Special Technical Report 15

COMPARISON OF C-2 IONOSPHERIC SOUNDER DATA WITH FREQUENCY PREDICTIONS FOR SHORT-RANGE COMMUNICATION WITH MAN-PACK TRANSCEIVERS IN THAILAND

By: CLIFFORD L. RUFENACH GEORGE H. HAGN

Prepared for:

U.S. ARMY ELECTRONICS COMMAND
FORT MONMOUTH, NEW JERSEY 07703

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SRI Project 4240

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ABSTRACT

This report briefly discusses several ionospheric parameter prediction techniques and compares values of f_oF2, f_{min}, and F-layer height (h_L) predicted using several of these techniques with observed data taken by the C-2 ionospheric sounder at Bangkok, Thailand from its initial operation in September 1963 through March 1965. The sounder data have been used to calculate a correction function for f_oF2, and corrected predictions are given for April 1965 through December 1966. When the correction functions are used it should be possible to predict the monthly median value of f_oF2 and f_{min} to within about 1.5 MHz for all times of day; and the observed values on any given day in the month will be, with probability 0.5, within 2 MHz of the corrected median predictions for all times of day. The magnitudes of these anticipated daily variations from the predicted monthly median values depend upon the local time, and are observed to be smallest near sunrise.

The effects of anomalous propagation on the predictions are inferred from the C-2 data, and indicate that some account must be made for sporadic E but that spread F and blackout are relatively unimportant during the period of small sunspot numbers. The effect of the lower frequency limit of an HF man-pack radio on communication failure is considered for near-vertical-incidence skywave propagation. The lowest usable frequency calculations for a 15-watt HF man-pack transceiver AN/PRC-74 (Hughes HC-162) employing horizontal dipole antennas agree very closely with f_{min} values calculated from observations with the C-2 sounder. Hence the useful frequency spectrum for this particular HF man-pack transceiver can essentially be approximated by the parameters f_oF2 and f_{min} scaled from the data from the modified C-2 sounder at Bangkok.

Communication failure in the early morning hours during sunspot minimum is shown to be critically dependent on the lower tuning limit

of the set. The parameter f_oF2 is extrapolated to the next sunspot maximum period to help estimate the design range for man-pack radios. A tuning capability of 2 to 18 MHz is recommended for sets designed to operate over distances out to 1000 km during all phases of sunspot cycle.

FOREWORD

The study of C-2 data from Bangkok was begun late in 1963 by one of the authors, George Hagn. At that time, it was decided to use the C-2 data to determine the value of the frequency predictions then available for Bangkok, and to determine how these predictions could be improved with knowledge of local ionospheric conditions provided by the C-2. It was learned that the existing predictions were reasonable, but that a significant improvement could be made by using C-2 data to set the scale on the midday dip in f_oF2. Predictions were made for Bangkok for 1966. These predictions were based on a correction function, derived from the Bangkok C-2 data, but it was observed that an uncertainty existed in the data from the C-2 which was somewhat in excess of that to be expected from a "typical" C-2. Consequently, the "corrected" predictions (presented in this report) were not issued; however, they were compared to subsequent C-2 observations by one of the authors, Rufenach, in Special Technical Report 28.

It should be emphasized that, while equipments and prediction techniques can be improved, the methods described in this report for determining the accuracy of predictions, for using local knowledge of the ionosphere to improve predictions, etc., remain valid.

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TABLES

DEFINITION OF TERMS

f_oF2	The ordinary wave critical frequency for the F2 ionospheric layer
f_{min}	The frequency below which no echoes are observed on vertical-incidence ionograms
h_L	Minimum virtual height of the F layer
f_oF1	The ordinary wave critical frequency for the F1 ionospheric layer
f_oE	The ordinary wave critical frequency for the E ionospheric layer
f_oE_s	The ordinary wave critical frequency for the sporadic E (E_s) ionospheric layer
MUF	Monthly median predicted value of the maximum usable frequency
LUF	Monthly median predicted value of the lowest usable frequency (by some quality criterion)
MOF	Maximum observed frequency on ionospheric sounder records
LOF	Lowest observed frequency on ionospheric sounder records--at vertical incidence, LOF is f_{min}.

I INTRODUCTION

Under the direction of the Advanced Research Projects Agency and the United States Army Electronics Command, Stanford Research Institute (SRI) has established a Communications Laboratory in Bangkok, Thailand. The purpose of this effort is to support the Military Research and Development Center (MRDC), a joint Thailand-United States agency, in the area of communications and electronics. One of the chief modes of communication in Southeast Asia is via HF skywave paths.[1-8]* Therefore, predictions of ionospheric behavior are of great importance both in the operation of existing HF systems in Thailand and in the design of new ones for use there. HF man-pack radio tests in Thailand[1] (1963) indicated that "radio propagation predictions, such as those developed and distributed by the United States Army Radio Propagation Agency (RPA), can be altered to apply to man-pack radio sets and can be used to predict their average performance." Nevertheless, it was anticipated that the predictions could be appreciably improved if vertical-incidence sounder data were available.

To satisfy this recognized requirement for ionosonde data, RPA provided a C-2 vertical-incidence sounder† and a two-man crew for operation, data scaling, and maintenance. This report describes the use of the sounder data to increase the accuracy of monthly median prediction values of several significant ionospheric parameters and to estimate the probable daily variations from the monthly medians during sunspot minimum.

For short ionospheric paths, the usable frequency range is usually governed on the upper end by the ordinary-wave critical frequency of the

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*References are listed at the end of the report.

†This unit was put into operation at Bangkok, Thailand, in September 1963. The Model C-2 sounder was modified on 13 March 1965 by the Central Radio Propagation Laboratory, National Bureau of Standards, to Model C-2/C-3/C-4.

F layer. The maximum usable frequency (MUF) is taken (by definition) to be equal to the predicted monthly median f_oF2.* The geomagnetic equatorial region must, however, be given special consideration[6,9-12] since low-latitude effects, primarily local inhomogeneities [such as sporadic E (E_s)], and horizontal gradients in ionospheric electron density may alter the MUF. This report considers some effects of E_s,[13] but the discussion of horizontal gradients (except for some inferences from Transit IV-A beacon satellite data)[14] is deferred until oblique-incidence sounder data are available.

The lowest usable frequency (LUF) is the predicted lowest frequency on which a given system may operate with the required reliability (where the reliability is defined as the percentage of the days within a given month that the hourly median signal-to-noise ratio equals or exceeds the required value for the service being considered). This report assumes a reliability such that a 10-dB signal-to-noise ratio is equaled or exceeded 50 percent of the time.

The LUF is typically determined by signal-strength and noise considerations (path loss, transmitter power, antenna efficiency, etc.) and therefore can be determined only for a completely specified system, whereas the MUF depends only on ionospheric conditions and (except for rather high-powered systems) is independent of all the system parameters (bandwidth, transmitter power, etc.). Thus, the same plot of MUF as a function of local time will apply to many different systems, but a LUF plot applies only to the specific system for which the calculation is made.

Excessive deviative absorption (high path loss) for systems operating near the critical frequency of the daytime ionospheric layers (f_oE and

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*In theory, the MUF could be defined as equal to the extra-ordinary-wave critical frequency f_xF2, which is higher than f_oF2 by about 500 kHz (in Thailand). However, the f_xF2 prediction might not hold for antennas of arbitrary alignment relative to the earth's magnetic field thus the more conservative figure is used here for greater reliability in practice.

f_oF1) below the F2 layer may cause the received signal to fall below the minimum required level for some ionospheric paths (short paths, less than about 50 km). Therefore, there may be daytime useless zones in the spectrum between LUF and MUF that would not exist on longer paths (see Fig. 1). These possibly useless zones are the topic of another study.

The purposes of this report are as follows:

(1) Compare long-term predictions of MUF and LUF (for the C-2 sounder and man-pack radio sets used on short paths) derived from several of the available techniques, with measured values of f_oF2 and f_{min} as observed on the C-2 vertical-incidence ionosonde at Bangkok, Thailand.

(2) Using measured monthly medians of f_oF2 and f_{min} and predicted monthly medians of MUF and LUF for the C-2 system from September 1963 through April 1964, to derive an error function to correct and improve the predictions for 1965 and 1966.*

(3) Show correlation between measured C-2 sounder data and the predicted usable frequency spectrum for HF man-pack transceivers.

(4) Compare measured and predicted layer-height values (F layer) used in calculating MUF on longer paths than those considered in (1) above.

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*The measurements cover the period from 1 September 1963 through 31 March 1965, while the predictions based on numerical mapping techniques are extended through December 1965. The slightly less accurate (but longer-term) SRI/RPA predictions are extended through 1966.

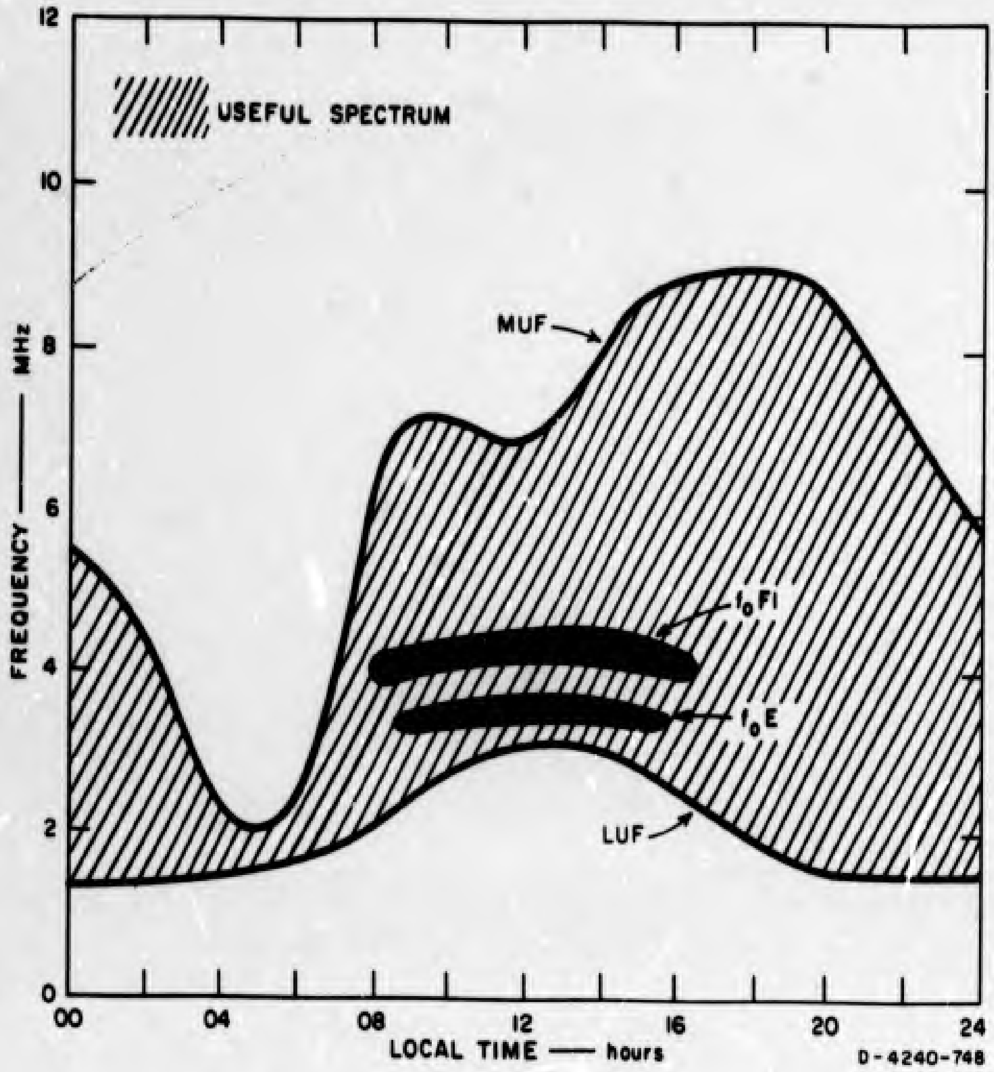

FIG. 1 EXAMPLE OF USEFUL FREQUENCY SPECTRUM FOR A NEAR-VERTICAL-INCIDENCE IONOSPHERIC PATH

(5) Evaluate the effect of the ionosphere on the lower-frequency limit of the AN/PRC-74 (Hughes HC-162) or the Sylvania AN/TRC-88 man-pack sets employing horizontal dipoles.

(6) Consider the design frequency range for HF man-packs radios for use on short ionospheric paths in the tropics.

(7) Consider the effects of anomalous propagation (spread F, sporadic E, blackout) on the predictions.

II IONOSPHERIC PREDICTION METHODS

A. Maximum Usable Frequency (MUF)

Shortly before World War II, the British developed a frequency-prediction technique for long paths, based on the assumption that the electron-density profile near the maximum of the F layer was, to a good approximation, parabolic.[15] Synoptic maps, based on observations throughout the world, were used to obtain predicted vertical-incidence critical-frequency information. The Radio and Space Research Station, Slough, England presently issues predictions in the form of a series of world maps (on GMT) for different levels of solar activity. The choise of which map(s) to use is left to the user.

For many years, the Central Radio Propagation Laboratory (CRPL) of the National Bureau of Standards (NBS)* has been providing predicted data on $f_x F2$ and MUF for many locations, based upon the work of Newbern Smith[16], M. Lindeman Phillips, S. M. Ostrow, T. N. Gautier, Margo Leftin, and others.[17] These predictions were provided as the familiar CRPL Series D predictions[18] until 1963, when they were superseded by more mathematically sophisticated predictions (hereinafter called NBS predictions) suitable for electronic computer calculations using numerical-mapping techniques.[19] Workers at CRPL have also developed electronic computer programs to predict performance of very short sky-wave circuits in temperate and tropical latitudes.[20,22] RPA has developed prediction techniques[23,24] for its own use, and Karl Rawer[25,26] has expressed still other ideas concerning how the prediction might best be made (SPIM). Russian workers use another technique,[27] referred to by some American workers as "IZMIRAN," which is an acronym for "Institut Zemnogo Magnetizma, Ionosfery i Rasprostraneniia Radiovoln Trudy."

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*The designation "CRPL" has since been changed to Institute for Telecommunication Sciences and Aeronomy (ITSA) of the Environmental Science Services Administration. Since this report deals with predictions issued under the old designation, this designation will be retained.

The National Physical Laboratory (NPL), New Delhi, India has developed prediction contour maps[28] for the E zone (50°E to 170°E longitude). These predictions rely on data from approximately twenty ionosondes and are issued about six months in advance. The Division des Prévisions Ionosphériques du Centre National d'Études des Télécommunications, Château de la Martinière, Saclay (Seine-et-Oise), France issues a Bulletin des Prévisions Ionosphériques, and the Radio Research Laboratories, Ministry of Posts and Telecommunications, Tokyo, Japan[29] issues world maps of observed F2 critical frequencies and maximum usable frequencies for 4000-km paths which (when properly interpreted) are useful for frequency prediction work.

Stanford Research Institute has developed an electronic computer prediction program for RPA[30,31] (SRI/RPA) that is very useful for long-term system performance prediction. The computer program is based on data taken during several sunspot cycles and need not be modified by current ionospheric data--only the sunspot number, the place, and the time of interest need be specified to obtain a prediction. However, such predictions tend to be less accurate for periods of sunspot minimum and maximum than for times in between when it is easier to predict sunspot number (see Appendix E). Recent ionosonde data are especially useful in improving predictions during these periods of maximum change of sunspot number with time.

B. Lowest Usable Frequency (LUF)

Many techniques have been developed for predicting the LUF. The British became interest in tropical HF communication on short paths approximately ten years ago and developed a method of LUF calculation* that can be used in equatorial regions.[5]

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*The equations used, however, are for quasi-longitudinal (QL) propagation, using equations appropriate to propagation in the ionospheric D region along the earth's magnetic field. A correction term is added to amend the calculation for situations where the propagation is more nearly transverse to the magnetic field. Nor do the equations apply for very short paths. Equations appropriate to the transverse case (short path near the magnetic equator) have been derived by one of the authors,[12] and a preliminary check[37] indicates that these new equations predict the ionospheric path loss more accurately than the QL-amended method of Ref. 5.

RPA has developed a method of computing LUF where the predicted values of required and received signal levels are plotted as functions of frequency and their intersection is, by definition, the LUF.[32] RPA has for many years also provided data for different geographic areas of interest, including a set for short[33] and intermediate[34] distances for Southeast Asia. CRPL[20] has also developed electronic computer programs that make the same calculations. The Germans have developed a computational technique that puts greater emphasis on simple reception conditions,[25,26] and the Canadians have developed a technique for high latitudes (QL case).[35] Also, as mentioned earlier, Stanford Research Institute has developed an electronic computer program for RPA[30,31] (SRI/RPA) that computes LUF as well as MUF. This program has been used to help calculate the probability of successful communication[36]--a more flexible approach to LUF determination.*

C. <u>Layer Height (h_L)</u>

Layer-height values are predicted by both the NBS and the SRI/RPA computer programs.† The value predicted is the virtual height corresponding to the minimum value for a given layer (usually the F layer) as indicated in Fig. 2, where h' is the virtual height and f_v is the vertical-incidence frequency of transmission. This value has the advantage of being easily scaled from ionograms but is not related easily to the theoretical propagation formulas.

The layer height, h_L, does give a reasonable estimate of true layer height, however, since h_L is that virtual height for which the difference

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*To calculate LUF, one needs to estimate the noise voltage induced in the receiving antenna. Measurements of the atmosphere noise level in Thailand are being carried out at Laem Chabang under another phase of the SRI SEACORE work, to provide this missing information.

†The prediction techniques worked out by RPA and programmed for computer calculation by SRI rely heavily on empirical formulas that use this parameter; and so long as one knows the appropriate empirical constants in the formulas, the technique[23,24,30,31] works reasonably well for predicting MUF.[38]

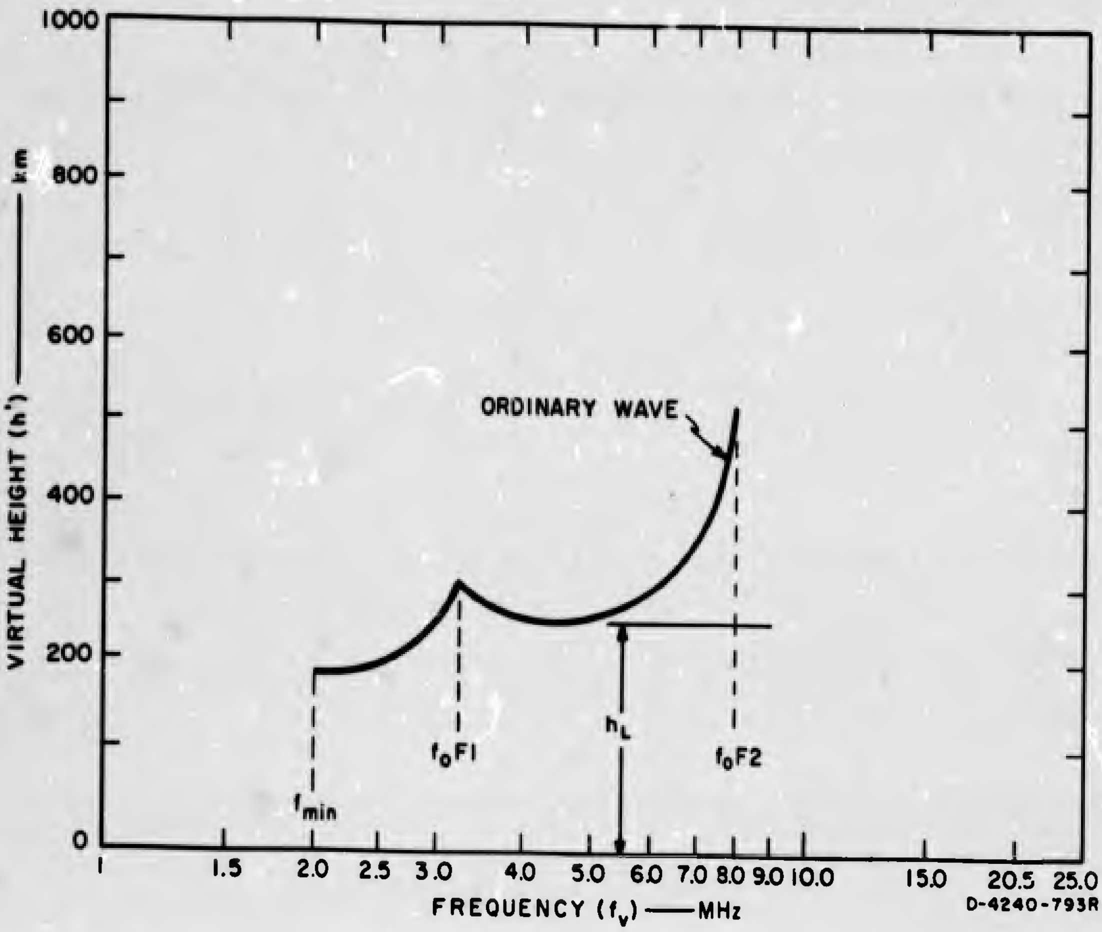

FIG. 2 EXAMPLE OF IONOSPHERIC VIRTUAL HEIGHT AS A FUNCTION OF FREQUENCY

between true and virtual height is a minimum. The actual difference in any given case depends upon the relationship between electron density and height existing when the ionogram record was made; no simply calculated relationship exists.

III COMPARISON OF PREDICTED AND OBSERVED DATA

A. Source of Bangkok Observed Data

The data are scaled from C-2 ionograms by the RPA field crew and recorded on CRPL Form 7-E. These data are then published in a monthly bulletin as "Ionospheric Data: Bangkok, Thailand."[39] The observed monthly median values of f_oF2 and f_{min} are taken from this bulletin.

B. Comparison of Predicted and Observed f_oF2

This section discusses three sets of f_oF2 predictions: CRPL, SRI/RPA, and NPL. The CRPL ppredictions are based on recent, world-wide ionosonde data, whereas the SRI/RPA predictions are based on the data in NBS Technical Note 2;[40] NPL relies on data from approximately 20 ionosondes in the E zone. The first two methods use the Zurich running-mean sunspot number to estimate solar ionizing flux, whereas the third relies upon a sunspot number derived from the Indian Solar Flare Patrol reports.*

One set of predictions is part of the input data for an HF prediction program composed by SRI (SRI/RPA) for RPA.[30,31] The GMT, the month and the Zurich running-mean sunspot number must be specified in order to use the program for a given set of geographic coordinates. Another set of predictions is obtained from the NBS using their numerical-mapping approach.[19,41] The third set of predictions uses data only from the E zone to obtain contour plots.[28] Shown in Fig. 3 are typical comparisons of the three sets of predicted monthly-median f_oF2 with the observed monthly median f_oF2 and of the associated prediction error function. (The comparison data from September 1963 through March 1965

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*It might be noted here that flares are, on the average, most easily detected by ionospheric methods near the geographic equator; hence the Indian sunspot numbers could be a better indicator of ionizing flux during sunspot minimum periods than the Zurich values. The Ottawa 10 cm flux observations by the Defense Research Telecommunications Establishment of Canada provide yet another measure of ionizing flux useful in ionospheric prediction work.

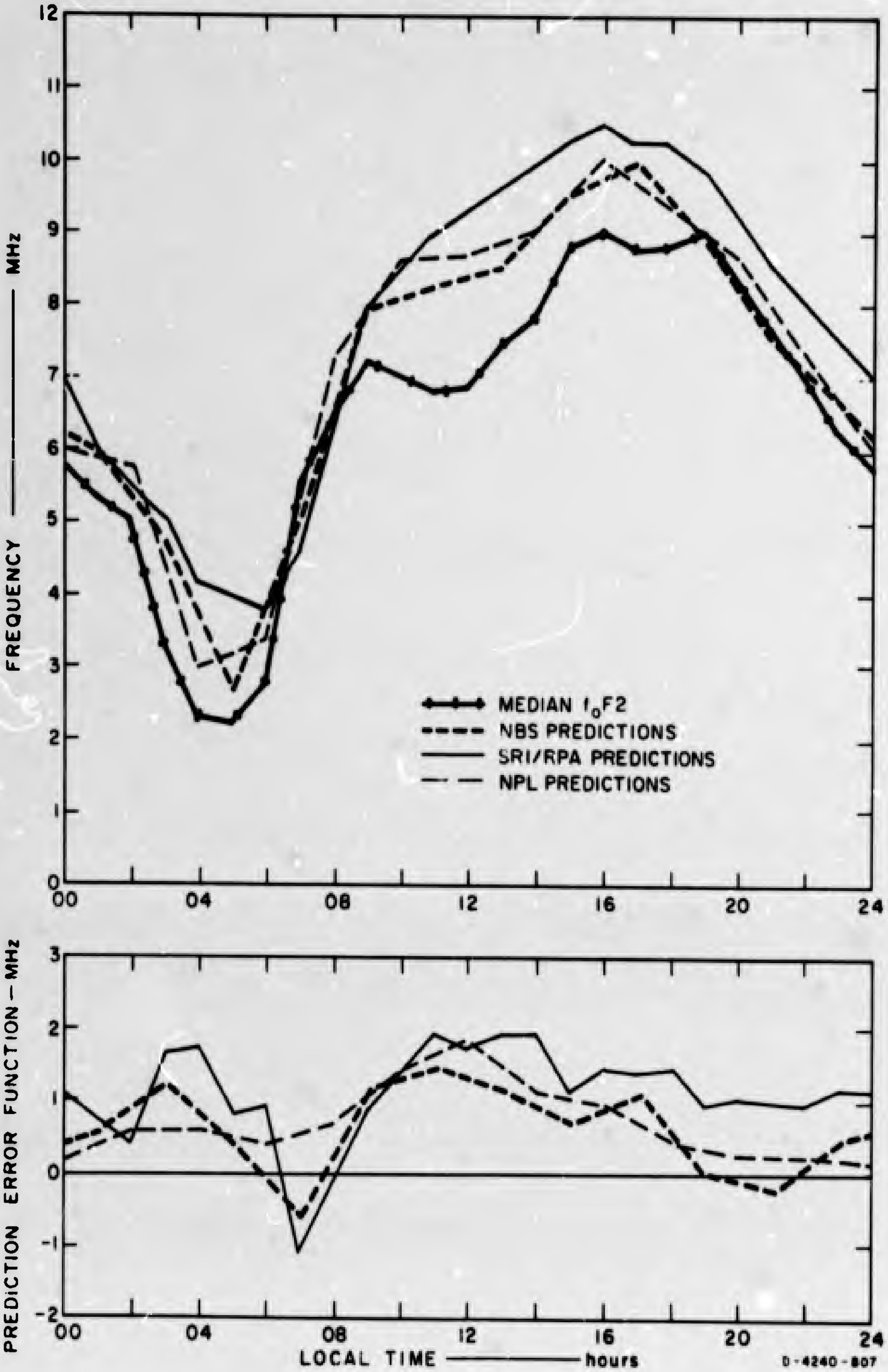

FIG. 3 COMPARISON OF OBSERVED AND PREDICTED MONTHLY MEDIAN f_oF2 FOR A TYPICAL MONTH

are given in Appendix A.) The prediction error function is the difference between the predicted and observed values of f_oF2; it will be used in a later section to derive a correction term for these predictions based upon the available C-2 data from Bangkok.

The three error curves using the available data usually have the same general shape when sampled over a year. The error in each of the three methods averages about 1 MHz or less, and the average absolute error is typically 1.5 MHz. There are often times of day during a given month when each would be best, and there is a month-to-month variation of relative prediction accuracy.

Table I compares the three sets of predictions shown in Fig. 3.

Table I

RELATIVE EVALUATION OF THREE SETS OF f_oF2 PREDICTIONS

	BEST	COMPARABLE	WORST
NBS	40%	55%	5%
NPL	25%	55%	20%
SRI/RPA	5%	35%	60%

The table shows the rough percentage of times (to within 5 percent) that each set of predictions fell into each category. The comparison was made by considering the relative value of the error for each of the three sets of predictions at each of the data points in the plots of Appendix A. The monthly median points for a given time of day were ranked "best," "comparable," or "worst." As one might anticipate, the NBS numerical-mapping predictions are best approximately 40 percent of the time and worst only about 5 percent of the time, making them the most reliable of the prediction techniques used; the SRI/RPA predictions are clearly the least reliable with NPL in between.

This is explained by the fact that the NBS predictions are calculated for a specific geographical point, and take recent ionosonde data into account as well as using the most elaborate mathematical technique. The NPL predictions also use recent ionosonde data, but are given for a wide geographical zone covering India and most of Southeast Asia. The SRI/RPA predictions are again calculated for a specific latitude and longitude, but do not consider recent ionosonde data. In view of this relative evaluation, it would appear the ionosonde data are of cardinal importance in obtaining the best predictions. It should be noted, however, that this evaluation is only relative; in terms of the actual size of the prediction error, even the SRI/RPA predictions are quite good.

The accuracy of the predictions (and of the sounder observation) for paths to within a few tens of kilometers of Bangkok should be quite good. However, they should not be considered applicable to long paths (greater than 100 km or so) in Thailand without modification. This necessary modification results from what is termed the "equatorial trough" in maximum electron density with time, and is discussed by Appleton (1946)[42] and Mitra (1946).[43] The effects of ionospheric tilts on both MUF and LUF have recently been discussed by Bergman.[44] Presumably, the use of recent C-2 data from Bangkok in the CRPL numerical maps will reduce the error in f_oF2.*

In general, the long-term prediction (3 months and longer) of f_oF2 for Bangkok using standard techniques is quite good except near noon and midnight. Indeed, traveling distrubances in the ionosphere often preclude predictions closer than 0.5 MHz.[45,46] Using locally produced C-2 data to obtain a correction should remedy the difficulty near noon, as this error is fairly regular.

The error near dawn, while not so large as near noon or midnight, is particularly important since for many systems the useful spectrum is quite narrow. This is expecially true during sunspot minimum. Here, the local sounder can also be used to provide a correction term; but its data serve mainly to alert communicators that difficulties are likely to be encountered on short paths for several hours near sunrise

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*CRPL began using data from the modified C-2 sounder in Bangkok in their numerical-mapping prediction program with predictions for January 1967. An initial check indicates an improvement in f_oF2 predictions near midday.

so that important traffic can be routed at other hours or via systems not involving an ionospheric reflection. This condition should improve in the next few years as the sunspot number increases. The prediction errors near midnight and in the early morning hours are the most difficult to correct. Indeed, only a token correction is justified because of the high variance of the f_oF2 observations at that time (see Sec. IV-A).

C. Comparison of LUF and LOF*

The figures of Appendix B show three sets of LUF predictions for September 1963 through March 1965. Two of these sets are from the same HF-propagation-rediction computer program (SRI/RPA),[30] but for two different sets of input data.

The first set of predictions is for a 15-watt man-pack transceiver with 3 kHz bandwidth, using horizontal dipoles 20 feet high oriented to maximize signal strength. (It has been shown that horizontal dipoles oriented along the magnetic field will maximize signal level when the QT approximation is satisfied.)[5,9,12]

The second set is for a Model C-2 vertical-incidence sounder with a 10-kW peak transmitter power, a 30-kHz bandwidth, and a delta antenna oriented at 45° to the projection of the earth's magnetic field onto the earth's surface.

The third set of predictions is from the RPA Short Distance Propagation Charts.[33] These predictions are issued quarterly for different systems and geographic areas. "Southeast Asia II" applies to Thailand. The Short Distance Propagation charts were revised starting March 1964, so that greater coverage could be given for different systems and geographic areas. The revised predictions provided finer resolution of diurnal changes.

The RPA predictions in this report are based on a transceiver with CW radiotelegraph modulation (15 words per minute), using a horizontal

*LOF for the C-2 is, by definition, f_{min}.

dipole 30 feet high. Two nominal levels of output power are assumed for this transceiver. Prior to March 1964 the output power used was 7W, and from 1 March 1964 to April 1965, the power was 10 to 17W.

The first two sets of predictions are part of an HF prediction program composed by SRI for RPA. To determine the received signal level, one must specify GMT, month, Zurich running-mean sunspot number, antenna gains, transmitter power, ground constants, gyro frequency, and geographic coordinates. However, since the LUF is defined as the frequency at which the received signal is equal to the required signal, one must know the atmospheric-noise level to determine the required signal level. The atmospheric-noise voltage predictions were calculated by the electronic computer program for one season, but seasonal conversions were interpolated from data compiled by the International Radio Consultive Committee (CCIR) of the International Telecommunication Union, Geneva, Switzerland.[47] It should be noted that these noise data pertain to the vertical component of noise only, and some modification is required to apply them to a horizontal antenna. A curve used by the U.S. Army Radio Propagation Agency (RPA) to convert the noise data given for a vertical monopole, for application to the horizontal dipole, is shown in Fig. 4.[48] Notice that the conversion is a function of frequency. For this report, however, a 30-dB conversion factor was used independent of frequency.

The third set of predictions comes from essentially the same basic program but covers many geographic regions and systems and hence will not, in general, have the accuracy of the SRI/RPA predictions. The figures of Appendix B (Fig. 5 is an example) compare the three sets of monthly median LUF with the monthly median LOF (monthly median f_{min} of C-2 vertical-incidence sounder). The prediction error is the difference between the LOF and the LUF.

The SRI/RPA predictions have the same general shape as the observed C-2 LOF, except during the middle of the day when the SRI/RPA C-2 sounder predictions average 1 MHz higher. The SRI/RPA 15W predictions show even less error, relative to the observed C-2 LOF. This trend indicates that either the diurnal variations of the received noise or

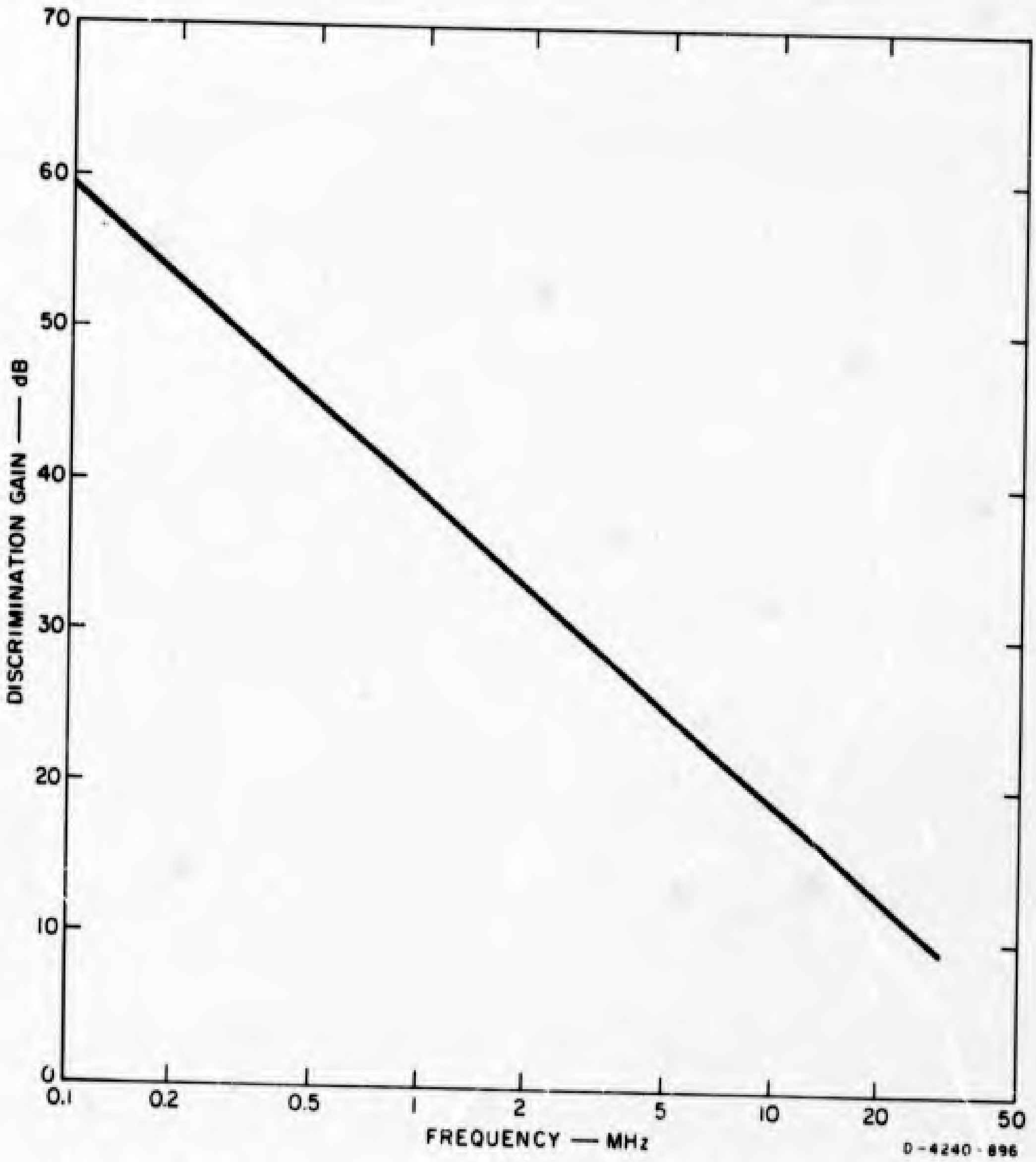

FIG. 4 DISCRIMINATION GAIN OF HALF-WAVE HORIZONTAL DIPOLE OVER QUARTER-WAVE VERTICAL MONOPOLE

the ionospheric absorption data used in the computations may be in error. The error function for the SRI/RPA 15W predictions averages 0.5 MHz, which means that the monthly median f_{min} of the Bangkok C-2 sounder appears to be a useful indication of the lower-frequency limit of such a man-pack transceiver for the first set of predictions. The relatively wide bandwidth of the C-2 sounder system tends to compensate for its higher transmitter power, giving it a system sensitivity not very different from the man-pack from an LUF standpoint. (See the discussion

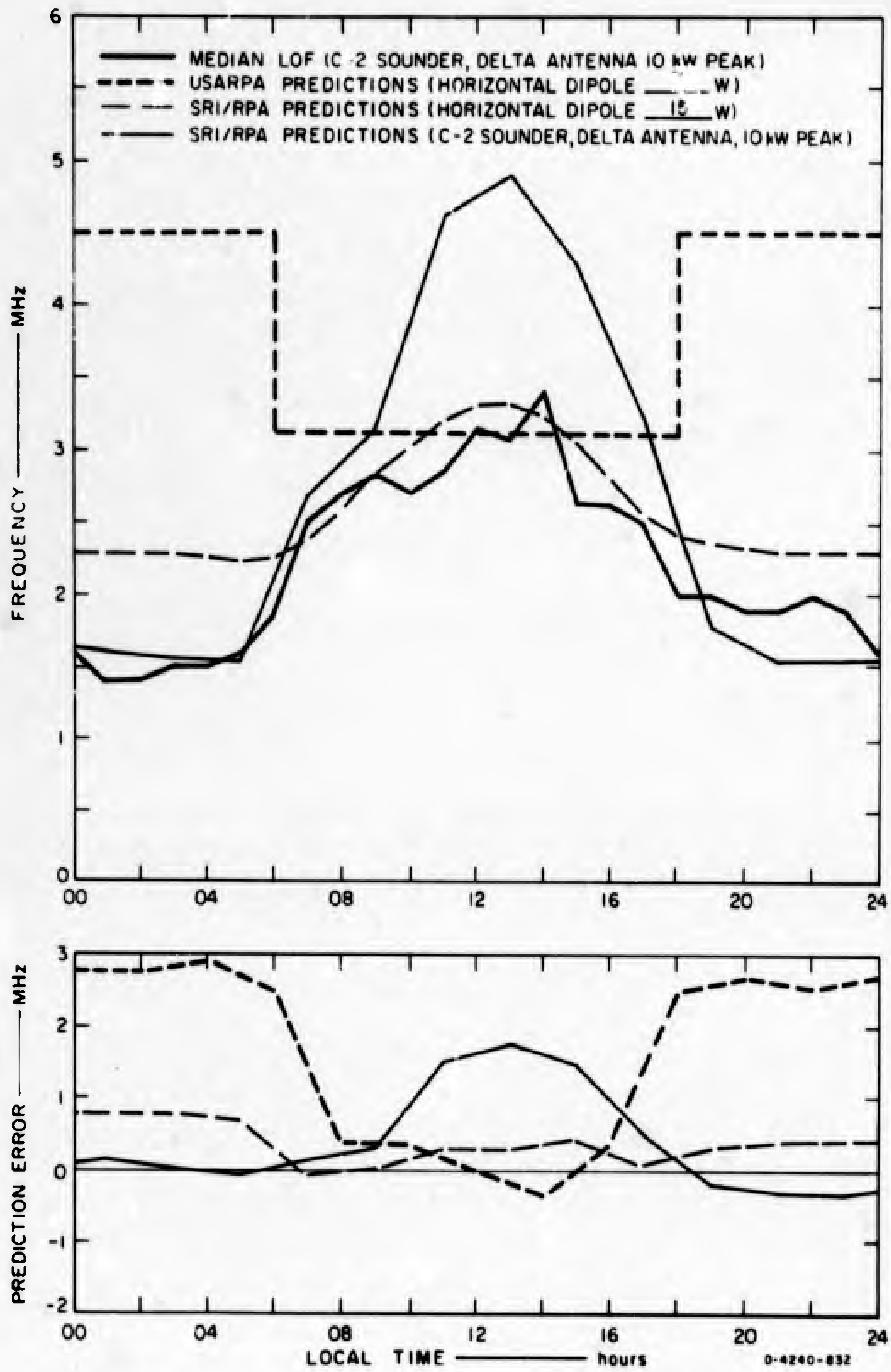

FIG. 5 COMPARISON OF LUF AND LOF (f_{min}) FOR A TYPICAL MONTH

of accuracy based on systems considerations given below.) This data comparison also indicates that the CCIR seasonal noise conversion factors compare very closely with seasonal noise variations controlling the observed monthly median.

The RPA predictions have the greatest variance in the early morning and late evening. The error may be as high as 2 to 3 MHz during these periods. It should be noted that this is the time of no appreciable ionospheric absorption and hence the greatest noise and interference. This is also the most difficult time to predict MUF. Fortunately, in most situations these are not usually hours of peak traffic, although they could become so in some military situations.

The accuracy of the predictions within Thailand should be quite good. These represent average monthly performance of a communication system; hence on any given day rather large variations (several MHz) may occur. This statistical variation is discussed in Sec. IV. The variation of LUF with effective radiated power is a nonlinear function and, for LUF's in the vicinity of 1 MHz or so, several tens of dB are required to change the LUF by 1 MHz. In addition to this, for actual systems, antenna efficiencies typically decrease rapidly with decreasing frequency in this same part of the spectrum. These effects, combined with the atmospheric-noise-vs.-frequency characteristic (which can be as drastic as 0.1 dB per kHz below 1 MHz), tend to make LUF rather insensitive to changes in system sensitivity. This partially compensates for the lack of accurate information about some of the system parameters, and reduces the error in LUF calculations.

D. Layer-Height Predictions and Observations

The height of the layer, h_L, is an indicator of the virtual reflection height in the ionosphere at frequencies typically several MHz less than f_oF2 (see Sec. II-C for a definition of h_L). The data show this parameter to have a large variation with local time. On many paths, this means that the angle between the wave normal (ray path for negligible collisions) and the magnetic field changes with local time for a fixed path. The result is that near the magnetic equator, on short ionospheric paths, there can be rather drastic changes with local time in the polarization of the down-coming waves for a fixed path and equipment setup. This is especially true for paths at and below the magnetic latitude of Bangkok, Thailand, for frequencies greater than 5 MHz.

The data indicate that prediction of monthly median values of h_L is slightly easier than prediction of f_oF2 (see Fig. 6, an excerpt from the October 1963 data summary with the predicted h_L values added to show the variation of h_L with local time). Of the two prediction techniques, the numerical mapping seemed the less accurate. The NBS technique predicted too high by about 15 percent during the day, whereas the SRI/RPA

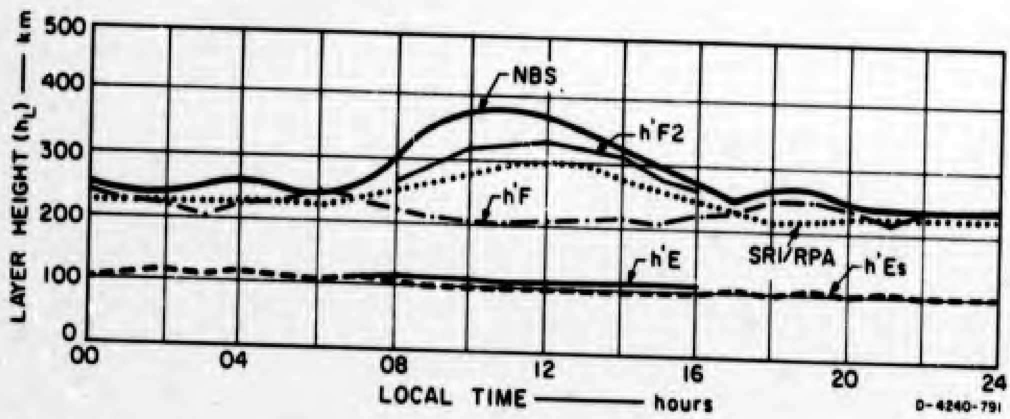

FIG. 6 COMPARISON OF PREDICTED AND MEASURED h_L — OCTOBER 1963

predictions were about 8 percent low for that time of day. However, the observed daily variation from monthly median predicted values was often 50 percent or more for both techniques. The standard deviation of daily observed differences from monthly median predicted values was least during early afternoon and evening.

IV MONTHLY MEDIAN USABLE FREQUENCY SPECTRUM PREDICTIONS, USING CORRECTED f_oF2 PREDICTIONS

A. Method of Correcting f_oF2 Predictions

The observed f_oF2 data at Bangkok have shown that f_oF2 predictions are consistently too high. (All available predictions were considered.)

The decrease in f_oF2 at Bangkok near noontime (midday dip) causes the greatest error in the predictions. This effect is a function of latitude, being greatest near the magnetic equator.[49] The midday dip is the most consistent error of significance in the f_oF2 predictions.

The comparison of observed C-2 sounder data at Bangkok and the f_oF2 predictions enables future f_oF2 predictions to be modified. The modification significantly improves the prediction accuracy, especially near local noon.

The modification or correction functions for NBS numerical-mapping predictions and SRI/RPA predictions can be obtained from a monthly median mass plot of the error function as shown in Figs. 7(a) and 8(a). The median value and quartile range of the error function are shown in Figs. 7(b) and 8(b).

The median NBS numerical-mapping error function appears to average about 0.5 MHz. It decreases to 0.1 MHz in the early morning hours, when the numerical-mapping prediction accuracy is the most reliable, and increases to 1.1 MHz near noon, indicating that an improvement in predictions is needed. The quartile range is smallest in the early morning hours and increases to a maximum value near midnight, indicating that this period had the greatest variations in monthly median values.

The median SRI/RPA error function appears to average about 1.0 MHz. The SRI/RPA predictions are the most reliable near sunset when the median error function decreases to 0.4 MHz. The maximum error-function value also occurs near noon, again implying that prediction improvement is needed near noon. The quartile range does not follow any standard

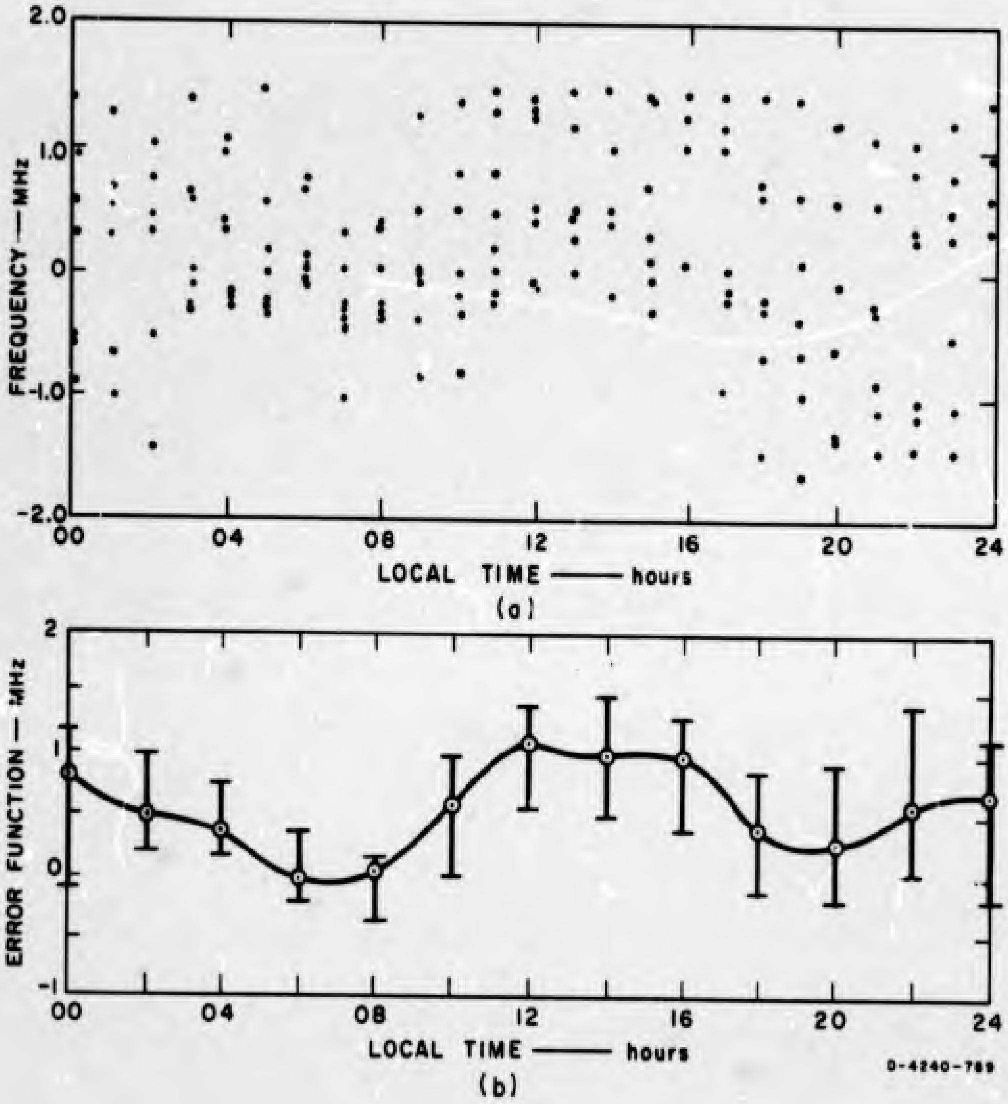

FIG. 7 VARIATIONS OF NBS MONTHLY MEDIAN f_oF2 ERROR FUNCTION, SEPTEMBER 1963 THROUGH MARCH 1965

pattern except that it decreases to a minimum near noon, indicating the least variance in monthly prediction during this time of day.

The necessary correction function is derived from the median values of the mass plots. The corrected NBS and SRI/RPA predictions are given as the sum of the values supplied by the prediction and correction functions: that is, f_oF2 corrected = f_oF2 predicted - Δf_{cor}. The correction functions are shown in Figs. 9(a) and 9(b).

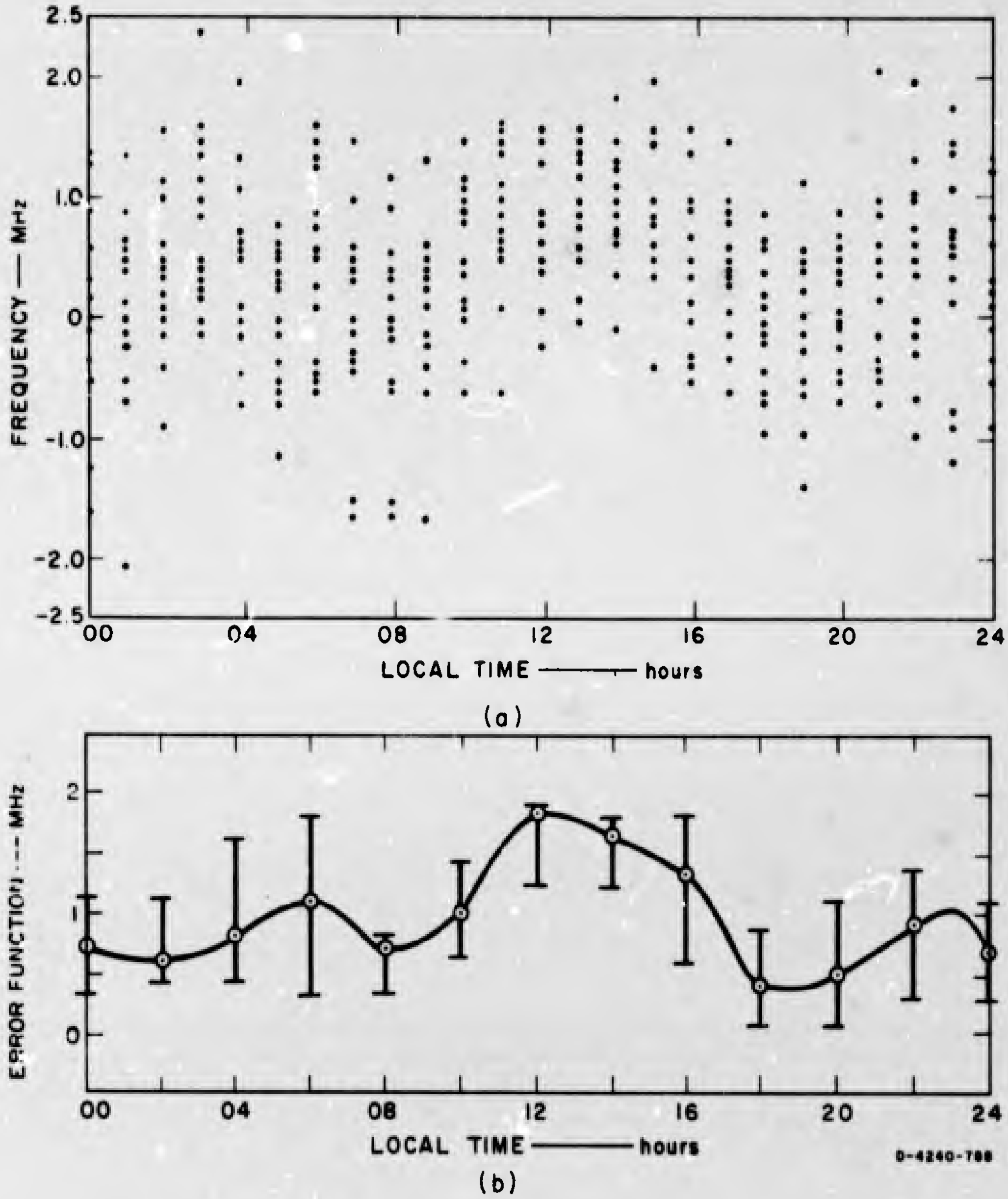

FIG. 8 VARIATIONS OF SRI/RPA MONTHLY MEDIAN f_oF2 ERROR FUNCTION, SEPTEMBER 1963 THROUGH MARCH 1965

The corrected predictions of monthly median values of f_oF2 should be accurate to ±1.5 MHz for all times of day except possibly near local midnight. It is possible that a correction function based upon the previous month's (or several months') error function could improve upon this somewhat. However, the chances of improving the accuracy more than several hundred kHz are small.

The following section uses the correct prediction to estimate the useful spectrum for several months during 1965 and all of 1966.

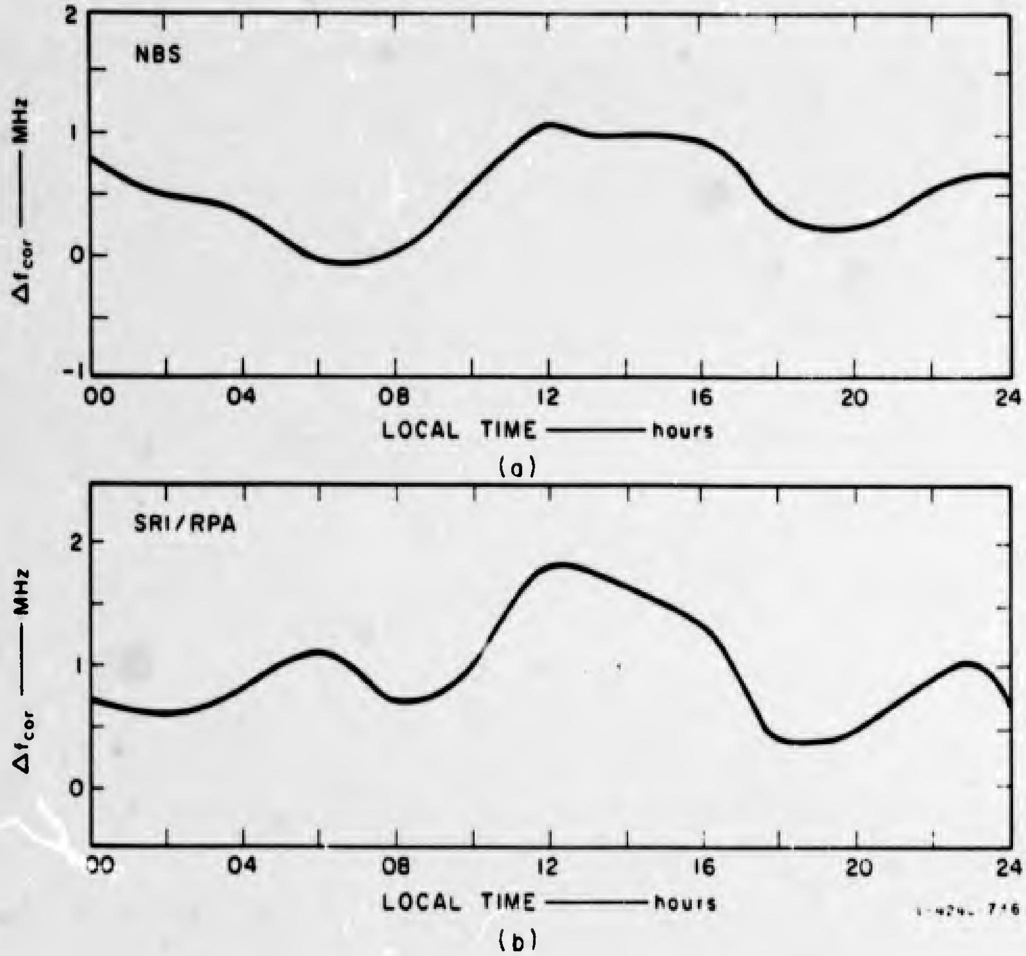

FIG. 9 CORRECTION FUNCTION DERIVED FROM MEDIAN VALUES OF MASS PLOT

B. Predicted Usable Frequency Spectrum

This section pertains to prediction of the usable frequency spectrum for an HF man-pack transceiver system with the following characteristics:

(1) Transmission power = 15W

(2) Bandwidth = 3 kHz

(3) Antenna: horizontal half-wave dipoles, 20 feet high

(4) Range = 0-200 km from Bangkok

Corrections based on the C-2 data (see Sec. V-A) have been applied to the NBS numerical-mapping predictions and the SRI/RPA predictions of f_oF2 and these are used to obtain the upper frequency limit for time intervals through 1965 and 1966 respectively.

The lower-frequency limit is the LUF calculated using the SRI/RPA computer program as described in Sec. III-B. The variations in LUF from one month to the next are due to seasonal atmospheric-noise variations. The predicted usable frequency spectrum is simply the difference between the upper-frequency limit (corrected f_oF2 prediction) and the lower-frequency limit (LUF prediction neglecting the useless zones). Appendix C shows the corrected NBS numerical-mapping predictions from April through December 1965 and the corrected SRI/RPA predictions from April 1965 through December 1966.

The prediction data presented are monthly median values that are representative of the average diurnal trands of the MUF and LUF. These estimates are used to predict the average or typical performance of a man-pack transceiver near Bangkok. However, on any given day the difference between actual and predicted usable spectrum may be several MHz (see Sec. IV). The NBS and SRI/RPA predictions of usable frequency bandwidth are usually less than 1.0 MHz in the early morning hours, and are sometimes zero, indicating communication failure. Thus, the presence of these errors could easily misrepresent the usable spectrum on a given day for several hours near dawn during the present sunspot minimum by indicating that the MUF prediction is higher than the LUF.

The error in prediction of the usable spectrum due to neglecting sporadic E (E_s) is discussed in Appendix D. Basically, E_s has the effect of increasing the usable spectrum for man-pack sets, which may to some extent compensate for the decrease in usable spectrum due to daily variations. This is of particular significance during sunspot minimum since the usable spectrum increases with increasing sunspot number.

Spread F, another ionospheric anomaly, will be detrimental to the communicator. Spread F echoes appear on the C-2 record as an increase of the F-layer retardation. For example, the 50-μs transmitted pulse may be "stretched" to over 1 ms. This pulse elongation causes deleterious distortion to the desired signal. At present (sunspot minimum) there is one type of scattered F-layer reflection that is often seen at Bangkok.

This type usually occurs shortly after midnight, continuing for several hours. It occurs frequently during equinoxes, and is similar to higher-latitude types of Spread F. Another type will occur in years of greater solar activity and also is more prevalent near equinoctial periods. This second type usually occurs in the early evening (shortly after local sunset), especially near the magnetic equator.[50] Short-distance skywave propagation is likely to be very difficult or even impossible when Spread F occurs in the early morning hours. This topic is also discussed in Appendix D.

The potentially useless zones mentioned briefly in the Introduction should not significantly decrease the usable spectrum; however, they might interrupt communication on a given frequency. These effects are presently being investigated in Thailand.

V OBSERVED DAILY VARIATIONS FROM MONTHLY MEDIAN VALUES

The data discussed as monthly median values in the preceeding sections are representative of the general diurnal trends of the pertinent ionospheric parameters f_oF2 (MUF zero-range), f_{min} ($\approx$ LUF for HF manpacks), and h_L. Prediction techniques exist that can be used to estimate the monthly median values of LUF and MUF to within 1.5 MHz or so and the layer height to within about 20 percent. It is the purpose of this section to discuss the daily variation from these monthly median values as a function of local time--a topic of interest to the practical communicator.

The monthly report "Ionospheric Data: Bangkok, Thailand"[39] presents the quartile values and quartile range values that were used for the following analyses. The quartile range (difference between 25-percent and 75-percent values) approximates the 50-percent confidence bound on the monthly median values and is sometimes referred to as the probable error. The quartile range is proportional to the variance; hence a large quartile range corresponds to a large variance and vice versa (e.g., for the normal distribution, the quartile range is 0.45 times the variance).

We are concerned here with the daily variation of the ionospheric parameters from their predicted monthly median values. This is a two-phase problem: we need to know the average error in predicting the observed monthly median values, and we need to know how the daily observed values vary from the observed monthly median values. The first phase of this problem was discussed in Sec. III.

The percentage of error is, of course, least around noon after the prediction has been corrected using previous data. One would expect prediction accuracy of all three ionospheric parameters to become somewhat worse as the solar cycle advances toward sunspot maximum (during 1968 and 1969), since the solar ionizing flux variations from day to day becomes greater during that period.

A. f_oF2 Variations

Nineteen months' data (sunspot minimum--sunspot number less than 50) of the monthly quartile range of f_oF2 as a function of local time are shown in the mass plot of Fig.10. Fewer than 19 points are visible at each hour because certain values occurred several times. These data are summarized in Fig.11, where the median quartile range for this sample

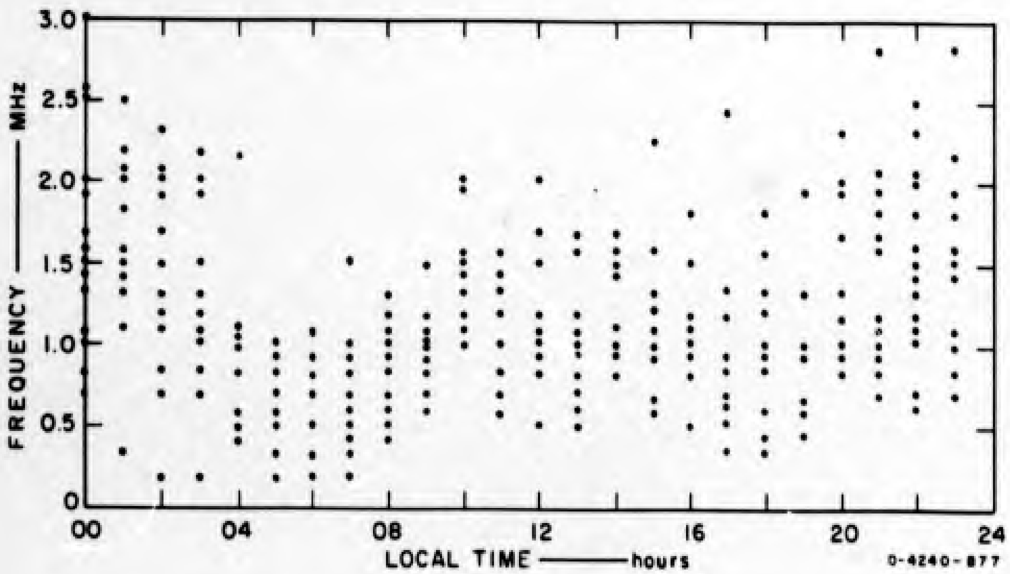

FIG. 10 f_oF2 MONTHLY QUARTILE RANGE — MASS PLOT

(which could be considered a good approximation of a yearly median) is shown. The bars indicate the decile bounds on the quartile range for the 19-month sample. Notice the decrease in quartile range at both sunrise and sunset, which is very similar to the correction function (see Sec. IV-A) used to amend the predicted monthly median values of f_oF2. Indeed, the quartile range and correction functions are surprisingly similar in most respects, including the absolute magnitude of both their median values and decile bounds; however the correction function relates to the variation of the measured and predicted median values of f_oF2, whereas the quartile range function relates to the variance of the observed values from the observed median. The implications of this striking coincidence as regards to the prediction error on any given day, however, need clarification.

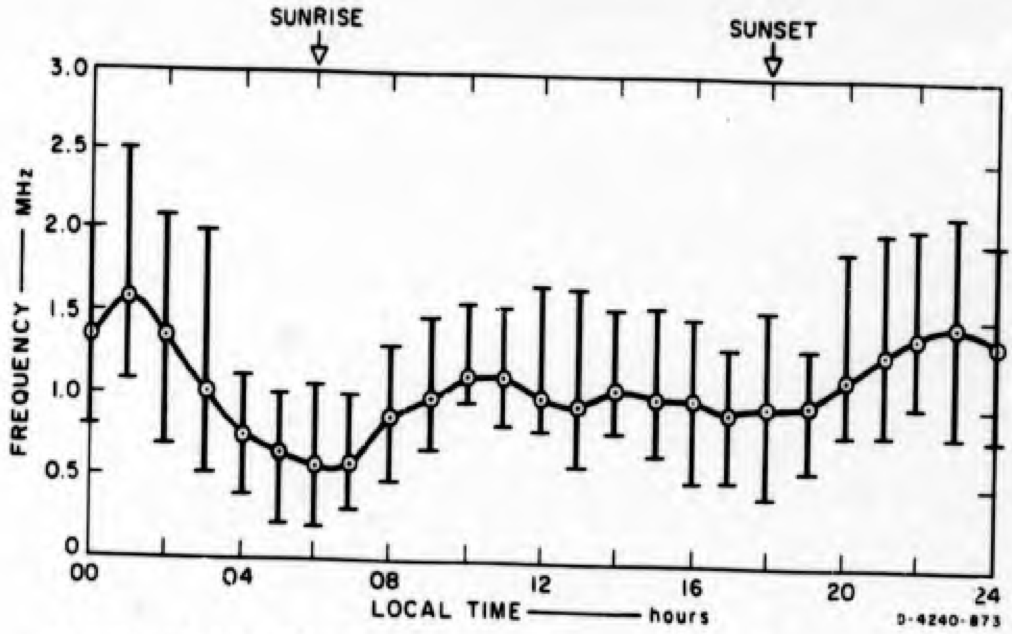

FIG. 11 DECILE BOUNDS ON MONTHLY QUARTILE RANGE OF f_oF2

The absolute error (in MHz) on any given day when the NBS-CRPL numerical-mapping predictions* are used should be the least around sunrise and should be within about 1.0 MHz for 50 percent of the time. The next best time of day for predicting f_oF2 should be sunset, when the absolute error should be within about 1.25 MHz for 50 percent of the time. Around noon, the prediction error should rise to about 1.5 MHz for 50 percent of the time, whereas near midnight (worst case) the prediction should be, on the average, within 2.0 MHz of the value observed on any given day. Figure 12 illustrates the 50 percent confidence bounds on a typical monthly median f_oF2 prediction for Bangkok during the sunspot minimum.

The day-to-day variability of f_oF2, as indicated by the data of Figs. 10 and 11, clearly is a greater percent of the monthly median f_oF2 during the middle of the night than during the middle of the day. Figure 3 shows the typical f_oF2 monthly median variation with time of day. The indication is that the standard practice of taking a fixed percentage of the predicted monthly median MUF (e.g., 85%) to predict the optimum frequency for traffic is not necessarily a sound practice, at least for paths at low latitudes.

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*Corrected by the error function derived from the Bangkok C-2 sounder data.

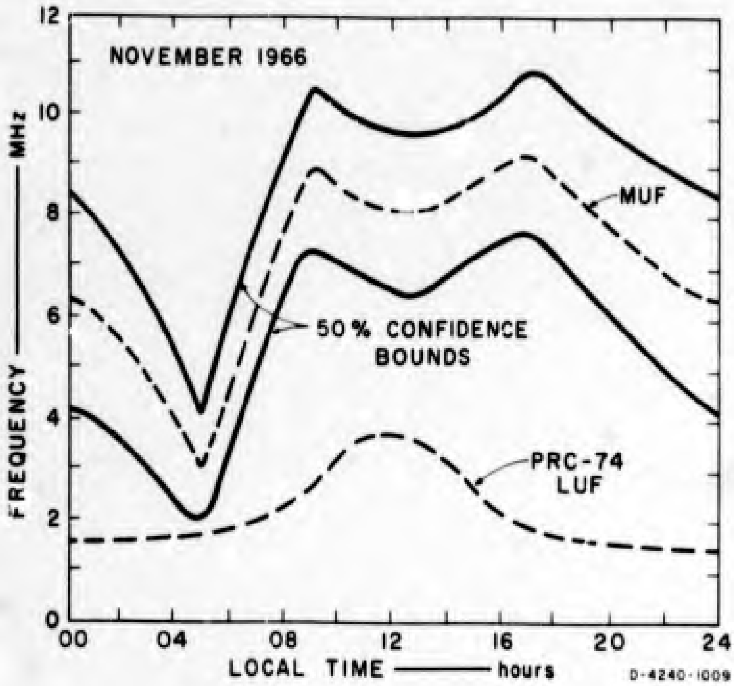

FIG. 12 50% CONFIDENCE BOUNDS ON TYPICAL MONTHLY MEDIAN f_oF2 PREDICTION

B. f_{min} Variations

The prediction error plotted in Sec. III-B for f_{min} indicates that a correction function could be deduced analogous to the case for f_oF2 which would reduce the prediction error to 1 MHz or less for all values of local time. (Recall that the man-pack predictions agreed rather well with the C-2 observations.) The quartile range of hourly values of f_{min} within a given month is shown in the mass plot of Fig. 13 for the period between September 1963 and March 1965. The data shown in the mass plot are summarized in Fig. 14, showing the median of the quartile range

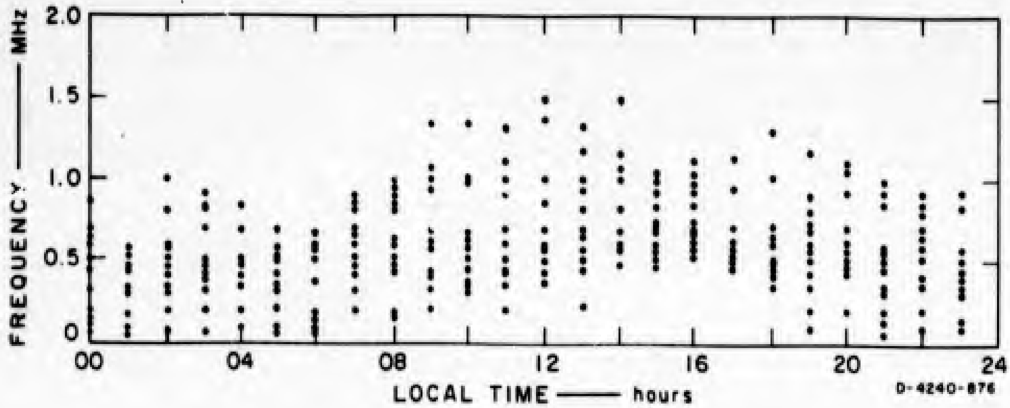

FIG. 13 f_{min} MONTHLY QUARTILE RANGE — MASS PLOT

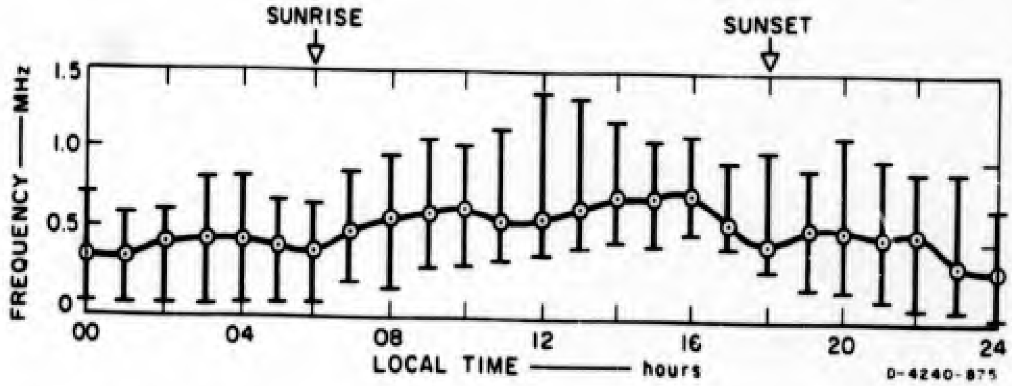

FIG. 14 DECILE BOUNDS ON MONTHLY QUARTILE RANGE OF f_{min}, SEPTEMBER 1963 THROUGH MARCH 1965 — BANGKOK, THAILAND

with decile bounds as a function of local time. Sunrise and sunset effects are observed, but these are not so marked, as for f_oF2. Whereas the variance of f_{min} is clearly the greatest near noon, the prediction error (after correction) tends to be minimum then; and one would expect that on the average, observed values of f_{min} (excluding the case of local man-made interference) should be within 1 to 1.5 MHz regardless of time of day. Prediction accuracy of f_{min} might be expected to decrease somewhat as the sunspot cycle advances toward maximum during the next few years.

C. h_L Variations

The quartile range variation of h_L with local time is shown in the summary plot of Fig. 15 for the same time interval discussed in the preceding sections. Again the bounds are decile values and the large dots are effectively yearly medians of quartile range during the sunspot minimum. Notice the sharp decrease both in quartile range and in the variation of quartile range near both sunrise and sunset. On the average, one should be able to predict h_L for the F layer to within 25 km very near sunrise and 50 km near sunset.

The variance of quartile range during the day is closely coupled to solar zenith angle. During midday, one should be able to predict the layer height for the F2 layer to within about 75 km, on the average.

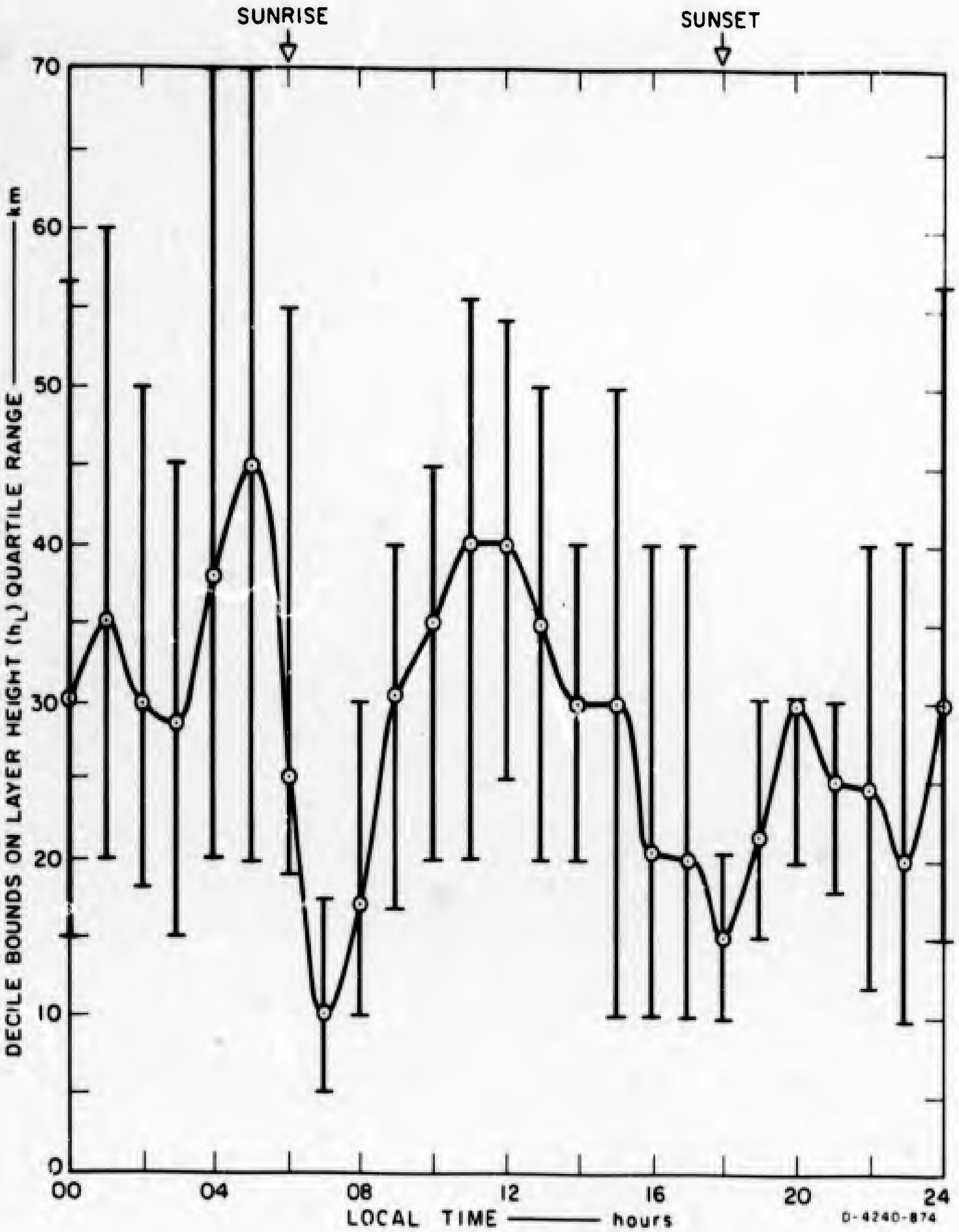

FIG. 15 DECILE BOUNDS ON MONTHLY QUARTILE RANGE, SEPTEMBER 1963 THROUGH MARCH 1965 — BANGKOK, THAILAND

At night, one should be able to predict h'F about as well as h'F2 during the day, and perhaps even better. This is because the error in predicting the monthly median layer height at night is quite small.

Fortunately, predictions of MUF for short paths (0 to 200 km) are relatively insensitive to errors in h_L. For example, on the 66-km path between Bangkok and Ayutthaya, a 100-percent error in h_L (150 to 300 km) would cause only about a 2-percent error in predicted MUF; and on a 166-km path between Ayutthaya and Nakon Sawan, the same height error produces only a 7-percent error in predicted MUF. For greater path lengths, the error increases rapidly.

Data on observed h_L are presented in the ionospheric data bulletin summary series.[39]

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VI CONSIDERATION OF THE DESIGN FREQUENCY RANGE OF HF MAN-PACK RADIOS FOR USE ON SHORT IONOSPHERIC PATHS IN THE TROPICS

The data presented in this report are for the recent period of minimum solar activity: 1963-1965. One can conclude that HF man-packs designed to operate in the range 2 to 8 MHz would have been satisfactory for use on short ionospheric paths for 95 percent of the time with a minimum spectrum available of 500 kHz. Considering sunspot maximum, a set designed to function between 2 and 18 MHz should function very satisfactorily when a half-wave dipole antenna at a height greater than 0.1 wavelength is employed.

The lower limit of 2 MHz was arrived at by a review of the 18-month period of data covered in this report. The effects of Sporadic E (see Appendix D) were included in considering MOF.

The daily curves of MOF as a function of time of day were plotted from 1 September 1963 through 31 March 1965. The number of hours during which a given operating frequency (1.5, 2.0, 2.5, 3.0, and 4.0 MHz) is larger than the MOF is tabulated from these daily MOF plots. Figure 16 shows the method used on a typical MOF plot when the given operating frequency is 2.0 MHz. The time during which 2.0 MHz is greater than a typical MOF plot is 1.8 hours, as shown in the figure. The daily hours for a given operating frequency are summed for any given month. Table II gives the percentage of time that five given operating frequencies are greater than the MOF, since the number of hours is easily converted into percent of time. Table II shows that the MOF is less than 2.0 MHz from a minimum of 0 percent of the time in August 1964, to a maximum of 4.3 percent of the time in November 1964, and averages 1.4 percent from September 1963, to March 1965.

The sunspot number for November 1964 is 10, which implies that this will be a worst case (MOF was considerably lower in the early

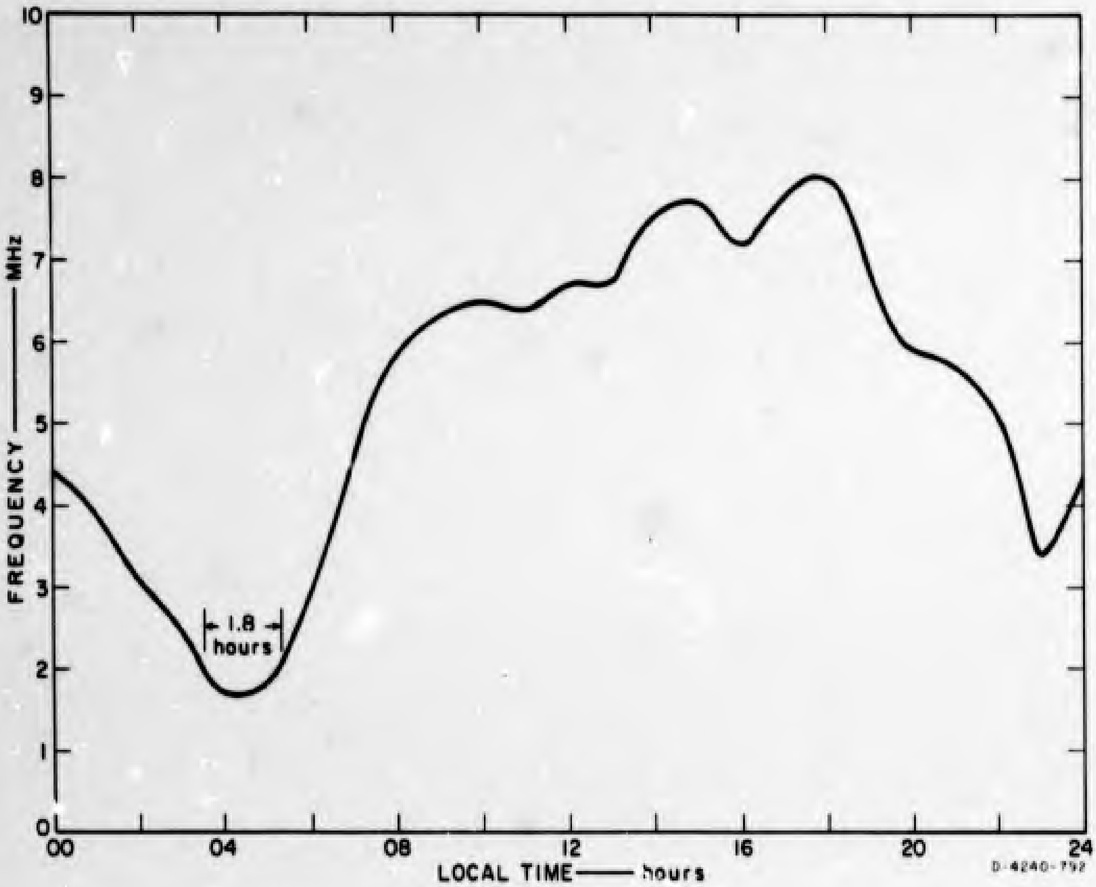

FIG. 16 TYPICAL PLOT OF MOF vs. LOCAL TIME (Includes E_s Effects)

morning hours than in adjacent months).* The sunspot number for August 1964 is 9.3 while the average value from September 1963 through March 1965 is 14.5. This illustrates the general tendency for the worst case (low MOF) to occur when the sunspot number is the smallest.

Table II also shows the average time in a given day that the operating frequency exceeded the MOF for each month. This percentage time can be thought of as the percentage communication failure at the lower limit of the transceiver frequency tuning range. Figure 17 gives essentially the same information as Table II except that the diurnal variation is

*It should be remarked that although this is an extremely low sunspot number for the cycle under discussion, values as low as 3 or 4 have been observed during previous cycles.

Table II

PERCENTAGE OF TIME A GIVEN OPERATING FREQUENCY EXCEEDS THE MOF

MOF < operation frequency / Month	MOF < 4.0 MHz	MOF < 3.0 MHz	MOF < 2.5 MHz	MOF < 2.0 MHz	MOF < 1.5 MHz
Sept. 63	15.6%	9.6%	4.4%	1.2%	0.0%
Oct. 63	12.8%	5.8%	1.8%	0.2%	0.0%
Nov. 63	16.7%	10.7%	7.7%	2.1%	0.0%
Dec. 63	27.7%	17.5%	8.8%	2.0%	0.1%
Jan. 64	30.7%	17.1%	11.1%	4.2%	0.1%
Feb. 64	19.9%	11.4%	6.5%	1.7%	0.0%
Mar. 64	15.9%	9.9%	4.4%	1.1%	0.0%
Apr. 64	13.9%	6.9%	1.4%	0.3%	0.0%
May 64	21.5%	5.9%	1.6%	0.3%	0.0%
June 64	26.4%	12.1%	5.7%	1.8%	0.0%
July 64	25.3%	10.0%	3.1%	1.3%	0.0%
Aug. 64	20.4%	5.8%	2.5%	0.0%	0.0%
Sept. 64	21.4%	5.0%	1.3%	0.2%	0.1%
Oct. 64	19.5%	10.1%	4.9%	1.6%	0.0%
Nov. 64	26.0%	15.4%	10.5%	4.3%	0.6%
Dec. 64	22.5%	13.8%	7.0%	3.0%	0.0%
Jan. 65	25.6%	12.8%	5.6%	1.6%	0.0%
Feb. 65	25.5%	10.6%	4.4%	0.4%	0.0%
Mar. 65	14.8%	8.3%	3.9%	0.7%	0.0%
AVERAGE	21.1%	10.4%	5.0%	1.4%	0.05%

also included. The vertical axis is the percent of time the transceiver operating frequency is exceed, which again can be considered as essentially equal to the percent communication failure due to the lower frequency limit of the transceiver tuning range. The horizontal axis gives the local time variation. The different curves are paremetric in operating frequency. Therefore for a given lower frequency tuning limit the percent of communication failure as a function of local time can

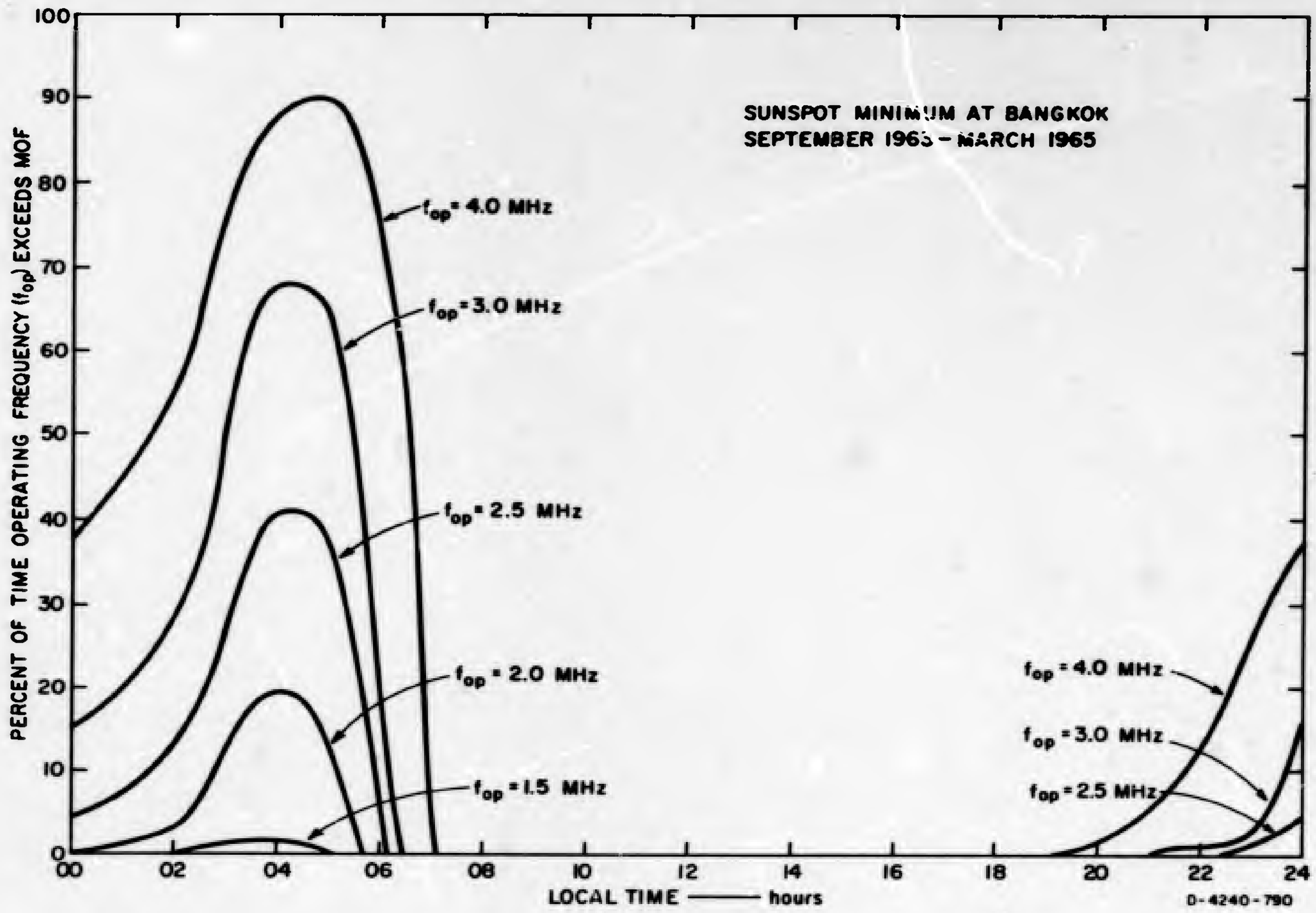

FIG. 17 PERCENT OF TIME THE OPERATING FREQUENCY EXCEEDS MOF

be estimated. The percentage of communication failure increases rapidly with increasing values of the lower frequency limit. The most difficult time to communicate is in the early morning hours between 0200 and 0700. The maximum communication failure occurs between 0400 and 0500. For a lower limit of 2.0 MHz the maximum percent failure averages 17% at 0430 in the early morning. If the communication system is considered for a complete day the failure averages 1.4%. Therefore it is anticipated that HF man-pack sets used on short ionospheric paths at low magnetic latitudes (e.g., Thailand) should be designed to have a lower frequency limit of not more than 2.0 MHz. If ionospheric paths are to be used during the brief pre-dawn minimum (0200-0600) during sunspot minimum, then a lower limit of 1.0 MHz would be required to ensure communication failure percentages of less than 10%.

The preceding discussion has covered the importance of low MOF on the lower design frequency for an HF man-pack radio for use on short ionospheric paths in the tropics. The usable spectrum below the MOF depends on the parameters of the specific system being considered, and a lowest-usable-frequency (LUF) calculation is required to determine if the system will operate below the MOF.

A typical calculated monthly median LUF for a dipole system and the extrapolated monthly median LUF for a slant-wire system are superimposed on a typical daily MOF plot as shown in Fig. 18. The LUF values apply only to the average performance of the following systems: Hughes HC-162 (AN/PRC-74) or Sylvania TRC-88 transceivers (transmission power, P_T = 15W, B_n = 3 kHz) with horizontal dipole 20 feet high, optimum orientation and impedance-matched antenna system over a 0-100 km path near Bangkok.

For this example, these particular sets should not be designed to operate below 3 MHz if only the slant-wire antenna is to be used. If the sets are intended for use with the dipole, then it would appear 1 MHz would be a better choice for 24-hour operation during the sunspot minimum. If the several hours just before dawn can be neglected, then 2 MHz seens an acceptable compromise. It should be repeated here that the LUF considerations do not change the conclusion that 2 MHz would have been a satisfactory lower limit for 95% of the time.

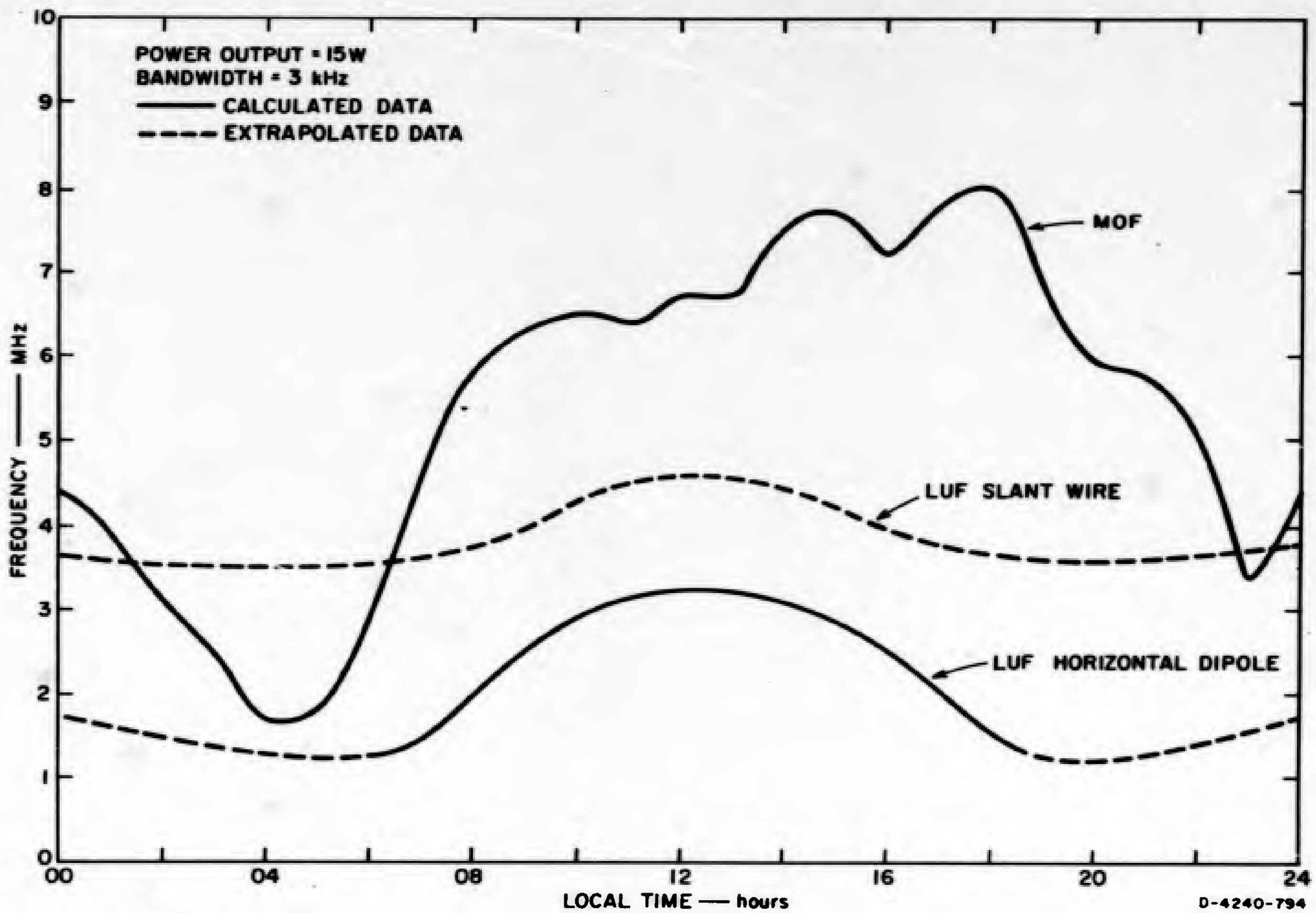

FIG. 18 TYPICAL LUF FOR DIPOLE AND SLANT-WIRE ANTENNAS SUPERIMPOSED ON A DAILY MOF PLOT

To evaluate the upper-frequency limit for the design of HF man-pack radios, we need to consider extrapolating the MUF predictions to sunspot maximum. Figure 19 shows this extrapolation for Bangkok, assuming a sunspot number of 130 is reached. For a very short path, this indicates that 13 MHz would be adequate. However, the authors think that for Thailand 18 MHz is preferable since it would permit operation near the MOF on paths out to about 1000 km near sunspot maximum.

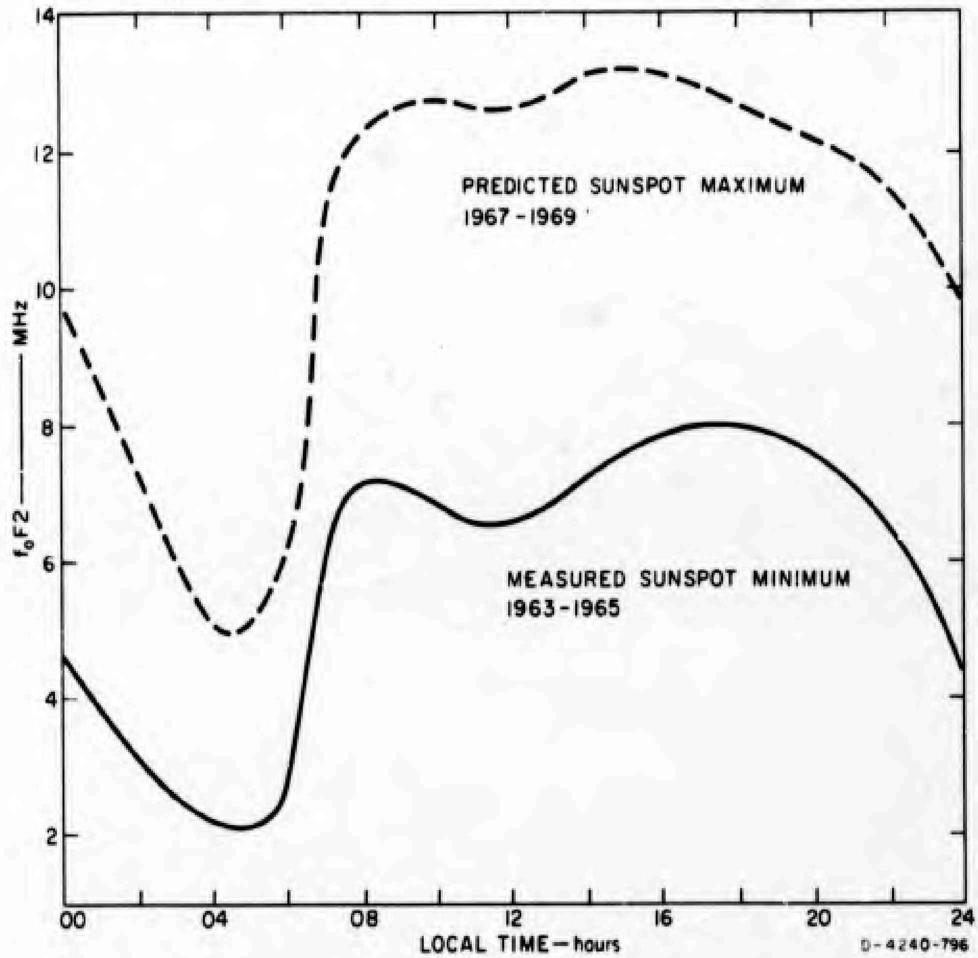

FIG. 19 TYPICAL f_oF2 VARIATION WITH SUNSPOT CYCLE LIMITS

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VII SUMMARY AND CONCLUSIONS

Three sets of frequency predictions were checked against the ionospheric observations performed in Bangkok, Thailand with a C-2 sounder from September 1963 through March 1965.

The numerical mapping technique (NBS), used to predict the monthly median value of f_oF2 was the best, or comparable with the best, 95% of the time. This technique required the most recent input data and predicts for a specific location. The next best set of predictions were those from the National Physical Laboratory, New Delhi, India, which were the best, or comparable to the best, 80% of the time. These predictions utilize recent ionosonde data but predict for a zone rather than a specific latitude and longitude. The SRI/RPA predictions, which utilize no recent ionosonde data, were the best or comparable with the best only 40% of the time. Remarkably, however, all three prediction techniques did a reasonably good job, being within 1 or 2 MHz most of the time.

The difference between the predicted and observed monthly median values of f_oF2 was used to generate a correction function which, when applied to the NBS and SRI/RPA predictions reduced the error to within about 1.5 MHz for all times of day. The correction functions obtained showed variation with local time during sunspot minimum, but additional data and further study would be required to determine if seasonal or solar-cycle variations are significant. Whereas one would not expect marked seasonal variations at low latitudes, variation of the correction function with solar-cycle variation might be rather pronounced. This is due primarily to the difficulty in predicting the solar cycle itself.[51]

The daily variation of f_oF2 from the monthly median value was also studied and found to be a function of time of day, being minimum around sunrise and maximum around midnight. The observed values should fall, with probability 0.5 or greater, within 2 MHz of the monthly median predicted value (as amended with the correction function) at all times of day. The observed daily variability indicates that determining the optimum frequency for traffic on short paths by taking a fixed percentage (e.g. 85%) of the predicted MUF independent of time of day is not valid for low latitudes.

The lowest usable frequency is more difficult to predict accurately, since a rather complete knowledge of the communication system is required. Also, adequate radio noise data for systems operating with horizontally polarized antennas are not available. Nevertheless, it appears that f_{min} from the Bangkok C-2 (higher power than a man-pack radio but partially compensating greater bandwidth) provides a reasonable estimate of LUF for typical HF man-pack radios operating in Thailand.

The data indicated that the layer height (h_L) predictions were somewhat more accurate than f_oF2 or LUF. The NBS predictions were about 15% high during the day, while the SRI/RPA predictions were about 8% low. The daily variations from the monthly median values were often 50% or greater for both techniques. Fortunately, for paths less than 200 km, even a 100% error in layer height causes an error of only 10% or less in MOF. For longer paths the MOF rapidly becomes sensitive to errors in h_L.

The SRI/RPA corrected short-path predictions were extended through 1966* and the usable spectrum for an HF man-pack (15 watts) employing a half-wave horizontal-dipole antenna at a height greater than $\lambda/10$ was estimated, assuming voice communication in a 3-kHz bandwidth. These predictions indicated communication difficulty in the pre-dawn hours for the example system even though the operating frequency is below the MOF. If a slant-wire antenna is used, this difficulty is increased.

The predictions of the maximum usable frequency for a short ionospheric path were extended to sunspot maximum. An examination of these

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*While the NBS predictions were the best of the three checked, they were not used to make the predictions for 1966 because they were not available to the authors that far in advance. It should be noted however that, by assuming a sunspot number (and possibly foregoing benefit from some recent ionosonde data), the NBS numerical-mapping predictions could be used in the same way as the SRI/RPA predictions to make predictions for any future time.

predictions and those for the sunspot minimum indicates that HF man-pack radios designed for use in the tropics should have the capability to operate from 2 to 18 MHz in order to be able to function near the MOF on short paths out to 1000 km during both sunspot minimum and maximum. The skywave communication failure at the lower limit of an HF man-pack frequency tuning range was considered. Failure was shown to be the most severe in the early morning hours. These data indicated that, for short ionospheric paths at low latitudes, radio sets should be designed to have a lower frequency limit of not more than 2.0 MHz. If communication failure of less than 10% is required for all hours of the day and all years of the solar cycle, then a lower limit of 1.0 MHz would be required in the early morning hours.

A study of anomalous propagation conditions during the recent sunspot minimum indicates that Spread F and blackout are statistically unimportant, and they necessitate no modification to the predictions for propagation via the regular layers. Sporadic E does occur about half the time as seen by the C-2 (and hence, by inference, by a typical HF man-pack radio), and this should be taken into account when predicting MOF, particularly for local times near the pre-dawn minimum in f_oF2. The occurence of Spread F and blackout should be expected to increase during the next few years as the sunspot number increases, but they should not become statistically significant until about 1967.

APPENDIX A

COMPARISON PLOTS OF PREDICTED AND OBSERVED f_oF2

AND ERROR FUNCTION, USING

C-2 DATA FROM SEPTEMBER 1963 THROUGH MARCH 1965

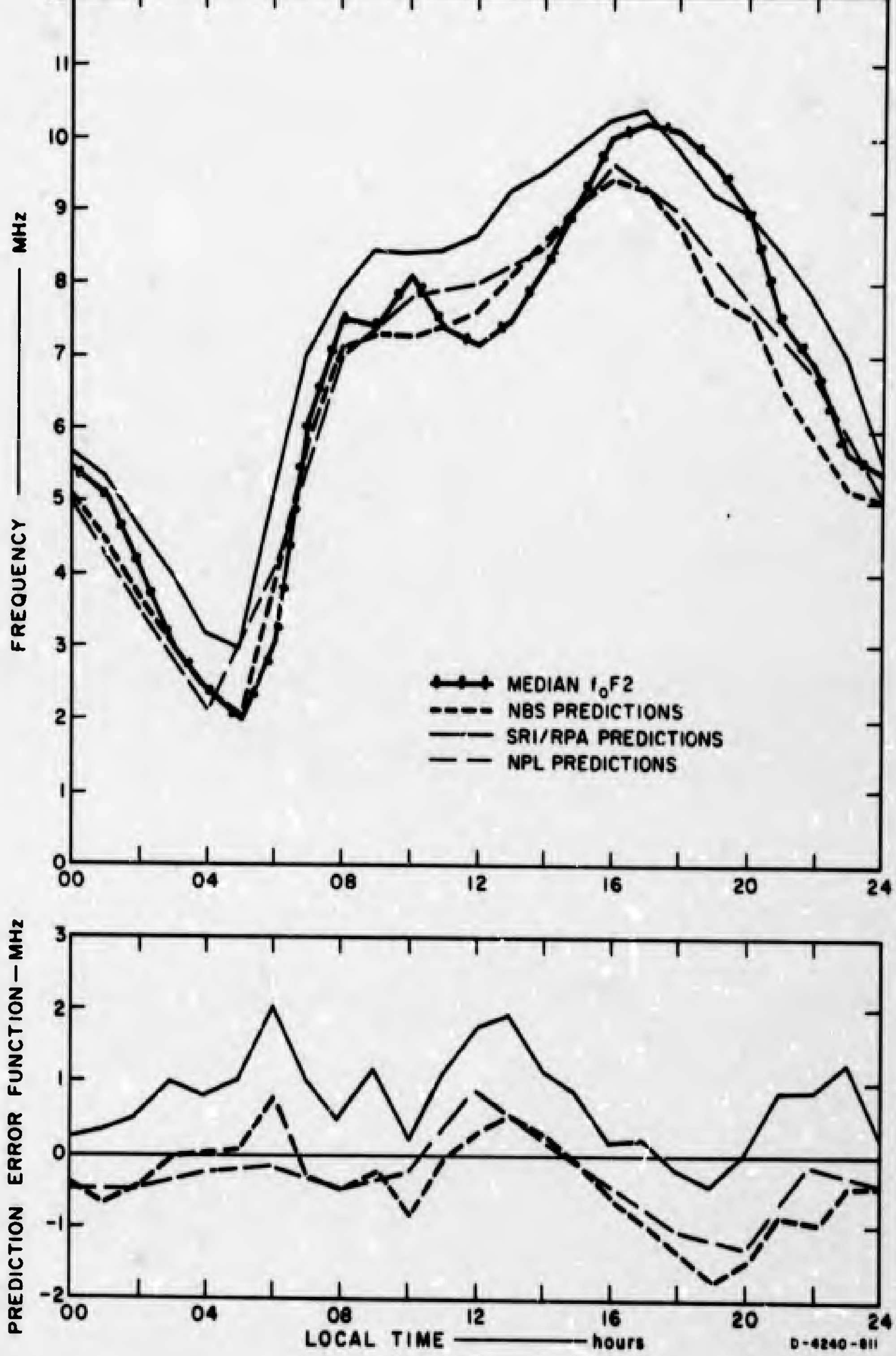

FIG. A-1(a) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — SEPTEMBER 1963

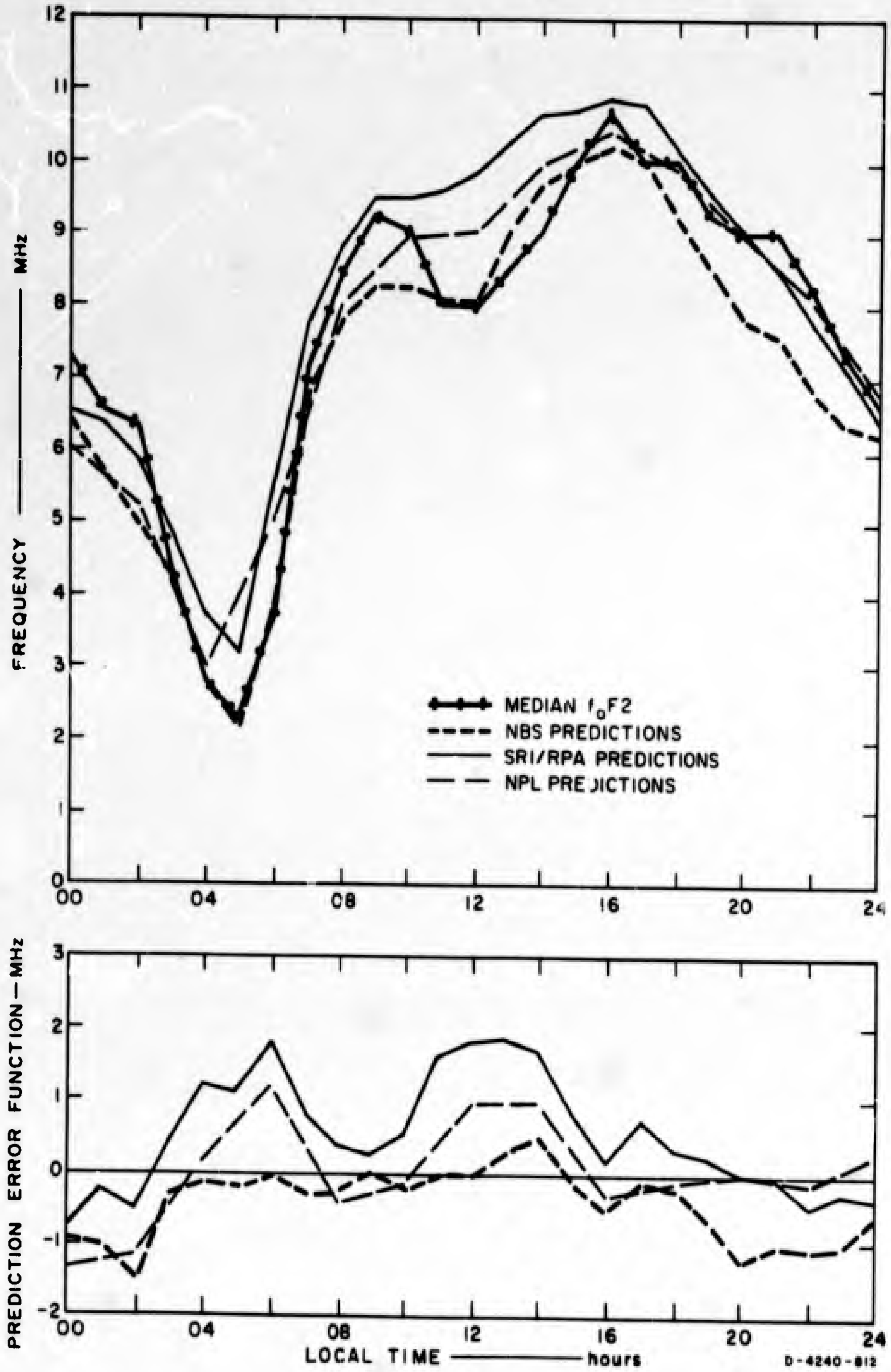

FIG. A-1(b) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — OCTOBER 1963

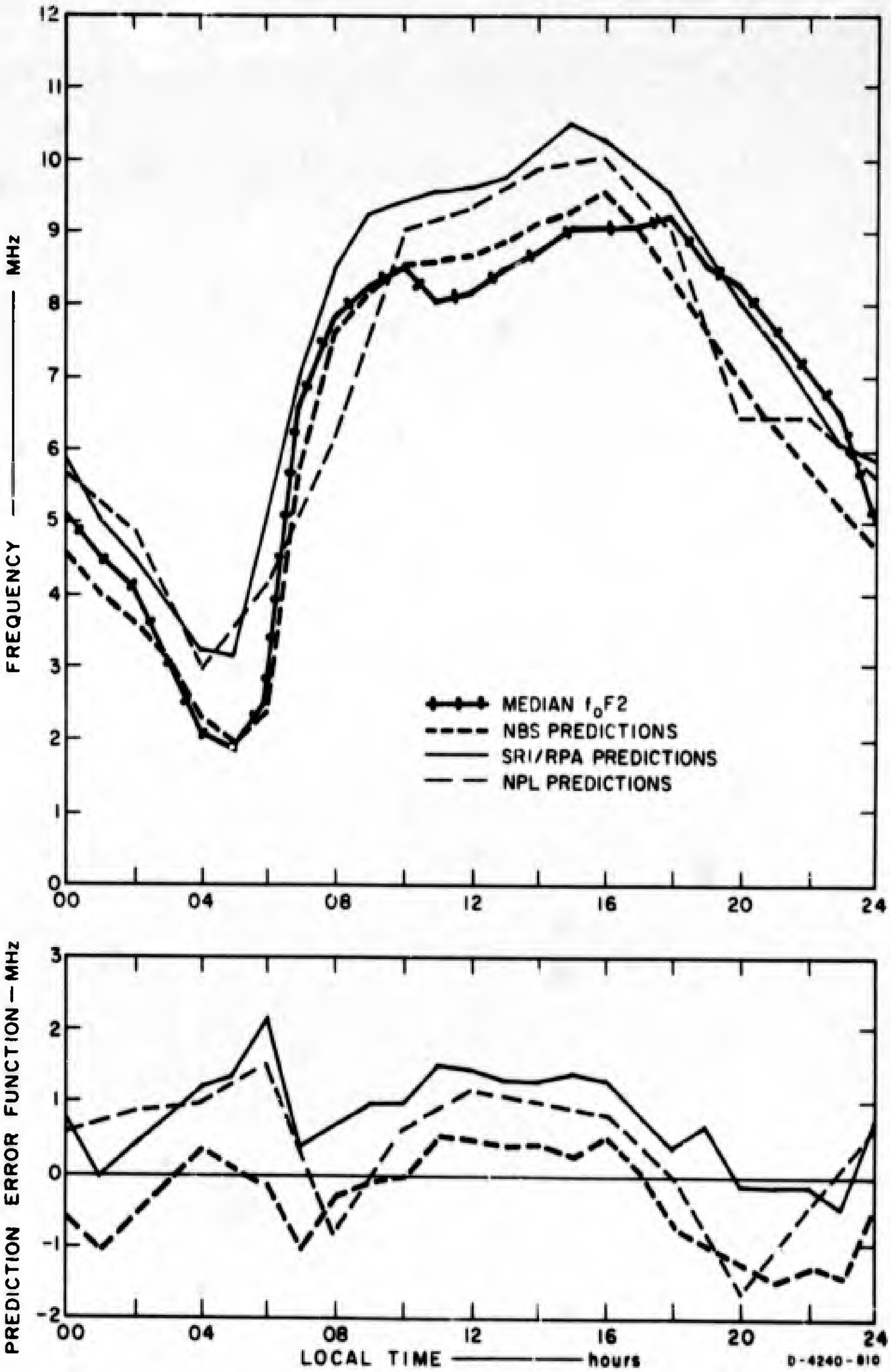

FIG. A-1(c) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — NOVEMBER 1963

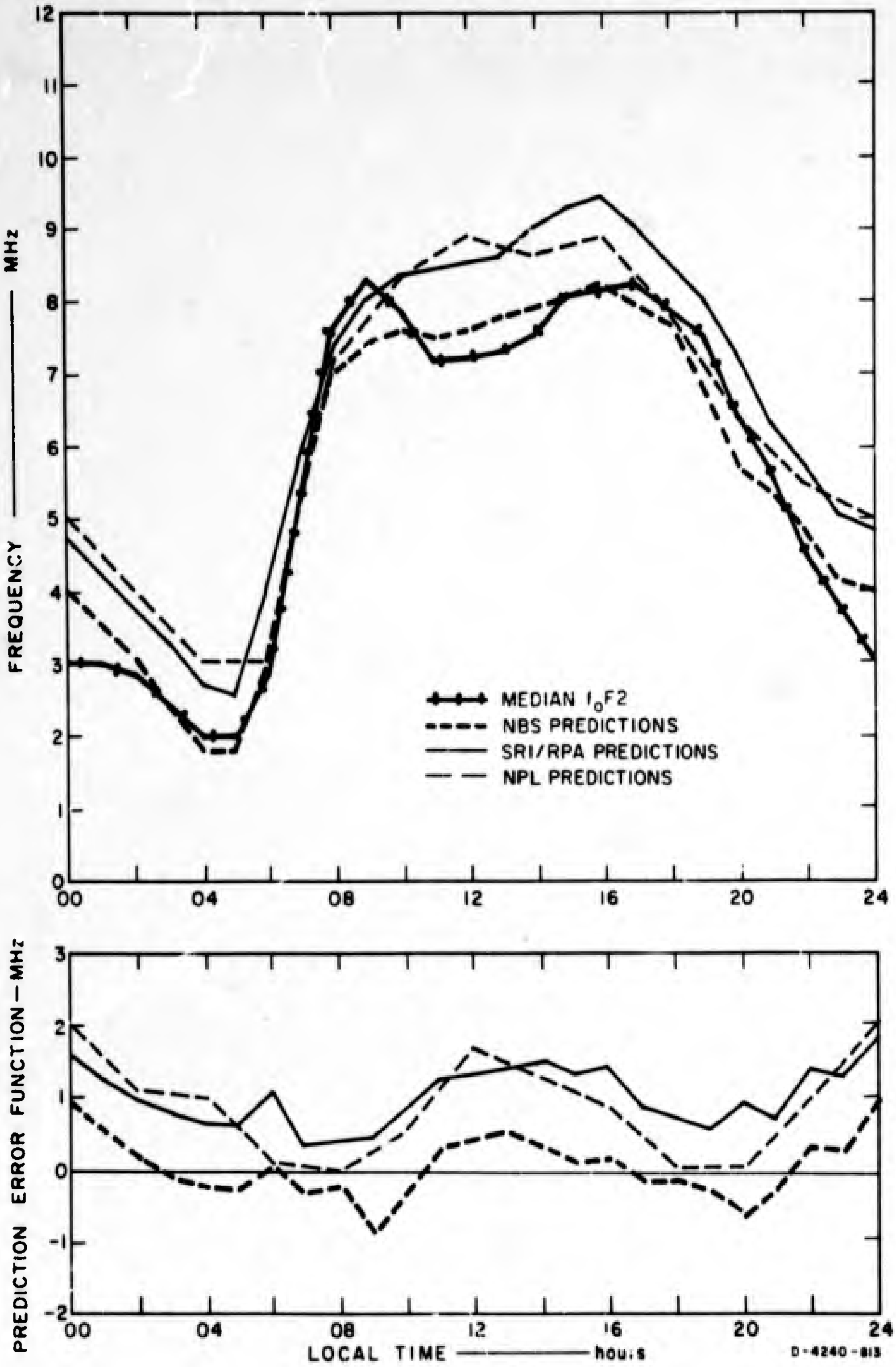

FIG. A-1(d) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — DECEMBER 1963

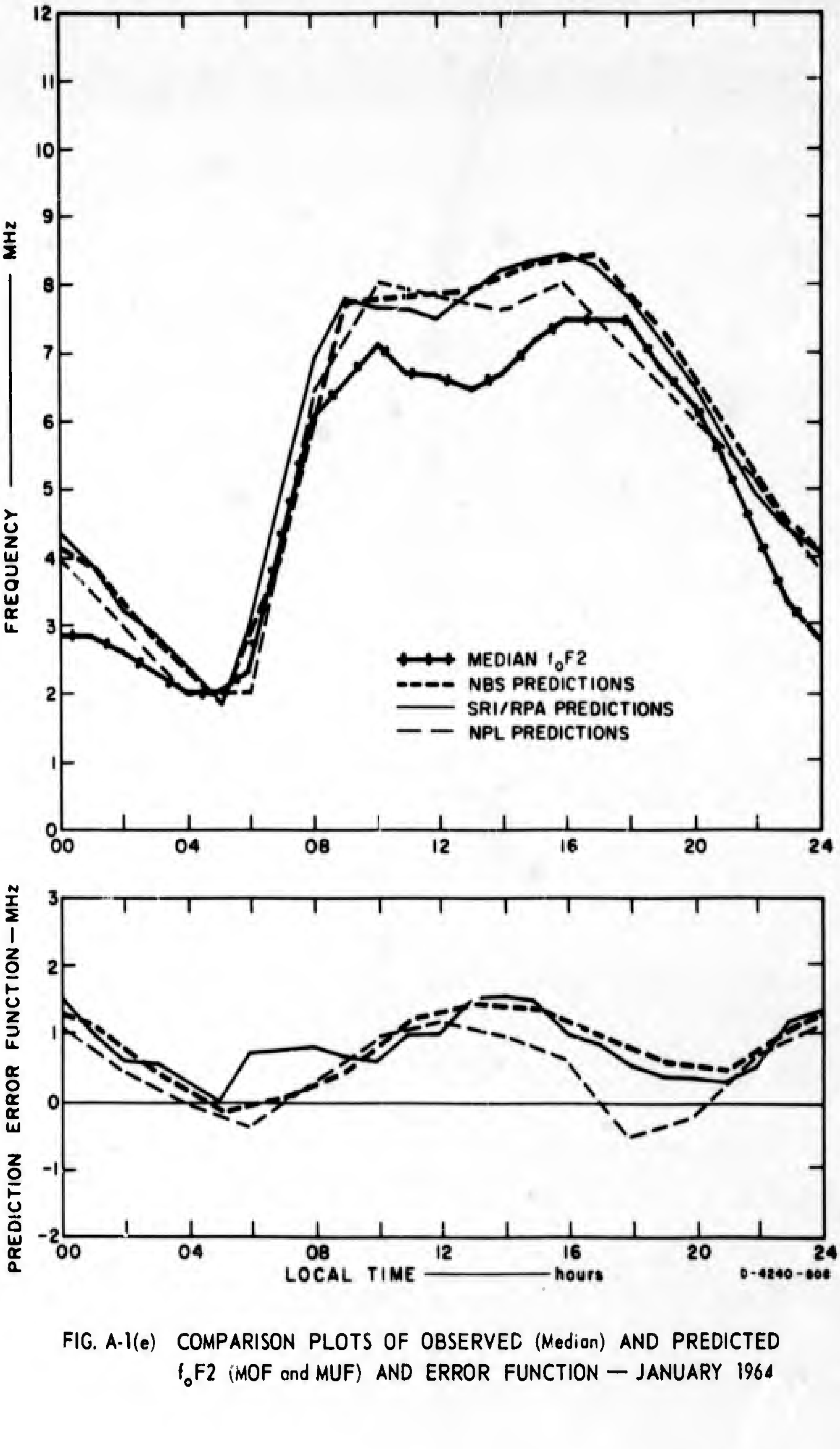

FIG. A-1(e) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — JANUARY 1964

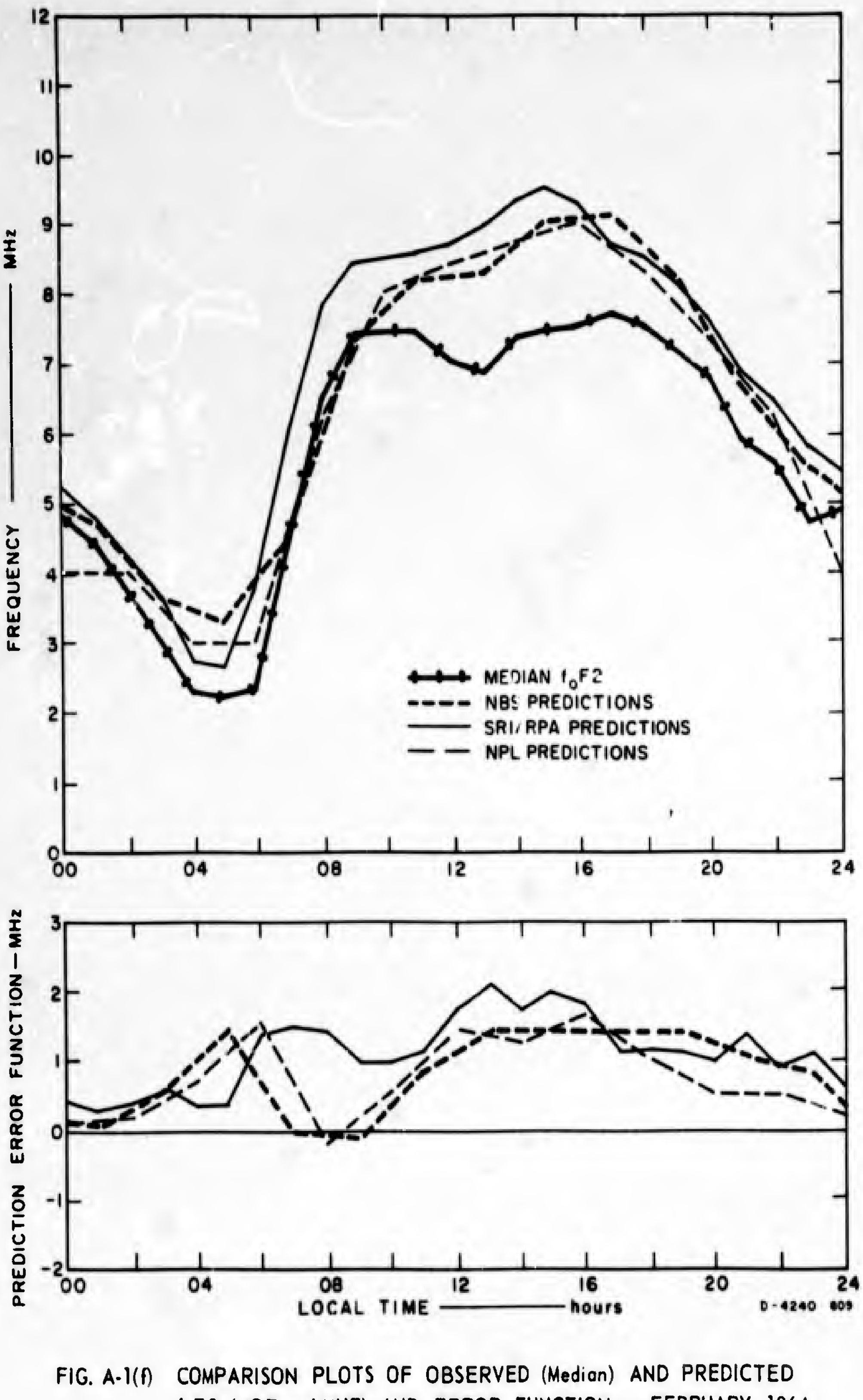

FIG. A-1(f) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION -- FEBRUARY 1964

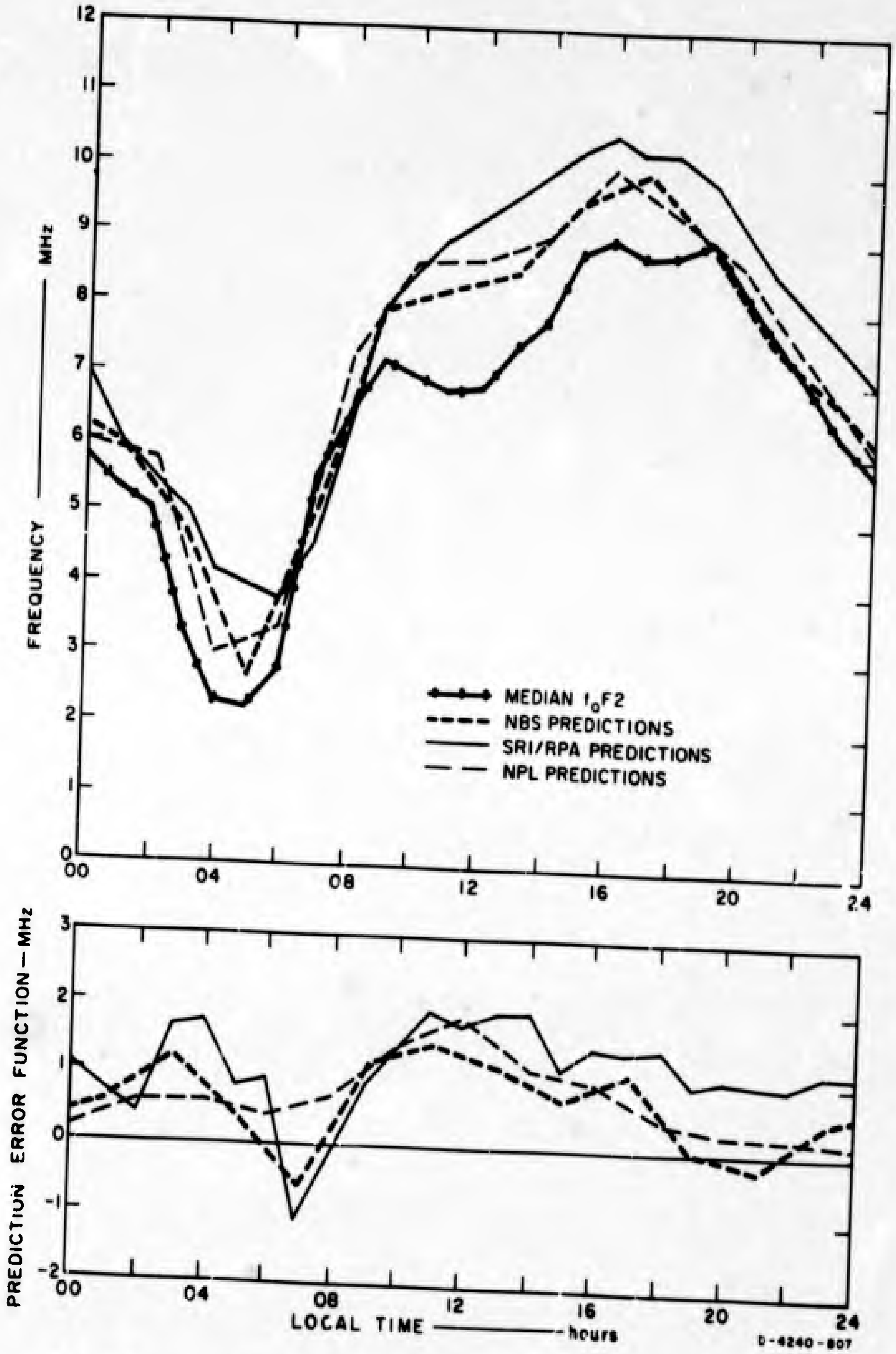

FIG. A-1(g) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — MARCH 1964

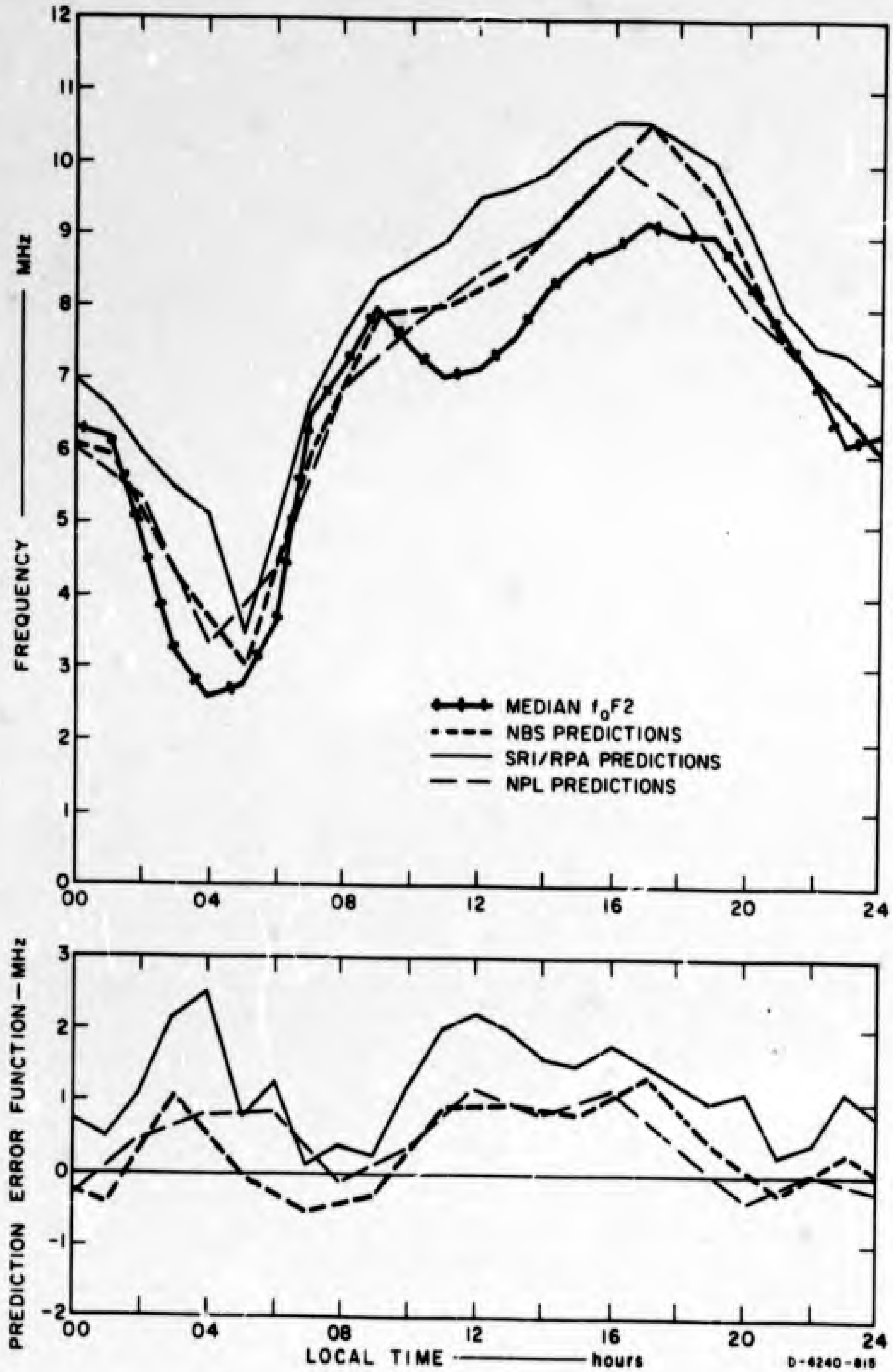

FIG. A-1(h) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — APRIL 1964

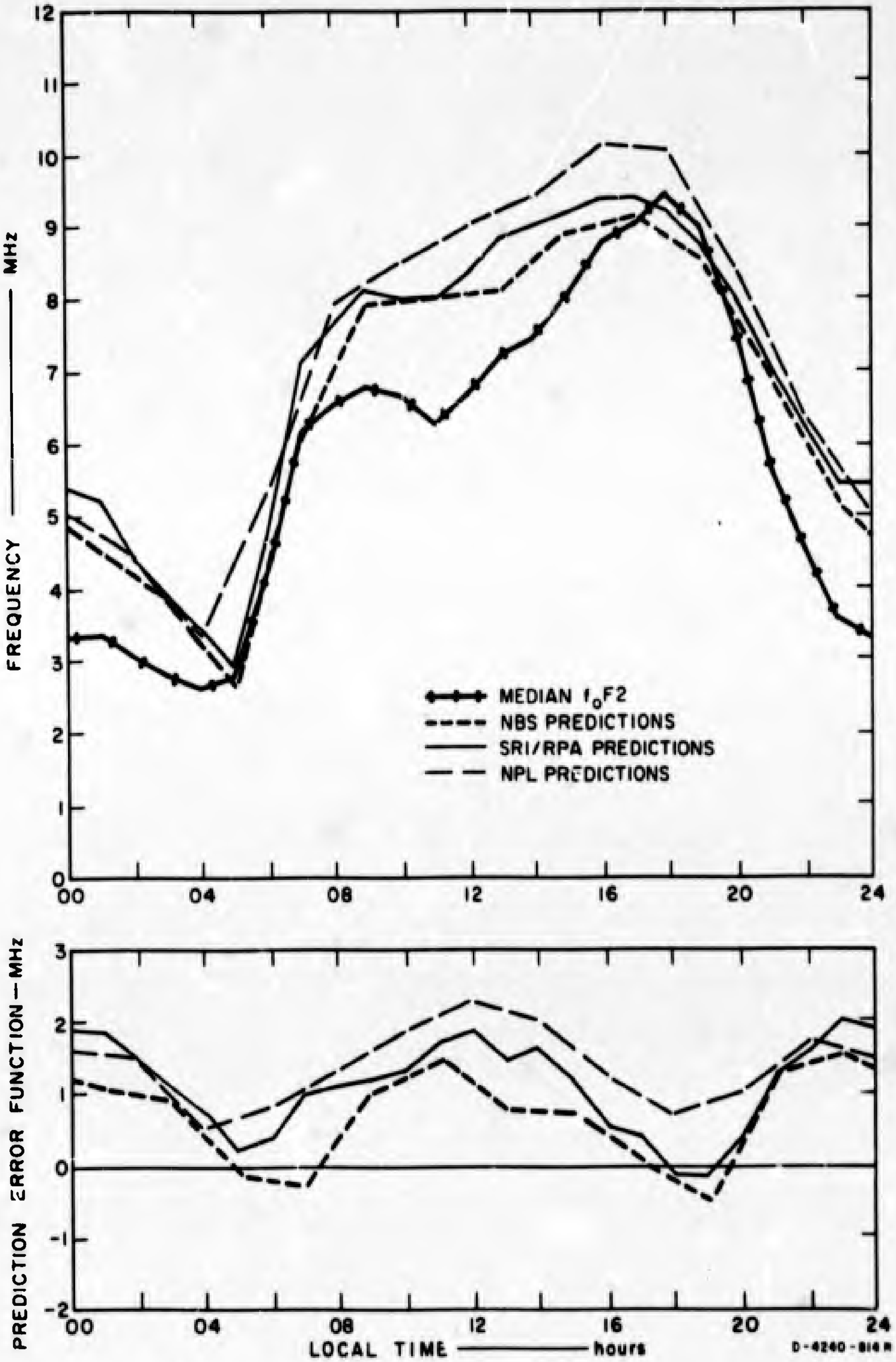

FIG. A-1(i) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — MAY 1964

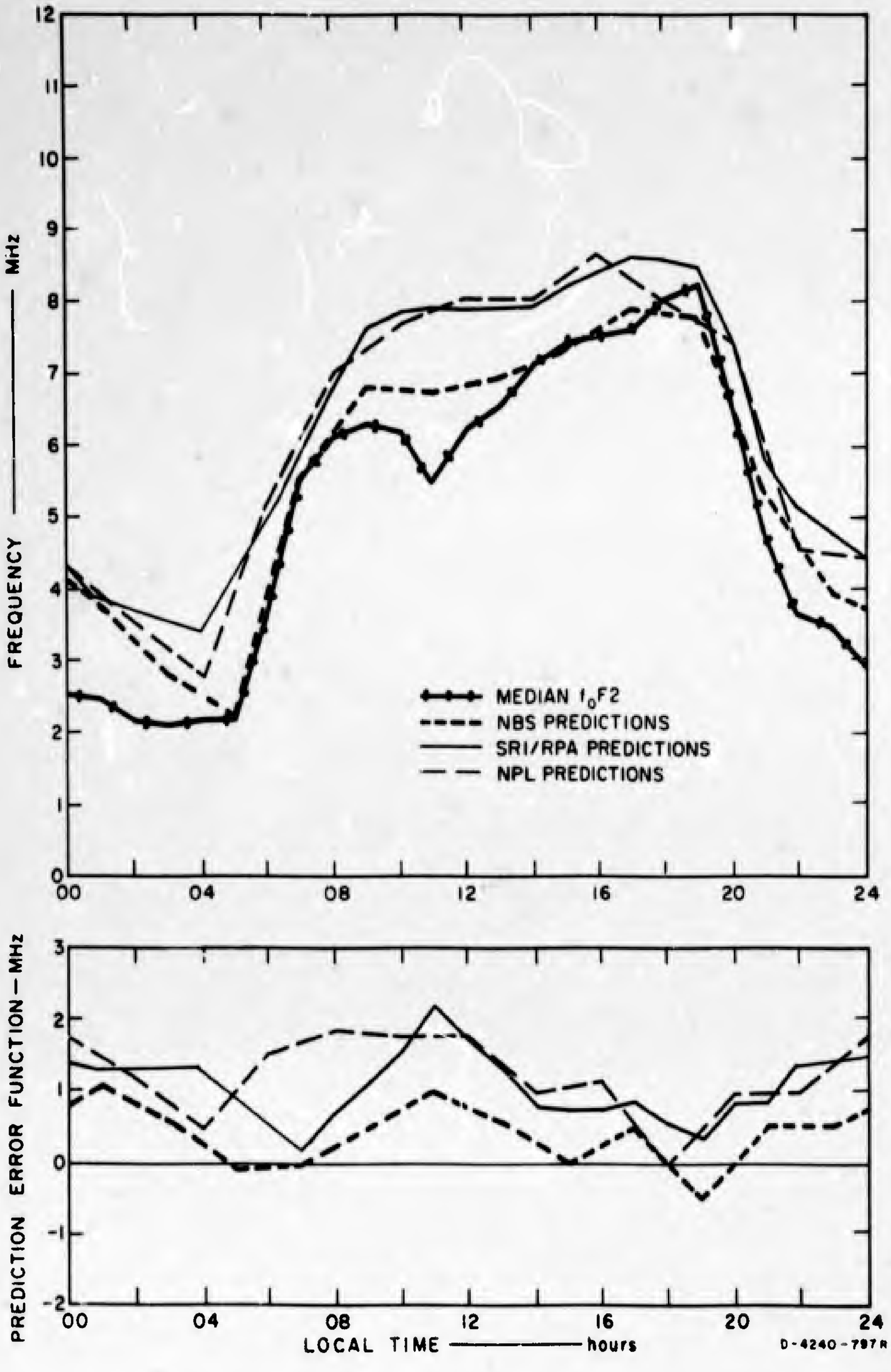

FIG. A-1(j) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — JUNE 1964

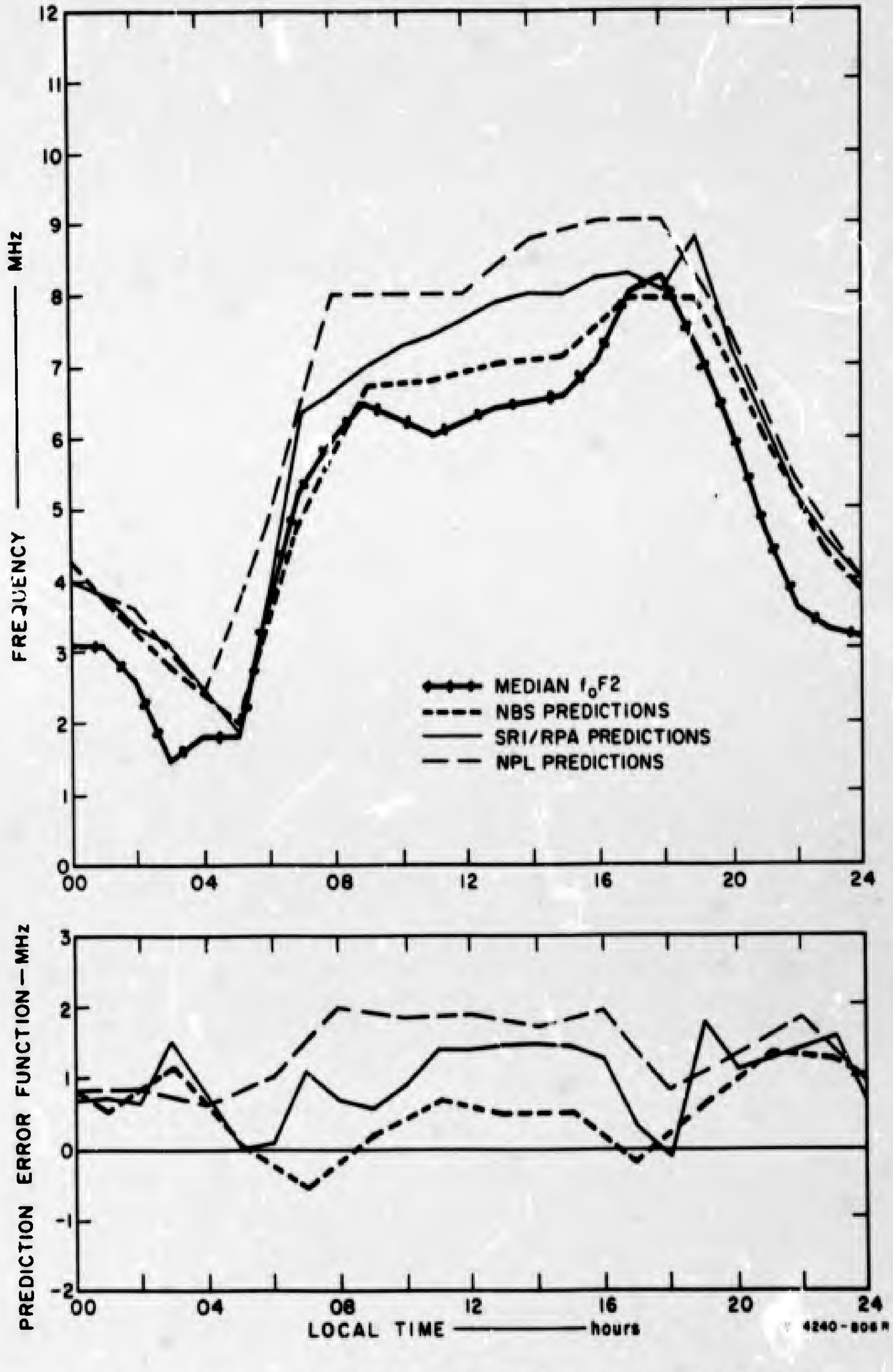

FIG. A-1(k) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — JULY 1964

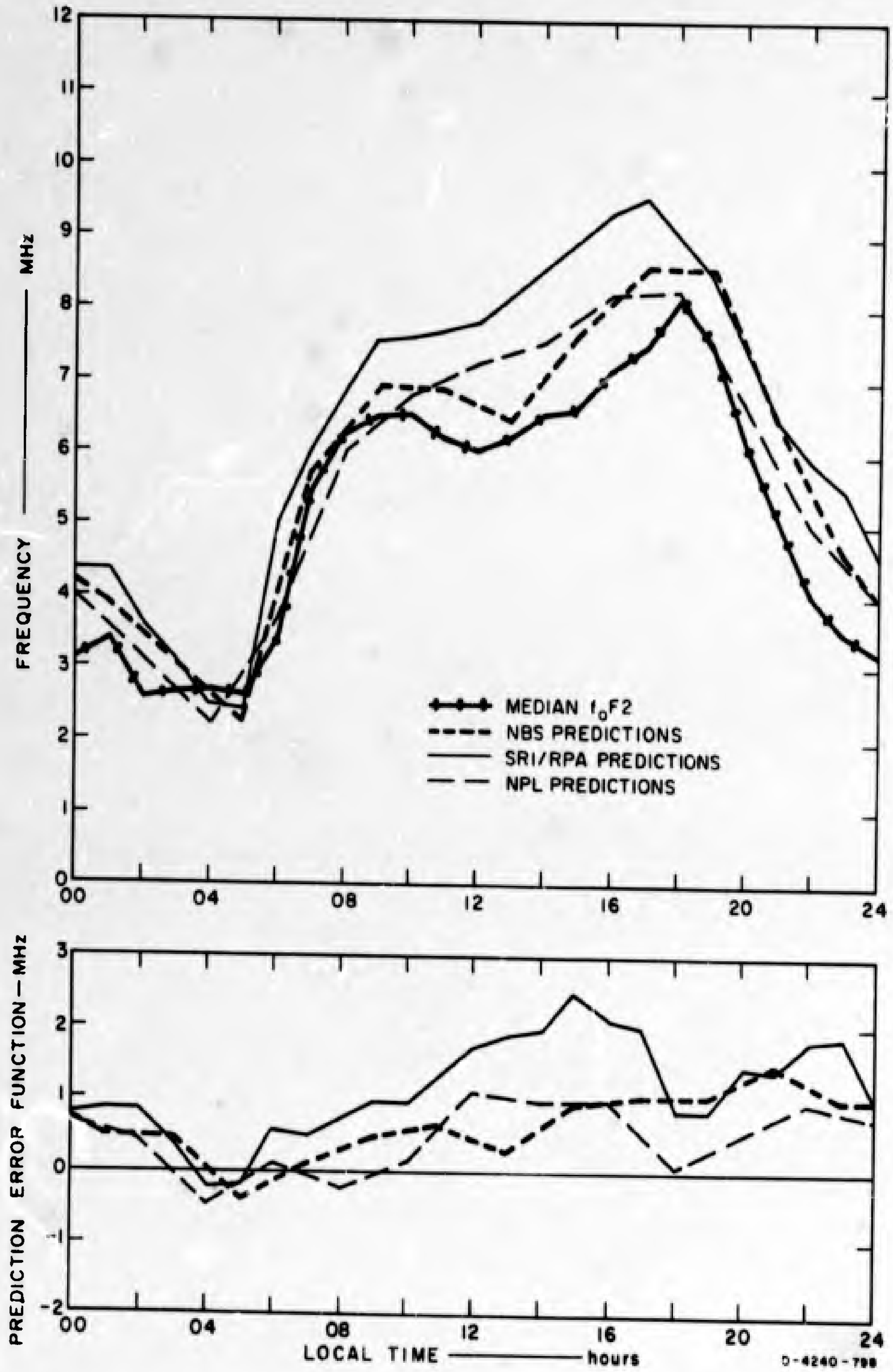

FIG. A-1(I) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION -- AUGUST 1964

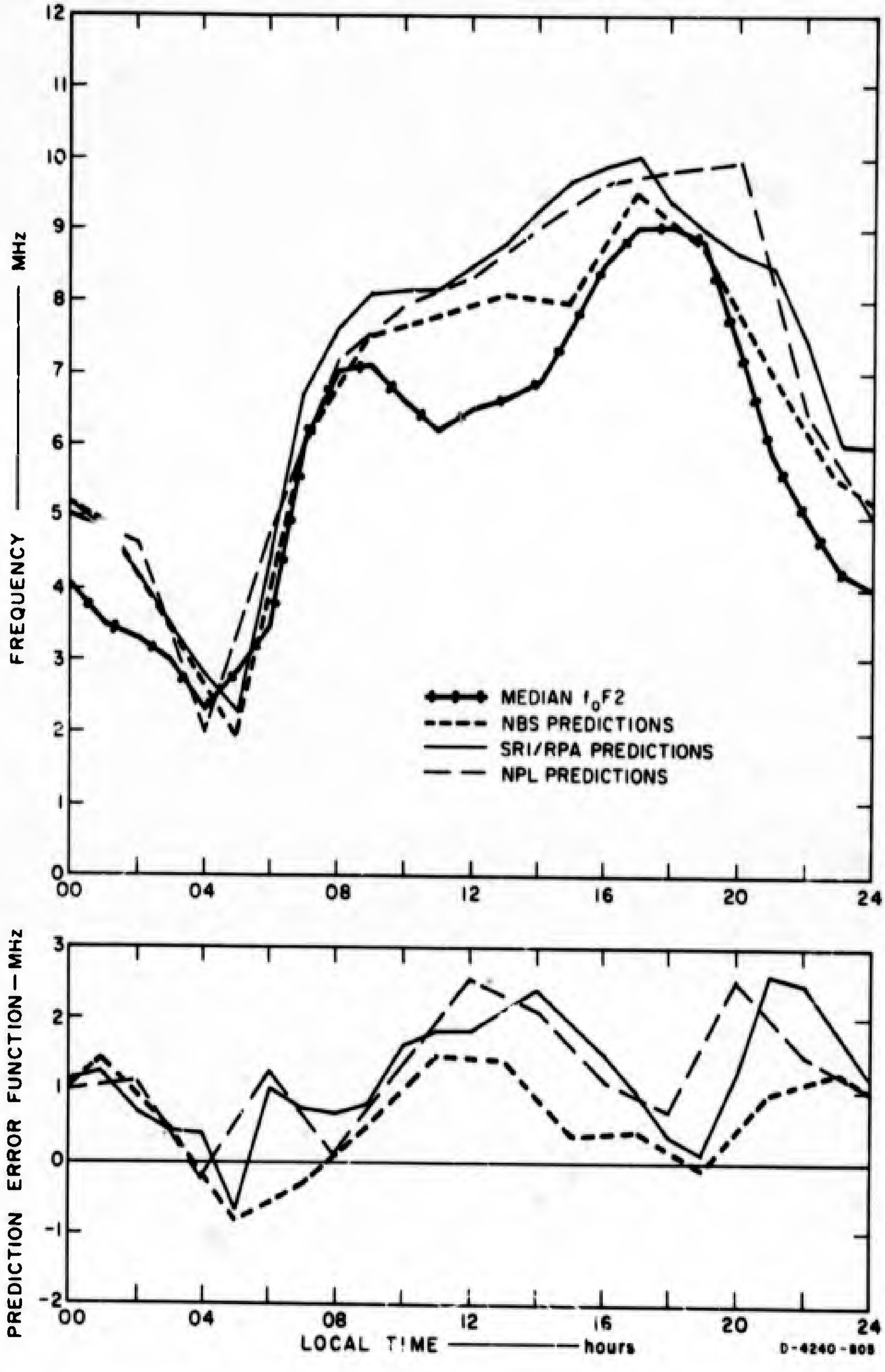

FIG. A-1(m) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — SEPTEMBER 1964

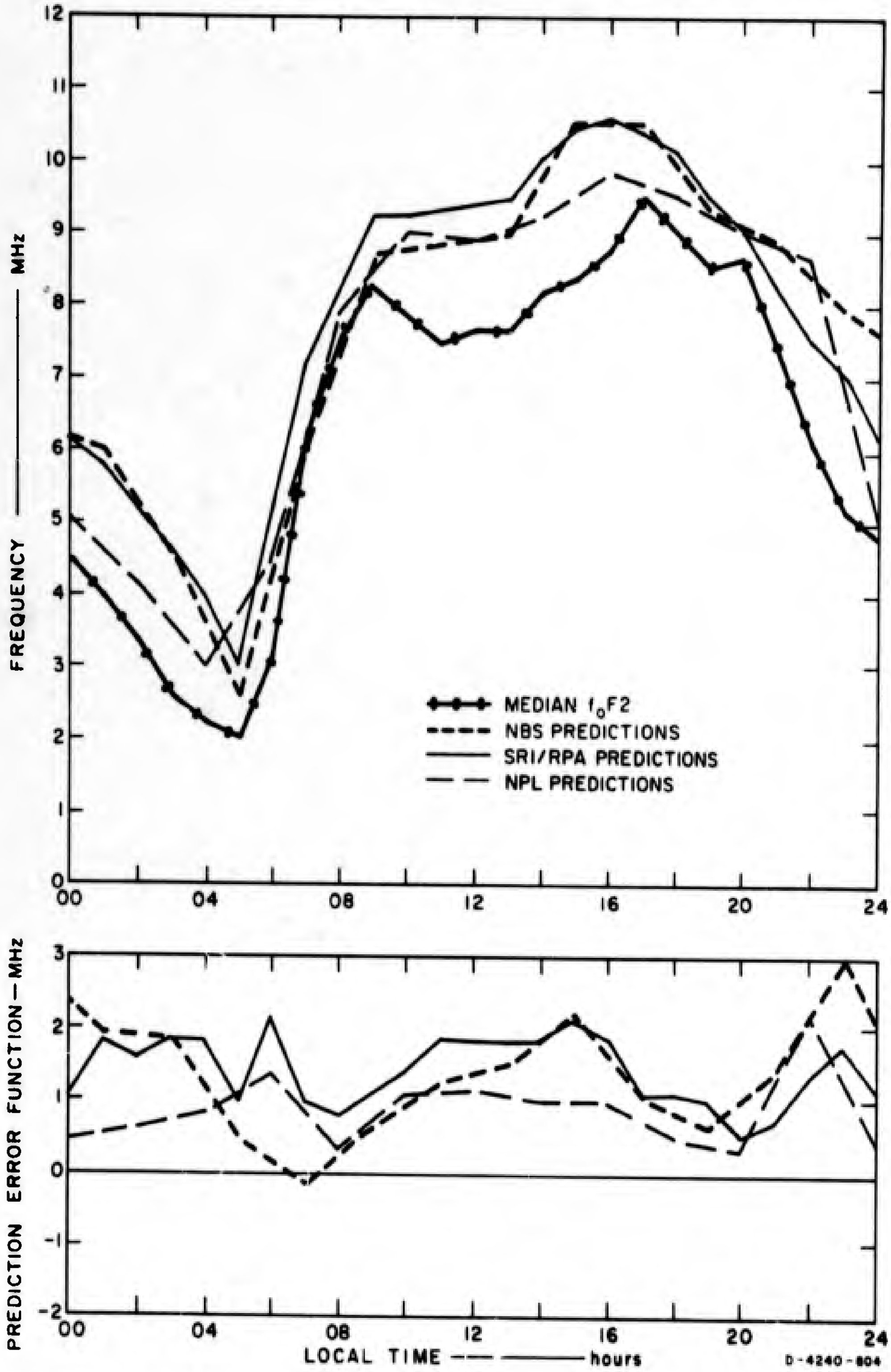

FIG. A-1(n) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — OCTOBER 1964

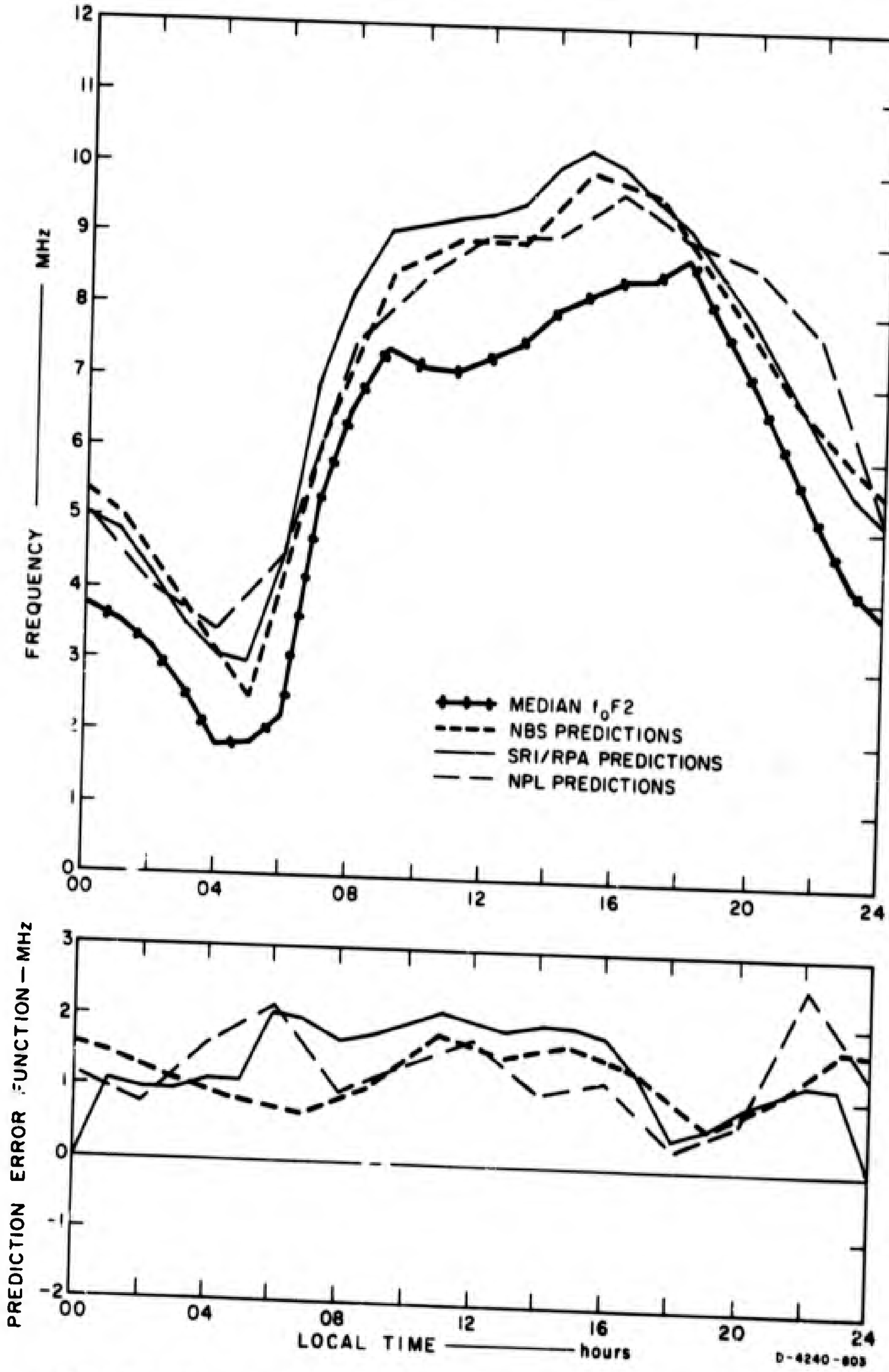

FIG. A-1(o) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — NOVEMBER 1964

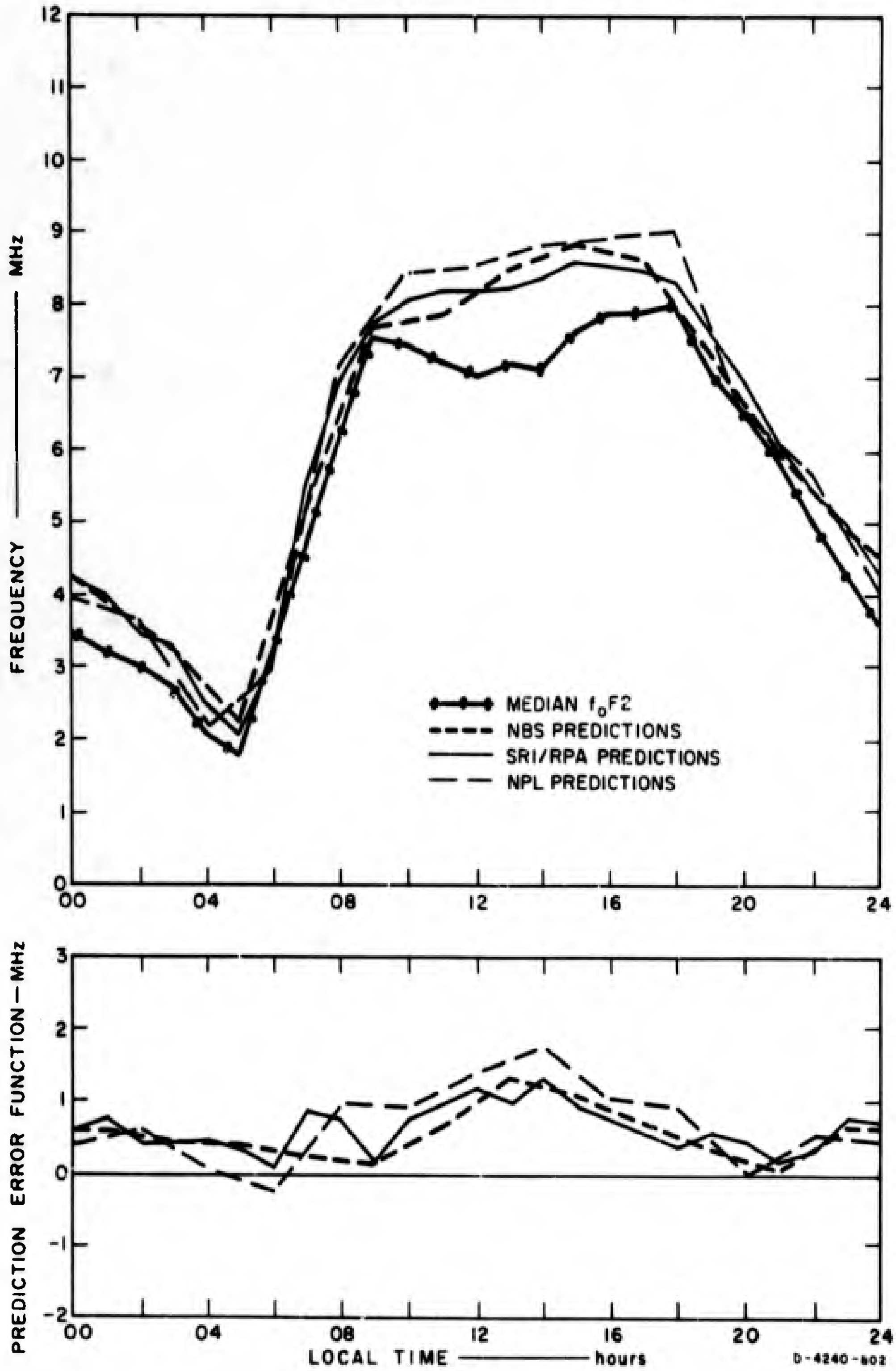

FIG. A-1(p) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — DECEMBER 1964

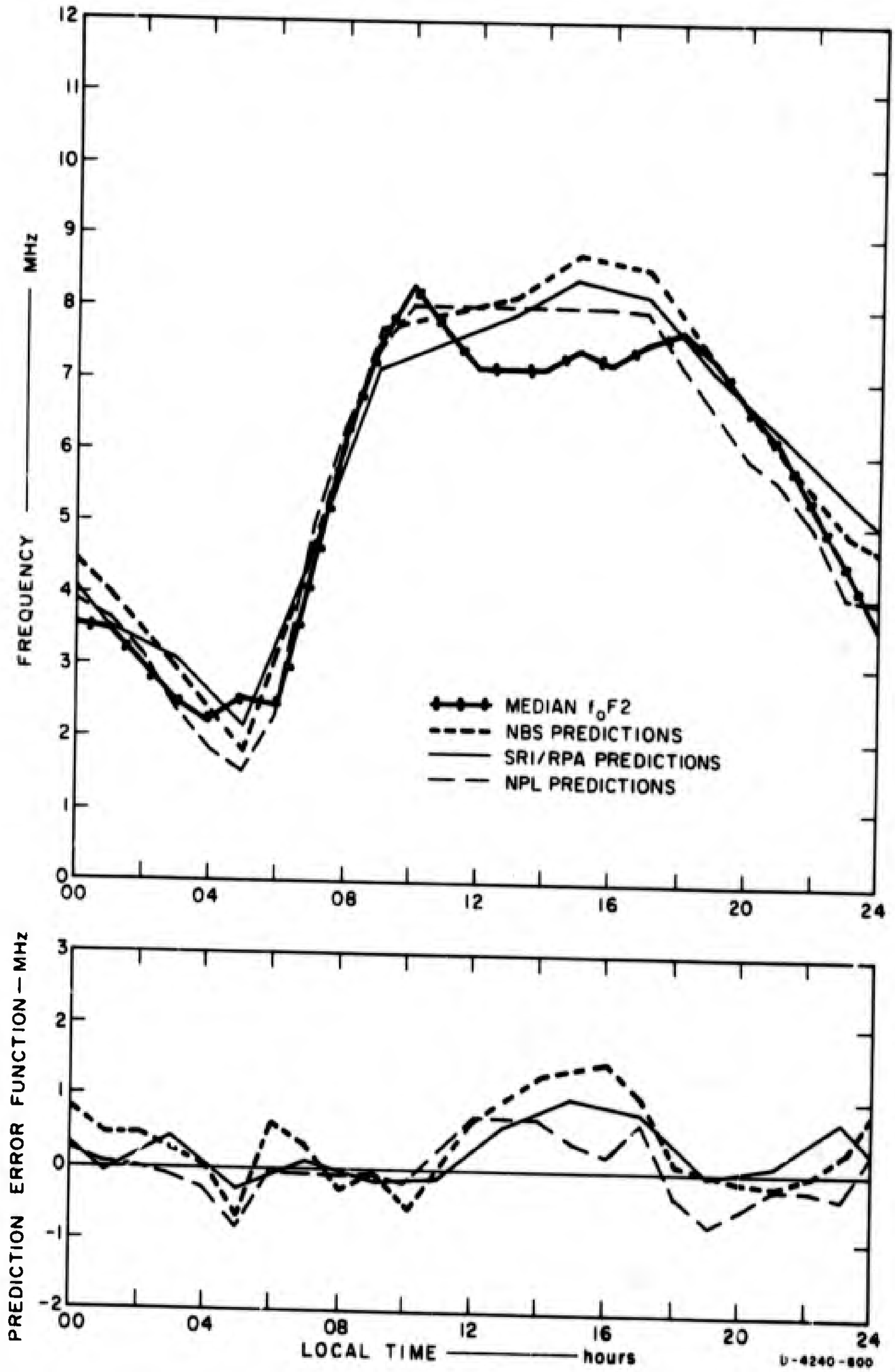

FIG. A-1(q) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — JANUARY 1965

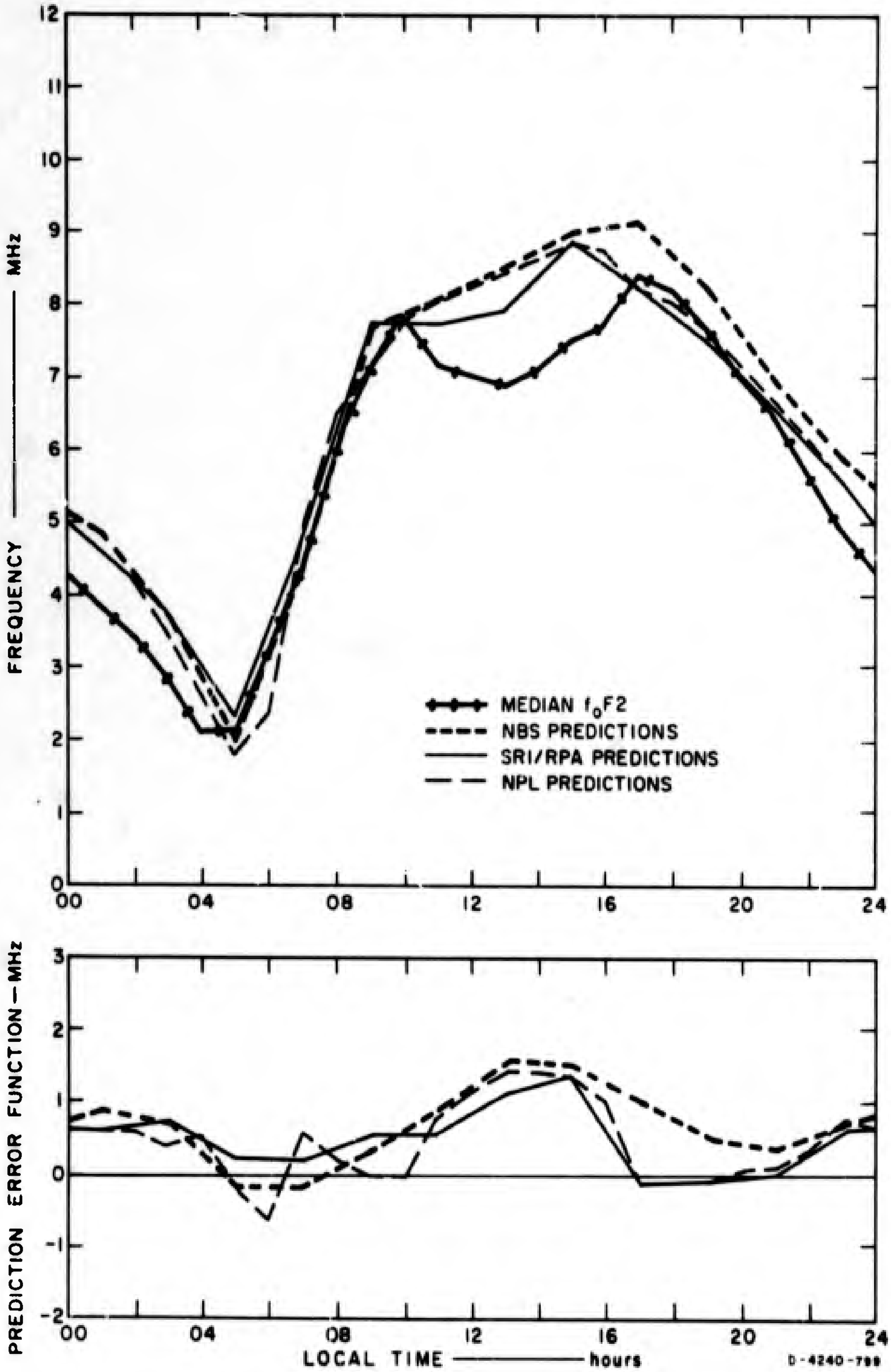

FIG. A-1(r) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_0F2 (MOF and MUF) AND ERROR FUNCTION — FEBRUARY 1965

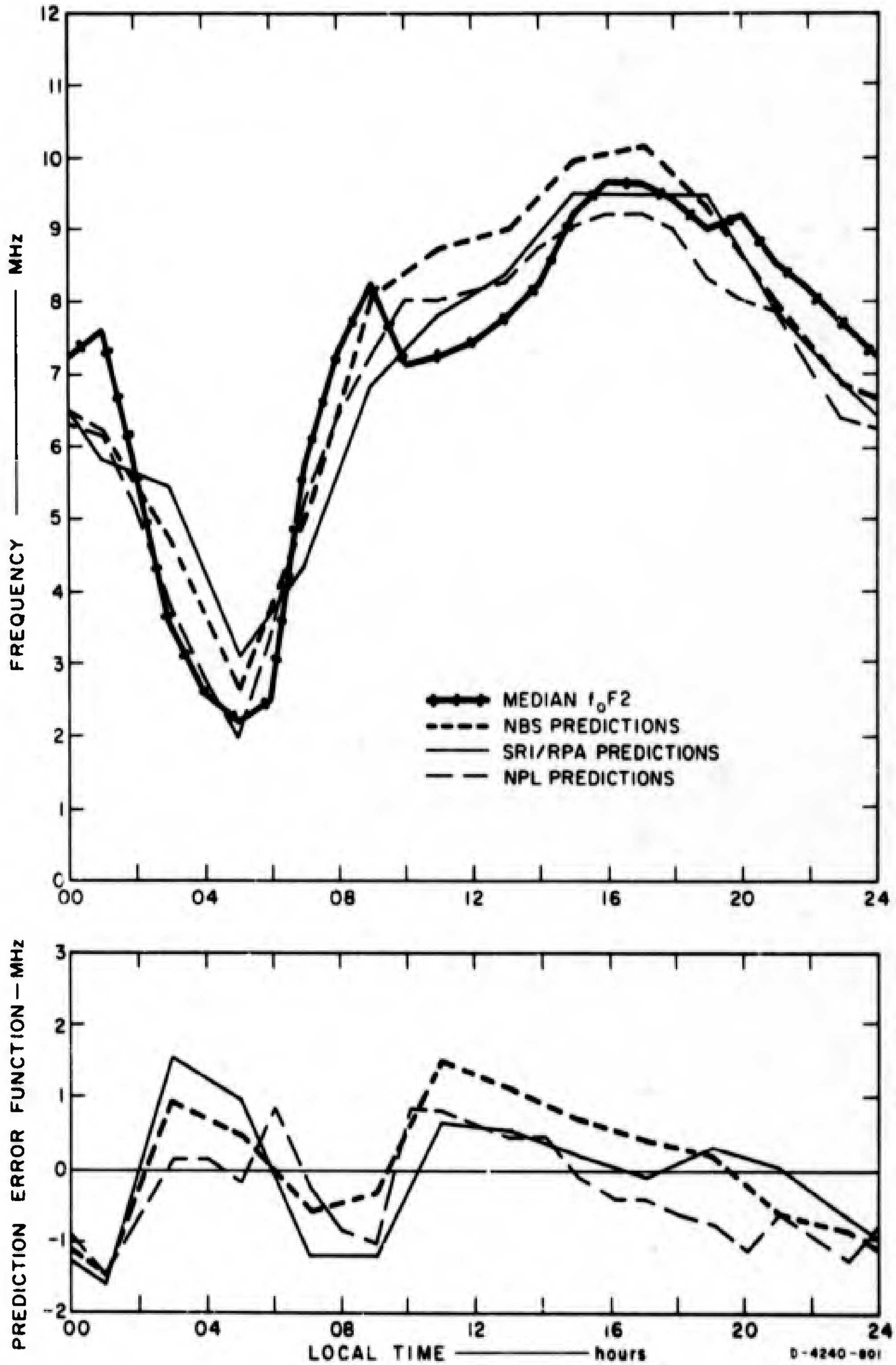

FIG. A-1(s) COMPARISON PLOTS OF OBSERVED (Median) AND PREDICTED f_oF2 (MOF and MUF) AND ERROR FUNCTION — MARCH 1965

APPENDIX B

COMPARISON PLOTS OF LUF AND LOF, WITH ERROR FUNCTION, USING C-2 DATA FROM SEPTEMBER 1963 THROUGH MARCH 1965

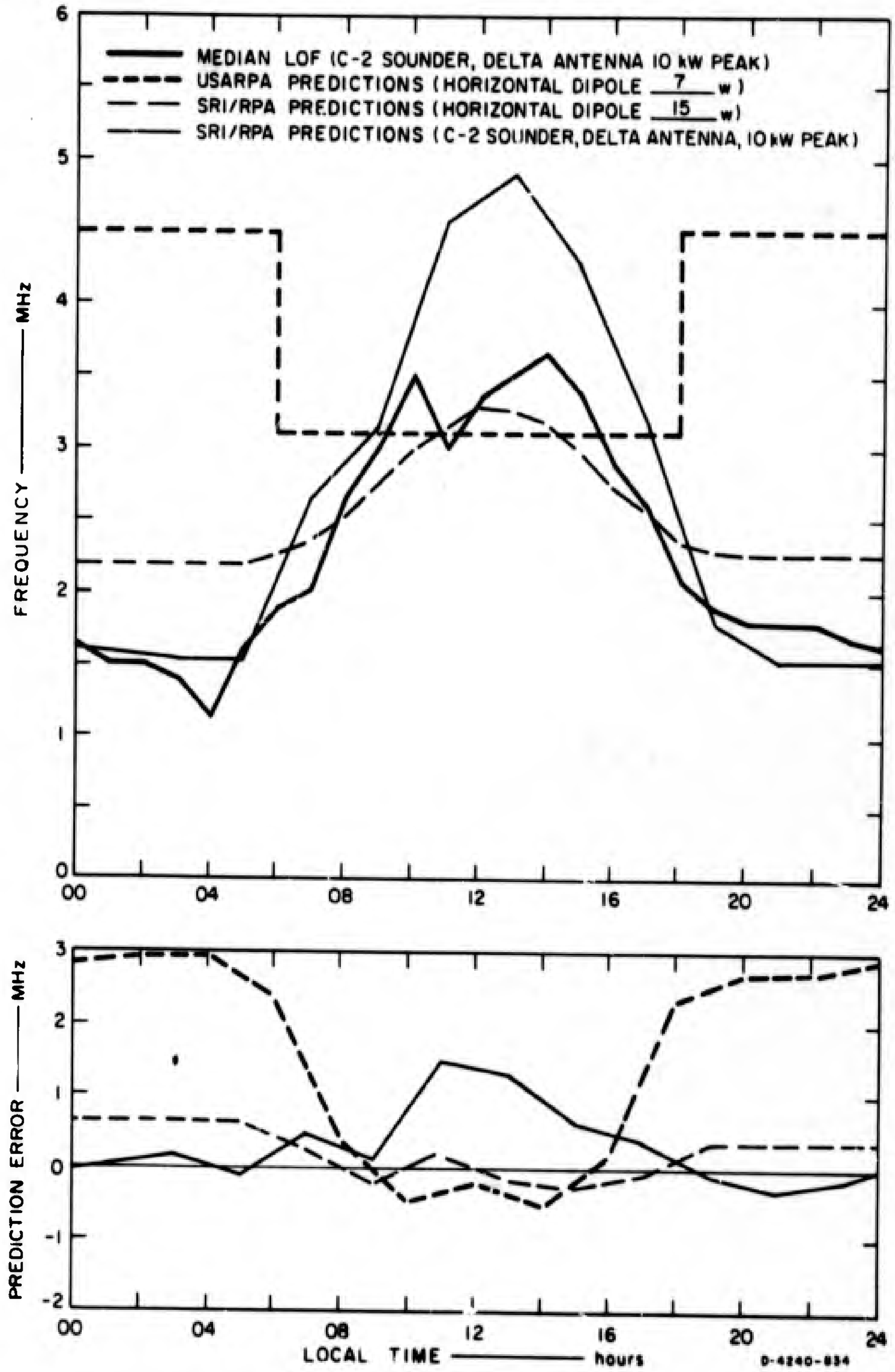

FIG. B-1(a) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — SEPTEMBER 1963

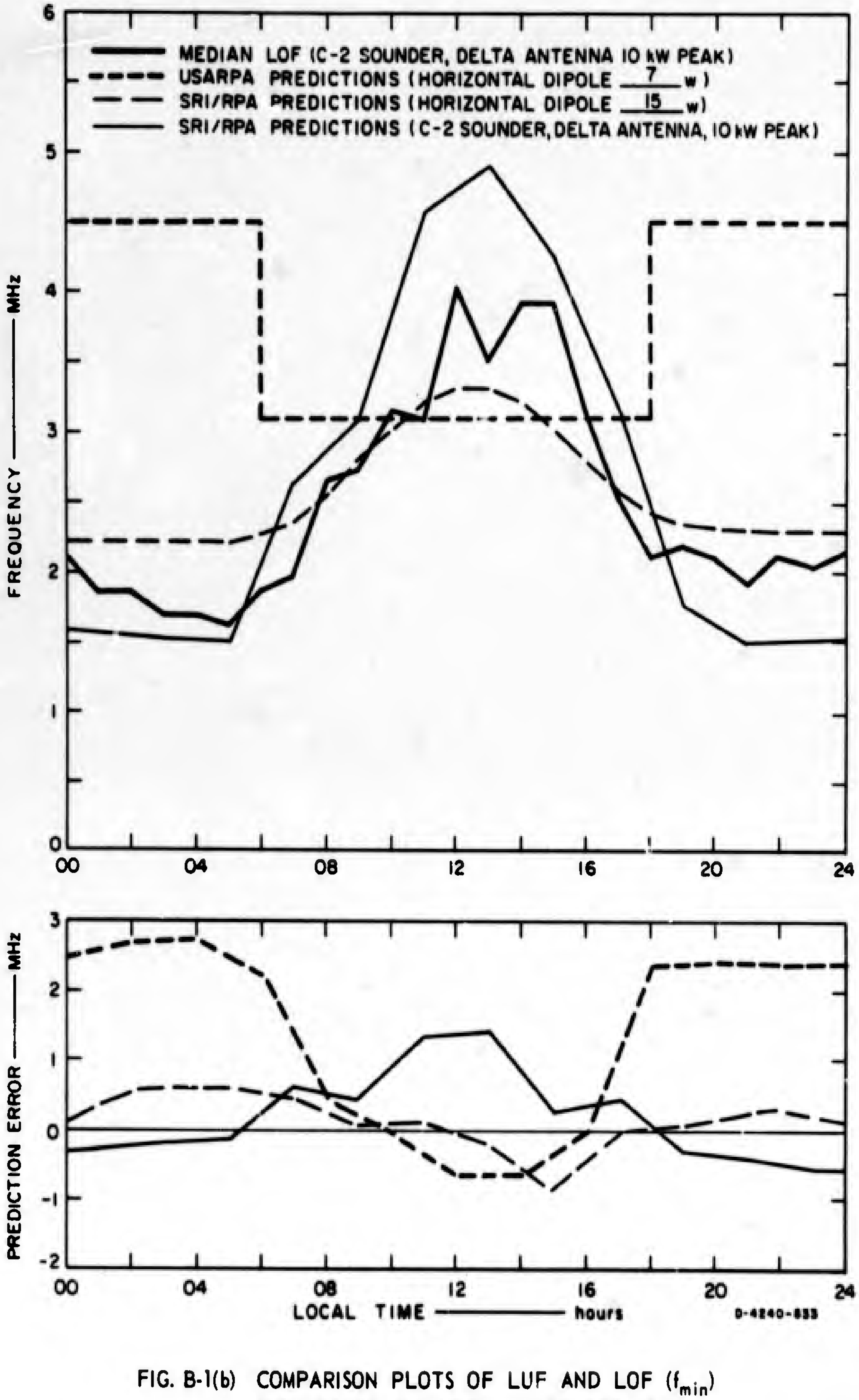

FIG. B-1(b) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — OCTOBER 1963

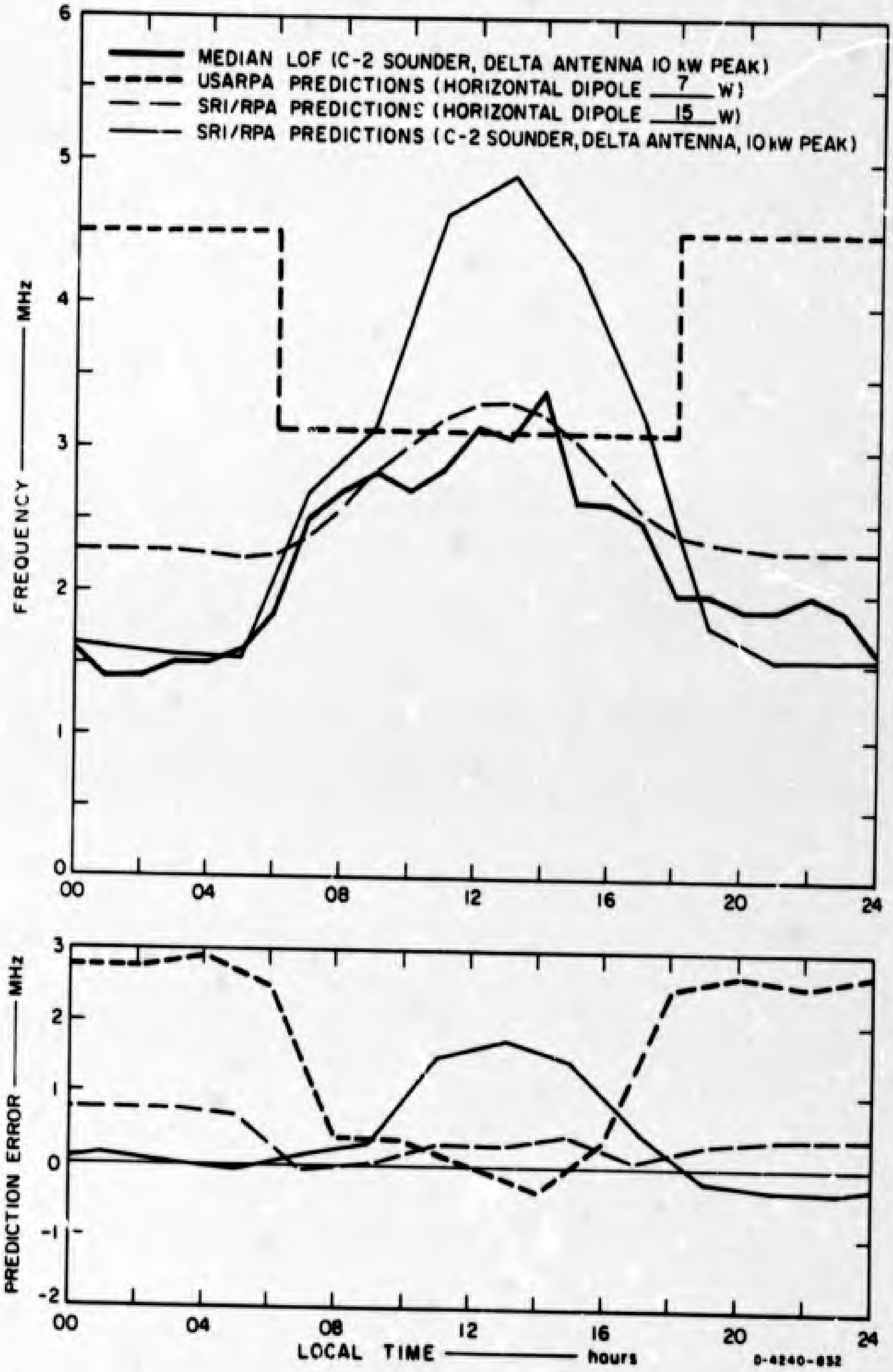

FIG. B-1(c) COMPARISON PLOTS OF LUF AND LOF (f_{min})
WITH ERROR FUNCTION — NOVEMBER 1963

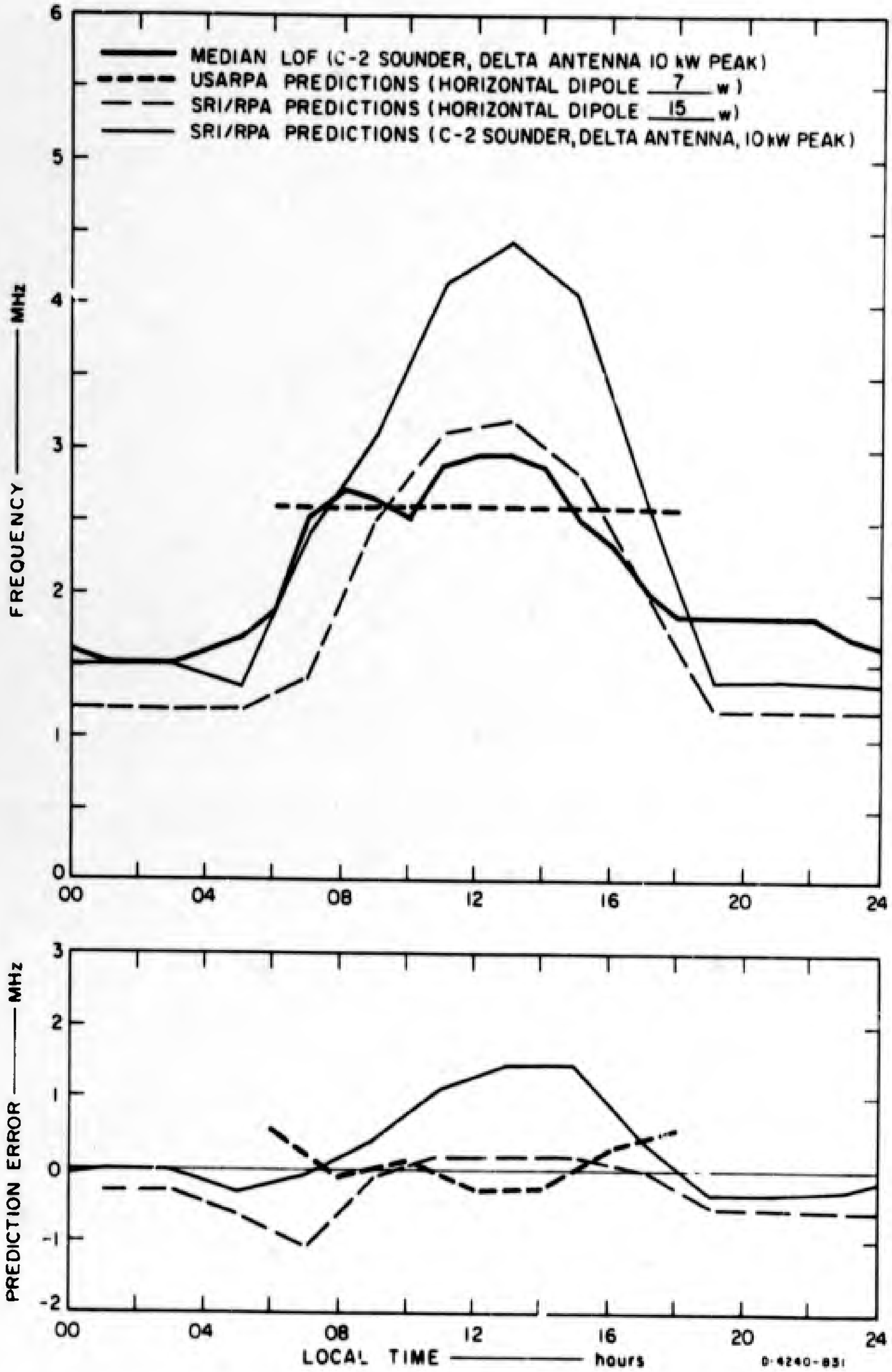

FIG. B-1(d) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — DECEMBER 1963

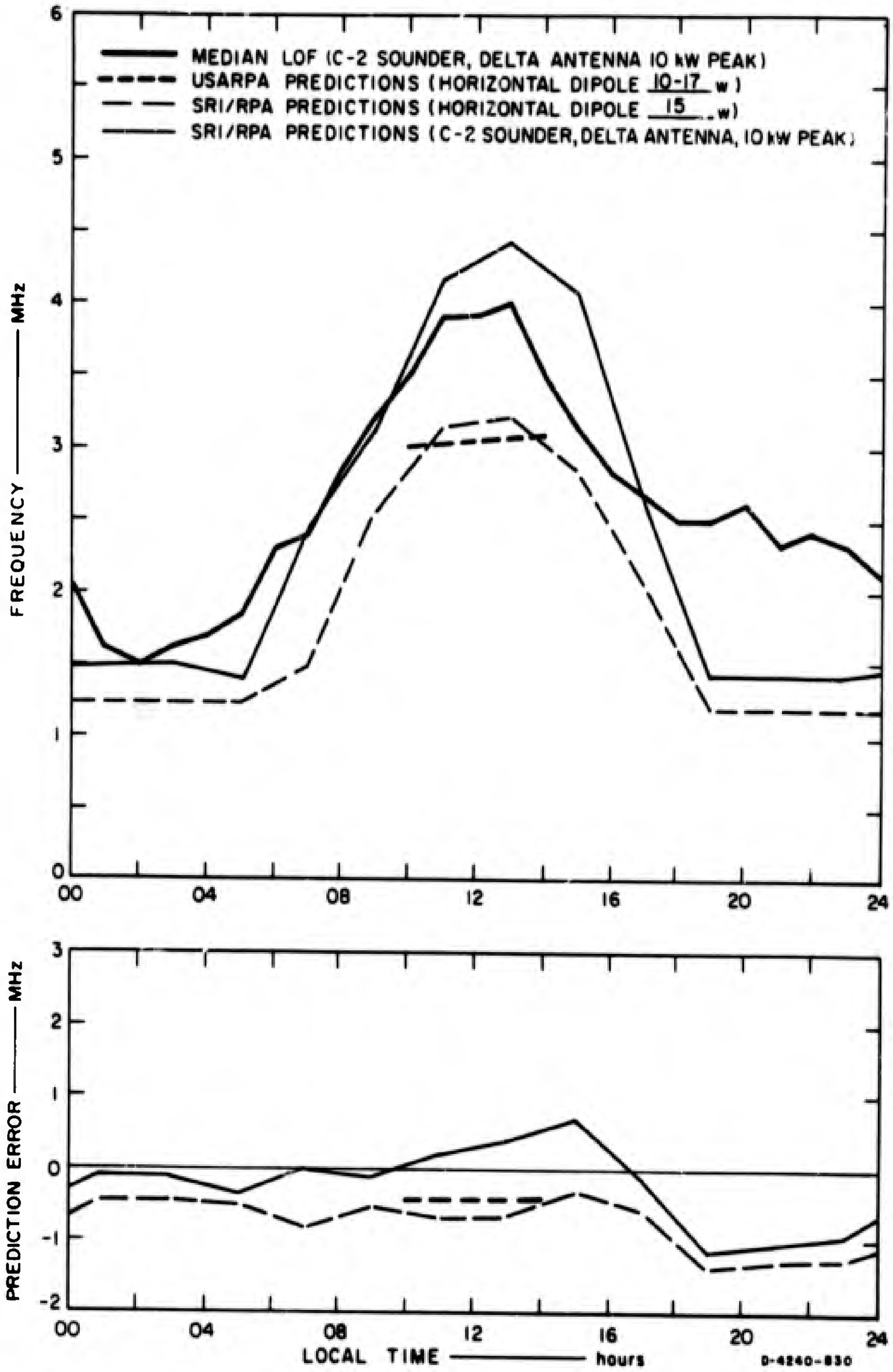

FIG. B-1(e) COMPARISON PLOTS OF LUF AND LOF (f_{min})
WITH ERROR FUNCTION — JANUARY 1964

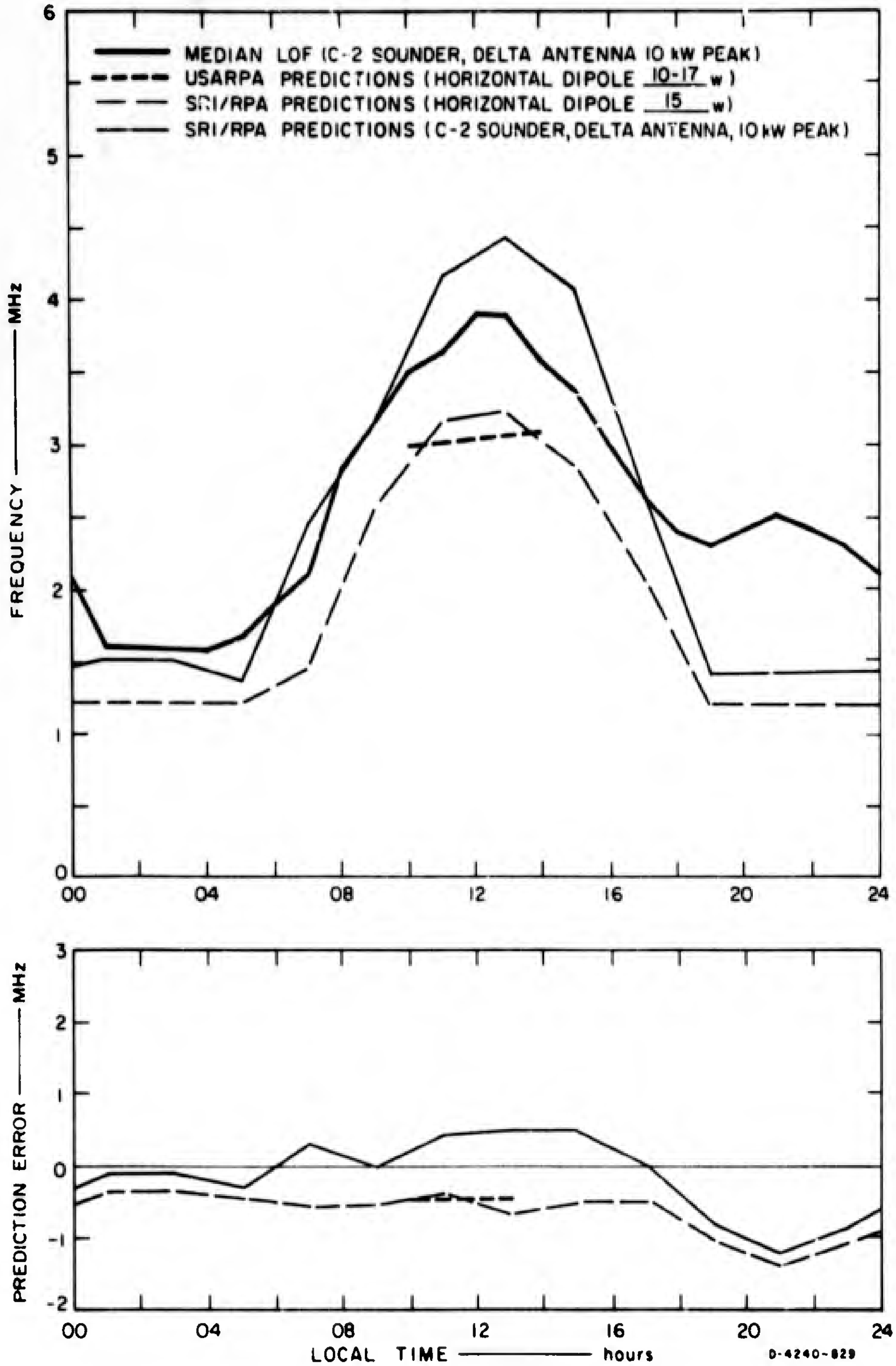

FIG. B-1(f) COMPARISON PLOTS OF LUF AND LOF (f_{min})
WITH ERROR FUNCTION — FEBRUARY 1964

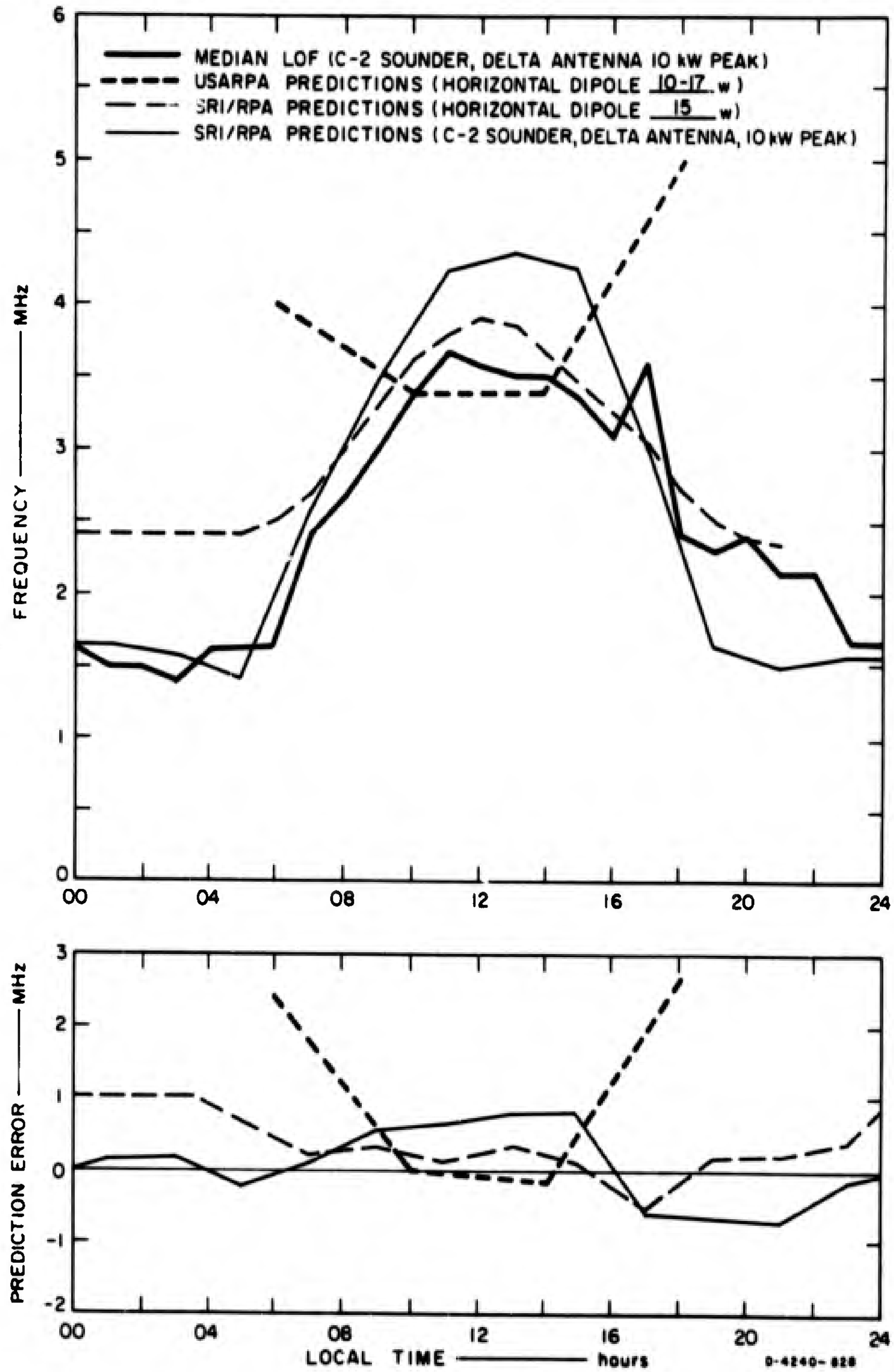

FIG. B-1(g) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — MARCH 1964

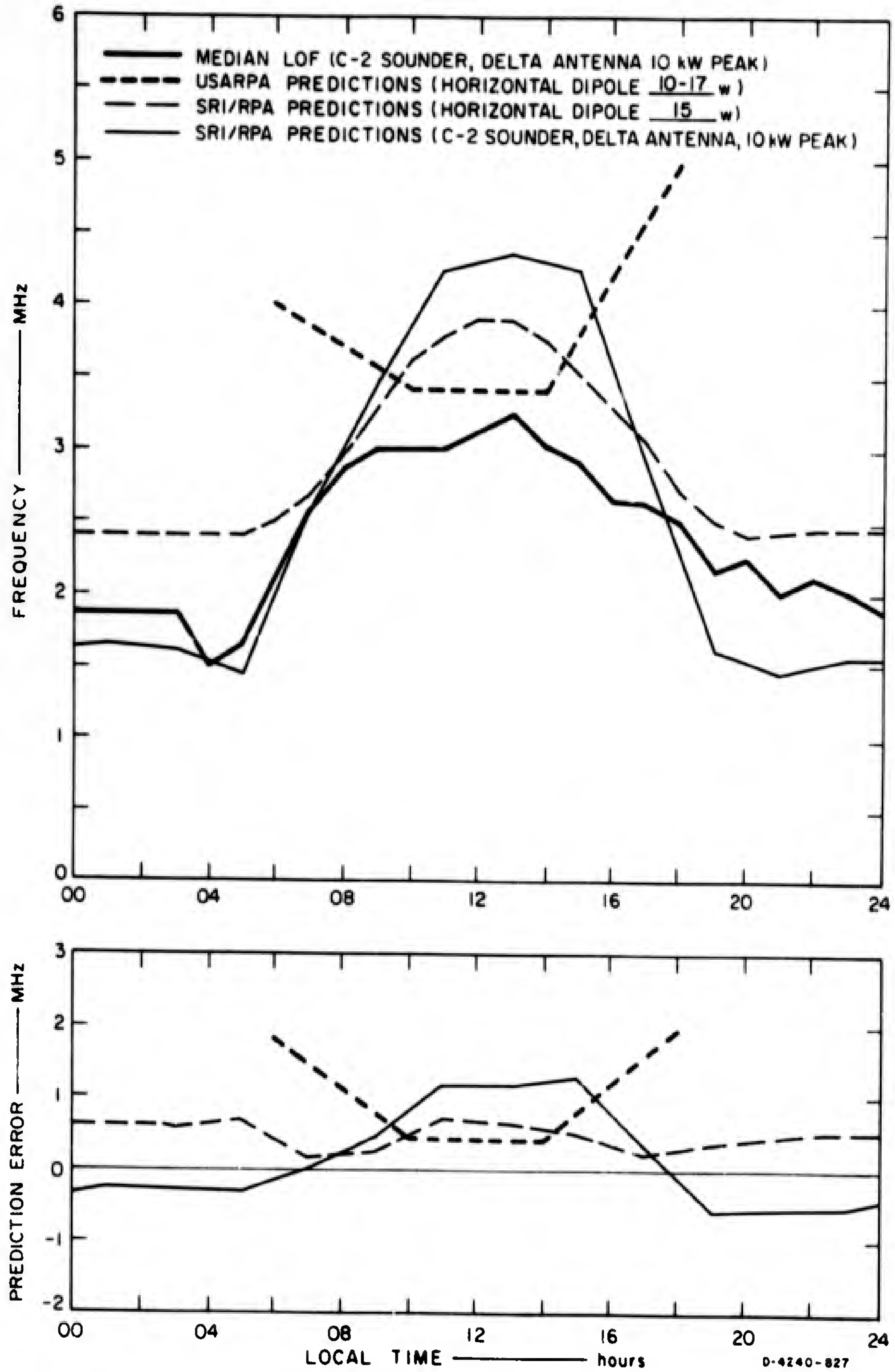

FIG. B-1(h) COMPARISON PLOTS OF LUF AND LOF (f_{min})
WITH ERROR FUNCTION — APRIL 1964

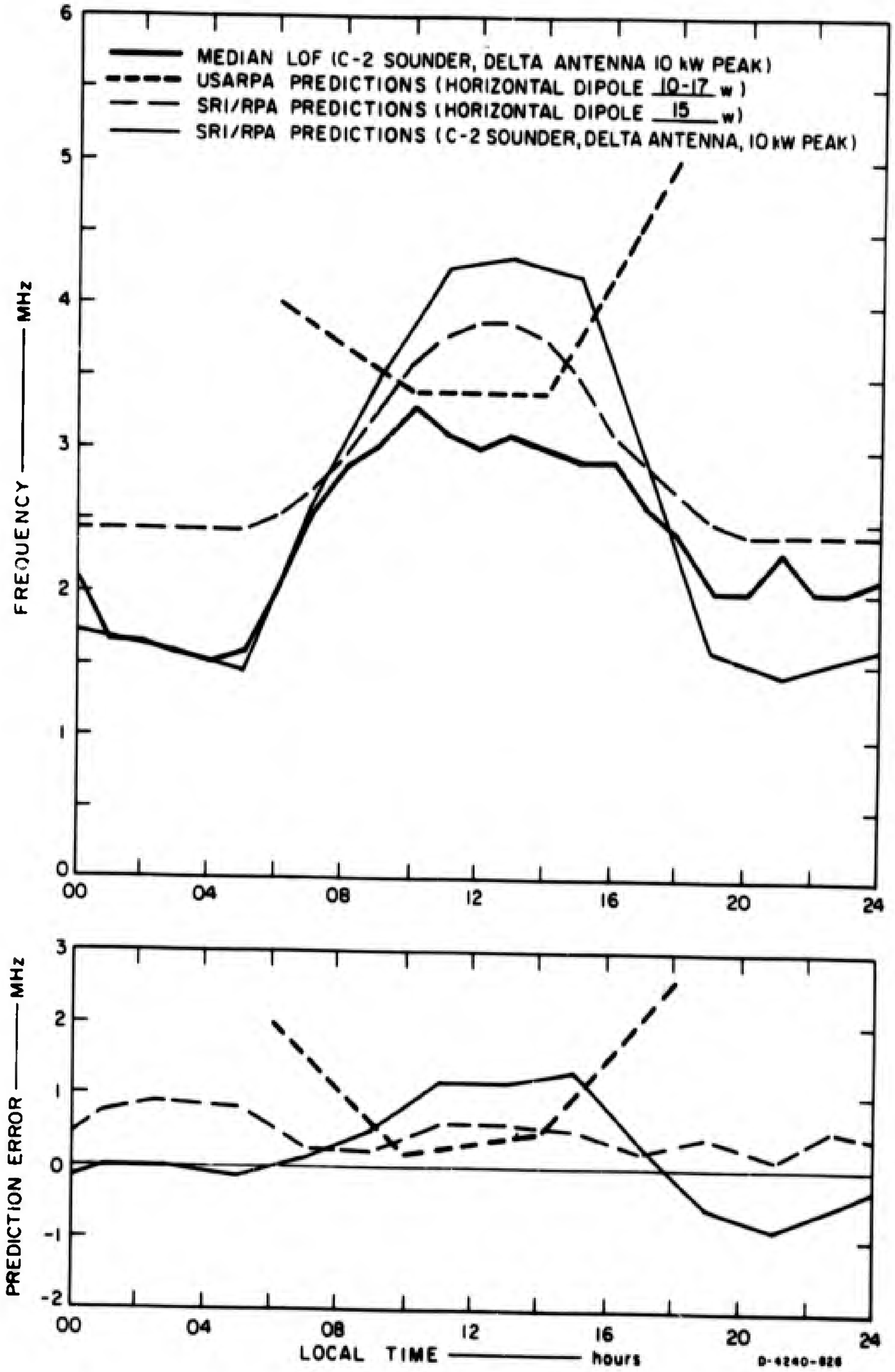

FIG. B-1(i) COMPARISON PLOTS OF LUF AND LOF (f_{min})
WITH ERROR FUNCTION — MAY 1964

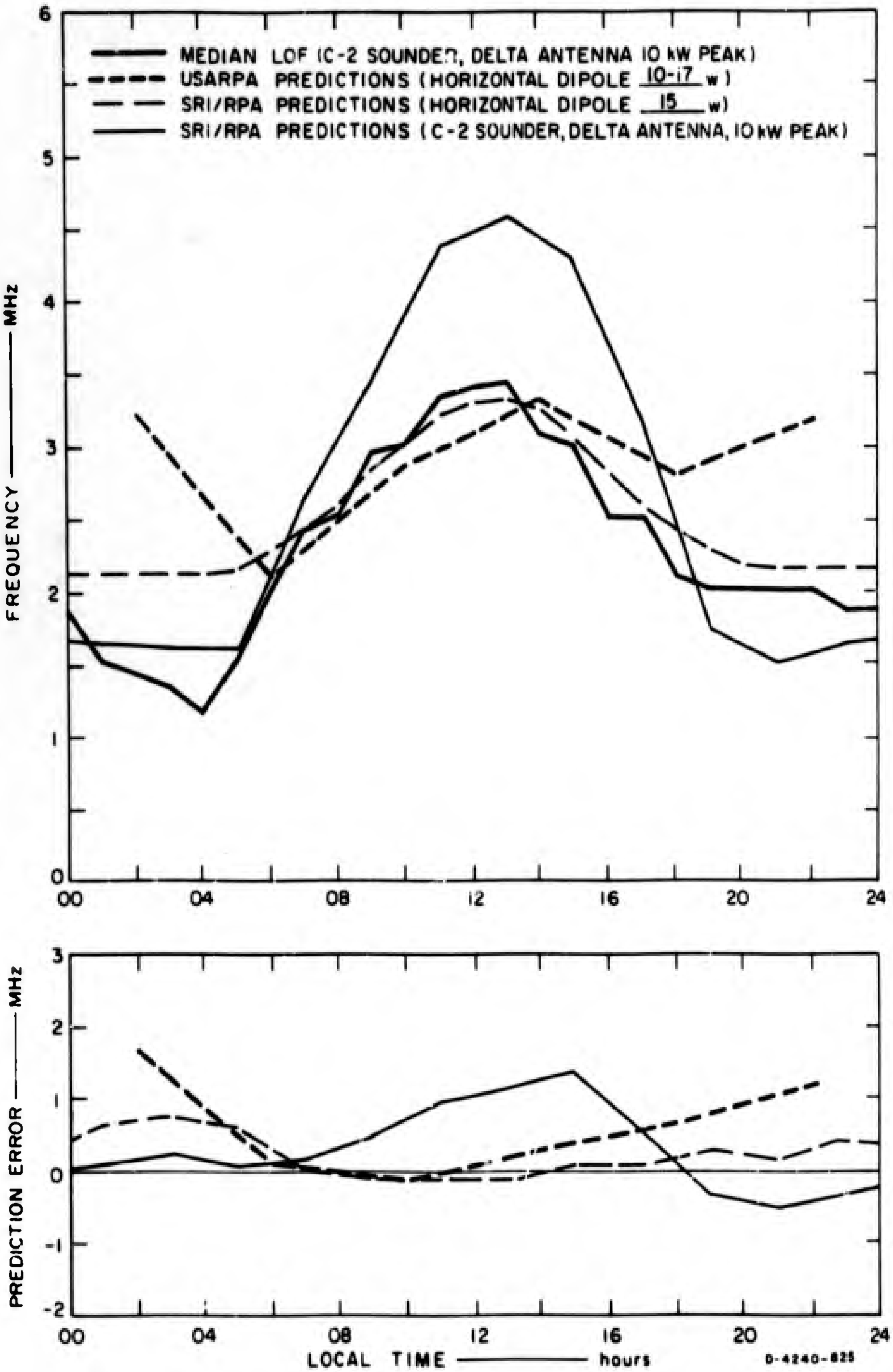

FIG. B-1(j) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — JUNE 1964

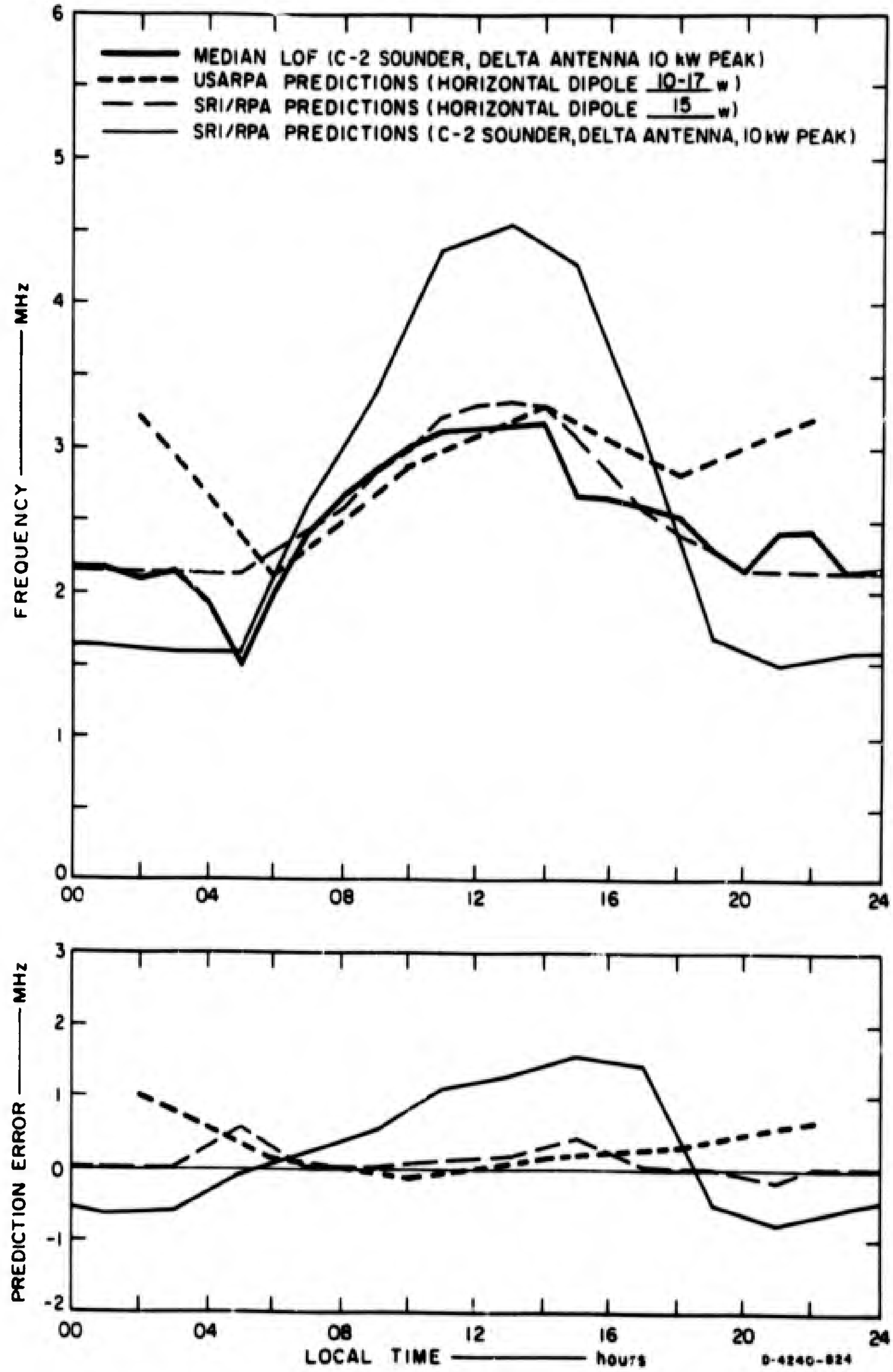

FIG. B-1(k) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — JULY 1964

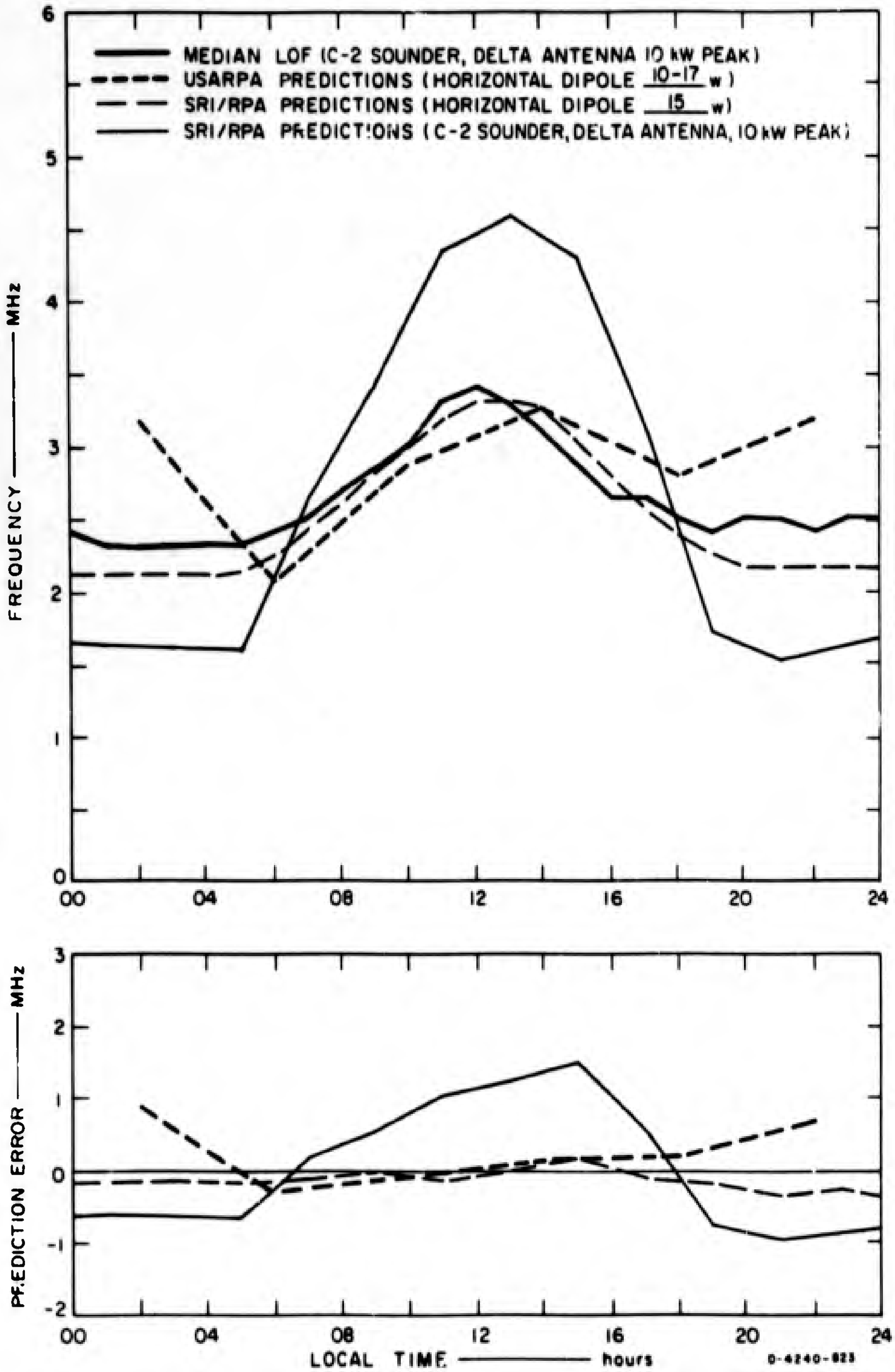

FIG. B-1(l) COMPARISON PLOTS OF LUF AND LOF (f_{min})
WITH ERROR FUNCTION — AUGUST 1964

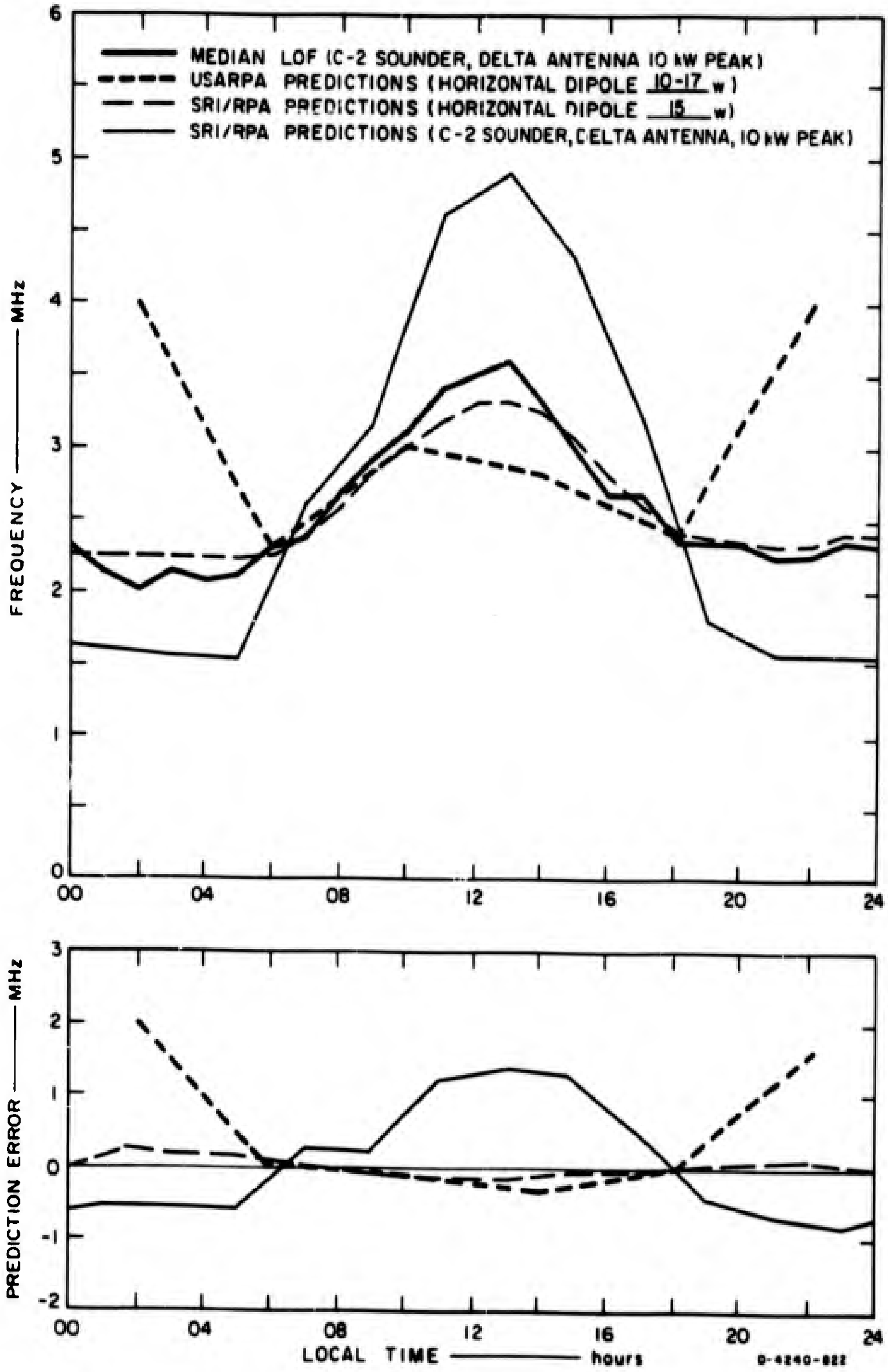

FIG. B-1(m) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — SEPTEMBER 1964

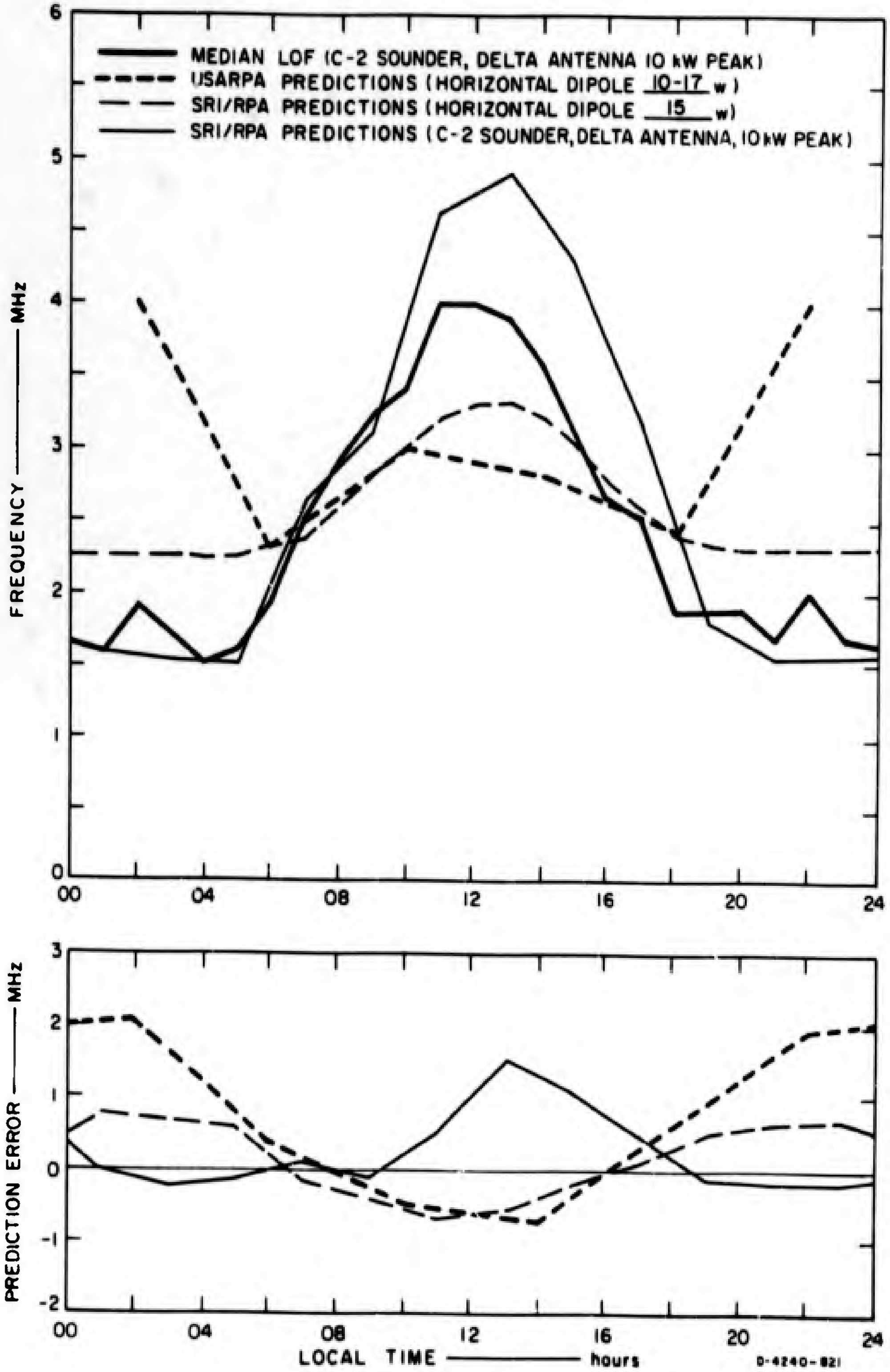

FIG. B-1(n) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — OCTOBER 1964

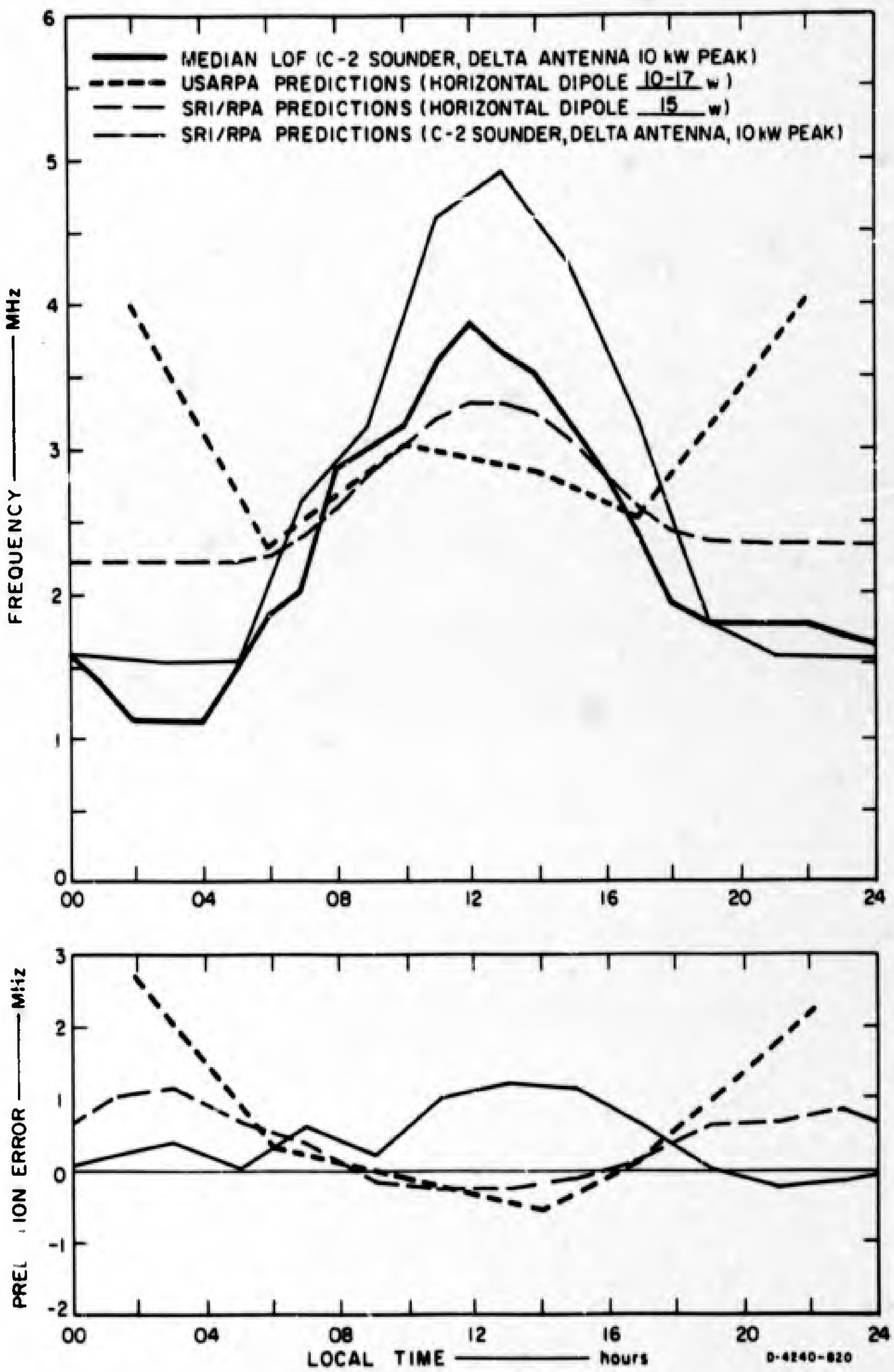

FIG. B-1(o) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — NOVEMBER 1964

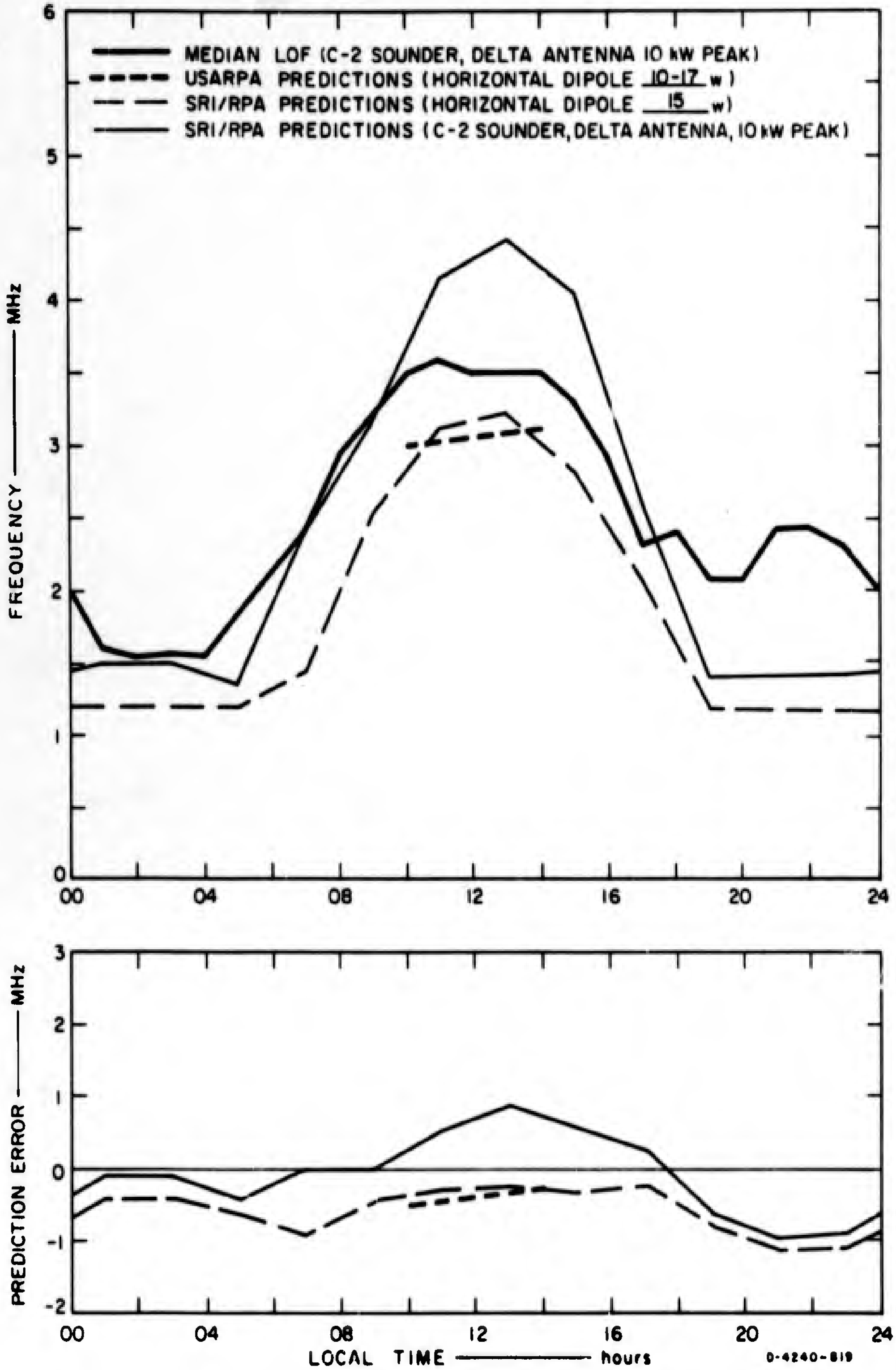

FIG. B-1(p) COMPARISON PLOTS OF LUF AND LOF (f_{min})
WITH ERROR FUNCTION — DECEMBER 1964

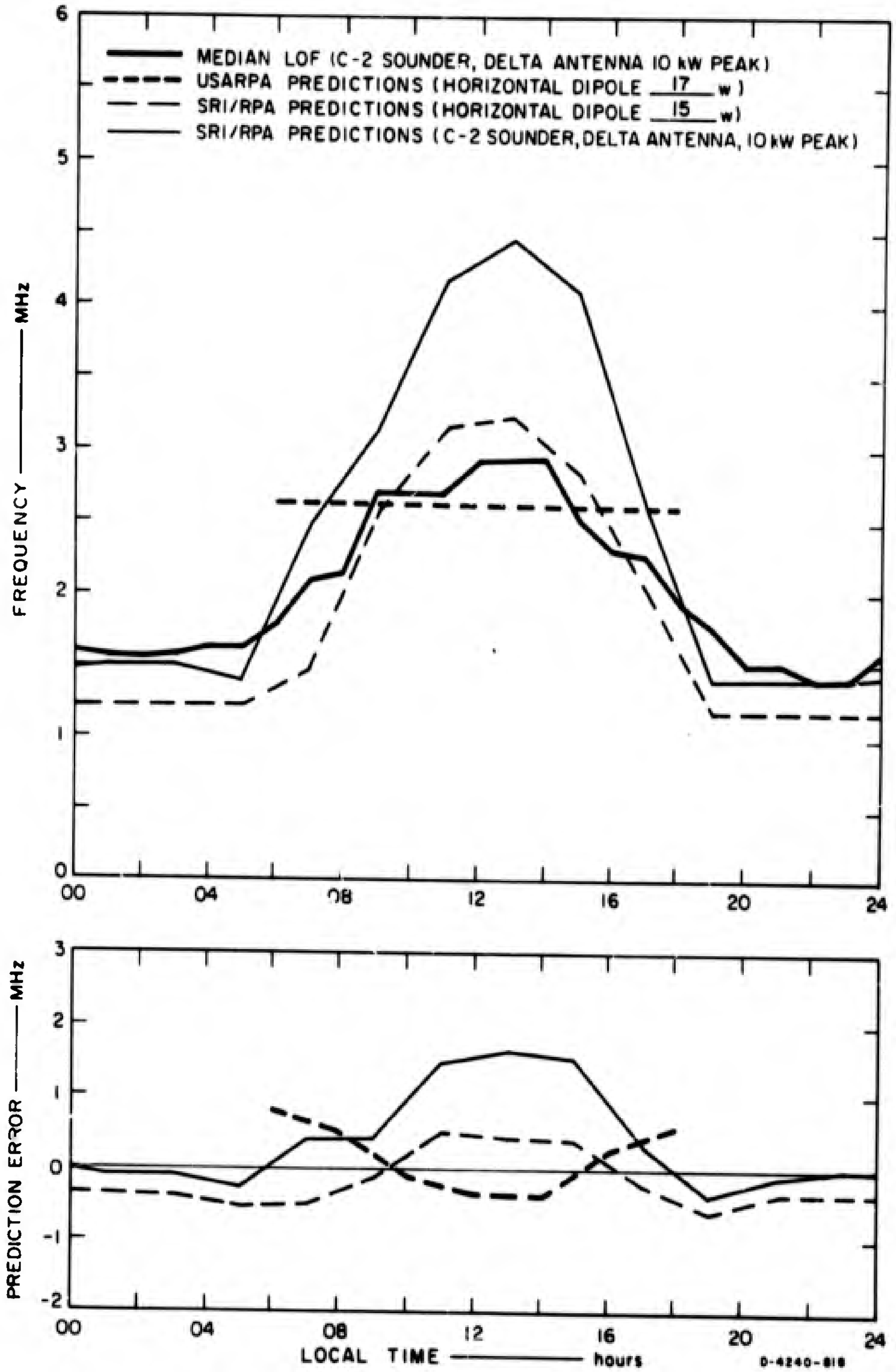

FIG. B-1(q) COMPARISON PLOTS OF LUF AND LOF (f_{min})
WITH ERROR FUNCTION — JANUARY 1965

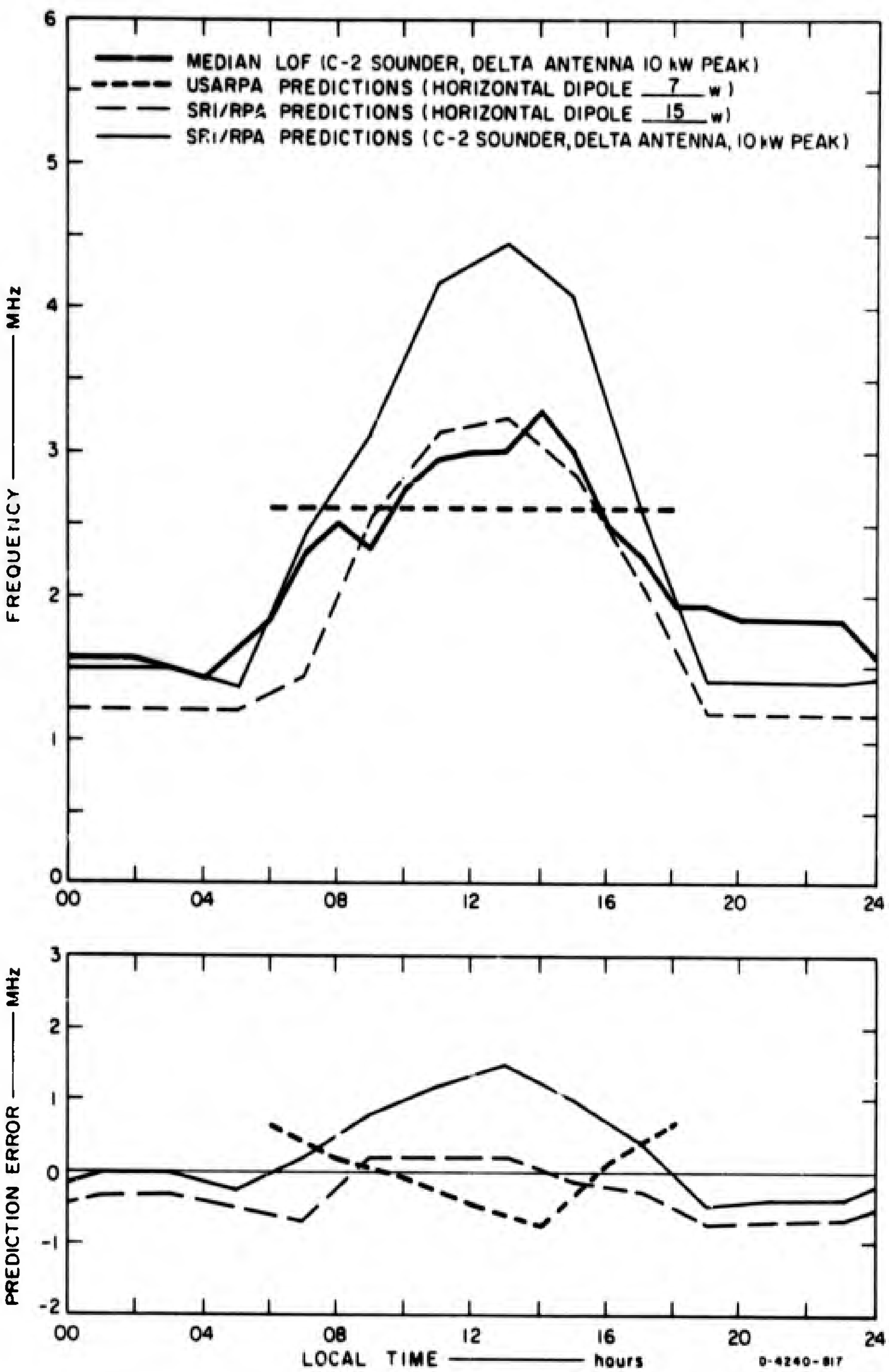

FIG. B-1(r) COMPARISON PLOTS OF LUF AND LOF (f_{min})
WITH ERROR FUNCTION — FEBRUARY 1965

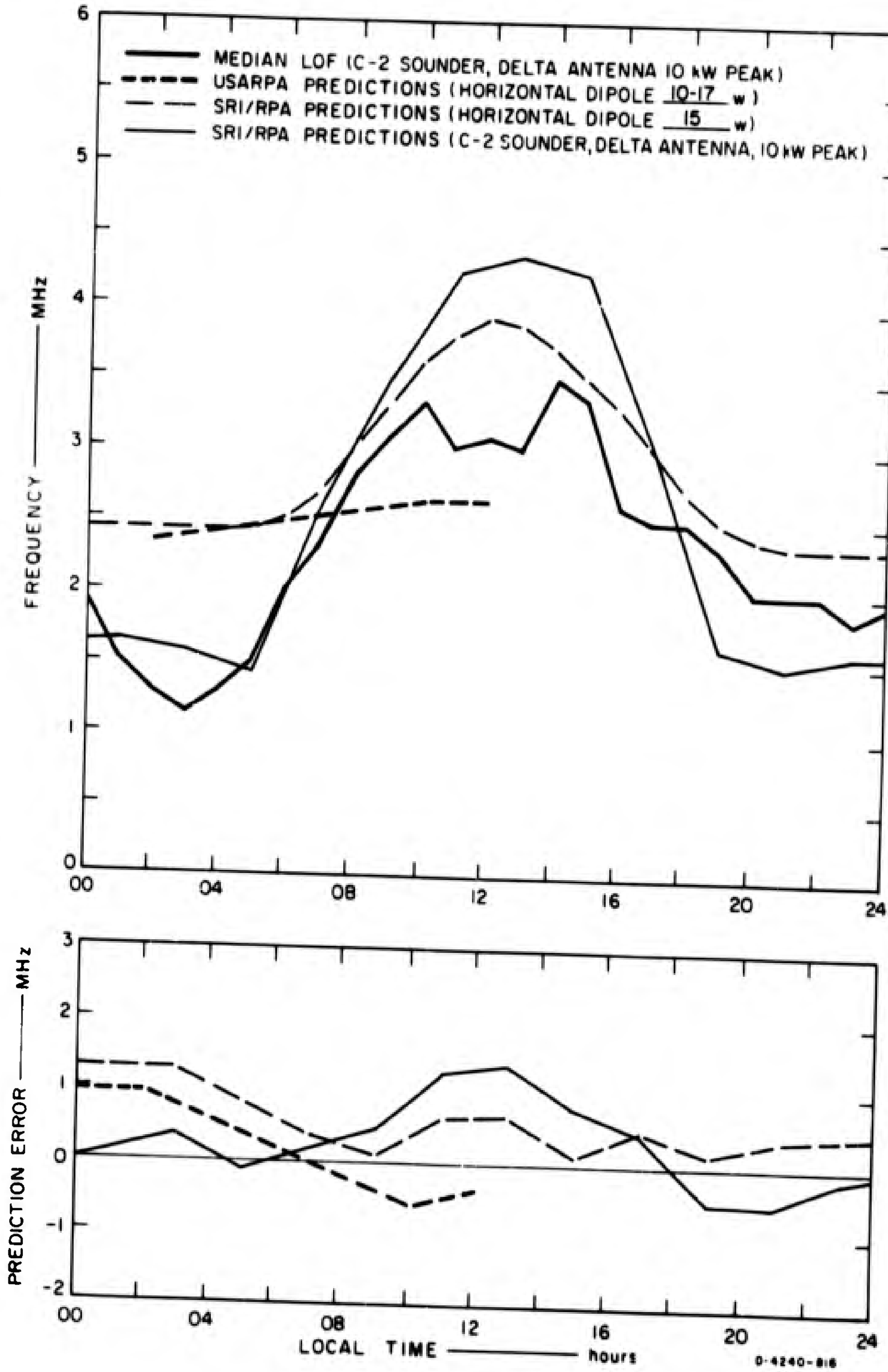

FIG. B-1(s) COMPARISON PLOTS OF LUF AND LOF (f_{min}) WITH ERROR FUNCTION — MARCH 1965

APPENDIX C

CORRECTED NBS PREDICTIONS, APRIL THROUGH DECEMBER 1965, AND CORRECTED SRI/RPA PREDICTIONS, APRIL 1965 THROUGH DECEMBER 1966

Note: The LUF predictions are for the 15-watt, 3-kHz bandwidth system with horizontal dipole antennas 20 feet above ground (voice circuit).

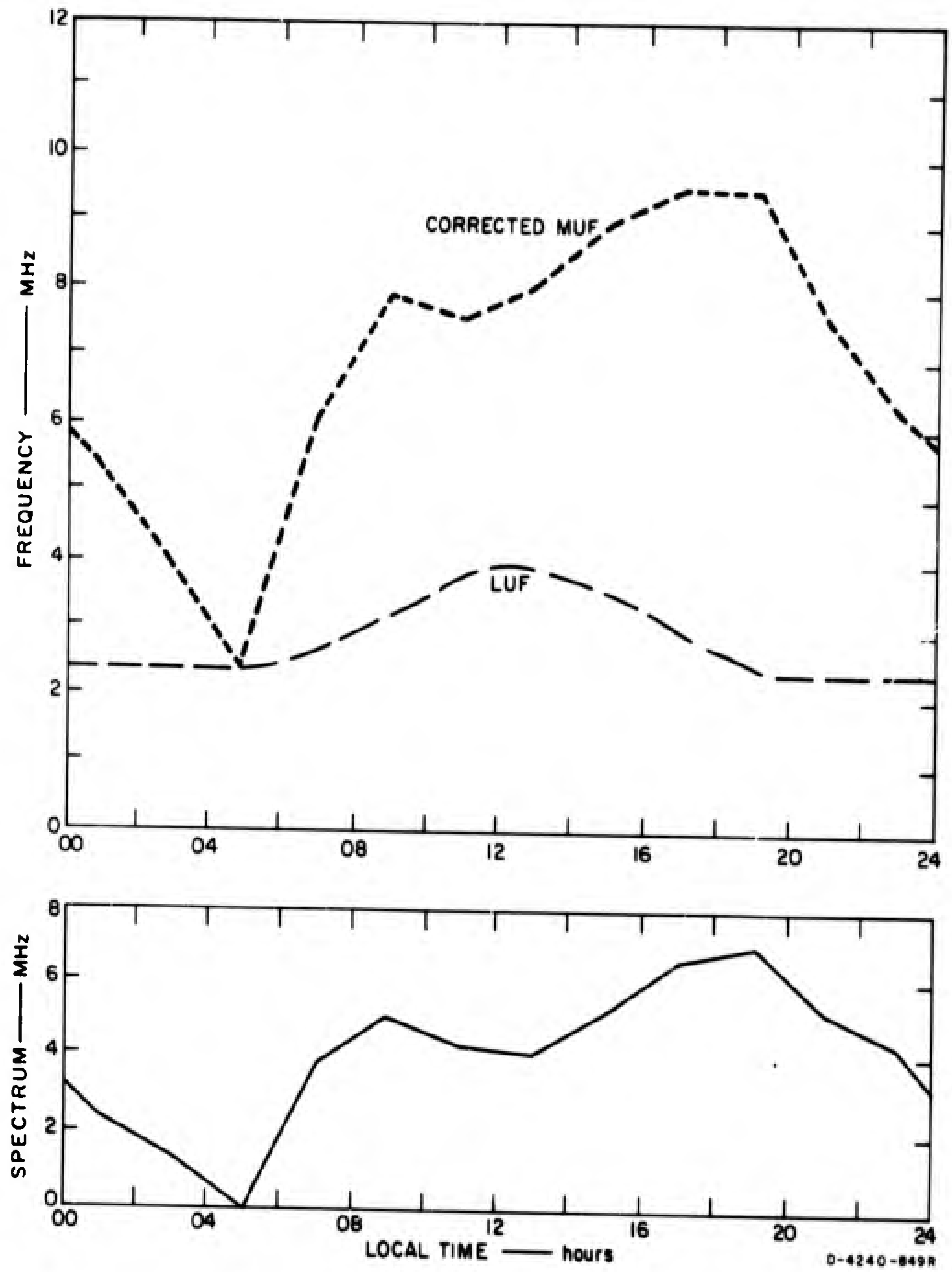

FIG. C-1(a) CORRECTED NBS PREDICTIONS — APRIL 1965

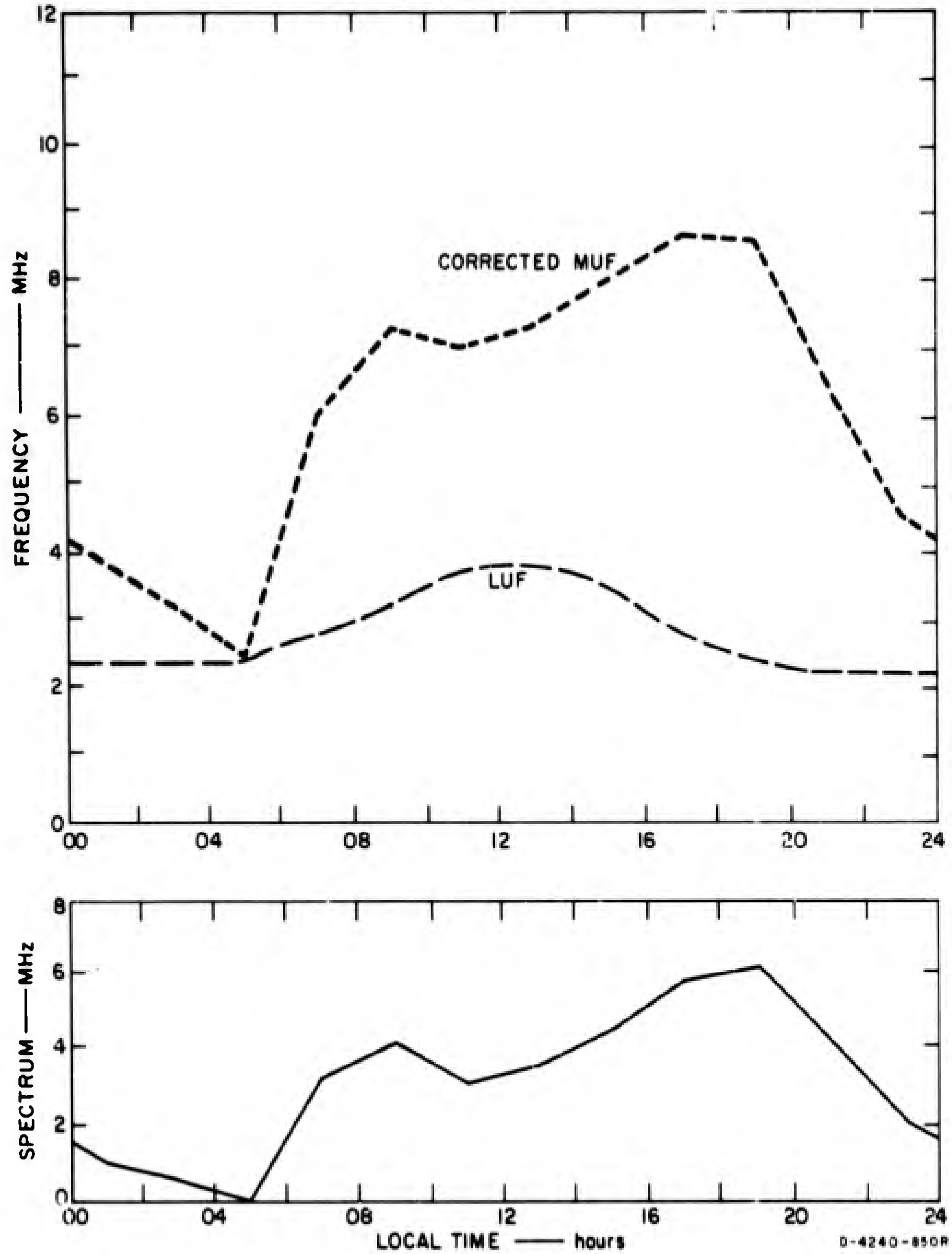

FIG. C-1(b) CORRECTED NBS PREDICTIONS -- MAY 1965

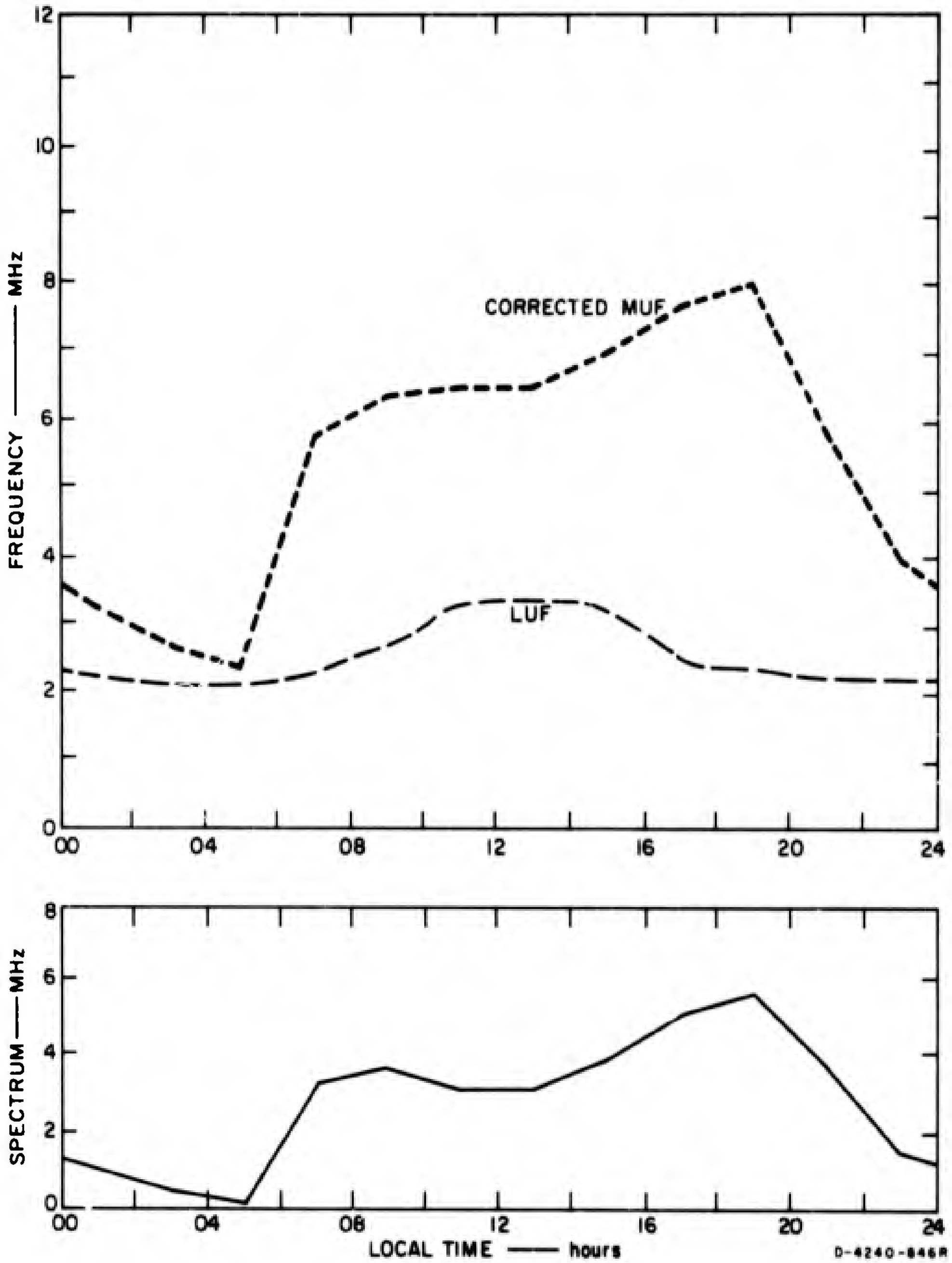

FIG. C-1(c) CORRECTED NBS PREDICTIONS — JUNE 1965

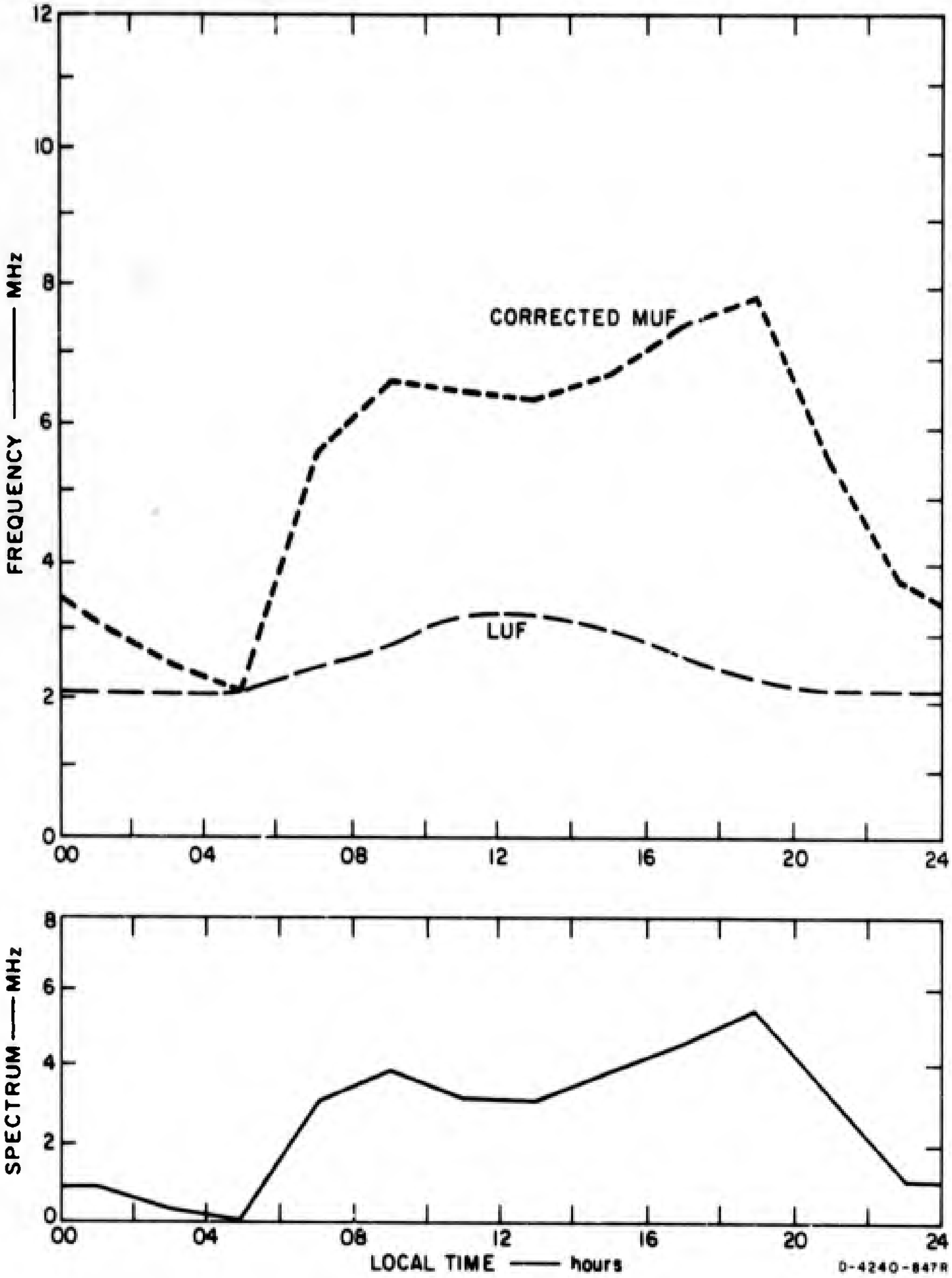

FIG. C-1(d) CORRECTED NBS PREDICTIONS — JULY 1965

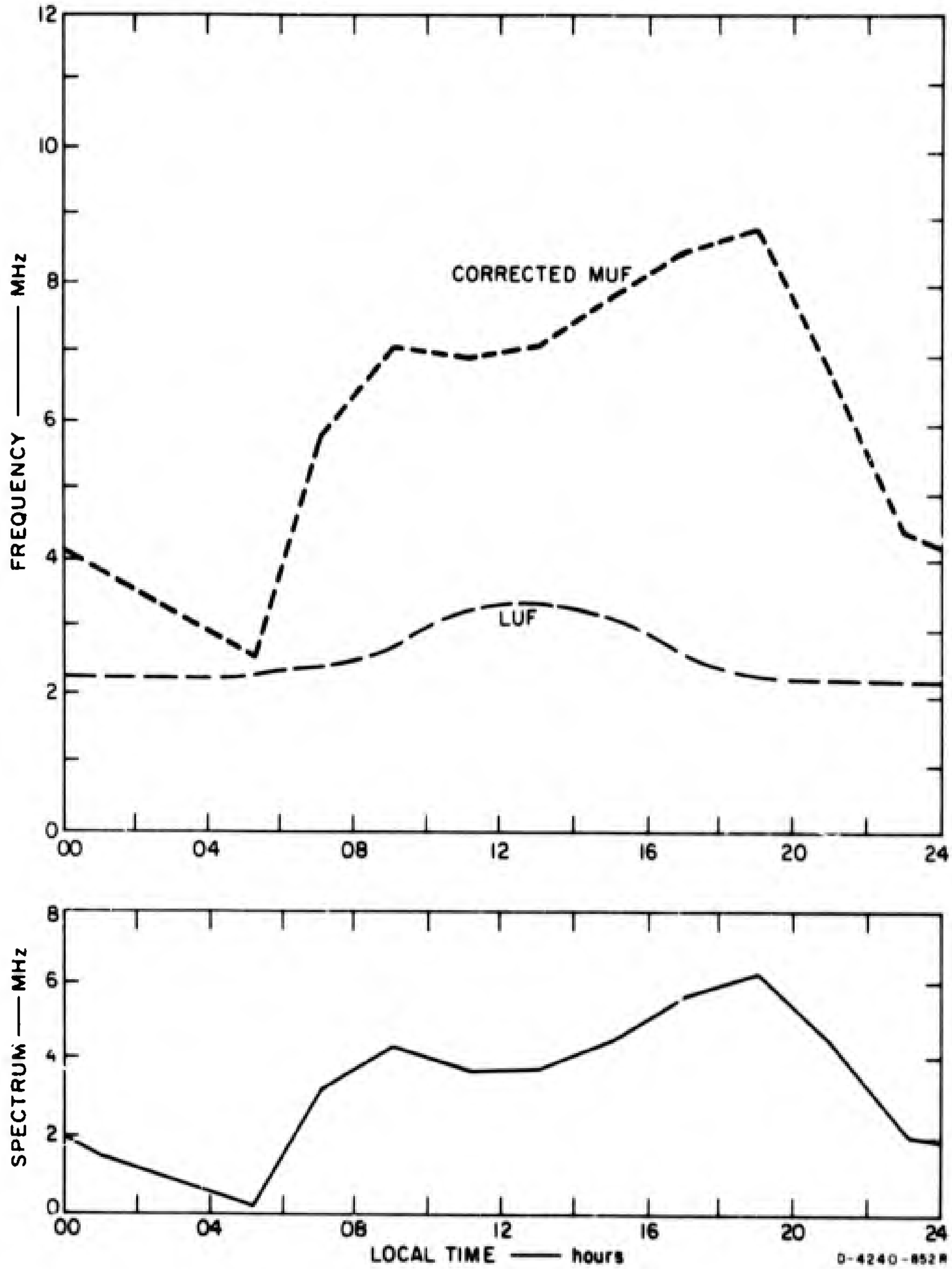

FIG. C-1(e) CORRECTED NBS PREDICTIONS — AUGUST 1965

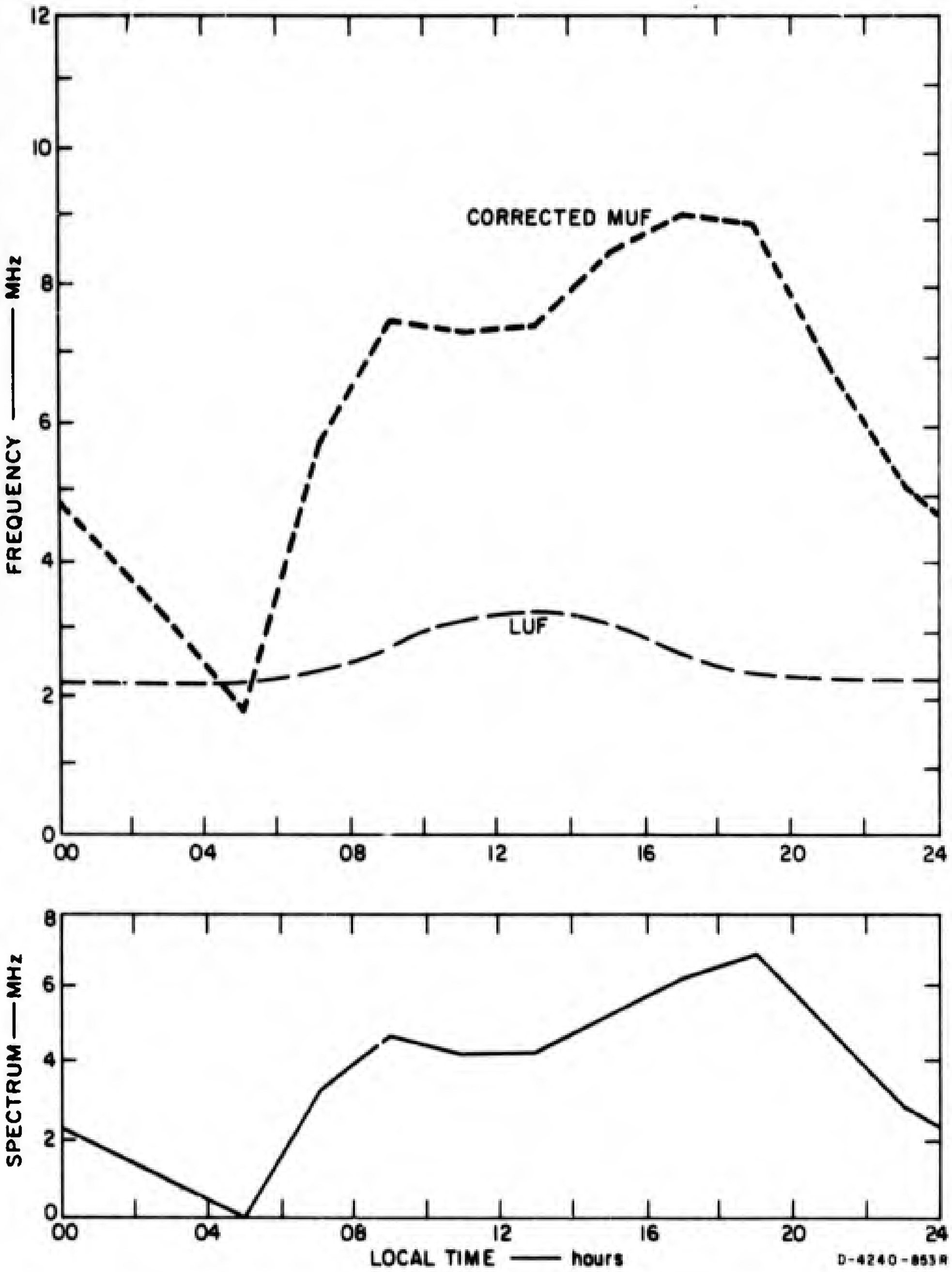

FIG. C-1(f) CORRECTED NBS PREDICTIONS — SEPTEMBER 1965

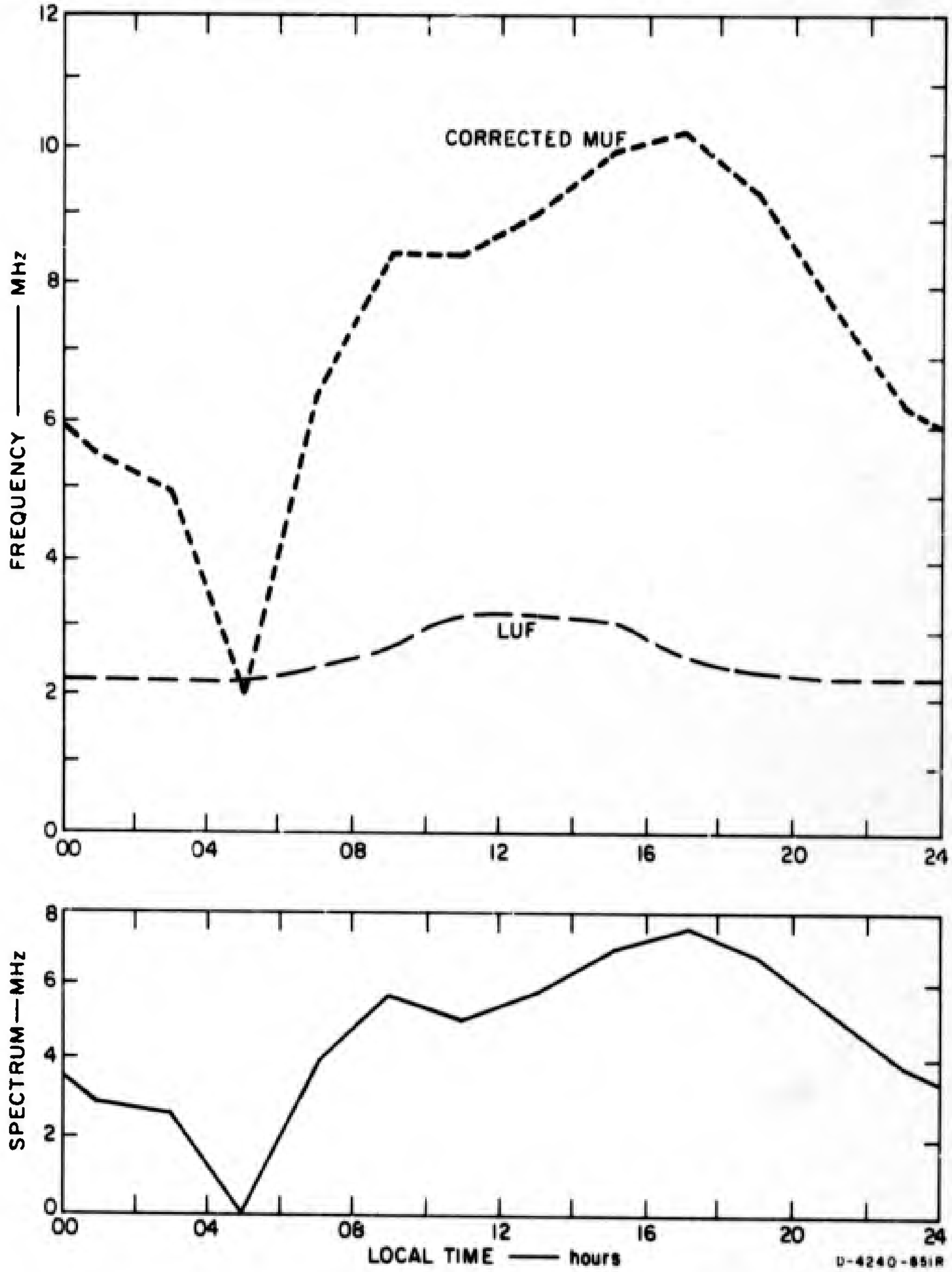

FIG. C-1(g) CORRECTED NBS PREDICTIONS — OCTOBER 1965

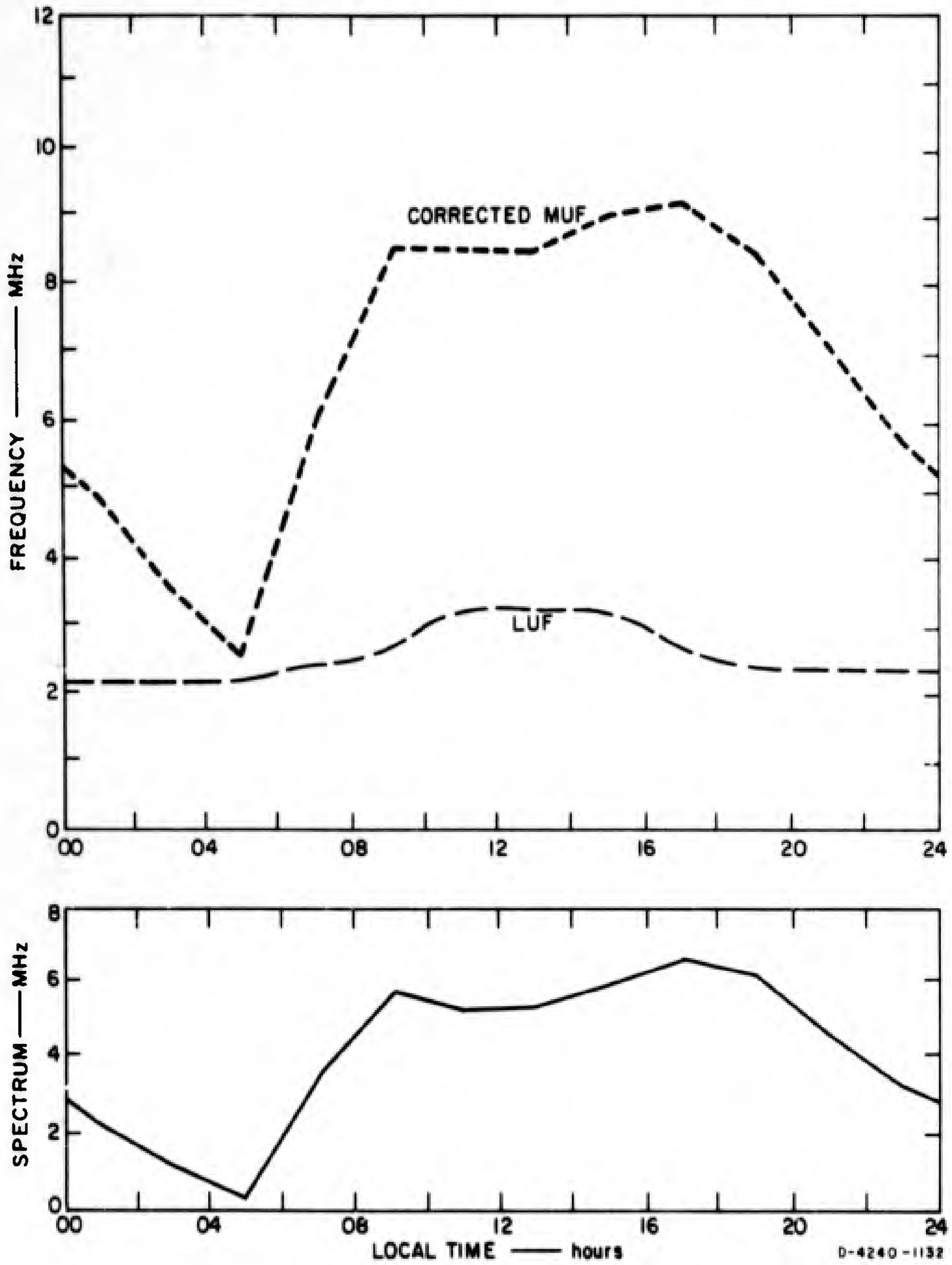

FIG. C-1(h) CORRECTED NBS PREDICTIONS — NOVEMBER 1965

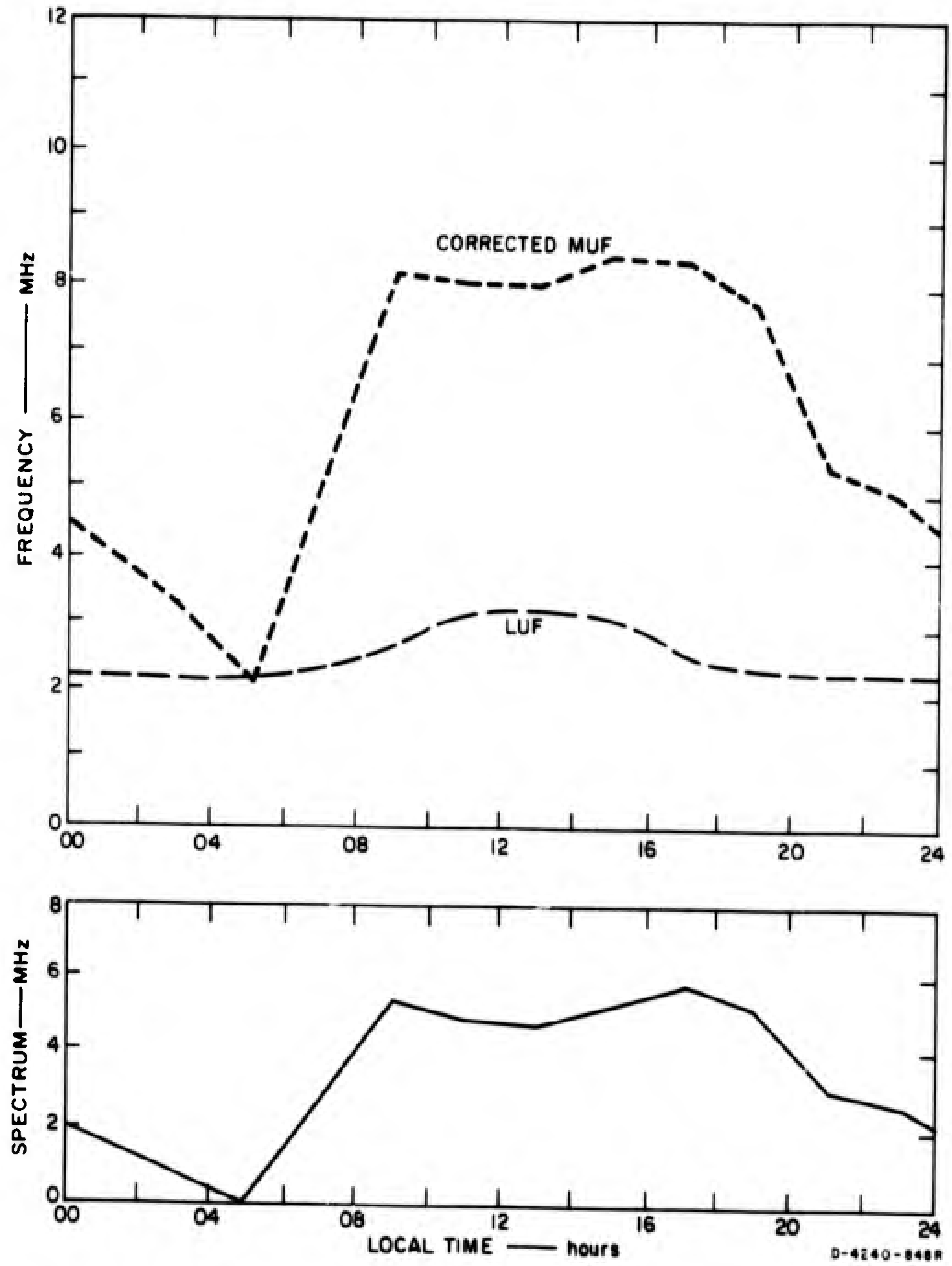

FIG. C-1(i) CORRECTED NBS PREDICTIONS — DECEMBER 1965

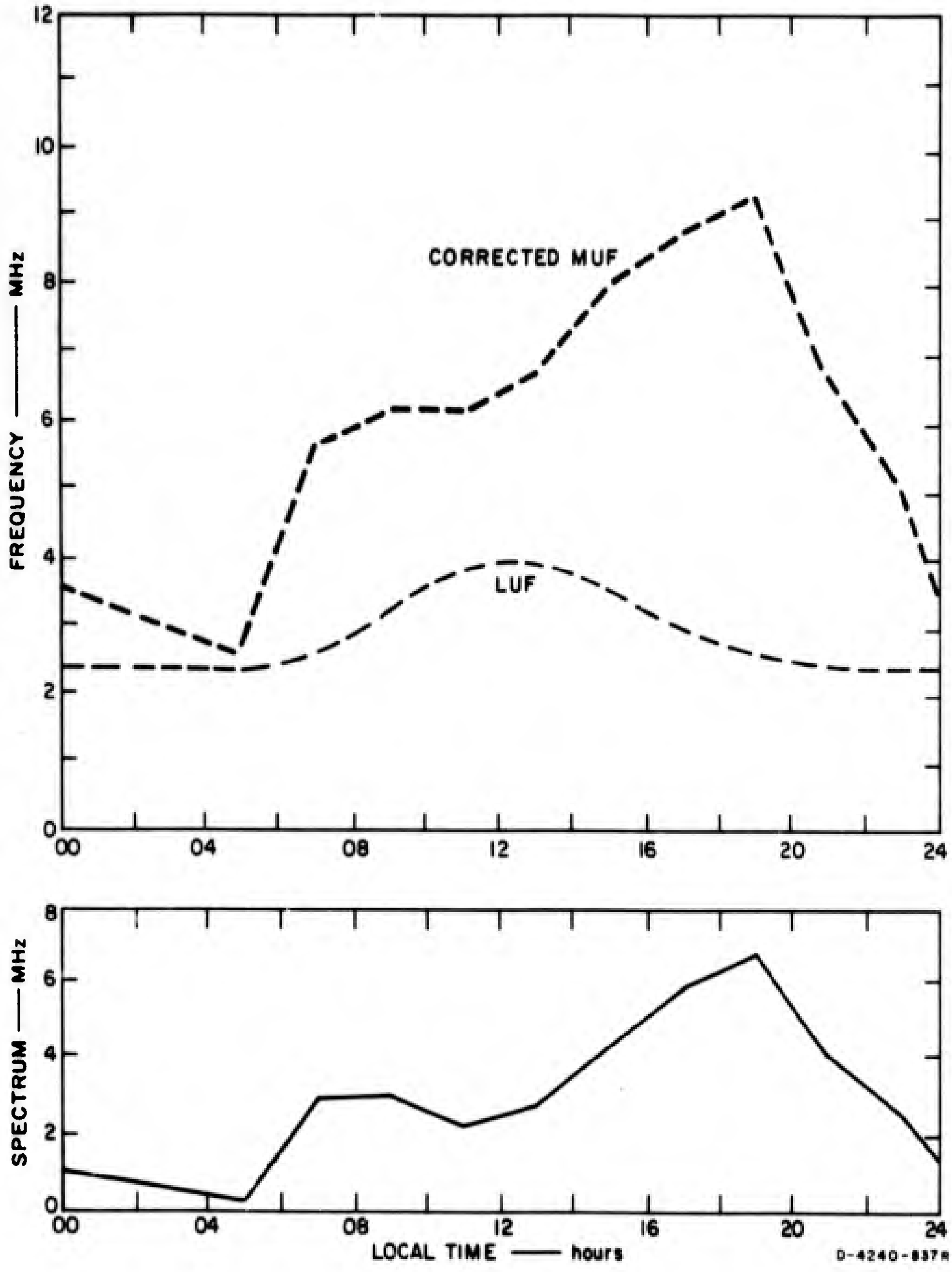

FIG. C-2(a) CORRECTED SRI/RPA PREDICTIONS — APRIL 1965

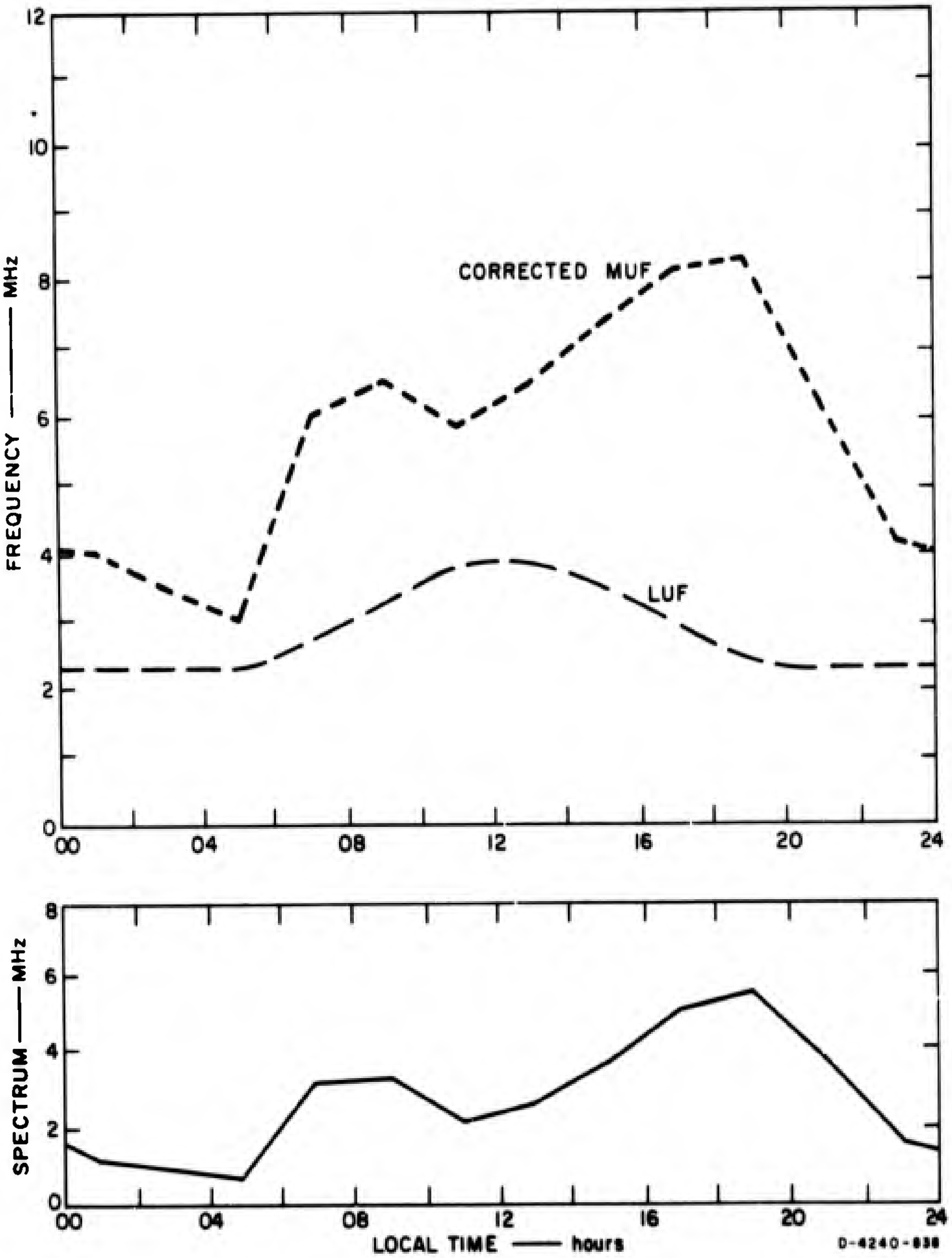

FIG. C-2(b) CORRECTED SRI/RPA PREDICTIONS — MAY 1965

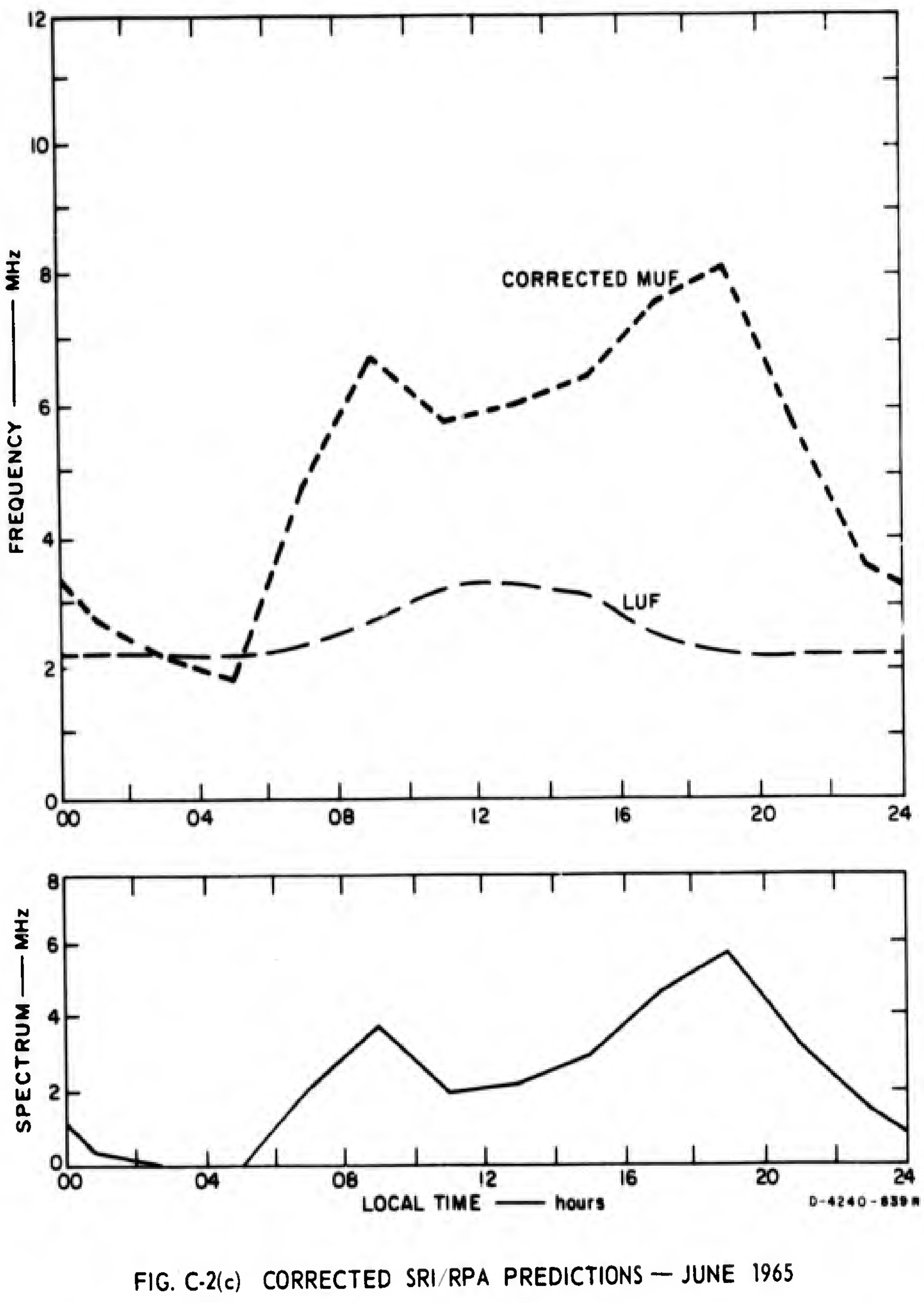

FIG. C-2(c) CORRECTED SRI/RPA PREDICTIONS — JUNE 1965

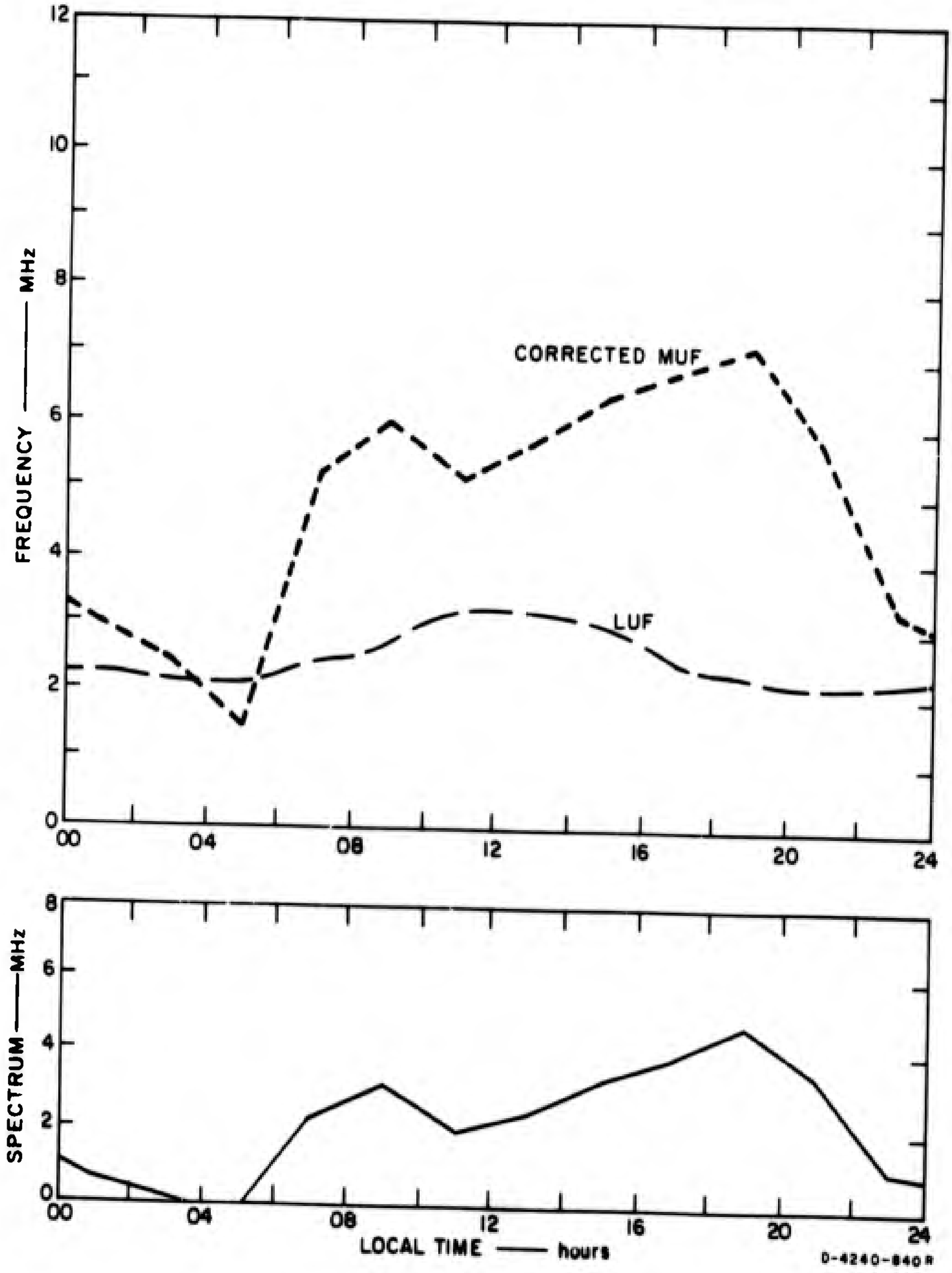

FIG. C-2(d) CORRECTED SRI/RPA PREDICTIONS — JULY 1965

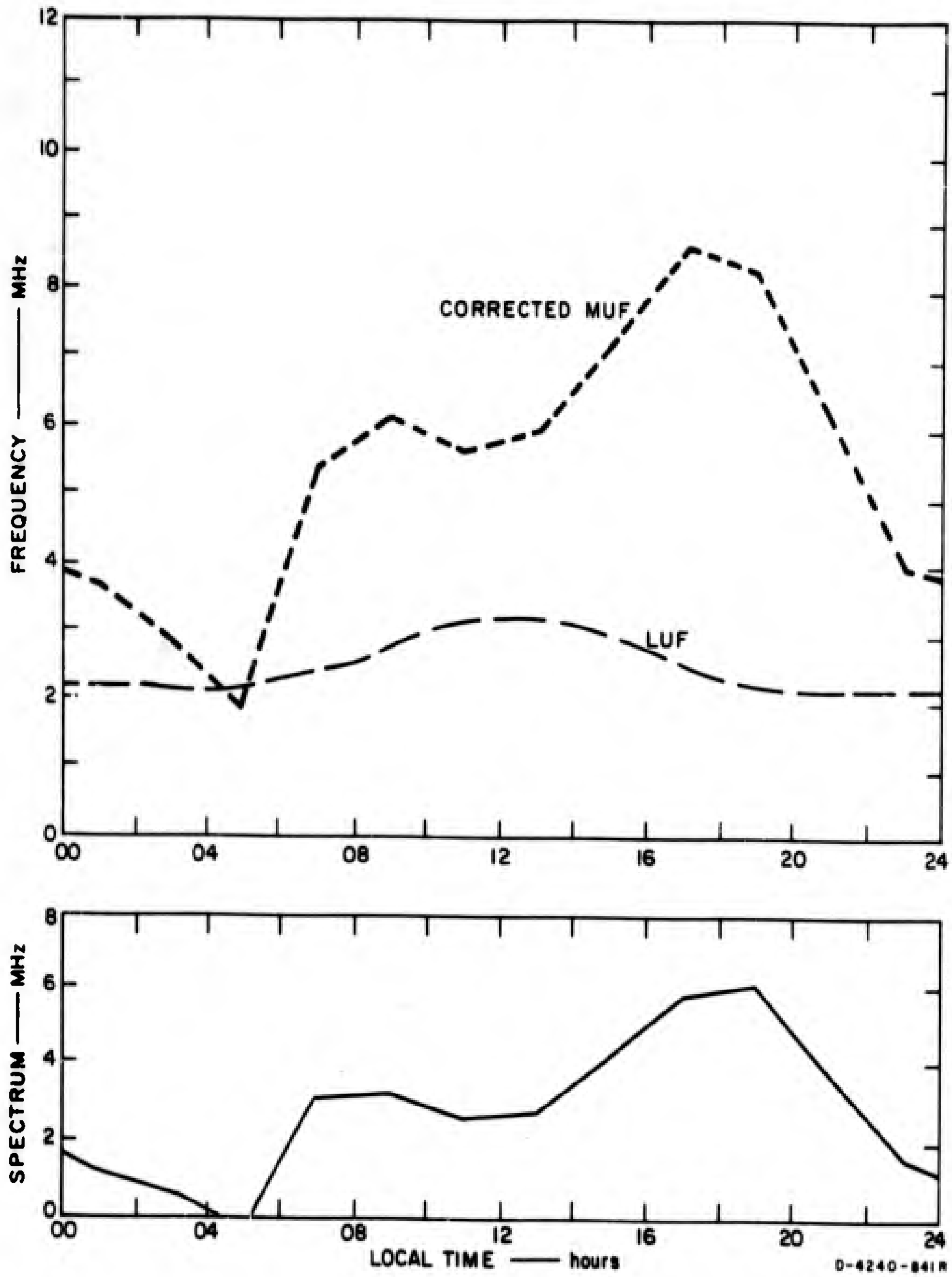

FIG. C-2(e) CORRECTED SRI/RPA PREDICTIONS — AUGUST 1965

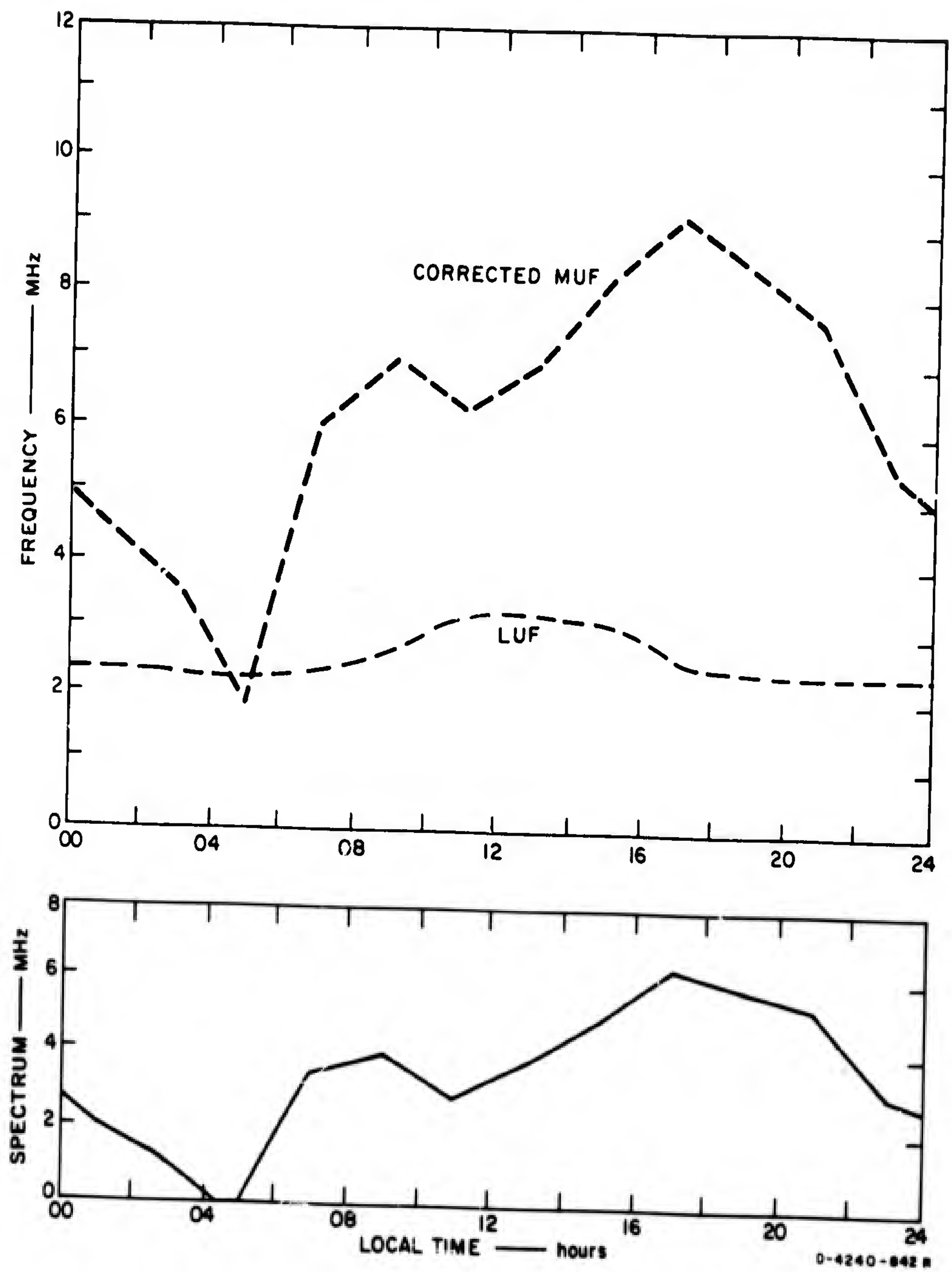

FIG. C-2(f) CORRECTED SRI/RPA PREDICTIONS — SEPTEMBER 1965

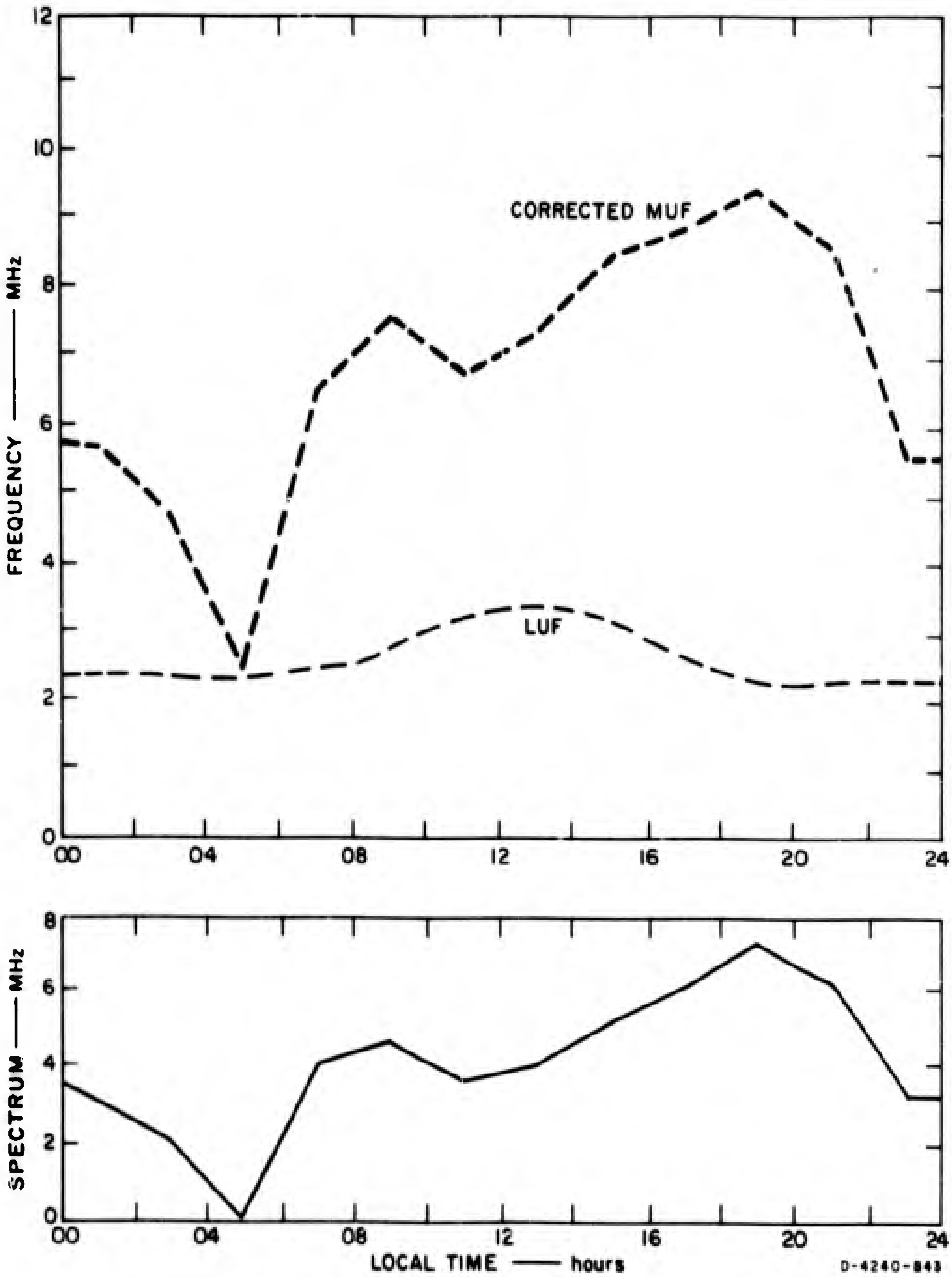

FIG. C-2(g) CORRECTED SRI/RPA PREDICTIONS — OCTOBER 1965

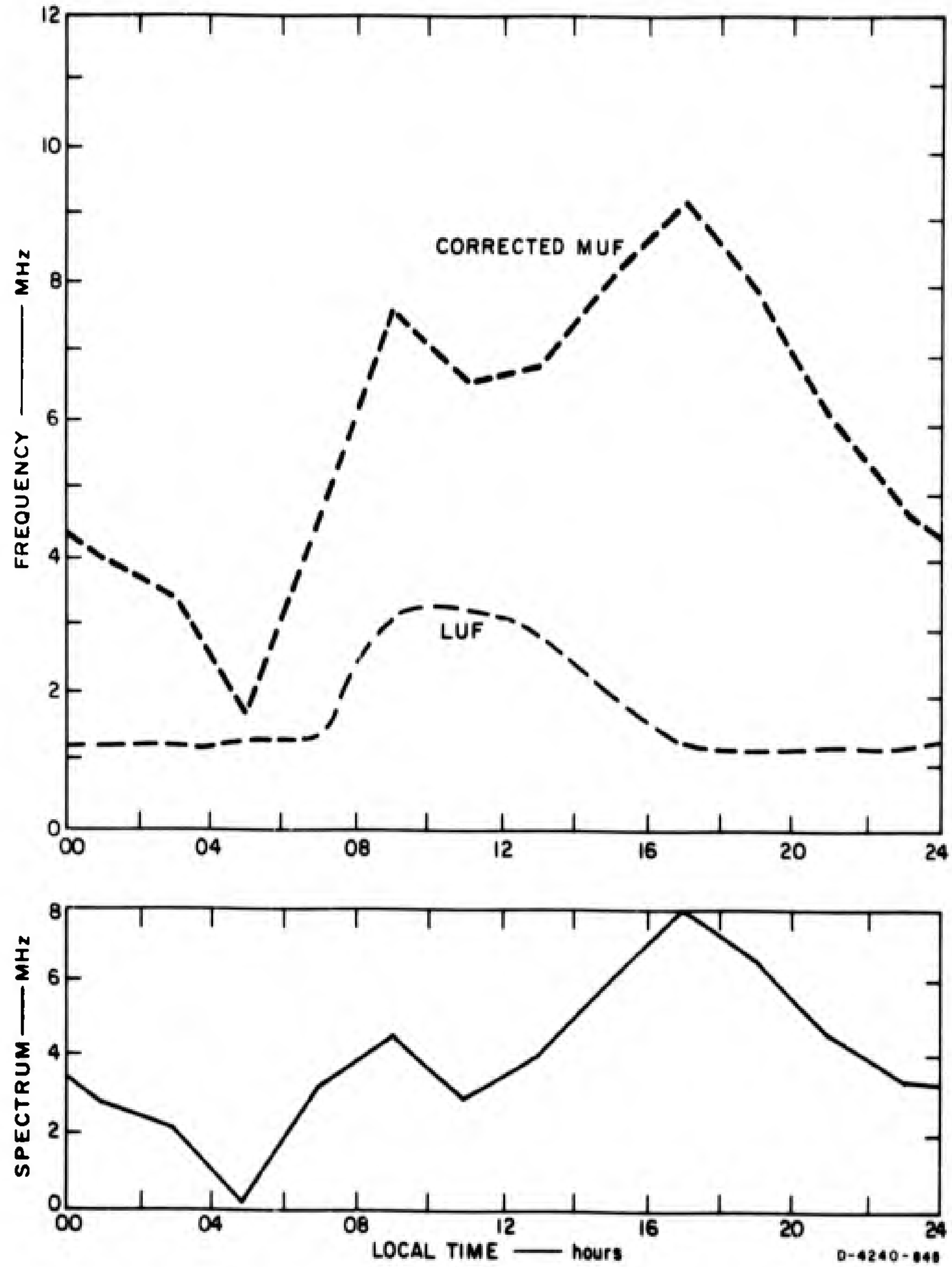

FIG. C-2(i) CORRECTED SRI/RPA PREDICTIONS — DECEMBER 1965

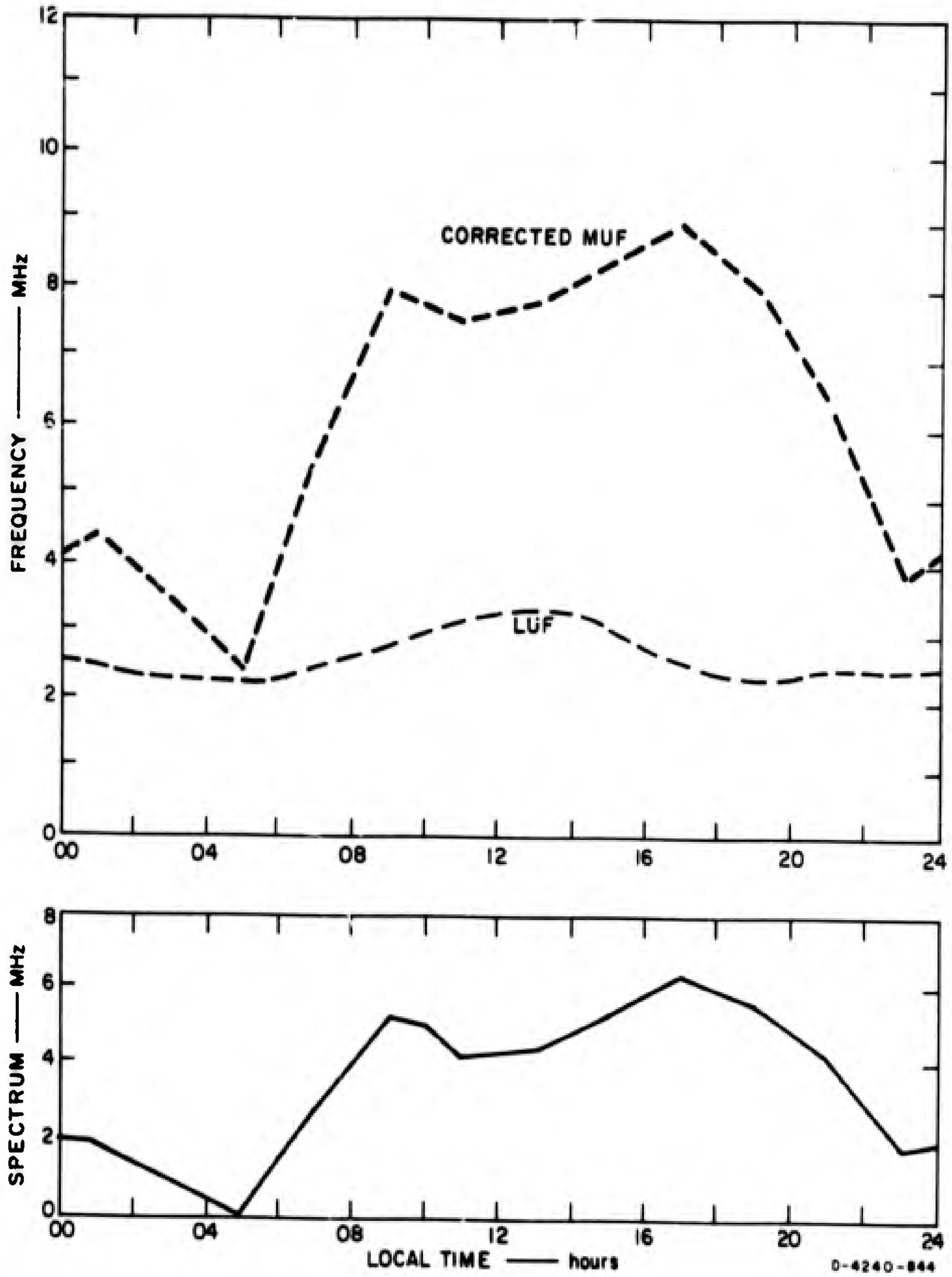

FIG. C-2(h) CORRECTED SRI/RPA PREDICTIONS — NOVEMBER 1965

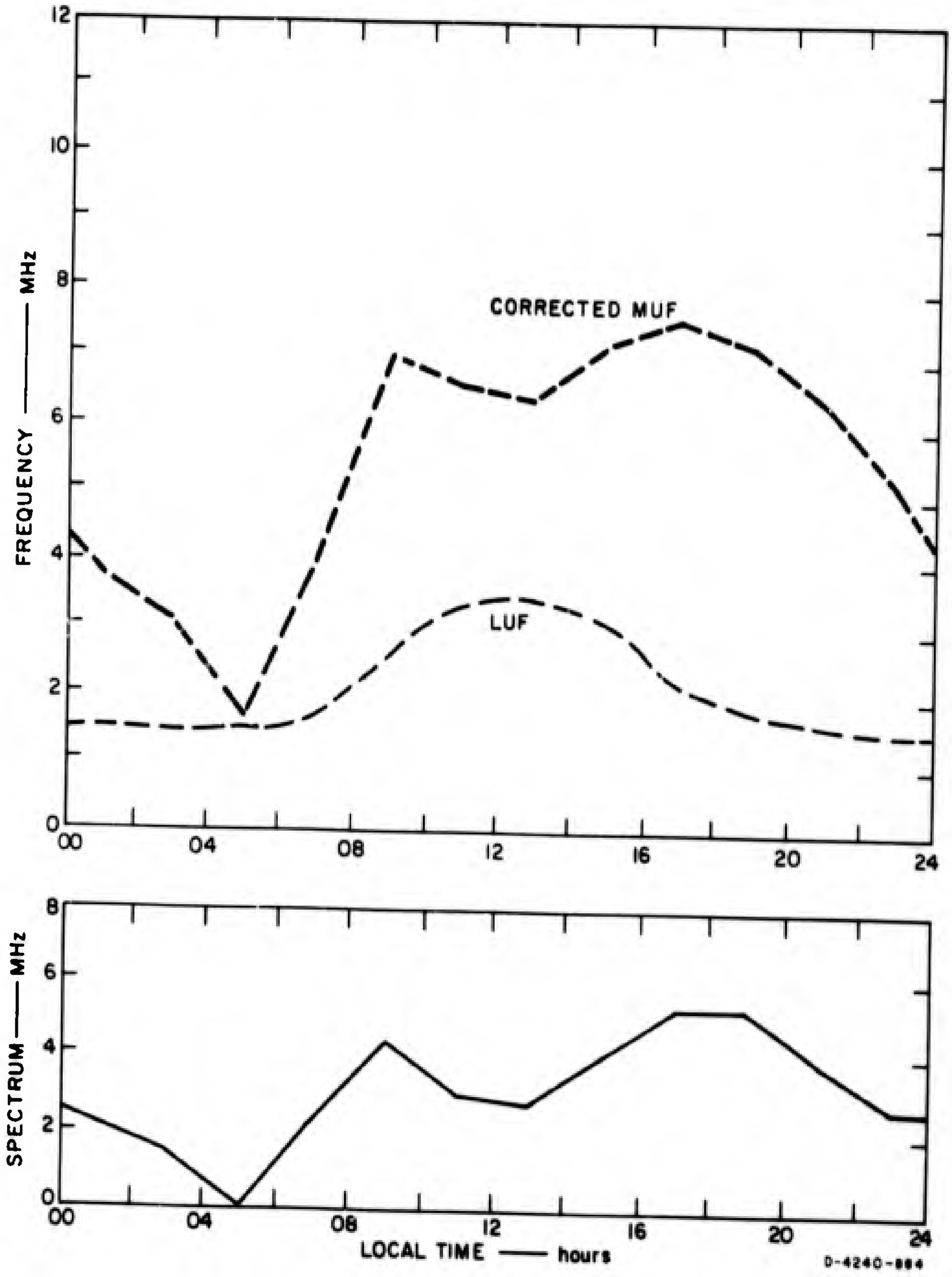

FIG. C-2(j) CORRECTED SRI/RPA PREDICTIONS — JANUARY 1966

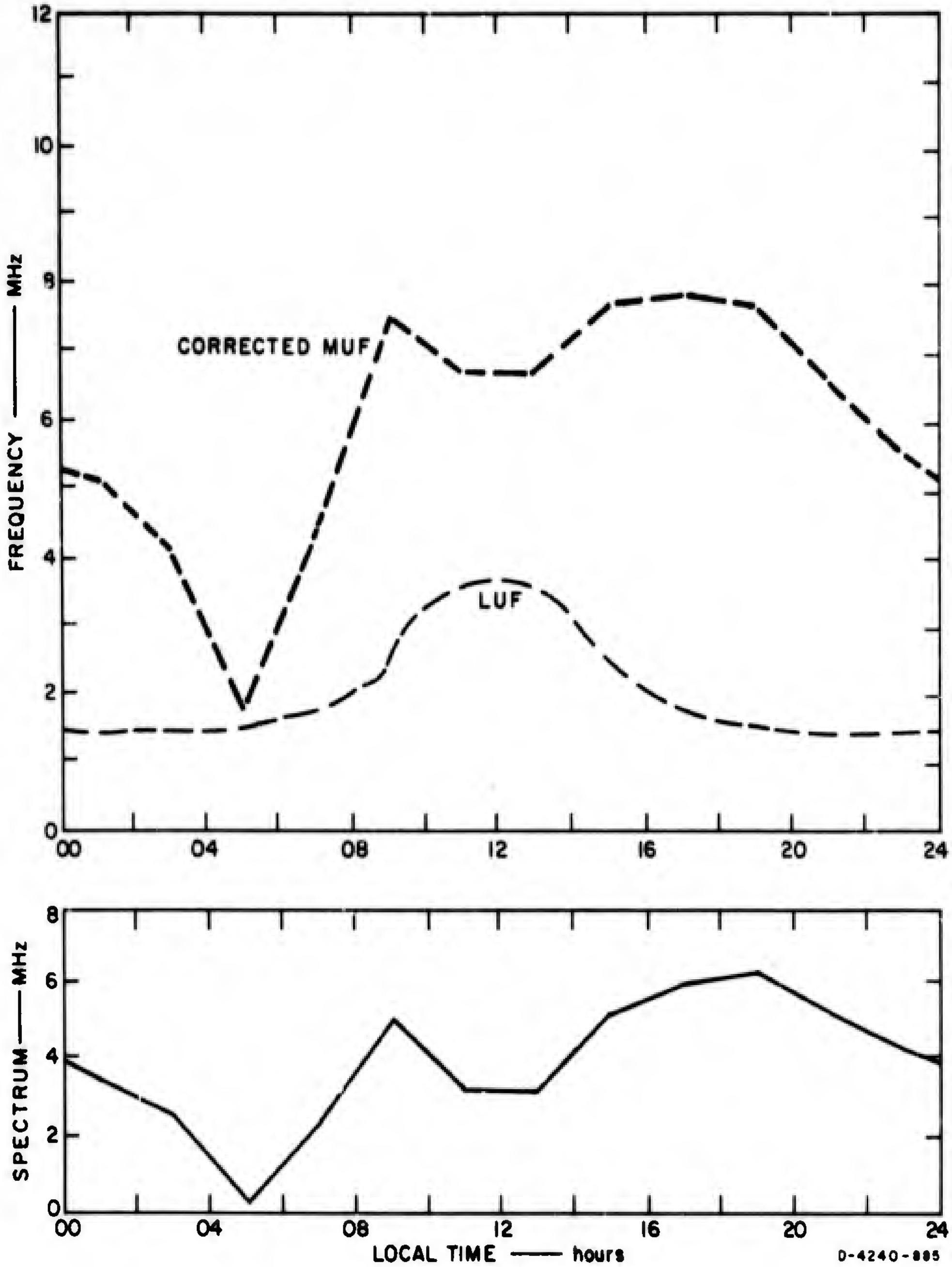

FIG. C-2(k) CORRECTED SRI/RPA PREDICTIONS — FEBRUARY 1966

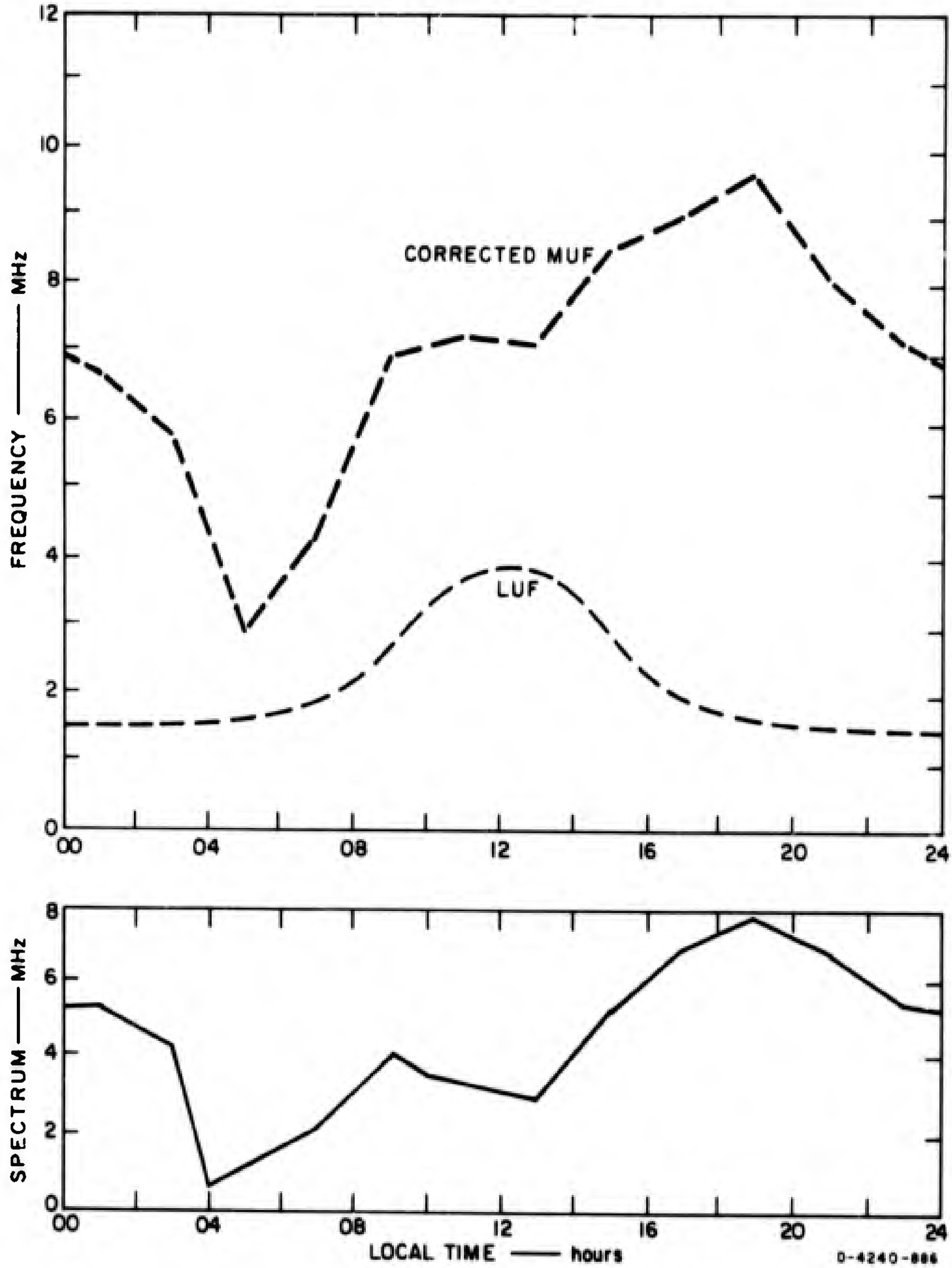

FIG. C-2(I) CORRECTED SRI/RPA PREDICTIONS — MARCH 1966

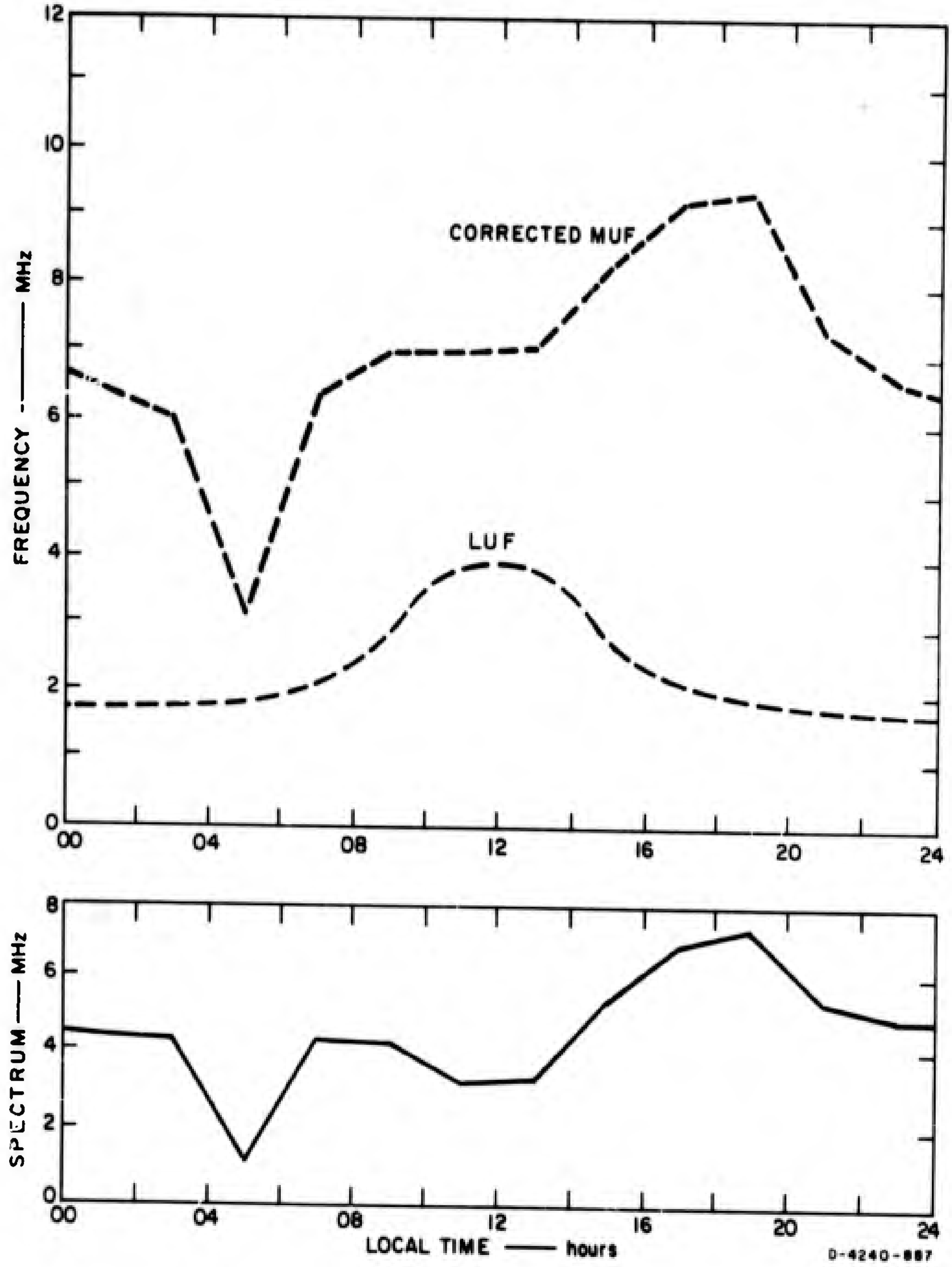

FIG. C-2(m) CORRECTED SRI/RPA PREDICTIONS — APRIL 1966

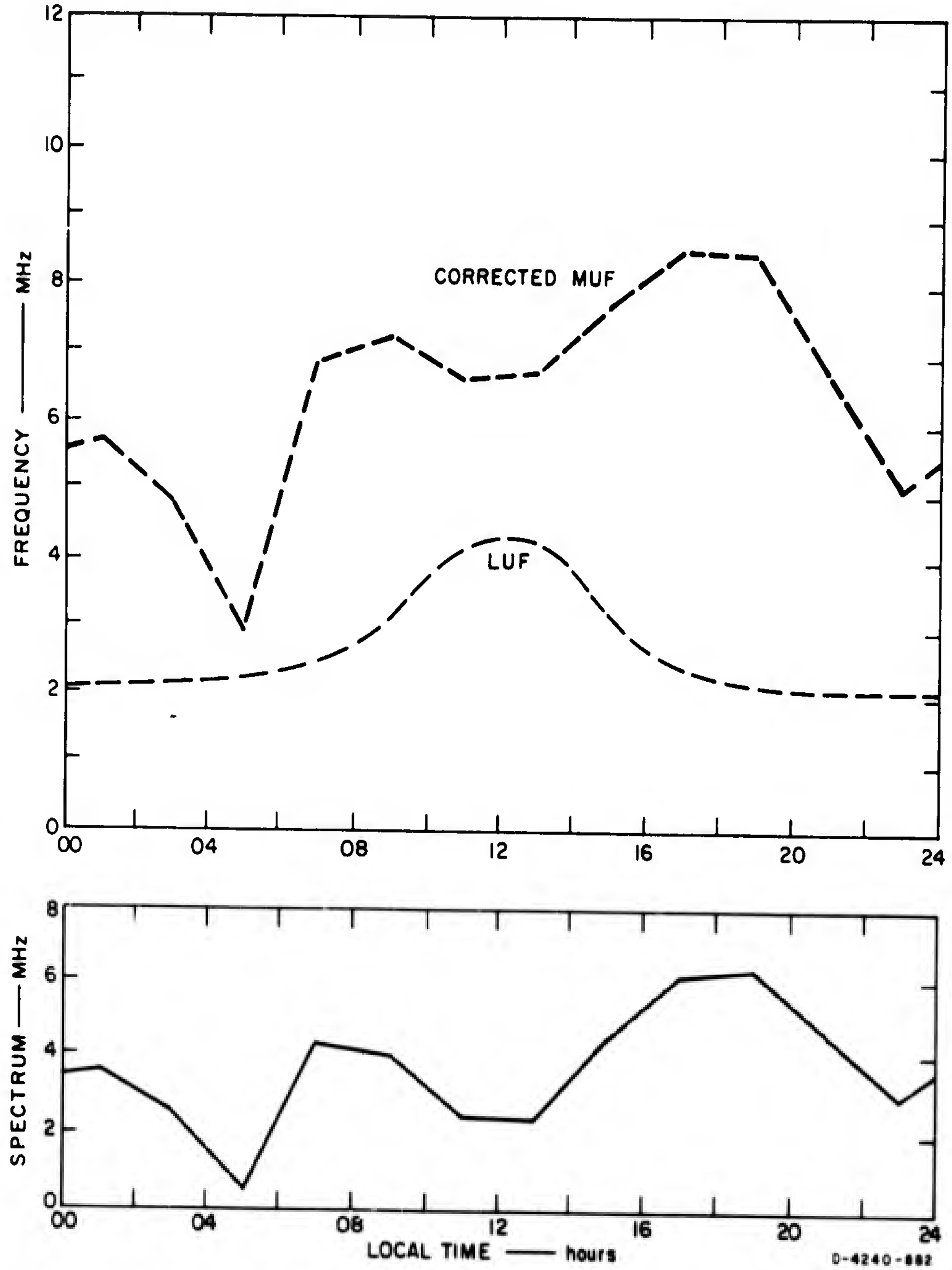

FIG. C-2(n) CORRECTED SRI/RPA PREDICTIONS — MAY 1966

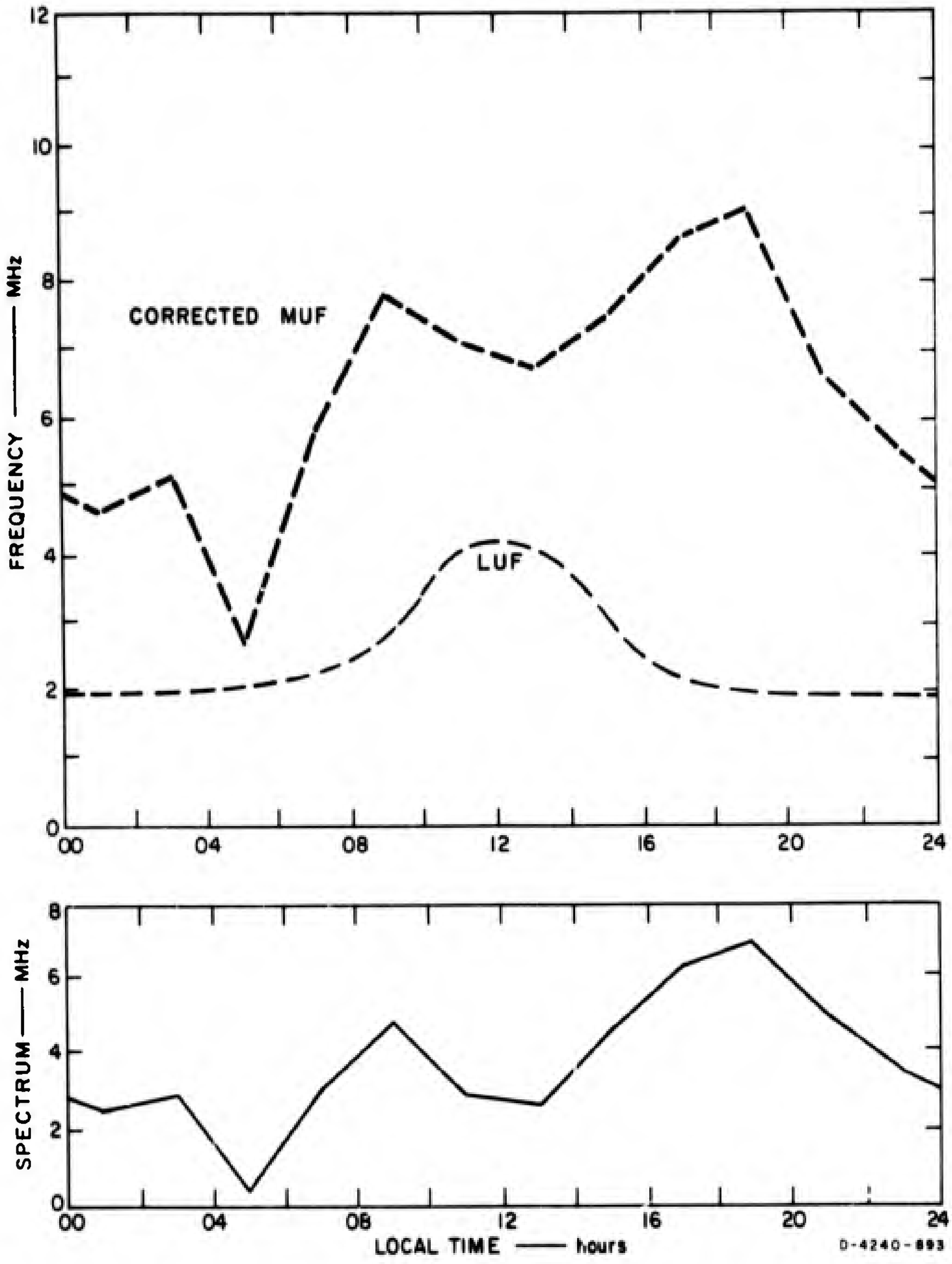

FIG. C-2(o) CORRECTED SRI/RPA PREDICTIONS — JUNE 1966

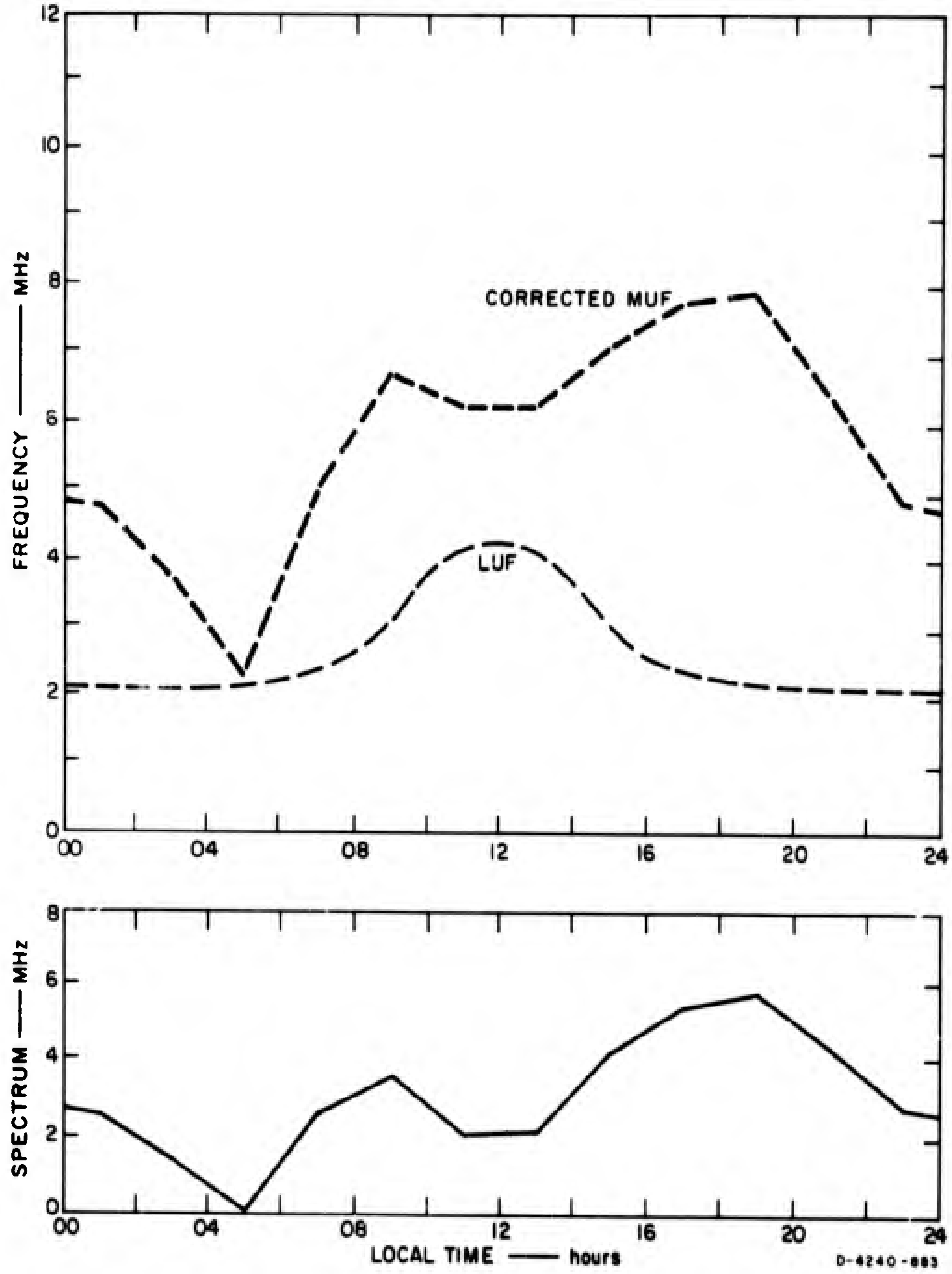

FIG. C-2(p) CORRECTED SRI/RPA PREDICTIONS — JULY 1966

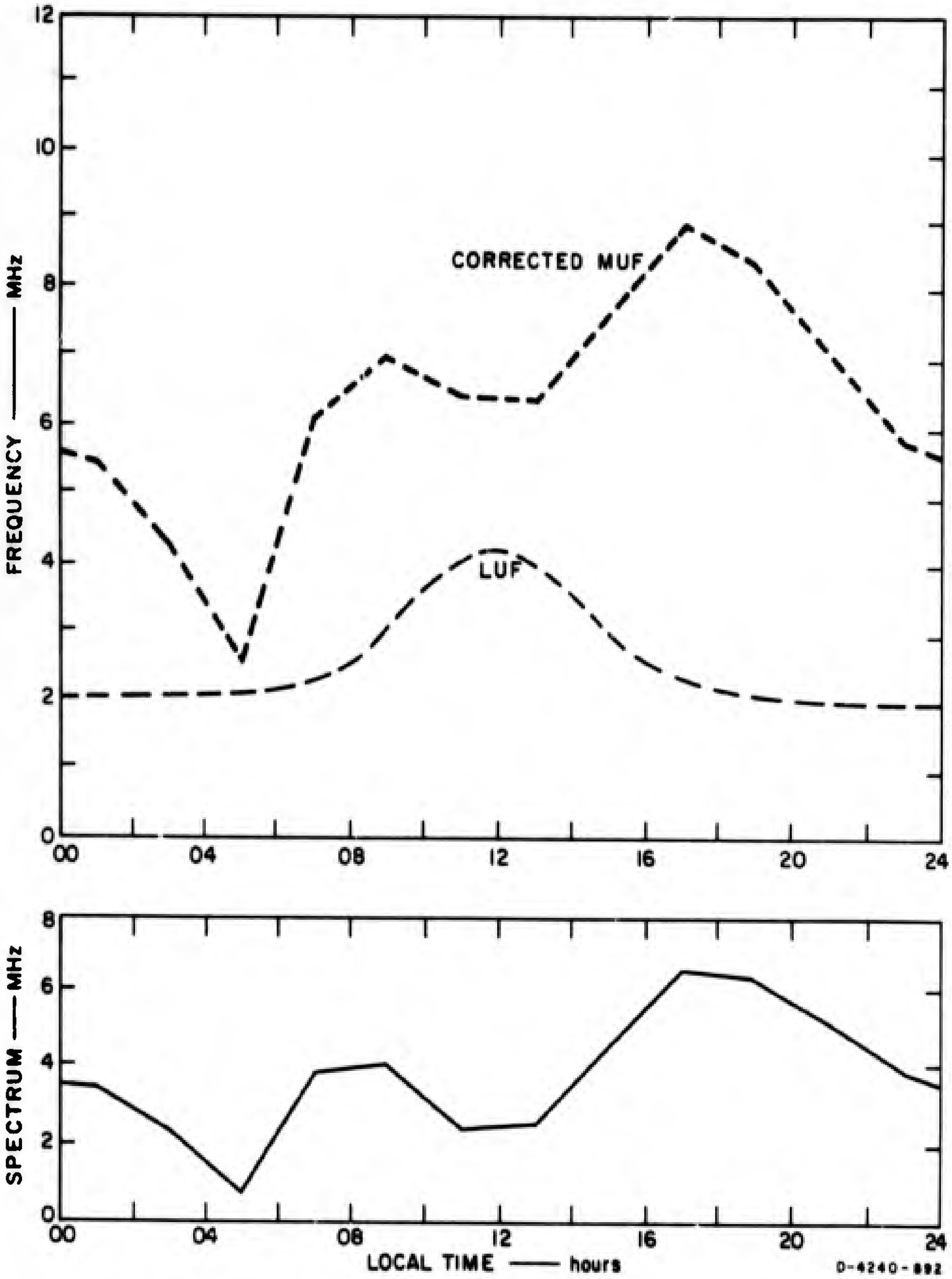

FIG. C-2(q) CORRECTED SRI/RPA PREDICTIONS — AUGUST 1966

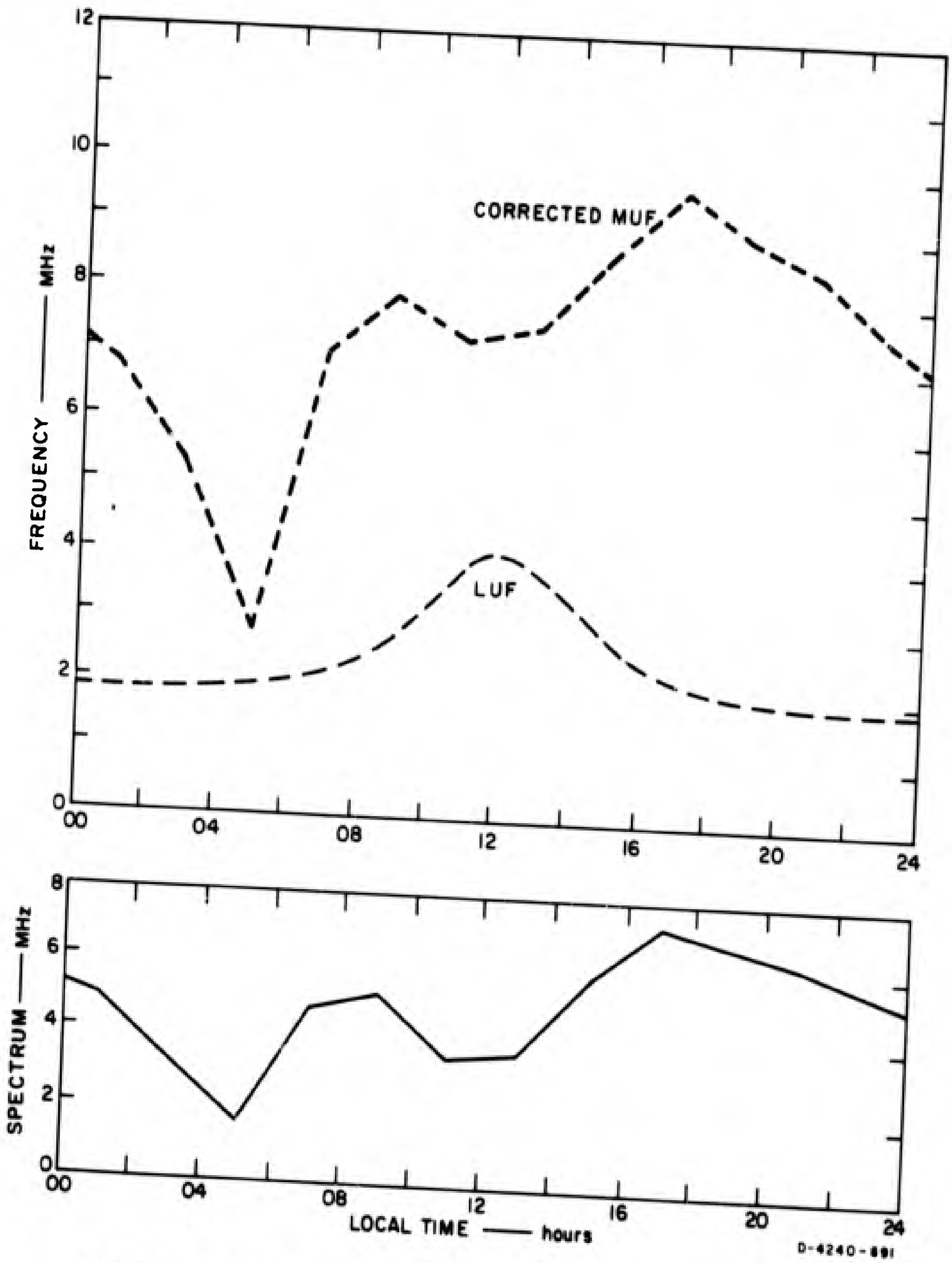

FIG. C-2(r) CORRECTED SRI/RPA PREDICTIONS — SEPTEMBER 1966

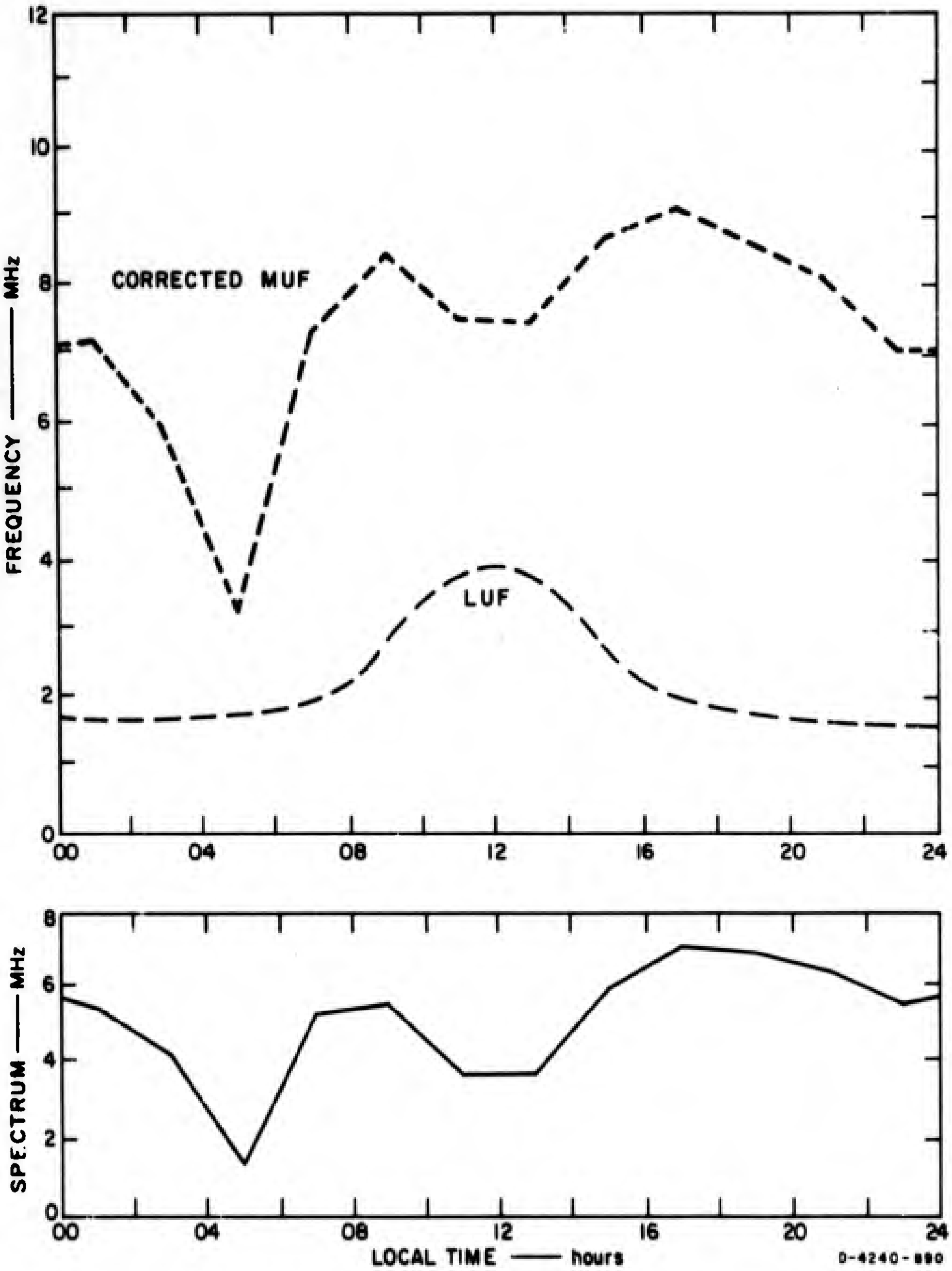

FIG. C-2(s) CORRECTED SRI/RPA PREDICTIONS — OCTOBER 1966

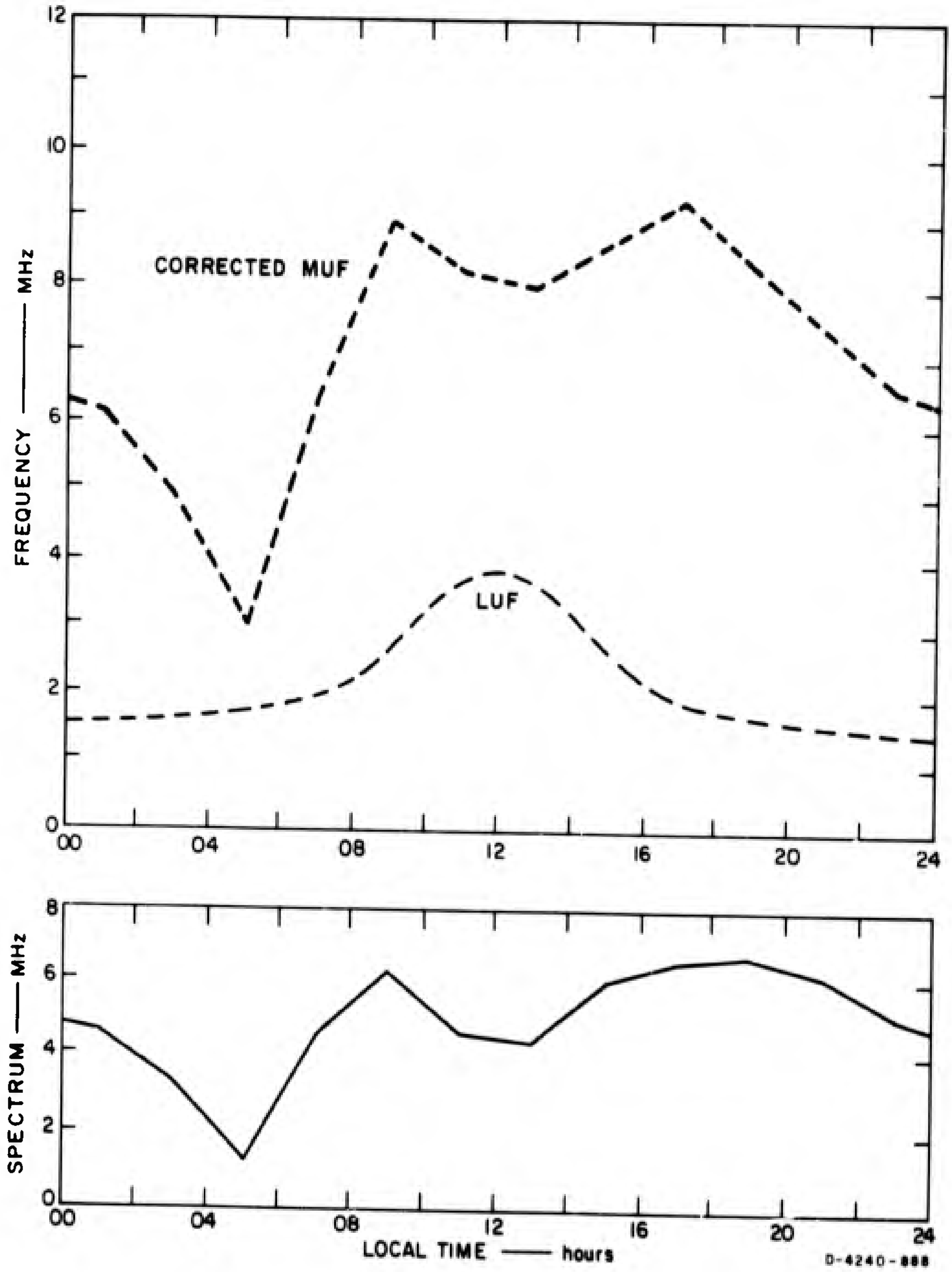

FIG. C-2(t) CORRECTED SRI/RPA PREDICTIONS — NOVEMBER 1966

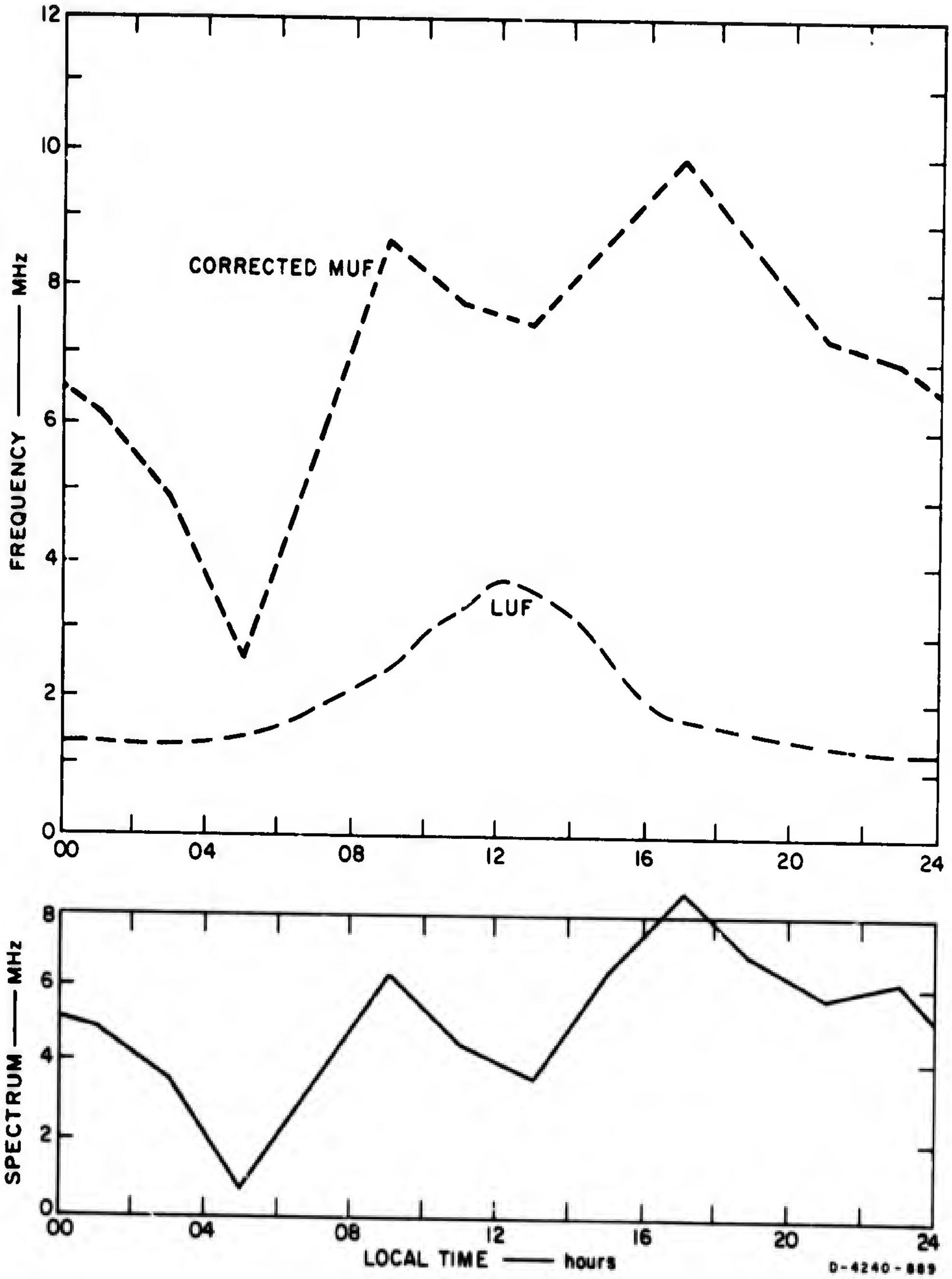

FIG. C-2(u) CORRECTED SRI/RPA PREDICTIONS — DECEMBER 1966

APPENDIX D

EFFECTS OF SPORADIC E, SPREAD F, AND BLACKOUT ON FREQUENCY PREDICTION

APPENDIX D

EFFECTS OF SPORADIC E, SPREAD F, AND BLACKOUT ON FREQUENCY PREDICTIONS

Sporadic E (E_s) ionization can have an appreciable effect on frequency prediction from the standpoint of usable spectrum. The usable spectrum predicted on the basis of variation of the normal layers, D, E, F_1, F_2, is conservative in that the maximum frequency that can be employed is often greater than that predicted. LUF is affected by E_s, but the degree of the influence of E_s upon LUF is difficult to determine from ionogram data. "Sporadic" is actually a misnomer when applied to the probability of occurrence of ionospheric echoes observed on equatorial ionosondes and resembling E_s echoes occurring at higher latitudes, since at equatorial latitudes such echoes are the rule rather than the exception, being present slightly more than half the time.[52]

Table D-1 gives the number of hours for which E_s, spread F, and blackout were observed for the first 19 months of C-2 operation, commencing in September 1963. Sporadic-E occurrence was determined by observing the hours for which a scaled value of f_oE_s was present. E_s occurs most frequently in the daytime. Spread-F[50] occurrence was determined by scanning the C-2 sounder station log for the descriptive letter "F" associated with f_oF2. Spread F occurs most frequently at night, and appears as a condition of time-delay spreading of the sounding pulse. Spread F is caused by ionospheric inhomogeneities at F-layer heights, and HF communication signals reflected from such layers suffer distortion.[53] Blackout occurrence was determined by scanning the station log for the descriptive letter "B" associated with f_{min}. Blackout is usually due to excessively large ionospheric absorption.

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Table D-1

OBSERVED OCCURRENCES OF BLACKOUT, SPREAD F, AND SPORADIC E

Date	No. of Hours Blackout		No. of Hours Spread F		No. of Hours Sporadic E	
	Hours Present	Hours Possible	Hours Present	Hours Possible	Hours Present	Hours Possible
Sept. 63	16	604	1	604	333	604
Oct. 63	7	717	7	717	218	717
Nov. 63	3	613	5	613	230	613
Dec. 63	1	719	17	719	305	719
Jan. 64	10	714	23	714	323	714
Feb. 64	2	677	44	677	352	677
Mar. 64	10	741	58	741	275	741
Apr. 64	9	603	27	603	313	603
May 64	23	656	40	656	424	656
June 64	31	662	47	662	427	662
July 64	26	506	36	506	376	506
Aug. 64	42	690	36	690	478	690
Sept. 64	16	566	19	566	354	566
Oct. 64	23	318	2	318	131	318
Nov. 64	21	611	5	611	194	611
Dec. 64	66	548	1	548	119	548
Jan. 65	50	526	0	526	313	526
Feb. 65	41	531	23	531	205	531
Mar. 65	4	422	35	422	213	422

It is readily observed from Table D-1 that blackout and spread F are relatively unimportant in determining useful spectrum in any operational context during the 1964 sunspot minimum. When present, they would have the effect of decreasing the usable spectrum available for use by a system of HF man-pack radios. It can be anticipated that their frequency of occurrence will increase as the sunspot cycle advances toward a maximum. On the other hand, E_s is more important and has the advantage of increasing the usable spectrum for man-pack systems.

Figures D-1 through D-3 give the diurnal and seasonal variations of percent occurrence in f_oE_s observed above 2.0, 3.0, and 5.0 MHz.

The temporal variation has the same general trend for all values of f_oE_s exceeded. The maximum occurs in the spring and summer months of April, May, June, July, and August, while the minimum occurs in the winter months of October, November, December, January, and February.

The f_oE_s > 2.0 MHz percent occurrence in the early morning hours averages about 20 percent during the winter months and approximately 40 percent during the spring-summer months. The percent occurrence decrease slightly for the f_oE_s > 3 MHz and drops off sharply for f_oE_s > 5 MHz. In the early morning hours the effect of E_s on usable frequency spectrum f_oE_s > 3 MHz occurs about 10 percent of the time during the winter months and about 30 percent during the spring and summer months. Therefore the E_s layer will increase the usable frequency spectrum slightly in the spring and summer early morning hours during sunspot minimum for frequencies less than 3.0 MHz, which is the range of interest.

The probability of occurrence of E_s over Bangkok is receiving further, more detailed study by the authors, and will be the topic of a future report when more C-2 data are available, covering each season several times.

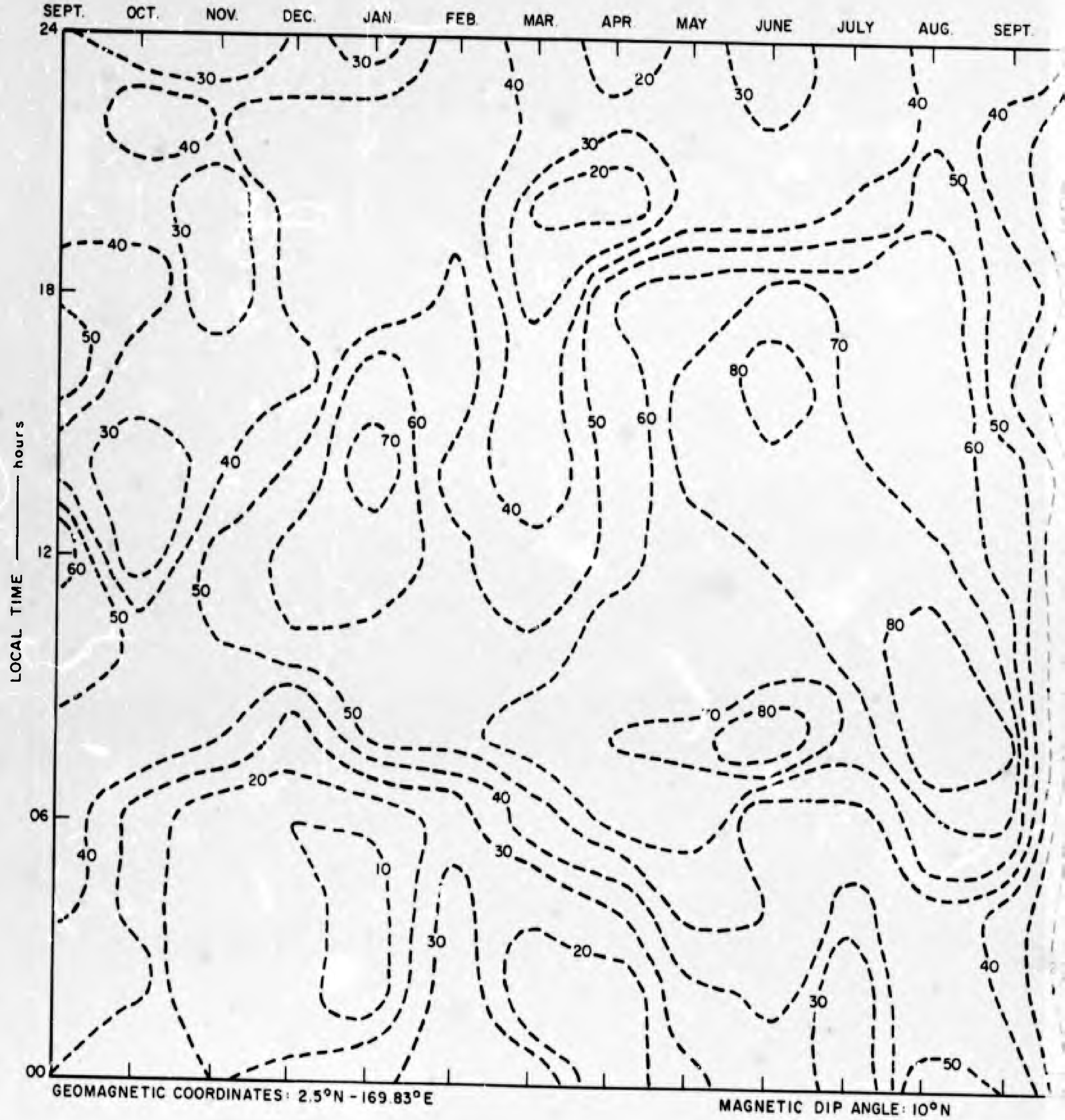
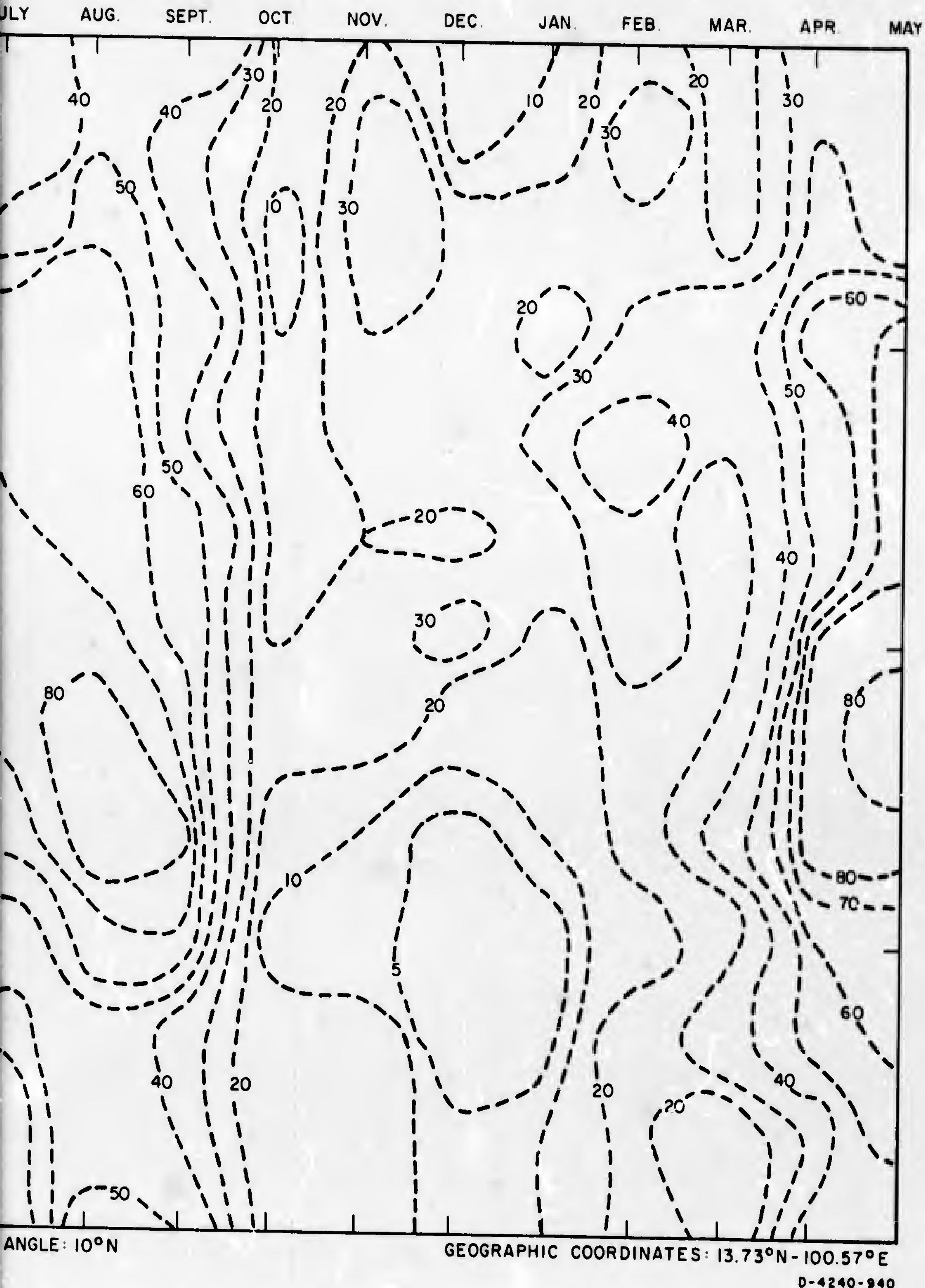


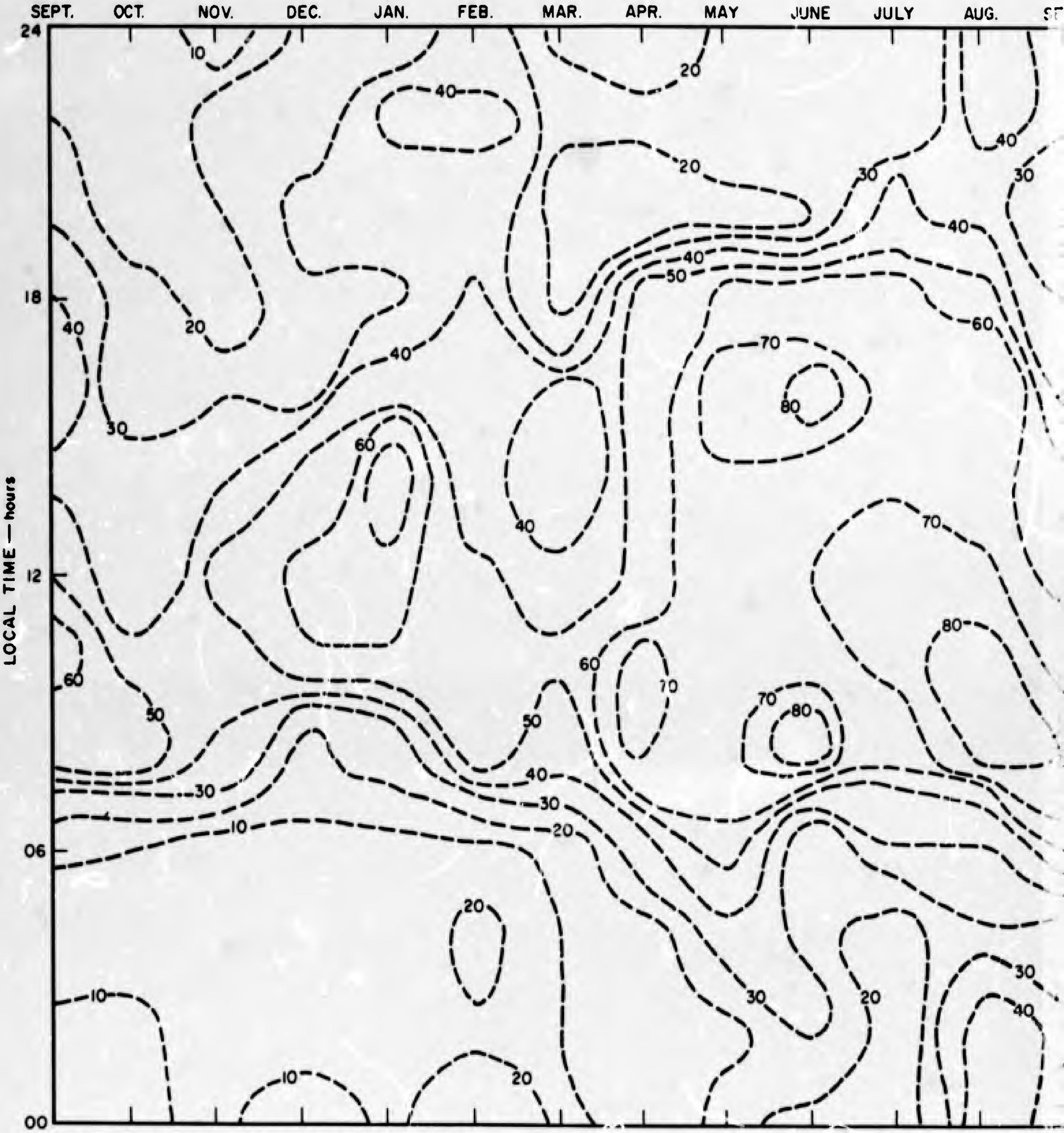
FIG. D-1 TEMPORAL VARIATIONS IN PERCENT OF TIME FOR WHICH f_oE_s EXCEEDS 2 MH

A.



f_oE_s EXCEEDS 2 MHz, SEPTEMBER 1963 THROUGH MAY 1965 FIG. D-1

B.

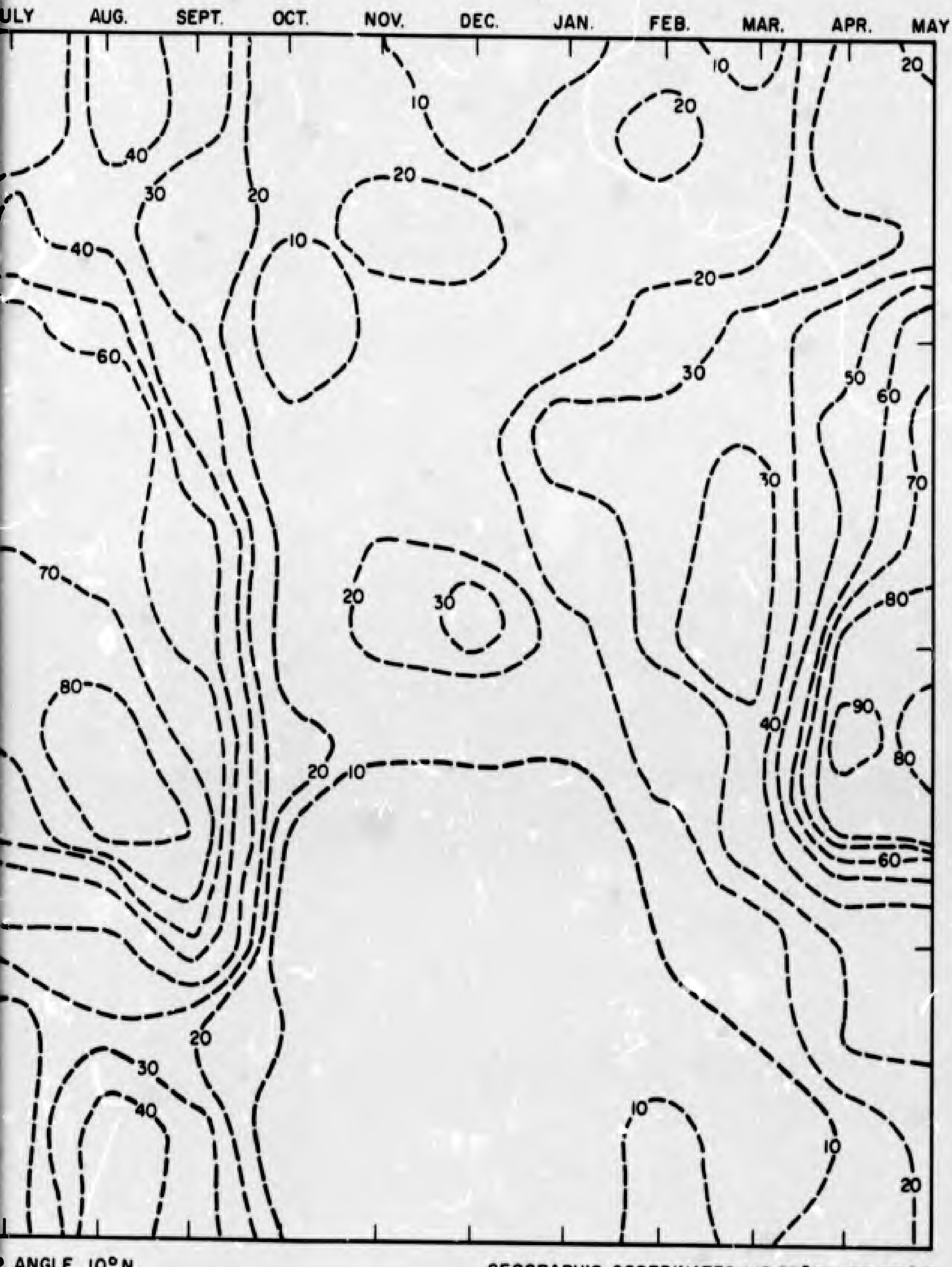


GEOMAGNETIC COORDINATES: 2.5° N – 169.83° E

MAGNETIC DIP ANGLE 10° N

FIG. D-2 TEMPORAL VARIATIONS IN PERCENT OF TIME FOR WHICH f_oE_s EXCEEDS

A.



f_oE_s EXCEEDS 3 MHz, SEPTEMBER 1963 THROUGH MAY 1965

FIG. D-2

B.

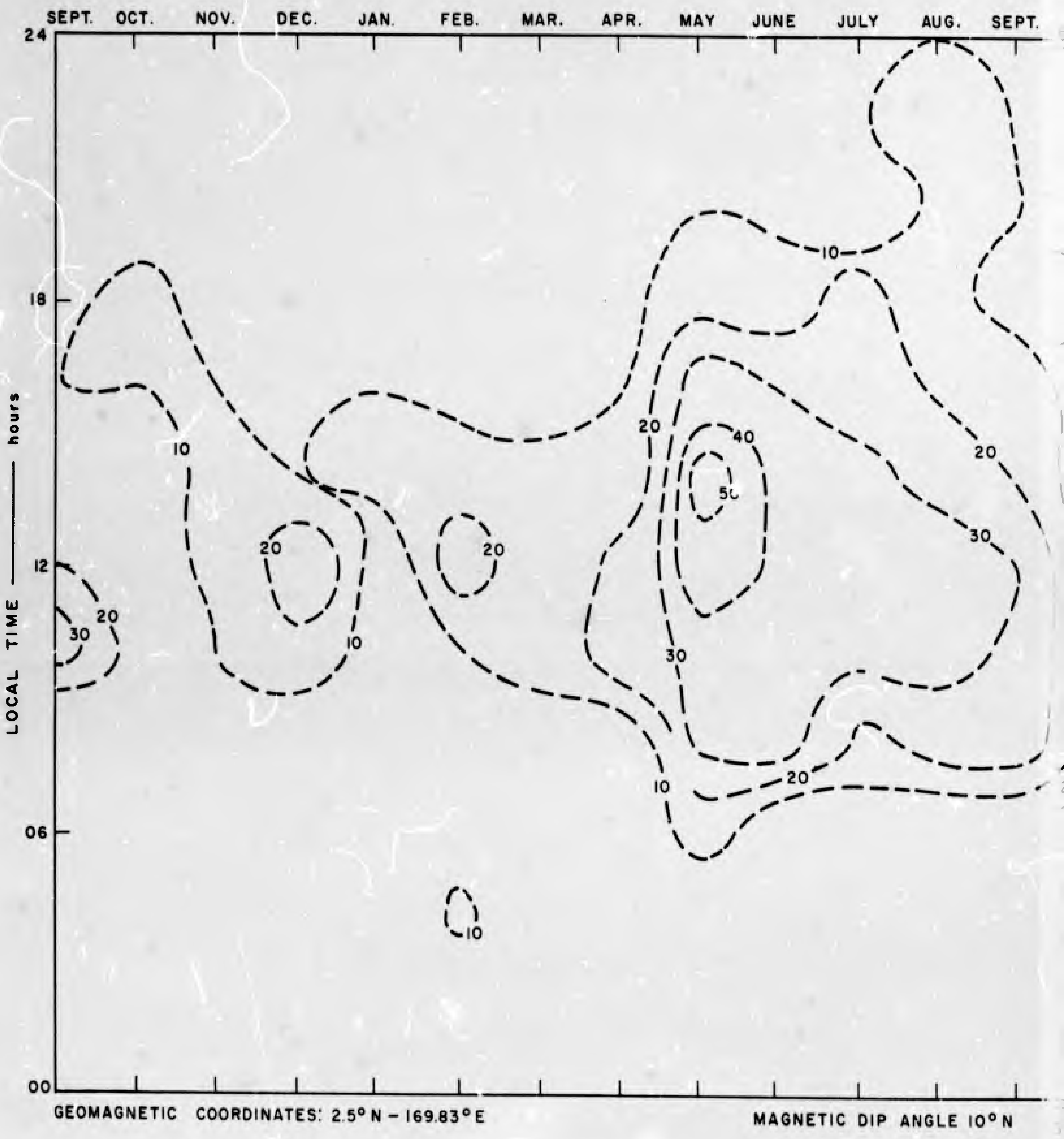
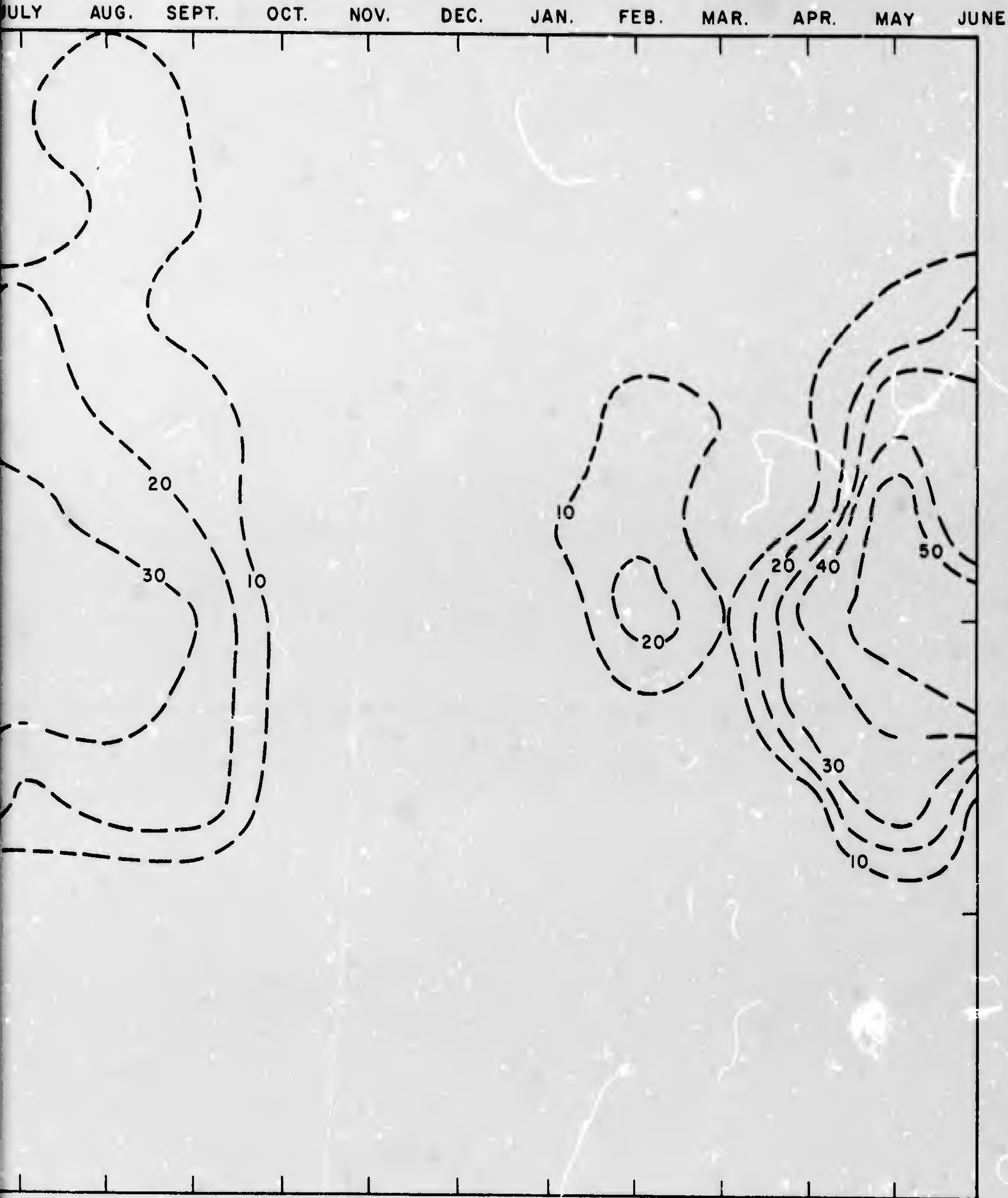


FIG. D-3 TEMPORAL VARIATIONS IN PERCENT OF TIME FOR WHICH f_oE_s EXCEEDS 5 Mc

A



DIP ANGLE 10° N

GEOGRAPHIC COORDINATES: 13.73° N – 100.57° E

D-4240-939R

ICH f_oE_s EXCEEDS 5 MHz, SEPTEMBER 1963 THROUGH JUNE 1965

FIG. D-3

B.

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ABSTRACT concluded

with f_{min} values calculated from observations with the C-2 sounder. Hence the useful frequency spectrum for this particular HF man-pack transceiver can essentially be approximated by the parameters f_oF2 and f_{min} scaled from the data from the modified C-2 sounder at Bangkok.

Communication failure in the early morning hours during sunspot minimum is shown to be critically dependent on the lower tuning limit of the set. The parameter f_oF2 is extrapolated to the next sunspot maximum period to help estimate the design range for man-pack radios. A tuning capability of 2 to 18 MHz is recommended for sets designed to operate over distances out to 1000 km during all phase of the sunspot cycle.

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13. ABSTRACT

This report briefly discusses several ionospheric parameter prediction techniques and compares values of f_oF2, f_{min}, and F-layer height (h_L) predicted using several of these techniques with observed data taken by the C-2 ionospheric sounder at Bangkok, Thailand from its initial operation in September 1963 through March 1965. The sounder data have been used to calculate a correction function for f_oF2, and corrected predictions are given for April 1965 through December 1966. When the correction functions are used it should be possible to predict the monthly median value of f_oF2 and f_{min} to within about 1.5 MHz for all times of day; and the observed values on any given day in the month will be, with probability 0.5, within 2 MHz of the corrected median predictions for all times of day. The magnitudes of these anticipated daily variations from the predicted monthly median values depend upon the local time, and are observed to be smallest near sunrise.

The effects of anomalous propagation on the predictions are inferred from the C-2 data, and indicate that some account must be made for sporadic E but that spread F and blackout are relatively unimportant during the period of small sunspot numbers. The effect of the lower frequency limit of an HF man-pack radio on communication failure is considered for near-vertical-incidence skywave propagation. The lowest usable frequency calculations for a 15-watt HF man-pack transceiver AN/PRC-74 (Hughes HC-162) employing horizontal dipole antennas agree very closely

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C-2 sounder						
Vertical-incidence ionosonde						
Frequency prediction						
MUF/LUF						
Useful spectrum						
HF man-pack radio						
Sporadic E						
Spread F						
Blackout						
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