Pre-Test SAA Contours for WFC3

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ABSTRACT
This ISR documents the preliminary selection of SAA contours for the WFC3. At the time of this writing, documentation on WFC3 instrument shielding is unavailable as are ground or in-flight testing. However, assumptions are made based on the experience of past HST instruments, ACS design, and on the current understanding of the SAA environs and its evolution over time (i.e., are the models applicable, does the SAA change with time, etc.) Based on the information briefly reviewed here, the model defined by WFPC2 empirically and used by ACS is appropriate for both channels of the WFC3.

At the writing of this memo, there are no obvious operational SAA restrictions associated with instrument reconfigurations, other than the limiting of observing in the WFC3 SAA contour. This assumption will be further tested as information from ground testing becomes available and of course verified in orbit.

Introduction
HST’s orbit intersects the “South Atlantic Anomaly (SAA)”, a region of high density and high intensity particle radiation. For HST instruments and all other low-earth-orbit satellites, the SAA threatens both instrument lifetime and exposure quality. Images are compromised by cosmic rays and high dark and background levels. Detectors exhibit both short and long term effects as a result of SAA interactions. Charge Transfer Efficiency (CTE) problems accelerate as an instrument’s exposure to radiation increases. Residual glow and high dark counts are measured after an SAA passage and the number of hot pixels may increase. The deposition of high energies into a material by a single particle can
damage electronics, flip memory bits, compromise instrument operations and sometimes alter material properties. Therefore, the SAA contours and the associated operational procedures are both clearly and uniquely defined for each instrument onboard the HST.

This TIR documents the selection of preliminary SAA contours for the WFC3 and the operational procedure with respect to the SAA. The Servicing Mission Orbital Verification (SMOV) timeline for WFC3 will include tests that demonstrate the impact of the radiation environment. As the ground system is being developed however, the SAA selection is based on indirect but high fidelity inputs such as:

- the history of previous science instruments (WFPC2, STIS, NICMOS);
- relevant ACS studies (many WFC3 systems are similar);
- knowledge of the geometry and temporal variability of the SAA.

This TIR reviews the SAA geometry and composition, relevant design specifications for the WFC3, the SAA impact on current HST instruments, the SAA variability with solar cycle, the applicability of SAA models and finally explains the selection of WFC3 SAA contours.

**The SAA: Geometry and Composition**

**SAA Geometry and Particle Spectrum**

The earth’s magnetosphere is offset and tilted with respect to the geographic axis, as seen in Figure 1. The South Atlantic Anomaly is the region where the Van Allen belts intersect the earth’s atmosphere closest to the earth. Low Earth Orbiting (LEO) satellites with altitudes < 800km and inclinations < 40 degrees will pass through regions of the SAA during a percentage of their orbits. Sensitive instruments like those aboard HST are protected in various ways against the adverse effects of particle radiation, e.g., by turning off electronics, precluding data takes during the SAA, or by scheduling brighter targets in SAA impacted orbits. As Biretta and Baggett (WFPC2 ISR98-04) point out, the SAA reduces the amount of HST time available by several hundred orbits per year. Available on average are 7-9 orbits of SAA free passage per day and ~ 6-8 SAA-impacted orbits. The actual numbers depend on the size and shape of the SAA as described uniquely for a particular instrument. One of the critical scheduling trades involves the relationship between SAA passage and the HST earth-shadow passages because the faintest target observations require the long exposures, dark skies and low background.

High energy protons and electrons trapped in the magnetosphere are the most effective “disrupters” for HST SIs. Heavier ions and other sources of radiation, e.g., solar flares, galactic and extragalactic sources, also make up the radiation environment of HST however natural magnetic shielding at the low orbital altitudes protect against many of these
sources. The proton flux in the SAA is much higher than the electron flux and has energies in the range 1-100MeV whereas the electron energy is softer (KeV to ~3 MeV) and less dense. Typical spacecraft shielding can block particles with energies in the 10 to 70 MeV range.

Figure 2 is a model contour plot of the SAA at an altitude of 590km (model run by G. Menchaca, M. Bielefeld, and K. Clark and available at site www.stosc.stsci.edu/prd/saa/1000km/saa1000.html). The density, particle rate and shape change as the altitude increases. We refer the reader to the web page to see model comparisons of the SAA at a variety of altitudes.

Figure 1: The Earth’s Magnetic belts
Figure 2: Model SAA contours for an altitude of 590km generated using the USAF APEXRAD radiation model for solar minimum (model run by G. Menchaca, M. Bielefeld, and K. Clark. Data and image are available at site [www.stosc.stsci.edu/prd/saa/1000km/saa1000.html](http://www.stosc.stsci.edu/prd/saa/1000km/saa1000.html)).

WFC3 Design and CEI Requirements

Flow-down analysis of WFC3 radiation shielding is unavailable at the writing of this memo, hence the WFC3 CEI specifications on radiation offers the best understanding of the WFC3 susceptibility to the SAA. The requirements are summarized here:

- All components must be immune to any impairment from radiation for 5 years with a goal of 8 years.
- All onboard computer, memory and control circuitry must be immune to single upsets (single event upsets (SEU), single event latchups, gate rupture, and burnout - the latter two effects causing component damage or destruction).
- For components susceptible to latchup, the Linear Energy Transfer (LET) threshold must be greater than 37 MeV-cm²/mg.
- All devices whose SEU LET thresholds < 15 MeV-cm²/mg require special reports.
- CCD detector-related requirements:
- the afterglow must be limited to 0.1 e/s-pix 5 minutes after leaving a WFC3 SAA contour.
- the median energy deposited should effect < 2000 electrons implying a detector thickness > 25 microns.
- limits are given for destructive single event gate ruptures and burnouts for power MOSFETS.

- IR detector requirements: readout noise, QE and dark current shall not change in performance by more than 10% after 15 kilorads radiation dosage.

Typical doses for LEO satellites at HST’s inclination due to the SAA are 100-1000 rad(Si)/year. An example of the shielding thicknesses needed to minimize radiation dosage is given in Figure 3 where the total ionizing dose over 2.5 years is given versus 4*pi aluminum shielding thickness for the worst case HST environment during solar minimum. This analysis was performed by M. Jones (1998) using the SHIELDOSE model. Jones points out that trapped protons dominate the dosage for shielding thicknesses greater than 100 mils.
Figure 3: Aluminum Shielding thickness versus Total Ionizing Dose over 2.5 years for the worst-case HST environment - from Figure 5 in Jones, 1998 - ACS00-09.

The NASA requirements on components for radiation tolerance refers to a “rad tolerant” component as one that can tolerate 20-250 krads and have SEU threshold LET of ~20MeV/cm²-mg. A “rad hard” component can tolerate > 200 krad to 1 Mrad and have SEU threshold LETs of 80-150 MeV/cm²-mg. The CEI specs for the WFC3 are consistent with these types of values for radiation tolerance.

The SAA and Current HST Instruments

The SAA contours associated with the current SIs are shown in Figure 3 and Table 1. Four physically unique contours are in use today by the SIs (Models 02, 05, 24, and 26) however each instrument has a unique name for its contours.
How is WFC3 similar to these SIs such that assumptions about the SAA impact on WFC3 can be derived? Similarities and differences exist, both lending credibility to WFC3 assumptions:

- as a difference, the WFC3 (and ACS) has an explicit CEI specification on the electronics minimizing Single Event Upset sensitivity. Opto-isolator electronics in both STIS and NICMOS were highly sensitive to high energy particle hits thus resulting in more stringent SAA management. WFC3 circuitry designs preclude this SEU problem.
- STIS, WFPC2, and WFC3 have similar CCD detectors and electronics.
- WFPC2 and WFC3 are both radial bay instruments with similar areas and bulkhead orientations.
- WFC3 IR channel and NICMOS have similar HgCdTe detectors and electronics.
- Engineering grade detectors for ACS and WFC3 have been exposed to energetic particles at high energy accelerators and the results were consistent with predicted degradation.

Table 1. SAA contours used by the scheduling system to restrict observations.

<table>
<thead>
<tr>
<th>SAA Contour (saa_avoid, QALIGNMENT)</th>
<th>Science Instrument</th>
<th>Comments (as of this writing)</th>
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</thead>
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<tr>
<td>SAA-02 FGS</td>
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</tr>
<tr>
<td>SAA-05 FGS</td>
<td>original astrometry contour</td>
<td></td>
</tr>
<tr>
<td>SAA-23 NICMOS</td>
<td>clone of model 05</td>
<td></td>
</tr>
<tr>
<td>SAA-24 STIS CCD</td>
<td>initially 07.05 now STIS recon</td>
<td></td>
</tr>
<tr>
<td>SAA-25 STIS MAMA</td>
<td>initially 07.05 now STIS recon</td>
<td></td>
</tr>
<tr>
<td>SAA-28 ACS MAMA</td>
<td>clone of 25 =24</td>
<td></td>
</tr>
<tr>
<td>SAA-27 ACS HRC/WFC</td>
<td>clone of 26</td>
<td></td>
</tr>
<tr>
<td>SAA-26 WFPC2</td>
<td>initially 05, now empiric. new</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4: SAA Model Contours used by the ground system for scheduling observations and transitioning to and from various operational states.

WFPC2

In a Technical Instrument Report TIR98-04, Biretta and Baggett (1998) examine the cosmic ray rates as measured by WFPC2 at various points along the HST orbit including points near, inside and outside the SAA. The conclusion of this thorough and clear study was to shrink the SAA avoidance contour for scientific observations and thereby increase the number of SAA-free orbits per day by more than half an orbit. The test results and conclusions are clearly illustrated in Figure 5 (Figure 7 from that paper kindly supplied by S. Baggett). The symbols denoting the highest cosmic ray rates (x, squares, and triangles) are clearly seen delineating the new WFPC2 contour (highlighted in red). The old contour SAA-05 (called 25 in the TIR and corrected in the addendum to that TIR) was originally adopted for WFPC1 in the late 80s based on 1970 data. One of the interesting findings (and one that agrees with a similar STIS result) is that the eastern side, which shows a lower CR density, was pulled in where as the western edge retained its cosmic ray density profile and hence its boundary. The northern boundary was retained because the original model did well in bounding higher regions of cosmic rays. These results are consistent with two properties of the SAA that will be discussed in more detail later: 1) that parti-
cles reaching a location from the west originate at higher altitudes than particles from the East, and 2) that the SAA drifts by 0.3 degrees westward per year, or ~ 9 degrees since the original SAA contours were derived from models and data available in the 60s and 70s. We refer the reader to the Biretta and Baggett TIR (and addendum) for additional details.

Figure 5: Results of the WFPC2 1998 SAA study: from Figure 7 (Biretta and Baggett WFPC2 TIR 98-04, kindly supplied by S. Baggett). The locations of the data points are denoted by symbols, with different symbols for different cosmic ray densities. The solid red (dark) line is the approximation to the revised WFPC2 contour. Actual values are given later in this report. HST orbital tracks tangent to the SAA are the curved lines. The original WFPC2 contour is marked with the dotted lines.

**STIS**

The STIS MAMA (and CCD) operational procedures for SAA avoidance are discussed in STIS TIR98-10 (1998, Baum, Reinhart, and Ferguson) and compared with WFPC2 in the TIR by Biretta and Baggett (2001). The STIS results are consistent with those of WFPC2: a higher radiation density occurs on the western edge of the SAA complex.
The STIS MAMA electronics are sensitive to single-event cosmic-ray induced upsets and hence SAA avoidance rules are more strict: the power supplies are turned on and off around each SAA passage using contour SAA-25. The single event upsets, plotted in Baum, et. al., ISR show a clear delineation of SAA contour 25.

NICMOS

The NICMOS sensitivity to the SAA was characterized in SMOV using cosmic ray hits in dark frames as a function of orbital position (ISR-97-032, Daou and Calzetti 1997) and later by a statistical study of the spatial noise in deep images (ISR NICMOS-98-001, Najita, Dickinson, and Holfeltz, 1998). Shortly after the servicing mission, NICMOS experienced Single Event Upsets as the HST crossed into and out of SAA-02. This result motivated shutting off the detectors during SAA passage. When the telescope was inside SAA-05 and closest to SAA-02, 1/6 of the chip was effected by cosmic ray events. Mirroring STIS and WFPC2 spatial results, the NICMOS measured its highest cosmic ray density in the western and north western region of the SAA complex (see Figures 1 and 4 in ISR-97-032). An additional effect which occurred only when the detectors were turned off in the SAA, known as persistence - a glowing residual of CR event, was measured as an elevated dark count (~100DNs/sec) with a 20-30 minute decay time. If the detector was left on during the SAA 05 passage, persistence did not occur and the pixels were back to normal within 4-5 minutes of exiting contour SAA-05. To keep the detectors on as much as possible, the authors recommended that a contour between 2 and 5 be designed for the detector on/off management. Contour SAA-05 was retained however as the SAA avoidance for science observations.

Cosmic Ray persistence was studied further (Najita et al ISR 98-001) by measuring the levels of spatial background noise in deep field images as a function of orbital position. These authors found that persistence from cosmic rays in deep images results in multipixel events which are very difficult to remove using conventional CR removal software. The resulting operational recommendation was to observe faint targets (or run programs requiring high photometric accuracy) in non-SAA impacted orbits only.

The SM3b SMOV plan for NICMOS includes dark current and read noise measurements. A study of radiation damage to the HgCdTe detector over the past few years will provide information pertinent to the WFC3 IR detector.

ACS

Both the ACS and WFC3 have similar shielding requirements. The Ball engineers determined that the ACS-WFC CCD needed the equivalent of 1 inch of aluminum shielding
across 99% of its 4-pi steradian FOV. A detailed study of the predicted radiation environment for ACS may be found in M. Jones’ ACS ISR 00-09. Although the goal of this report was the specification of cyclotron irradiation levels for ACS detector studies, the report discusses the accuracy of SAA modelling, the relative contributions of high energy particles and provides estimates of the radiation damage taking into account the types of shielding on the ACS.

SMOV3b proposals which include assessing the impact of the SAA on electronics, memory loads, buffer ram, and on image data are #9002, 9003, 9022 and possibly others. These results will verify the selection of the ACS contours and provide information to assist in finalizing the launch-ready SAA contours for WFC3.

**WFC3 Radiation Test Results**

Engineering detectors similar in design to the WFC3 flight detectors were irradiated with high energy proton flux (63MeV) for the equivalents of 1 year, 2.5 years, and 5 years. ISRs WFC3-2000-05, WFC3-2001-03, and WFC3-2001-04 by the team of Hanley and Cawley describe the effects of the high energy proton doses by measuring the Charge Transfer Efficiency and the background noise before and after the irradiation. Their results are consistent with the predictions of the CTE performance of these detectors proving that the detectors are well understood. The CTE degraded after exposure as expected according the dose. The detectors complied with the WFC3 CEI specifications.

**SAA Variability, Asymmetry and Models**

*Variability*

In this section, the variability of the SAA is assessed in order to determine if existing models based on past data will be relevant in 2004 and if the contours are adequate to handle anticipated changes in the SAA structure.

The typical SAA proton and electron energy spectra are plotted in Figures 6 and 7 where the differential flux, in units of particles/cm^2-day-MeV, is plotted versus energy. One can deduce from Figure 6, where the dotted curve is the proton flux during solar maximum and the solid curve is the flux during solar minimum that the proton flux is anti-correlated with solar cycle whereas the opposite is true for the electron flux, as shown in Figure 7. In addition, the geomagnetic field shifts with time carrying the SAA with it. Measurements have shown the drift rate, 0.3 degrees/year, to be constant and in the westward direction. There is also a directional asymmetry such that particles reaching a
location from the west originate at higher altitudes than particles from the East. The ratio of the East-West flux differential is \( \sim 4.6 \).

**Figure 6:** Differential Proton Flux as a function of particle Energy from models. The flux is in units particles/cm\(^2\)-sec-MeV. Note the solar cycle anti-correlation.
Figure 7: Differential Electron Flux as a function of particle Energy from models. Units particles/Cm^2-sec-MeV. Note the solar cycle correlation.

The solar cycle is depicted in Figure 8 (Hathaway, 2001). According to solar physicists, the cycle 23 (in progress) may produce large solar activity but is well within the expected tolerance. Where available, the epoch of the SI data used for the analyses are shown in relation to the solar cycle. Most of the WFPC2, STIS and NICMOS data were taken during the solar minimum where the proton flux was maximum and the electron flux (less of a problem to SI instruments) was minimum.
Figure 8: Solar Cycle #23 from sunspots (jagged line) and predictions (Hathaway 2001 Solar Physics Marshall Space Flight Center).

A note on SAA Models

The original SAA models, NSSDC APMIN and APMAX, were based on data obtained in the 60s and 70s. Several adjustments have been made to these models. Numerous references are available in the literature that critique, update, and correct existing solar min and max models of the high energy radiation environment (e.g., Armstrong and Colborn, NASA/CR-2000-210071; Daly et al 1996). Jones 1998 provides references and a summary of the model status. Data from various LEO satellites including the space shuttle, MIR, LDEF, APES and others are used to assess the fidelity of NASA’s AP8 and AE8 models for protons and electrons respectively. As an example, the APEXRAD model, a low altitude dose model for solar minimum predicts dosages that are a factor of ~2 larger
than the AP8 MIN model. Several references mentioned underestimates and overestimates by factors up to ~2. The SAA contours are therefore conservative such that these uncertainties as well as the solar cycle variations do not hamper their usefulness. A recommendation however is given for a future study on the placement of the SAA, i.e., small shifts to the west may be in order for the “out years” of Hubble.

**Conclusions: WFC3 SAA Contours and Operational Requirements**

Each HST SI requires two sets of contours: the *observational contours which are* used for scheduling science exposures (TRANS alignment SAA, section 9.4 in the TRED), and the *operational contours* which govern the scheduling of transitions from one operational state to another.

**Observational Contours**

The data from previous SI instruments, especially those similar to WFC3, have been used to bound the SAA environment. The following observational contours have been selected for WFC3 based on the information and assumptions stated in the previous sections:

1) **WFC3 UVIS:**

   The WFC3 UVIS observational contour will be a clone of SAA-26, the contour established empirically by WFPC2 and also used for the ACS WFC. This contour tracks the most conservative SAA-05 model in the north and western region of the SAA but shrinks the eastern edge. SAA-26 is therefore consistent with the evolution of the position of the SAA. Pending ACS in-orbit test results, small adjustments may be made to this contour. The WFPC2 results demonstrate that this contour adequately accounts for predictable variability of the SAA, i.e. solar min and solar max.

2) **WFC3 IR Channel:**

   For the following reasons, the observational contour adopted for the WFC3 IR channel will also follow SAA-26 for the following reasons:

   - NICMOS data has shown that the eastern edge of the SAA-05 contour is overly conservative. Figures 1 and 4 in the NICMOS ISR 97-032 (Daou and Calzetti 1997) demonstrate that the SAA-05 contour can be reduced on the eastern side to the values of the SAA-26 contour. Refer to the crosses numbered 7 and 8 from the right in Figure 4 of NIC97-032 and from the east in the positional map in Figure 1 of NIC ISR-032. These two data points represent less than1000 “pixel-hits” each. A more thorough understanding of the NICMOS reaction to the radiation environment is expected as a result of special SMOV3b tests.

   - Improvements in shielding designs for WFC3 based on STIS and NICMOS experience should be enough to handle the levels of radiation coming from the eastern edge of contour SAA-05. This assumption of course will be verified during SMOV4.
The WFC3 contours will be assigned the next two slots, numbers, #29 and #30. Even though the contours are the same for both channels at this juncture, future experiments may reveal different sensitivities. The ground system data base requires a set of vertices which bound a concave area in latitude and longitude. Table 2 lists the vertices for models 29 and 30.

**Operational Contours**

The SI reconfiguration software is an operational description of instrument modes and operational states and the rules for transitioning between the states. The most stringent contour assigned to an instrument is the “observational contour” described in the previous subsection. The operational contours govern the scheduling of transitions from one operational state to another. and these restrictions protect electronics, computers, and low and high voltage power supplies from the high radiation background. As an example, ACS cannot turn its low or high voltage power supplies on while in SAA model 28 (and hence cannot observe either) however, there are no restrictions governing the powersupply operation of the CCD. CCD data however cannot be obtained in contour 28. NICMOS uses SAA23 to restrict power supply operations, observations and activities using the lamp to preclude SEU problems.

**Table 2.** Latitude and Longitude boundaries for Models 29 and 30 (same as 26).

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Acknowledgements

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Ball SER ACS-CCD-019, 1997 (D. Feaver).
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    at site www.estec.esa.nl/wmwww/wma/ecss/ecsspres/index.htm
Jones, M. 2000, ISR ACS-00-09.
Mackenty, J. 2000 WFC3 CEI Specifications
Trans Requirements Document (TRED - on SAA models for Alignments).

Model results for 590km to 1000 km altitude may be found at

NASA models AE8 and AP8 - www.nssds.gsfc.nasa.gov/space/model/models_home.html