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Correction of the geomagnetically-induced image motion problem on the Hubble space telescope's faint object spectrograph.

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ABSTRACT

During the Science Verification phase of the Hubble Space Telescope mission, it was determined that the Faint Object Spectrograph's (FOS) Red detector displayed significant image motions which correlated with orbital changes in the geomagnetic field. The Blue detector exhibited similar but less pronounced motions. The cause of this motion was determined to be inadequate magnetic shielding of the instrument's Digicon detectors. The results of these motions were decreases in onboard target acquisition accuracy, spectral resolution, and photometric accuracy.

The Space Telescope Science Institute and the FOS Investigation Definition Team, set about correcting this Geomagnetically-induced Image Motion Problem (GIMP) through a real-time on-board correction scheme. This correction required modifications to almost all aspects of the HST ground system as well as additional NSSC1 flight software and the use of an existing software 'hook' in the FOS microprocessor firmware.

This paper presents a detailed description of the problem, the proposed solution, and results of on-orbit testing of the correction mechanism.

1. DESCRIPTION OF PROBLEM AND IMPACT ON FOS PERFORMANCE

1.1 Discovery and Cause

Early testing of the FOS Red Digicon in the Orbital Verification phase of the HST mission showed that the aperture images drift, in the detector X,Y plane, well after the nominal detector stabilization period. Unlike the slow, monotonic drift that is characteristic of Digicon stabilization, the observed drift is cyclical, with a period of approximately half that of th HST orbit, and correlates well with geomagnetic field models. The amplitude of the drift was measured to be about +/- microns. Since this is comparable to the FOS spectral resolution width, the drift has a significant impact on science data quality. The maximum drift rate is about 5 microns/minute, or .04 arcsec/minute. Since onboard, autonomous target acquisition (TA) generally requires of order 10 minutes, the drift can also have a deleterious effect on TA performance.

When the FOS Blue side detector was brought into operation (this was delayed because of an apparent EMI problem whereby closure of the high voltage relay caused the microprocessor to reset), the image drift was seen to be present, but only at about 25% of the amplitude measured on the Red side.

The magnetic shielding surrounding the Digicons is believed to be at fault. Shields from the same batch from which the Red detector shield was taken attenuate external fields by as little as 7% of the specified level in lab tests; measurements show a rejection factor of approximately 10, whereas the specification was 140. Inquiries of the shielding manufacturer indicate that this shielding had to be worked intensively to fit the Digicon, and that it was apparently not subsequently re-annealed. Shields of the same vintage as that installed on the FOS Blue detector were also tested and shown to be closer to the specification, with a rejection factor of approximately 102. Thus, it is clear that the problem is due to the shielding deficiency. The shielding problem and the lab testing are detailed in Baity, et al.[1]

A special test to better characterize the problem was performed, on the Red side only, on 5 March 1991. The resulting data shows that the image motion correlates extremely well with a standard geomagnetic field model, in each of the four spacecraft orientations used, throughout full orbits. The images do not suffer any distortion; spectral lines at one end of the spectrum move the same as those at the other end. The sensitivity to the geomagnetic field (microns of image deflection per gauss of external field) is independent of spacecraft pointing, and is the same along both Digicon (X and Y) axes. Thus it does not appear that local distortions of the geomagnetic field are important and the image drift should, at least in principle, be readily modelled.

The accurate modeling of the GIMP which we have been able to achieve suggests that the effect should be correctable to a large degree (to less than 3 microns). Recovery of most of the spectral resolution may be effected by reading out spectra at short (1-2 minute) intervals and shifting by the predicted drift before coadding. This post-observation processing does no however, address the possible loss of signal due to drift in the cross-dispersion direction, or target acquisition complications Real-time dithering of the image deflections is required to regain full photometric accuracy, to permit accurate spectropolarimetry, and to alleviate TA difficulties.

1.2 Impact on Target Acquisition

TA into the FOS science apertures is most efficiently performed with the onboard Binary Search mode. However, this mode is most affected by the image drift problem, and can fail if the image moves by relatively small amounts over the approximately 7 minute period during which successive images are obtained. The firmware mode is less affected, since a single frame is obtained, usually with short (< 1 minute) exposure time, which is then analyzed by the FOS microprocessor to determine the pointing offset. However, the NSSC1 implementation of firmware TA is slow and inefficient, incurring about twice the overhead as Binary Search. Still less efficient, but relatively immune to the image drift, is peakup mode; this will be required for TA into the smaller (<1.0 arcsec) apertures.

Binary Search TA is susceptible to failure if the image moves during the search phase, when a series of images at decremented Y-offsets are used to place the target image on an edge of the diode array. If an incorrect 'decision' is made in this sequence, convergence will not be obtained, in which case no spacecraft offset is requested. In order to prevent possible failure in this mode, the tolerances for convergence have been set rather wide, but this leads to less accurate target centering. This effect, together with the unstable mapping of the Digicon X,Y to spacecraft coordinates caused by the GIMP and filter-grating wheel non-repeatability, have resulted in target decenter of .3 arcsec. With the aberrated OTA images, this degree of decenter causes very significant loss of throughput in the FOS science apertures. The STScI has recommended that observations through apertures smaller than 1.0 arcsec be preceded by a (costly) peak-up TA stage, following the Binary Search.

Although it will not fail in the way that Binary Search can, firmware TA can nevertheless result in poor placement of the target in the aperture, since (like Binary Search) the offsets are determined from the Digicon coordinates of the target image, which no longer map in a stable manner to the aperture plane. Furthermore, firmware TA is slow, in its current implementation, and is also less tolerant than Binary search to 'spoiler' stars in the field. An accurate firmware TA is performed in two stages: a coarse map covering the 4.3 arcsec square TA field, followed by a second map of the centra portion, with finer Y spacing. Each stage now requires about 14 minutes of spacecraft time; in contrast, Binary Search typically takes about 8 minutes. While our investigation into the relative inefficiency of firmware TA has shown that there are excessive time pads now in place that could (and should) be reduced, it is clear that our most efficient and robust mode of autonomous TA is Binary Search. Unfortunately, it is also the mode most affected by the GIMP, and it is apparent that real-time GIMP correction will have an immediate payoff in terms of TA efficiency and accuracy.

1.3 Impact on Spectrophotometry

Drift of the spectral images in the Y (cross-dispersion) direction can cause loss of signal, as registration with the narrow diode array is lost. This is exacerbated by the filter/grating wheel non-repeatability and the non-ideal distortion characteristics of the Red Digicon, especially. Although desirable from the point of view of throughput (and better preserving the spectral resolution than the 4.3 aperture), the 1.0 apertures are particularly susceptible to flux loss in this manner. Use of the 4.3 (TA) aperture, with its concomitant loss of spectral resolution, may be required for spectrophotometry; simulations show that flux variations (from a point source) of about +/- 1.2%, reasonably independent of wavelength, result from the image drift when the 4.3 aperture is selected.

1.4 Impact on Spectorpolarimetry

For the reasons described above, it is likely that some signal will be lost as portions of the image fall above or below the diode array. This effect is especially important with the larger circular apertures that are required for polarimetry with the aberrated OTA images. FOS spectropolarimetry is extremely sensitive to any temporal variation in this loss, since the polarization is measured by comparison of fluxes observed through a sequence of analyzer waveplate orientations. Since the polarization of typical astronomical sources is less than one percent, very small spurious variations in measured signal can result in large polarimetric errors. Because of these inaccuracies, all polarimetric science observations and calibrations on the Red side have been deferred and only Blue side polarimetric observations are permitted until a real-time correction of the GIMP is implemented.

It is not possible to correct polarimetric data in post-observation processing for the GIMP-induced flux variations, since there is no way to model the losses. The filter-grating wheel non-repeatability and random target centering errors render such corrections intractable. However, if the temporal variation is removed by real-time GIMP correction, these effects become small, as it is the differences in flux in the series of polarized spectra that characterize the target polarization. We therefore expect that the accurate polarimetric capability of the FOS will be restored on the more efficient Red side and that the accuracy of Blue side polarimetry will also be improved, with real-time GIMP correction.

Early restoration of this capability of the FOS is particularly important and urgent, since FOS polarimetry will not likely be possible after COSTAR is deployed. This is due to instrumental polarization effects caused by the large incidence angles on the correcting mirrors.

2. THE SOLUTION

A variety of solutions to the GIMP problem were discussed and evaluated. All solutions required modifications to almost all aspects of the ground system as well as modifications to some flight software.

The concept of the solution itself was rather simple: Determine the expected drift in image from the detectors' alignment in the earth's magnetic field, and command an equal but opposite addition to the detectors X and Y deflection coils.

The correction to the deflection coils had to be accomplished by the FOS microprocessor as this is what computes the proper deflections and commands the X and Y DACs which control the current going to the X and Y coils. This is accomplished by the microprocessor several times per second in normal operation.

A firmware 'thread' was devised in August of 1990, which could be used to reprogram the microprocessor to add the contents of an FOS RAM memory location each time the DACs were updated. In the original firmware, there exists a 'hook' at the point directly after the microprocessor computes the X and Y DAC values, but before the DACs are loaded. Prior to GIMP correction, the 'thread' for that 'hook' was a no operation command. (Essentially the microprocessor just continued and loaded the DAC's). After GIMP correction is enabled, the 'thread' tells the microprocessor to get a value from memory, add it to the DAC value, and then load the DAC. This is done for both X and Y.

To correct the GIMP to better than the resolution of the detector (ie.,0.1 diodes) , given the errors in the ephemeri[illegible] and geomagnetic field model, the deltas to the DACs had to be updated at least every 40 seconds. This then lead to a determination that sending the commands directly from the stored command buffer in the SIC&DH (Science Instrument Command & Data Handling system) would lead to a command volume problem for normal operations.

The solution became one of fitting a polynomial to the computed DAC deltas and evaluating that polynomial at the appropriate time on board. This computation could either be handled by the FOS microprocessor or by the NSSC1 (NASA Standard Spacecraft Computer). The FOS microprocessor would require substantial additional reprogramming each time the FOS went from its Low voltage state to HOLD. This may occur several times per day, whenever the instrument goes from one side to the other. The overhead associated with the FOS microprocessor therefore became quite large and a solution using the NSSC1 was pursued.

Given the errors associated with the ephemeris and geomagnetic field models, a third order polynomial fit to the predicted deltas, updated every 30 minutes, would correct the problem to within 0.1 diodes. NASA's Code 512 at GSFC set to work on modifying the NSSC1 Flight software to accomplish the task.

The solution took the form of a modification to the FOS Housekeeping application processor (AP). This AP runs every 15 seconds essentially continuously. The modifications expand the 3rd order polynomial every 30 seconds, using a new table load of coefficients for each observation or every 30 minutes, whichever comes first. Once evaluated for the proper time, the AP then places the Delta X and Delta Y corrections into FOS RAM memory such that they will be picked up by the microprocessor thread and added to the DACs. The deltas are evaluated as 8 bit 2's complement numbers.

The NSSC1 FSW modifications were completed as part of software build 4.0 and uplinked to the NSSC1 in June of 1992. (FSW 4.0 was the first major FSW build since launch.) At that time, the modifications to activate the new FSW were not completed in the rest of the ground system, so the correction mechanism remained off.

On the ground, the proper ephemeris for the spacecraft is known to a system called PASS. PASS also had a working model of the geomagnetic field. The calculation of the deltas would therefore have to occur in PASS and modifications to their software to calculate the deltas, fit a polynomial, and uplink a table to the NSSC1 were made. These modifications became available in the late fall of 1992.

Finally, PASS had to be told when to uplink these tables for specific observations which required the FOS commanding software at STScI to be modified. (STScI is responsible for scheduling all observations with the HST as well as producing the commanding required to carry them out.) These changes were carried out by STScI/SESD/ESB commanding personnel and became available in late 1992. These modifications included changing the way 'degaussing' was commanded.

'Degaussing' is carried out by the FOS microprocessor each time a 'Begin Data Acquisition' command is received. This procedure caused the X and Y deflection coils to be commanded in a decreasing spiral pattern in an attempt to remove any localized residual magnetic alignments in the FOS detector. The original on-orbit test to characterize the exact nature of the GIMP, detected different GIMP coefficients (Diodes/Gauss) dependant upon the operating mode of the detector. Ground testing of the flight spare detectors at UCSD determined that this was most likely due to the frequency of the 'degaussing' routine.[1] Because the scheduling system would therefore have to compute the GIMP coefficients depending upon the observing history of the detector (not currently feasible), an alternative solution was sought. This took the form of turning off the 'degaussing' for all observations and allowing the FOS detectors' magnetic materials to stabilize. This raised the possibility of allowing an absolute positional hysteresis effect into the data. (That is the relative GIMP would be removed for a given observation, but the absolute detector magnetic field from observation to observation would not be known.) To show that the commanding to turn off degaussing could be accomplished without introducing additional errors, an on-orbit test was devised and run in September of 1992. (See analysis section for details.)

The ground system processing of the science data was modified for GIMP corrected data, to show that on-orbit correction of GIMP had taken place and that no errors in the GIMP correction had occured during the observation.

Figure 2.1 is a flow diagram of the overall GIMP correction mechanism.

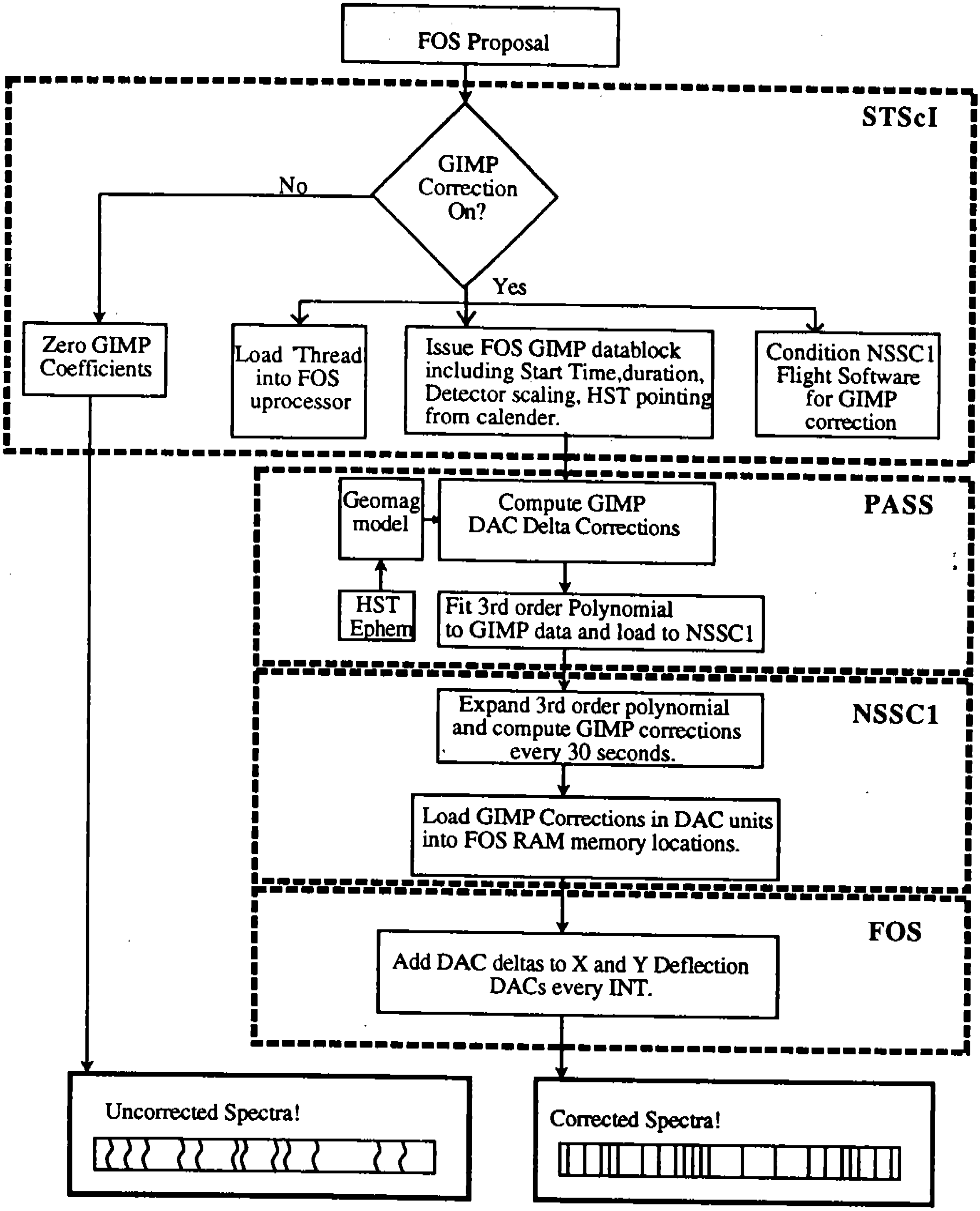

Figure 2.1: FOS GIMP Correction Flow Diagram

3. ON ORBIT TESTING

Four separate on orbit tests have been run to verify the GIMP correction mechanism. The first was run in March of 1991 on the Red detector to characterize the image motion as a function of spacecraft position and pointing. Data were taken during several orbits with both the internal wavelength calibration lamps and as images with the Target acquisition LEDs. The data were acquired at four orthogonal pointings. The analysis showed that indeed the correction could be made and pointed out the differences from the degaussing commanding between several short observations and single long observations. (See discussion above.) The results from this test were used to develop post processing software which would correct for the majority of relevant science. To accommodate this, the instrument had to be read out every several minutes compared to the normal methodology of long accumulations. This did not however allow for accurate photometric results, as the GIMP problem still allowed portions of the PSF to fall off of the detector elements.

The second on orbit test was run in September of 1992 and was designed to show three items. First that the GIMP sensitivity factor (diodes/gauss) had not changed significantly since the initial test in March of 1991. Secondly that turning off the degaussing caused the GIMP factors to become mode (or timing) independent. And thirdly, that turning off degaussing did not allow any absolute positional hysteresis.

Sample results from that test are shown in figures 3.1 and 3.2. Figure 3.1 shows one of the TALED series of observations both before and after GIMP correction is applied. (Note GIMP correction is applied during post processing in this case.) The centroid of a given series of corrected images should always fall in the same location with the centroid of any other series of images, if no positional hysteresis is evident. Figure 3.2 shows the centroid of the two series of corrected TALED images. It can be seen that there is roughly 0.2 diodes (~10 microns) separation in the X direction and 20 y-base units (~16 microns) in the Y direction separating the centroids. Unfortunately, after identifying this item, it was noticed that the way the test was run, there was a filter grating wheel movement between these series of observations. The separations could be explained by filter grating wheel non repeatability as easily as positional hysteresis from turning off degaussing. To determine this, analysis of the March 1991 data in terms of absolute image position was done. Since all of the March data was taken with degaussing on, if a similar error was seen between sets of these data, then the error can be attributable to non-repeatability of the filter grating wheel. The results of that study are shown in figure 3.3. From this, we can see that similar errors were evident in the March data and can conclude that if there is positional hysteresis from turning off the degaussing, it is not the dominant effect and is less than 0.1 diodes.

The second test also showed no significant change in the GIMP coefficients since March of 1991. The test verified that once degaussing is turned off, the GIMP factors as measured by various modes are similar.

The third test occured in January of 1993 and was the first use of the on orbit correction mechanism. The test was designed to provide an end-to-end test of the correction mechanism. The test was carried out in a similar fashion to the previous tests. There was a series of GIMP corrected Rapid observations, followed by GIMP corrected TALED observations, followed by an uncorrected TALED observation, and finally a series of GIMP corrected rapid observations.

Analysis of the Science and Engineering data as well as the commanding from this test showed the following results:

-PASS properly modelled the GIMP problem, fit a 3rd order polynomial, and uplinked the proper tables to the NSSC1 at the proper times.

-The NSSC1 FSW properly interpreted the tables from PASS and sent the correct values to the FOS microprocessor at the appropriate time.

-The FOS microprocessor properly applied the deltas it was given however it generated a series of spurious X and Y DAC readback errors throughout the test. (see discussion below)

-The science data exhibited large but continuous deviations as a function of time. This was traced to sign errors in the interpretation of the application of the deltas in the original requirements. Once these sign errors were taken into account, the residual errors in X and Y appeared to be within specifications.

-All post processing flags were properly set and interpreted by the ground system software.

-Loading of the 'thread' caused benign NSSC1 status buffer messages.

The most significant problem associated with this test was the multitude of spurious error messages which resulted from deflection DAC readback errors. The problem was traced to the following. The FOS microprocessor is a 16 bit machine. The deflection DACs are 12 bits. When the FOS microprocessor computes a 16 bit deflection DAC value, it is masked to 12 bits before being loaded and verified in the deflection DAC. The 'hook' for the GIMP 'thread' was after the

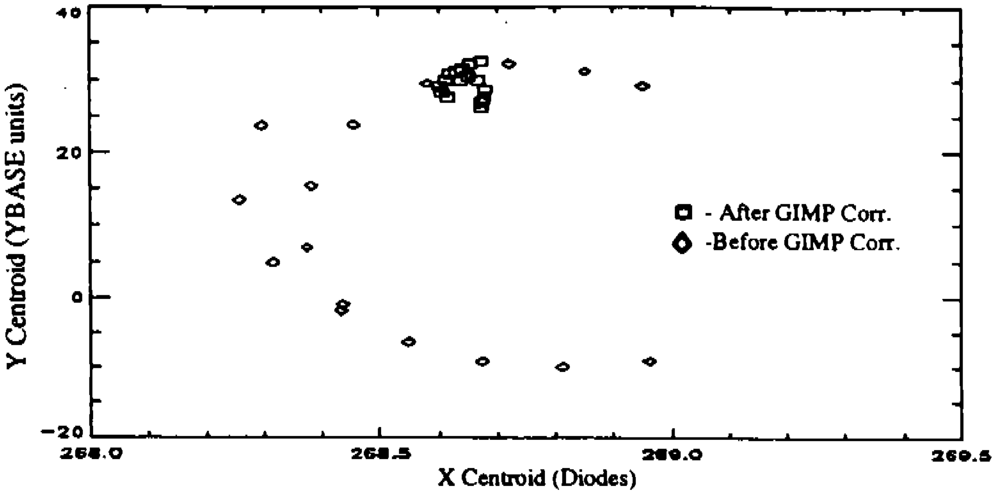

Figure 3.1: Image Centroids Before and After GIMP Corrections - Y13N0101-0W

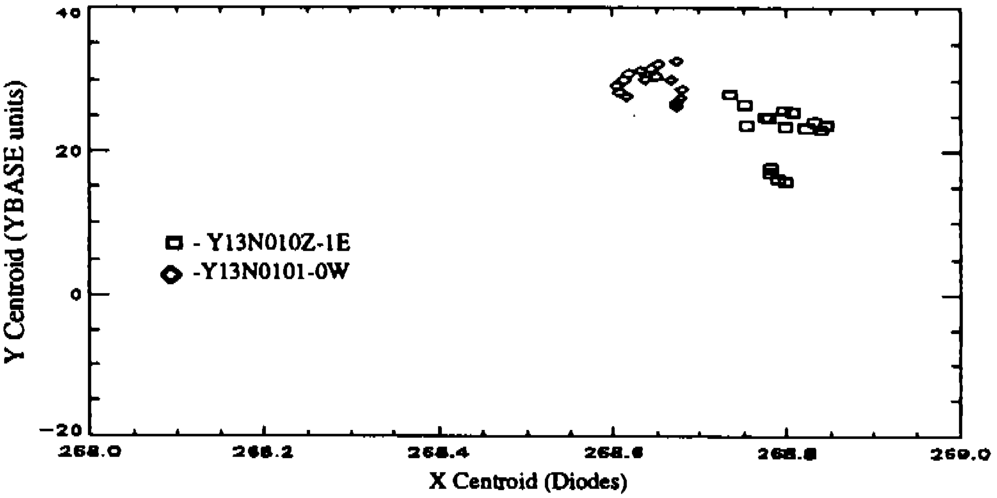

Figure 3.2: Image Centroids with Degaussing OFF, FGWH movement

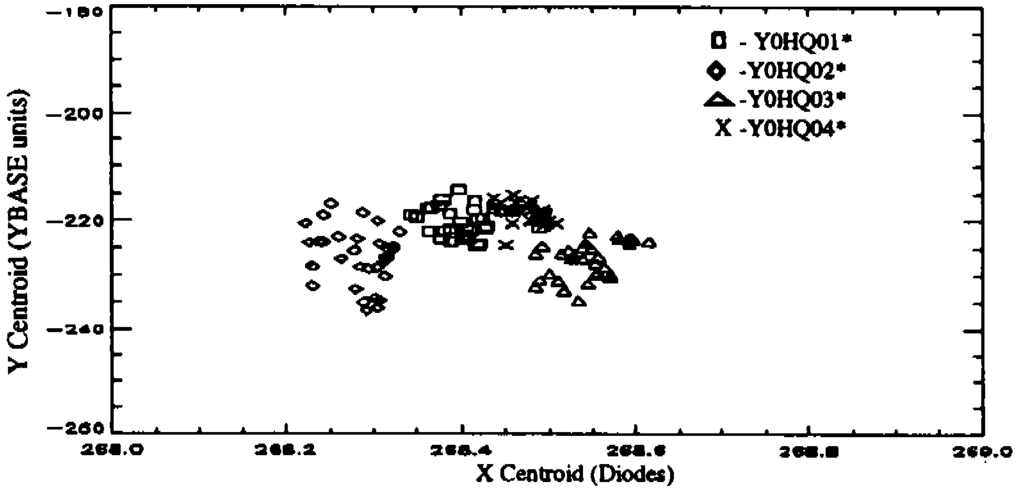

Figure 3.3: Image Centroids with Degaussing ON, FGWH movements

Figures 3.4a through 3.4d show comparison plots of data taken prior to GIMP correction, and during the Feb 25th test. The data are all shown at the same scale and are stacked images of calibration lamps read out every 40 seconds. Figures a and b are for the Red detector, c and d for the Blue detector.

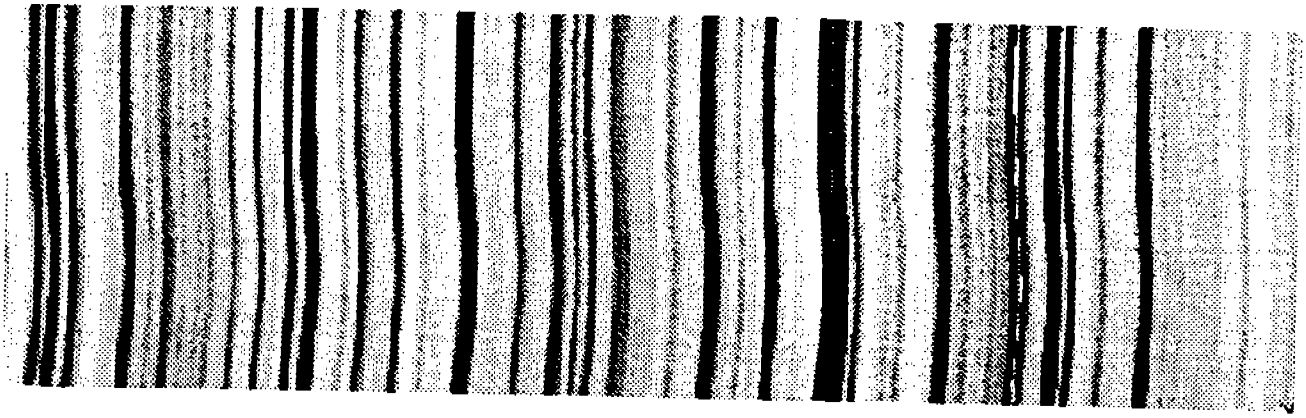

Figure 3.4a: Red Detector 2880 Second Observation without GIMP Correction (Y13N010X)

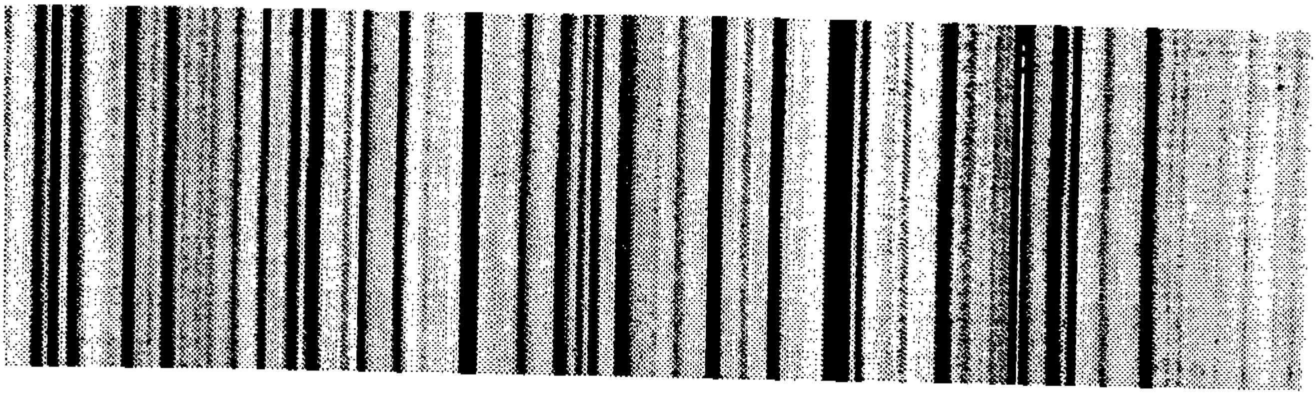

Figure 3.4b: Red Detector 2880 Second Exposure with GIMP Correction (Y18H5101)

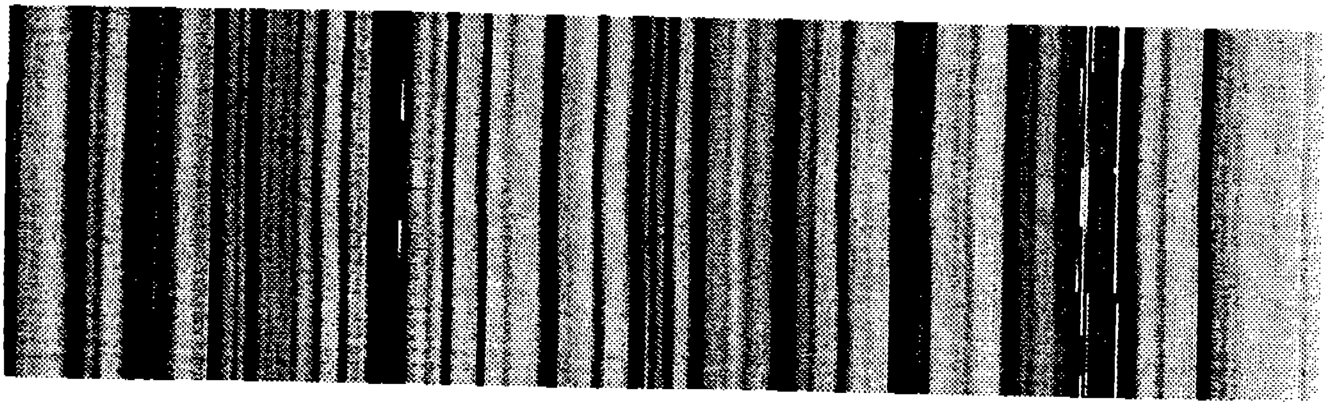

Figure 3.4c Blue Detector 2880 Second Exposure with twice normal GIMP error (Y18H0201)

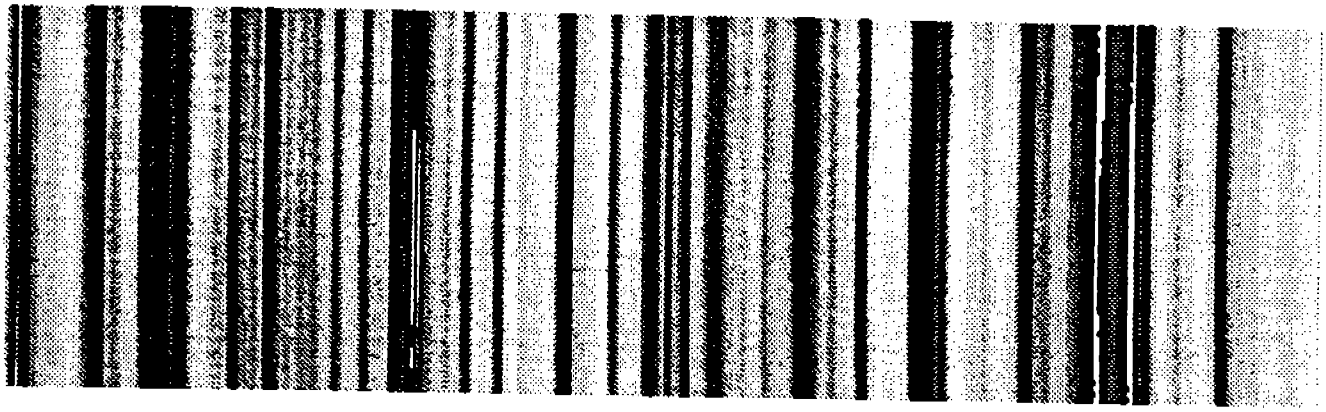

Figure 3.4d: Blue Detector 2880 Second Exposure with GIMP Correction (Y18H5201)

Figures 3.5 a and b, show the results of a single wavelength line as a function of time for a Rapid mode observation. These are plots of eight equally spaced readouts during a 2880 second observation. Figure 3.5a shows the line movement prior to GIMP correction. Figure 3.5 b shows the line movement after GIMP correction. Both observations had 1 pixel = 0.25 diodes.

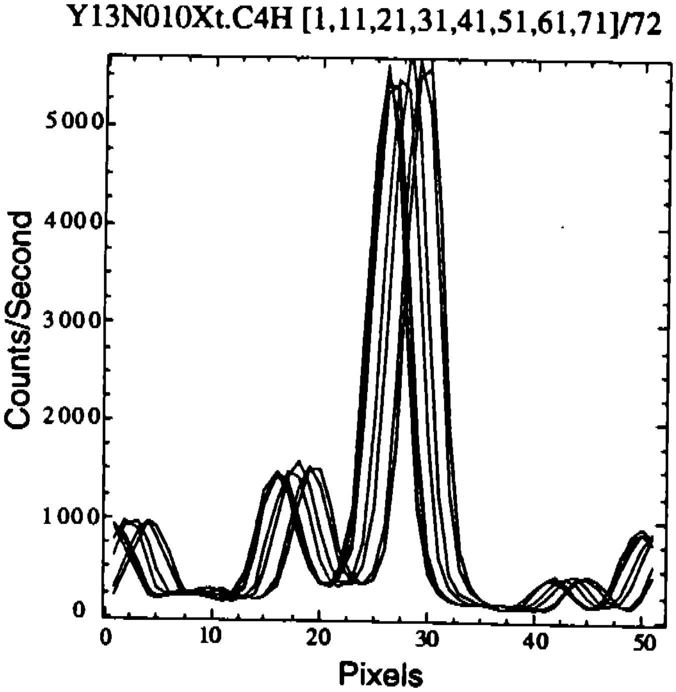

Figure 3.5a: Single line spread, 2880 Sec Red Detector No GIMP correction

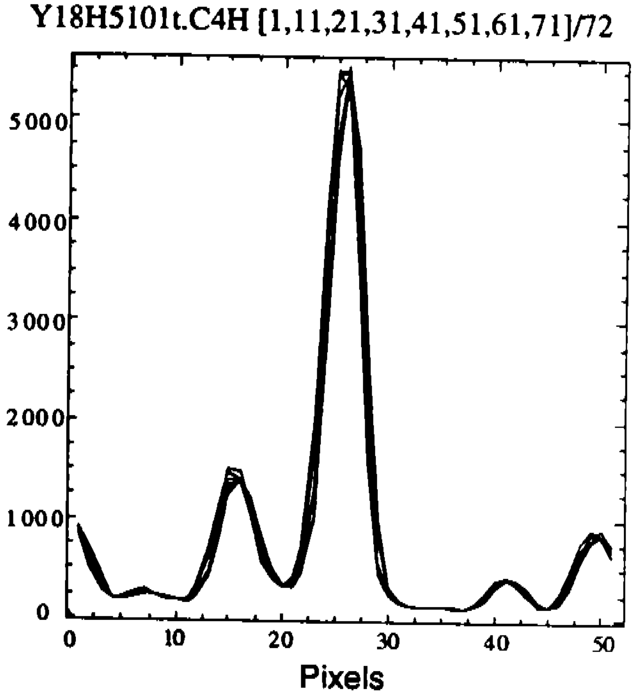

Figure 3.5b: Single line spread, 2880 Sec Red Detector with GIMP correction

masking to 12 bits, but prior to the load and verify of the DACs. In cases where the addition of the GIMP delta value caused change in the effective sign of the 12 bit DAC value, some of the upper 4 bits will be populated. This number is then loade[illegible] into a 12 bit DAC and compared against the readback. The 12 bit DAC will always produce zeros in bits 13-16 and will therefore produce a miscompare if any of the upper 4 bits loaded were non-zero. Engineering telemetry was analysed to show that in all cases where errors occured, it was due to this problem. The reprogramming of the microprocessor was modified to mask the summed value to 12 bits prior to loading into the DACs.

This modification and the changing of the GIMP coefficient signs in the Project Data Base were made prior to a rerun of the test on Feb 25th, 1993. This execution of the test produced no unexpected errors and properly corrected the GIMP.

As stated previously, the goal of the GIMP correction was to remove image drift to within 0.1 diodes in the X direction and 9 YBASE units in the Y direction for both the RED and BLUE detectors. All of the results are presented in terms of X and Y DAC units as these are the units used in all of the computations on the spacecraft . The following conversions apply for going from DAC units to diodes or YBASE units.

RED detector:	0.1 Diodes in X = 2.38 XDAC units 9 YBASE units = 8.06 YDAC units
BLUE detector:	0.1 Diodes in X = 2.47 XDAC units 9 YBASE units = 8.11 YDAC units

Table 3.1 shows the summary of all of the residual errors from all of the data taken on February 25, 1993. The results show that the Standard Deviation of the residual errors are approximately 50% of the 0.1 diode requirement in X and less than 40% of the 9 YBASE requirement in Y, for both the RED and BLUE detectors. The peak to peak residual errors are approximately equal to the requirements for exposures spanning less than 1000 seconds, but increase to 150% of the requirement in Y and almost twice the requirement in X for exposures of greater than 2000 seconds. Note that for the Red detector, the amplitude of the correction for the first Rapid mode observation was 37 XDAC units and 60 YDAC units. Similarly, for the Blue detector the amplitude of the correction for the first Rapid mode observation was 7 XDAC units and 7 YDAC units.

The final column in the summary table shows the Mean X DAC position for all of the exposures. The center of the image falls within 0.02 diodes in all cases where observations were taken without movement of the FGWH. Separations in image centroid of up to 0.24 diodes were observed between FGWH movements. This points out the fact that absolute image position error is dominated by FGWH non repeatability, not positional hysteresis even after degaussing was removed.

Table 3.1: February 25, 1993 GIMP Test Residual Error Summary

Exposure	Detector	Mode	Time(sec)	# reads	Residual Error Analysis DAC units				X Avg
					X Std. Dev.	Y Std. Dev.	X Pk-Pk	Y Pk-Pk	
Y18H5101	Red	Rapid	2880	72	1.28	n/a	4.201	n/a	146
Y18H5102	Red	Rapid	2880	72	1.066	n/a	3.718	n/a	146.52
Y18H5103-0Y	Red	Image	8340*	32	1.296	2.986	4.554	10.99	n/a
Y18H5110	Red	Rapid	920	23	0.723	n/a	2.27	n/a	152.27
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Figures 3.6a and b show the residual error in line centroid as a function of time for a 2880 second Rapid read observation with GIMP correction enabled. The results are shown in terms of X DAC units for the Red and Blue detectors respectively.

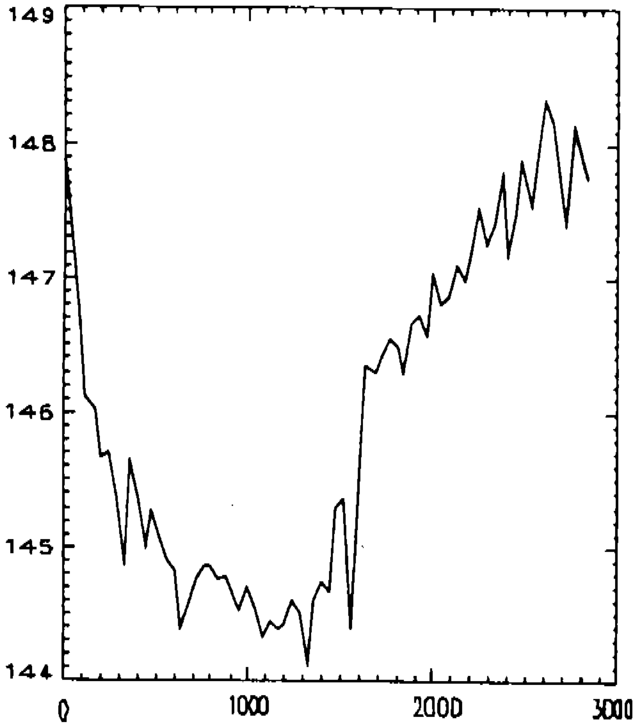

Figure 3.6a: Red Detector Residual Error (XDAC units) vs. Time (Sec)

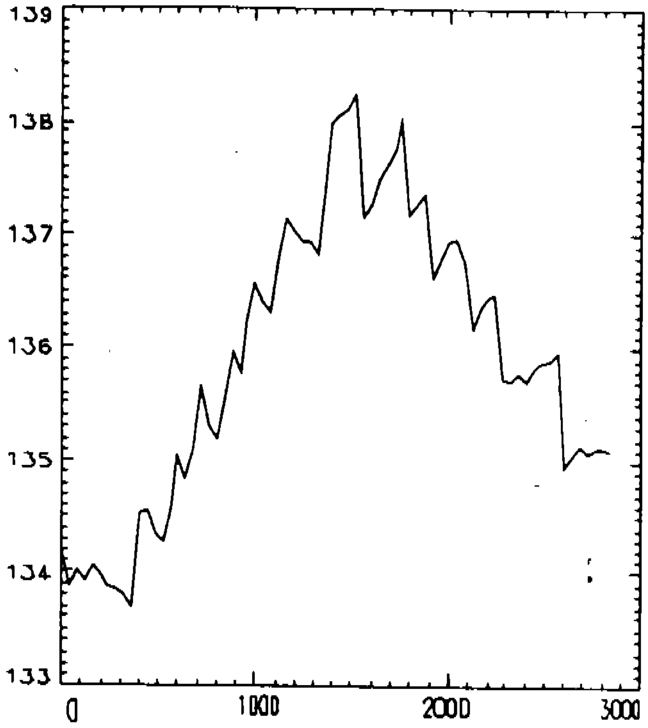

Figure 3.6b: Blue Detector Residual Error (XDAC units) vs. Time (Sec)

4. SUMMARY

Through a complex and ingenious design using available resources, we have been able to successfully manufacture an imaginary magnetic shield for the Hubble Space Telescope's Faint Object Spectrograph. The design required several man years of effort spread over almost every area of the HST ground system to accomplish. The on orbit results show that the instrument is restored to its original specification of image stability. Full operations using the GIMP correction mechanism are scheduled to begin on April 5, 1993.

5. ACKNOWLEDGEMENTS

Many thanks go out to the multitude of individuals at a host of organizations, who in some way contributed to this task. The UCSD portion of this work was supported by NASA contract NAS 5-24463 and grant NAG 5-1630.

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