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AUTUMN COURSE ON GEOMAGNETISM, THE IONOSPHERE AND MAGNETOSPHERE

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IONOSPHERIC FORECASTING

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Autumn Course of Geomagnetism, the Ionosphere and Magnetosphere

Workshop on Radio Propagation in the Tropics

Lecture IV

Ionospheric Forecasting

by

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4.1 Need for Forecasting

Ionospheric forecasts, as used here, differ from predictions in two respects: (1) they refer to periods less than one solar rotation (27 days) and (2) they involve operational aspects rather than circuit planning. While the prediction systems described in Lecture 3 are adequate for long-term planning of frequency allocations and for the design of long-distance circuits on HF, forecasting is in a relatively primitive state although it has been carried on for some 40 years. Both civilian and military communicators, navigators etc. need improved forecast services that would enable them (a) to provide for alternative means (b) to warn users that the cause of their problems are geophysical rather than equipment malfunction (AGARD 1970). The prospects for improvements in forecasting are moderate. The biggest improvements over the past 10 to 20 years have resulted largely from technological advances in data aquisition, processing and distribution.

Most short-term disturbances result from solar disturbances, such as solar flares, which emit bursts of ionizing radiations (X-rays, extreme ultraviolet or EUV), charged particles (mostly protons and electrons) and radio noise. All of these can affect radio communications. A list of effects on the ionosphere is given in Figure 4.1 (Lincoln 1970; Donnelly 1979).

In this lecture we shall consider these aspects in some detail.

4.2 Solar Disturbances

Figure 4.2 shows the sun with many of its features such as: the photosphere (visible surface), the chromosphere, the corona (outer atmosphere), sunspots, prominences, flares and coronal holes. The sun in X-rays is quite different from that in visible light as seen in Figure 4.3. The dark regions are coronal holes which emit energetic charged particles. Forecasting depends primarily on continuous observation of the sun (particularly in the visible, X-ray and radio parts of the spectrum) supplemented by ground-based measurements of the geomagnetic field, ionosphere etc. and satellite measurements of magnetospheric ion fluxes. A visible "watch on the sun" is conducted by the observatories, shown in Figure 4.4, and other cooperating observatories. Data on solar flares are transmitted to certain regional locations where they are processed and evaluated by experienced forecasters who formulate alerts and forecasts which are promptly disseminated. Such groups include the Space Environment Services Center (SESC) of NOAA in Boulder, CO.: the Tokyo Regional Warning Center; the Moscow Regional Warning Center; etc.

At Boulder, flares are classified, according to their X-ray emissions in the 1 to 8 Å range, as C, M and X flares. X flares usually have disruptive ionospheric consequences.

4.3 Ionospheric Effects of Flares

Solar flare associated effects can be classified broadly as

(1) sudden ionospheric disturbances (SID), that occur simulteneously with the visible flare

(2) polar cap absorption (PCA) that starts within about an hour of the flare

(3) ionospheric storms that start 24 to 48 hours after the flare and may last several days.

4.3.1 Sudden ionospheric disturbances

Data on these disturbances are given in monthly issues of Solar-Geophysical Data (1977). In the 1930's it was discovered that solar flares were sometimes accompanied by short wave fadeouts (see Figure 4.5) which consist of large decreases in HF radio signals lasting from a minute or so to up to half an hour. These are accompanied by (see Figure 4.6): sudden cosmic noise absorption (SCNA) on VHF, sudden phase anomalies (SPA) on VLF, sudden enhancements of atmospherics (SEA) on VLF, radio noise, magnetic crochets etc. Information of SID phenomena are published monthly by NOAA in Solar Geophysical Data. All these effects result from enhanced ionization in the lower ionosphere. A sudden frequency deviation (SFD) is caused by ion production in the upper E and lower F regions (120 to 180 km).

Sudden ionospheric disturbances are confined to the sunlit hemisphere. Their intensity depends on the size of the solar disturbance (e.g. X-ray burst) and the solar zenith angle. Fortunately, these disturbances last only for short periods and do not, in general, pose a major threat to most users of the ionosphere except users of navigation systems. They are more important in low latitudes than in high latitudes.

4.3.2 Polar cap absorption

Polar cap absorption (PCA) is high absorption of radio waves in the D region. The events start shortly after a flare (15 min to $\approx$ 1 hour) and last from one day to several days. They are caused by ionization in the D region by highly energetic solar proton bombardment of the polar caps. Some characteristics of PCA are:

(1) They are almost always preceded by a major flare. The time interval between the appearance of the flare and the start of the PCA is from a fraction of an hour to several hours.

(2) The duration is typically 3 days but can be 1 day to 10 days.

(3) They are not usually accompanied by noticeable increases in either geomagnetic or auroral activity, except in the later stages when an auroral storm may set in. PCAs are thought to occur simultaneously in both N and S polar caps. They are not confined to absorption since they affect the phases of VLF signals.

Since PCA events are relatively rare and are confined to the sparsely populated polar caps they are not important in middle-and low-latitude ionospheric usage.

4.3.3 Storms

Ionospheric storms are global and are associated with a whole complex of storm phenomena which include: magnetic storms, ionospheric storms, auroral storms, magnetospheric storms all of which are different aspects of a solar-terrestrial disturbance.

Magnetic storms are disturbances in the earth's magnetic field which is, broadly speaking, characterized by an increase in the horizontal component of the earth's field (the initial phase) for the first few hours followed by the main phase in which the horizontal component falls well below normal -- see Figure 4.7. Following this is the recovery phase which may take up to several days (Matsushita and Campbell 1967). The storm is worldwide and is evident at the magnetic equator but is most pronounced in the auroral zones (Matuura 1972; Obayashi 1972).

Auroral storms are associated with bright displays of visible aurora which, in severe storms, can be seen in Boulder (48° magnetic latitude). These storms are accompanied by high auroral radio absorption and strong reflections from magnetic field aligned radio-aurora. Auroral storms are accompanied by large electric currents, near the midnight meridian, which produce Joule heating of the neutral atmosphere, by electron-molecule collisions. This heating expands the gas which rises and sets up a large scale atmospheric circulation (Rishbeth 1972).

Magnetospheric storms are disturbances in the magnetic field surrounding the earth -- see Figure 4.8. The main features of the magnetosphere are the magnetopause on the sunward side, the clefts and the long drawn out magnetotail. Electrons, protons and other ions are in the magnetosphere. When a storm occurs these particles move towards the earth and are energized so that their mirroring height is lowered into the atmosphere ($\approx$ 100 km) where they are absorbed creating ionization and heat.

Ionospheric storms are characterized by one or more of the following: an initial increase in the critical frequency of the F2 layer (and the total electron content) followed by a depression of foF2, radio blackout in the vicinity of the auroral zone, enhanced spread F and sporadic E. These ionospheric effects may last from two to three days during sunspot maximum years while during sunspot minimum they tend to last longer (4 - 5 days) but are less intense. The course of an 'average' storm in total electron content (TEC) is shown in Figure 4.9. There is an enhancement of TEC on the afternoon of day 1 followed by a recovery over the next few days (Mendillo 1973). The behavior of foF2 is somewhat similar.

There is a depression in the foF2 in middle latitudes (40° to 60° of geomagnetic latitude) as illustrated in Figure 4.10. Equatorward of this depression there is an enhancement of foF2. The larger the storm the closer the depression extends towards the equator and only in the case of the most intense storms is there a depression of the critical frequencies at the magnetic equator. Furthermore, in a positive storm (increase in foF2) near the equator there is an increase in the height of the F2 layer such that the MUF is almost unchanged.

The depression of the critical frequencies of the F2 layer is brought about by changes in the molecular composition of the neutral atmosphere. Heating of the air in the auroral zone causes a lifting of air, rich in O_2 and N_2, to F2 heights which normally contains mostly O atoms. The disappearance of electrons is governed by charge interchange: the reaction

$$O^+ + e \rightarrow O$$

is too slow to remove the F2 layer. The dominant mechanism is

$$O^+ + N_2 \rightarrow NO^+ + N$$

followed by $NO + e \rightarrow N^* + O^*$

where asterisks represent excited atomic states.

Severe storms have other effects on the low latitude ionosphere for example the effect on spread F which tends to be suppressed as shown by contracting oblique ionograms in Figure 4.11 (quiet) with Figure 4.12 (disturbed). Also there is evidence that the equatorial anomaly is reduced during some storms. The equatorial anomaly is dominated by vertically upward electromagnetic drift, which is particularly important after sunset. Plasma is lifted up over the equator and "slides" down the magnetic field to produce maxima on either side of the dip equator, see Figure 4.13. This plasma motion results in a trough of ions near the equator and humps on either side. Because of day-to-day changes in the eastward electric field, ion production etc., there are large fluctuations in the F region parameters in low latitudes. The positions of the density "humps" vary in latitude from day to day, seasonally, with sunspot numbers and during storms. Thus, a given location on the earth's surface may be outside or inside the equatorial trough depending on the prevailing conditions. During some storms it appears that the $\underline{E} \times \underline{B}$ drift is suppressed and the size and latitude of the humps decrease. Bubbles of depleted plasma are thought to result from the intrusion of neutral gas into the ionized F2 layer from below producing an unstable situation in which the bubbles rise and produce small scale irregularities (Costa and Kelley, 1976) that cause spread F and give rise to radio scintillations.

The low latitude F region, unlike that in middle and high latitudes, is largely protected from particle effects except near the South Atlantic magnetic anomaly.

5. Forecasting Procedures

The first stage in forecasting is to predict the occurrence of a flare from solar observations.

In assessing the state of the sun the present day forecaster has many sources of data such as: solar X-rays from satellite sensors, solar magnetic fields from Zeeman splitting of visible lines, Hα observations (red), radio observations, etc. These data give him/her information on the shape of the solar magnetic fields (neutral lines) that alert him/her to an impending center of activity. Solar flare forecasting is still largely an art in which the forecasters' experience and skill in recognizing and interpreting solar features plays the the dominant role. This expertise has been developed to a fairly high level so that a skilled forecaster can often accurately forecast that a flare will occur within 1 to 3 days but without being precise about just when the flare will occur, its magnitude or its terrestrial consequences.

The following questions arise when a solar flare is observed (1) Will it result in a ST disturbance and when? (2) How big will the disturbance be? (3) How long will it last?

Some improvement in assessing the terrestrial effects and when they will occur may come from modeling the propagation of shock waves through the solar wind. Figure 4.14 illustrates the modeling work being carried out in the Space Environment Laboratory (sum of thermal and magnetic pressure) in the ecliptic plane. The shock propagates outward and, if it interacts with the Earth, a disturbance would be predicted. Presently, there is no reliable method for forecasting, precisely, the geophysical effect of a flare. One indication that a flare will result in a PCA is the U shape of the spectrum of the solar microwave (1 to 10 GHz) burst.

In recent years a useful source of data for forecasting has been the ISEE-3 satellite which is located around the libration point between the sun and the earth -- Figure 4.15 -- about 1.5 million km from the earth. A shock wave in the solar wind would reach ISEE-3 about half an hour before arriving at the earth as shown in Figure 4.16.

Ionospheric and magnetic data are also available from ground networks of observatories, data from high latitudes (where a storm begins) are transmitted to the forecasting centers -- e.g. via satellite in the case of the International Magnetospheric Study (IMS) network. At the forecasting center the data are displayed and evaluated by skilled forecasters and the alert is transmitted to users by various means.

This brings us to a primary need of users of forecasts and alerts namely a timely dissemination system; there is, after all, little value in receiving a forecast or alert after a disturbance has affected the user. Some indication of the way in which a user should respond to a forecast/alert would be valuable: e.g. change radio frequency, use relay station etc. In general the user of a forecast/alert will use only information of proven reliability. Some methods of dissemination are: telephone, teletype, computer links, WWV broadcasts, TWX messages, letters. Even priority TWX messages can take over 24 hours to reach their destination a time span over which forecasts are not always reliable. Forecasts are usually issued or updated once or twice daily.

One of the most reliable techniques for forecasters is the 27-day recurrence. A disturbed solar region rotates with the sun in about 27 days as viewed from the earth. Even after a flare has disappeared the regions' activity can continue for many months especially at relatively low sunspot numbers when flare occurrence is low. Coronal holes, from which particles are emitted, continue their activity so that individual storms do not necessarily have their individual flares.

The difficulty with forecasting the consequences of a solar flare is that any two flares are rarely identical. Furthermore, two similar flares can produce very different effects at the earth. Even more frustrating is the fact that when similar flares produce storms the duration, size and times of onset may be entirely different.

Although the climatological (average) picture of ionospheric storms has been established with reasonable confidence, it is of little value in forecasting the course of an individual storm. It is now clear that at a given geographical location no two storms are exactly alike and a given storm, at two locations, produces different responses.

Disturbance warning is, therefore, achieved in four steps: (1) observation and data transmission (2) data processing and display (3) evaluation and forecast and (4) dissemination. A sample geophysical forecast by SESC is given in Figure 4.17 and a sample radio propagation forecast is given in Figure 4.18.

6. Value of Forecasts?

The answer to this question is very difficult and depends upon several factors. The most important consideration is whether or not the recipient of a forecast can take remedial action. Even when the user cannot take action, the forecast may be of value in alerting the operator to the fact that the outage is natural whereas he/she may be inclined to attribute it to equipment failure. Remedial action, when it can be taken, may consist of several alternatives such as: changing radio frequency, increasing transmitter power, relaying messages via an undisturbed relay circuit, using an entirely different communications system such as microwave circuit or satellite link.

The value of a forecast also depends on its timeliness and accuracy. A storm prediction, issued for tomorrow, is of little value if the storm occurs today and vice versa -- even if the characteristics of the storm are accurately forecast.

In general forecasting is in a rather primitive state. The present solar cycle has been particularly frustrating to forecasters. While the 12 month average sunspot numbers have been high ($\gtrsim$ 160), from the point of view of geophysical disturbance it has been only a moderate cycle. Time and time again, flares that would be expected to produce storms have ended up having little terrestrial consequences. This illustrates an important point namely that we still know little about the solar-terrestrial system.

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Figure Captions

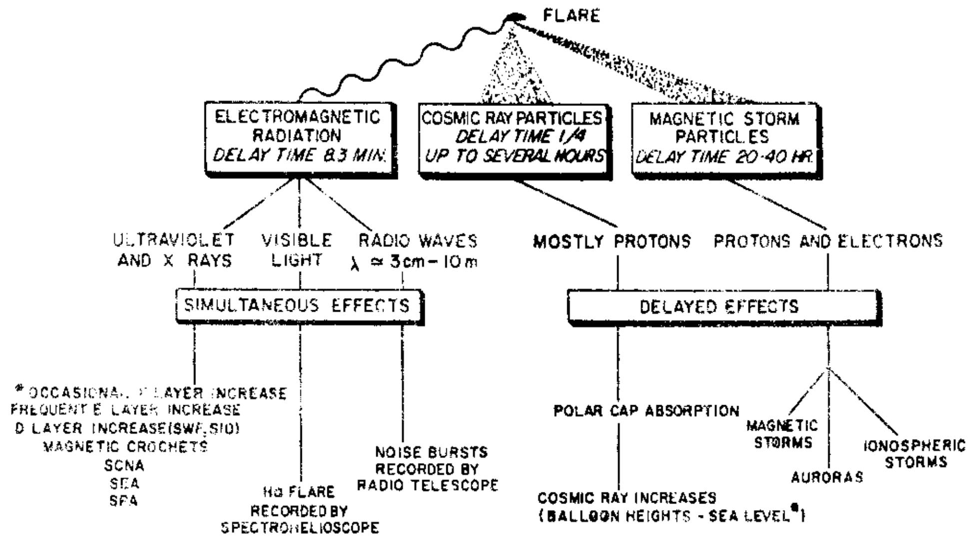


Figure 4.1 List of short term disturbances

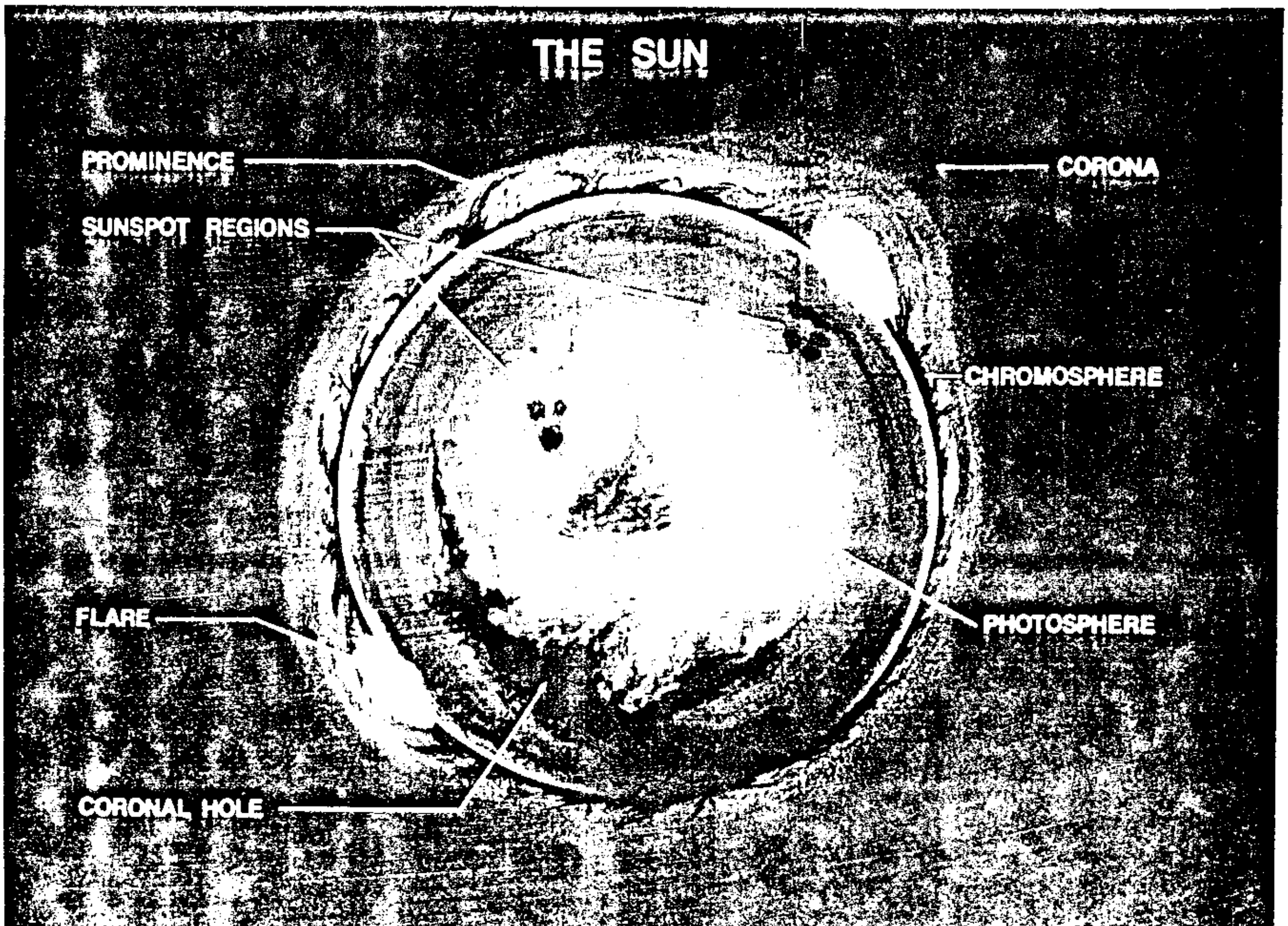


Figure 4.2 The Sun

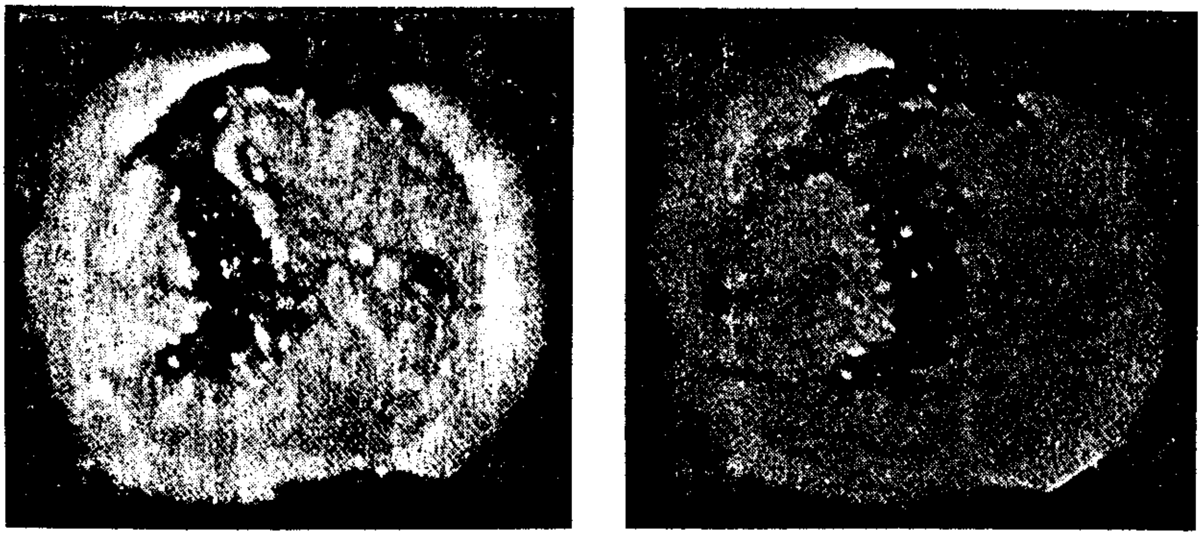


Figure 4.3 The Sun in X-rays

SOLAR OBSERVING NETWORK

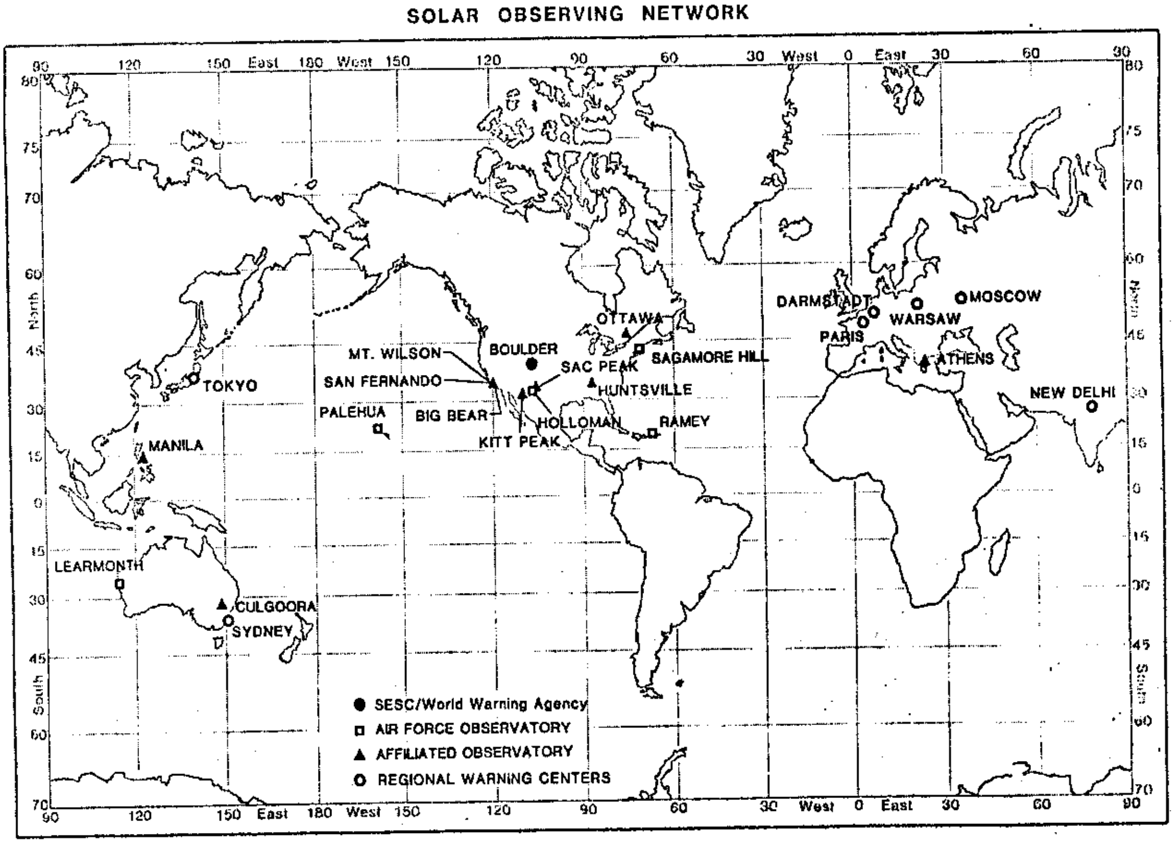


Fig. 4.4 Network of reporting solar observatories

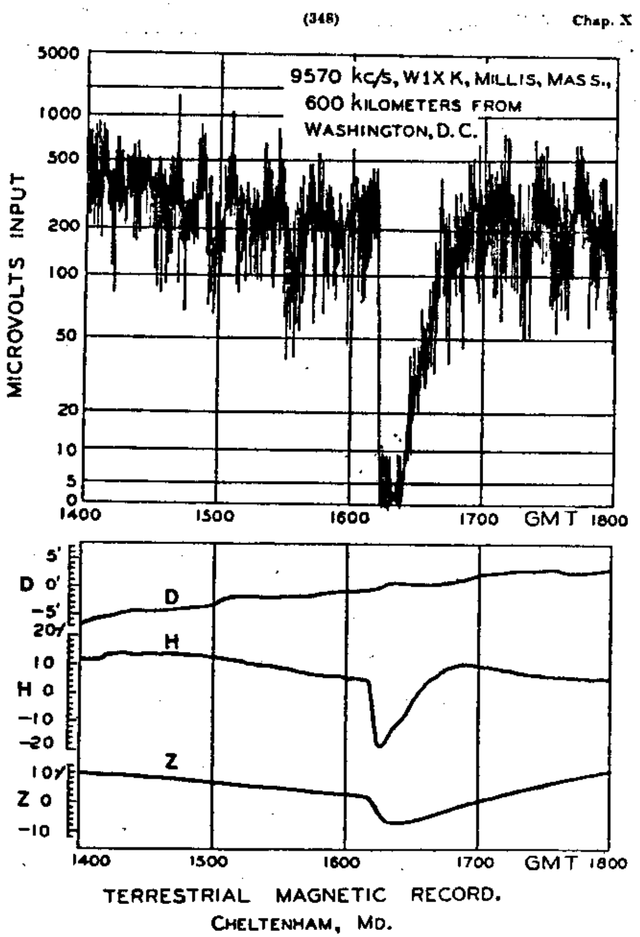


Figure 4.5 Radio fade-out (low signal intensity) and magnetic disturbance on November 26, 1936

SUDDEN IONOSPHERIC DISTURBANCES

PHENOMENON	FREQUENCY BANDS INVOLVED
Sudden Frequency Deviation (SFD)	HF
Short-Wave Fadeout (SWF)	HF and Lower VHF
Sudden Phase Anomaly (SPA)	VLF
Sudden Enhancement of Atmospherics (SEA)	LF
Sudden Enhancement of Signal (SES)	VLF
Sudden Cosmic Noise Absorption (SCNA)	HF and Lower VHF

Figure 4.6 Sudden ionospheric disturbances

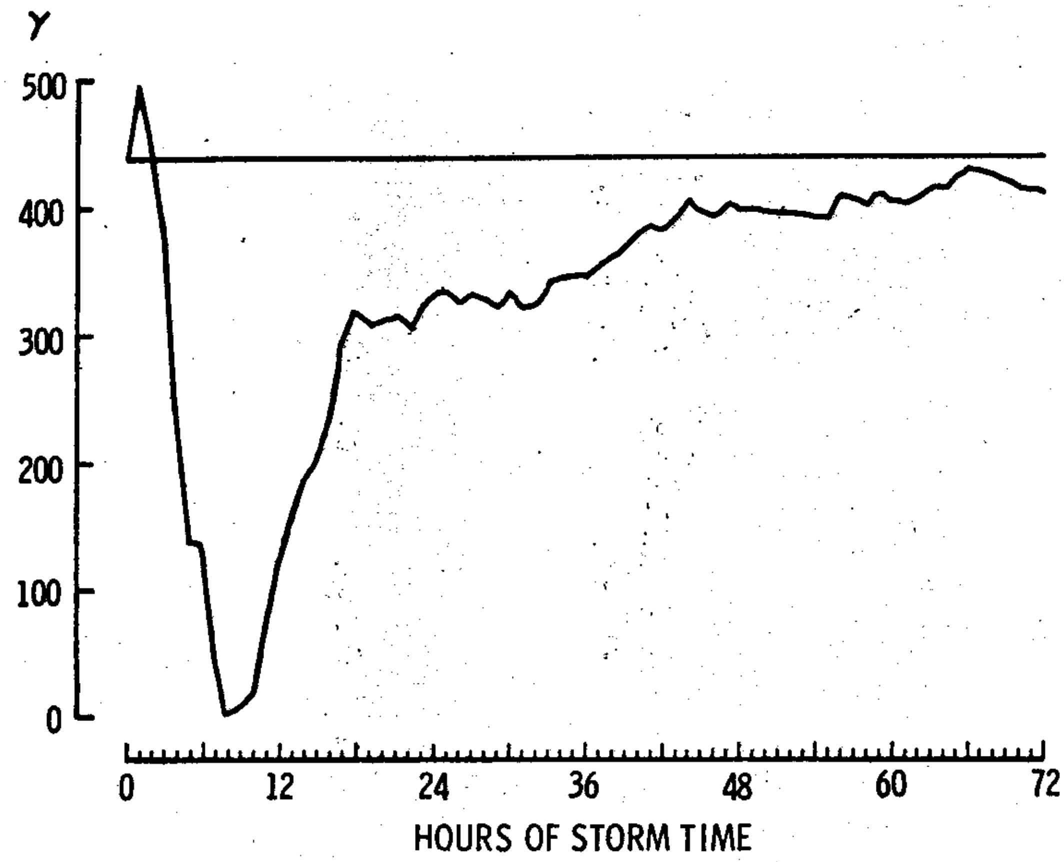


Fig. 4.7 Magnetic storm variation

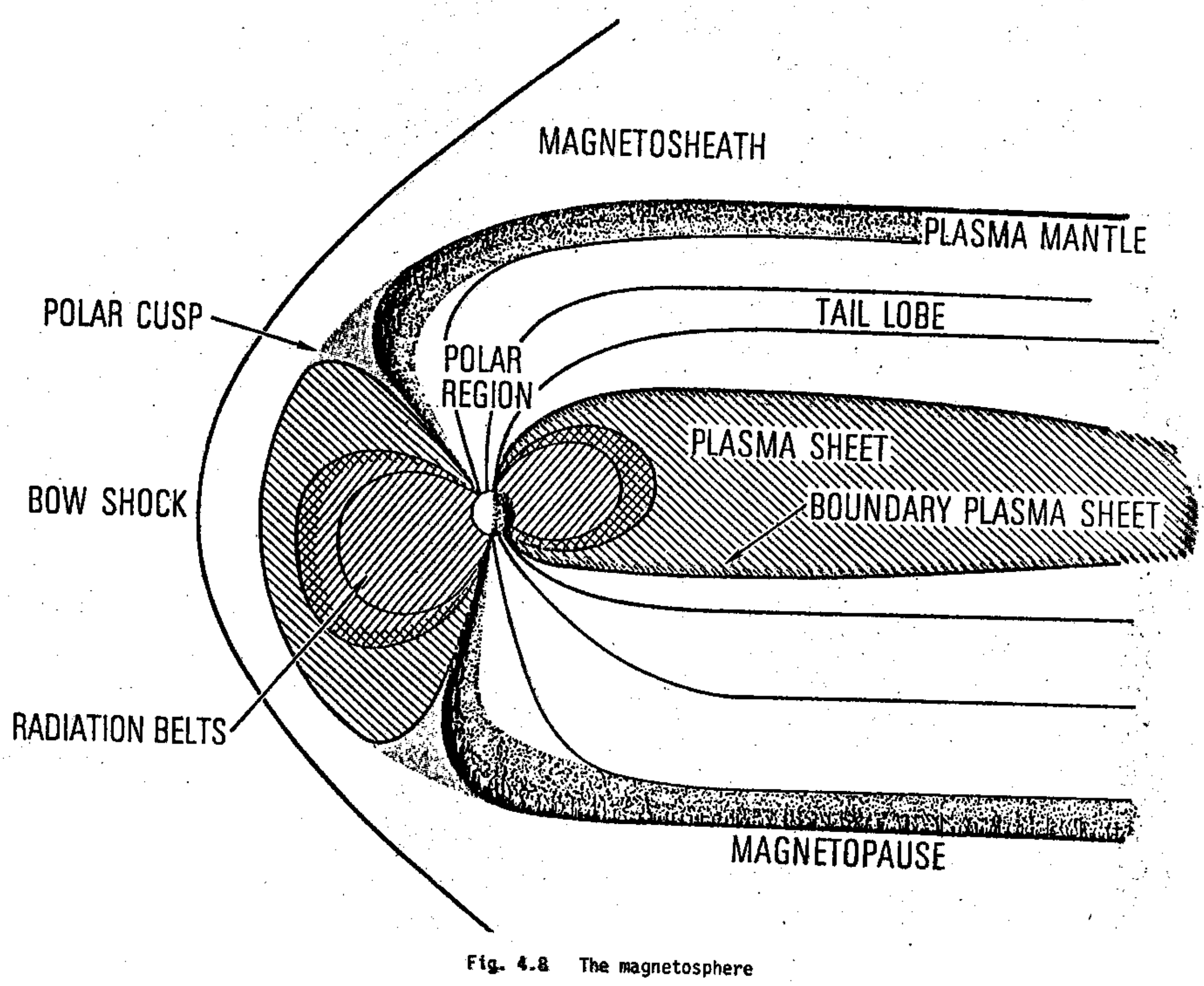


Fig. 4.8 The magnetosphere

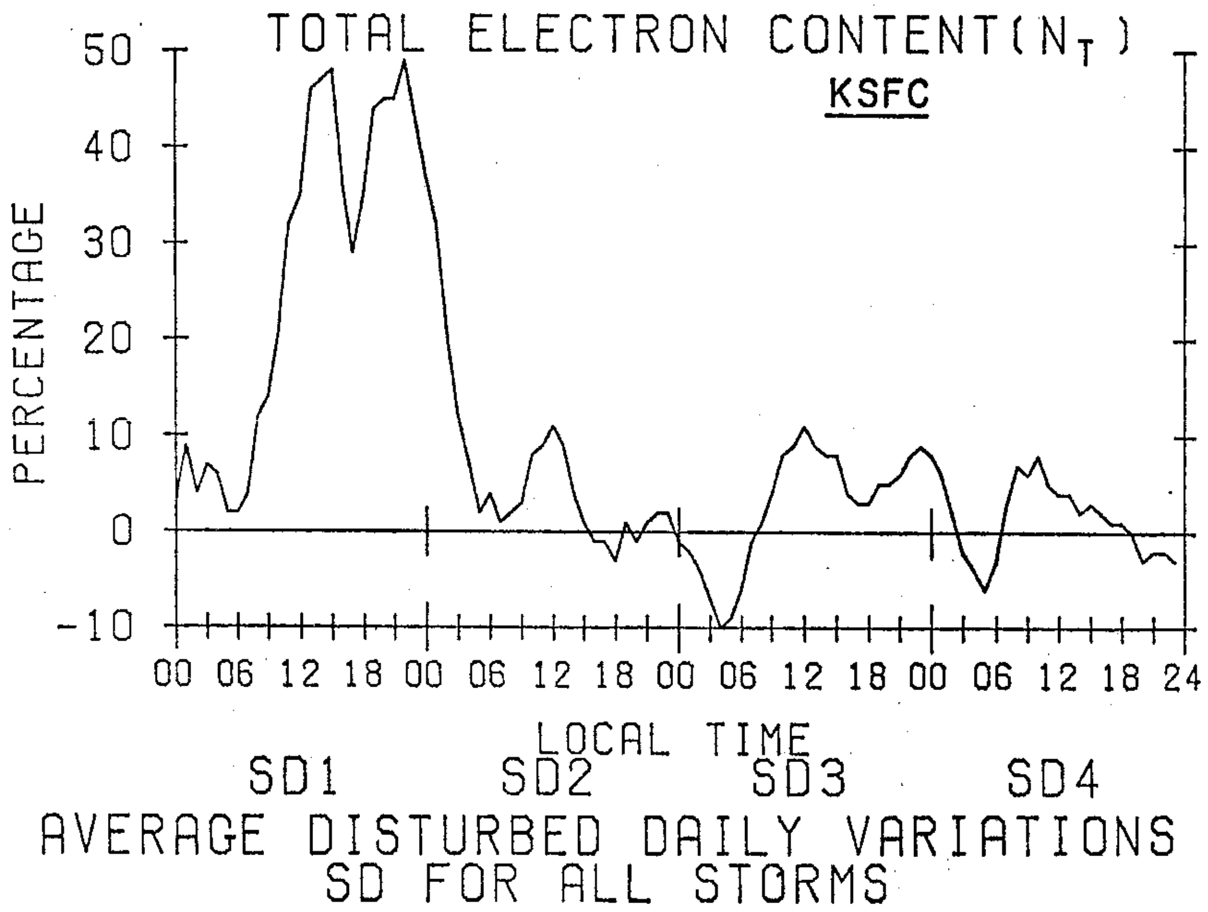


Fig. 4.9 Average TEC storm at Athens, Greece

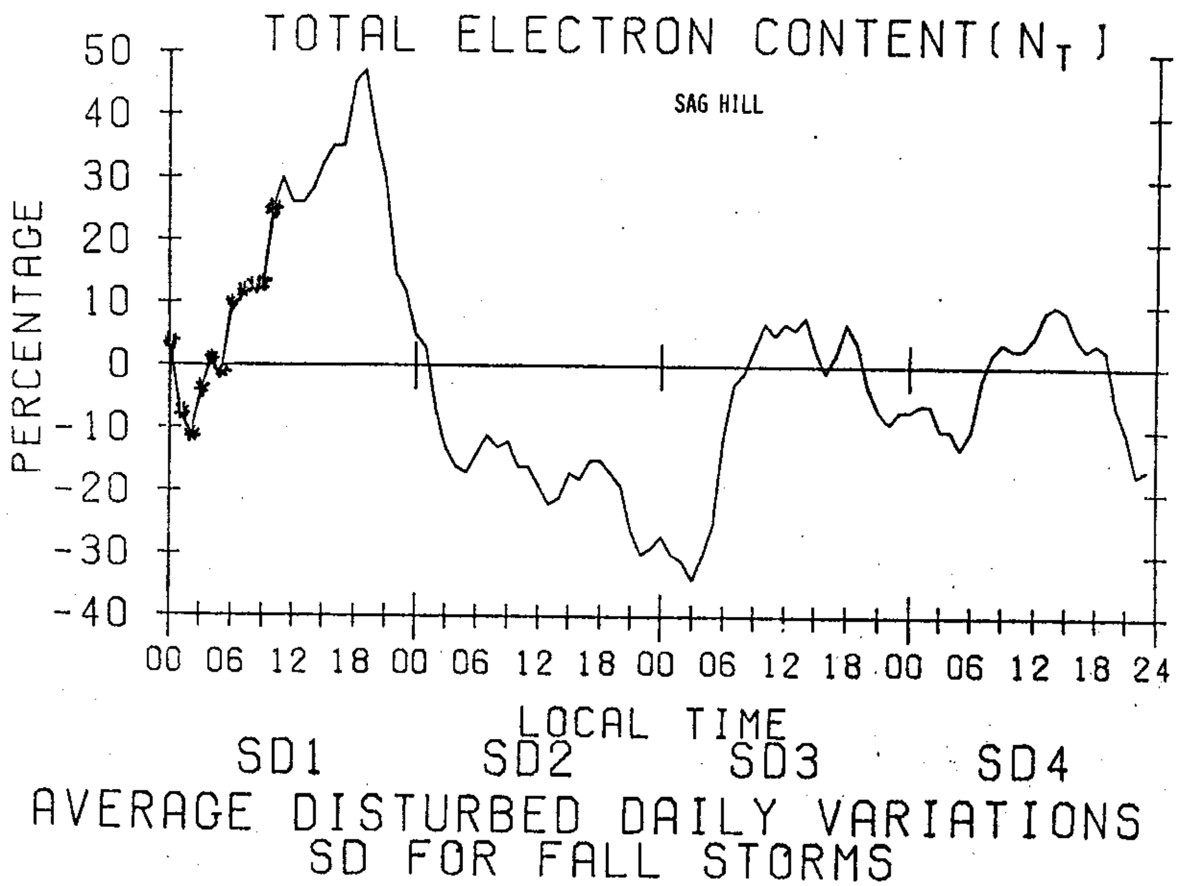
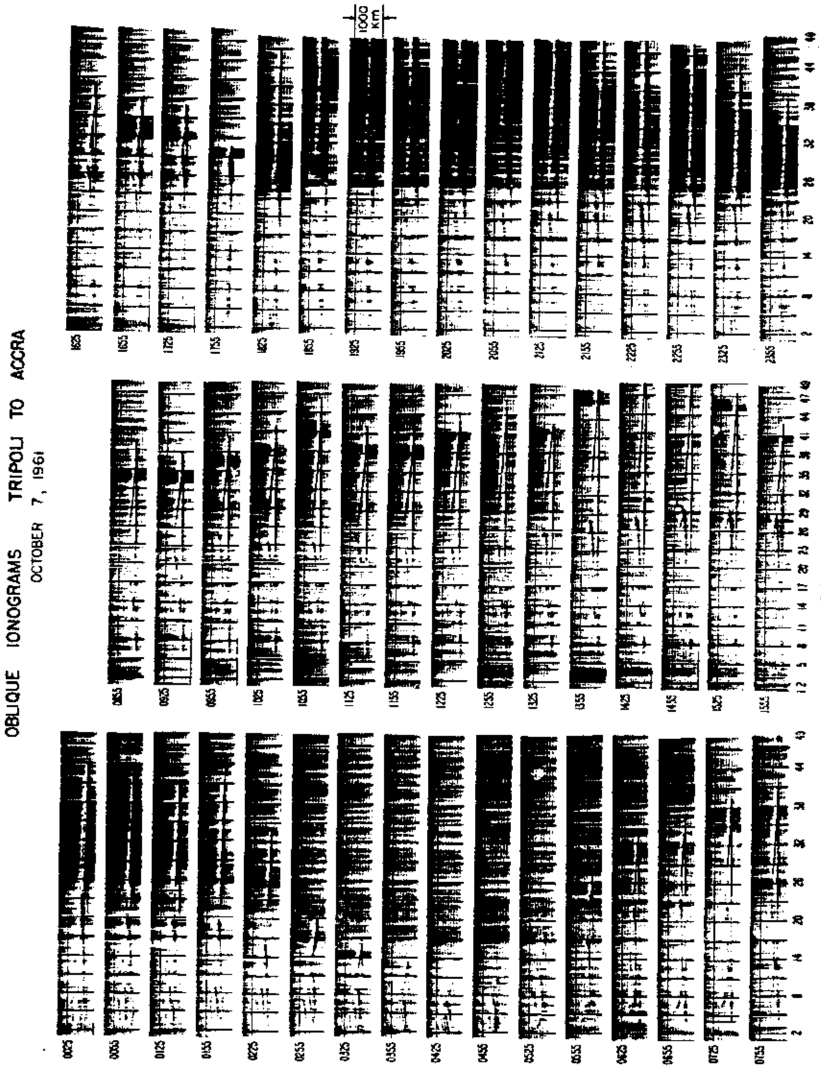


Fig. 4.10 ~~Average~~ TEC at Sagamore Hill, Mass



B-32656

Fig. 4.11 Oblique ionogram sequence, quiet day

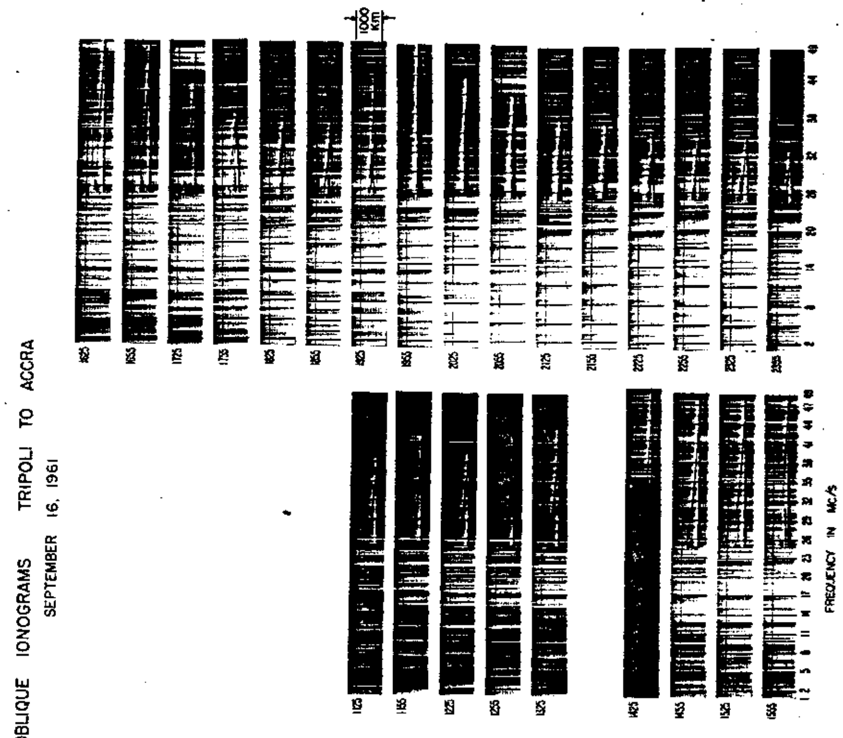


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Fig. 4.12 Oblique ionogram sequence, disturbed day

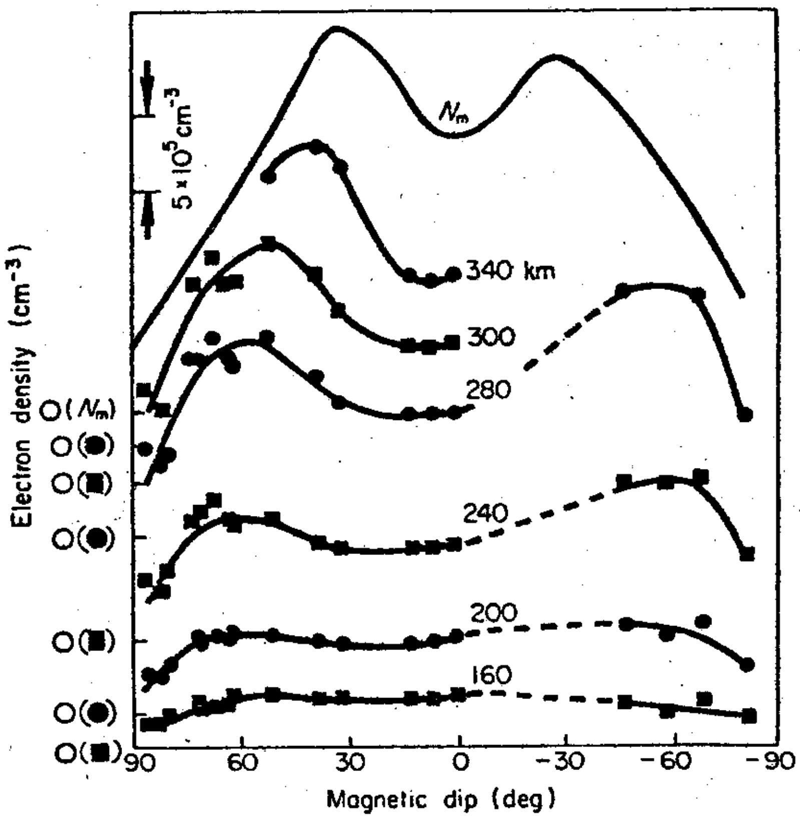

Fig. 4.13 Equatorial anomaly -- Variation of N_mF2 and N_e with magnetic dip for noon on magnetically quiet days in September 1957

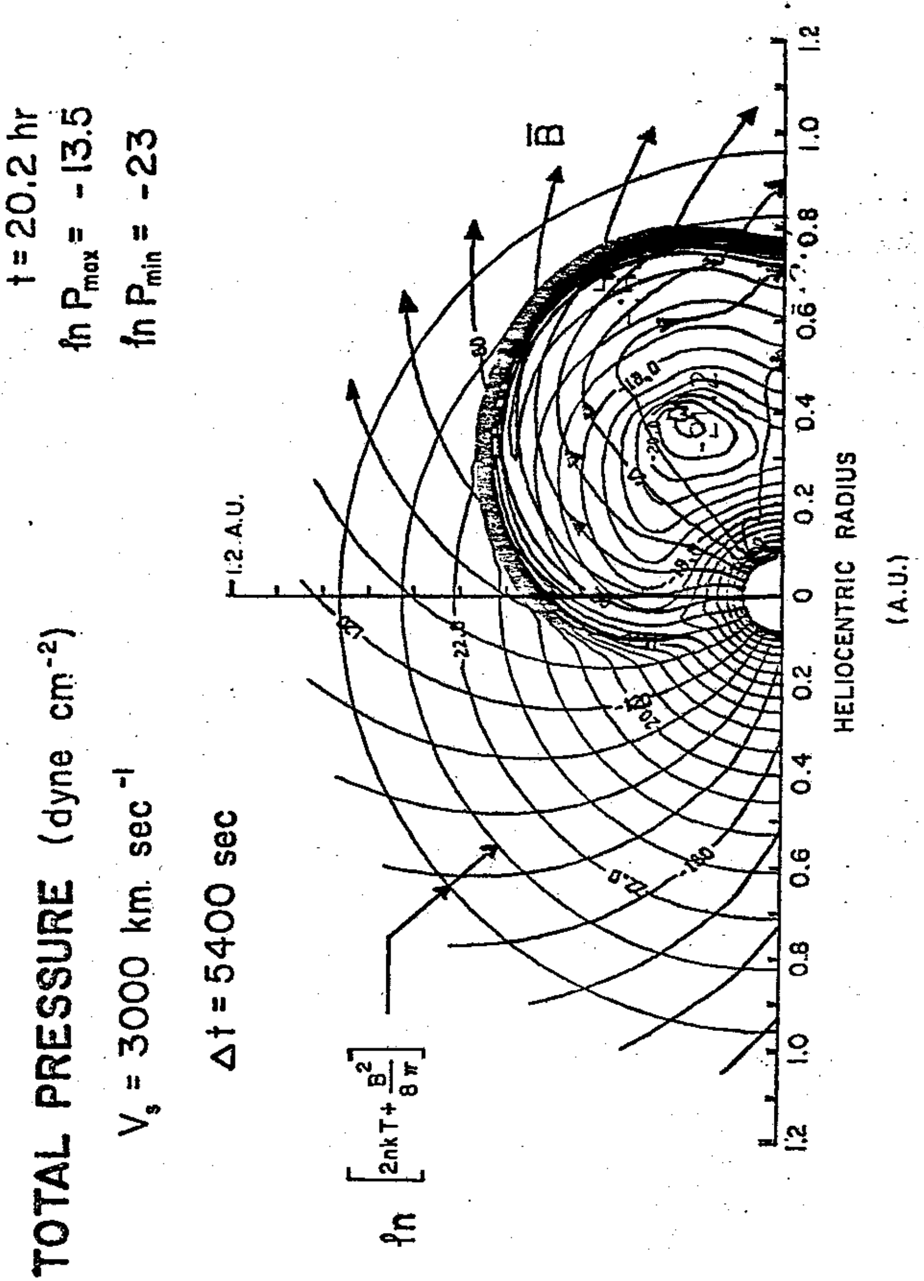

Fig. 4.14 Solar Wind Disturbance

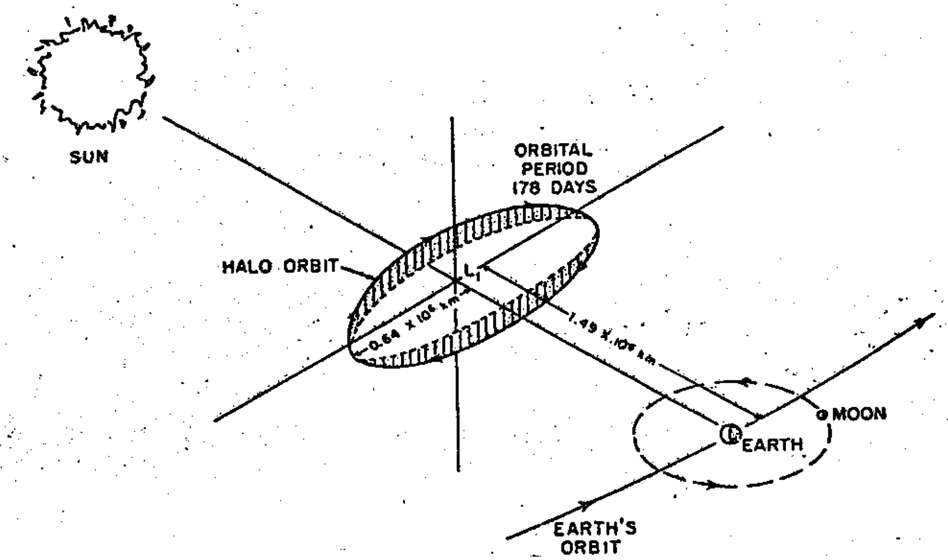

Fig. 4.15 Schematic showing the International Sun Earth Explorer-3 (ISEE-3) orbit about the Sun-Earth libration point L1.

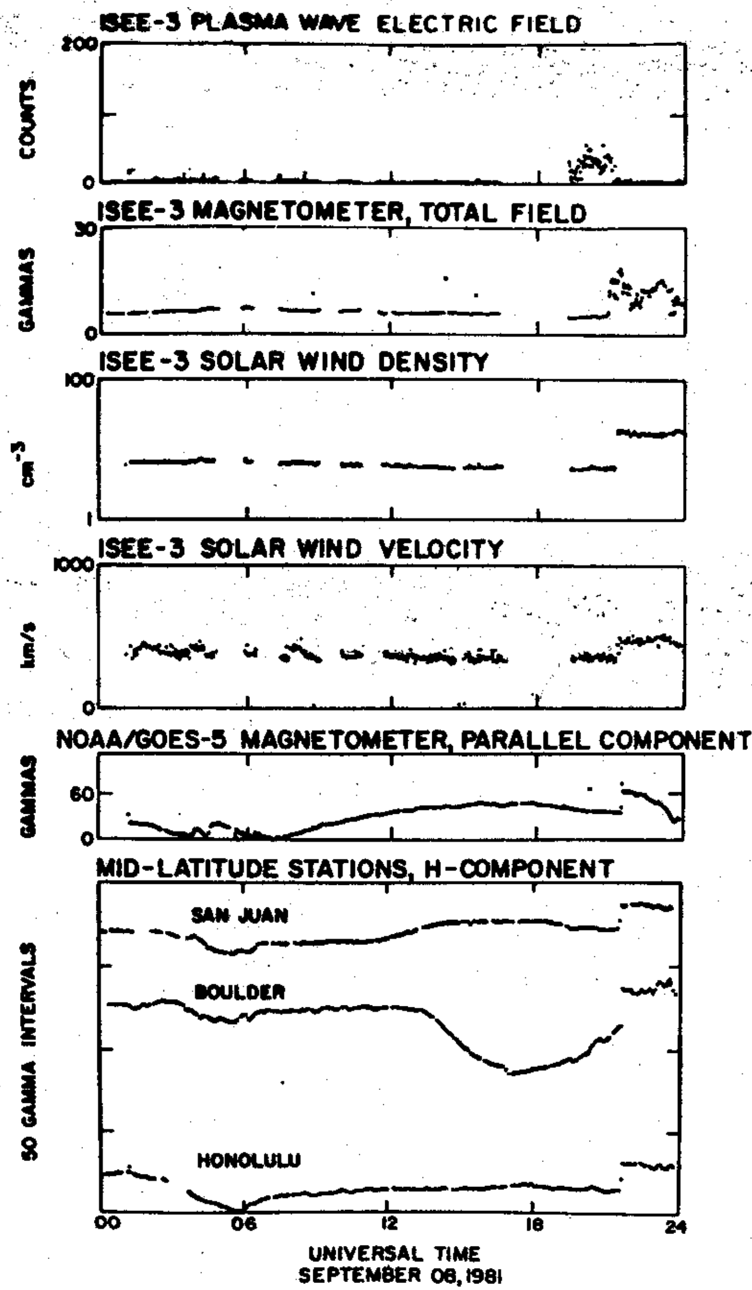

Fig. 4.16 ISEE-3 data

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KBOU
HFUS BOU 192200
FROM SPACE ENVIRONMENT SERVICES CENTER BOULDER COLO
SDF NUMBER 200
JOINT AFGWC/SESC PRIMARY REPORT OF SOLAR AND GEOPHYSICAL ACTIVITY ISSUED
2200Z 19 JULY 1974
IA. SOLAR ACTIVITY HAS BEEN VERY LOW WITH THREE NON-ENERGETIC SUBFLARES
REPORTED DURING THE PAST 24 HOURS. REGIONS 438 (S08W72) AND 443 (S12E06)
HAVE BEEN STABLE. MINOR INTENSITY FLUCTUATIONS HAVE OCCURRED IN REGIONS
442 (S10W34) AND 445 (S04W37). AN ACTIVE PROMINENCE (S13E90) PARTIALLY
ERUPTED, AND THEN TOTALLY DISSIPATED, BETWEEN 0715-0840Z. NO OTHER ACTI-
VITY HAS BEEN REPORTED TO SUBSTANTIATE AN ACTIVE RETURN OF OLD REGION 435.
IB. SOLAR ACTIVITY IS EXPECTED TO REMAIN LOW.
II. THE GEOMAGNETIC FIELD HAS BEEN QUIET. IT IS EXPECTED TO BE QUIET TO
UNSETTLED.
III. EVENT PROBABILITIES 20 - 22 JULY
CLASS M 03/03/03
CLASS X 01/01/01
PROTON 01/01/01
PCAF GREEN
IV. OTTAWA 10.7 CM FLUX
OBSERVED 19 JULY 84.
PREDICTED 20 - 22 JULY 83/85/85
90-DAY MEAN 19 JULY 90
V. GEOMAGNETIC A INDICES
OBSERVED FREDERICKSBURG 18 JULY 06
ESTIMATED AFR/AP 19 JULY 04/06
PREDICTED AFR/AP 20 - 22 JULY 07/08 - 09/10 - 11/12
SOLTERWARN
SPAN
BT

Fig. 4.17 Sample geophysical forecast by SESC

AIR FORCE GLOBAL WEATHER CENTRAL
DAILY PRIMARY HF RADIO PROPAGATION REPORT
PART I. DESCRIPTION OF GENERAL HF RADIO PROPAGATION CONDITIONS
FOR THE 24 HOUR PERIOD ENDING 12240Z JAN 77.
HF PROPAGATION CONDITIONS WERE GENERALLY FAIR TO GOOD IN MOST AREAS EARLY IN THE RADIO DAY, BECOMING GENERALLY GOOD DURING THE LATTER HALF. MUFS ON LOW LATITUDE CIRCUITS CONTINUED TO BE SOMEWHAT LOWER THAN SEASONAL NORMALS, GENERALLY NEAR 20 TO 30 PERCENT. THE PREDAWN DIP IN MUFS WAS LESS PRONOUNCED HOWEVER, SOME AREAS WERE STILL ENCOUNTERING DIFFICULTIES IN LOCATING SUITABLE WORKING FREQUENCIES DURING THE TRANSITION PERIOD. MUFS TENDED TO REMAIN SLIGHTLY ABOVE NORMAL AFTER LOCAL SUNSET ON MID LATITUDE PATHS, RESULTING IN THE DAYTIME FREQUENCIES OPERATING LATER THAN HAS BEEN THE CASE DURING THE PAST FEW DAYS. CONDITIONS OVER THE HIGH LATITUDES WERE GENERALLY GOOD, ALTHOUGH SHORT PERIODS OF INTENSE ABSORPTION, AND CONSEQUENTLY REDUCED SIGNAL STRENGTHS AND ELEVATED NOISE LEVELS OCCURRED BETWEEN LOCAL MIDNIGHT AND DAWN. THE GEOMAGNETIC FIELD WAS UNSETTLED TO ACTIVE UNTIL 1500Z, BECOMING QUIET FOR THE REST OF THE DAY.
PART II. SUMMARY OF POSSIBLE HF RADIO PROPAGATION DISTURBANCES ON SUNLIT PATHS FOR THE 24 HOUR PERIOD ENDING 122400Z JAN 77.

BEGIN	END	CONFIRMED	FREQUENCIES AFFECTED
1315Z	1341Z		
1746Z	1825Z		
1924Z	1944Z		
2144Z	2220Z	YES	UP TO 11 MHZ

PART III. OUTLOOK FOR GENERAL HF RADIO PROPAGATION CONDITIONS FOR THE 24 HOUR PERIOD BEGINNING 130400Z JAN 77.
HF PROPAGATION CONDITIONS WILL CONTINUE TO SHOW IMPROVEMENT OVER MOST AREAS. MUFS WILL REMAIN GENERALLY BELOW SEASONAL NORMALS OVER THE LOWER LATITUDES, BUT WILL BE NEAR NORMALS ELSEWHERE. THE GEOMAGNETIC FIELD SHOULD BE GENERALLY QUIET, ALTHOUGH SOME SLIGHTLY UNSETTLED PERIODS ARE LIKELY FOR BRIEF PERIODS DURING THE NIGHTTIME HOURS. THE CHANCE OF A SOLAR FLARE INDUCED SHORT WAVE IS MODERATE.

Fig. 4.18 Sample radio propagation forecast