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IONOSPHERIC CHARACTERISTICS FOR IRI IN REAL TIME

Bodo W. Reinisch,* Robert R. Gamache* and Lucien G. Bossy**[1]

*University of Lowell Center for Atmospheric Research, Lowell, MA 01854, U.S.A.
**Institut d'Aeronomie Spatiale, B-1180, Bruxelles, Belgium

ABSTRACT

Within a year's time, approximately forty Lowell Digisondes will provide ionospheric characteristics in real time. Since the echo traces of the E, Es, F1, and F2 layers are automatically identified and scaled, all standard characteristics (critical frequencies, minimum heights, MUFF2) are available. In addition, the Digisonde calculates the vertical electron density profiles, providing for the first time an extensive data set of bottomside profiles that can be used for the IRI modeling. Efforts to express the Digisonde profile in terms of LAY functions are underway.

INTRODUCTION

Currently 34 Lowell Digisonde 256 systems /1/ are either in operation, or are close to beginning operation, worldwide. Figure 1 shows the locations of the digital sounders, and corresponding station coordinates. The systems provide ionospheric characteristics in real time, and discussions on how to make use of this data base are beginning to evolve.

The first section considers the ionogram characteristics and the data quality. The method of converting the autoscaled traces to vertical electron-density profiles is then described and the final section discusses the problem of fitting LAY functions to the profiles.

AVAILABLE REAL-TIME IONOGRAM CHARACTERISTICS.

The Digisonde scales the ionograms within 20 to 30 seconds after completion of the ionogram scan using the ARTIST (Automatic Real Time Ionogram Scaler with True height) routine based on the approach described by Reinisch and Huang /2/. Figure 2 is a typical example of an on-line ARTIST printout. On top of the page are the station identification, date, time (always UT), and the sounder parameters. The ionogram characteristics scaled by ARTIST are listed next: foF2, foF1, h'F, h'F2, M3000, fmin, foEs, MUF(3000), fminF, fxl, fminE, foE, h'E, h'Es, and the range and frequency spread for F and E traces, QF, QE, FF, FE. The autoscaled traces h'(f)F and h'(f)E are given in km for every 100 kHz increment. The results of the ULCAR profile inversion algorithm are listed in terms of coefficients for the Chebyshev polynomial expansion.

All these data are available for authorized external users via modem/telephone links. The ionogram in Figure 2 is an optional on-line printout, either on-site or at a remote terminal, allowing one to check the accuracy of the autoscaling. ARTIST determines the

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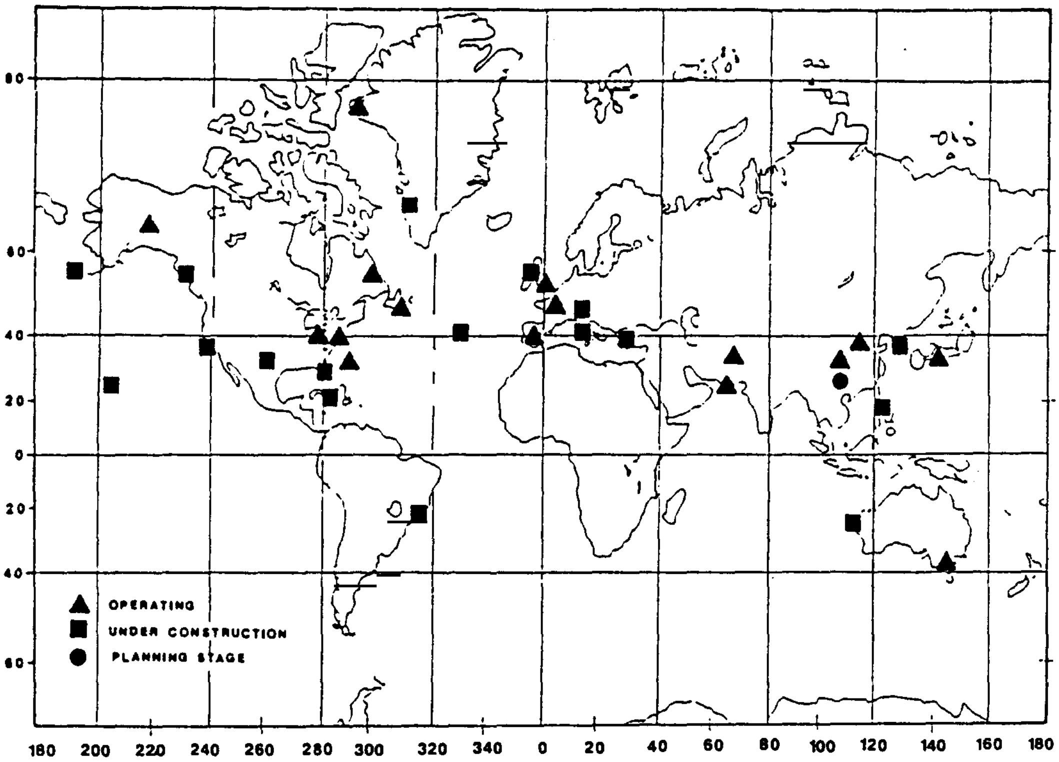
[1] Also Universite Catholique de Louvain



STATION	LATITUDE	LONGITUDE	STATION	LATITUDE	LONGITUDE
Baguio	N16.3	E120.6	Lowell	N42.6	E288.5
Ramey	N18.5	E292.9	Camp Darby	N43.5	E010.3
Maui	N20.5	E203.7	Argentia	N47.6	E307.3
Karachi	N24.8	E067.1	Munchen	N48.2	E011.6
Patrick	N28.2	E279.4	Dourbes	N50.1	E004.6
Central Texas*	N29.4	E261.7	Croughton	N52.0	E358.8
Bermuda	N32.4	E295.3	Attu	N52.6	E186.9
Islamabad	N33.8	E072.9	Goose Bay	N53.3	E299.5
Vandenberg	N34.7	E239.4	Slough	N51.5	E359.4
Xinxiang	N35.3	E113.9	Sitka	N57.0	E224.8
Kokubbunji	N35.7	E139.5	College	N64.9	E212.2
Kunsan	N36.0	E126.6	Sondrestrom	N67.0	E309.0
San Miguel Is.	N37.5	E334.5	Qaanaaq	N77.5	E290.8
Wallops Is.	N37.9	E284.5	Learmonth	S22.1	E114.0
Diyarbakir	N37.9	E040.2	Sao Paulo	S23.5	E313.5
Beijing	N39.9	E116.5	La Trobe	S37.8	E145.0
Roquetes	N40.8	E000.3			

*Nominal Location

Fig. 1 Global DIGISONDE 256 network as of July 1988.

leading edge of the E, Es, and F traces; h'(f)E and h'(f)Es are marked by the letter E, and h'(f)F1 and h'(f)F2 by F.

In tests to verify the quality of the autoscaled data, samples of printed ionograms have been manually scaled. Comparison of the autoscaled with the manually scaled data shows that ARTIST provides acceptable values for about 93% of the time at a mid-

```
+--------------------------------------------------------------+
+      ULCAR - MILLSTONE HILL, WESTFORD, MASSACHUSETTS         +
+            LAT 42.6, LONG 71.5W       DIP 72.9  FH 1.4       +
+      DIGISONDE 256 - VS.02.5       UNIVERSITY OF LOWELL, USA +
+--------------------------------------------------------------+

STATION YEAR DAY H  M      OUT DPT W  E  Q CAB XLZT NRW HEIG PROGRAM
  033   1987 293 13:54 UT 0484100 01-11 1 32E 41D3 334 123A    2
                 --------

FOF2  FOF1  H'F   H'F2  M3000 FMIN  FOES  MUF   FMINF
 7.4  3.9   215.  256.  3.40   1.6   2.9  25.2   3.0

FXI   FMINE FOE   H'E   H'ES  OF    OE    FF    FE
 8.2  1.6   2.9   110.  110.   5.    5.    .1    .1

AUTOSCALED TRACES (KM):
-------------------
 3.  215.  215.  217.  217.  222.  227.  237.  247.  253.  258.
 4.  260.  260.  260.  260.  260.  260.  260.  255.  255.  255.
 5.  255.  255.  255.  255.  255.  255.  255.  255.  255.  260.
 6.  260.  260.  265.  265.  270.  270.  275.  275.  285.  290.
 7.  300.  310.  325.  345.  360.
 1. ***** ***** ***** ***** ***** *****  110.  110.  110.  115.
 2.  115.  115.  120.  120.  125.  130.  135.  140.  150.  170.

NORMALIZED AMPLITUDE AS AT REFLECTION HEIGHT 100KM IN (DB)
        TOPF    2.    3.    4.    5.    6.    7.
 F       37.    0.   49.   63.   68.   69.   66.
 E       19.   46.
ES       19.   46.

PROFILE - ULCAR
---------------
   W =    .0  KM
   FSTART PEAK HT   A0       A1       A2       A3       A4     DEV   ROOTS
    (MHZ)  (KM)    (KM)     (KM)     (KM)     (KM)     (KM)   (KM)/PT
E    .199 121.348 -35.133   5.206   -6.432                      2.0   -
F1  2.999 169.894 -43.323   -.170   -4.926   1.894   -2.034   12.9   -
F2  3.999 237.602 -54.244 -10.270   -2.109  -1.428     .339    3.2   -
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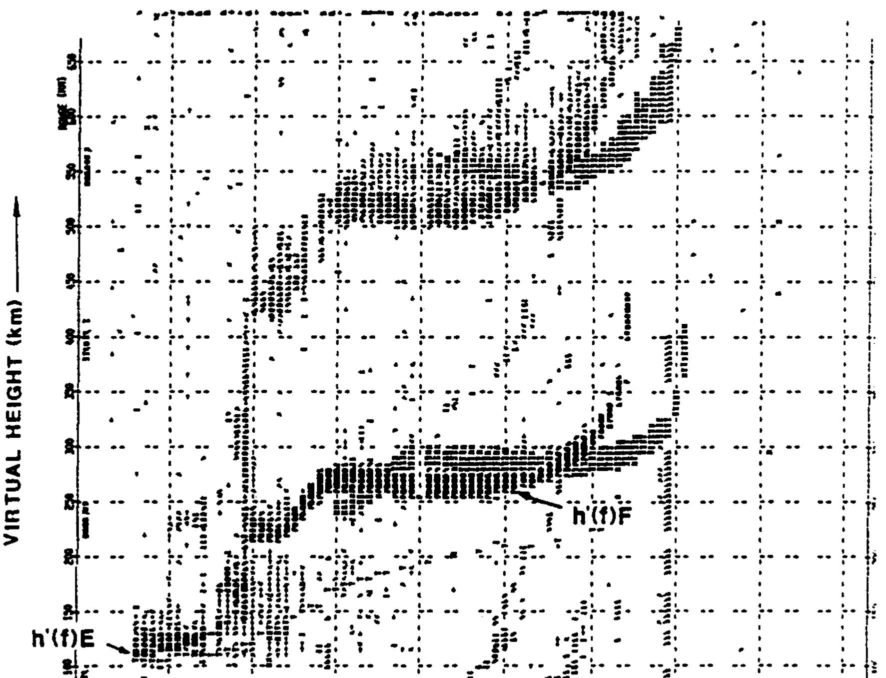

Fig. 2. Automatically scaled Digisonde ionogram.

latitude station /3/. For 97% of the analyzed ionograms, foF2 was determined within 0.5 MHz. This is somewhat better than the 87% found in 1983 for the auroral station at Goose Bay, Labrador (64.6°N Corrected Geomagnetic Latitude) /2/. Of course, the scaling software is under continuous review, and the current emphasis is on proper identification of multiple Es traces.

Post editing of the data is recommended before they enter a data base and be used for ionospheric modeling. ULCAR has developed a software package ADEP (ARTIST Data Editing and Printing) that allows to survey the raw and scaled ionogram data, detect inconsistencies, correct the errors, and display the data on screen and printout. Figure 3 shows one of the outputs of ADEP; the frequency plots are in the upper half and the electron density contours below. The contours are given in terms of plasma frequencies in half MHz increments. Data availability, i.e. existence of scaleable ionograms, is indicated by dots below the contour panel. Local midnight and noon are marked by M and N, F and E region sunrise/sunset by F and E respectively. This daily data display reveals the diurnal variations and makes it easy to investigate the day-to-day changes.

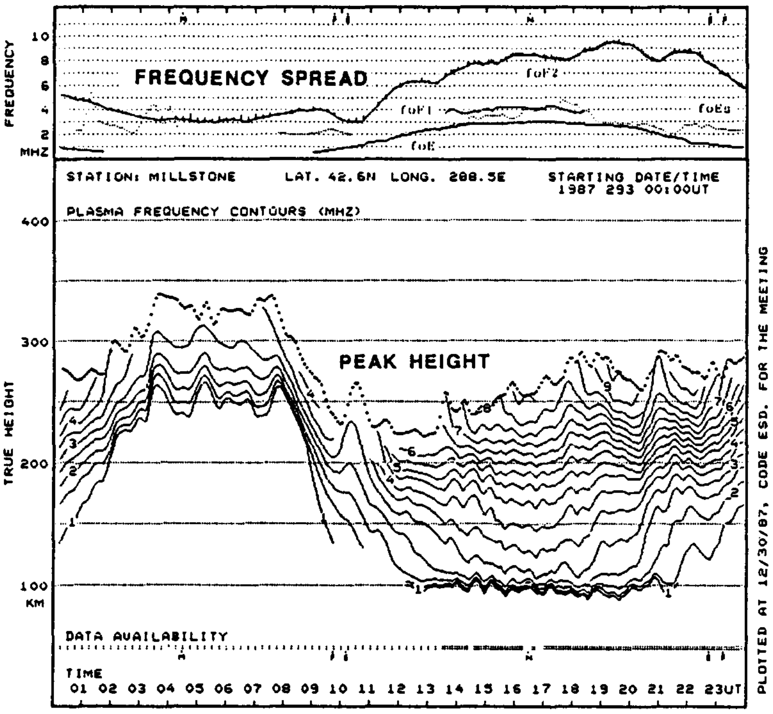

Fig. 3. Example of the output from ADEP package (Millstone Hill, 20 Oct 1987).

ELECTRON - DENSITY PROFILES

The Digisonde ARTIST system calculates the electron-density profile via inversion of the autoscaled traces. In the ULCAR method each ionospheric layer (E, F1, F2) is treated separately (figure 4) and is represented by a single analytical function /4/. This function is expressed in terms of shifted Chebyshev polynomials, $T^*(g)$, /5/ defined as

$$T^*_0(g) = 1 \qquad T^*_2(g) = 8g^2 - 8g + 1$$

$$T^*_1(g) = 2g - 1 \qquad T^*_3(g) = 32g^3 - 48g^2 + 18g - 1$$

and $$T^*_i(g) = 2(2g-1)\,T^*_{i-1}(g) - T^*_{i-2}(g) \quad .$$

For each layer segment, the true height is defined by

$$z - z(f_s) = A_{I+1} + g^{1/2} \sum_{i=0}^{I} A_i\, T^*_i(g) \tag{1}$$

with $g = \dfrac{\ln(f/f_c)}{\ln(f_s/f_c)}$ and $0 \le g \le 1$

where f is the plasma frequency, f_c the critical frequency, i.e. the plasma frequency at the segment peak, and f_s is the start frequency of the segment.

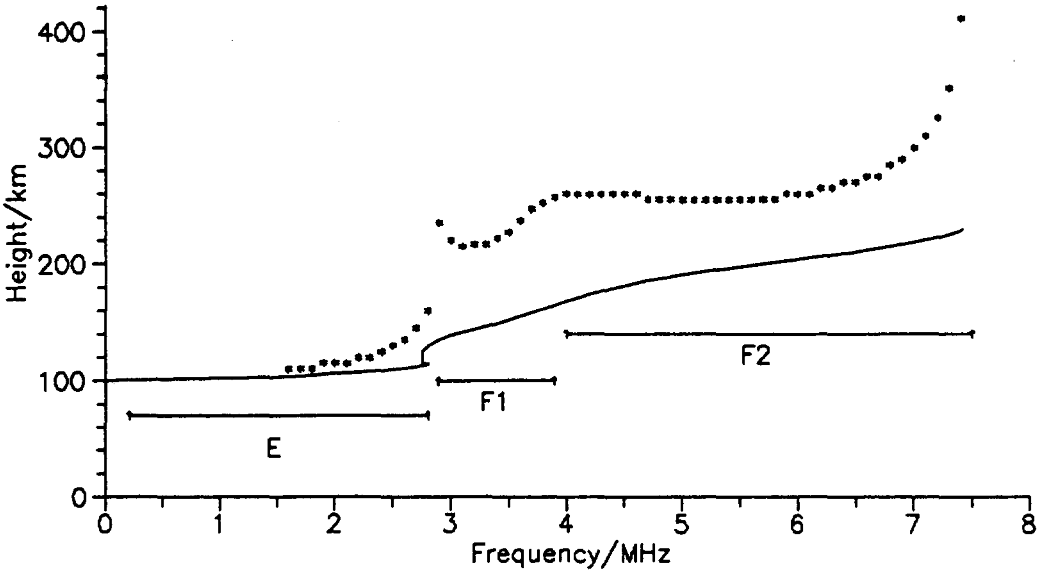

Fig. 4. Example of ionogram and corresponding electron-density profile derived from ARTIST (Millstone Hill, 20 Oct 1987, 13:54 UT).

The A_i's are determined by a least squares fit. The details of the method are discussed in /6/ and /2/. The term A_{I+1} is the thickness of the layer and is given by

$$A_{I+1} = z(f_c) - z(f_s) - -\sum_{i=0}^{I} A_i \qquad (2)$$

In the current algorithm, the number of coefficients selected for each layer is 3 for the E-layer ($i = 0,2$), 5 for the F1-layer ($i = 0,4$) when present, and 5 for the F2-layer. A model valley, as proposed by Titheridge /7/, is used between the E-F regions and is defined by a valley width W and a valley depth D related to the peak height of the E layer:

$$W = 0.5 \bullet z_{mE} - 40 \text{ km (km)} \qquad (3)$$

and

$$D = \frac{0.008\, W^2}{W + 20} \text{ (MHz)} \qquad (4)$$

The shape of the model valley is shown in Figure 5. The top section for the E layer is extrapolated upwards to the frequency (foE-D). The scale height used for this extrapolation is 40% greater than the scale height for the bottom side. The remainder of the valley width, Q, consists of two sections. The first section increases for 0.6Q at the frequency (foE-D) followed by a linear increase to the point at foE at the full width.

The starting height of the profile is determined from the data. Assuming a parabolic layer and no field, the corresponding virtual height formula is least squares fitted to the recorded trace to determine the starting height. If the correlation of the fit is poor or the starting height unphysical, the program defaults to the starting height model of McNamara/8/.

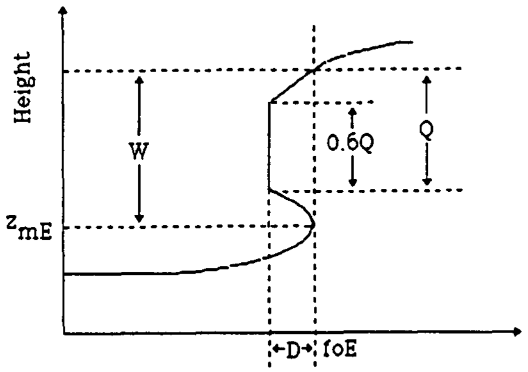

Fig. 5. Valley used in ARTIST (from /7/).

For each layer ARTIST records the start and end frequencies, the peak height of the layer and the polynomial coefficients. The valley parameters are totally determined from the E layer peak height. With these parameters the electron density profile may be recomputed at any later time. Figure 4 shows the resulting electron-density profile (solid line) from the autoscaled (asterisks) Millstone Hill ionogram.

ANALYTICAL REPRESENTATIONS OF ELECTRON-DENSITY PROFILES

Electron-density profiles are usually computed and stored in digital form as plasma frequency (or density N) vs. height. Accurate calculations for propagation that rely on this type of data are very time consuming. The development of an analytical electron density profile representation is advantageous for many applications, especially oblique ray tracing. This was addressed as part of an international project titled the International Reference Ionosphere (IRI) /9/ originated by COSPAR and co-sponsored by the International Union of Radio Science, URSI. The method proposed /10/ starts from a graph of the logarithmic derivative of the profile, dlogN/dz, and approximates of the discontinuous steps is replaced by one fully continuous Epstein-step-function, Eps_0, which is given by

$$\mathrm{Eps}_0\,(z;HX,SC) = 1\Big/\left(1 + \exp(-\zeta)\right) \qquad (5)$$

with $\zeta = (z-HX)/SC$. Asymptotically Eps_0 approaches one at the right hand side and zero at the left. The main variation occurs inside the width SC and is centered at HX, where the function takes the value 1/2. By linearly combining several functions Eps_0 with different, suitably chosen parameters (plus a constant), the original skeleton can be quite well approximated. The profile itself must then be found by integration. The integral function to Eps_0 reads /11/

$$\mathrm{Eps}_{-1}\,(z;HX,SC) = \ln\left(1 + \exp(\zeta)\right) \qquad (6)$$

and is called Epstein-transition. It has the right-hand asymptote equal to z/SC, while the left-hand asymptote is the z-axis (as for Eps_0). For completeness the derivative of Eps_0 is

$$\mathrm{Eps}_1\,(z;HX,SC) = \exp(\zeta)\Big/\left(1 + \exp(\zeta)\right)^2 \;. \qquad (7)$$

It peaks at $\zeta = 0$, i.e. $z = HX$, and has on both sides the z-axis as asymptote. It is called the Epstein-layer. After integration this reproduction of the profile is a sum of Eps_{-1} functions plus a linear term which stems from the constant in the skeleton. This fitting procedure is essentially layer-by-layer, i.e. by successive approximation. There are many problems with applying this procedure as discussed by the Task Group on IRI /9/.

After much study of the methodology, a function given in terms of a sum of the various Epstein functions was developed that satisfies the constraints encountered in the fitting procedure. The function is called a LAY function and is given by

$$\begin{aligned} \mathrm{LAY}\,(z;HX,SC) = \mathrm{Eps}_{-1}\,(z;HX,SC) - \mathrm{Eps}_{-1}\,(z_m;HX,SC) \\ - (z-z_m)\;\mathrm{Eps}_0\,(z_m;HX,SC) \end{aligned} \tag{8}$$

where z is the height coordinate, z_m the height of the extremum, HX a height parameter and SC a scale parameter. The LAY function can also be written as

$$\mathrm{LAY}\,(x_m;x) = \left[\ln\frac{1+e^{x}}{1+e^{x_m}} - (x - x_m)\,\frac{e^{x_m}}{1+e^{x_m}} \right] \tag{9}$$

where $x = (z-HX)/SC,\qquad x_m = (z_m-HX)/SC\,.$ (9a)

This function looks like the Epstein transition (6) and is well suited to represent

$$\log_{10}\frac{N_m}{N(z)} = 2\,\log_{10}\frac{f_c}{f(z)} \tag{10}$$

where $f_c=f(z_m)$ is the critical frequency of the layer and f(z) the plasma frequency at height z.

By fitting the LAY function to $\log(N(z)/N_m)$ one can determine SC and HX. There are different ways to accomplish the fitting, e.g. in /12/ a sum of LAY functions is used to represent the profile,

$$\log(N(z)/N_m) = \sum_{i=1}^{I} A_i \bullet \mathrm{LAY}(z;HX_i,SC_i) \tag{11}$$

where the HX_i and SC_i are precalculated from "average" profiles and the linear coefficients are chosen to fit the profile at hand.

Another procedure is to evaluate the HX and SC for the particular profile in question. For single layer fits this has been accomplished /13/. For representation of several layers (E, F1, F2) this can be achieved by a summation of LAY functions where for each function used the HX and SC are determined separately. Both of these methods are discussed in this report.

Bossy et. al. /14/ described the fitting of a LAY function to a single layer. To obtain the parameters SC and HX of the LAY function, three points are selected from the profile: the critical frequency and peak height (f_c and z_m), and two more points at prescribed fractions of the critical frequency $f_1 = k_1 \cdot f_c$ and $f_2 = k_2 \cdot f_c$ giving the points (f_1, z_1,) and (f_2, z_2) (see Figure 6). The fraction k_2 is always less than k_1, so $f_2 < f_1$. From the properties of the LAY functions, relationships were developed /13/ which yield SC and HX in terms of numerical coefficients for (eleven) sets of prescribed fractions k_1 and k_2.

For any given profile, a total of eleven LAY functions can be generated to fit the profile by possible choices of k_1 and k_2. The decision of which LAY function best fits the profile can be based on several criteria; overall error per point, the one that fits the greatest region of the profile to within some threshold or a combination of the two. In a study /14/ of some three thousand profiles from seven locations, the combination of a 5 km threshold and the length of the fit was used with good results.

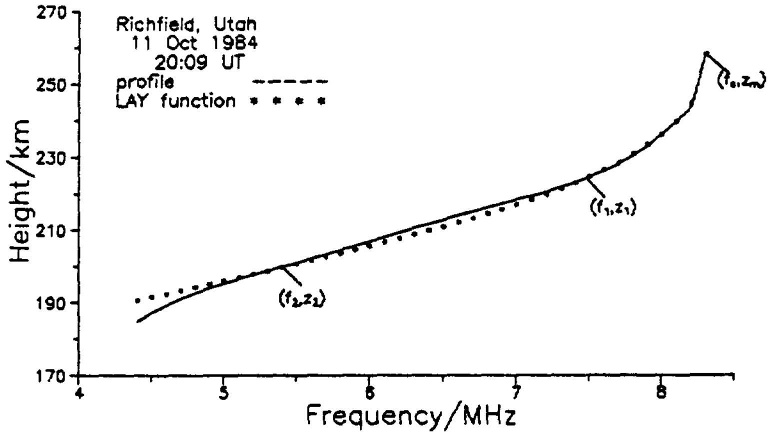

Fig. 6. Fitting LAY function to profile (from /14/).

While the results of /14/ established the use of the LAY function to fit the profile of a single layer (F2), an analytic description of the entire electron density profile (E-F1-F2) is needed for wave propagation studies. Summation of LAY functions with average predetermined SC and HX values and adjusted factors A_i (eq. 11) to represent the profiles is used by Suchy and Rawer /12/. In the present approach the entire F profile *L* is represented by

$$\mathcal{L} = \log_{10}\left(\frac{N_m}{N(z)}\right) = \mathrm{LAY}_1 + \mathrm{LAY}_2 \qquad (12)$$

The first of these functions LAY_1 is determined by fitting the F2 part of the profile by the methods discussed above. A residual *R* is then obtained for $f<foF1$

$$R = \mathcal{L} - \mathrm{LAY}_1 - \mathrm{LAY}_2 \qquad (13)$$

which permits the determination of parameters of the F1 layer. Selection criteria for LAY_1 among the possible choices have been investigated. The choice of a LAY_1 function which gives the best fit to the overall profile (i.e. the combination LAY_1 and LAY_2) must be formulated in view of the fact that the slope of the LAY_1 affects the fit of the residual *R* to a large extent. At the point fminLAY where the LAY_1 function exceeds the 5 km threshold, LAY_1 functions that have a slope near that of the profile may afford reasonable fits of the residual by the LAY_2 function. Test were made applying several slope criteria to the eleven possibilities for LAY_1; this however eliminates many of the choices of the possible LAY_1 functions. To provide more functions, we have considered fitting by other LAY functions which were generated by varying the heights of the determining points (f_1, z_1) and (f_2, z_2) by 1 to 4 km (see Figure 6). This yields many more LAY functions and hence gives a larger set with which to test the slope criteria.

The first criterion used was to calculate the slope of $\log_{10}(Nm/N)$ at fminLAY and to only include LAY functions that have a slope within 5% of this value. This we call Method I (maximum slope constraint). Next, the mean slope of $\log_{10}(Nm/N)$ between (foF2 - 1 MHz) and (fminF2 + 1 MHz) has been used and only LAY functions which have this mean slope at the point (fminF2 + 1 MHz) considered. This is called Method II. Tests of the two methods have been conducted for over 300 profiles from Millstone Hill, MA, USA. In Figure 7, the diurnal variation of the parameter HX/z_m for the two methods is plotted. The results for the mean slope method (II) show some variation from a low of about 0.95 to a high of 1.12; note the upper and lower quartiles are very close to the mean curve. Method I (maximum slope constraint) differs mainly in the data spread, and it shows a steeper change at 06 LT. Those preliminary results indicate that the Method II leads to a more consistent LAY function description of the profile. The scale heights SC for the 300 sample ionograms were 20 km ± 10 km, both for Method I and Method II. It is concluded that the LAY function fitting of F2 profiles with consideration of the existing F1 layer is possible leading to consistent values of the ratio HX/z_m and the scale height parameters SC. Extensions of this work to considering multi-layer profiles should be attempted.

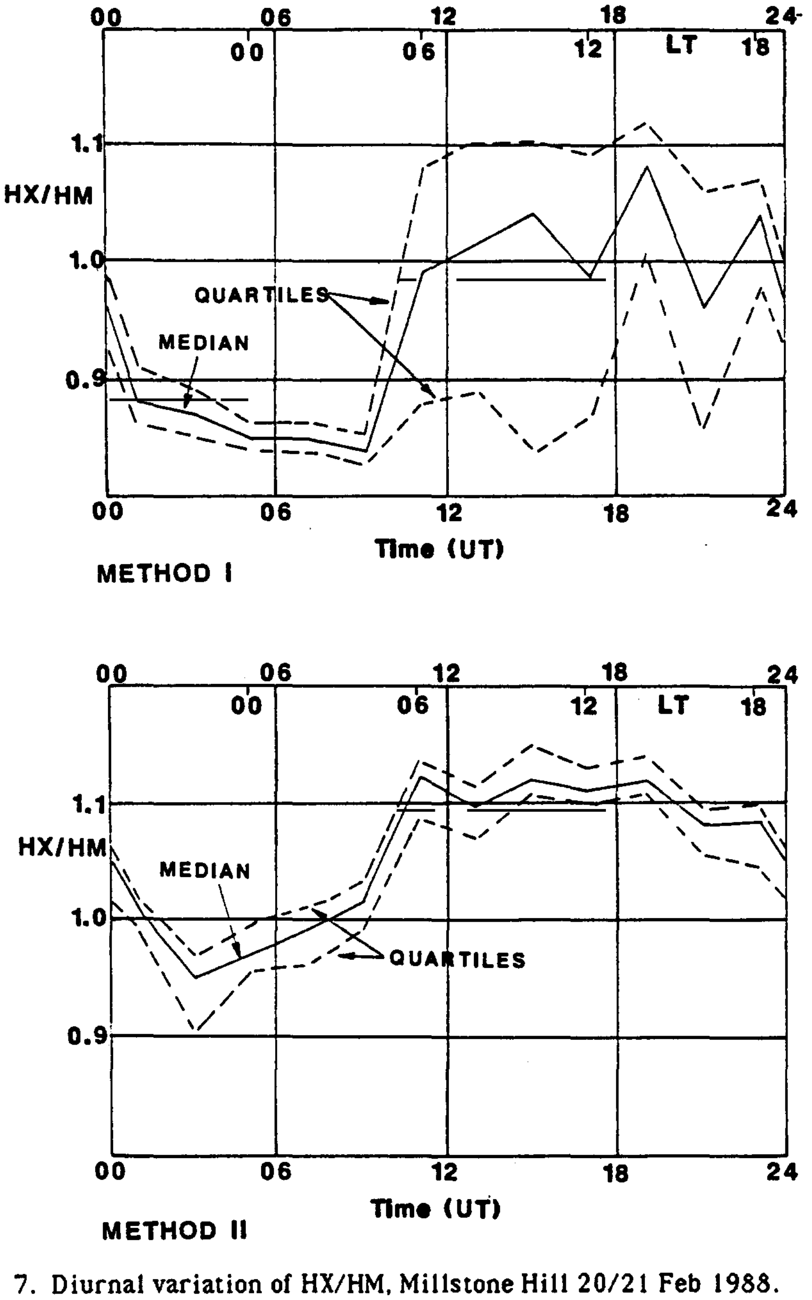

Fig. 7. Diurnal variation of HX/HM, Millstone Hill 20/21 Feb 1988.

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