UAH Research Report No. 188

IONIZATION EFFECTS DUE TO SOLAR FLARE ON TERRESTRIAL IONOSPHERE

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S. T. Wu and Arjun Tan

Final Technical Report

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ACKNOWLEDGEMENT

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LIST OF FIGURES

SUMMARY

The SFD (sudden frequency deviation) events of May 18 and 19, 1973, due to the solar flares as observed from the NASA/Marshall Space Flight Center high-frequency doppler sounder array system in Huntsville, Alabama, are investigated. The results are compared with those observed at Table Mountain near Boulder, Colorado and at the University of Hawaii.

TABLE OF CONTENTS

I. INTRODUCTION

A sudden frequency deviation (SFD) is a type of sudden ionospheric disturbance (SID) caused by bursts of X-rays and extreme ultraviolet (EUV) radiation from solar flares. It consists of a rapid change in the received frequency of a high frequency radiowave propagated from an ultra-stable transmitter and reflected at altitudes in the 120-300 Km range or higher in the ionosphere.

The characteristic frequency derivation results from a time-varying ionospheric electron density produced by the time-varying ionizing radiation from a solar flare and is only sensitive to the impulsiveness of the flare radiation. Conversely, one can deduce the flare enhancement of the ionizing radiation from the sudden frequency deviation event.

This report presents the results of the study of the SFD events of the flares of May 18 and 19, 1973, as observed from NASA/MSFC high-frequency doppler sounder array system in Huntsville, Alabama. The results are compared with those observed at Table Mountain near Boulder, Colorado and at the University of Hawaii.

II. FLARE INDUCED EFFECTS IN THE IONOSPHERE

II.1 Solar Flare

Solar flare generally means a burst of radiation occurring in the chromosphere of the sun. A flare is customarily observed in the Hα light (6563 Å) as well as X-Ray emissions, although some flares are seen in white light also. The development of a flare is usually as follows: a rapid rise to peak intensity, a brief period of peak intensity followed by a steady decline. During a flare, there is a temporary brightening of a small portion of the solar chromosphere, usually near a sunspot. The active areas are associated with sunspots, plages, filaments and high magnetic field gradients.

As expected, the flare is a complex phenomenon comprising diversified dynamical processes occurring in the solar atmosphere. Flares are frequent occurrences, particularly during the peak of the sunspot cycle.

During most flares, there is a marked increase in the flux of solar ionizing radiation in the far ultraviolet and soft X-ray regions of the radiation spectrum. There are also radio noise emissions and explosive outbursts of corpuscular emission ranging from relativistic to lower speeds. These radiations mark their imprints in the appearance of various ionospheric effects, such as enhancement in the electron densities in the D and E regions, auroras, magnetic storms, etc.

Nearly all important extensive disturbances in the ionosphere are associated in some way or other with a flare on the sun. These disturbances are important from the point of view of radio communications because they often result in interruptions of communications. The absorption in the D-region is enhanced so much that intelligible radio communication becomes impossible for periods lasting from a few minutes to several days. Also, the critical frequencies of the F2 layers are sometimes depressed during an ionospheric storm resulting in loss of the signal due to MUF (Maximum Usable Frequency) failure. The study of these disturbances is important for a better understanding of the interaction of the solar radiation with the earth's atmosphere and ultimately a better understanding of the solar flare itself.

The flare-induced effects can be broadly classified into two categories: (1) the simultaneous effects and (2) the delayed effects. The former effects are due to electromagnetic radiation enhancements and the latter due to solar cosmic ray particles, both relativistic and non-relativistic. The relativistic particles (mostly protons) having transit times from 15 minutes to several hours induce polar cap absorption and cosmic ray enhancements. Slower particles (both protons and electrons) which take 20 to 40 hours to reach the earth are responsible for ionospheric storms, magnetic storms and visible displays of aurora.

The fact that many of the ionospheric effects begin at the time of visual sighting of the flare indicates that they are due to electromagnetic rather than corpuscular radiation. The occurrence of a flare is accompanied by the emission of radio waves, UV - and X - rays, all of which arrive at the same time with visible light. The various types of radio noise are thought to be produced by bremsstrahlung synchrotron emission and plasma oscillations in the solar atmosphere (Wild, 1964; Smerd, 1964).

As a result of a solar flare, all layers of the ionosphere are affected, although the E layer is not strongly affected except for the occurrence of sparadic E in certain ionospheric storms. The D and F layers are subject to much stronger effects.

The general classification "sudden ionospheric disturbance" or SID includes the phenomena which accompany solar flares occurring simultaneously with the optical Hα flare (Dellinger, 1973). SID observations form two groups. The first group consists of SID effects observed in the ionosphere at D region heights below 100 Km caused by soft X-rays (10Å) and includes SWF (Short Wave Fadeout), SPA (Sudden Phase Anomaly), SCNA (Sudden Cosmic Noise Absorption), SEA (Sudden Enhancement of Atmospheries) and so on. These SIDs provide useful information for studying the transient response of the poorly understood D region (Mitra, 1972).

II.2 D Region Effects

The D region effects tend to involve large percentage increases in ionization relative to preflare values. Satellite measurements have shown that the total solar X-ray emission can easily rise by several orders of magnitude in the wavelength 2-10 Å in a class 2 flare (Culhane, et. al., 1964). An increase in electron concentration in the D region by a factor of 10 was measured by the certical reflection technique (Belrose and Centiner, 1962). This clearly identifies the X-ray enhancement as responsible for the D region SID effects. The threshold effect results from cosmic rays and the solar hydrogen Lyman α line, the dominant source of ionization in the D region, until the soft X-ray flux raises this threshold value.

The production of ionization in the D region gives rise to associated phenomena such as the short wave fadeout (SWF), sudden cosmic noise absorption (SCNA) received on frequencies above the F2 layer critical frequency, the sudden phase anomaly (SPA) and the sudden enhancement of atmospherics (SEA) on very low frequencies. In the following, we shall give a brief description for these terminologies.

a. Short Wave Fadeout (SWF) - At times communications on high frequency by skywave propagation over the daylight hemisphere of the earth are blacked out or strongly absorbed by enhanced ionization in the D region. There is a sudden decrease in the received signal strength beyond the normal fading of the HF radio wave reflected from the ionosphere. The association between these short wave fadeouts and solar flares was discovered by Dellinger (1935).

b. Sudden Cosmic Noise Absorption (SCNA) - During a flare, there is a sudden decrease in galactic cosmic noise received at frequencies high enough to penetrate the ionosphere yet low enough to encounter measurable absorption (Jansky, 1937). A fairly large flare may cause a 2 db increase in absorption of frequencies of 18 to 25 MHz which pass completely through the ionosphere without reflection (Shain and Mitra, 1954).

c. Sudden Phase Anomaly (SPA) - The increase in ionization produces a phase advance of low frequency radio waves reflected from the ionosphere due to a lowering of several kilometers in the height of reflection (Budden and Ratcliffe, 1937).

d. Sudden Enhancement of Atmospherics (SEA) - During a flare, there is a sudden increase in signal strength of noise (atmospherics) from lightening storms around the world. These are recorded between 20 to 40 k Hz (Bureau, 1937). Like the SPA, this indicates a change in very low frequency propagation conditions.

e. Solar Flare Effect (SFE) or Magnetic Crochet - SWFs are sometimes accompanied by transient variations in the earth's magnetic field. The horizontal component of the geomagnetic field undergoes a sudden small change (McNish, 1937). This indicates the existence of electric currents in the D region ionosphere, due to increased ionospheric conductivity.

II.3 E and F Region Effects

The solar hydrogen Lyman α line is the dominant source of the SID effects at heights above 100 Km in the well-understood day-time E and F1 regions caused by solar radiation in the 10 to 1030 Å wavelength range. These SID effects involve much smaller percentage increases in the electron density but much larger absolute increases in comparison to those in the D region.

Most of the results on the EUV flare radiation are deduced from ground-based measurements based on one observing technique where the flare effect is called a sudden frequency deviation (For review, see Donnelly, 1970). In this experiment, the frequency of a very stable radio signal is observed after reflection from the E or F1 layers. An increase in the electron content of the ionosphere during a solar flare brings about a decrease in the phase path of the signals and induces a small transient change in frequency of the observed signal. Although the extra D region ionization produces large absorption effects, it contributes very little to the phase path changes measured in an SFD. These changes are mostly due to extra ionization deposited in the E and F1 regions by longer wavelength X-rays and EUV radiation (Kanellakos, et al., 1962).

III. SUDDEN FREQUENCY DEVIATIONS

III.1 History of Sudden Frequency Deviations

The sudden frequency deviations due to solar flares were identified at a much later date than most other SIDs (Chan, et al., 1961). Chan and Villard (1963) used the term "sudden frequency deviations" to describe the HF Doppler observations of SIDs. Davies, et al. (1962) derived the frequency deviation for the case of a thin enhancement region below the height of reflection and for the case where the enhancement of ionization is at the height of reflection. They showed that the frequency deviation is inversely and directly proportional to the transmitter frequency in the first and second cases, respectively.

Statistical studies of SFDs have been made by Chan and Villard (1963) and Agy, Baker and Jones (1965). Recent investigations have been made by Donnelly (1970) and Donnelly, et al. (1974). The main assets of SFD observations are 1 sec time resolution, low cost, ground-based equipment and essentially continuous daylight coverage.

III.2 Characteristics and Wavelength Dependence of the SFDs

In an SFD event, the received frequency of a high frequency radio wave, usually reflected from the F region of the ionosphere, increases suddenly, peaks and then decays to the transmitted frequency. The received frequency usually decreases below the preflare frequency from the peak and then increases back to the preflare frequency. At other times, no negative frequency deviation takes place. Some SFDs have more than one peak, and most SFDs have some fine structure. The start-to-maximum time is typically about one minute and the peak deviation is usually less than 0.5 Hz. The size of the frequency deviation is very small relative to the transmitted frequency, rarely more than one part per million. Unlike most other detectors of solar radiation, the SFDs are sensitive to the impulsiveness of the solar radiation and insensitive to the non-flare radiation.

The SFDs differ from the other SID effects in that the frequency deviation is proportional to the time rate of change of electron density primarily in the E and F1 regions produced by flare radiation in the 10-1030 Å wavelength range. Radiation enhancements in the 1-10 Å range, although responsible for SFDs from the bottom of E layer and the sporadic E, contribute mainly to the D region electron density enhancements and the resulting SID effects. Radiations at wavelengths greater than 1030 Å are ineffective in ionizing any of the major constituents of the atmosphere, and are therefore, unable to contribute to any SID effect. The sensitivity of SFDs to the 1-1030 Å bursts depends upon the spectrum of the 1-1030 Å radiation, the solar zenith angle, time of the day and season, the preflare electron density as a function of height, the upper atmospheric neutral densities, etc.

III.3 Sensitivity of SFDs to the Solar Radiation

The sensitivity $S(\lambda)$ of SFDs to incident radiation as a function of the wavelength λ of the ionizing radiation is defined by

$$S(\lambda) = \frac{\Delta f \; (f_v)}{R_t \; R_\chi \; \Delta\phi(\lambda) \; d\lambda}$$

where Δf is the frequency deviation in Hz, $\Delta\phi$ is the radiation enhancement in ergs cm^{-2} sec^{-1} $\mathring{A}^{-1}$, R_t is a dimensionless factor that accounts for the time-dependence of $\Delta\phi$, R_χ accounts for the solar zenith angle dependence and f_v is the equivalent vertical-incidence frequency of the SFD probing radio wave.

Figure 1 gives a plot of $S(\lambda)$ for a radio wave reflected at 200 Km altitude. The value of $S(\lambda)$ drops off rapidly with decreasing wavelength below about 1 Å, because radiation at those wavelengths produces ionization mainly low in the D region, where most of the freed electrons are rapidly lost via attachment to form negative ions.

Because of small ionospheric fluctuations that are always present, the smallest 1-1030 Å flux enhancement detectable by mid-latitude SFD observations under the best conditions is about 4×10^{-3} erg cm^{-2} sec^{-1} and more typically 10^{-2} erg cm^{-2} sec^{-1}. The frequency deviation is linearly related to the 1-1030 Å flux enhancement for enhancements less than 1 erg cm^{-2} sec^{-1}, above which a small non-linearity may occur after the EUV flux has been in progress for about 100 sec.

Figure 2 illustrates the sensitivity of SFDs to the impulsiveness of 1-1030 Å radiation. The solid curve represents the time dependence of a hypothetical EUV burst of ionizing radiation in the 10-1030 Å wavelength range, or the resultant rate of electron production with a linear rise to a peak in time t_m followed by an exponential decay with a 1/e time constant t_d set arbitrarily equal to $\frac{1}{2}t_m$. The dashed curve illustrates the time-dependence of the rate of change of electron density and hence the SFD for the case where the rise time t_m and the decay time

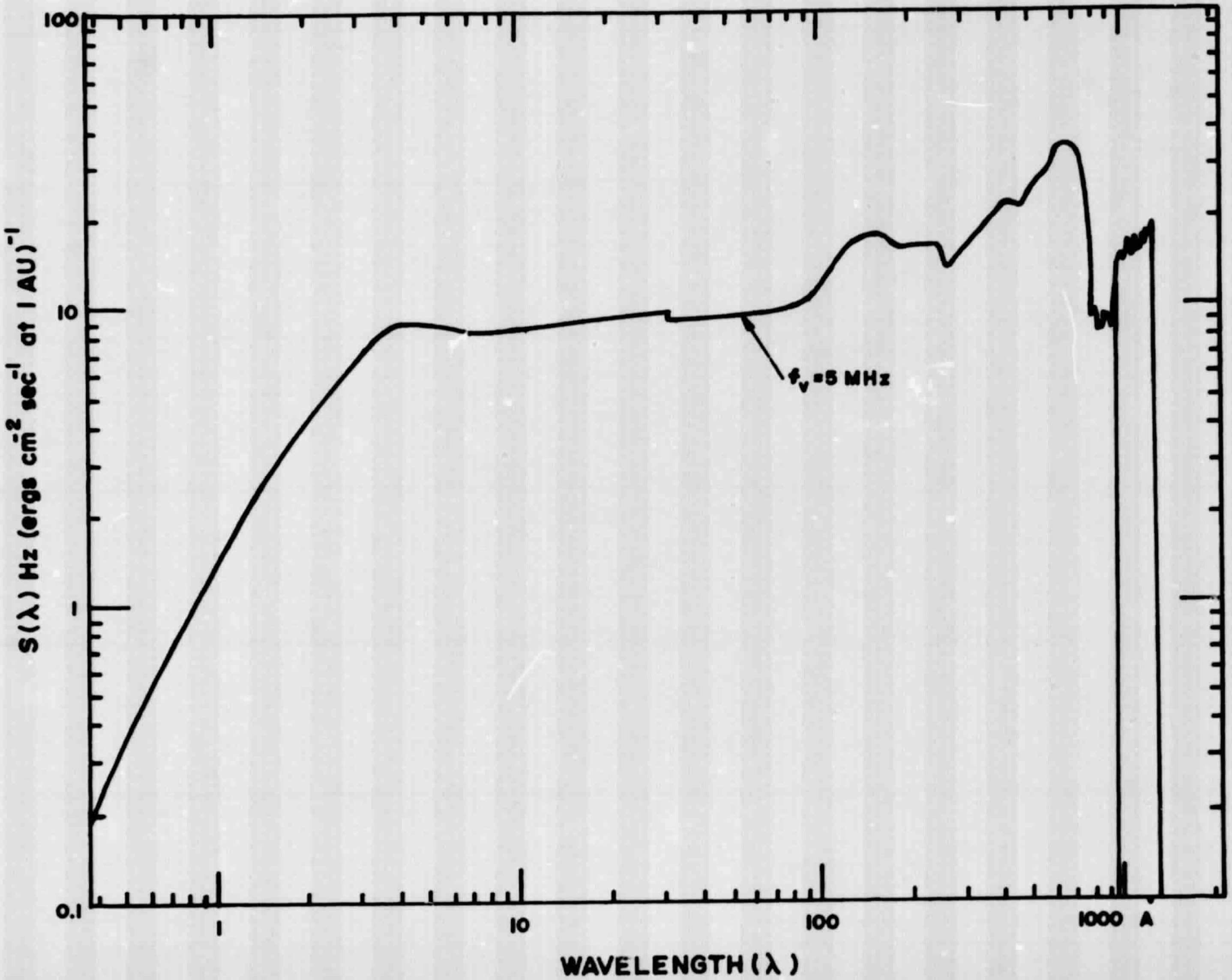

Figure 1. SFD sensitivity to ionizing radiations as a function of radiation wavelength.

t_d of the burst are much less than the effective electron-loss time constant t_c in the E and Fl regions of the ionosphere. In this case, the SFD time dependence is essentially the same as that of the incident radiation enhancement, except late in the decay stage. The dash-dot curve illustrates the case when the rise and decay times of the burst of radiation are comparable to the effective electron-loss time constant. The SFD in this case has a time dependence similar to the EUV burst but with a marked negative deviation during the decay stage. Most SFDs fit into this case. The dotted curve illustrates the case when the burst time constants are much larger than the electron-loss time constant. Here the resulting SFD is smaller and flatter. The electron-loss time constant in the E and Fl region is typically between 15 and 60 secs. Hence, SFD observations are relatively insensitive to radiation bursts with smooth rises of a few minutes or more. This illustrates the SFD dependence on the impulsiveness of the flare radiation.

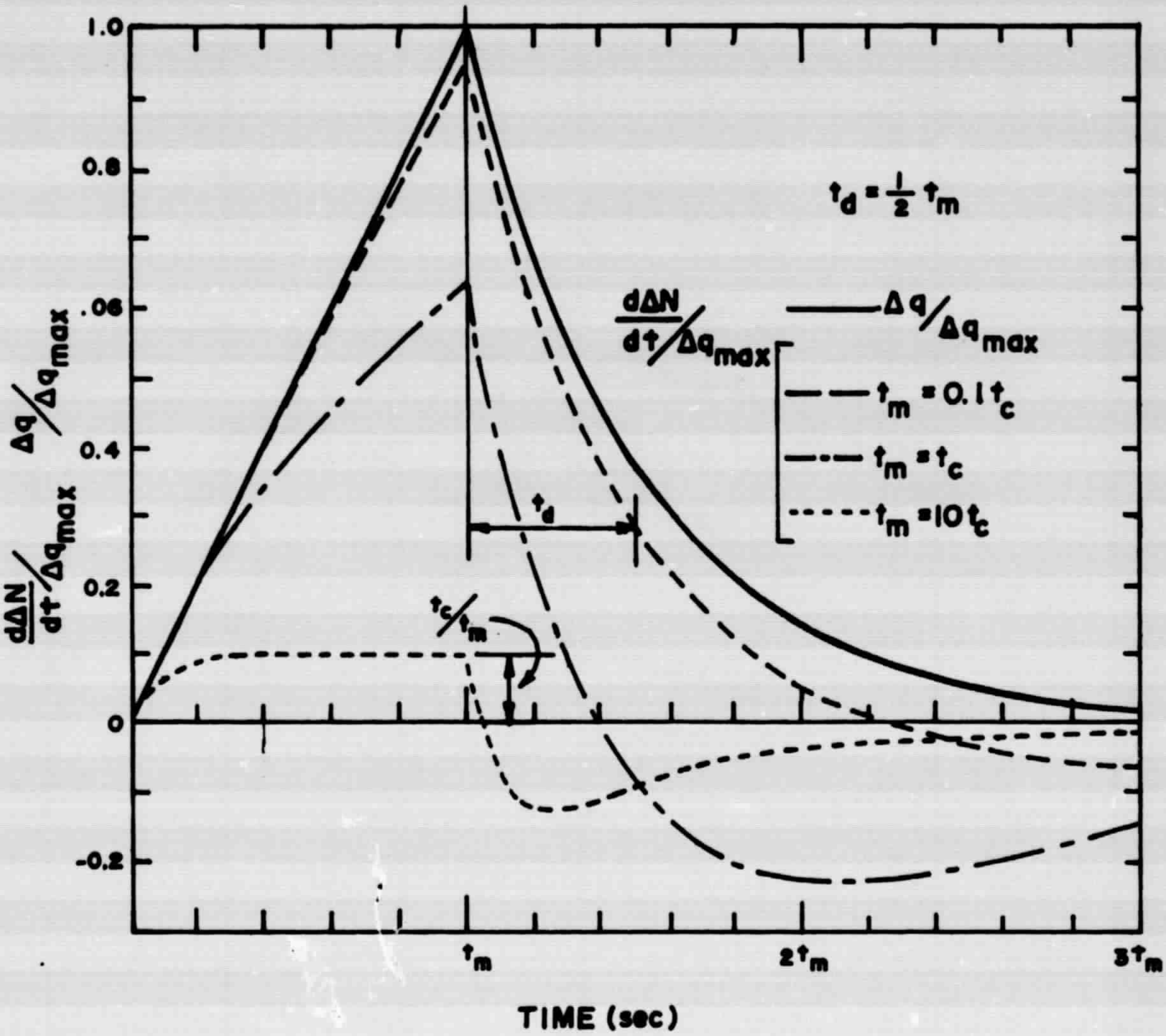

Figure 2. The dependence of SFD's on the impulsiveness of the flare enhancements of ionizing radiation, t_c = the effective electron-loss rate in the ionosphere.

IV. ANALYSES OF SFDs OF MAY 18 AND 19, 1973

IV.1 Description of Observed Events

Figure 3 shows the map of the National Aeronautics and Space Administration/Marshall Space Flight Center high frequency doppler sounder system near Huntsville, Alabama, which was designed to study moving ionospheric irregularities including traveling waves excited by static ground tests of large rocket engines. Huntsville is located at 34.7°N latitude and 86.6°W longitude.

The two SFD events as observed in Huntsville and analyzed in this report are shown in Figures 4 and 5. The event of May 18, 1973 started at 1525 UT (Universal Time) which corresponds to 9.25 a.m. local time and a solar zenith angle of 33.3°. The event showed two major peaks at 1528 UT and 1530.7 UT and also negative frequency deviation between the two peaks. The maximum frequency deviation Δf_{max} was .664 Hz at 1528 UT. The prominent SFD event of May 19, 1973 started abruptly at 2243 UT corresponding to 4.43 P.m. local time in Huntsville and a solar zenith angle of 67.3°. The event had a single major peak at 2245 UT corresponding to Δf_{max} = 2.254 Hz. This large SFD event accompanied a 1B Hα flare in McMath Plage Region 12352 at N09 E20 starting at 2233 UT and peaking at 2245 UT (see Donnelly, et al., 1974). This event as well as the event of May 18 as observed in Huntsville appeared too smooth and devoid of fine structures.

The same event (of May 19, 1973) observed near Boulder (40.2°N, 105.3°W) at 137 MHz frequency and in Hawaii (21.3°N, 157.8°W) at 10 MHz are shown in Figures 6 and 7 (Donnelly, 1976). This corresponds to a

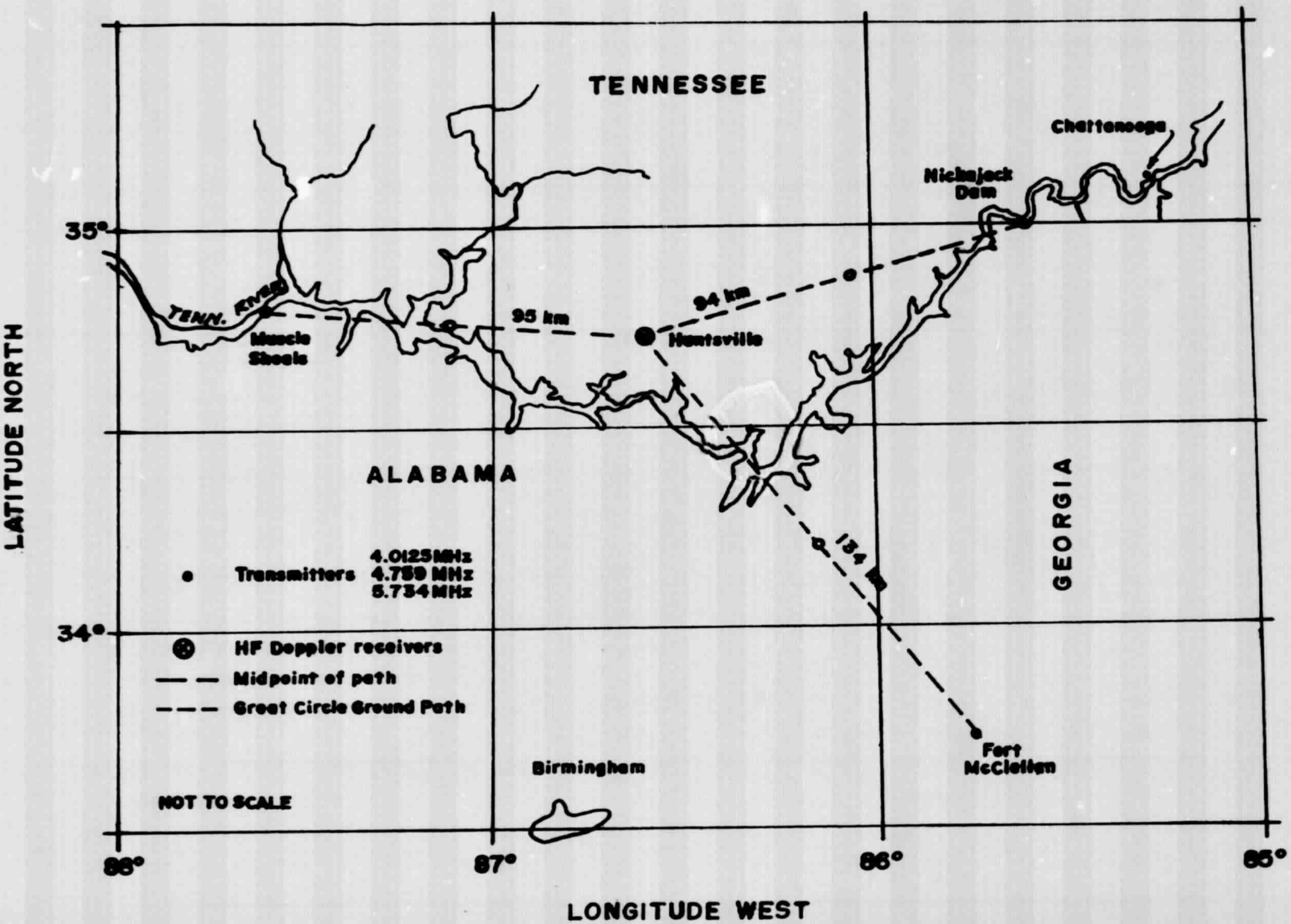

Figure 3. Locations of transmitters, receivers, and ground paths for HF Doppler observations at NASA/Marshall Space Flight Center, near Huntsville, Alabama.

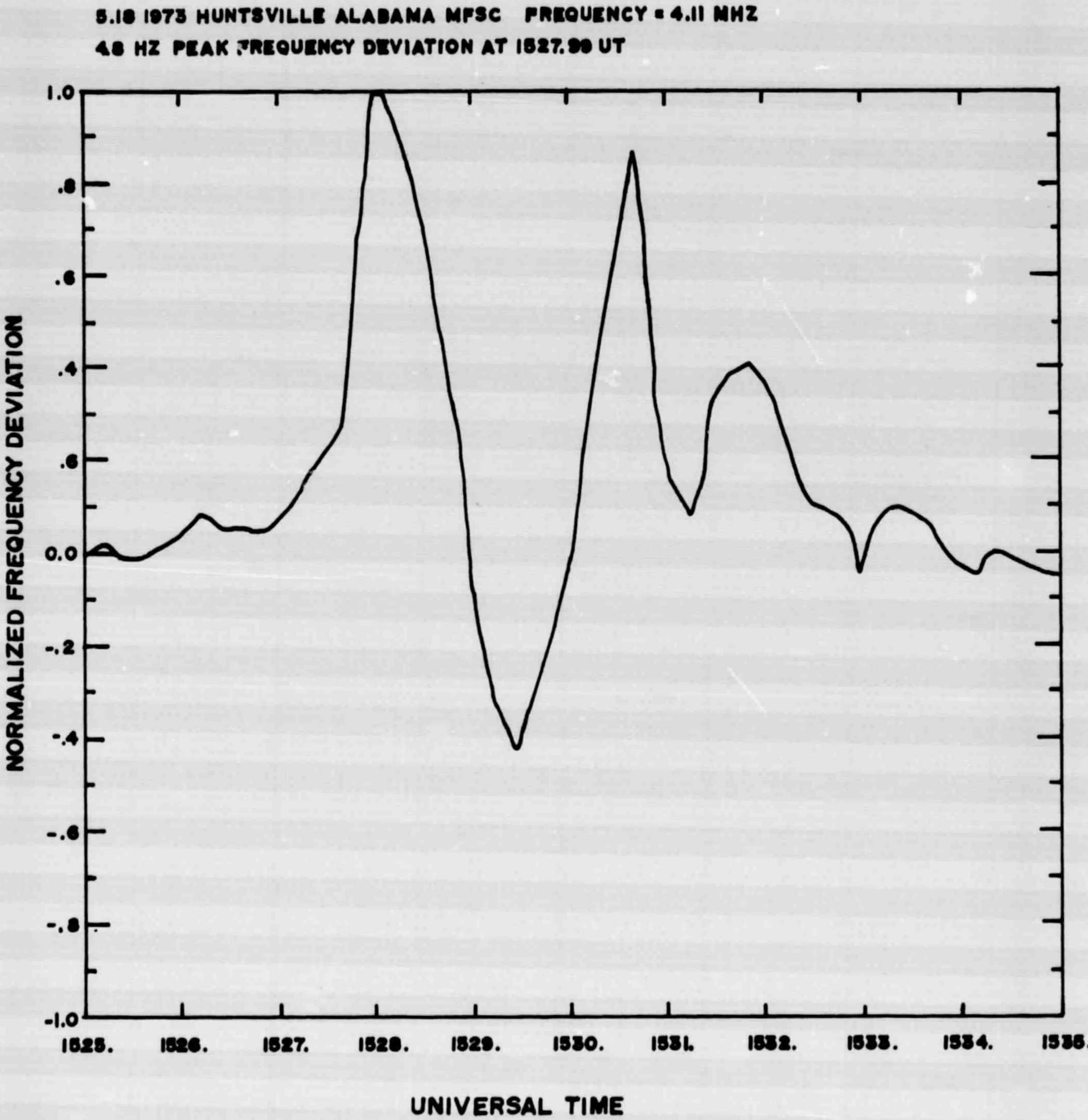

Figure 4. Observed SFD event as a function of UT (Universal Time) on May 18, 1973 at NASA/Marshall Space Flight Center high frequency doppler sounder system near Huntsville, Alabama (34.7° latitude and 86.6° W longitude).

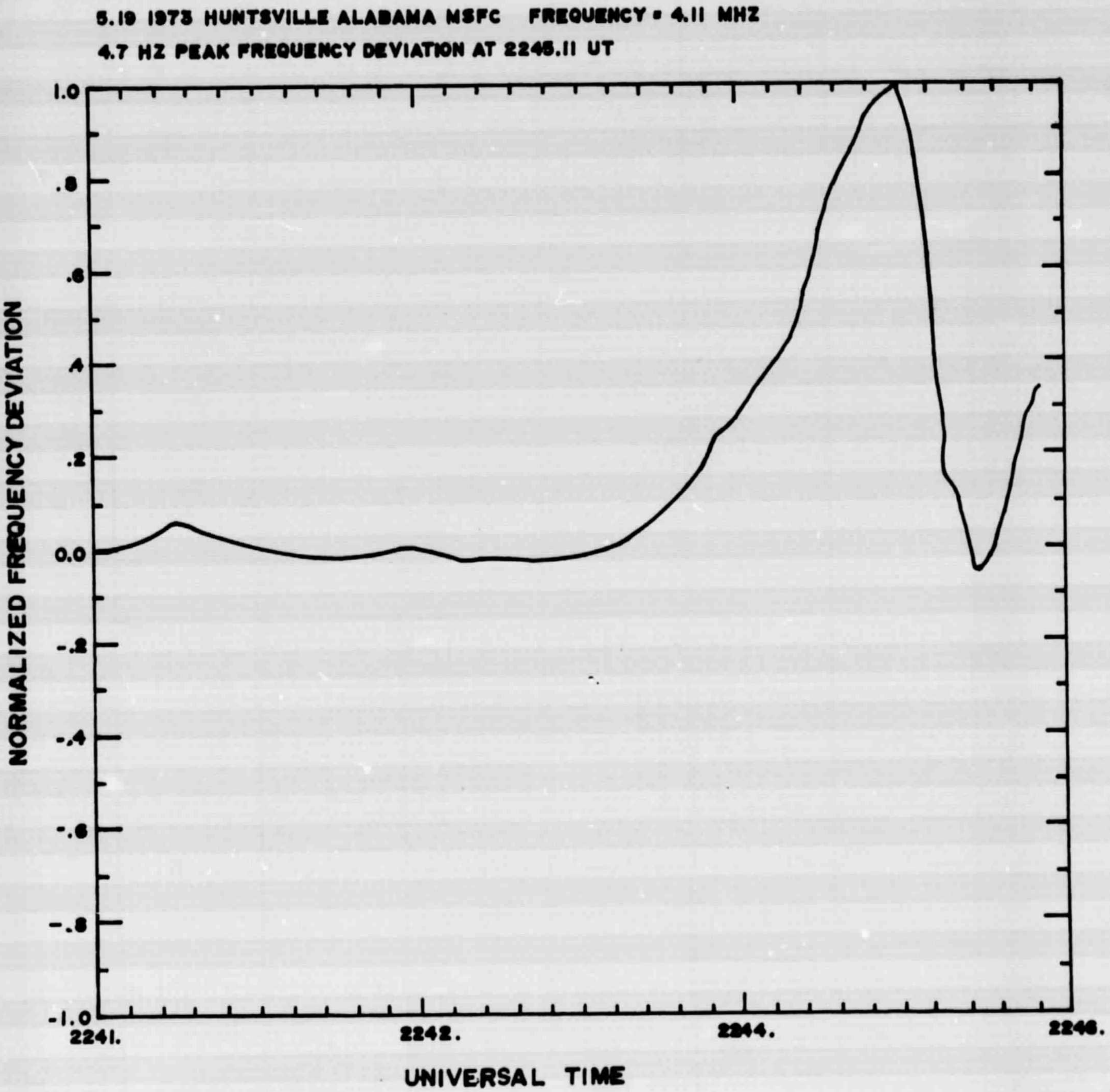

Figure 5. Observed SFD event as a function of UT (Universal Time) on May 19, 1973 at NASA/Marshall Space Flight Center high frequency doppler sounder system near Huntsville, Alabama (34.7° latitude and 86.6° W longitude).

local time of 4:45 p.m. at Boulder and 12:45 p.m. in Hawaii, and therefore, to smaller solar zenith angles. The maximum frequency deviations observed were also larger. The 4.0 MHz transmitter trace at Boulder was lost due to high flare-induced absorption and no comparison with that at Huntsville was possible. However, both the Boulder and the Hawaii data showed distinct fine structures.

IV.2 Deduction of the Flare-Enhancement of the 10-1030 Å Radiation Flux

The 10-1030 Å flux enhancement $\Delta\phi$ is related to the flare-enhanced production of ionization $\Delta q(t)$ by

$$\Delta\phi \; (10\text{-}1030 \; \text{Å}, t) = a \sec \chi \, \Delta q(t)$$

where $a = 6.56 \times 10^{-13}$ watt. m-sec. and χ is the solar zenith angle at the midpoint of the propagation path at the time of the peak of the event (Donnelly, 1970).

$\Delta q(t)$ is given by

$$q(t) = \frac{dN_e}{dt} + \frac{\Delta N_e}{\tau_{eff}} + B_{eff} \, (\Delta N_e)^2$$

where τ_{eff} is the effective electron loss time-constant and the non-linear term in B_{eff} is small relative to $\frac{\Delta N_e}{\tau_{eff}}$.

The procedure used to calculate the 10-1030 Å flux enhancement for the results of this report was method three of Donnelly (1970). This method employs two main related simplifying assumptions:

(1) The time rate of change of electron density $\frac{dN_e}{dt}$ in the ionosphere during the solar flare is approximately constant with height h_o, from just above the bottom of the E layer to the height of reflection h_r.

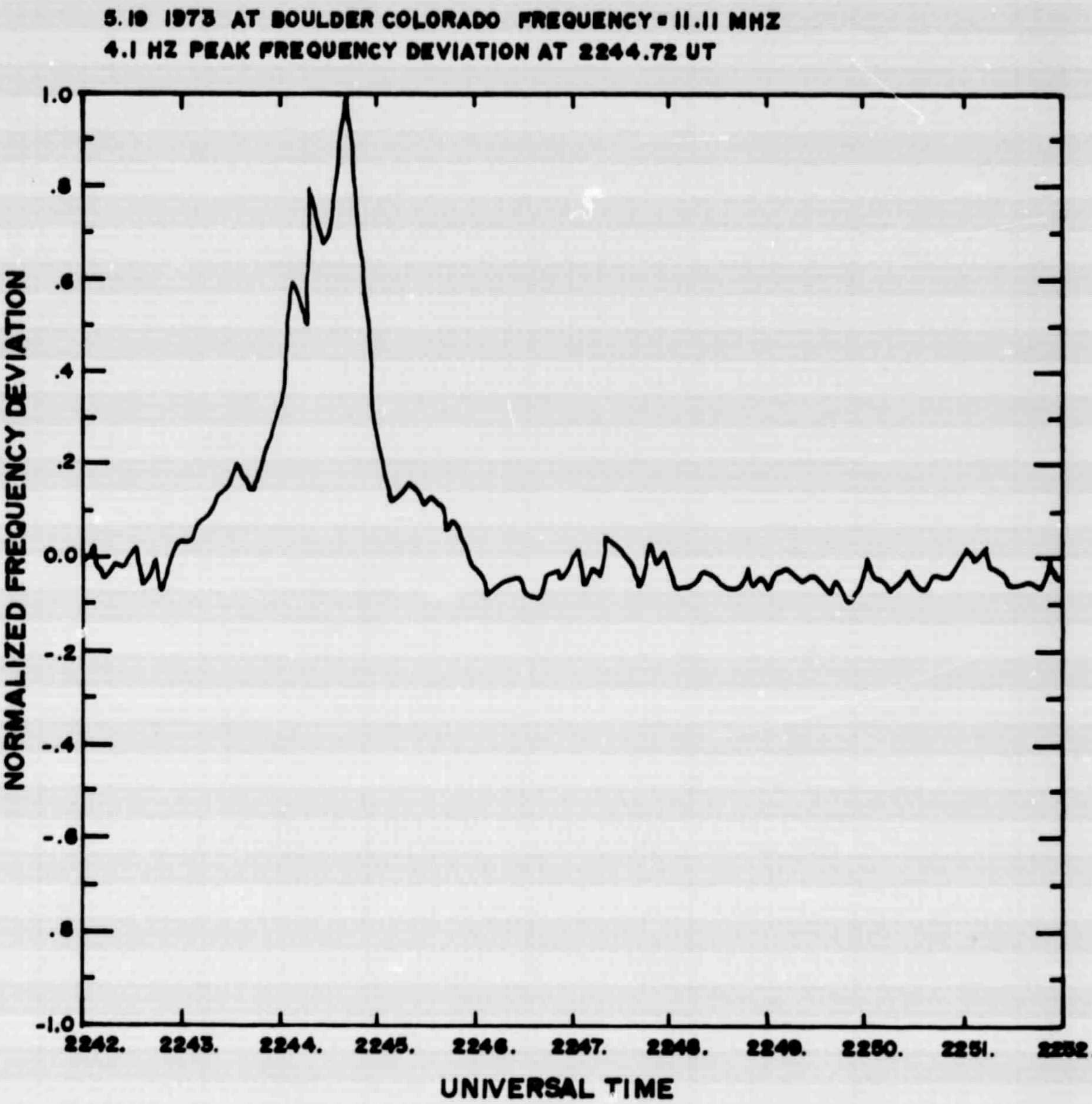

Figure 6. Observed SFD event as a function of UT (Universal Time), on May 19, 1973 at Boulder, Colorado (40.2°N latitude and 105.3° W longitude).

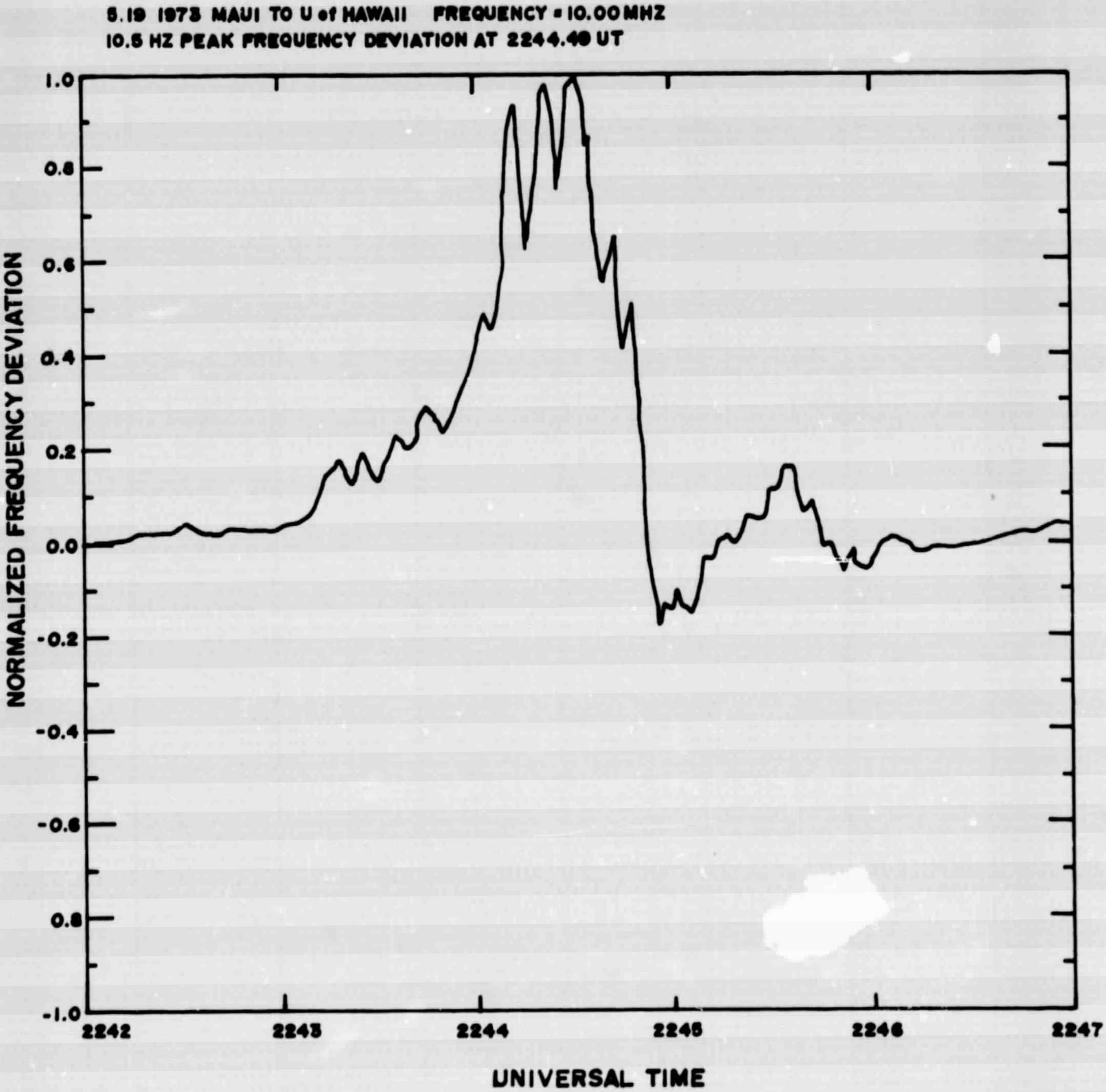

Figure 7. Observed SFD event as a function of UT (Universal Time), on May 19, 1973 in Hawaii (21.3° N latitude and 157.8° W longitude).

(2) The electron loss time constant $\tau_{(h)}$ is approximately constant with height over the range from h_o to h_r.

The first assumption is approximately satisfied at heights 110 to 200 Km if the second assumption is true and because the EUV flare spectrum is spread over the 10-1030 Å range in continuum emission and in a large number of emission lines. The first assumption simplifies the relation between Δf and $\frac{dN_e}{dt}$ (Agy, et al., 1965)

$$\frac{dN_e}{dt} \approx \Delta f \quad \frac{f_v c}{k\,(h_r' - h_o)}$$

in the altitude range from h_o to h_r, where $k = 80.6\ Hz^2m^3$, f_v is the equivalent vertical incidence frequency, c is the speed of light, and h_r' is the vertical height of reflection. Transmission curves (Smith, 1939) and ionograms taken just before the flare at a location near the HF Doppler propagation path are used to determine h_r', h_o and f_v for each event and channel analysed.

The values of τ_{eff} and B_{eff} are determined from models of α_{eff} (L) β_{eff} (L). The electron density as a function of height is calculated for each flare and HF Doppler observatory using the corresponding preflare ionograms and the methods of Wright (1967). The true height of reflection h_r is then determined from $N_e(h)$, where $N_e(h_r) = \frac{f_v^2}{k}$. Using several models of $\alpha_{eff}(h)$ or $B(h) = 0$ including those of Mitra and Banerjee (1971), τ_{eff} and B_{eff} are computed as a function of altitude from $\tau(h) = [2\alpha_{eff}(h)\ N_e(h)]^{-1}$, or $\tau(h) = \beta^{-1}$ at the higher altitudes, and $B(h) = \alpha_{eff}$ (h), or $B(h) = 0$ at altitudes where β applies. Averages of $\tau(h)$ and $B(h)$ are computed over the height range from h_o to h_r to determine τ_{eff} and B_{eff}.

IV.3 Results and Discussions

The normalized 10-1030 Å flux enhancements as a function of time as deduced from the two SFD events by the method 3 of Donnelly (1970) are shown in Figures 8 and 9. The maximum increase in the flux density $\Delta\phi$ max for the May 18 event was $3.24 \times 10^{-4} W/m^2$ at 1533.7 UT. $\Delta\phi_{max}$ for the May 19 event was $8.79 \times 10^{-4}\ W/m^2$ at 2245 UT. This compares with $1.56 \times 10^{-3}\ W/m^2$ as obtained from the Hawaii data (Donnelly, 1976).

The $\Delta\phi$(10-1030 Å) values computed using this method are estimated to be accurate to within a factor of four (Donnelly, 1970). The impulsive structure in $\Delta\phi$(10-1030 Å) with time constants less than τ_{eff} are insensitive to the height variations of τ or to the $\alpha(h)$ and $\beta(h)$ models, while the flux variations with time variations larger than τ_{eff} are quite sensitive. Ionospheric variations unrelated to solar flare effects produce noise in the SFD observations that mainly affect the $\Delta\phi$(10-1030 Å) estimates during the slow flare emissions. SFD data provides good information on the impulsive emissions of flares, poor information on the slow flare emission and no information on the non-flare solar radiation.

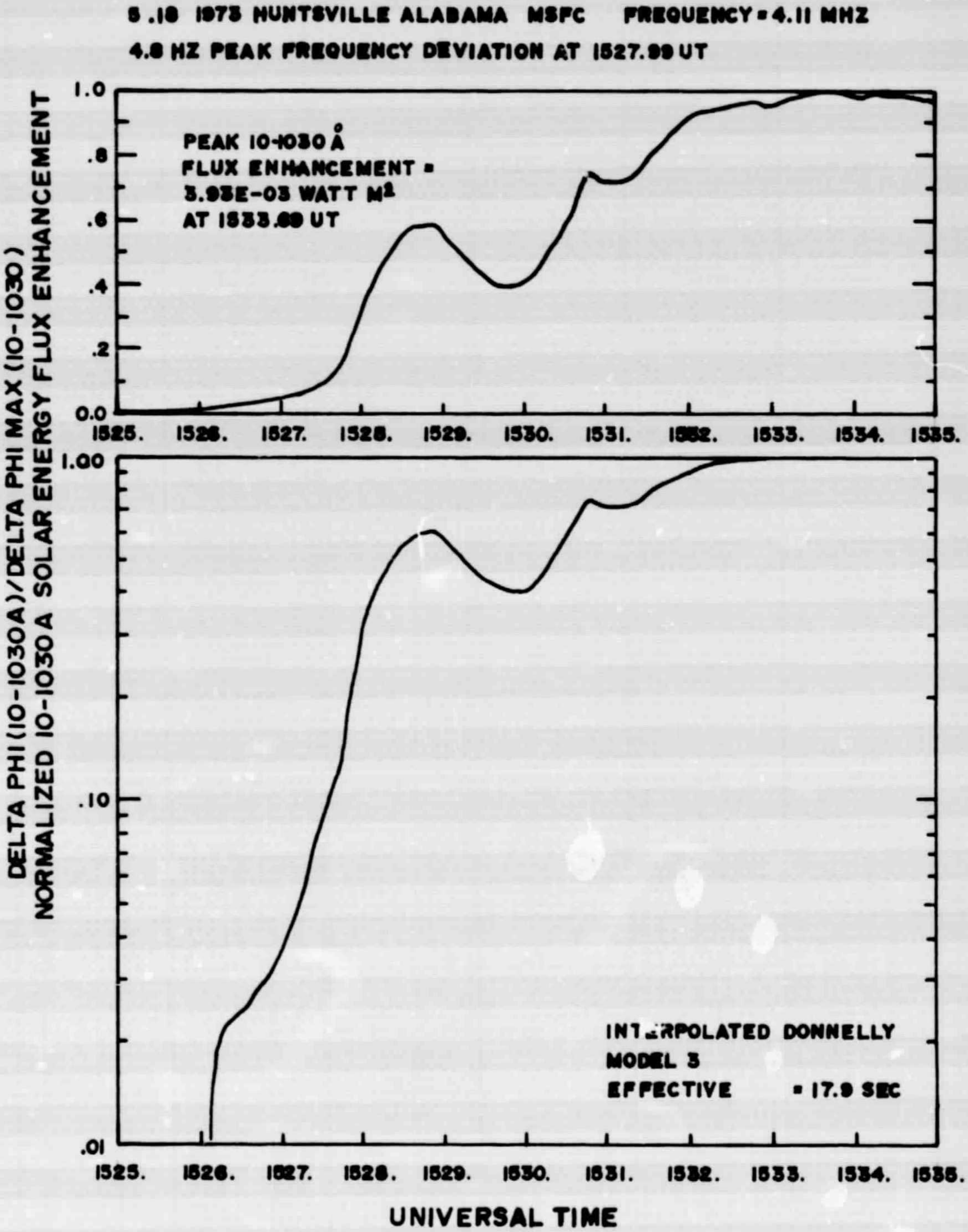

Figure 8. Best Estimate of 10-1030 Å Flux Enhancements of 1528 UT, May 18, 1973.

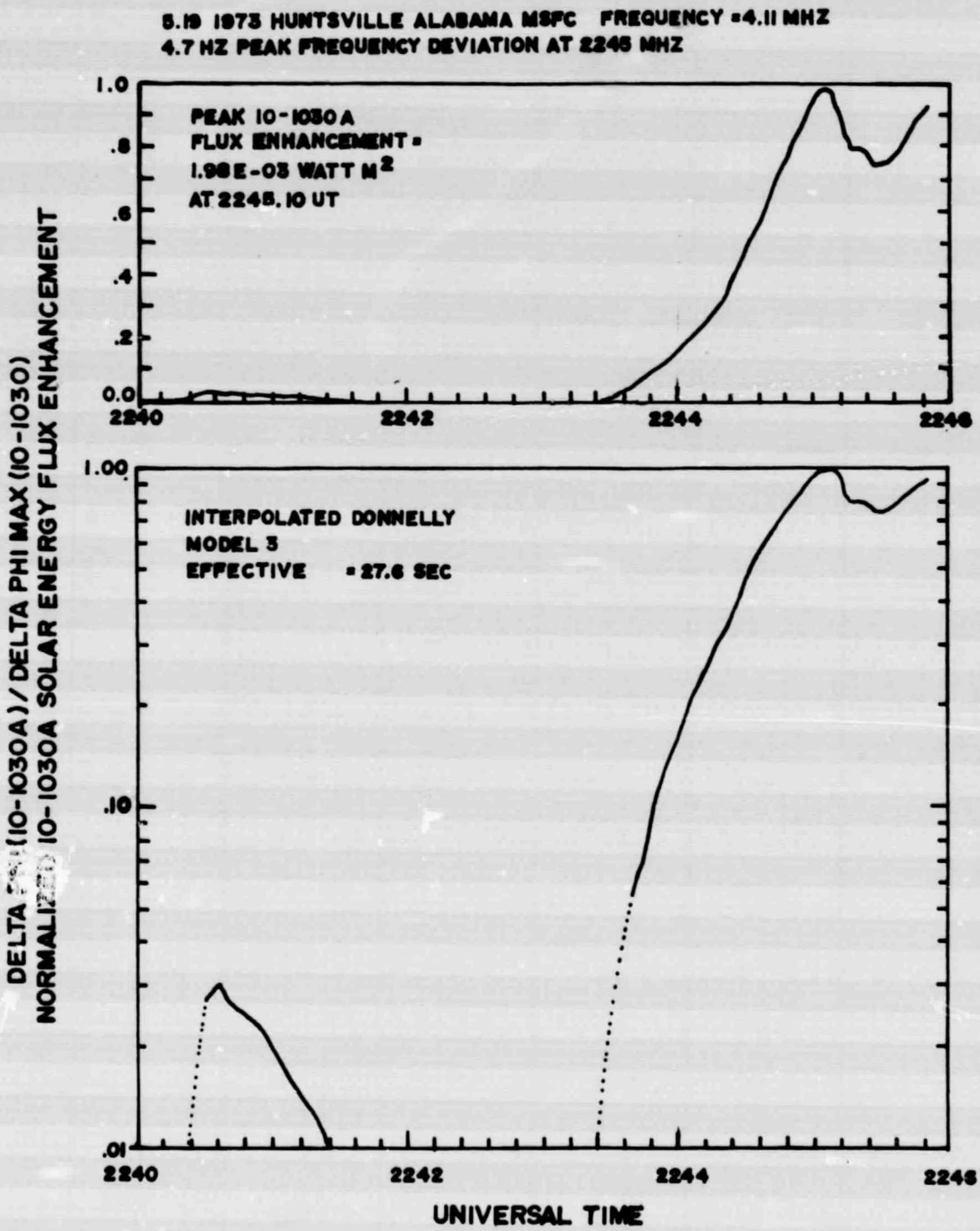

Figure 9. Best Estimate of 10-1030 Å Flux Enhancements of 2245 UT, May 19, 1973.

CHAPTER V. CONCLUDING REMARKS

During this study, we investigated SFD events recorded on May 18 and 19, 1973, from NASA/Marshall Space Flight Center high-frequency doppler sounder array system near Huntsville, Alabama. The May 19, 1973 SFD event has been identified with a 1B Hα flare in McMath plage region 12352 at N09E20 of the solar surface. The maximum increase in the flux density has been deduced from these two observed SFD events, by using method 3 suggested by Donnelly (1970). We found that the maximum increase in the flux density for the May 18 event was 3.24×10^{-4} w/m^2 at 2245 UT. This was a factor of ~ 2 to 5 smaller than the results obtained from the Hawaii data (Donnelly, 1976). Also, we have noted that the observed SFD events recorded in Huntsville are much smoother than those recorded at Boulder, Colorado and in Hawaii, which means that the observed results recorded in Huntsville, Alabama have less structure than those recorded in Boulder, Colorado and in Hawaii. This may be caused by local environmental conditions. However, the overall features from the observation show no significant differences.

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