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# Specification for HF Maximum Usable Frequency (MUF) Model

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## 1.0 INTRODUCTION

Any communication system operating in the high-frequency (HF) spectrum between 2 and 32 MHz is subject to certain physical limitations on the propagation of its signal. These limitations determine propagation boundaries which are unique and definable for any given point in time and over any path. The upper boundary is called the maximum usable frequency (MUF). The instantaneous MUF is a direct function of ionospheric electron density and is an absolute frequency limit, since the ionosphere is not capable of supporting propagation by the refraction of higher frequencies for that path. Ionospheric electron density is driven both by solar activity and by seasonal and diurnal variations. A model developed to predict MUF must be able to deal with these variations.

In 1978 a semiempirical model for MUF prediction, called MINIMUF-3.5, was developed at the Naval Ocean Systems Center (NOSC). It was used on small mobile propagation forecast (PROPHET) terminals (Ref. 1 and 2). Values for the parameters used in the model were determined by using HF oblique sounder propagation data. A data base of HF oblique sounder data was used in 1981 to evaluate the accuracy of this model (Ref. 3).

In 1986 MINIMUF-3.5 was improved. Called MINIMUF-85, the new model contained improvements in the  $f_oF2$  algorithms, high sunspot number predictions, an  $M$ -factor algorithm, and a polar region algorithm (Ref. 4). The accuracy of this improved model was evaluated in 1987 by using an expanded data base of HF oblique sounder data (Ref. 5). During this period several user's manuals were also published. These manuals contain specific information on how to use the HF propagation prediction models developed at NOSC (Ref. 6 and 7).

## 2.0 MUF MODEL INPUT AND OUTPUT PARAMETERS

MUF model input and output parameters and parameter limits are listed in Table 2-1. Monthly median sunspot values can be found in the Solar Indices Bulletin, published by the National Geophysical Data Center, Solar-Terrestrial Physics Division, located in Boulder, Colorado.

**Table 2-1.** MUF Model Input and Output Parameters.

Parameter Description	Parameter Limits
INPUT	
Transmitter Latitude	$-\pi/2$ to $\pi/2$ radians (90 deg south to 90 deg north latitude)
Transmitter West Longitude	0 to $2\pi$ radians (0 deg to 360 deg west longitude)
Receiver Latitude	$-\pi/2$ to $\pi/2$ radians (90 deg south to 90 deg north latitude)
Receiver West Longitude	0 to $2\pi$ radians (0 deg to 360 deg west longitude)
Month	1 to 12
Day	1 to 31
Hour	0 to 23 (Universal time)
Minute	0 to 59 (Universal time)
Julian Day	1 to 366
Year	Example: 89 for 1989
Monthly Median Sunspot Number	0 to 300
OUTPUT	
Maximum Usable Frequency	2 to 50 MHz
Distance Between Transmitter and Receiver	0 to $\pi$ radians
Latitude of the Path Midpoint	$-\pi/2$ to $\pi/2$ radians
West Longitude of the Path Midpoint	0 to $2\pi$ radians
Latitude of a Point 1000 km from Receiver	$-\pi/2$ to $\pi/2$ radians
West Longitude of a Point 1000 km from Receiver	0 to $2\pi$ radians
Latitude of a Point 1000 km from Transmitter	$-\pi/2$ to $\pi/2$ radians
West Longitude of a Point 1000 km from Transmitter	0 to $2\pi$ radians
Azimuth from Receiver to Transmitter	0 to $2\pi$ radians

### 3.0 MUF MODEL COMPUTER PROGRAM, SUBROUTINES, AND FUNCTIONS

A program called CMUF passes input parameters to the subroutine MUF85 and receives the calculated MUF and geographic path information from this subroutine. The MUF85 subroutine calls the subroutines PATH and RAZGC and the functions FOF2 and SYGN.

The subroutine PATH computes eight values of geographic path information for a given propagation path. The computation assumes a spherical earth with a radius of 6371 km. Required inputs for this routine are transmitter and receiver latitude and west longitude in radians. The following information, in radians, is returned by this subroutine: distance between transmitter and receiver, midpoint latitude, midpoint west longitude, latitude of a point 1000 km from the transmitter and receiver, west longitude of a point 1000 km from the transmitter and receiver, and azimuth from receiver to transmitter. Subroutines GCRAZ and RAZGC are called by PATH.

Subroutine GCRAZ computes the great circle range and azimuth between two points on the earth's surface in radians. Latitude and west longitude of the two points, in radians, are required as input. This computation assumes a spherical earth and recognizes the degenerate cases of a point at the North or South Pole and coincident points.

Subroutine RAZGC computes the latitude and west longitude in radians of a point a specified distance and azimuth from a given point on the earth's surface. Latitude, west longitude, distance, and azimuth, in radians, of the given point to the new point are required as inputs. This computation assumes a spherical earth and recognizes the degenerate cases of the given point at the North or South Pole and when distance is zero.

Function FOF2 provides a correction to the calculation of the *F2*-layer critical frequency for polar latitudes by using the Chiu polar model (Ref. 8). Inputs to this function are the critical frequency in megahertz, local mean time at the control point, month, day, hour (UT), minute (UT), Julian day and year, geographic latitude and west longitude of the control point in radians, magnetic latitude of the control point in radians, and sunspot number (SSN). This function calculates the corrected *F2*-layer critical frequency, in megahertz, which is passed to the MUF85 subroutine.

Function SYGN returns the value of zero if the input value is zero, -1 if the input value is less than zero, and +1 if the input value is greater than zero.

#### 4.0 MUF MODEL ALGORITHMS

The expression for the MUF used in MINIMUF-85 is given by

$$\text{MUF} = A_2 (\text{SSN}) \cdot A_3 (\text{month}) \cdot A_4 (\text{time}) \cdot M \cdot f_o F2 \quad (1)$$

where  $M$  is the obliquity, or  $M$ -factor, which reflects the dependence of the MUF on the transmission path length. The parameter  $f_o F2$  is the critical or penetration frequency at vertical incidence for the  $F2$  layer. The parameters  $A_2$ ,  $A_3$ , and  $A_4$  contain the sunspot dependence, the seasonal dependence, and the time dependence in the  $M$ -factor.

The equation for the  $A_2$  parameter is

$$A_2 (\text{SSN}) = 1.3022 - (0.00156)R \quad (2)$$

where  $R$  is the monthly median sunspot number. The  $A_2$  parameters provide a linear decrease as a function of sunspot number.

The equation for the  $A_3$  parameter is

$$\begin{aligned} A_3 (\text{month}) = & 0.9925 + 0.011 \sin (m) + 0.087 \cos (m) \\ & - 0.043 \sin (2m) + 0.003 \cos (2m) \\ & - 0.013 \sin (3m) - 0.022 \cos (3m) \\ & + 0.003 \sin (4m) + 0.005 \sin (5m) \\ & + 0.018 \cos (6m) \end{aligned} \quad (3)$$

where  $m = 2\pi \cdot (\text{month})/12$  and  $\text{month} = 1, 2, 3, \dots, 12$ . This seasonally dependent factor attempts to account for unusually high electron density during winter months, which allows higher frequencies to propagate on a given transmission path.

The equation for the  $A_4$  parameter is

$$A_4 (\text{time}) = 1.11 - 0.01 T_{\text{local}} \quad (4)$$

which adequately fits daytime data and for night

$$\begin{aligned} A_4 (\text{time}) = & 1.0195 - 0.06 \sin (2T) - 0.037 \cos (2T) \\ & + 0.018 \sin (4T) - 0.003 \cos (4T) \\ & + 0.025 \sin (6T) + 0.018 \cos (6T) \\ & + 0.007 \sin (8T) - 0.005 \cos (8T) \\ & + 0.006 \sin (10T) + 0.017 \cos (10T) \\ & - 0.009 \sin (12T) - 0.004 \cos (12T) \end{aligned} \quad (5)$$

where  $T = T_{\text{local}} - T_{\text{sunset}}$ , which represents elapsed time in hours after sunset.

The expression for the  $M$ -factor is given by

$$M = \{1 + 2.5[\sin(2.5 \psi k)]^{3/2}\} \cdot G_1(\Delta T) \cdot G_2(L_o) \cdot G_3(L_1, L_2) \quad (6)$$

where  $\psi$  is the great-circle arc length, in radians, of the transmission path,  $L_o$  is the latitude of the path midpoint,  $L_1$  and  $L_2$  are the transmitter and receiver latitudes, and  $\Delta T$  is the duration of daylight at the path midpoint in hours. The  $k$  parameter is equal to 1.0 for path lengths less than or equal to 4000 km and 0.5 for greater path lengths. The value of  $2.5 \psi k$  is limited to a maximum of  $\pi/2$  for path lengths greater than 8000 km.

The first factor of Eq. 6 contains the range dependence of the  $M$ -factor and was obtained by curve-fitting to exact results for a parabolic layer at a height of 290 km with a ratio of semithickness to base height equal to 0.4. The  $G_1$  factor gives recognition to the approximately 50% increase in  $F_2$  layer heights observed at high (northern) latitudes during the summer at or near "midnight sun" conditions. The equation for the  $G_1$  parameter is

$$G_1 = 1 - 0.1 \exp[(\Delta T - 24)/3] \quad (7)$$

which has the effect of a 10% reduction in MUF under full midnight sun conditions, with  $G_1$  recovering rapidly as the midpath latitude moves toward the equator.

The  $G_2$  parameter is designed to produce further, seasonally independent, reductions in MUF for high latitude paths. Since propagation data indicate a fairly abrupt onset of this reduction for absolute values of latitude greater than or equal to 45 degrees, a step function is used which is equal to 1 for absolute values of latitude less than 45 degrees and to 0.8 (20% reduction) for absolute values of latitude greater than or equal to 45 degrees.

The  $G_3$  parameter is a correction factor for transequatorial paths to approximate the well-known MUF increases on such paths. The factor applies another 20% correction as a step function equal to 1.0 if the transmitter and receiver latitudes are the same sign and equal to 1.2 if the transmitter and receiver are of opposite sign.

The expression for the critical frequency,  $f_o F2$ , is given by

$$f_o F2 = [A_o + A_1(\text{SSN}) \cdot (\cos \chi_{\text{eff}})^{1.2}]^{1.2} \quad (8)$$

where  $A_o$  is equal to 6 and

$$A_1(\text{SSN}) = 22.23 + (0.814)R \quad (9)$$

where  $R$  is the monthly median sunspot number. The  $A_1$  parameter provides a saturation effect in the behavior of the critical frequency as a function of sunspot number.

In Eq. 8,  $\chi_{\text{eff}}$  is an "effective" solar zenith angle.  $\cos \chi_{\text{eff}}$  is modeled as the lagged response of a dynamic linear system "driven" by the instantaneous value of  $\cos \chi$ . By using an effective value of the zenith angle, recognition is given to the fact that the  $F2$  layer, unlike the  $E$  and  $D$  layers, does not show a relatively simple  $\cos^n \chi$  diurnal dependence on  $\chi$ . The dynamic behavior of the  $F2$  layer is more complicated because of various other dependencies. In keeping with the uncomplicated nature of the  $f_o F2$  model, defining an effective  $\chi$  allows relatively accurate modeling without explicitly including these other dependencies. To model  $\cos \chi_{\text{eff}}$  at night, the following quantity is constructed:

$$(\cos \chi_{\text{eff}})_{\text{night}} = (\cos \chi_{\text{eff}})_{\text{sunset}} \cdot \exp [-(T - T_{\text{sunset}})/\tau_N] \quad (10)$$

In Eq. 10,  $\tau_N$  is a nighttime relaxation time, equal to 2 hours, which is taken to be a constant independent of season and geographical location.  $T - T_{\text{sunset}}$  is the elapsed time in hours since sunset.

However, during the day, a different relaxation time,  $\tau_D$ , is assumed. In contrast to  $\tau_N$ ,  $\tau_D$  does depend on location and position. The daytime relaxation time is assumed to be a function of the actual noontime solar zenith angle ( $\cos \chi_{\text{noon}}$ ) and can be expressed as

$$\tau_D = \tau_o (\cos \chi_{\text{noon}})^{P_2} \quad (11)$$

where  $\tau_o$  and  $P_2$  are constants, equal to 9.7 and 9.6 hours, respectively, and are independent of season or location. The value of  $\tau_D$  is not allowed to fall below 0.1. Note that during summer at equatorial and moderate latitudes,  $\tau_D \rightarrow \tau_o$ , whereas in the winter at high latitudes,  $\tau_D \ll \tau_o$ .

The time dependence of the actual  $\cos \chi$  in terms of its value at noon,  $\cos \chi_{\text{noon}}$ , is

$$\cos \chi \approx \cos \chi_{\text{noon}} \cdot \sin \left[ \frac{\pi(T - T_{\text{dawn}})}{\Delta T} \right] \quad (12)$$

where  $\Delta T$  is the daytime duration given by

$$\Delta T = T_{\text{sunset}} - T_{\text{dawn}} \quad (13)$$

and noon occurs when  $T = T_{\text{dawn}} + \Delta T/2$ .

Next,  $\cos \chi_{\text{eff}}$  is assumed to represent the response of a linear first-order system driven by the actual  $\cos \chi$ :

$$\tau_D \frac{d}{dt} (\cos \chi_{\text{eff}}) + \cos \chi_{\text{eff}} = \cos \chi \quad (14)$$

By using Eq. 12 for  $\cos \chi$  in Eq. 14, we obtain the daytime  $\cos \chi_{\text{eff}}$ :

$$(\cos \chi_{\text{eff}})_{\text{day}} = \frac{\cos \chi_{\text{noon}}}{1 + \beta^2} \left\{ \sin(\alpha) + \beta \left( \exp \left[ -\frac{(T - T_{\text{dawn}})}{\tau_D} \right] - \cos(\alpha) \right) \right\} \quad (15)$$

where

$$\beta = \frac{\pi \tau_D}{\Delta T} \quad (16)$$

and

$$\alpha = \frac{\pi(T - T_{\text{dawn}})}{\Delta T} \quad (17)$$

At sunset ( $T - T_{\text{dawn}} = \Delta T$ ) and  $(\cos \chi_{\text{eff}})_{\text{sunset}}$  is

$$(\cos \chi_{\text{eff}})_{\text{sunset}} = \frac{\cos \chi_{\text{noon}}}{1 + \beta^2} \left\{ \beta \left[ 1 + \exp \left( \frac{-\Delta T}{\tau_D} \right) \right] \right\} \quad (18)$$

To avoid discontinuities in  $\cos \chi_{\text{eff}}$  just after sunrise,  $(\cos \chi_{\text{eff}})_{\text{day}}$  is not allowed to fall below its value just before sunrise.

$$(\cos \chi_{\text{eff}})_{\text{day}} = \max \{ (\cos \chi_{\text{eff}})_{\text{sunset}} \cdot \exp [(\Delta T - 24)/\tau_N], (\cos \chi_{\text{eff}})_{\text{day}} \} \quad (19)$$

The basic  $f_oF_2$  model is therefore given in Eq. 8, 10, and 18 for nighttime (i.e.,  $T_{\text{sunset}} < T < T_{\text{dawn}}$ ) and Eq. 8, 15, and 19 for daytime ( $T_{\text{dawn}} < T < T_{\text{sunset}}$ ).

Simple analytical approximations for the times of local noon, sunrise, and sunset and for the noon value of the solar zenith angle are presented in the following equations. To an acceptable degree of accuracy, for the Universal time of local noon the approximation

$$T_{\text{noon}} = 12 \left( \frac{W}{\chi} + 1 \right) + 0.13 [\sin(Y_1) + 1.2 \sin(2Y_1)] \quad (20)$$

where

$W$  = longitude west of Greenwich [0,  $2\pi$  radians]

$Y_1 = 0.0172 (D + 10)$

$D = 30.4 (M1 - 1) + D1$

$D1$  = day values which range from 1 to 31

$M1$  = month values which range from 1 to 12

In terms of the subsidiary variable  $Y_2$ , defined by

$$Y_2 = 0.409 \cos(Y_1) \text{ [radians]} \quad (21)$$

and

$$\cos \chi_{\text{noon}} = |\cos(L + Y_2)| \quad (22)$$

where

$L$  = north latitude in radians ( $-\pi/2, \pi/2$ )

The duration of the daytime,  $\Delta T$ , is approximated by

$$\Delta T = \frac{24}{\pi} \arccos \left( \frac{-0.26 + \sin(Y_2) \sin(L)}{\cos(Y_2) \cos(L)} \right) \quad (23)$$

where the factor -0.26 approximates the difference between sunrise (or sunset) at the surface of the earth and at  $2F_2$  layer heights. From Eq. 23

$$T_{\text{dawn}} = T_{\text{noon}} - \Delta T/2 \quad (24)$$

and

$$T_{\text{sunset}} = T_{\text{noon}} + \Delta T/2 \quad (25)$$

where

$T_{\text{noon}}$  is given in Eq. 20.

The fact that high-latitude ionospheric behavior differs sharply from that at lower latitudes has been recognized for some time. This sharp difference required the addition of a routine to MINIMUF-85 specifically tailored to model the behavior of the MUF at high latitudes. This is accomplished by using a folding function,  $f$ , to merge a polar model with the model of lower latitude behavior.

The folding function determines when polar effects (particle precipitation) become dominant. It is a function of geomagnetic latitude and sunspot number and makes an abrupt transition from 0 to 1 between geomagnetic latitudes of 60 degrees to 75 degrees. When the folding function is near 1, particle precipitation effects will dominate, and when the folding function is near 0, solar zenith angle is the major factor in causing ionization. In between, there exists a narrow transition region where both sources of free electrons are significant. The equation for merging the two models is

$$N_{\text{total}} = (1 - f) N_{\text{MINIMUF}} + f N_{\text{polar}} \quad (26)$$

where  $N$  is the electron density calculated from the expression

$$f_o F2 \text{ (MHz)} = 2.85 N^{1/2} \text{ [electrons/cm}^3\text{]} \quad (27)$$

The total electron density at the control point is then converted back to  $f_o F2$  by using Eq. 26, and the MUF is obtained by multiplying the value of  $f_o F2$  by the range-dependent portion of the  $M$ -factor.

The equation for the folding function is

$$f = \exp(-X^6) \quad (28)$$

where

$$X = [2.2 + (0.2 + R/1000) \sin(L_1)] \cos(L_1) \quad (29)$$

where

$R$  = monthly median sunspot number

and

$L_1$  = magnetic latitude of the control point in radians.

The equation for the polar model of electron density for northern geomagnetic latitudes is

$$N_{\text{polar}} = (2.0 + 0.012R)(1.0 + 0.3V)W \quad (30)$$

where

$$V = \sin(\pi \text{month} / 12) \quad (31)$$

and

$$W = \exp\left(-1.2 \left\{ \cos \left[ L_1 - 0.41015 \cos \left( \frac{\pi T}{12} \right) \right] - \cos(L_1) \right\}\right) \quad (32)$$

with

$L_1$  = magnetic latitude of the control point in radians

and

$T$  = the local mean time at the control point in hours

The expression for electron density for southern geomagnetic latitudes is

$$N_{\text{polar}} = \left\{ 2.5 + R/50 + U[0.5 + S(1.3 + 0.002R)] \right. \\ \left. + (1.3 + 0.005R) \cos \left[ \frac{\pi T}{12} - \pi(1 + B) \right] \right\} \\ \cdot [1 + 0.4(1 - V^2)] \exp(-VS) \quad (33)$$

where

$$U = \cos(2\pi \text{month} / 12) \quad (34)$$

$$S = \cos^4(D_4/2 - \pi/20) \quad (35)$$

$$B = V \{ [\sin(D_4/2) - \sin(D_4)] \cdot 2 \sin^8(D_4/2) \} \\ - (1 + V)U \sin(D_4/2) \exp[-4 \sin^2(D_4/2)] \quad (36)$$

and

$$Z = |\sin(D_4)|^{1/2} \quad (37)$$

where

$$D_4 = \sin^{-1}(D_3) \quad (38)$$

where

$$D_3 = \text{the maximum of } D_2 \text{ or } -1.0$$

and

$$D_2 = \text{the minimum of } D_1 \text{ or } 1.0$$

with

$$D_1 = \cos(L_o) \sin(D_o - 1.2043) \cos(L_1) \quad (39)$$

where

$$L_o = \text{geographic latitude in radians}$$

and

$$D_o = \text{geographic west longitude in radians}$$

The equations in the preceding sections yield  $f_o F_2$  at a specified latitude,  $L$ , and west longitude,  $W$ . In an actual application, the latitude and longitude of the receiver and transmitter are given quantities, and  $L$  and  $W$  are to be evaluated at specific control points along the great-circle propagation path.

From spherical trigonometry, one obtains the following expressions for the great-circle arc length,  $\psi$  (in radians), connecting two points defined by the (latitude, longitude) pairs  $(L_1, W_1)$  and  $(L_2, W_2)$ :

$$\psi = \text{arc cos} [\sin(L_1) \sin(L_2) + \cos(L_1) \cos(L_2) \cos(W_2 - W_1)] \quad (40)$$

If one travels a fraction,  $K$ , of the distance from point 1 to point 2, the north latitude,  $L_K$ , and west longitude,  $W_K$ , of this location are determined from

$$L_K = \text{arc sin} \left\{ \frac{\sin[\psi(1 - K)] \sin(L_1) + \sin(\psi K) \sin(L_2)}{\sin(\psi)} \right\} \quad (41)$$

and

$$W_K = \text{arc cos} \left\{ \frac{\cos(L_1) \cos(W_1) \sin[\psi(1 - K)] + \cos(L_2) \cos(W_2) \sin(\psi K)}{\cos(L_K) \sin(\psi)} \right\} \quad (42)$$

The calculated MUF is the minimum value evaluated at specific control points along the great-circle propagation path. In MINIMUF-85 these control points are located at the path midpoint for path lengths less than or equal to 4000 km, 2000 km from either terminus for path lengths greater than 4000 km, but less than or equal to 6000 km and at 1/4, 1/2, and 3/4 of the path length for paths greater than 6000 km and less than or equal to 8000 km in length. For path lengths greater than 8000 km and less than or equal to 12000 km, the control points are located at 1/6, 1/3, 1/2, 2/3, and 5/6 of the path length.

In MINIMUF-85 the geomagnetic latitude dependence accounts for critical frequency separation between ordinary and extraordinary ionospheric propagation by adding one-half the gyrofrequency to the  $f_oF2$  for latitudes greater than  $55^\circ$  N geomagnetic. The gyrofrequency for an earth-centered dipole field is given by

$$f_H = 0.3789 [1 + 3 \sin^2 (\theta)]^{1/2} - 0.5 \text{ [MHz]} \quad (43)$$

where

$\theta$  = latitude of the midpoint of the propagation path in magnetic coordinates (radians)

The geomagnetic latitude  $\theta$  is given by

$$\sin (\theta) = \sin (\phi) \sin (\phi_o) + \cos (\phi) \cos (\phi_o) \cos (\lambda - \lambda_o) \quad (44)$$

where

$\phi$  = latitude of the midpoint of the propagation path (radians)

$\lambda$  = longitude of the midpoint of the propagation path (radians)

$\phi_o$  = latitude of the North Magnetic Pole (1.3666 radians or  $78.3^\circ$  N)

$\lambda_o$  = longitude of the North Magnetic Pole (1.2043 radians or  $69^\circ$  W).

Substituting the values of  $\phi_o$  and  $\lambda_o$ , Eq. 44 becomes

$$\sin (\theta) = 0.9792 \sin (\phi) + 0.2028 \cos (\phi) \cos (\lambda - 1.2043) \quad (45)$$

## 5.0 MUF MODEL TEST CASES

The following tables of test case results are provided as an aid in determining the proper operation of the MUF model algorithms. Table 5-1 lists the results of exercising the MUF model for the range of season values. A sunspot value of 75 was used to generate these values. Transmitter latitude was 0.5712 radian, transmitter longitude was 2.0450 radians, receiver latitude was 0.5304 radian, and receiver longitude was 1.5645 radians. Seasonal values were calculated for the 15th day of January, April, July, and October.

**Table 5-1.** MUF model season results (MHz).

Time (UT)	Season (month number)			
	Winter (1)	Spring (4)	Summer (7)	Fall (10)
0000	22.28	28.08	24.22	26.85
0400	11.39	21.97	21.59	16.56
0800	11.29	17.71	16.71	14.52
1200	8.94	14.25	13.71	13.29
1600	28.10	25.68	21.32	32.63
2000	29.05	29.08	24.21	33.49

Table 5-2 lists the results of exercising the MUF model for a solar cycle. Locations of the transmitter and receiver were the same as those in Table 5-1. The date used was 15 January.

**Table 5-2.** MUF model solar cycle results (MHz).

Time (UT)	Solar cycle (sunspot number)				
	Minimum (10)	Rise and Decline (45)	Near Maximum (75)	Maximum (105)	High Maximum (150)
0000	16.23	20.01	22.28	23.96	25.66
0400	10.37	11.00	11.39	11.67	11.89
0800	11.27	11.31	11.29	11.22	11.05
1200	9.37	9.14	8.94	8.72	8.36
1600	19.96	25.06	28.10	30.34	32.62
2000	20.42	25.83	29.05	31.41	33.83

Tables 5-3 through 5-7 list the results of exercising the MUF model for various locations of the transmitter and receiver. The date used for the following tests was 15 January at 1200 UT and the sunspot number was 75.0.

**Table 5-3.** MUF model results (MHz) for transmitter at 75 degrees north latitude (1.3090 radians) and 150 degrees west longitude (2.6180 radians).

Receiver, North Latitude, deg (radians)	Receiver, West Longitude, deg (radians)					
	0 (0.0000)	60 (1.0472)	120 (2.0944)	180 (3.1416)	240 (4.1888)	300 (5.2360)
75 (1.3090)	17.40	13.81	6.63	5.98	10.55	13.60
35 (0.6109)	18.78	15.13	8.08	7.54	8.73	9.85
0 (0.0000)	18.73	14.61	11.19	10.78	10.55	11.13
-35 (-0.6109)	18.46	12.39	11.59	12.03	11.46	11.89
-75 (-1.3090)	11.04	10.54	11.66	12.40	11.50	11.61

**Table 5-4.** MUF model results (MHz) for transmitter at 35 degrees north latitude (0.6109 radian) and 150 degrees west longitude (2.6180 radians).

Receiver, North Latitude, deg (radians)	Receiver, West Longitude, deg (radians)					
	0 (0.0000)	60 (1.0472)	120 (2.0944)	180 (3.1416)	240 (4.1888)	300 (5.2360)
75 (1.3090)	9.67	9.11	7.67	8.01	9.57	9.97
35 (0.6109)	9.62	10.28	10.75	11.44	12.54	9.17
0 (0.0000)	10.31	11.78	12.68	14.18	14.04	10.67
-35 (-0.6109)	13.40	15.44	16.49	17.50	16.75	15.71
-75 (-1.3090)	18.17	17.43	17.35	17.77	18.02	18.46

**Table 5-5.** MUF model results (MHz) for transmitter at 0 degrees north latitude (0.0 radians) and 150 degrees west longitude (2.6180 radians).

Receiver, North Latitude, deg (radians)	Receiver, West Longitude, deg (radians)					
	0 (0.0000)	60 (1.0472)	120 (2.0944)	180 (3.1416)	240 (4.1888)	300 (5.2360)
75 (1.3090)	10.57	11.73	10.58	11.20	10.32	11.20
35 (0.6109)	9.96	11.91	12.53	14.15	14.64	10.79
0 (0.0000)	15.35	15.35	18.25	22.25	22.67	22.67
-35 (-0.6109)	17.39	16.47	15.04	19.26	23.38	21.42
-75 (-1.3090)	19.95	20.72	19.90	18.36	17.60	18.30

**Table 5-6.** MUF model results (MHz) for transmitter at -35 degrees north latitude (-0.6109 radian) and 150 degrees west longitude (2.6180 radians).

Receiver, North Latitude, deg (radians)	Receiver, West Longitude, deg (radians)					
	0 (0.0000)	60 (1.0472)	120 (2.0944)	180 (3.1416)	240 (4.1888)	300 (5.2360)
75 (1.3090)	11.57	11.79	11.60	12.30	11.18	11.48
35 (0.6109)	18.77	16.75	15.13	17.37	17.73	26.67
0 (0.0000)	18.21	18.37	14.51	19.90	26.58	20.62
-35 (-0.6109)	17.90	19.67	14.93	21.04	25.79	17.22
-75 (-1.3090)	18.65	16.23	15.31	15.42	16.30	18.74

**Table 5-7.** MUF model results (MHz) for transmitter at -75 degrees north latitude (-1.3090 radians) and 150 degrees west longitude (2.6180 radians).

Receiver, North Latitude, deg (radians)	Receiver, West Longitude, deg (radians)					
	0 (0.0000)	60 (1.0472)	120 (2.0944)	180 (3.1416)	240 (4.1888)	300 (5.2360)
75 (1.3090)	20.95	10.80	11.62	11.93	11.22	11.32
35 (0.6109)	25.18	26.95	14.86	18.11	17.81	18.35
0 (0.0000)	23.67	26.64	16.12	22.51	17.65	19.56
-35 (-0.6109)	22.98	23.73	16.08	16.97	16.43	18.34
-75 (-1.3090)	25.91	22.32	11.82	11.16	15.46	17.93

## 6.0 REFERENCES

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## Appendix

### **FORTRAN 77 PROGRAM AND SUBROUTINE LISTINGS FOR MUF MODEL**

The MUF calculation program and subroutines that follow are written in FORTRAN 77. The parameters passed to the subroutines and those returned are described in the comments portion of the routines.

```

program cmuf
cp*****
c   This program calculates the classical maximum usable frequency
c   (MUF) given the values specified.
c
c   Parameters input:
c     tlat:  transmitter latitude (radians), + north, - south
c     tlon:  transmitter longitude (radians), + west, - east
c     rlat:  receiver latitude (radians), + north, - south
c     rlon:  receiver longitude (radians), + west, - east
c     itime(1): month
c     itime(2): day
c     itime(3): hour (UT)
c     itime(4): minute (UT)
c     itime(5): julian day
c     itime(6): year
c     ssn:   monthly median sunspot number
c
c   Parameters returned:
c     muf:  classical MUF value in MHz
c     cpnt: geographic path information in radians
c
c   Subroutines used:  muf85
c
cz*****
  real cpnt(8)
  real tlat
  real tlon
  real rlat
  real rlon
  real ssn
  real muf
  integer itime(6)

c
c   Initialize MUF and geographic path information variables
c   prior to MUF85 subroutine call
c
  muf=0.0
  do 100 i=1,8
    cpnt(i)=0.0
100 continue

c
c   Enter MUF calculation parameters
c
  tlat=0.37385
  tlon=2.76024
  rlat=0.57125
  rlon=2.0450
  itime(1)=1
  itime(2)=1
  itime(3)=0
  itime(4)=0
  itime(5)=1
  itime(6)=89
  ssn=100.0

c
c   Calculate classical MUF using MINIMUF-85
c

```

call muf85 (tlat, tlon, rlat, rlon, itime, cpnt, ssn, muf)  
end

```

subroutine muf85 (tlat, tlon, rlat, rlon, itime, cpnt, ssn,cmuf)
cp*****
c
c      subroutine muf85
c
c      call muf85(tlat,tlon,rlat,rlon,itime,ssn,cmuf)
c
c      Updated Nov. 1985
c      An improved version of muf35 which includes sunspot,season and
c      diurnal dependence in the M-factor plus an improved FOF2 model
c      which includes a polar region modification.
c
c      This routine computes the classical maximum useable frequency
c      (cmuf) for a given propagation path.  The required input is:
c
c      tlat: transmitter latitude in radians
c      tlon: transmitter west longitude in radians
c      rlat: receiver latitude in radians
c      rlon: receiver west longitude in radians
c      itime: six element array containing the (1)month,(2)day
c            (3)hour,(4)minute,(5)julian day, and (6)year
c      ssn: sunspot number
c
c      parameters returned:
c      cpnt: geographic path information in radians
c      cmuf: classical muf in megahertz.
c
c      called by subroutine or function:  mufluf
c
c      subroutines and functions called:  fof2
c
c
c      path
c      razgc
c      sygn
c
c      method:  Uses the functional form for the foF2 and M-factor
c              described in NOSC TR-186 (MINIMUF-3: A simplified
c              HF MUF Prediction Algorithm, Rose R.B.,J.N. Martin
c              and P.H. Levine, 1978). Includes improvements as
c              described in NOSC TR-1121 (MINIMUF-85: An improved
c              HF MUF Prediction Algorithm, Sailors,D.B.,R.A.
c              Sprague and W.H. Rix).
c*****
cz
integer itime(6)
integer khop
integer kkhop
real    cpnt(8)
real    mfctk
real    cplat
real    lmt
real    ltnoon
real    daylen
real    mfctor
real    cpmlat
real    sn(6)
real    cn(6)
real    tlat
real    tlon
real    rlat
real    rlon

```

```

real    ssn
real    tday
real    qn
real    arg
real    cfssn
real    mfssn
real    mfmth
real    pthlen
real    azim
real    pl4000
real    cmuf
real    cplon
real    xk1
real    xhop
real    ak1
real    plkhop
real    smg
real    gyro
real    tsol
real    soldec
real    mfdrn1
real    cosxef
real    tsunrs
real    tsunst
real    cnxef
real    tdr1x
real    tday1
real    tnite
real    tnite1
real    ag
real    ag1
real    ag2
real    ag3
real    ag4
real    ag5
real    ag6
real    a14
real    a24
real    a34
real    a44
real    beta
real    relax
real    dayrix
real    alpha
real    trnxef
real    cpmuf
data    pi/3.14159265/,twopi/6.2831853/,halfpi/1.57079632/,
&       dtr/0.017453293/,rtd/57.2957795/,r0/6371./

```

c

```

    tday = float( itime(3) ) + float( itime(4) )/60.0

```

c

```

c mfdrn1: contains the diurnal dependence of the M-factor
c mfmth:  calculated using a 6th order fourier series which is
c         a function of month in the new M-factor
c mfssn:  a linear function of ssn in the M-factor
c cfssn:  a linear function of ssn in the critical frquency
c         expression
c

```

c

```

c M-factor seasonal dependence calculation
c
  do n = 1,6,1
    qn = float(2*n)
    arg = pi*qn*itime(1)/12.0
    sn(n) = sin(arg)
    cn(n) = cos(arg)
  end do
  mfmth = .9925+.011*sn(1)+.087*cn(1)-.043*sn(2)
&      +.003*cn(2)-.013*sn(3)-.022*cn(3)
&      +.003*sn(4)+.005*sn(5)+.018*cn(6)
c
c foF2 sunspot number dependence calculation
c
  cfssn = .814*ssn+22.23
c
c M-factor sunspot number dependence calculation
c
  mfssn = 1.3022-.00156*ssn
c
c control point calculation
c
  call path(tlat,tlon,rlat,r lon,cpnt)
  pthlen = cpnt(1)
  azim = cpnt(8)
c
c control point changes for muf85
c
  pl4000 = 1.59*cpnt(1)
  if(pl4000 .lt. 1.0)pl4000=1.0
  mfctk = 1.0/pl4000
  if(mfctk .ne. 1.0) mfctk = .5
  khop = int(cpnt(1)/.62784)+1
  kkhop = khop
  if(cpnt(1) .gt. 0.94174)kkhop = 2*khop-1
c
  cmuf=100.0
  do 800 k1 = 1,kkhop
c
c cplat, cplon = latitude and west longitude of control points
c control point method for muf85
c
  if(cpnt(1) .gt. .94174) then
    xk1 = k1
    xhop = khop
    ak1 = xk1/(2.0*xhop)
  else
    ak1 = 1.0/(2.0*pl4000)+float(k1-1)*(.9999-1.0/pl4000)
  end if
c
  plkhop = pthlen*ak1
c
  call razgc( rlat, rlon, plkhop, azim, cplat, cplon )
c
c lmt = local mean time in hours at the control point
c cpmlat = geomagnetic latitude at the control point
c
  if ( cplon .ge. 0.0 ) then

```

```

        lmt = cplon
    else
        lmt = cplon + twopi
    end if
    lmt = tday - lmt*rtd/15.0
    if ( lmt .lt. 0.0 ) then
        lmt = lmt + 24.0
    else if ( lmt .ge. 24.0 ) then
        lmt = lmt - 24.0
    end if
c
c calculation of geomagnetic latitude at the control point
c
    smg = 0.9792*sin(cplat) + 0.2028*cos(cplat)*cos(cplon - 1.2043)
    smg = amax1( amin1( smg, 1.0 ), -1.0 )
    cpmlat = asin( smg )
c
c geomagnetic latitude foF2 dependence calculation
c gyro frequency for latitude > 55 degrees
c
    if ( abs( cpmlat ) .lt. 0.95993 ) then
        gyro = 0.0
    else
        gyro = 0.3789*sqrt( 1.0 + 3.0*smg*smg ) - 0.5
    end if
c
c calculation of local noon time
c tsol = 2*pi*date/365.25
c soldec = -solar declination
c ltnoon = time of local noon
c
    tsol = 0.0172*(10.0 + float(itime(1)-1)*30.4 + itime(2))
    soldec = 0.409*cos(soldec)
c
    ltnoon = 3.82*cplon+12.0+0.13*(sin(soldec)+1.2*sin(2.0*soldec))
    if ( ltnoon .gt. 24.0 ) then
        ltnoon = ltnoon - 24.0
    else if ( ltnoon .le. 0.0 ) then
        ltnoon = ltnoon + 24.0
    end if
c
c M-factor range dependence calculation
c mfactor = M-factor = muf/foF2
c
    mfactor = amin1( 2.5*pthlen*mfctk, halfpi )
    mfactor = sin( mfactor )
    mfactor = 1.0 + 2.5*mfactor*sqrt( mfactor )
c
c daylen = length of daylight
c tsunrs = time of sunrise
c tsunst = time of sunset
c tdrlx = daytime relaxation time
c night time relaxation time = 2 hours
c
    if ( cos( cplat + soldec ) .gt. -0.26 ) go to 600
c
c no daylight on path at any time during the day
c

```

```

        cosxef = 0.0
        daylen = 0.0
        mfdrn1 = 1.0
        go to 700
600    continue
c
c    delta T = length of daylight calculation T(sunset)-T(dawn)
c
c        daylen = (-0.26+sin(soldec)*sin(cplat))/(cos(soldec)*cos(cplat)
&          +1.0e-3)
        daylen = amax1( amin1 ( daylen, 1.0 ), -1.0 )
        daylen = 12.0 - asin( daylen )*7.6394
c
c    T(dawn) calculation
c
c        tsunrs = ltnoon - daylen/2.0
        if ( tsunrs .lt. 0.0 ) tsunrs = tsunrs + 24.0
c
c    t(sunset) calculation
c
c        tsunst = ltnoon + daylen/2.0
        if ( tsunst .gt. 24.0 ) tsunst = tsunst - 24.0
c
c    calculation of the cosine noon time solar zenith angle
c
c        cnxef = abs( cos( cplat + soldec ) )
c
c    calculation of the day time relaxation time
c
c        tdr1x = 9.7*( amax1( cnxef, .1 ) )**9.6
        tdr1x = amax1( tdr1x, 0.1 )
        tday1 = tday
        if (( tsunst .lt. tsunrs .and. (tday-tsunst)*(tsunrs-tday) .gt.
&          0.0 ) .or. ( tsunst .ge. tsunrs .and. (tday-tsunrs)*
&          (tsunst-tday) .le. 0.0 ))then
c
c    night time at control point
c    M-factor night time dependence calculation
c    6th order fourier series night time factor for M-factor,
c    based on hours after sunset, tnite
c
c        if ( tsunst .gt. tday ) tday1 = tday1 + 24.0
        tnite = tday1 - tsunst
        tnite1 = 14.0*tnite/(24.0-daylen)
        ag = pi *(tnite1+1.0)/15.0
        ag1 = 2.0*ag
        ag2 = 4.0*ag
        ag3 = 6.0*ag
        ag4 = 8.0*ag
        ag5 = 10.0*ag
        ag6 = 12.0*ag
        a14 = 1.0195 -.06*sin(ag1)-.037*cos(ag1)+.018*sin(ag2)
        a24 = -.003*cos(ag2)+.025*sin(ag3)+.018*cos(ag3)
        a34 = .007*sin(ag4)-.005*cos(ag4)+.006*sin(ag5)
        a44 = .017*cos(ag5)-.009*sin(ag6)-.004*cos(ag6)
        mfdrn1 = a14+a24+a34+a44
c
c        beta = pi*tdr1x/daylen

```

```

c
c (T(sunset)-T)/night relaxation time
c
c      relax = (tsunst-tdayl)/2.0
c      relax = aminl( amaxl( relax, -75.0 ), +75.0 )
c
c - delta T/day relaxation time
c
c      dayrlx = -daylen/tdrlx
c      dayrlx = aminl( amaxl( dayrlx, -75.0 ), +75.0 )
c
c calculation of sunset cosine effective solar zenith angle
c
c      cosxef = cnxef*(beta*(exp(dayrlx)+1.0))*exp(relax)/
c      &      (1.0+beta*beta)
c      else
c
c day time at the control point
c
c      if ( tsunrs .gt. tdayl ) tdayl = tdayl + 24.0
c
c M-factor day time dependence calculation
c
c      mfdrn1 = 1.11-.01 * lmt
c
c      alpha = pi*( tdayl - tsunrs )/daylen
c      beta = pi*tdrlx/daylen
c
c (T(dawn)-T)/day relaxation time
c
c      relax = ( tsunrs - tdayl )/tdrlx
c      relax = aminl( amaxl( relax, -87.0 ), +87.0 )
c      dayrlx = -daylen/tdrlx
c      dayrlx = aminl( amaxl( dayrlx, -87.0 ), +87.0 )
c
c calculation of day cosine effective solar zenith angle
c
c      cosxef = cnxef*(sin(alpha)+beta*(exp(relax)-cos(alpha)))/
c      &      (1.0+beta*beta)
c
c sunrise transition
c
c      trnxef = cnxef*( beta*( exp( dayrlx ) + 1.0 ) )
c      &      *exp( ( daylen - 24.0 )/2.0 )/( 1.0 + beta*beta )
c      cosxef = amaxl( cosxef, trnxef )
c
c      end if
c
c cpmuf = muf at the control point
c calculation of foF2
c
c 700 cpmuf = sqrt(6.0 + cfssn * sqrt(cosxef)) + gyro
c
c MUF high latitude season dependence calculation
c
c      cpmuf = cpmuf*( 1.0 - 0.1*exp( ( daylen - 24.0 )/3.0 ) )
c
c MUF transequatorial path dependence calculation

```

```

c
      cpmuf = cpmuf*( 1.0 + ( 1.0 - sygn( tlat )*sygn( rlat ) )*0.1 )
c
c MUF high latitude path dependence calculation
c
      cpmuf = cpmuf*( 1.0 - 0.1*( 1.0 + sygn( abs( sin( cplat ) )
&      - cos( cplat ) ) ) )
c
c fof2 function corrects for polar region foF2
c result is cpmuf if control point not in polar region
c
      if ( abs( cpmlat ) .ge. 0.95993 ) then
        cpmuf = mfctor*fof2( cpmuf, lmt, itime, cplat, cplon, cpmlat, ssn )
      else
        cpmuf = cpmuf*mfctor
      end if
c
c MUF sunspot, season and diurnal dependence
c
      cpmuf = cpmuf*mfssn*mfsmth*mfdrnl
      cmuf = amin1( cmuf, cpmuf )
800 continue
c
c MUF minimum value 2MHz, maximum value 50 MHz
c
      cmuf = amin1( amax1( cmuf, 2.0 ), 50.0 )
c
      return
      end

```

```

subroutine path (tlat, tlon, rlat, rlon, cpnt)
cp*****
c      subroutine path
c
c      call path(tlat,tlon,rlat,rлон,cpnt)
c
c      This routine computes the range, azimuth and control point
c      coordinates for a given propagation path. The method assumes
c      a spherical earth with a radius of 6371 km.
c
c      Parameters input:
c          tlat: transmitter latitude in radians
c          tlon: transmitter west (positive) longitude in radians
c          rlat: receiver latitude in radians
c          rлон: receiver west (positive) longitude in radians
c
c      This subroutine returns geographic path information in an 8 word
c      real array (cpnt).
c
c      Parameters returned:
c          cpnt(1): distance between the receiver and transmitter in
c                   radians
c          cpnt(2): latitude of midpoint in radians
c          cpnt(3): west longitude in radians
c          cpnt(4): latitude of point 1000 km from the receiver in radians
c          cpnt(5): west longitude of point 1000 km from receiver in radians
c          cpnt(6): latitude of point 1000 km from transmitter in radians
c          cpnt(7): west longitude of point 1000 km from transmitter
c                   in radians
c          cpnt(8): azimuth from receiver to transmitter in radians
c
c      * cpnt(4) through cpnt(7) will not be computed for paths less
c        than 1000 km (0.15696 radians) in length.
c
c      Subroutines and functions used:  gcraz
c                                       razgc
c
c      Common blocks:  none
c*****
cz
c
c      real cpnt(8)
c      real rlat
c      real rлон
c      real tlat
c      real tлон
c      real pl
c
c      Get range and azimuth between points 1 and 2
c
c      call gcraz( rlat, rлон, tlat, tлон, cpnt(1), cpnt(8) )
c
c      Get mid-point coordinates
c
c      pl = cpnt(1)/2.0
c      call razgc( rlat, rлон, pl, cpnt(8), cpnt(2), cpnt(3) )
c
c      Is path length >= 1000 km?

```

```
c
if ( cpnt(1) .ge. 0.156961231 ) then
c
c   Get coordinates of 1000 km points
c
      pl = 0.156961231
      call razgc( rlat, rlon, pl, cpnt(8), cpnt(4), cpnt(5) )
      pl = cpnt(1) - 0.156961231
      call razgc( rlat, rlon, pl, cpnt(8), cpnt(6), cpnt(7) )
      return
else
      return
end if
end
```

```

subroutine razgc( lat1, lon1, range, azim, lat2, lon2 )
cp*****
c
c      subroutine razgc
c
c          call razgc(lat1,lon1,range,azim,lat2,lon2)
c
c          This routine computes the latitude and west(positive) longi-
c          tude (lat2, lon2) of a point a specified range from a given
c          point on the earth's surface. Also required for input
c          is the azimuth (azim) to the new point in radians. This
c          method assumes a spherical earth (6371.0 km) and recognizes
c          the degenerate cases of the given point being at the north
c          or south pole. For the degenerate cases, azim should be 0
c          or pi and lon2 is undefined. However, azim is not checked,
c          and lon2 is arbitrarily set equal to lon1. This routine
c          recognizes the degenerate case when range is set to zero.
c          All coordinates are in radians.
c
c          Parameters input: lat1, lon1, range, azim
c
c          Parameters returned: lat2, lon2
c
c          Subroutines and functions used: none
c
c          Common blocks: none
c
c          Method: Uses law of cosines for sides on spherical triangle
c                  defined by (lat1,lon1), north pole and point defined
c                  by azim and range.
cZ*****
c
c      real lat1
c      real lon1
c      real lat2
c      real lon2
c      real sl
c      real cl
c      real cr
c      real ca
c      real cg
c      real a
c      real g
c      real sa
c
c      data pi/3.141592654/,twopi/6.283185308/,halfpi/1.570796327/
c      &      rtd/57.29577951/,dtr/0.017453293/
c
c      Test for degenerate cases
c      1)Given point is north or south pole:
c
c      if ( abs( lat1 - halfpi ) .le. 1.0e-5 ) then
c
c          The given point is the north pole
c
c              lat2 = halfpi - range
c              lon2 = lon1
c              return
c      else

```

```

        if ( abs( lat1 + halfpi ) .le. 1.0e-5 ) then
c
c   The given point is the south pole
c
        lat2 = range - halfpi
        lon2 = lon1
        return
    end if
end if

c
c   2)Coincident points:
c
    if ( range .eq. 0.0 ) then
c
c   Point 2 coincident with point 1
c
        lat2 = lat1
        lon2 = lon1
        return
    end if

c
c   General case
c
    s1 = sin( lat1 )
    c1 = cos( lat1 )
    cr = cos( range )
    ca = s1*cr + c1*sin( range )*cos( azim )
    ca = amin1( amax1( ca, -1.0 ), +1.0 )
    a = acos( ca )

c
c   Test if destination ends up on the poles
c
    if( abs(a).le.1.0e-5 ) then
        lat2 = halfpi
        lon2 = lon1
        return
    else
        if( abs(a-pi) .le. 1.0e-5 ) then
            lat2 = -halfpi
            lon2 = lon1
            return
        end if
    end if

c
c   Get destination coordinates
c
    cg = ( cr - s1*ca )/( c1*sin( a ) )
    cg = amin1( amax1( cg, -1.0 ), +1.0 )
    g = acos( cg )
    lat2 = halfpi - a
    sa = sin( azim )
    if ( sa .ge. 0.0 ) lon2 = amod( lon1 - g, twopi )
    if ( sa .lt. 0.0 ) lon2 = amod( lon1 + g, twopi )
    return
end

```

```

subroutine gcraz( lat1, lon1, lat2, lon2, range, azim )
cp*****
c
c   subroutine gcraz
c
c       call gcraz (lat1,lon1,lat2,lon2,range,azim)
c
c       This routine computes the great circle range and azimuth
c       between two points on the earth's surface. lat1 and lon1
c       are the coordinates of point 1 , lat2 and lon2 are the
c       coordinates of point 2. Both longitudes are west longitudes.
c       West longitudes are positive throughout the Muf85 algorithm.
c       Latitudes are positive if north and negative if south.
c       The output is range, the distance between the two points
c       in radians and azim, the azimuth from one point to the other
c       in radians. This method assumes a spherical earth and
c       recognizes the degenerate cases of point 1 at the north
c       or south pole or points 1 and 2 coincident. All coordinates
c       are in radians.
c
c       Parameters input: lat1, lon1, lat2, lon2
c
c       Parameters returned: range, azim
c
c       Subroutines and functions used: none
c
c       Common blocks: none
c
c       Method: Uses law of cosines for sides on spherical triangle
c               defined by (lat1,lon1),(lat2,lon2) and north pole.
c
cz*****
c
c       real lat1
c       real lon1
c       real lat2
c       real lon2
c       real range
c       real azim
c       real s1
c       real c1
c       real s2
c       real c2
c       real cr
c       real ca
c
c       data pi/3.141592654/,twopi/6.283185308/,halfpi/1.570796327/,
&       dtr/0.017453293/,rtd/57.29577951/
c
c       Test for degenerate cases
c       1)Point 1 at north or south pole:
c
c       if ( abs( lat1 - halfpi ) .le. 1.0e-5 ) then
c
c       Point 1 is at the north pole
c
c       range = halfpi - lat2
c       azim = pi
c       return

```

```

else
  if ( abs( lat1 + halfpi ) .le. 1.0e-5 ) then
c
c
c
    Point 1 is at the south pole
c
c
c
      range = halfpi + lat2
      azim = 0.0
      return
    end if
  end if

c
c
c
    2)Coincident points:
c
c
c
    if ( abs( lat1 - lat2 ) .le. 1.0e-5 .and.
&      abs( lon1 - lon2 ) .le. 1.0e-5 ) then
c
c
c
      Points 1 and 2 are coincident
c
c
c
        range = 1.0e-8
        azim = 0.0
        return
      end if

c
c
c
      General case
c
c
c
      s1 = sin( lat1 )
      c1 = cos( lat1 )
      s2 = sin( lat2 )
      c2 = cos( lat2 )
      cr = s1*s2 + c1*c2*cos( lon1 - lon2 )
      cr = amin1( amax1( cr, -1.0 ), +1.0 )
      range = acos( cr )
      ca = ( s2 - s1*cr )/( c1*sin( range ) )
      ca = amin1( amax1( ca, -1.0 ), +1.0 )
      azim = acos( ca )
      if ( sin( lon1 - lon2 ) .lt. 0.0 ) azim = twopi - azim
      return
    end

```

```

function fof2( ff2, lmt, itime, lat, lon, mlat, ssn )
cp*****
c
c   function fof2
c
c   x = fof2( ff2, lmt, itime, lat, lon, mlat, ssn )
c
c   This function corrects the f2-layer critical frequency
c   computed by muf85 for polar latitudes using the Chiu model.
c
c   Parameters input:
c   ff2:  critical frequency from muf35 in mhz
c   lmt:  local mean time at lat,lon in hours
c   itime: integer array containing month, day,
c         hour, minute, julian day, and year
c   lat:  geographic latitude in radians
c   lon:  geographic west longitude in radians
c   mlat: magnetic latitude in radians
c   ssn:  sunspot number
c
c   Parameters returned:
c   fof2  the f2-layer critical frequency in mhz - real
c
c   Subroutines and functions called:  none
c
c   Common blocks referenced:          none
c
c   Method:  uses the high latitude electron density model
c            developed by B.K. Ching and Y.T. Chiu (Ching,B.K.,
c            Y.T. Chiu, J. Atmos. Terr. Phys., 35, 1615,(1973))
c            and later improved by Chiu (Chiu Y.T., J. Atmos.
c            Terr. Phys., 37, 1563, (1975)). The peak electron
c            density is then converted to foF2 and used to cor-
c            rect the value input from muf85. A folding function is
c            used in transition latitudes to provide continuity
c            of the transition.
c
cZ*****
integer itime(6)
real lat
real lmt
real lon
real mlat
real mlon
real phi
real tmo
real cmlat
real x
real ssn
real ff
real gg
real t
real v
real y
real ys
real z
real w
real plr
real u

```

```

real za
real am
real b
real ys4
c
data pi /3.1415926/
c
phi = lmt*pi/12.0
tmo = itime(1) + ( itime(2) + itime(3)/24.0 + itime(4)/1440.0 )/30.0
& - 0.5
cmlat = cos( mlat )
mlon = cos( lat )*sin( lon - 1.2043 )/cmlat
mlon = amax1( amin1( mlon, 1.0 ), -1.0 )
mlon = asin( mlon )
x = ( 2.2 + ( 0.2 + ssn/1000.0 )*sin( mlat ) )*cmlat
ff = exp( -( x**6 ) )
gg = 1.0 - ff
t = pi*tmo/12.0
v = sin( t )
if ( mlat .ge. 0.0 ) then
w = exp( -1.2*( cos( mlat - 0.41015*cos( phi ) ) - cmlat ) )
plr = ( 2.0 + 0.012*ssn )*w*( 1.0 + 0.3*v )
else
u = cos( t+t )
y = sin( mlon/2.0 )
ys = cos( mlon/2.0 - pi/20.0 )
z = sin( mlon )
za = sqrt( abs( z ) )
am = 1.0 + v
b = v*( ( y - z )/2.0 - y**8 ) - am*u*( z/za )*exp( -4.0*y*y )
ys4 = ys**4
plr = ( 2.5 + ssn/50.0 + u*( 0.5 + ( 1.3 + 0.002*ssn )*ys4 )
& + ( 1.3 + 0.005*ssn )*cos( phi - pi*( 1.0 + b ) ) )
& * ( 1.0 + 0.4*( 1.0 - v*v ) )*exp( -v*ys4 )
end if
c
fof2 = gg*ff2*ff2/8.12 + 0.66*ff*plr
if (fof2 .gt. 0.0) then
fof2 = 2.85*sqrt(fof2)
else
fof2 = ff2
end if
return
end

```

```

      function sygn( y )
cp*****
c
c   real function sygn
c
c   x= sygn( y )
c
c   This function returns the value 0 if y=0, -1 if y is less than 0
c   or 1 if y is greater than 0.
c
c   Subroutines and functions used: none
c
c   Common blocks: none
c
c   Parameters input: y
c
cz*****
c
c   real y
c
c   if(y)100,200,300
100  sygn=-1.0
      go to 1000
200  sygn=0.0
      go to 1000
300  sygn=1.0
1000 return
      end

```