South Atlantic Anomaly Entry and Exit As Measured by the X-Ray Timing Explorer

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Abstract

The Rossi X-Ray Timing Explorer (RXTE) carries instruments that must switch off high voltages (HV) when passing through the South Atlantic Anomaly (SAA). The High Energy X-Ray Timing Experiment (HEXTE) contains a particle monitor that detects the increased particle flux associated with the SAA and autonomously reduces its voltage. The Proportional Counter Array (PCA) relies on uplinked predictions of SAA entry/exit times based on ephemeris data provided by the Flight Dynamics Facility (FDF). A third instrument, the All-Sky Monitor (ASM) also uses a predicted SAA model to reduce voltage when passing through the SAA. Data collected from the HEXTE particle monitor, as well as other instrument readings near the times of SAA entry/exit offer the potential for refining models of the boundaries of the SAA.

The SAA has an increased particle flux which causes high rates of detection in the RXTE instruments designed to observe X-rays. The high counting rates could degrade the PCA if HV is not reduced during SAA passages. On the other hand, PCA downtime can be minimized and the science return can be optimized by having the best possible model of the SAA boundary. Thus, the PCA team planned an extensive effort during in-orbit checkout (IOC) to utilize both HEXTE particle monitor data and instrument counting rates to refine the model of the SAA boundary.

The times of SAA entry and exit are compared with the definitive ephemeris to determine the precise location (latitude and longitude) of the SAA boundary. Over time, the SAA and its perimeter were mapped. The RXTE Science Operations Center (SOC) is continuously working to feed back the results of this effort into the science scheduling process, improving the SAA model as it affects the RXTE instruments, thus obtaining more accurate estimates of the SAA entry/exit times.

1. Introduction

The X-Ray Timing Explorer (XTE) was launched from the Eastern Test Range (ETR) on December 30, 1995, aboard a Delta II rocket. XTE was designed and built at the Goddard Space Flight Center (GSFC) and both the Mission Operations Center (MOC) and Science Operation Center (SOC) are located at GSFC. The XTE mission is intended to study the X-ray universe with unprecedented time-resolution (References 1 and 2). On February 28, 1996, NASA renamed XTE the Rossi X-ray Timing Explorer (RXTE) in honor of Bruno B. Rossi, the early pioneer in the field of X-ray astronomy.

The RXTE orbit is a 580-km altitude, near-circular orbit with a 23-degree inclination. The mission design altitude was the result of a trade-off between conflicting requirements. Arguing for a higher altitude was the goal of maximizing the longer achievable orbital lifetime. However, a lower altitude avoids to a greater degree the South Atlantic Anomaly (SAA), which has a larger spatial extent at higher altitudes. There is also an increased overall particle flux at higher altitudes. The reduced inclination, which required a plane-change maneuver at the first ascending node, also helps to reduce time spent in the SAA. Achieving an even lower inclination, though desirable, was not possible since the RXTE mass (2840 kg) was near the maximum for the launch vehicle. Without a plane-change maneuver, it is not possible to achieve an orbit with an inclination less than the latitude of the launch site, in this case, 28.5 degrees.

The SAA is a region of increased particle flux where the Van Allen radiation belts extend to lower altitudes than normal. X-ray detectors are sensitive to particle events in addition to X-rays. The SAA interferes with RXTE science operations since the energetic particles trigger high counting rates in the RXTE detectors, degrading them over time. The RXTE instruments must safe themselves during passages through the SAA to avoid damage to the detectors. Though this damage is cumulative, even short exposure to high SAA particle rates with the high voltage (HV) turned on was considered unacceptable for the PCA.

This paper discusses the efforts of the RXTE SOC to optimize an SAA model for use in science planning. The following section provides additional background about the RXTE detectors and SAA models for past X-ray astronomy missions. Section 3 describes the development of the initial SAA model. Section 4 describes the post-launch efforts to collect, analyze and interpret the data that led to the optimized SAA model. Section 5 presents the new SAA contour. Section 6 gives the conclusions of this study.

2. Background

RXTE carries three instruments for studying the X-ray universe. Each of these must reduce HV when passing through the SAA. The High Energy X-Ray Timing Experiment (HEXTE) (Reference 3), designed and built at the University of California - San Diego (UCSD), consists of two clusters of four phoswich crystal scintillators that are sensitive in the range from 15 to 250 KeV. HEXTE contains two particle monitors that detect the increased particle flux associated with the SAA and autonomously reduce the HV. The Proportional Counter Array (PCA) (Reference 4), designed and built at GSFC by the Laboratory for High Energy Astrophysics (LHEA), consists of five gas proportional counter units (PCUs) co-aligned with HEXTE. For reducing HV, the PCA relies on uplinked predictions of SAA entry/exit times calculated using the SAA model discussed in this paper with ephemeris data provided by the Flight Dynamics Facility (FDF). A third instrument, the All-Sky Monitor (ASM) (Reference 5), designed and built at the Massachusetts Institute of Technology (MIT) consists of three Scanning Shadow Cameras (SSCs) for monitoring the X-ray sky for transient behavior. The three detectors, one-dimensional imaging gas proportional counters, also must reduce HV when passing through the SAA. The ASM considers other factors besides just the SAA contour in its algorithm for calculating when to reduce HV.

All astronomical satellites in low Earth orbit are adversely affected by the SAA. Before launch, an initial estimate was made of the contour of satellite longitude and latitude for which the particle fluxes would be potentially harmful to the PCA detectors. Once in orbit, the size of the SAA model was increased more than once during the first 2 weeks, before a safe contour was obtained. Later, based on the analysis presented here, the size and shape were changed to a more optimal contour.

High counting rates associated with the SAA degrade the PCA if HV is not reduced during SAA passages. The PCA contains a High Rate Monitor (HRM) that switches off the HV when excessive counting rates are detected. The HRM works on signals from within the active PCUs and does not use a separate particle monitor device as HEXTE does. Each of the five PCUs has its own independent HRM protection system. The HRM could be used to lower the HV upon SAA entry, but it cannot provide information about when to increase the HV back up to operational levels. The PCA proposal included a Geiger counter that would monitor the particle rate and provide a signal when the HV should be turned back up. This was the method of detector protection used on the Cosmic X-ray Spectroscopy Experiment on the Orbiting Solar Observatory (OSO-8). This part of the instrument was eliminated by the program managers in a cost-cutting measure based on the belief that the expense of building hardware to do the job of HV management would exceed the expense of commanding HV on the basis of calculations and commands stored on-board.

For the first 2 months of the mission, PCA HV was simply reduced by stored command to a minimal level during SAA passages. However, the HRM was a safety feature that was utilized several times during the in-orbit checkout (IOC) phase of the RXTE mission before an SAA model of sufficient size was implemented. These switch-offs avoided the most intense fluxes of the SAA, and thus damage to the detectors, but were inconvenient since ground commanding was required to restore the PCA to operating condition. So the first step in the optimization process was to find an SAA model that was bigger on all borders than the actual SAA contour. Even after several attempts, the SOC would still occasionally find a new extension of the SAA that was not included in the latest model.

Although having an oversized SAA model avoids damage to the PCA, or at least the inconvenience of having to turn it back on by ground command, PCA downtime can be minimized and the science return can be optimized by having the best possible model of the SAA boundary. Thus, the PCA team, in conjunction with the SOC, conducted an extensive effort during in-orbit checkout (IOC) to utilize both HEXTE particle monitor data and instrument counting rates to refine the model of the SAA boundary.

3. Initial SAA Model

Prior to launch, the RXTE SOC arrived at an initial starting definition for the SAA based on three independent sources of information. The World Maps of B, L and Flux Contours (Reference 6) provided information about proton and electron predicted flux levels. However, there are difficulties relating these flux levels directly to estimated PCA count rates, prompting the more practical approach of relying on past mission history.

The HEAO-A mission of 1977 carried many large detectors. The A-2 experiment, comprised of proportional counters, was the basis for the RXTE PCA design. That experiment also did not fly a Geiger counter for budgetary reasons, and the detectors were turned on and off by command. The detector data for the period when the detectors were on provided evidence about the contours of the SAA that applied at that time. Furthermore, the HEAO-A4 experiment carried a particle monitor (for protons) and, as the orbit decayed from 453 km to 333 km, the science team built up a data cube of the integrated history of all scans through the SAA region. This data set (Reference 7) showed an SAA profile with a pronounced funnel shape, rapidly increasing in size at higher altitudes. Unfortunately, the top layer of the cube was still well below the planned RXTE orbital height, leaving the problem of trying to extrapolate to the higher altitude, as well as the question of whether the boundaries applicable in 1977-1978 were applicable to 1996. The extent of the SAA appears to show a variation correlated with the 11-year solar cycle.

The current Japanese ASCA mission has a higher inclination than RXTE and therefore scans all the geographic locations that RXTE can overfly. The ASCA orbital altitude of 566 km is similar to the 580-km RXTE orbital altitude. However, the ASCA imaging detectors are much smaller than the PCA and thus likely to be able to operate nearer the mean SAA center. The SAA perimeter in use for ASCA was compared with the HEAO-A perimeter. Except for an eastward extension at low latitude, the ASCA SAA profile fell inside of the HEAO-A profile. After examining these sources for determining the geographical extent of the SAA, a contour was chosen with the intent of adjusting it after launch. The contour described an approximately "half moon" shape centered on the South Atlantic. The Science Operations Facility (SOF) scheduling tools, SPIKE and Needle, require a string of longitude, latitude pairs. This format became the standard for the initial and subsequent deliveries to the SOF.

It was realized that the HRM might turn off the PCA detectors during the entrance to the SAA if the SAA model was too small, and that then ground commands would be required to turn them on again. Since the detector HVs were turned down and not off, the PCA detectors still provided information, at a reduced count rate, of the particle flux. This data, PCA counting rates at reduced HV, supplemented the HEXTE particle monitor data as a source of information for determining the appropriate SAA contour for RXTE science operations.

4. Post-Launch Analysis

The SAA model is incorporated into the SOF scheduling software, SPIKE and its derivative, Needle. Needle is used for fine-tuning the schedule, allowing the user to visualize the various constraints on an observation. The primary constraints are: (1) the target is not Earth-occulted; (2) RXTE is not within the SAA; (3) the target is not within 30 degrees of the Sun. The times of SAA entry and exit are determined by Needle using the RXTE ephemeris provided by the FDF, and the current SAA model, which has already been iterated several times since launch. The SAA entry and exit times trigger PCA HV up or down commands that are incorporated into the Daily Activity Plan (DAP), which is the primary means of conveying science commands to the spacecraft. The RXTE MOC processes the DAP, and uploads the commands to the spacecraft. By monitoring the instrument data in the SOF, it is possible to quickly assess whether any given SAA model is adequate for HV management.

Following launch, there was a 30-day IOC period. The first week was devoted primarily to overall spacecraft checkout, but the RXTE instruments were also activated and checked out. The balance of the IOC period was used for astronomical calibrations and pointings. The regular program of peer-reviewed science targets by Guest Observers (GOs) started as scheduled around day 30 of the mission.

For the first week, the MOC conducted general spacecraft testing primarily during the daytime shift, while the SOC was able to proceed with instrument checkout much of the nighttime hours. Fortuitously, almost all SAA passes occurred in the spacecraft priority daytime shift, meaning that nighttime checkouts were essentially un-hindered by SAA passages. Before the PCA high voltages could be left on at the end of the night shifts' testing, it was essential to check that the PCA HV up and down commands were happening at the specified time. By the end of the third night after launch, all five of the Proportional Counter Units (PCUs) had been run at their full HV settings.

At the start of the third night, the PCA was tripped off unexpectedly by the HRM. This was the first indication that an SAA pass had occurred at a time other than that predicted by the SAA model. The HRM safety trip had been fully tested on the previous night. As all other aspects of the chain of events relating to PCA SAA HV commanding had been checked and were working, the failure to predict this extra SAA pass was clearly due to the SAA perimeter definition being optimistically small. By monitoring the PCA HRM trip-offs over the following few days, a process of trial and error was begun leading to a gradually increasing SAA perimeter size.

Due to the relative orbit geometry, RXTE traverses the SAA during consecutive orbits for a portion of each day. With the pre-launch model, this portion amounted to about half a day. With the eventual model that resulted after several increases in size that were required to prevent HRM trip-offs of the PCA, the SAA passages occurred on about three quarters of the orbits each day. Additionally, each SAA passage was extended in time by a few minutes. As a result, there was a significant increase in the amount of time that the PCA had to be operated with HV off due to predicted SAA passages. The desire to reclaim some of this time for doing actual science observations prompted the more systematic approach to optimizing the SAA definition that is the primary focus of this paper. It is worth pointing out, however, that science data collected near the SAA boundary may still have high background counting rates, or rapidly changing rates, making the data unsuitable for some science programs. On the other hand, the PCA design includes a propane layer that acts to veto out false detections caused by particles events.

5. Optimization of the SAA Contour

Data collected from the HEXTE particle monitor, as well as PCA data collected in, or just outside, the SAA offer the potential for refining models of the boundaries of the SAA. The times of SAA entry and exit are evident from the HEXTE particle monitor data. These times are compared with the RXTE ephemeris to determine the precise location (latitude and longitude) of the SAA boundary. In addition, the PCA HRM trip-offs, though inadvertent, provided a good measurement of the SAA border since any point where the PCA tripped off represented a practical limit for commanding the HV reduction. For the most efficient science operations, RXTE should get as close to the SAA as possible before turning down the PCA HV since science data are then lost until SAA exit. However, a safe margin must be maintained to account for SAA time-variability and spatial shifting. Over time, the entire SAA region was mapped and thus an outer perimeter of the SAA was determined.

Each refinement of the SAA model was fed back into the science scheduling process. The RXTE ephemeris and the latest SAA model are used to predict future SAA entry and exit times, and then commands to reduce high voltage are inserted into the daily activity plan (DAP). Figure 1 shows a contour map of the SAA at the RXTE altitude based on HEXTE HRM data. Figure 2 shows a similar contour based on data from the PCA. The PCA was able to map the central region of the SAA because the HV was only lowered, not turned completely off. (The 0 setting, or lowest high voltage, setting is about 1000 V, while typical operational settings are around 2200 V.) However, on March 20, 1996, the PCA mode of operation was changed such that the PCA HV is now turned off for passages through the SAA. The PCA HRM trip-offs show up as small diamonds. This occurs because identical particle rates generate much higher counting rates when the HV is at the operational setting.

It is interesting to look at the concept of weather in the SAA. Figures 3a and 3b show the maximum and minimum contours, respectively, from the HEXTE particle monitor count rates. Similarly, figures 4a and 4b show the maximum and minimum contours, respectively, from the PCA count rates at low voltage settings. This weather, or day to day variability in the SAA, complicates efforts to optimize the contour. For operational reasons, the boundary should be larger than the maximum extent of the SAA.

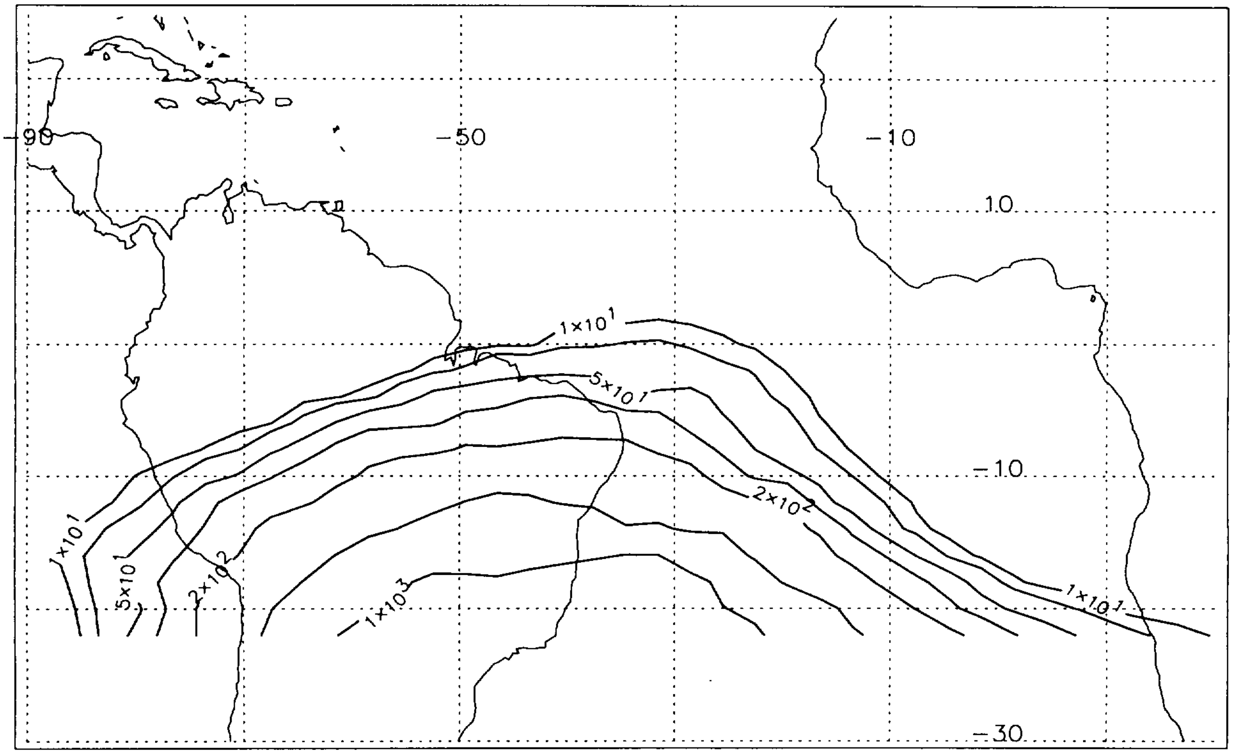

Figure 1. SAA Contour from Average HEXTE Particle Monitor Count Rates

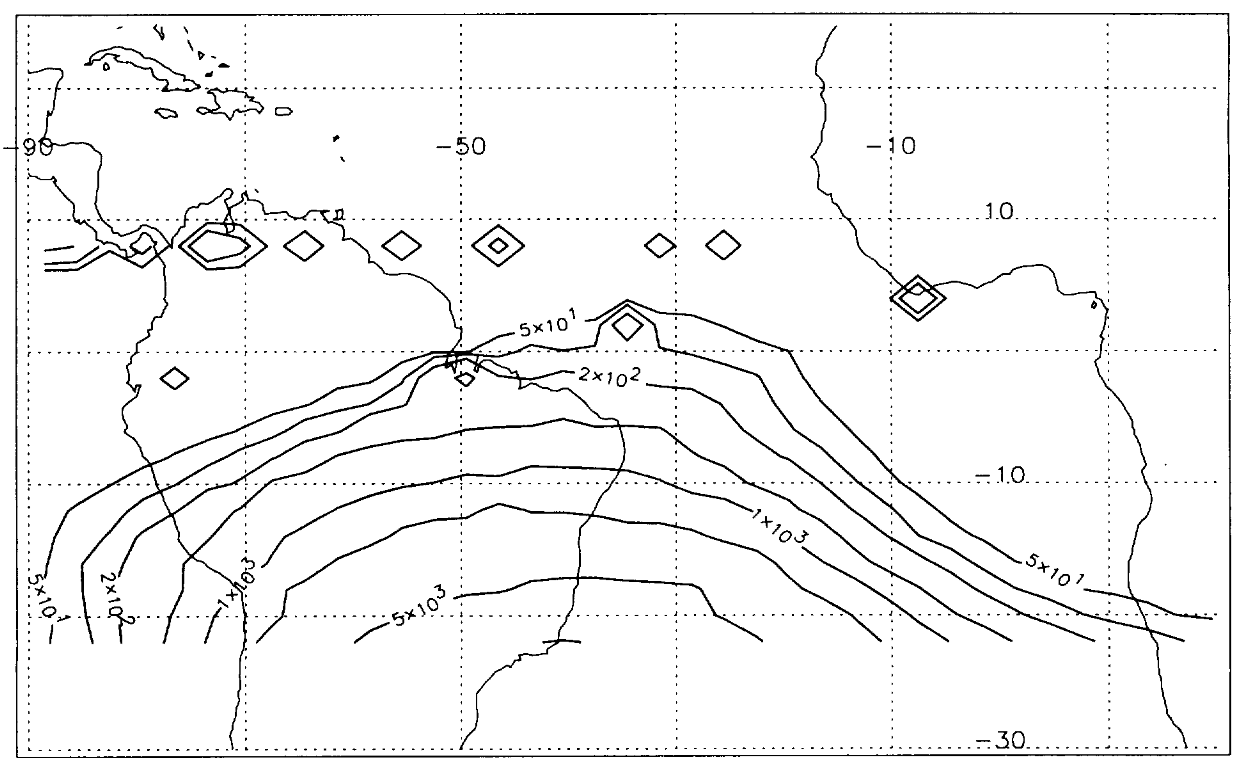

Figure 2. SAA Contour from Average PCA Count Rates at Reduced HV

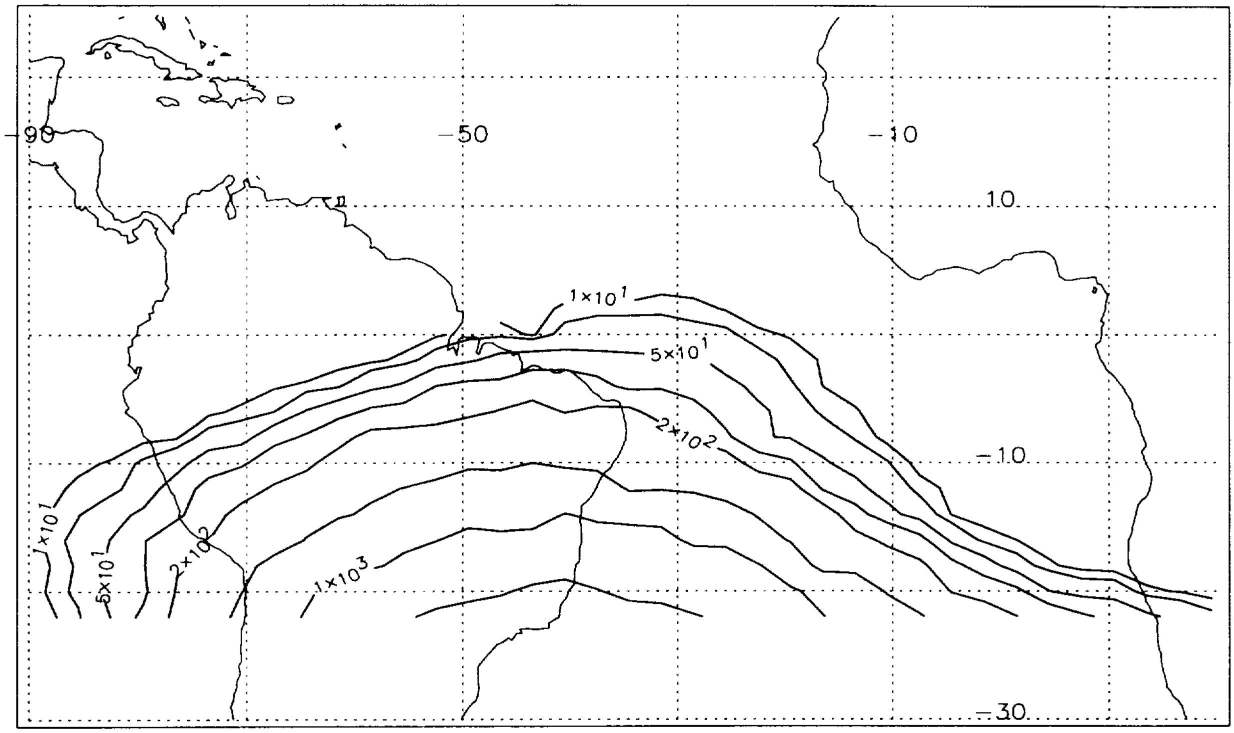

Figure 3a. SAA Contour from Maximum HEXTE Particle Monitor Count Rates

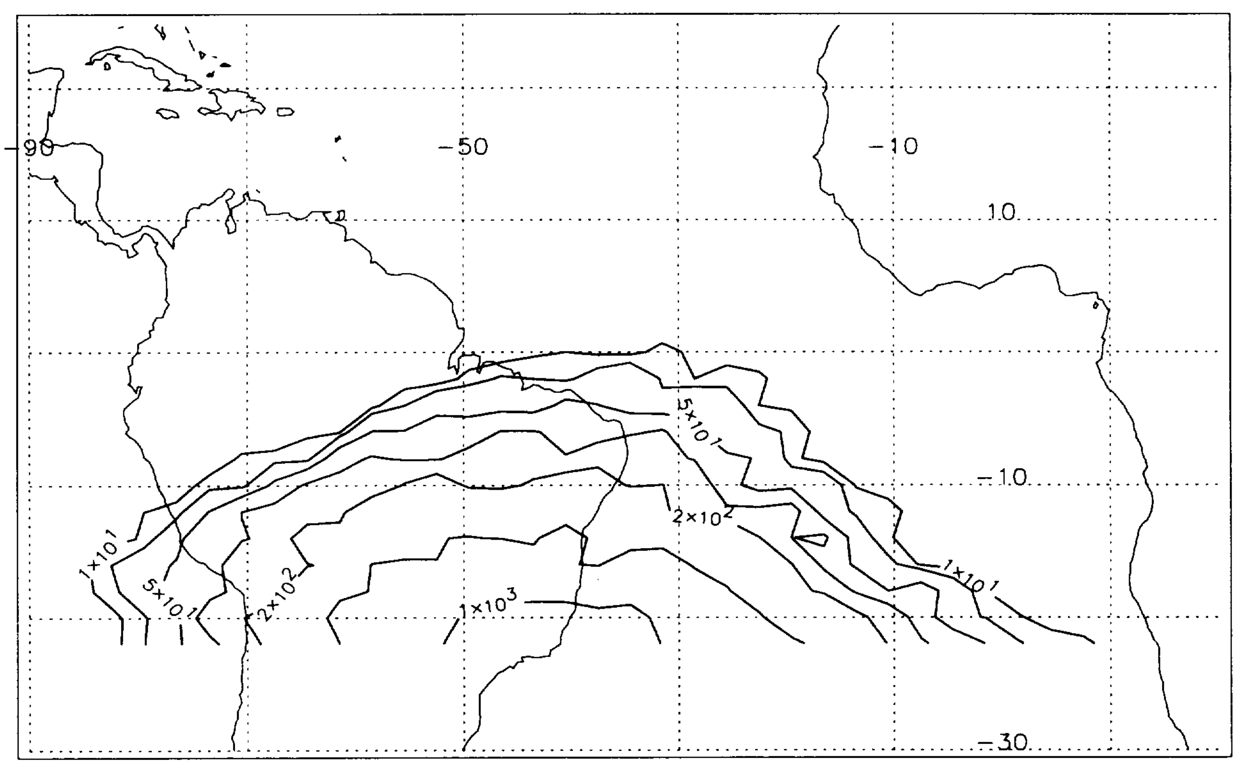

Figure 3b. SAA Contour from Minimum HEXTE Particle Monitor Count Rates

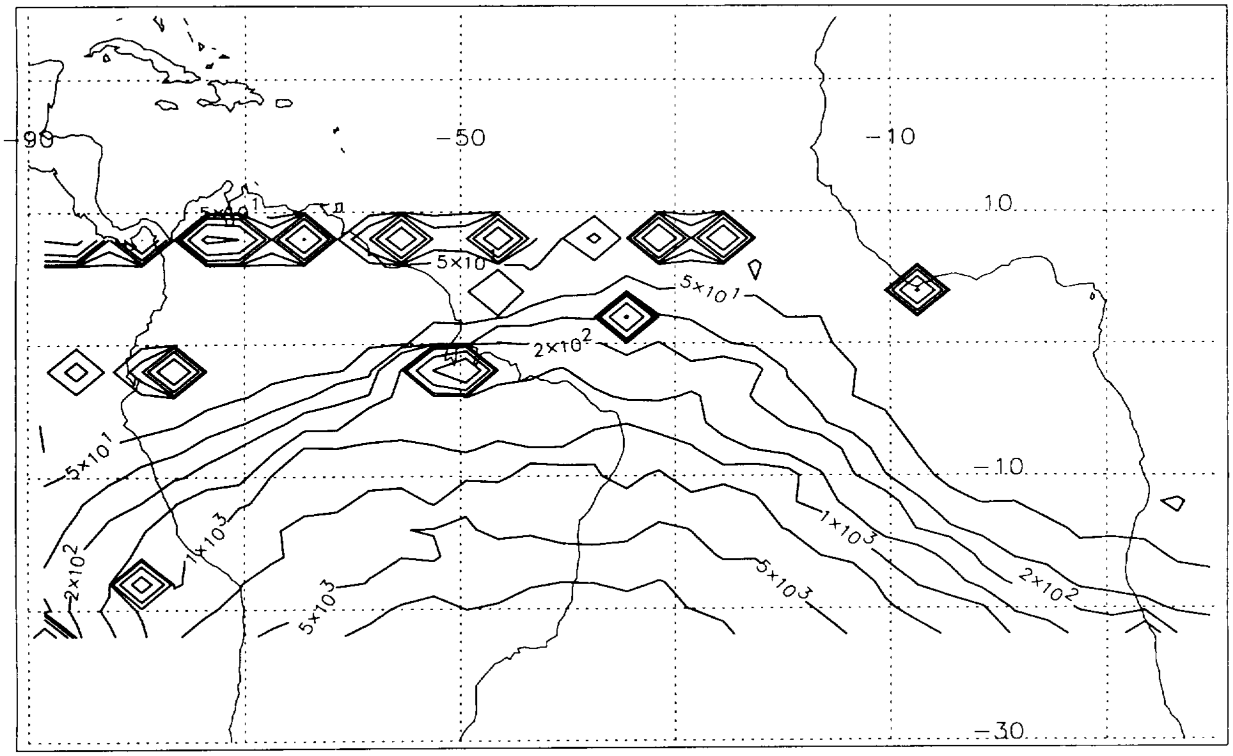

Figure 4a. SAA Contour from Maximum PCA Count Rates at Reduced HV

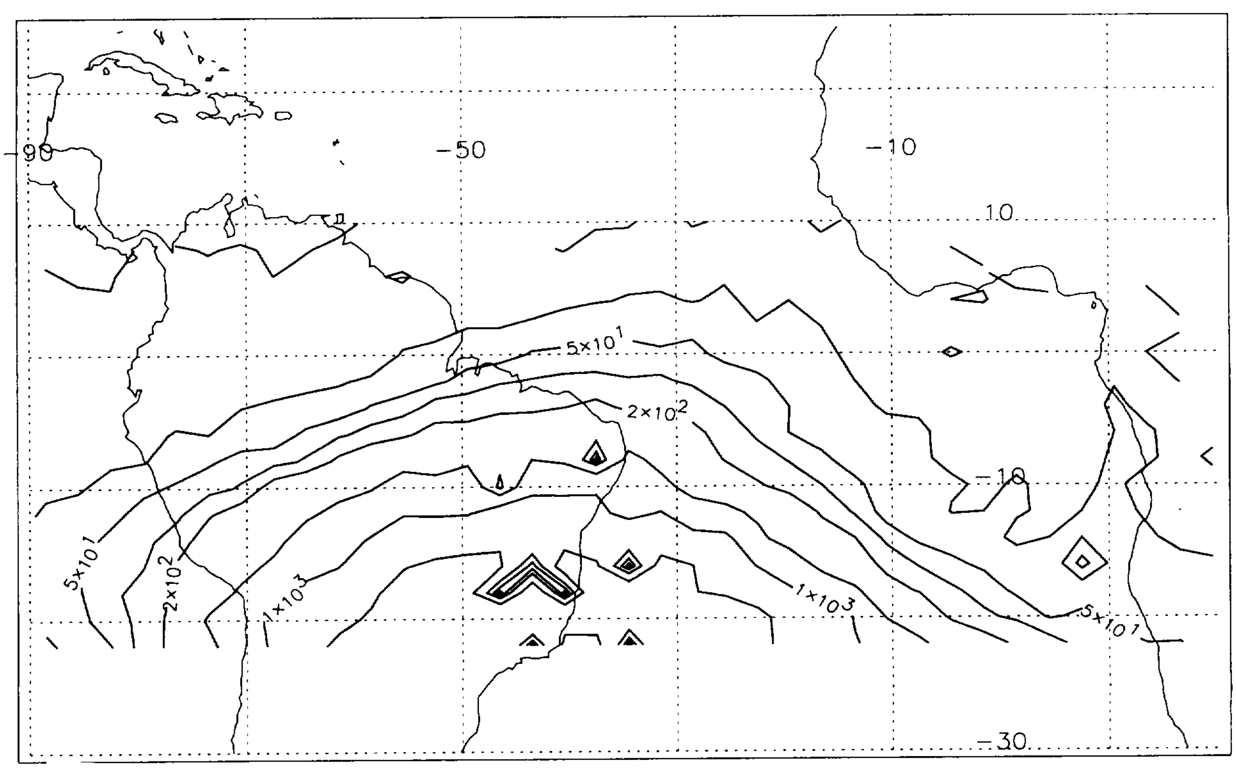

Figure 4b. SAA Contour from Minimum PCA Count Rates at Reduced HV

6. Conclusions

This effort to optimize the SAA model demonstrates a practical application of flight dynamics products and concepts in a science operations arena. Based on the precise ephemeris data available from the FDF, the time-tags for instrument readings could be accurately converted into a longitude and latitude of the sub-Earth point. The instrument counting rates are thus converted into contour maps of the SAA at the RXTE orbital altitude. By trial and error, the SAA contours are fed back into the science planning process to increase the efficiency of RXTE science operations.

Additionally, the contour maps of instrument counting rates can be used by scientists studying the near-Earth environment. At the very least, these data will be useful to planners of future X-ray astronomy missions, just as the RXTE science team relied on similar data from previous X-ray missions.

Although a savings in on-source science time was achieved by optimizing the SAA perimeter, the variability of the SAA on both short and long timescales limits the gain in efficiency. The SAA model must be larger than the maximal extent of the SAA or unplanned HV switch-offs will nullify the increased on-source time. In fact, the difficulties encountered in ground commanding of SAA management argue the case for using hardware to accomplish this task for future X-ray astronomy missions. Having a feedback control loop for turning down HV gets around the problem of imprecise knowledge of the SAA boundary, and has worked very well for HEXTE.

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