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BIT HIT/SOLAR ACTIVITY CORRELATION STUDY

by

Capt Mary L. Hart

DECEMBER 1992

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Walter F. Miller

WALTER F. MILLER
Branch Chief

Mary L. Hart

MARY L. HART
Author/Analyst

FOR THE COMMANDER

Walter S. Burgmann

WALTER S. BURGMANN
Scientific and Technical Information
Program Manager

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13. Abstract: This report documents a study of statistical correlations between Global Positioning System (GPS) satellite anomalies ("bit hits") and the state of the actual space environment from 1 October 1984 through 31 March 1991. The study compared distributions of space environmental data with GPS anomalies to determine the correlations (if any) of GPS anomaly occurrences with space environment variables such as global geomagnetic index and proton/electron counts. Using stepwise linear regression and discriminant analysis, correlations were found to be very low. Regression equations were found to predict the probability of satellite anomalies only slightly better than random chance.

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PREFACE

In June 1991, Det 1, 4 WW (now 50 OSS/WE), asked the United States Air Force Environmental Technical Applications Center (USAFETAC), to study past Global Positioning System (GPS) satellite anomalies and determine if a statistical correlation could be found between commonly observed space environmental data and the GPS satellite anomalies. The request (performed under USAFETAC project number 910824) was assigned to USAFETAC'S Simulation and Techniques Branch (SYT). This report documents the work done on this project and the results, which are of interest to the space environmental community in general, and in particular to those who support GPS.

USAFETAC/SYT analysts compared distributions of space environmental data to determine if there were differences between the environment during anomalies and the general space environment and calculated correlation coefficients for space environmental variables. We used stepwise linear regression and discriminant analysis to determine which environmental elements had the greatest influence on the occurrence of GPS anomalies, and how successfully these elements could distinguish cases in the past when GPS anomalies occurred.

The author wishes to thank Mr J. Berg and the other employees of Aerospace Corporation, and Capt C. Larcomb, SSD/WE, for their assistance in telephone consultations on GPS and in acquiring GPS orbital data as well as the tracking models DGEN and PCSOAP. The author also wishes to thank Capt G Deuel, National Geophysical Data Center, for his help in acquiring Geostationary Operational Environmental Satellite (GOES) x-ray and energetic proton data for this study.

TABLE OF CONTENTS

FIGURES

TABLES

1. INTRODUCTION

1.1 Purpose of Study. This study undertook to find correlations (if any) between solar/geomagnetic activity and the occurrence of Global Positioning System (GPS) satellite anomalies (called "bit hits" because of their effects of satellite software). When GPS satellite anomalies occur, space environmental forecasters at the AF Space Forecast Center (AFSFC) examine solar, geomagnetic, and satellite particle data to determine if the space environment caused the anomaly. There has been no comprehensive study, however, to determine if there is a *pattern* between certain types of activity in the space environment and the occurrence of GPS satellite anomalies over time. This study examines commonly observed space environmental factors and provides guidance on how influential they are in the occurrence of GPS bit hit anomalies.

1.2 Limitations. The number of GPS anomalies reported during the 7 years covered by this study was relatively small, making the occurrence of a satellite anomaly at any one time a relatively rare event. Such a small sample size increases the risk that a few bad data points or extreme cases in the anomaly data could have a disproportionate influence on the results.

The regression equations used to predict the probability of anomaly events are closely tied to the database used to derive them. When different time periods within the 7 years of the study were used to derive the equations, the results sometimes varied a great deal. No independent dataset was available to test how well the equations could predict the probability that an anomaly would occur.

To determine which environmental variables could distinguish between anomaly cases and those hours without anomaly reports, we had to assume an anomaly did not occur when no report was in the database. Since indications imply the anomaly database is incomplete, our technique may perform differently than the skill indicators provided.

1.3 Methodology. GPS anomaly reports were combined with all available space environmental data to create databases. These databases were sorted into a frequency distribution for each environmental variable so that the type of space environment occurring during anomalies could be compared to the general space environment. Statistical analysis was also done on the databases to determine which environmental variables might significantly influence the occurrence of satellite anomalies.

1.4 Results. Our results are described in three sections:

- Results from comparisons of the environmental variable distributions.

- Correlation coefficients between the environmental variables and the occurrence of satellite anomalies.

- Results from discriminant analysis using linear regression equations to classify the data into yes/no cases, based on the probability of an anomaly occurring.

Figure 1 contains regression equations for seven groups of environmental variables discussed in Section 5 of this study. To classify the data by cases in which anomalies were likely or unlikely to occur, the probability of anomaly occurrence was calculated using the results of the regression equations in this formula:

$$Prob\ (Yes) = \frac{1}{\exp\ (No - Yes) + 1} \qquad [1]$$

The probability of .5 or greater was used to infer that an anomaly occurred. The equations for the second group of variables seem to perform the best of the seven attempts. Further details are provided in Section 5.

Group 1: Environment at time of anomaly (1986-91)
Yes =-3.24 +0.0243*MIN50 +0.0345*F10 -4524*XRAY +0.00001*MIN.2 +6.03E-7*MIN95 -0.0049*MIN10 -0.0008*MAX50 +0.0006*MAX10 +0.0015*AVG5
No =-4.17 +0.0017*MIN50 +0.0438*F10 -8711*XRAY +9.16E-6*MIN.2 +8.69E-7*MIN95 -0.0017*MIN10 +0.0007*MAX50 -0.0005*MAX10 +0.0007*AVG5

Group 2: Environment at time of anomaly (1986-91)
Yes =-1.65 +0.0214*MIN50 +0.0274*F10 -4530*XRAY -0.0022*MIN10 +0.0007*MAX50-0.0010*MAX10 +0.0012*AVG5
No =-2.71 +0.0004*MIN50 +0.0372*F10 -7962*XRAY -0.0007*MIN10 +0.0002*MAX50 +6.96E-6*MAX10 +0.0014*AVG5

Group 3: Environment 24-hours before anomaly (1986-91)
Yes =-3.10 +0.035*F10 -0.0001*MIN1 +0.0052*AP24 +0.000012*MIN.2 -5515*XRAY +4.2819E-9*AVG30
No =-4.11 +0.045*F10 -0.0001*MIN1 +0.0014*AP24 +0.000011*MIN.2 -8838*XRAY +2.9812E-9*AVG30

Group 4: Environment 48-hours before anomaly (1986-91)
Yes =-3.26 +0.034*F10 +0.0005*MIN1 +0.000012*MIN.2 -0.0004*MIN5 -.0004*MIN10 -0.0002*AVG1 +0.0376*AP
No =-4.22 +0.043*F10 -0.0006*MIN1 +0.000011*MIN.2 +0.0026*MIN5 -.0034*MIN10 +0.0001*AVG1 +0.0347*AP

Group 5: Environment 72-hours before anomaly (1986-91)
Yes =-3.24 +0.034*F10 +0.000011*MIN.2 +0.0020*MIN50 +0.034*AP -0.00007*MAX1 +4.242E-7*MIN95
No =-4.24 +0.042*F10 +9.90E-6*MIN.2 -0.0024*MIN50 +0.032*AP -0.00004*MAX1 +6.009E-7*MIN95

Group 6: Environment during solar min (1986-88)
Yes =-3.53 +0.038*F10 +0.0106*MIN50 +7.12E-6*MIN.2 +7.60E-7*MIN95 -3.2E-9*MAX30 +3.04E-8*AVG30 -2.32E-8*MIN30
No =-5.12 +0.082*F10 +0.0007*MIN50 +6.19E-6*MIN.2 +1.07E-7*MIN95 +5.0E-11*MAX30 +5.29E-9*AVG30 +4.17E-9*MIN30

Group 7: Environment during solar max (1989-91)
Yes =-1.30 +0.003*MAX5 -0.0005*MAX50 +0.0518*AVG50 +8590*XRAY -0.00014*AVG1 +0.0005*AVG10 -0.007*MAX10 -0.0004*MIN10
No =-0.02 -0.0005*MAX5 -0.0004*MAX50 +0.0013*AVG50 +4644*XRAY +0.00012*AVG1 -0.0006*AVG10 +0.0009*MAX10 +0.0002*MIN10

Figure 1. Regression equations to predict the probability of anomaly occurrence. Environmental variables are defined in Figure 2.

Environmental Variable	Data Type	Units
24-Hour A_p	AP24	None
3-Hour a_p	AP	None
Hourly 30-300 KeV Electron Flux	MIN30, AVG30, MAX30	Particles/Steradian/Sec/MeV
Hourly 95-300 KeV Electron Flux	MIN95	Particles/Steradian/Sec/MeV
Hourly .2-2 MeV Electron Flux	MIN.2	Particles/Steradian/Sec/MeV
10.7 Cm Radio Flux	F10	10^{-22} Watts/M^2/Hertz
X-ray Flare Report	XRAY	Watts/M^2
Hourly >1 MeV Proton Flux	MIN1, AVG1, MAX1	Particles/Steradian/Sec/MeV
Hourly >5 MeV Proton Flux	MIN5, AVG5, MAX5	Particles/Steradian/Sec/MeV
Hourly >10 MeV Proton Flux	MIN10, AVG10, MAX10	Particles/Steradian/Sec/MeV
Hourly >50 MeV Proton Flux	MIN50, AVG50, MAX50	Particles/Steradian/Sec/MeV

Figure 2. Environmental Variables Used in the Study. Data types are defined below:

AP24	24-hour global geomagnetic index (unitless)
AP	3-hour global geomagnetic index (unitless)
AVG1	hourly average >1 MeV protons in particles/ster/sec/MeV
AVG5	hourly average >5 MeV protons in particles/ster/sec/MeV
AVG10	hourly average >10 MeV protons in particles/ster/sec/MeV
AVG30	hourly average 30-300 KeV electrons in particles/ster/sec/MeV
AVG50	hourly average >50 MeV protons in particles/ster/sec/MeV
F10	10.7 cm solar radio flux in 10^{-22} watts/m^2/hertz
MAX1	hourly max >1 MeV protons in particles/ster/sec/MeV
MAX5	hourly max >5 MeV protons in particles/ster/sec/MeV
MAX10	hourly max >10 MeV protons in particles/ster/sec/MeV
MAX30	hourly max 30-300 KeV electrons in particles/ster/sec/MeV
MAX50	hourly max >50 MeV protons in particles/ster/sec/MeV
MIN.2	hourly min .2 - 2 MeV electrons in particles/ster/sec/MeV
MIN1	hourly min >1 MeV protons in particles/ster/sec/MeV
MIN5	hourly min >5 MeV protons in particles/ster/sec/MeV
MIN10	hourly min >10 MeV protons in particles/ster/sec/MeV
MIN30	hourly min 30-300 KeV electrons in particles/ster/sec/MeV
MIN50	hourly min >50 MeV protons in particles/ster/sec/MeV
MIN95	hourly min 95-300 KeV electrons in particles/ster/sec/MeV

2. DATA

2.1 Satellite Anomaly Data. We assembled a data file of reported GPS bit-hit anomalies from PC relational databases maintained by AF Global Weather Central (AFGWC) and the National Geophysical Data Center (NGDC), for the period 1 October 1984 to 30 September 1990. The 50 OSS/WE provided additional GPS anomaly reports in hardcopy for 1 October 1990 through 31 March 1991; these were manually added to the data file. Table 1 is an example of the GPS anomaly information stored in the data file.

TABLE 1. GPS satellite anomaly data. Latitude (Lat) and longitude (Lon) data is given in decimal degrees. Longitude is degrees *east* of Greenwich. The satellite orbital inclination (Inc) is rounded to the nearest degree.

Satellite ID	Anomaly Date	Start Time (Z)	End Time (Z)	Start Time (L)	Lat	Lon	Alt (km)	Inc (Deg)
GPS 5113	84/10/01	12:01:00	12:20	10:47	51.0	341.7	17600	63
GPS 9783	87/11/04	10:17:00	11:00	19:01	00.6	130.2	20042	63

2.2 Space Environmental Data. We obtained particle fluxes observed from geostationary satellites and geomagnetic indices from the USAFETAC SESS Climatic Database (SCDB). Solar radio flux, x-ray reports, and GOES particle fluxes were obtained from NGDC. GOES particle data was available for the period 1 January 1986 through 31 March 1991 only. All other data types were available for 1 January 1984 through 31 March 1991. Table 2 describes the space environmental data used in the study.

TABLE 2. Space Environmental Variables. A_p is a dimensionless index that provides a linear measure of the level of disturbance of the geomagnetic field. X-ray flares were observed by the GOES satellites.

Environmental Variable	Data Type	Source	Units
24-Hour A_p	Geomagnetic Index	SCDB	None
3-Hour a_p	Geomagnetic Index	SCDB	None
30-300 KeV Electron Flux	Satellite Particle	SCDB	Particles/Steradian/Sec/MeV
95-300 KeV Electron Flux	Satellite Particle	SCDB	Particles/Steradian/Sec/MeV
.2-2 MeV Electron Flux	Satellite Particle	SCDB	Particles/Steradian/Sec/MeV
10.7 Cm Radio Flux	Solar Flux	NGDC	10^{-22} Watts/M^2/Hertz
X-ray Flare Report	1-8 Angstrom Flux	NGDC	Watts/M^2
>2 MeV Electron Flux	Satellite Particle	NGDC	Particles/Steradian/Sec/MeV
>1 MeV Proton Flux	Satellite Particle	NGDC	Particles/Steradian/Sec/MeV
>5 MeV Proton Flux	Satellite Particle	NGDC	Particles/Steradian/Sec/MeV
>10 MeV Proton Flux	Satellite Particle	NGDC	Particles/Steradian/Sec/MeV
>50 MeV Proton Flux	Satellite Particle	NGDC	Particles/Steradian/Sec/MeV

2.3 GPS Orbital Data. We estimated GPS latitudes and longitudes missing from the satellite anomaly reports using GPS orbital prediction models. Archived GPS orbital variables were used to initialize the models. Aerospace Corporation provided the GPS orbital data and two orbital prediction models, PCSOAP and DGEN.

PCSOAP is the Personal Computer Satellite Orbit Analysis Program; it models the dynamics of artificial satellites orbiting the earth. DGEN is a mainframe model that does integrations of the equations of motion to predict the locations of GPS satellites.

3. METHODOLOGY

3.1 Database Creation. Using two databases (a GPS anomaly database and an environmental database covering the period 1 October 1984 through 31 March 1991), the state of the space environment during GPS anomalies could be compared to the general state of the space environment. The GPS and environmental data collected for this study were put into the two databases. The GPS anomaly start times were matched to the corresponding environmental data to form the GPS anomaly database, which contains the environmental variables (mentioned in Table 2) that specified the space environment during each GPS anomaly. The time window before the start of each anomaly for each environmental variable observation (as shown in Table 3) varies because the amount of time varies before different parts of the space environment (such as the energetic particle or geomagnetic environment) react to solar activity.

TABLE 3. GPS Environmental Observations. The time resolutions described below are the result of consultations between solar forecasters at AFGWC and space analysts at USAFETAC; they are the variables used in real-time GPS anomaly assessment.

Environmental Data Type	Observation Window
X-ray Flare	Largest x-ray flare reported within 24 hours of anomaly start time
24-hour A_p	Value for calendar day
3-hour a_p	First value reported after anomaly begins
10.7 cm Radio Flux	Value for calendar day
Satellite Particle Fluxes	Particle fluxes at the time anomaly begins

The environmental database is a control database separate from the GPS anomaly database, and contains environmental variables reported for each hour of each day during the period 1 October 1984 through 31 March 1991. The exception to this is the GOES particle data, which was not kept in the NGDC archive prior to 1 January 1986. Table 4 shows time resolution for the environmental variables in the database.

TABLE 4. Environmental Observations. The time resolutions described below were requested by the solar forecasters at AFGWC.

Environmental Data Type	Database Time Resolution
X-ray Flare	Largest flare in progress during each hour
24-hour A_p	Value for calendar day
3-hour a_p	Latest value reported before start of each hour
10.7 cm Radio Flux	Value for calendar day
Satellite Particle Fluxes	Maximum 5-minute value reported each hour Minimum 5-minute value reported each hour Average 5-minute value reported each hour

3.2 Statistical Comparisons. Statistical Analysis System (SAS) software was used to sort the variables in the GPS anomaly database and the environmental database into statistical distributions and to plot each distribution to allow differences between the environment during satellite anomalies and the normal space environment to be seen.

3.3 Statistical Calculations. SAS was also used in a multi-step process on the environmental database to quantify any correlation between activity in the space environment and the occurrence of GPS anomalies. Since the differing time resolutions between the GPS anomaly database and the environmental database made it impossible to calculate direct correlations between the environmental variables and anomaly occurrence, a modified version of the environmental database was used for the statistical calculations. First, a new element was added to the environmental database: whether or not an anomaly occurred during each hour of the period between 1 January 1986 and 31 March 1991. Even though we have GPS anomaly reports for 1984-5, data from these years was not used in these calculations because GOES proton fluxes were not archived for that period.

Correlation coefficients were calculated between all the environmental variables and the occurrence/non-occurrence of anomalies during each hour of the study period.

Next, a stepwise linear regression was done on the modified environmental database to determine which environmental variables had the best correlation to the occurrence of an anomaly. Since some of the effects of a solar disturbance take several days to reach the Earth, linear regressions were done on the environmental variables during the hour the anomaly occurred and, 24, 48, and 72 hours before the anomaly occurred. In each case, those environmental variables selected by SAS as the most significant in the occurrence of anomalies were noted.

Finally, discriminant analysis was used to estimate the probability of anomalies occurring, based on the different environmental variables previously selected. Discriminant analysis produces a matrix that shows how well the selected variables can classify the environmental database into two categories: either a GPS anomaly occurred or did not occur. Discriminant analysis uses the regression equations previously derived to predict the probability of an anomaly occurring for each hour of the study period, and uses that probability to sort the study data into yes/no categories for anomaly occurrence. We assumed that for any hour of the study period, an anomaly occurred when the probability was greater than 50%.

4. LIMITATIONS

4.1 Percent of Anomalies Reported. In order to do the statistical calculations described in Section 3.3, the assumption had to be made that every GPS anomaly that occurred between 1 October 1984 and 31 March 1991 is in the GPS anomaly database. This assumption is questionable for two reasons:

• There are long periods of time, such as the last 6 months of 1988 and the first 4 months of 1989, during which no GPS anomalies were reported.

• Even though the AFGWC and NGDC satellite anomaly databases cover the same period of time and were supposed to contain the same information, they had only five anomaly reports in common.

4.2 Lack of Environmental Data. The magnetosphere is a data-sparse region; few observations of the space environment are taken consistently there. For this study, we used whatever satellite particle data was available, even though the observing satellites were often in a different part of magnetosphere than the GPS satellites when an anomaly occurred. The particle data observed, therefore, may not have been representative of the space environment at the GPS satellite. Although some limited datasets of particle data observed by sensors on GPS satellites exist, USAFETAC was not able to obtain any GPS data for this study.

4.3 Incomplete Satellite Reports. In using orbital dynamics models, missing ops locations had to be filled after the fact; this introduced the possibility of error to the database. A more significant problem in the GPS database was the lack of end times for GPS anomalies. In order to complete this study, we made the assumption that all anomaly reports without end times (about 35% of the database) were brief anomalies of less than 1 hour in duration.

4.4 Accuracy of Anomaly Times. Twenty percent of the anomaly start times reported in the database were the times that the anomalies were reported to the groundstation, and not the times that the anomalies actually occurred; GPS anomalies with start times exactly on the hour, along with those with start times between 2200 and 2212Z, fall into this category. All such anomalies were eliminated from the database and the statistics were recalculated. Dropping the questionable anomalies changed the results of the statistical analysis by less than 2% and had no effect on which environmental variables were selected as significant predictors of anomalies. Statistical companions between the daily space environment and the occurrence of GPS anomalies also showed no difference in the environmental varibales slected as significant or in the results of the analysis.

5. RESULTS

5.1 Statistical Comparison Results. The Appendix contains charts of distributions of each environmental variable in the GPS anomaly database, along with the corresponding variable from the environmental database. Comparisons between the environment during anomalies and the general environment show several contradictory features. Some of the charts show a higher than expected frequency of occurrence for higher values of the variable. The x-ray flare chart, and many of the high-energy proton charts, show a cluster of values in the "tail" of the distributions, implying that for some anomalies the environment is disturbed. However, many charts also show higher than expected frequency of occurrence for lower values of the variable. The 10.7 cm flux, the a_p, the 24-hr A_p, x-ray flares, and some of the low-energy electrons show this feature. These charts show that any relationship between the space environment and satellite anomalies is complex and not very well understood.

5.2 Statistical Correlation Results. Linear correlations between the occurrence of satellite anomalies and the environmental variables were calculated. The correlation coefficients indicate the amount of linear dependence between each environmental variable and the occurrence of satellite anomalies. If the environment were ideally correlated with the occurrence of anomalies, the correlation coefficient would be -1 or +1, showing total linear dependence. A correlation coefficient of zero indicates the variable are linearly independent of anomaly occurrence. Figure 3 shows the correlation coefficients for the environmental database.

All the correlation coefficients are extremely low, showing hardly any linear dependence between the occurrence of anomalies and the space environment. In the case of environmental data, a correlation coefficient of >.6 or <-.6 would be a sign of a strong correlation. The best correlations seen above are for hourly minimum >50 MeV protons and the 10.7 cm flux. These environmental variables will be frequently selected during the stepwise linear regression as being statistically significant.

Environmental Variables	Correlation	Environmental Variables	Correlation
>50 MeV Proton Flux min	.088	10.7 Cm Radio Flux	-.087
>5 MeV Proton Flux avg	.066	>10 MeV Proton Flux min	.066
>5 MeV Proton Flux min	.066	>10 MeV Proton Flux avg	.065
>5 MeV Proton Flux max	.064	>10 MeV Proton Flux max	.063
>50 MeV Proton Flux avg	.063	>1 MeV Proton Flux avg	061
>1 MeV Proton Flux avg	.059	>1 MeV Proton Flux max	.053
.2-2 MeV Electron Flux min	.037	>50 MeV Proton Flux max	.036
24-Hour A_p	-.019	3-Hour a_p	-.011
>2 MeV Electron Flux max	.009	>2 MeV Electron Flux avg	.009
>2 MeV Electron Flux min	.008	X-ray Flare Report	.007
.2-2 MeV Electron Flux max	-.005	95-300 KeV Electron Flux min	.004
30-300 KeV Electron Flux max	-.003	30-300 KeV Electron Flux avg	-.003
30-300 KeV Electron Flux min	-.003	95-300 KeV Electron Flux avg	-.001
95-300 KeV Electron Flux max	-.001	.2-2 MeV Electron Flux avg	-.001

FIGURE 3. Pearson correlation coefficients for environmental database. Correlated variables are listed from left to right in order of descending importance.

5.3 Discriminant Analysis Results. We tried several different discriminant analysis techniques to select which environmental variables are most significant in showing differences in the space environment between cases in which GPS anomalies do or do not occur. Tables containing classification matrices will show how well certain groups of environmental variables did in classifying the environmental database into categories of occurrence/non-occurrence of anomalies. Skill scores were also used to quantify the accuracy of the environmental variables in classifying anomalies.

5.3.1 Skill Scores. A skill score is a statistical formula used to determine if a categorical (yes/no) weather forecast technique will work better than random chance. For this study, the Hanssen and Kuiper discriminant "V" score was used to determine the relative accuracies of the environmental variables used to classify the environmental database into yes/no cases of anomaly occurrence. This skill score is considered the best for rare events like satellite anomalies. The discriminant "V" score (VDS) was calculated using Equation 2.

$$VDS = \frac{AD-BC}{[(A+B)X(C+D)]} \qquad (2)$$

where A, B, C, and D are as shown in the matrix; Note that A, B, C, and D are observation counts and not percentages.

	GPS ANOMALIES Expected	
Occurred	**No**	**Yes**
No	A	B
Yes	C	D

VDS ranges between -1 (no skill; worse than random chance) and +1 (totally accurate). A VDS of zero means the environmental variables are no better than chance in determining if an anomaly may occur. For the purposes of this study, a VDS higher than .3 indicates that the environmental variables used to classify anomalies do significantly better than chance.

5.3.2 Classification Matrices. Skill scores alone are not enough to judge the accuracy of environmental variables in forecasting or classifying events. Classification matrices are also used to provide more detailed information on important factors like "capability," or the number of missed events (events not forecast that occurred), and "reliability" (the number of "false alarms," or events forecast that did not occur). Equations 3 and 4 show the formulas used to calculate reliability (REL) and capability (CAP).

$$REL = \frac{D}{(B+D)} \qquad (3)$$

$$CAP = \frac{D}{(C+D)} \qquad (4)$$

where B, C, and D are observation counts as shown in the matrix on the next page.

	GPS ANOMALIES Expected	
Occurred	**No**	**Yes**
No	A	B
Yes	C	D

Reliability shows the number of correctly classified anomaly events over the total number of events classified as anomalies. The higher the reliability, the fewer false alarms. *Capability* shows the number of correctly classified anomalies vs the total number of anomalies that occurred. The higher the capability, the fewer missed anomalies. The regression equations used to classify all the environmental observations into the matrices in this section are listed in Figure 1. The matrices in this report use the format shown in Table 5.

TABLE 5. Classification Matrix Format. The values in the matrices are numbers of observations used to calculate skill scores, reliability, and capability, as well as the percentages of observations for easier comparison between groups of variables. The percentages running horizontally across the matrix (the expected yes and no) add up to 100%. The skill scores, reliability, and capability for all groups of environmental variables will be shown in Table 9 at the end of this section.

	GPS ANOMALIES Expected	
Occurred	**No**	**Yes**
No	# Correct % Correct non-anomaly events	# False Alarms % False Alarms
Yes	# Missed Anomalies % Missed Anomalies	# Correct % Correct anomaly events

5.3.3 Environment During Anomalies. The results shown in Table 6 are for two groups of environmental variables for the hours that GPS anomalies occurred. Both groups had identical "V" skill scores of .34, which border on being significantly better than chance. There is some variation between the groups in the percentages of false alarms and missed anomalies, but not enough to be significant.

TABLE 6. Classification of the environment during GPS anomalies. The variables listed below each matrix are in their order of statistical importance as selected by the SAS stepwise discriminant analysis procedure.

Group 1

25420 62	15600 38
313 28.3	797 71.7

__Group 1 variables:__ Hourly minimum >50 MeV protons; 10.7 cm flux; x-ray flux; hourly minimum .29-2 MeV electrons; hourly minimum 95-300 KeV electrons; hourly minimum >10 MeV protons; hourly maximum >50 MeV protons; hourly maximum >10 MeV protons; hourly mean >5 MeV protons.

Group 2

26217 59.7	17718 40.3
306 25.4	900 74.6

__Group 2 variables:__ Hourly minimum >50 MeV protons; 10.7 cm flux; x-ray flux; hourly minimum >10 MeV protons; hourly maximum >50 MeV protons; hourly maximum >10 MeV protons; hourly mean >5 MeV protons.

In Group 2 we tried to improve the accuracy of the discriminant analysis by dropping the low energy electrons, which seemed to be less significant than the high energy protons, x-ray flares, and 10.7 cm radio flux. The Group 2 results had a slightly lower percentage of missed anomalies but a higher false alarm rate. These results imply that low energy electrons by themselves do not have a significant effect on the occurrence of anomalies. This is in line with the results of the stepwise regression technique, which indicated that the correlation between any one variable and the occurrence or non-occurrence of anomalies is weak.

5.3.4 The Environment 24-72 Hours Before GPS Anomalies. Since some effects of solar disturbances can take several days to effect the near-Earth space environment, we did statistical studies of the environment before anomalies occurred to determine if any environmental variables had a significant effect on anomaly occurrence. The results shown in Table 7 are for environmental variables observed 24, 48, and 72 hours before each anomaly. As the anomaly time lags further behind the environmental observation, the variables selected change but the matrix percentages and the skill scores degrade only slightly. The "V" skill score was .3 for the 24-hour case, .29 for the 48-hour case, and .28 for the 72-hour case. In all three cases, the skill scores and the percentage of correctly classified anomalies are lower than in the cases at the times of the anomalies described in Section 5.1.3.

TABLE 7. Classification of the environment 24-72 hours before GPS anomalies. The three groups of variables listed below are in their order of statistical importance as selected by the SAS stepwise discriminant analysis procedure. Since the percentages in the classification matrices changed by less than 1 percent for the three cases, one matrix with the percentages rounded off to the nearest degree is shown.

Groups 3 - 5

22573 55	18415 45
299 26	834 74

Group 3 variables (24-hours previous): 10.7 cm flux; hourly mean >1MeV protons; 24-hour Ap; hourly minimum .29-2 MeV electrons; x-ray flux; hourly maximum 30-300 KeV electrons.

Group 4 variables (48-hours previous): 10.7 cm flux; hourly minimum >1MeV protons; hourly minimum .2-2 MeV electrons; hourly minimum >5MeV protons; hourly minimum >10MeV protons; hourly mean >1MeV protons; 3-hour a_p.

Group 5 variables (72-hours previous): 10.7 cm flux; hourly minimum .29-2 MeV electrons; hourly minimum >50 MeV protons; 3-hour a_p; hourly maximum >1MeV protons; hourly minimum 95-300 KeV electrons.

Statistically, the 10.7 cm radio flux is the most important environmental variable in all three cases. The others don't contribute as much, which is why the matrix percentages and skill scores are similar in all three cases. As the time lag before anomaly occurrence lengthens, x-ray flare reports become less significant and the geomagnetic index (a_p) becomes more significant.

5.3.5 Environment During Solar Minimum and Maximum. The period of time covered by the statistical study (1986 to 1991) includes a solar cycle minimum in 1986 and a maximum in 1989. We divided the database into two cases: the solar minimum years 1986-88 and the solar maximum years 1989-91 to see if the general level of solar activity had any influence on the correlation between the environmental variables and the occurrence of GPS anomalies. Table 8 shows the results for Group 6 (significant environmental variables during the solar minimum period) and Group 7 (significant environmental variables during the solar maximum period). The "V" skill score for Group 1 is slightly lower (.30) than for the entire study period (see Section 5.1.3), while the score for Group 7 is the lowest found in this study (.12).

TABLE 8. Classification of the environment during solar min and max. The variables listed below each matrix are in their order of statistical importance as selected by the SAS stepwise discriminant analysis procedure.

Group 6

11843 50.8	11470 49.2
171 21.0	642 79.0

Group 6 variables: 10.7 cm flux; hourly minimum >50 MeV protons; hourly minimum .29-2 MeV electrons; hourly minimum 95-300 KeV electrons; hourly maximum 30-300 KeV electrons; hourly mean 30-300 KeV electrons; hourly minimum 30-300 KeV electrons.

Group 7

19049 98.7	258 1.3
290 87.1	43 12.9

Group 7 variables: Hourly maximum >5 MeV protons; hourly maximum >50 MeV protons; hourly mean >50 MeV protons; x-ray flux; hourly mean >1 MeV protons; hourly mean >10 MeV protons; hourly maximum >10 MeV protons; hourly minimum >10 MeV protons.

The 10.7 cm radio flux, 50 MeV protons, and low energy electrons show the greatest influence as anomaly predictors in the solar minimum case. In the solar maximum case, high energy protons (>1 MeV and up) and the x-ray flux are preferred variables.

Similar percentages occur for the solar minimum classification matrix and results for the entire period of the study (see Table 6). The percentage of missed anomalies dropped by 7%, but at the expense of a higher percentage of false alarms. However, the solar maximum matrix shows very different results. The false alarm rate during solar max is practically nonexistent, but 87% of the anomalies that occurred were not correctly classified, resulting in a much lower skill score.

This result is in line with an empirical finding by solar forecasters: that is, during periods of quiet solar activity it's easier to correlate the occurrence of occasional solar disturbances with particular satellite anomalies. During periods of high solar activity, there are so many disturbances occurring almost simultaneously that it's difficult to determine which (if any) might be the cause of a particular satellite anomaly. The higher levels of energetic particles saturate the satellite sensors and affect how satellites react to changes in the environment.

Table 9 shows the "V" skill scores, capability, and reliability for all seven groups of environmental variables studied.

TABLE 9. Summary of results for all groups of environmental variables.

Group	"V" Skill Score	Capability Score	Reliability Score
1: 9 Variables	.34	.72	.05
2: 7 Variables	.34	.75	.05
3: 24-hrs Previous	.30	.74	.04
4: 48-hrs Previous	.29	.74	.04
5: 72-hrs Previous	.28	.73	.04
6: Solar Minimum	.30	.79	.05
7: Solar Maximum	.12	.13	.14

Groups 1 and 2, the general environmental groups, had the best skill scores. The others, with the exception of Group 7, had scores only slightly worse. Group 7, the solar maximum group, had a significantly lower skill score than the other groups, due to the large number of missed anomalies. The capability scores show that when anomalies occur, all groups except for Group 7 did well in correctly classifying those events. For Group 7, large numbers of missed anomalies made the capability score low. Reliability scores are very low for all groups, because the number of false alarms are always very high compared to the number of correctly classified anomalies. The large difference in size (two orders of magnitude) between the number of observations in which no anomaly was reported and the number in which an anomaly *did* occur, biases the results.

Group 7 did somewhat better in reliability only because the number of false alarms was much lower (only one order of magnitude larger) than for the other groups.

5.3.6 Geomagnetic Latitude and Occurrence of Anomalies. In addition to the normal environmental variables, we also examined whether or not a satellite's position had any bearing on the occurrence of an anomaly. We calculated hourly positions for GPS satellites 5113, 5114, and 5118 for the years 1987-91. Figure 6 is a comparison between distributions of corrected geomagnetic latitude during anomalies versus the distribution of corrected geomagnetic latitudes along the satellites' orbit.

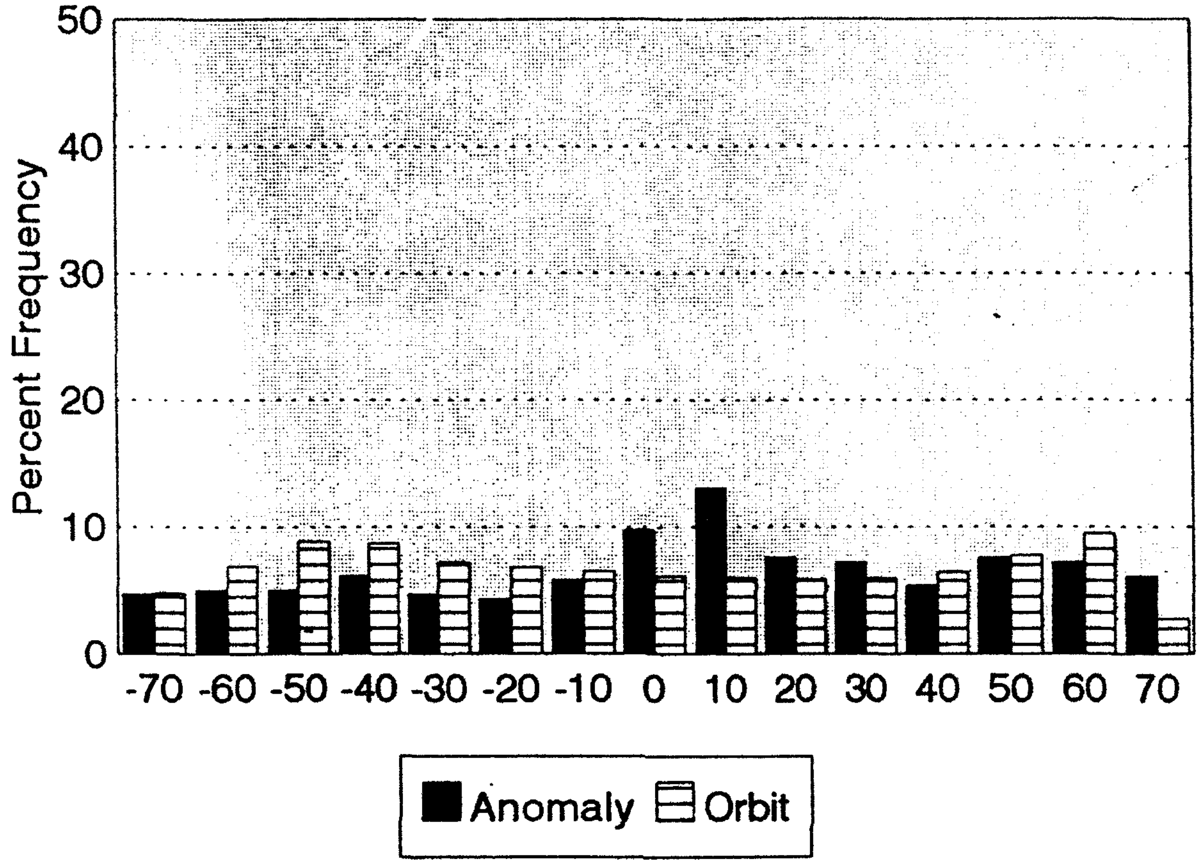


Figure 4. Distribution of Positions for GPS 5113, 5114, and 5118 (corrected geomagnetic latitude).

Certain geomagnetic latitudes have a higher percentage of anomalies than would be expected from the normal orbital track. One area of high anomaly frequency is in the low latitudes of the Northern Hemisphere, possibly due to the equatorial anomaly. Another area of relatively frequent anomalies is in the Northern Hemisphere polar region; this may be caused by the orientation of the magnetic field lines into the Earth. However, when statistical analysis was done on the effect of the environment on one satellite (GPS 5113), geomagnetic latitude was not selected as a statistically significant predictor of satellite anomalies. The skill score and classification matrix were virtually identical to that for the general environment (Groups 1 and 2 in Section 5.3.3). Examination of Figure 6 raises other questions. The high frequency of anomalies seen near the equator and pole in the Northern Hemisphere is not seen in the Southern Hemisphere. Are the satellites commanded more in the Northern Hemisphere, triggering the occurrence of an anomaly (such as a sudden discharge)? The extremely small size of the GPS 5113 anomaly database used in analysis (241 anomalies) may have also handicapped our analysis.

6. CONCLUSIONS AND RECOMMENDATIONS

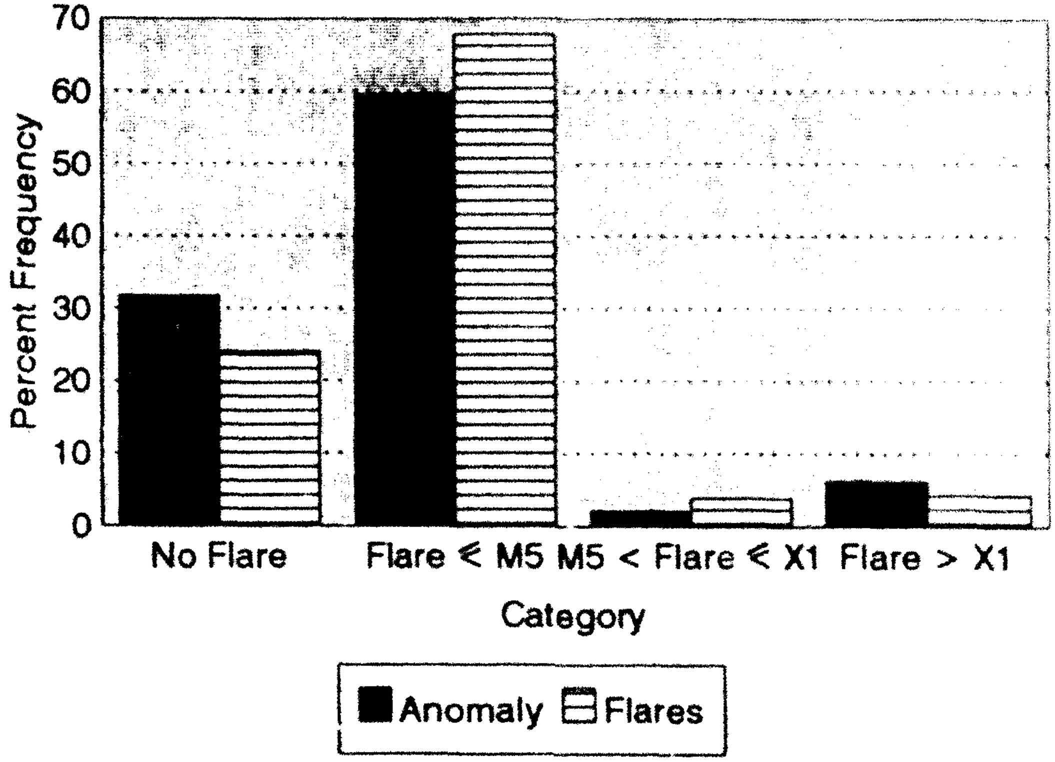
6.1 Conclusions. The objective of this study was to examine a group of GPS anomalies collected over a period of time and determine if there were relationships between commonly observed space environmental variables and the occurrence of anomalies.

We found the relationship between environment and anomaly occurrence to be somewhat better than chance, but could find no definite link between any one environmental variable and the occurrence of anomalies. The Group 2 variables did best in categorizing anomalies in general, but the large variability seen in environmental data over the solar cycle and the very low correlations between environmental variables and satellite anomalies make it risky to use these results for more than general guidance. Unless these results are tested on independent data and found to be valid, they should not be used to evaluate individual anomalies.

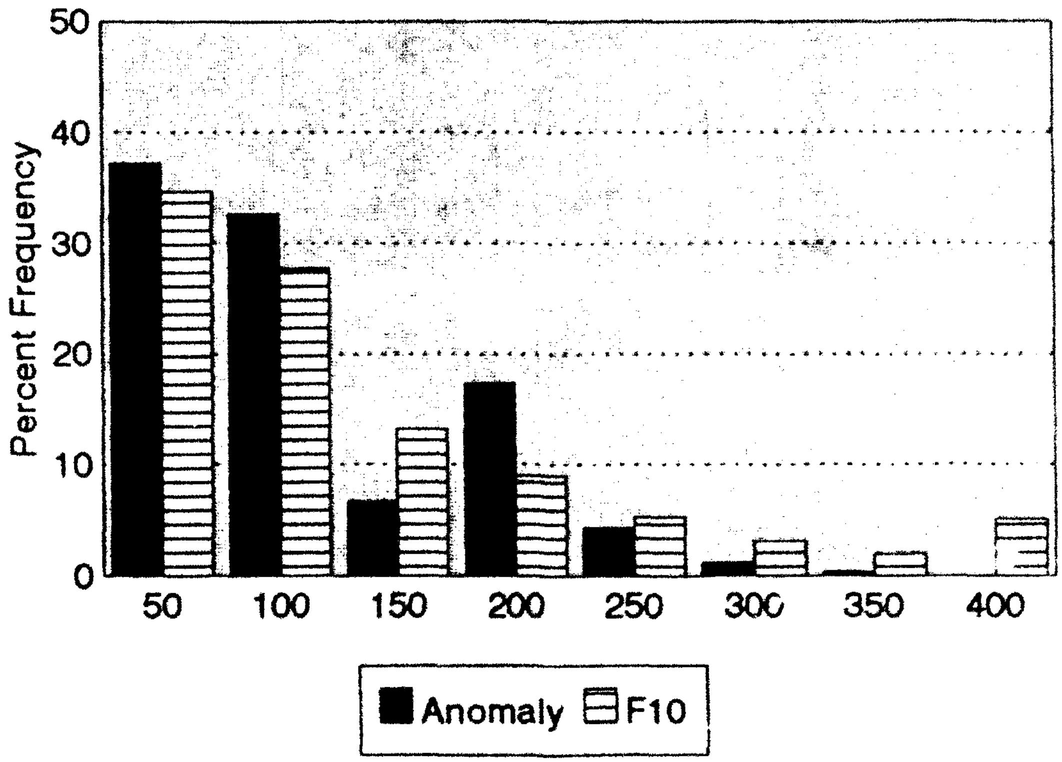
6.2 Recommendations. Better documentation of GPS anomalies is needed. More consistent reporting of positions, start and end times, and whether or not the satellite was commanded when an anomaly occurred, might help separate environmental factors from engineering factors in classifying anomaly causes. The organizations involved in satellite operations need to make sure that all anomalies are reported and stored in the anomaly database now maintained by the AF Space Forecast Center. The amount and quality of space environmental data will improve over the next 10 years as more sensors and better models come into operational use. Once the space environment at the location of each satellite can be specified, a follow-on to this study several years from now might yield more definitive results. The importance of space systems necessitates continuing study of space climate and its influence on system effects.

APPENDIX

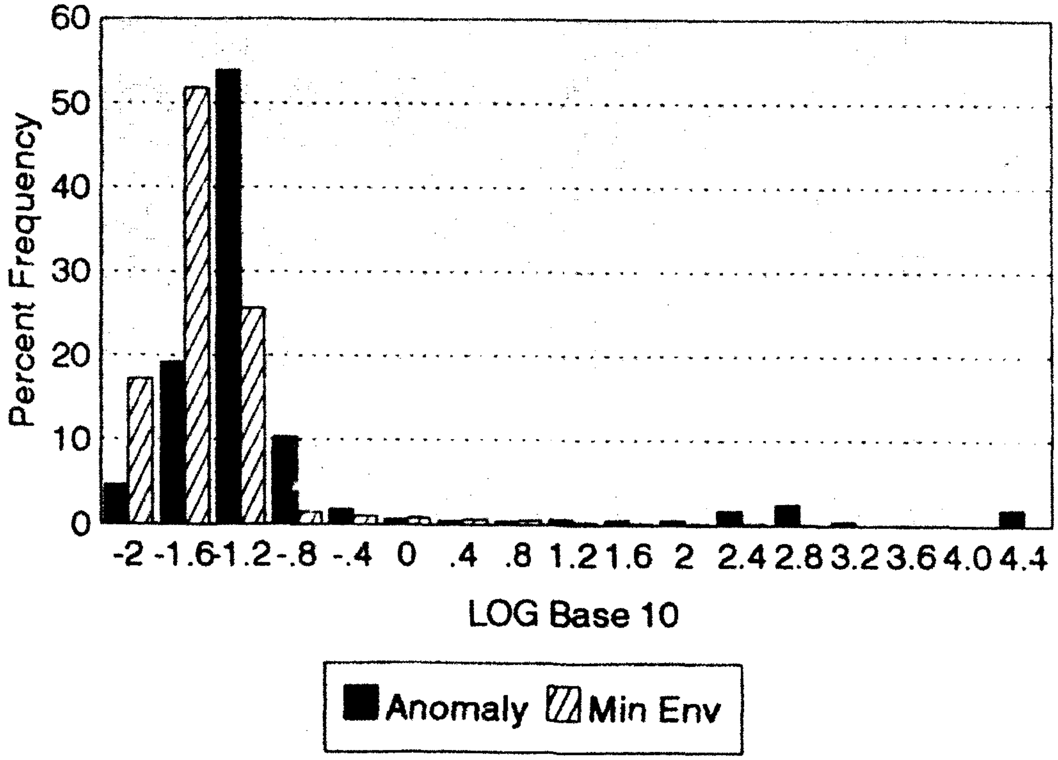
Solar and Geomagnetic Comparison Charts



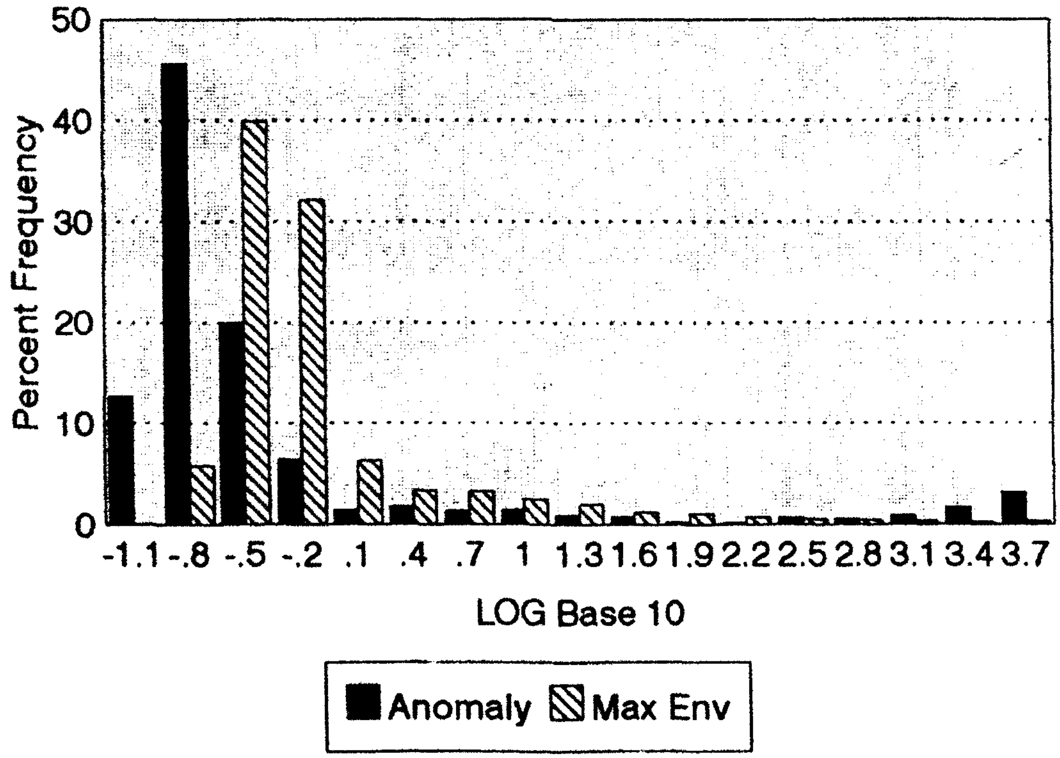
A-1. Distribution of Solar Flares, X-ray Levels.



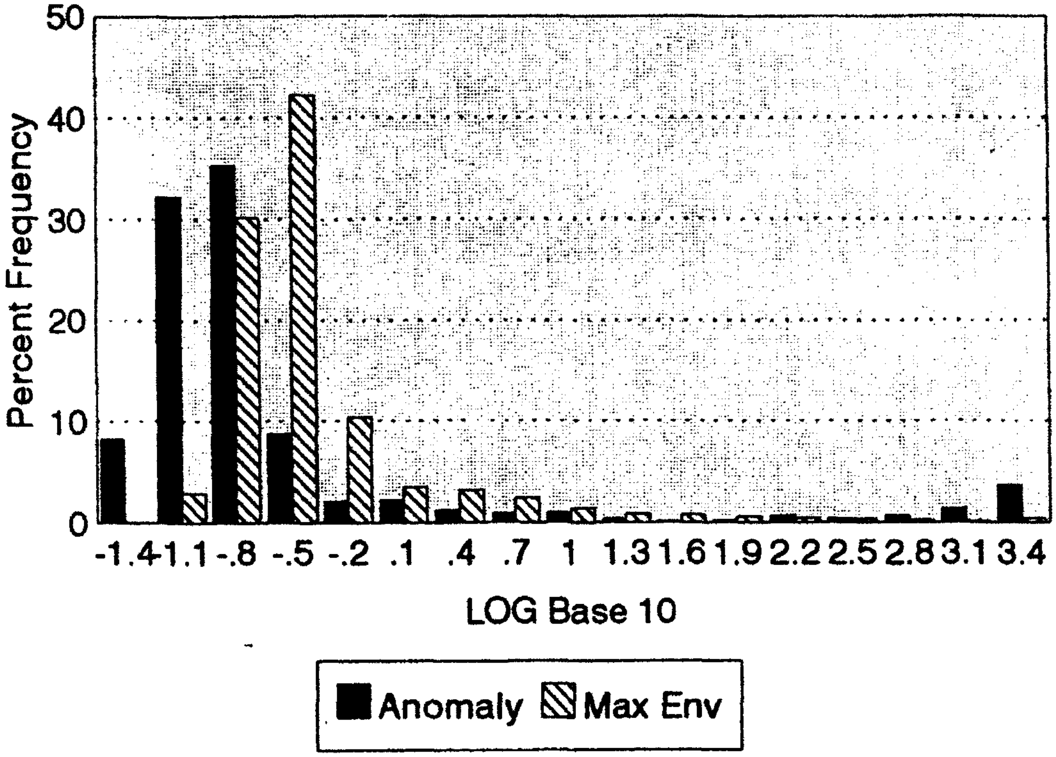
A-2. Distribution of Daily 10.7cm Radio Flux 10-22 Watts/Sq M/Hz.



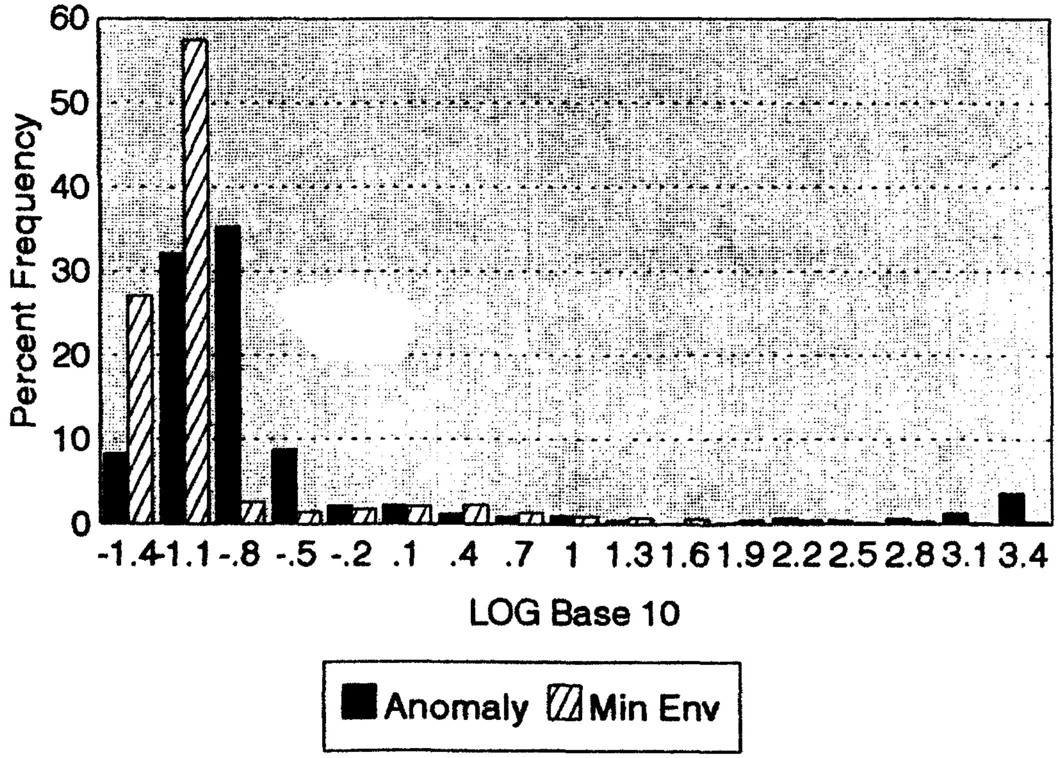
A-3. Hourly Distribution of GOES Protons, > 50 MeV.



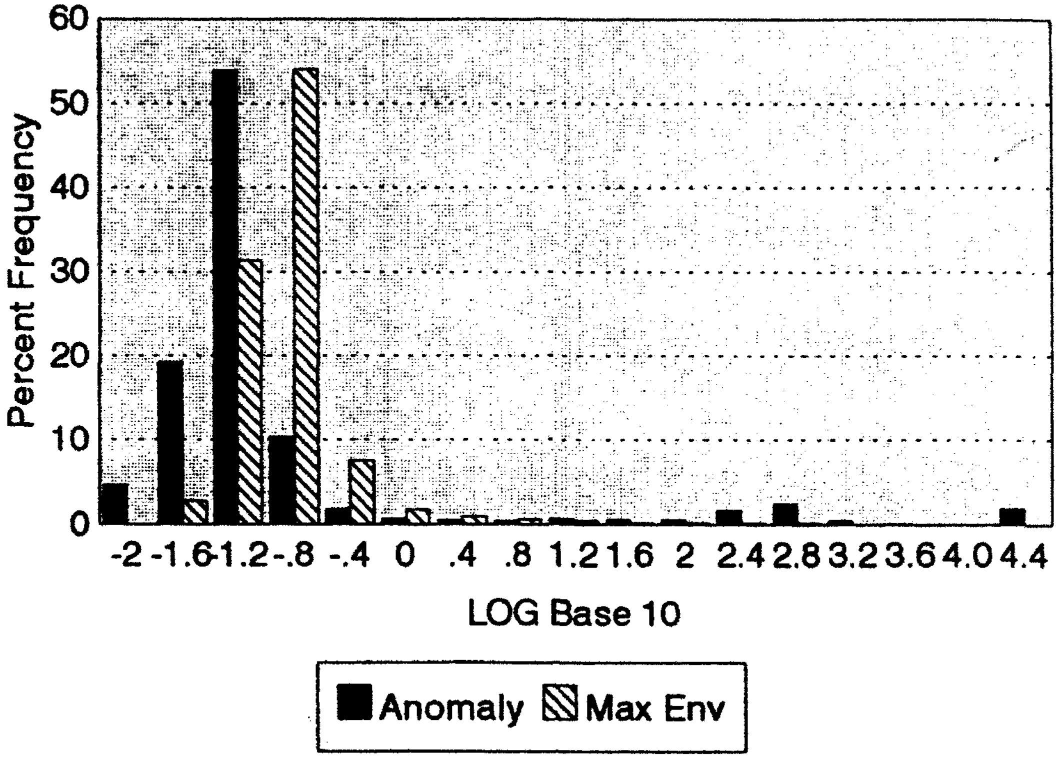
A-4. Hourly Distribution of GOES Protons, > 5 MeV.



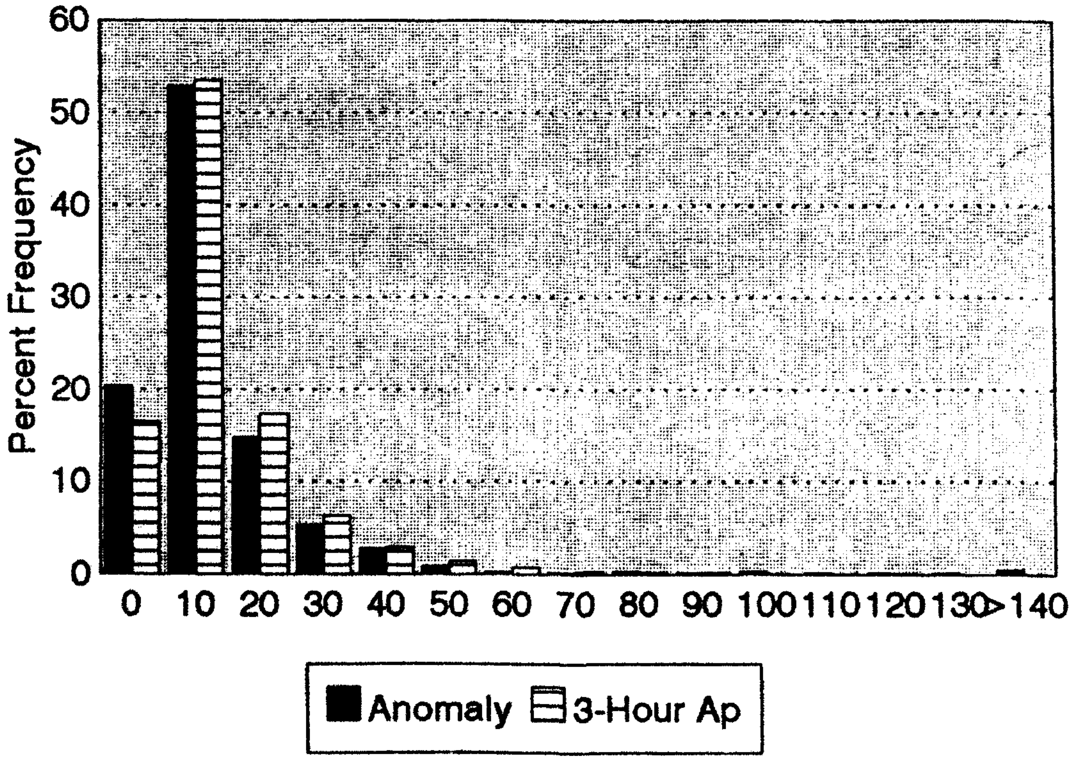
A-5. Maximum Hourly Distribution of GOES Protons, > 10 MeV.



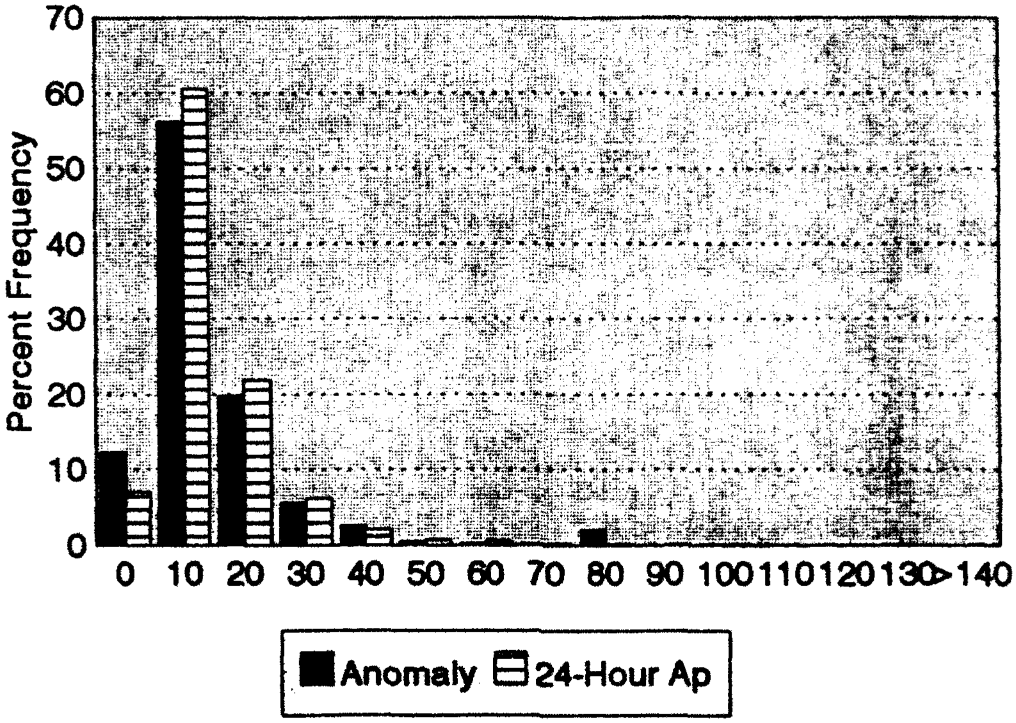
A-6. Minimum Hourly Distribution of GOES Protons, > 10 MeV.



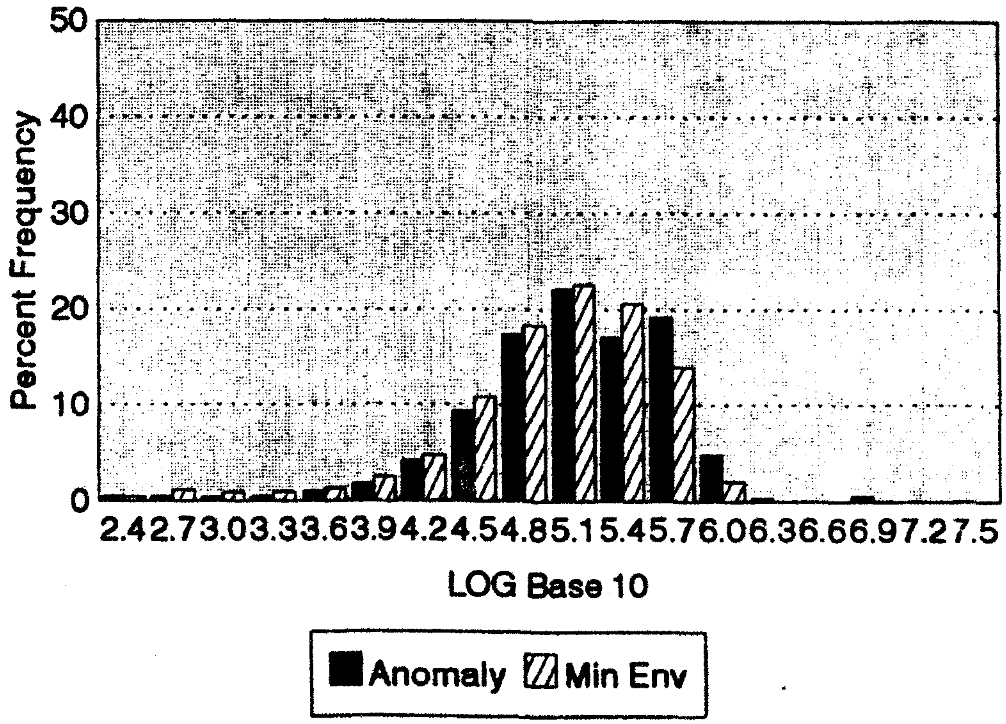
A-7. Hourly Distribution of GOES Protons, > 50 MeV.



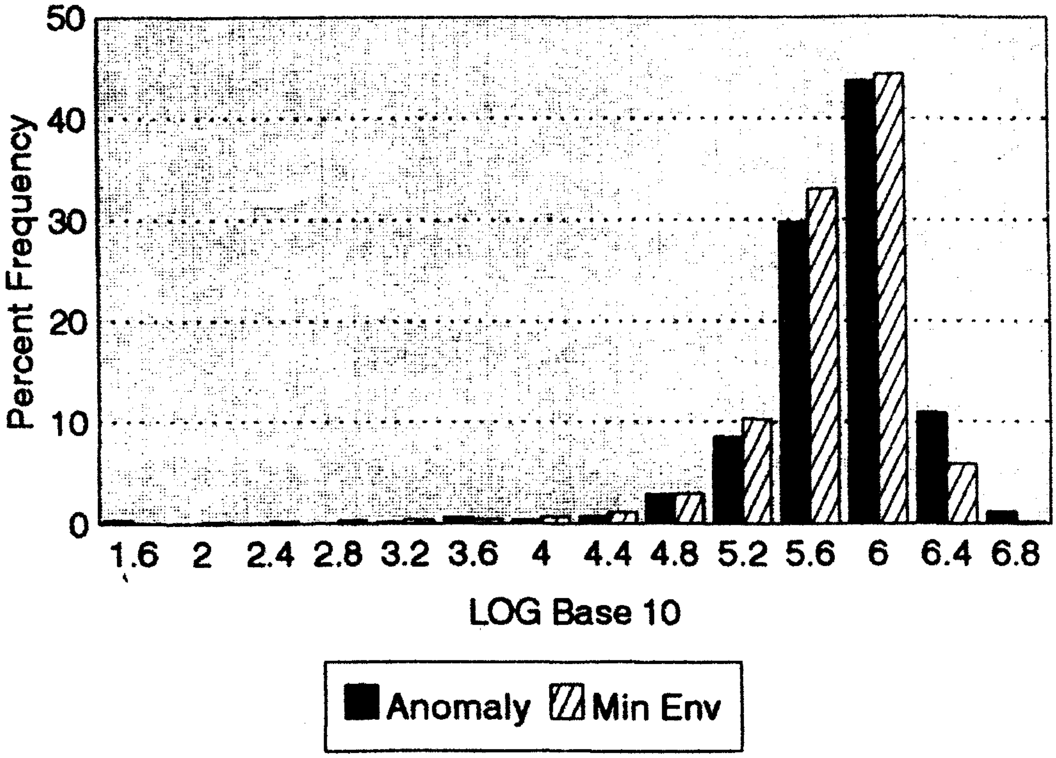
A-8. Distribution of 3-Hour Ap, Geomagnetic Index.



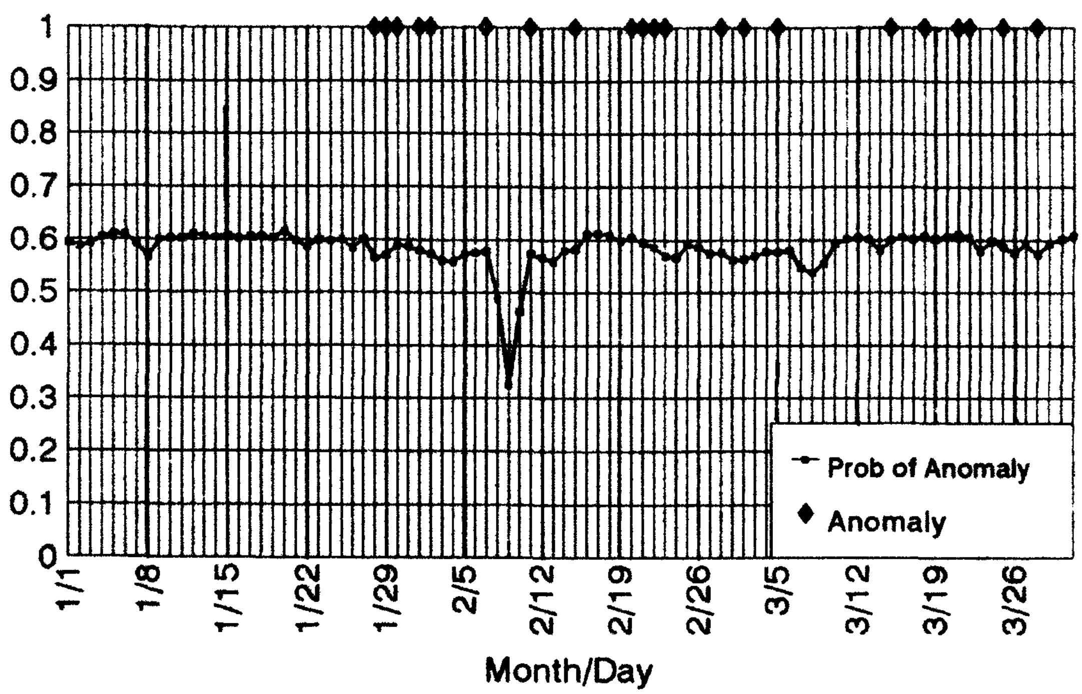
A-9. Distribution of 24-Hour Ap, Geomagnetic Index.



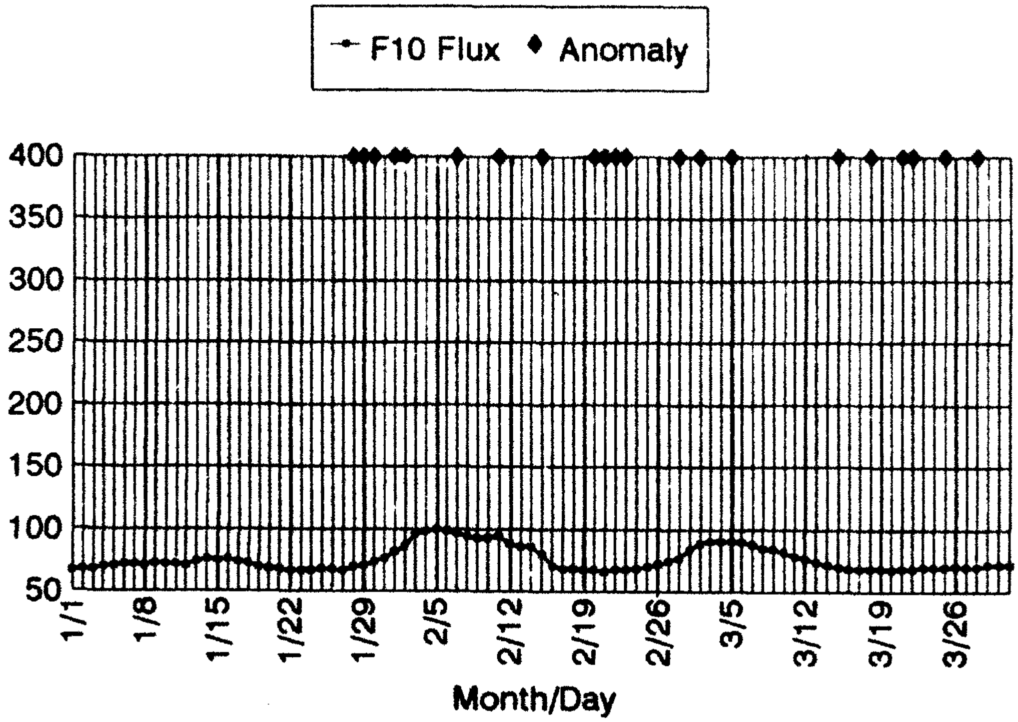
A-10. Hourly Distribution of Energetic Electrons .29-2 MeV.



A-11. Hourly Distribution of Energetic Electrons, 95-300 KeV.



A-12. Daily Satellite Anomalies 1986.



A-13. Daily Environmental Data 1986.

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