very unusual result occurs in ICEPAC as the Qe value is raised from 3 to 8 for disturbed conditions. The reliability during the nighttime rises to over 80%. This increase is caused by the Qe value alone. Then during sunrise and sunset, the reliability falls to zero percent with Qe = 8. The investigators reported that during periods of disturbed conditions, the circuit reliability was zero percent for the entire day. The conclusions of this report state that the ICEPAC predictions had sizeable errors in both absorption prediction and circuit performance during periods of disturbed conditions.

ICEPAC Method 20 is the recommended way of modeling full system performance on HF paths. Ray hop propagation is considered for paths from ~0 to 10,000 km and the long path forward scatter model for paths >10,000 km. The recommended VOACAP method for full system performance predictions is Method 30 (Short Path/Long Path Smoothing Model) [Lane and Vo, 1995; and Lane, 2001]. In the range between 7000 and 10,000 km both the ray hop and the forward scatter models are used to compute a distance weighted signal power distribution in a manner very similar to the one in ITU-R Recommendation 533-7 [2001]. The forward scatter model uses ionospheric control points which are the closest to the terminals for the circuit and ignores the intervening control points. On a long transpolar path reported by Lane, et al. [1999] from Germany to California, reasonable broadcast coverage was achieved for a full month of monitoring which agreed well with VOACAP Method 30 predictions. ICEPAC Method 20 for identical input showed no coverage possible in California but show good coverage well off the coast of California where the forward scatter (long Path) prediction took effect at >10,000 km.

5. DISCUSSION

ICEPAC is a highly modified version of IONCAP. IONCAP, itself, is a direct off-shoot of the original ITSA-1 program [Lucas and Haydon, 1966]. All three programs use the same excess system loss tables. These crucial tables of correction factors forced the ITSA-1 signal power predictions to correlate with actual circuit measurements. The concept of additional system loss was first described by the Army Signal Radio Propagation Agency [Laitinen and Haydon,1950]. The loss factors were based on 43 circuit-years of receiver input voltage recordings. There were 33 different circuits ranging from 55 to 15,000 km in length on frequencies ranging from 2 to 20 MHz [Davis, 1969].

The detailed description of Excess System Loss is rather difficult to trace as it evolved. Lecture 26 <u>Computation of System Loss</u> by R. M. Davis, Jr. during the HF Ionospheric Radio Propagation, Prediction Methods, and Applications short course [Boulder, CO;1969] gives the best historical development of the excess system loss computations up to that time. The National Bureau of Standards informally published data [NBS internal Report 7249, Haydon, Lucas and Hanson, 1962] showing the probability function for the excess system loss for temperate and two high latitude paths for day and night. Next data from the 1959 - 1960 Arctic Experiment for a short auroral path, a long auroral - temperate path and a polar cap path were used to revise the Excess System Loss tables [NBS internal report 8810, Davis and Groome, 1965]. These became the tables used in ITSA-1 computer prediction program [Lucas and Haydon, 1966] and are the same values as used in IONCAP labeled as Distribution of Transmission Loss [Lloyd, et al., 1978]. Changes made to the Excess System Loss tables used in ITS-78 computer program (also known as HFMUFES and ITU Recommendation 252) were not used by Lloyd in the creation of IONCAP.

The ICEPAC Technical Manual [Stewart, undated] describes the use of the standard deviations of the Excess System Loss tables and the procedure to compute the minimum excess system loss (median level) based on Over-the-Horizon radar data developed for the Naval Research Laboratory program RADAR [Lucas, et al., 1972]. The reason for these changes is that IONCAP and RADAR compute the signal power delivered by individual modes (up to 21 modes for a single frequency-path-hour). Great care was taken to compare the summed signal power for all possible modes to that obtained by ITSA-1. Since the ITSA-1 predictions were forced to fit the 43 plus circuit years of measured signal levels, this correlation had to be maintained. If the sporadic E layer model is disabled by entering a critical frequency multiplier of zero rather than the recommended 0.7 in the FPROB settings, the predictions revert to the same losses as would be given by the ITSA-1 Excess System Loss tables [private communication ,J. Lloyd, 1978]. If one uses the IONCAP recommended sporadic E layer multiplier of 0.7, the system performance increases by about 3 dB based on many path comparisons [Lane, 2001].

ICEPAC is a semi-empirical model which uses Excess System Loss functions to adjust the magnitude of the signal power predictions, as did IONCAP and now VOACAP. However, ICEPAC uses very different models to obtain the electron density profile which affects the modes including their MUF values. Auroral absorption models are very different. Consequently, the computation of signal power is very different than IONCAP. There is no indication that any attempt was made to maintain the correlation with the Excess

System Loss tables which were based on actual measurements. If this assumption is correct, then the ICEPAC signal power predictions can significantly deviate from actual performance. The standard deviation of the Excess System Loss ranges from 6 to over 30 dB depending on path, season, time of day and geomagnetic latitude. Therefore, these correction factors being used in ICEPAC with the new propagation model may be erroneous by many dB.

6. CONCLUSIONS AND RECOMMENDATION

- ICEPAC represents a substantial step toward a more comprehensive HF system performance prediction program and it is now documented. However, the program still seems to be in the development stage with some significant errors.

- The mode structure as a function of frequency is unstable above the predicted MUF. In many cases a lower order mode than the MUF mode is found at higher frequencies. From oblique ionograms, it is known that modes above the MUF tend to be scatter modes which are often not related to the great circle azimuth. Having a lower order mode predicted above the MUF is not normally considered to be physically possible.

- On a high latitude path, the ICEPAC auroral absorption prediction was too high by 100 to 200 dB.

- It is observed that ICEPAC predictions of circuit reliability tend to be too high on high latitude paths except for an hour in the morning and another in the evening. Also as the Qe index is increased from quiet to disturbed conditions the circuit reliability prediction increases rather than decreases.

- For paths exceeding 7000 km, ICEPAC can provide predictions that can show thousands of kilometers of no received signal and then at greater distances a strong signal is returned to the ground. Such predictions do not agree with measurement.

- There is reason to feel that the major changes in ionospheric modeling in ICEPAC may require a new correlation with measurement in order to correct the needed distribution of transmission loss.

- It is recommended that ICECAP be used with caution. It would be well worth the effort to run both VOACAP and ICEPAC. VOACAP should be quite accurate for undisturbed conditions. If ICEPAC deviates greatly from VOACAP output, the predictions should be considered suspect.

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Fig. 1 Comparison of ICEPAC Predicted MUF Values and Measured Best Frequency (URSI-88 Coef)

ICEPAC Minimum Angle set at 0.1 and 3 degrees

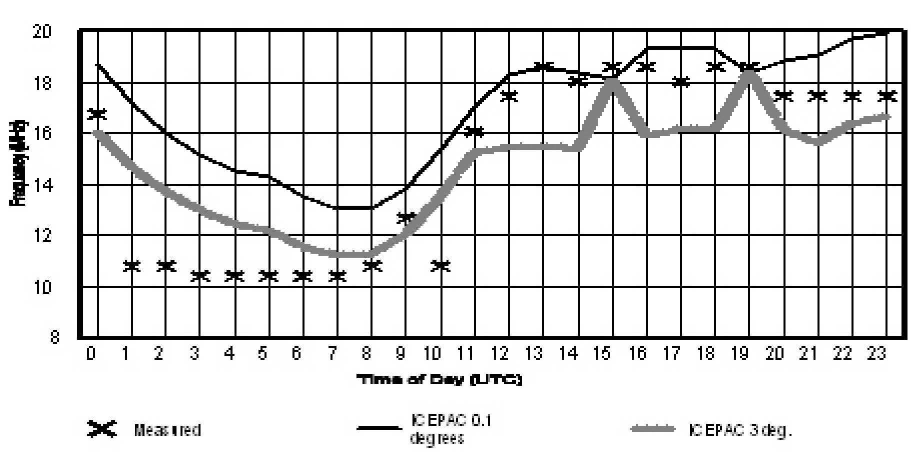

Fig. 2 Transmission Loss Comparison -Norway 3/88

VOACAP, ICEPAC Q = 0, 3 & 8

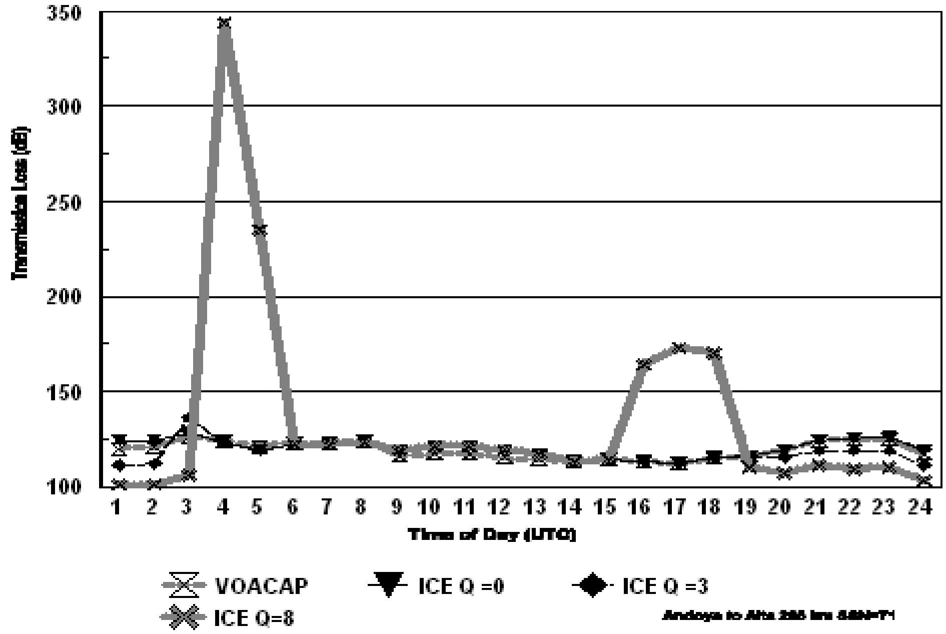

Fig. 3 Reliability Comparison- Norway 3/88

VOACAP, ICEPAC Q = 0, 3 & 8