Serendipitous Background Monitoring of the Hubble Space Telescope's Faint Object Spectrograph

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ABSTRACT

The nature of the Hubble Space Telescope's (HST) low Earth orbit imposes scheduling restrictions and interruptions in the data collection periods for it's compliment of scientific instruments. During many of these times the Faint Object Spectrograph (FOS) is in a full operational configuration and is taking detector background measurements which are continually reported in HST's engineering telemetry stream. These data are primarily used to monitor the instrument for changes in behavior resulting, principally, from intermittently noisy diodes in its digicon arrays. These same data may be used to monitor temporal changes in the charged particle environment of HST's near-earth orbit.

We present here the results of a study of two years of on-orbit FOS background data obtained serendipitously during periods while the FOS in an operational state, but not exposing on external, or calibration targets. These *in situ* data, which represent more than 100,000 discrete samples (equivalent to more than 1100 orbits) have allowed us to accurately measure variations in the background proton flux seen by the FOS. An analysis of these variations have permitted us to model the geomagnetic environment of the South Atlantic Anomaly (SAA) as a function of time as well as the change in detector background as a function of geomagnetic latitude.

1.0 INTRODUCTION

The Faint Object Spectrograph on board the Hubble Space Telescope contains two digicon detectors each with a 512 element diode array. During normal operation, the digicons are kept at roughly 22 kV and are transitioned to a low voltage state only in the event of a gap between observations of more than approximately 4 hours. Due to scheduling constraints, a large portion of each orbit cannot be spent observing the primary target. These non-observing periods include target occultation (by the Earth), intrusion of the SAA, maneuvering of the spacecraft, and acquiring (or re-acquiring) guide stars. Generally, these precluded scheduling intervals occur between observations, but they can also occur during an observing sequence. In the case of the FOS, during these periods the high voltage remains on and the detector remains active although no science data is being collected or processed.

The FOS has its own microprocessor which controls observations. When a given observation ends, the microprocessor continues to accumulate data in the last commanded configuration, but no longer transfers and sums that data in its science data buffer. The FOS microprocessor does however, collect the accumulated data in a separate engineering buffer as a means of detecting excessive current draw on the photocathode. This so called 'Overlite' telemetry represents the summation of the counts from all the active diodes over the previous 60 seconds. During the times when the FOS is in a stable operate condition, and no photons are being collected from a target, the Overlite sum gives an accurate representation of the dark background for the detector during that minute.

0-8194-1181-7/93/$6.00

The Overlite data have been post-processed to provide a background count rate by taking into account the number of active channels employed during the minute summation, the live-time to dead-time ratio of the data collection, telemetry indications that the aperture door was closed, that noisy diodes have been disabled, and that the calibration and flat field lamps were off. The background Overlite data are routinely examined, on a monthly basis, to determine if intermittently noisy diodes have appeared. To this end only those data which were taken outside of the geographical confines of the SAA are considered. The result is a measured background count rate for the previous minute with an uncertainty of approximately 5%. The measurements occur serendipitously with ongoing operations and have resulted in an average of 35.8 hours of data per month with the Red detector, and 38 hours of data per month with the Blue detector. Note that these data do not give any insight into the diode-to-diode response since the Overlite value is summed across all active diodes. Noisy diodes are turned off roughly 1-2 months after they are detected and confirmed, and therefore add a noise component into the data. This noise, however, is typically quite intermittent and manifests itself along single orbital paths. Discussions below show how this noise component is removed in this study.

Although HST has been in orbit since April of 1990, trending of the dark data available from the Overlite counter did not begin until January 1991. Robust processing of engineering telemetry at STScI did not begin until November 1990. This was primarily because the engineering data management system itself was not fully functional until that time, and that the responsibility for the Science Instruments (SIs) did not transfer to the STScI until January of 1991. (Previously, the SIs had been the responsibility of the Instrument Definition Teams (IDTs)). We currently have FOS dark data from from January 1991 to the present. This large data set, containing some 106,505 Overlite sums, consists of the of the latitude and longitude of the mid-point of each observation, the detector employed, the count rate (in cts s^{-1} per diode) for each minute, and the U.T. of each sample.

Three areas of analysis of these data are discussed in this paper. The first is a practical matter concerning HST observing efficiency. This data set allows us to determine the FOS SAA avoidance region very accurately. The smaller the operational contour defining this region for a given background rate, the greater the target visibility period per orbit. A determination of operational SAA contours for the FOS is presented. The second area of interest is the measurement of the average detector background outside of the SAA as a function of time. This analysis is used to ascertain any changes in detector characteristics due to prolonged on-orbit use. The third area of discussion concerns the increase in the measured background flux as a function of geomagnetic latitude.

2.0 SAA CONTOUR DEFINITION

The quality of spectroscopic data obtained on external astronomical targets, using the FOS, is adversely affected in the presence of increased background noise arising from particle (principally proton) interactions with the instrument's digicon detectors. A marked decrease in the measured Signal-to-Noise ratio is noted in data which have been collected when HST is in the region of the Earth's geomagnetic field commonly referred to as the South Atlantic Anomaly. The strongly anisotropic structure of the field results in gradients over the South Atlantic which cause charged particles to "dip" down to low orbital altitudes. Proton flux rates in excess of 0.04 cts s^{-1} per diode have been deemed excessive in terms of the degradation of the spectroscopic data collected with the FOS. As a result, FOS observations are not scheduled when HST is in a position along it's orbital track where the background count rate is expected to exceed this operational threshold. Therefore, HST's Science Planning and Scheduling system must have a accurate model of this SAA avoidance region. If the model of the avoidance region is too small the data will be corrupted. However, adopting an overly large avoidance region would result in scheduling inefficiencies by precluding observations from taking place under conditions where such a prohibition is not warranted.

The initial on-orbit FOS SAA avoidance region was defined by the FOS IDT from *in situ* measurements taken during 10 SAA passages in the period spanning 1 October and 6 October 1990 as described by Instrument Science Report CAL/FOS-71[1]. As detailed in that report five SAA contours were constructed for the FOS Red detector corresponding to count rates of 0.02, 0.04, 0.10, 0.50 and 0.1 cts s^{-1} per diode. The operational contour adopted for normal FOS SAA avoidance corresponds to a threshold exceeding 0.04 cts s^{-1} per diode. This same report noted that there was "insufficient data available at present to construct SAA contours for the blue detector, but it is expected that these should not differ significantly from the red". As a result a single operational contour was adopted for scheduling observations for both FOS detectors.

For each side of the instrument individually, whenever the FOS high voltage is turned on, the total number of counts detected in all active diodes is reported as the "Overlite sum" as an engineering telemetry item. The dark counts reported in the overlite sum varies with the incident particle event rates, and proton flux levels. Thus, the Overlite sum provides a serendipitous measure of the background intensity integrated over all active diodes. The Overlite sum is accumulated over a period of 1 minute, and reported at the end of that minute's integration. Since HST's orbital period is approximately 95 minutes, a single Overlite sum gives the total counts seen as the spacecraft moves approximately 4° along it's orbit track.

The SAA is known to be dynamic, due to interactions between the geomagnetic field and the time-variable solar wind, and a study was undertaken to assess both the temporal stability and long term variations of the SAA contours measured by the FOS. The ultimate aim in this study was to determine if the geographical coordinates of the FOS operational contour (0.04 cts s^{-1} per diode) had moved since this contour was initially defined.

All FOS Overlite sum measurements from January 1, 1991 - December 31, 1992 were retrieved from the archived engineering data. Data corresponding to times when the FOS was taking science and/or internal calibration exposures were excluded - since only background measurements were for this analysis. Table 3.1 summarizes the amount of overlite background data which has been taken on-orbit during this time interval. For this analysis the data were organized, roughly, by month (but in integral numbers of weeks). Each row on this table gives the starting date and number of days in a collection of samples (i.e., approximately monthly), the number of discrete 1-minute dark overlite sums both for total accumulations and non-saa measurements, and the average non-saa background count rates for each detector.

Definitive HST orbit data were obtained and positional ephemerides were generated for this interval. Based on the definitive ephemerides the geographical coordinates of HST, for the instant each Overlite sample, was determined. The worst case uncertainty in the HST ephemerides derived from these orbit data was ~15 seconds in time (or 1° along the orbit track). For each "month" the data were collected into 2°x2° bins (4-square degrees) in latitude and longitude, twice the width of the in-track error, and half the width of the corresponding integration periods. Mean count rates were computed for each bin.

Short term variations in the core of the SAA, at count rates far exceeding the tolerable level for taking FOS science data, were readily apparent on month-to-month time scales. However, the contours corresponding to lower flux levels (0.01 - 0.1 cts s^{-1} per diode) exhibited little month-to-month variation. At the defined operational level (0.04 cts s^{-1} per diode) a very small reduction on the western and south-eastern low-latitude (~ -24°) edges was seen from the start of 1991 to the end of 1992. At the lowest levels of sensitivity (<0.02 cts s^{-1} per diode) these FOS Overlite data provide an excellent probe of the low flux-level eastern "tail", as well as the variation in time of the proton-flux with geomagnetic latitude.

Given the long-term (but small scale) secular changes in the position of the 0.04 cts s^{-1} per diode contour, the *in situ* Overlite sum dark data were used to define new contours for the recent observational epoch. To define these contours the most recent three months of available data were used (October - December, 1992). For each side of the FOS these data provided more than 8000 measurements, giving a geographically well sampled set, with many points multiply sampled.

Figure 2.1 shows the results of binning the Overlite data, as discussed above, for the FOS Red detector. This figure illustrates the geographical areas for which the background count rate exceeds the operational threshold. The gray scale is indicative of the measured mean count rate, where a black square corresponds to 0.8 cts s^{-1} per diode, and light gray is 0.04 cts s^{-1} per diode. White squares indicate regions sampled which were below this threshold. Figure 2.2 shows the measured mean background count rates for the FOS Blue detector. These figures indicate that for the blue detector the 0.04 cts s^{-1} per diode contour is significantly smaller than for the red detector. This might have been expected, given the lower sensitivity of the blue side (by roughly a factor of 2). Although as noted in ISR CAL/FOS-71, since no blue data were available when the FOS contour was first established, only a single contour was defined.[1]

As a result of this study it was recommended that separate FOS Red and Blue contours be established. By using a generic FOS contour for both sides of the instrument, significant inefficiencies were manifesting themselves in scheduling blue side observations. When compared to the initial single SAA avoidance contour the new FOS red

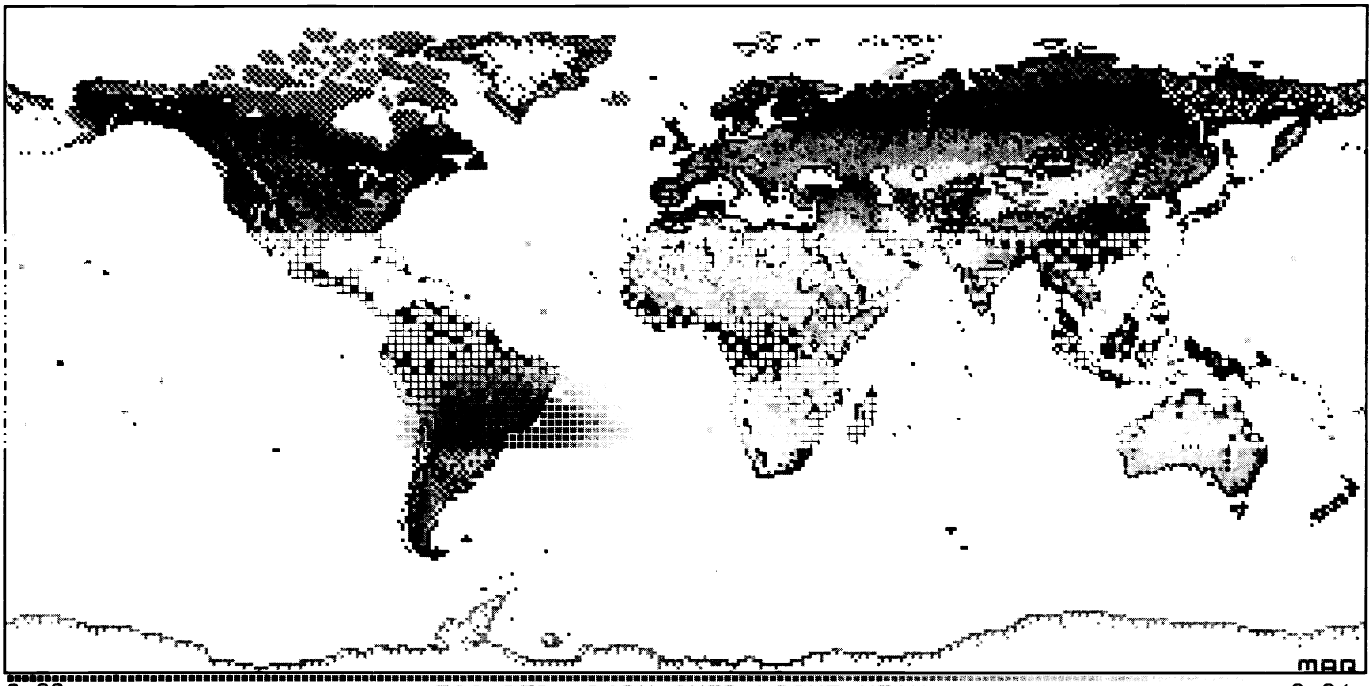

Figure 2.1: FOS Red Detector Background Count Rates from Overlite Dark Measurements

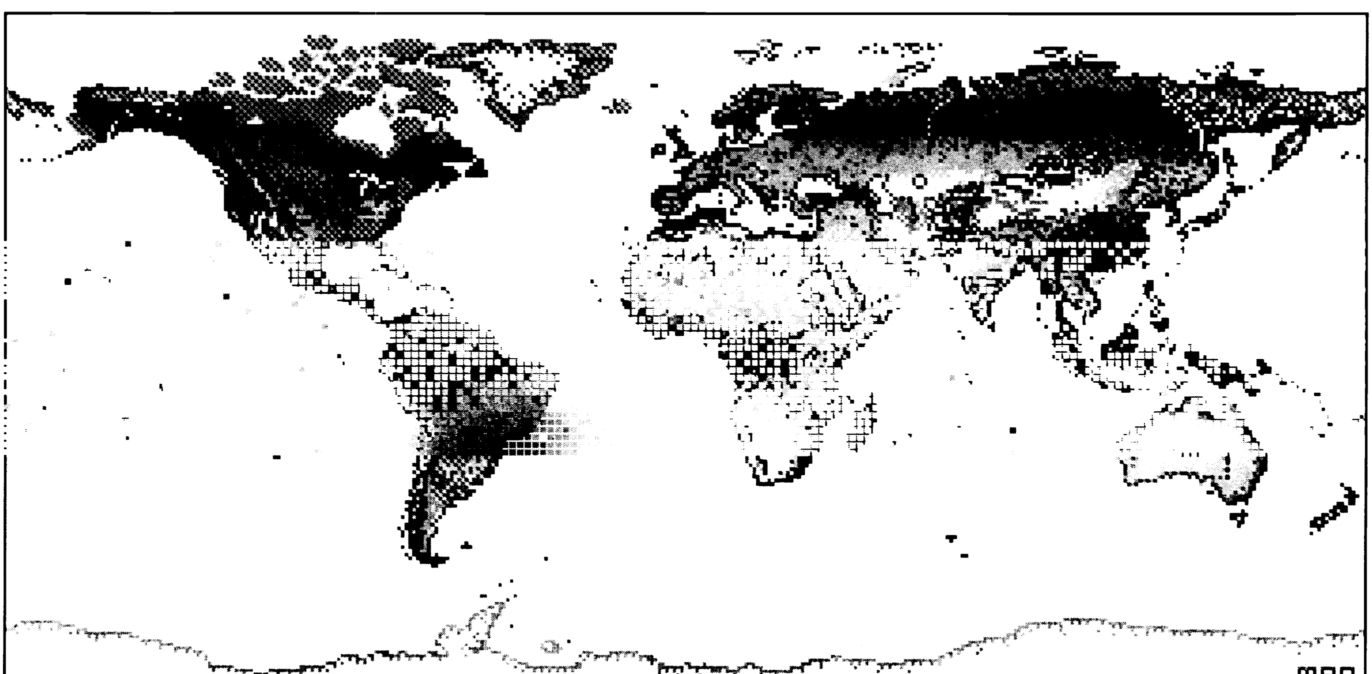

Figure 2.2: FOS Blue Background Count Rates from Overlite Dark Measurements

contour is 1.6% smaller, in area, and the blue contour is 14.7% smaller. This gives an indication, by a geometrical mean, of the relative decrease in the SAA crossing times and corresponding gain in available observing time in SAA impacted orbits.

In an absolute sense, the savings in time (by means of greater availability of time in scheduling FOS observations) may, on average be expressed as follows. On the red side approximately half of all SAA impacted orbits have crossing times reduced by 45 seconds. Also on the red side approximately 1% of the orbits which would have been SAA impacted using the initial contour would not be impacted using the proposed new contour.

A significant savings in otherwise unusable science time is gained on the blue side of the FOS where the mean SAA crossing time would be reduced by 2.5 minutes (with some orbits gaining as much as 4 minutes). Additionally, on the blue side, approximately one out of every 12 orbits which would have been SAA impacted would not be.

3.0 DETECTOR BACKGROUND MEASUREMENTS

The FOS Instrument Science Team calculated the detector background during the orbital verification phase of the HST mission. Their results were based on data taken in the summer and fall of 1990 and presented in an Instrument Science Report, CAL/FOS-071 of April 1992.[1] These observations differed from those reported here in that they were obtained using science data and therefore also showed diode-to-diode dependency. The results of their analysis showed an average red detector background (outside of the SAA) of 0.012 - 0.02 cts s^{-1} per diode depending upon geomagnetic latitude. The blue detector showed a slightly lower background measurement of between 0.0065 - 0.015 cts/s/d depending upon geomagnetic latitude.

Table 3.1 FOS Overlite Background Summary

Beginning DOY	# Days	Total Samples Red Samples(min)	Total Samples Blue Samples(min)	Non-SAA Bkgrd Samples Red Samples(min)	Non-SAA Bkgrd Samples Blue Samples(min)	Red Avg Bkgrd C/S/D	Blue Avg Bkgrd C/S/D
91.001	28	1279	1411	781	880	0.01259	0.00865
91.035	28	1693	1833	1169	1273	0.01197	0.00729
91.056	35	1096	1269	570	897	0.01052	0.00773
91.091	28	1602	1322	1060	1094	0.01120	0.00689
91.119	35	1067	1892	743	1352	0.01112	0.00698
91.154	28	2273	4174	1679	3061	0.00979	0.00700
91.182	28	3460	2863	2524	1960	0.01073	0.00763
91.210	35	2207	2339	1563	1780	0.01125	0.00685
91.245	28	2506	1872	1838	1519	0.01081	0.00732
91.273	35	5316	1523	3801	1223	0.01114	0.00690
91.308	28	2141	2351	1496	1865	0.01162	0.00744
91.336	28	1657	79	1174	75	0.01107	0.00701
92.001	33	2675	2797	1923	2293	0.01006	0.00686
92.034	28	2169	1975	1524	1308	0.01076	0.00712
92.062	28	2352	2547	1765	1724	0.01091	0.00798
92.090	28	1734	798	1219	602	0.01056	0.00765
92.118	35	1692	2985	1338	2247	0.01070	0.00728
92.152	28	1667	3570	1179	2802	0.01077	0.00715
92.181	35	1917	3497	1489	2590	0.01141	0.00754
92.216	28	1712	1928	1325	1501	0.01104	0.00758
92.244	28	1318	3138	967	2344	0.01130	0.00780
92.272	35	3064	3529	1945	2695	0.01096	0.00751
92.307	28	2136	4205	1531	3382	0.01109	0.00794
92.335	35	2969	906	1918	694	0.01113	0.00752

For this analysis, non-SAA background values were determined based on measurements from 8° to 248° longitude or >-8° latitude. In addition, to remove any background measurements which were most likely due to intermittently noisy diodes prior to their turn off, rates above 0.023 cts s^{-1} per diode on the red detector, and 0.018 cts s^{-1} per diode on the blue detector, were disallowed. (This is 0.003 cts s^{-1} per diode greater than the highest values seen in CAL/FOS-071. That analysis had the ability to remove noisy diodes due to their independent measurement of all 512 diodes.) The results are presented in table 3.1 .

Figures 3.1a and 3.2a show the average count rates for the Red and Blue detectors, respectively, as a function of time. Figures 3.1b and 3.2b show the time history of disabled diodes for the Red and Blue detectors respectively. From these data we can see corresponding drops in the average count rates whenever a diode is disabled. These decreases are on the order of 10% of the average background and represent the noise contribution from dead diodes which cannot be removed from this analysis. The error bars on these plots incorporate this error.

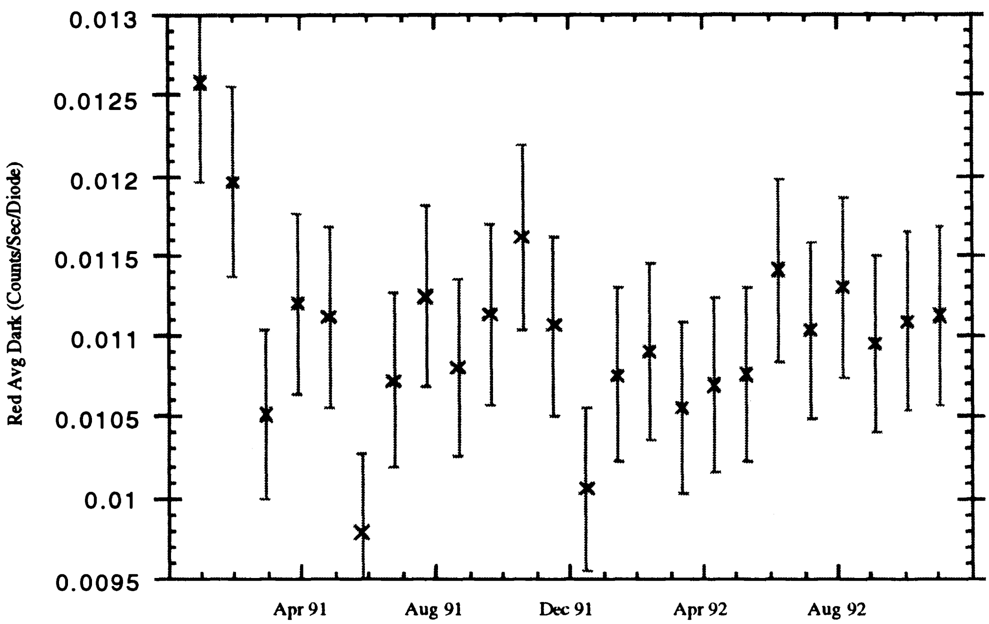

Figure 3.1a: FOS Red Average Background Rate vs. Time

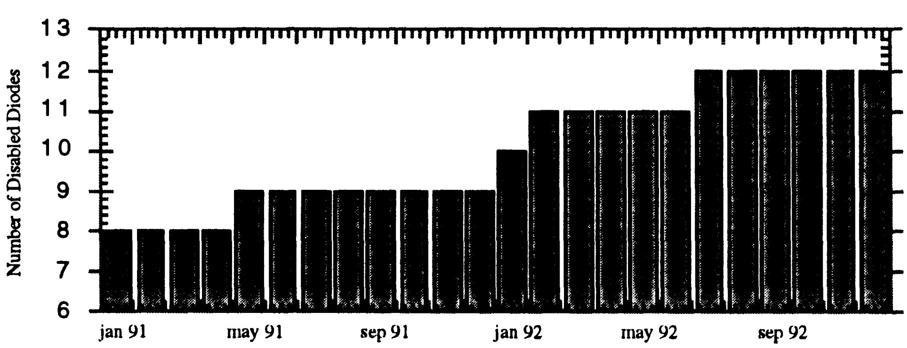

Figure 3.1b: FOS Red Detector Disabled Diode History

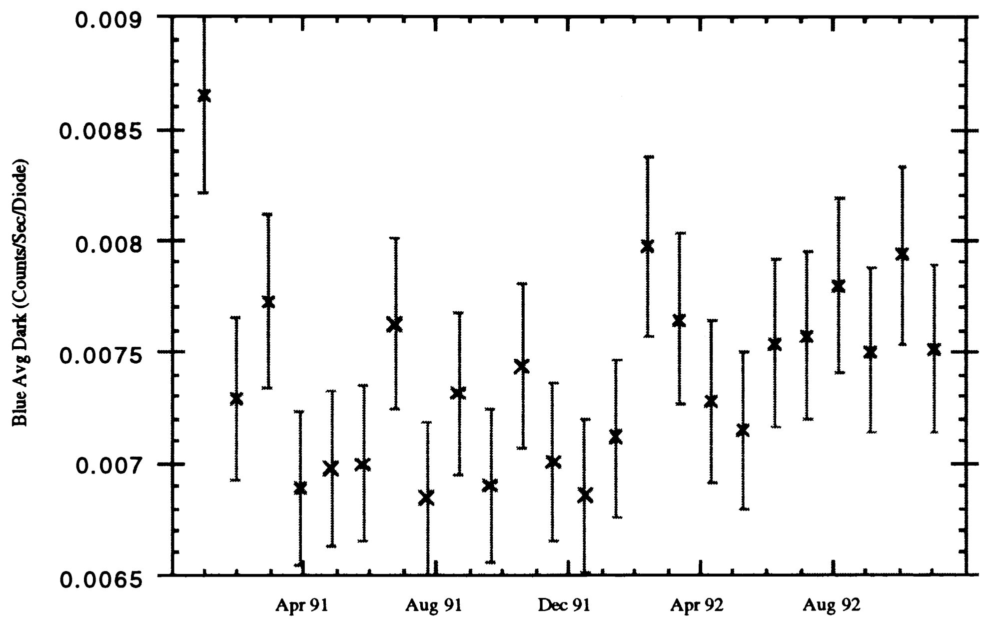

Figure 3.2a: FOS Blue Average Background Rate vs. Time

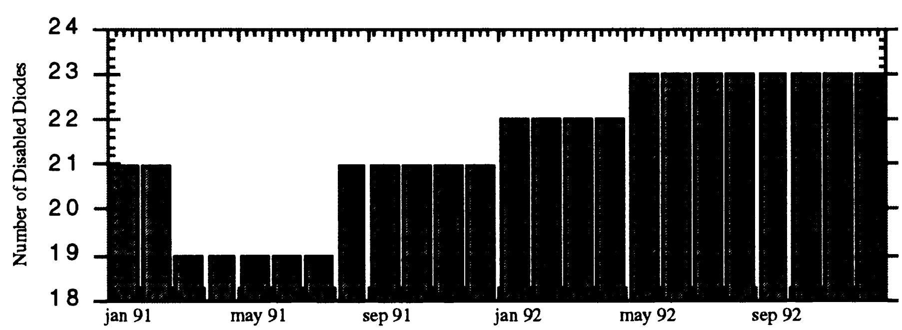

Figure 3.2b: FOS Blue Detector Disabled Diode History

Plots 3.1 a and 3.2 a suggest that the average background count rate has remained relatively stable for each of the digicons over the last two years. The overall average for the Red detector was 0.011 cts s^{-1} per diode. The overall average for the Blue detector was 0.0074 cts s^{-1} per diode.

4.0 GEOMAGNETIC LATITUDE DEPENDENCY

In ISR CAL/FOS-071, the dominant source of background in the FOS digicons is identified as being due to Cerenkov radiation emitted from proton events in the FOS detector face plates.[1] In the HST orbital environment, the proton flux incident on HST varies as a function of geomagnetic latitude.

Haffner[2] predicted that at solar maximum, the proton flux at 40° geomagnetic latitude should be roughly 4 times greater than at the geomagnetic equator. The measured increase in flux as reported in CAL/FOS-071 from geomagnetic latitude 0° to 40° was approximately a factor of two.[1] Those results, however, were based on a total of approximately 4 hours of data on each of the red and blue detectors, and as such do not have much statistical significance in attempting to determine the geomagnetic latitude dependency.

By using the better sampled FOS Overlite dark data the geomagnetic latitude dependency in measured proton flux was established. Since this dependency was expected to vary, to some degree, with the sunspot cycle, one year of on-orbit FOS overlite data was employed to determine this relationship for the recent observational epoch. The criteria for using dark Overlite data were the same as those presented in section 3. Those positional data from the HST ephemerides were transformed into a geomagnetic frame applying a simple dipolar field with the North Magnetic Pole located at geographic Latitude 78.5°N and Longitude 291°E.

Figures 4.1a and 4.1b show the average background count rate (from the FOS Overlite dark data) for 1992 for the red and blue detectors as a function of geomagnetic latitude. The error bars represent the minimum and maximum monthly average background rates for each detector. The HST orbit is constrained between geomagnetic latitudes +41.5° and -41.5°. Because of the geometry of the orbit, relatively more time is spent at lower geomagnetic latitudes. This is the reason for the increase in the magnitude of the statistical error at the extremes of geomagnetic latitude. Nevertheless, a statistically significant volume of data has been obtained at all geomagnetic latitudes accessible to HST.

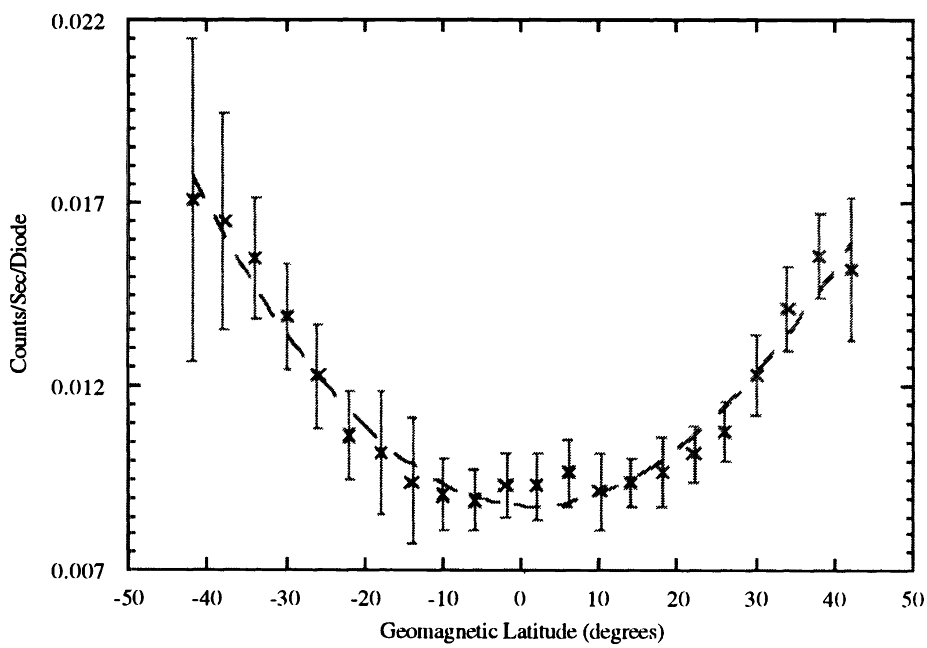

Figure 4.1a : FOS Red Average 1992 Background Count Rate as a function of Geomagnetic Latitude.

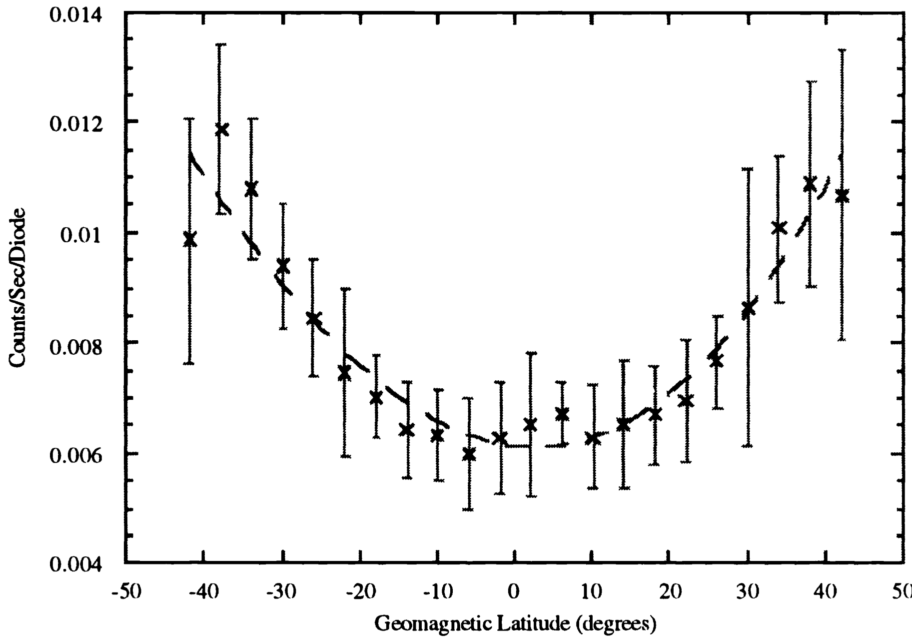

Figure 4.1b : FOS Blue Average 1992 Background Count Rate as a function of Geomagnetic Latitude.

The data presented in figures 4.1a and 4.1b have been fit by least squares to a 3rd order polynomial. The FOS Red and Blue background count rate as a function of geomagnetic latitude (ϕ_m degrees), may then be expressed as:

Red Detector:

$$\text{Counts/Sec/Diode} = 0.0088 - 1.273\text{x}10^{-5}\phi_m + 4.557\text{x}10^{-6}\phi_m^2 - 5.083\text{x}10^{-9}\phi_m^3$$

Blue Detector:

$$\text{Counts/Sec/Diode} = 0.0062 - 1.553\text{x}10^{-5}\phi_m + 3.000\text{x}10^{-6}\phi_m^2 - 8.579\text{x}10^{-9}\phi_m^3$$

Thus, the Red detector has an average background count rate of 0.0088 cts s^{-1} per diode at the geomagnetic equator, rising to 0.0159 cts s^{-1} per diode at 42° geomagnetic latitude. This represents an 80% increase over the range of the HST orbit. For the Blue detector, the background rate increases from 0.0062 cts s^{-1} per diode at the geomagnetic equator to 0.010 cts s^{-1} per diode at 42° Geomagnetic latitude. This represents a 61% increase over the range of HST orbit.

The variation in background count with geomagnetic latitude is apparent in Figure 4.2. Here, the gray scale map illustrates count rates between 0.01 and 0.04 cts s^{-1} per diode. At the extremes of the HST orbit, close to the geomagnetic poles, the incidence of increased background counts is readily seen.

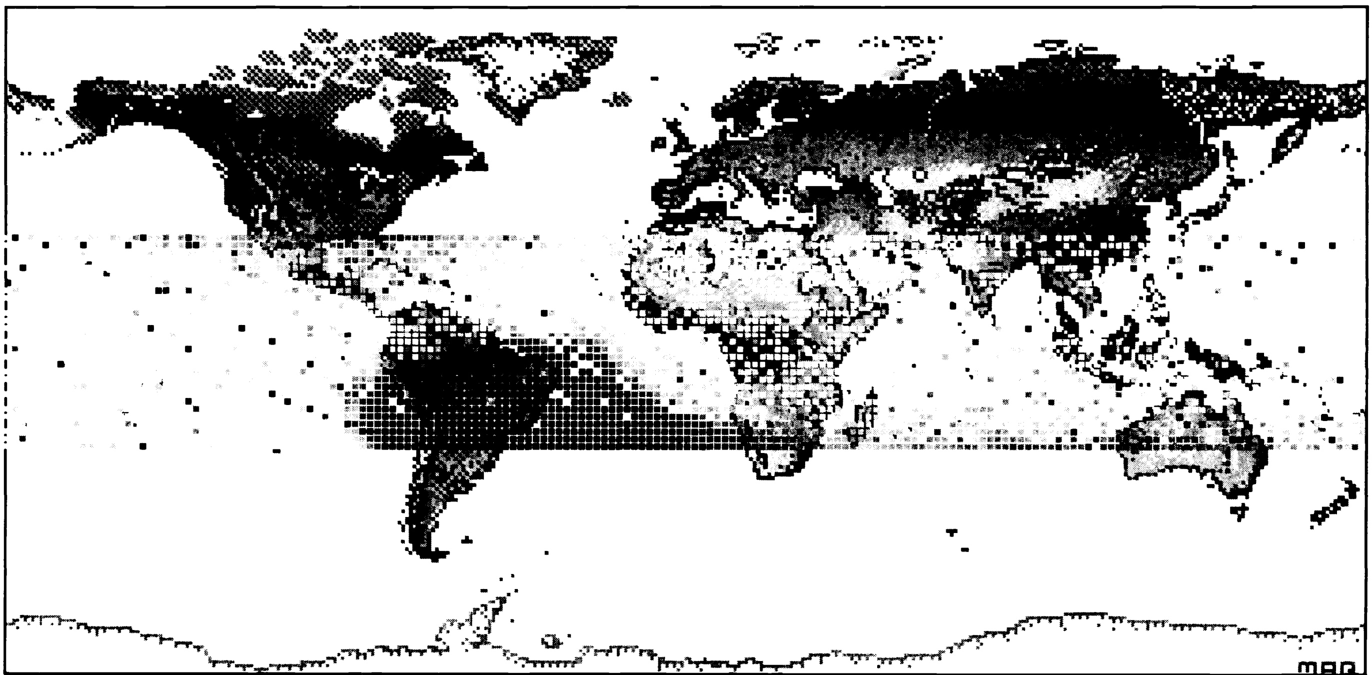

Figure 4.2: FOS Red Detector Overlite Averages showing Geomagnetic dependency

5.0 SUMMARY

By taking advantage of the available data from the engineering stream of the FOS detectors, we have been able to build up statistically significant insights into the background count rates of the instrument. These insights have allowed us to optimize the SAA avoidance criteria, monitor the stability of the instrument, and determine the geomagnetic latitude dependency of the background. In addition, the temporal variations in the SAA have been monitored, giving insight into the stability of the defined operational avoidance contours.

This analysis has been accomplished without using any prime spacecraft time and without imposing any scheduling constraints whatsoever. This technique will continue to be used to monitor the health of the FOS as well as to monitor the defined edges of the SAA for possible science impacts.

6.0 REFERENCES

1. Rosenblatt, E.I., Baity, W.A., Beaver, E.A., Cohen, R.D., Junkkarinen, V.T., Linsky, J.B., and Lyons, R.W. 1992, " An Analysis of FOS Background Dark Noise," CAL/FOS-71.

2. Haffner, J. W. 1967, "Radiation and Shielding in Space", Academic Press, p. 289.