Monitoring the Health and Safety of the ACIS Instrument On-Board the Chandra X-ray Observatory

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ABSTRACT

The *Chandra X-ray Observatory* (CXO), NASA's latest "Great Observatory", was launched on July 23, 1999 and reached its final orbit on August 7, 1999. The CXO is in a highly elliptical orbit, approximately 140,000 km x 10,000 km, and has a period of approximately 63.5 hours ($\approx$ 2.65 days). Communication with the CXO nominally consists of 1-hour contacts spaced 8-hours apart. Thus, once a communication link has been established, it is very important that the health and safety status of the scientific instruments as well as the Observatory itself be determined as quickly as possible.

In this paper, we focus exclusively on the automated health and safety monitoring scripts developed for the Advanced CCD Imaging Spectrometer (ACIS) to use during those 1-hour contacts. ACIS is one of the two focal plane instruments on-board the CXO. We present an overview of the real-time ACIS Engineering Data Web Page and the alert schemes developed for monitoring the instrument status during each communication contact. A suite of HTML and PERL scripts monitors the instrument hardware house-keeping electronics (*i.e.*, voltages and currents) and temperatures during each contact. If a particular instrument component is performing either above or below pre-established operating parameters, a sequence of email and alert pages are spawned to the Science Operations Team of the Chandra X-ray Observatory Center so that the anomaly can be quickly investigated and corrective actions taken if necessary. We also briefly discuss the tools used to monitor the real-time science telemetry reported by the ACIS flight software.

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Keywords: *Chandra*, Space Missions, ACIS, Operations, Health and Safety, Automated Monitoring

1. INTRODUCTION

Just past midnight on July 23, 1999, the space shuttle *Columbia* lifted-off from Cape Canaveral, Florida. In its payload bay lay the *Chandra X-ray Observatory* (CXO), the primary cargo of the *STS-93* mission. Just under 8 hours after launch, *Chandra* was deployed from the space shuttle. However, it would be nearly two weeks later, after an Inertial Upper Stage booster "burn" and several "burns" by its own propulsion system, that *Chandra* would reach its final orbit. The CXO is now the third of NASA's "great observatories" in space.

The CXO's operational orbit has an apogee of approximately 140,000 km and a perigee of nearly 10,000 km, with a 28.5° initial inclination. The CXO's highly elliptical orbit, with an orbital period of approximately 2.65 days, results in high observing efficiency. Moreover, the fraction of the sky occulted by the Earth is small over most of the orbital period, as is the fraction of time when the detector backgrounds are high as the CXO dips into the Earth's radiation belts. Consequently, approximately 85% of *Chandra*'s orbit is available for observing. In fact, uninterrupted observations lasting as long as 2.3 days are possible.[1]

The CXO carries two focal plane science instruments: the High Resolution Camera (HRC) and the Advanced CCD Imaging Spectrometer (ACIS). The Observatory also possesses two objective transmission gratings: a Low Energy Transmission Grating (LETG) that is primarily used with the HRC, and the High Energy Transmission

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Grating (HETG) that is primarily used with the ACIS. In addition to these instruments, *Chandra* also carries a radiation monitor – the *Electron, Proton, Helium Instrument* (EPHIN) particle detector.

In order to maintain this high level of observing efficiency, a robust monitoring and alert system must be in place to verify the health and safety status of not only the instruments themselves, but the whole observatory as well. This requirement is a result of the fact that the CXO is not in constant communication with the ground. Communication with the CXO is obtained through NASA's Deep Space Network (DSN) of ground-tracking stations. Since the DSN supports satellite operations of many different NASA missions, this resource is shared amongst all satellites currently in space.

Chandra's nominal communication schedule consists of 1-hour contacts spaced approximately 8-hours apart. Therefore, over the course of one 24-hour period, the *Chandra* X-ray Observatory Center (CXC) receives telemetry from the observatory three times per day for a total of three hours, on average. Of course, during the periods in which the ground is not in contact with *Chandra*, routine science operations continues autonomously on-board the spacecraft. Each week, a new set of command loads is generated, reviewed, and uplinked to *Chandra* for use in the following week. These command loads contain all the necessary information for the observatory to execute and perform a week's worth of science observations and spacecraft maintenance activities. In a companion paper,[2] we review the command load inspection procedure for the ACIS instrument. The science data and observatory health and safety telemetry are stored on *Chandra*'s solid state recorders (SSR). During a real-time communication contact, these data are telemetered to the ground and transfered to the CXC for data processing (via the Jet Propulsion Laboratory). Another paper in this volume[3] discusses the monitoring and trends analysis of the SSR data. However, since it can take as much as 12-24 hours for the SSR data to be processed, analysed, and hence a putative anomaly found, it is vital that the health and safety status of the Observatory be quickly established during each communication pass. In addition to telemetering SSR data, "live" or real-time telemetry data from the observatory and all instruments, *i.e.*, the current values of all the observatory and instrument house-keeping electronics, are sent immediately to the *Chandra* Operations and Control Center (OCC) during each DSN communication pass.

In this paper, we focus exclusively on the real-time monitoring of the Advanced CCD Imaging Spectrometer (ACIS) on-board the CXO during these one hour communication contacts. In Section 2, we provide a brief synopsis of the CXO and its primary focal plane instruments while Section 3 illustrates the data flow from spacecraft to monitoring. In Section 4 we discuss the method by which we arrived at our set of health and safety limits. In Section 5, we present the real-time monitoring schemes developed for the ACIS instrument. Our conclusions follow in Section 6.

2. CHANDRA X-RAY OBSERVATORY'S FOCAL PLANE INSTRUMENTS

The observatory consists of a spacecraft system and a telescope/science-instrument payload. The spacecraft system provides mechanical controls, thermal control, electric power, communication/command/data management, and pointing and aspect determination. This section briefly describes the two focal plane instruments on-board the CXO, the HRC and the ACIS, while the main emphasis in this paper is the real-time health and safety monitoring of the ACIS instrument. The *AXAF Observatory Guide*[4] and the *AXAF Science Instrument Notebook*[5] contain a wealth of information about the *CXO* and its scientific instruments. More in depth discussions of the Chandra mission, spacecraft, other instruments and subsystems are presented elsewhere.[6,7,8,9,10,11]

2.1. High Resolution Camera (HRC)

The High Resolution Camera, *HRC*, is a microchannel plate (MCP) instrument. It is comprised of two detector elements, a $\sim$ 100 mm square optimized for imaging (HRC-I) and a $\sim$ 20 x 300 mm rectangular device optimized for the Low Energy Transmission Grating (LETG) Spectrometer readout (HRC-S).

The HRC has the highest spatial resolution imaging on *Chandra* – $\leq$ 0.5 arcsec (FWHM) – matching the High Resolution Mirror Assembly (HRMA) point spread function most closely. The HRC energy range extends to low energies, where the HRMA effective area is the greatest. The HRC-I has a large field of view (31 arcmin on a side) and is useful for imaging extended objects such as galaxies, supernova remnants, and clusters of galaxies as well as resolving sources in a crowded field. The HRC has good time resolution (16 μsec), valuable for the analysis of bursts, pulsars, and other time-variable phenomena but has limited energy discrimination, $E/\Delta E \sim 1$ ($<$ 1 keV). The HRC-S is used primarily for readout of the low-energy grating, LETG, for which its large format with many pixels gives high spectral resolution ($>$ 1000, 40-60 $\mathring{A}$) and wide spectral coverage (3 - 160 $\mathring{A}$).

2.2. Advanced CCD Imaging Spectrometer (ACIS)

ACIS is the Advanced CCD Imaging Spectrometer. It is comprised of two arrays of CCDs, one optimized for imaging wide fields (ACIS-I; a 2x2 chip array with 16 arcmin on a side), the other optimized for grating spectroscopy and for imaging narrow fields (ACIS-S; a 1x6 chip array; 8 arcmin x 48 arcmin). Each array is shaped to follow the relevant focal surface. In conjunction with the HRMA, the ACIS imaging array provides simultaneous time-resolved imaging and spectroscopy in the energy range $\sim$ 0.5 - 10.0 keV. When used in conjunction with the High Energy Transmission Gratings (*HETG*), the ACIS spectroscopic array acquires high resolution (up to $E/\Delta E = 1000$) spectra of point sources.[12] The CCDs had an intrinsic energy resolution ($E/\Delta E$) which varied from $\sim$5 to $\sim$50 across the energy range. However, due to radiation damage early in the mission, this has been significantly compromised.[13,14] Nevertheless, approximately 90% of all *Chandra* science observation time available during the first four years of the mission has utilized the ACIS instrument.

ACIS employs two varieties of CCD chips. Eight of the 10 chips are "front-side" (or FI) illuminated. That is, the front-side gate structures are facing the incident X-ray beam from the HRMA. Two of the 10 chips (S1 and S3) have had treatments applied to the back-sides of the chips, removing the insensitive, undepleted, bulk silicon material and leaving only the photo-sensitive depletion region exposed. These "back-side", or BI chips, are deployed with the back side facing the HRMA. BI chips have a substantial improvement in low-energy quantum efficiency as compared to the FI chips because no X-rays are lost to the insensitive gate structures but suffer from poorer charge transfer inefficiency and poorer spectral resolution (prior to launch). In addition, early analysis from on-orbit data indicate that the BI CCDs are more susceptible to "background flares", which may compromise a measurement, than are FI CCDs.[15] These background flares (*i.e.*, rapid increases in detector background) are thought to be a consequence of *Chandra's* radiation environment.[11]

3. OUTLINE OF DATA FLOW

As outlined in the Introduction, there are two data streams that are monitored for health and safety issues: (1) data received from the solid state recorder, and (2) "live" or "real-time" data received directly from the CXO via the DSN. In this section, we will briefly outline the data flow associated with the second stream. The former is presented elsewhere in these proceedings.[3]

Once a communication link has been established with a ground-tracking station, real-time telemetry begins flowing immediately to the CXO Operations and Control Center in Cambridge, MA. The relevant ACIS house-keeping telemetry must be extracted from the raw telemetry before any health and safety monitoring may be performed. To accomplish this task, a C++ software package called ACORN (A Comprehensive object-ORiented Necessity) was written by programmers at the CXC.

In our implementation, the real-time raw telemetry stream is fed to ACORN via a User Datagram Protocol (UDP) port. The raw *Chandra* telemetry consists of approximately 11,000 mnemonic string identifiers (MSIDs). Every spacecraft and instrument sensor, thermistor, meter, *etc.* are identified and tracked via a unique MSID. ACORN decodes the real-time telemetry stream and writes MSIDs, values, and spacecraft times to either a tab-delimited file or standard output. For our purpose, ACORN-decoded data is written to a tab-delimited file so that it may be analyzed. This entire process of real-time raw spacecraft telemetry to output files that can be processed, is depicted in Figure 1.

4. DETERMINING ACIS HEALTH AND SAFETY LIMITS

In order to monitor the health and safety status of the ACIS instrument, a set of MSIDs as well as a set of limits must first be established. In total, there are 65 ACIS MSIDs that are regularly sent by the instrument to the observatory for incorporation into the telemetry stream that constitute the ACIS *hardware* "house-keeping telemetry". These MSIDs consist of components like the camera-body temperature to the ACIS focal plane temperature (please see Figure 2). By and large, these are the principle electronic (*i.e.*, voltages and currents) and temperature MSIDs reported by ACIS.

Prior to launch, as well as during the first 2 years of the mission, there were several sets of "limits" used by various teams within the CXC to ostensibly suit their own particular purpose. The original health and safety limits (*i.e.*, pre-launch) were established based on the qualification tests conducted during the instrumental and observatory thermal-vacuum tests. Therefore, the first task was to update and streamline the use of various limit sets to one

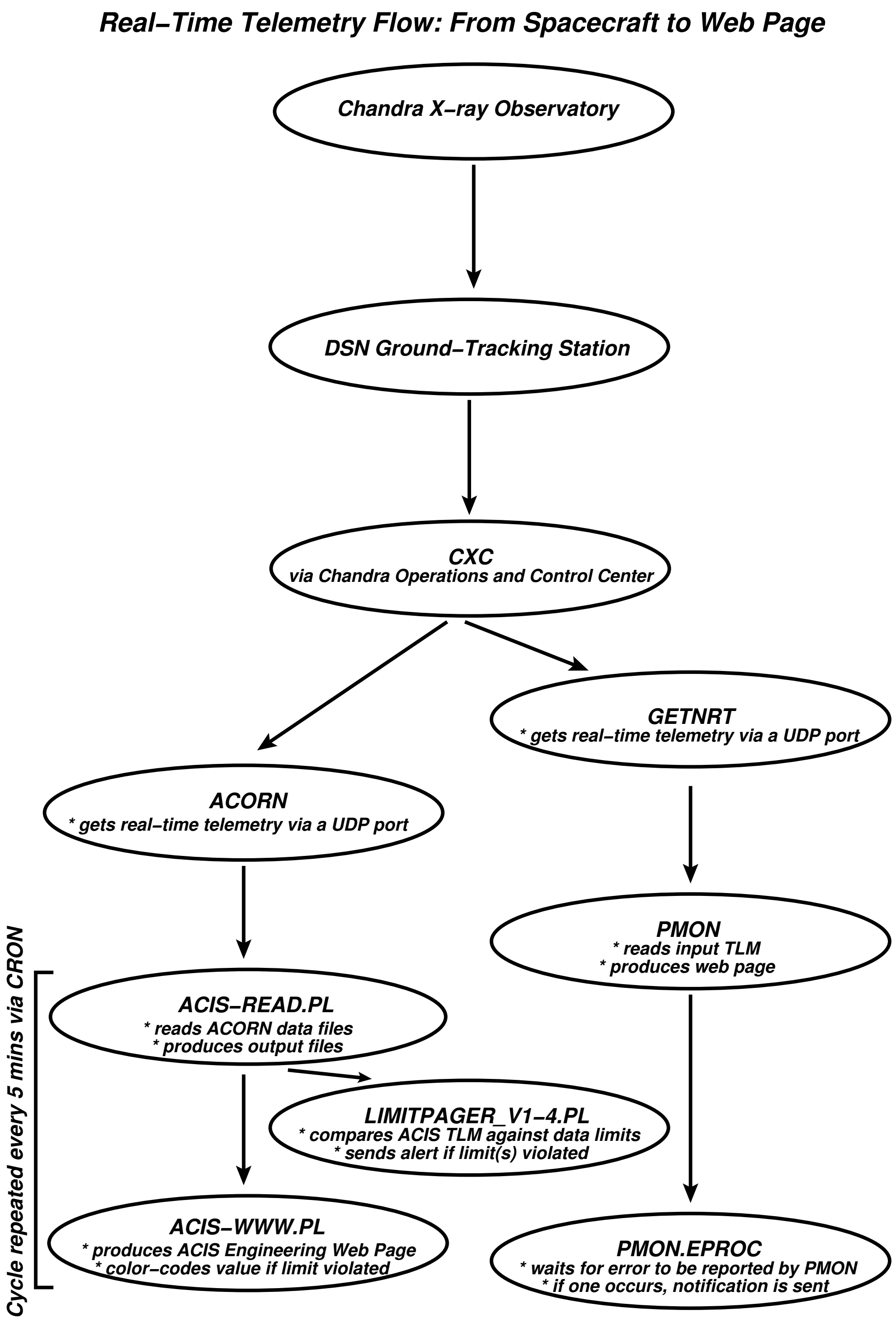

Figure 1. Real-time Data Flow: The pathway by which real-time telemetry from the spacecraft results in ACIS monitoring web pages.

definitive set. Two years into the mission, after sufficient experience had been gained with instrument response to on-orbit use, various members of the CXC convened to identify a robust set of limits to check against the real-time ACIS telemetry feed.

It was quickly decided that one set of limits would not be desirable since there are principally two concerns that would govern what the limits should be: (1) health and safety concerns, and (2) data quality concerns. Clearly, the former is more important than the latter since the former is used to monitor and maintain vital mechanical operation whereas the latter serve to indicate possible reduction in data quality. Moreover, the philosophy of the the health and safety limits is such that should a "red" limit violation occur, the CXC response will be immediate. Should a "yellow" limit occur, further analysis may be performed before any response would be initiated. With this operating principle, two sets of limits were created for each MSID, with each set containing *caution* (color-coded yellow) low and high values and *warning* (color-coded red) low and high values that would be applicable to health and safety concerns as well as concerns that would affect data quality.

Nearly 300 days worth of data from the second year of the mission were analyzed to arrive at the ACIS health and safety as well as data quality "yellow" and "red" limits. Limits from the MIT/ACIS instrument team were compared against this 300-day baseline and modified on a case-by-case basis. For some MSIDs, the concept of either a low or high "yellow" and/or "red" limit has no meaning and so these MSIDs were assigned a nominal value of "999" to indicate such a condition. These limits are presented in Figure 2. Once this definitive set of limits was determined, they were implemented by every group within the CXC that monitor the telemetry from the spacecraft. One caveat that should be noted is that these MSIDs label telemetered sensor readouts such as the camera-body temperatures and the various voltages and currents generated by the ACIS power supply (see figure 2). The ACIS focal-plane temperature, FP-TEMP, is not included with the MSID values sent to ACORN but is extracted from the Digital Electronics Assembly (DEA) house-keeping packets reported by the ACIS flight software. It is unavailable when the flight software is halted or when the DEA house-keeping is disabled.

5. REAL-TIME MONITORING OF THE ACIS INSTRUMENT

There are two different ways in which the health and safety of the ACIS instrument is monitored. The first is by monitoring and limit-checking the 65 ACIS house-keeping MSIDs discussed in the preceding section. The second method is by monitoring the ACIS science data packets produced by the ACIS flight software system. The former is discussed in Section 5.1 while the latter is discussed in Section 5.2. The principle difference between these two methods is that the former monitors telemetry reported by the *hardware* components on ACIS, whereas the latter monitors the *science* telemetry reported by the ACIS flight *software*.

5.1. Monitoring the ACIS House-keeping Telemetry

With the ACIS health and safety limits as well as access to real-time telemetry to perform limit-checking established, we now outline the process by which the ACIS telemetry is monitored and key ACIS personnel notified in case of an anomaly.

As stated in Section 3, ACORN produces tab-delimited ASCII files for a set of ACIS MSIDs. ACORN constantly monitors a given UDP port for spacecraft telemetry. When the telemetry is flowing, *i.e.* when the OCC has established a communication contact with the CXO, data from these MSIDs are appended to various ASCII files. When the OCC is not in contact with the CXO, these ASCII files are not modified and contain data from the last communication pass.

Three PERL scripts were written that facilitate the monitoring process. One PERL script (`acis-read.pl`) reads the ACIS ACORN log files and calculates an average and sigma (based on 10 samples of data) for each MSID that is followed. These values and timestamps are then written to another tab-delimited ASCII file. The second PERL script (`acis-www.pl`) reads these log files and produces an HTML file that displays this information for team members to inspect while at work, home, or on travel (see http://cxc.harvard.edu/acis). The HTML headers instruct the user's browser to ask for a new version of the page once every 150 seconds. This second PERL script also incorporates the instrument "red" and "yellow" limits discussed in the preceding section. If a given MSID deviates from its nominal value such that it falls within the "red" or "yellow" regime, the value for that MSID is either color-coded "red" or "yellow" on the web page. A third PERL script (`limitpager_v1-4.pl`) also reads the ASCII log files produced by `acis-read.pl`. It compares the average value for each MSID reported against its database of "red" and "yellow" limits. If a MSID breaches its nominal value such that it falls within the "red" or "yellow" value span, a pager

ACIS Limits Evaluation

	Health & Safety				Data Quality				
mnemonic	yel lo	yel hi	red lo	red hi	yel lo	yel hi	red lo	red hi	description
1CBAT	-70.50	-52.00	-75.50	-50.00	-63.00	-57.00	-75.50	-50.00	Camera Body Temp A
1CBBT	-70.50	-52.00	-75.50	-50.00	-63.00	-57.00	-75.50	-50.00	Camera Body Temp B
1CRAT	-137.00	-100.00	-142.00	-90.00	-130.00	-125.00	-142.00	-90.00	Cold Radiator Temp A
1CRBT	-137.00	-100.00	-142.00	-90.00	-130.00	-125.00	-142.00	-90.00	Cold Radiator Temp B
1DACTAT	68.00	75.00	65.00	80.00	68.00	75.00	65.00	80.00	DA Collimator-Top Temp A
1DACTBT	-40.00	-5.00	-52.50	0.00	-21.00	-5.00	-52.50	0.00	DA Collimator-Top Temp B
1DAHACU	-998.00	0.16	-999.00	999.00	-998.00	0.16	-999.00	999.00	Detector Assy. Htr Current A
1DAHAT									Detector Assy. Housing Temp A Offset
1DAHAVO	-998.00	1.00	-999.00	999.00	-998.00	1.00	-999.00	999.00	Detector Assy. Htr Voltage A
1DAHBCU	0.20	0.80	-999.00	999.00	0.20	0.80	-999.00	999.00	Detector Assy. Htr Current B
1DAHBT									Detector Assy. Housing Temp B Offset
1DAHBVO	3.50	10.50	-999.00	999.00	3.50	10.50	-999.00	999.00	Detector Assy. Htr Voltage B
1DAHHAVO	-998.00	1.00	-999.00	999.00	-998.00	1.00	-999.00	999.00	DA Housing Htr +28V Input A
1DAHHBVO	25.00	34.00	-999.00	999.00	25.00	34.00	-999.00	999.00	DA Housing Htr +28V Input B
1DE28AVO	26.00	34.00	-999.00	999.00	26.00	34.00	-999.00	999.00	DEA +28V Input A
1DE28BVO	26.00	34.00	-999.00	999.00	26.00	34.00	-999.00	999.00	DEA +28V Input B
1DEAMZT	-20.00	20.00	-37.50	40.50	4.00	12.00	-37.50	40.50	DEA -Z Panel Temp (RT830)
1DEICACU									DEA Input Current A
1DEICBCU									DEA Input Current B
1DEN0AVO	-6.70	-5.90	-7.50	-5.00	-6.70	-5.90	-7.50	-5.00	DEA -6V Voltage A
1DEN0BVO	-1.00	998.00	-999.00	999.00	-1.00	998.00	-999.00	999.00	DEA -6V Voltage B
1DEN1AVO	-16.50	-15.00	-19.00	-14.00	-16.50	-15.00	-19.00	-14.00	DEA -15V Voltage A
1DEN1BVO	-1.00	998.00	-999.00	999.00	-1.00	998.00	-999.00	999.00	DEA -15V Voltage B
1DEP0AVO	5.90	6.52	5.00	7.50	5.90	6.52	5.00	7.50	DEA +6V Voltage A
1DEP0BVO	-998.00	1.00	-999.00	999.00	-998.00	1.00	-999.00	999.00	DEA +6V Voltage B
1DEP1AVO	14.80	17.00	13.00	19.00	14.80	17.00	13.00	19.00	DEA +15V Analog A
1DEP1BVO	-998.00	1.00	-999.00	999.00	-998.00	1.00	-999.00	999.00	DEA +15V Analog B
1DEP2AVO	23.90	26.50	22.00	28.00	23.90	26.50	22.00	28.00	DEA +24V Analog A
1DEP2BVO	-998.00	1.00	-999.00	999.00	-998.00	1.00	-999.00	999.00	DEA +24V Analog B
1DEP3AVO	29.30	32.30	27.00	34.00	29.30	32.30	27.00	34.00	DEA +28V Analog A
1DEP3BVO	-998.00	1.00	-999.00	999.00	-998.00	1.00	-999.00	999.00	DEA +28V Analog B
1DP28AVO	26.00	34.00	-999.00	999.00	26.00	34.00	-999.00	999.00	DPA +28V Input A
1DP28BVO	26.00	34.00	-999.00	999.00	26.00	34.00	-999.00	999.00	DPA +28V Input B
1DPAMYT	-20.00	20.00	-37.50	40.50	1.00	14.00	-37.50	40.50	DPA -Y Panel Temp (RT810)
1DPAMZT	-20.00	20.00	-37.50	40.50	4.00	17.00	-37.50	40.50	DPA -Z Panel Temp (RT830)
1DPICACU	0.90	1.75	-999.00	999.00	0.90	1.75	-999.00	999.00	DPA Input Current A
1DPICBCU	0.70	1.75	-999.00	999.00	0.70	1.75	-999.00	999.00	DPA Input Current B
1DPP0AVO	5.02	5.54	4.75	5.75	5.02	5.54	4.75	5.75	DPA +5V Analog A
1DPP0BVO	5.02	5.54	4.75	5.75	5.02	5.54	4.75	5.75	DPA +5V Analog B
1MAHCAT	210.00	998.00	200.00	999.00	210.00	998.00	200.00	999.00	Door Close Actuator Temp A
1MAHCBT	210.00	998.00	200.00	999.00	210.00	998.00	200.00	999.00	Door Close Actuator Temp B
1MAHOAT	210.00	998.00	200.00	999.00	210.00	998.00	200.00	999.00	Door Open Actuator Temp A
1MAHOBT	210.00	998.00	200.00	999.00	210.00	998.00	200.00	999.00	Door Open Actuator Temp B
1OAHAT	-40.00	20.00	-56.50	36.50	-40.00	20.00	-56.50	36.50	Open Actuator Temp Cold, Side B
1OAHBT	-40.00	20.00	-56.50	36.50	-40.00	20.00	-56.50	36.50	Open Actuator Housing Temp, Side B
1PDEAAT	-10.00	50.00	-36.50	58.50	0.00	50.00	-36.50	58.50	PSMC DEA Power Supply Temp A
1PDEABT	-10.00	50.00	-36.50	58.50	0.00	50.00	-36.50	58.50	PSMC DEA Power Supply Temp B
1PIN1AT	-20.00	30.00	-36.50	36.50	-5.00	30.00	-36.50	36.50	PSMC Temp 1A
1SSMYT	-20.00	20.00	-37.50	40.50	8.00	20.00	-37.50	40.50	Suppt Structure -Y Panel Temp (RT811)
1SSPYT	-20.00	20.00	-37.50	40.50	8.00	20.00	-37.50	40.50	Suppt Structure +Y Panel Temp (RT810)
1VAHCAT	210.00	998.00	200.00	999.00	210.00	998.00	200.00	999.00	Vent Valve Close Actuator Temp A
1VAHCBT	210.00	998.00	200.00	999.00	210.00	998.00	200.00	999.00	Vent Valve Close Actuator Temp B
1VAHOAT	210.00	998.00	200.00	999.00	210.00	998.00	200.00	999.00	Vent Valve Open Actuator Temp A
1VAHOBT	210.00	998.00	200.00	999.00	210.00	998.00	200.00	999.00	Vent Valve Open Actuator Temp B
1WRAT	-90.00	-70.00	-103.50	-60.00	-88.00	-75.00	-103.50	-60.00	Warm Radiator Temp A
1WRBT	-90.00	-70.00	-103.50	-60.00	-88.00	-75.00	-103.50	-60.00	Warm Radiator Temp B
FP-TEMP	-998.00	-102.00	-999.00	-100.00	-122.00	-117.90	-999.00	-100.00	Focal Plane Temp

Figure 2. ACIS Health and Safety MSIDs: This listing is a compilation of all the 65 ACIS MSIDs that are monitored for health and safety reasons. A description and the corresponding "red" and "yellow" limits of each MSID are presented.

Date: Sun, 4 Aug 2002 18:10:42 −0400 (EDT)
From: <author>
To: <distribution list>
Subject: ACIS LIMIT TRIP!

ACIS ALERT During Current COMM Pass!
YELLOW_LO limit tripped 2 times!
MSID: 1CRAT
Last Violation Value: −122.19
****
Current OBSID: 61094
Current Altitude / Direction: 53761 / A
Date and Time: Sun Aug 4 22:10:40 GMT 2002
Check http://asc.harvard.edu/mta/RT/acis/www/acis−mean.html for latest info.

Figure 3. Email Alert Example: An example of what an email alert looks like when the MSID `1CRAT` breaches its "yellow limit".

alert (for "red limit" violations) or an email alert (for "yellow limit" violations) is issued by the script to key ACIS personnel so that they are immediately notified and so that corrective actions may be taken if required. To reduce the probability of false alerts due to either spurious data or a "noisy" communication contact, the data violation must persist for at least 3 samples before an alert is dispatched.

These three PERL scripts are executed every 5 minutes via a CRON task maintained by a general group UNIX account. This way the thorny issue of permission and read/write priviledges is eliminated. When the OCC is in communication with the CXO, the web page produced by `acis-www.pl` is updated with fresh values. When the OCC is not in communication with the CXO, `acis-www.pl` reproduces the last values recorded from the previous communication contact. Since the beginning and end timestamp for each MSID value that went into calculating an average and sigma for that MSID is also presented on the web page, the reader is able to determine whether the displayed value is representative of the current instrument status or whether it is an "old" value from the preceding pass.

This web page, the ACIS Engineering Data Web Page, is a key element in monitoring the health and safety status of the ACIS instrument, and is the primary means by which ACIS anomalies may be identified. Since this web page is world-accessible, it allows key personnel of the CXC to monitor the instrument status whether they are at their office, at home, or even on travel as long as they have internet access. In Section 5.1.1, we provide examples of what was discussed in this section.

5.1.1. Examples

In determining the health and safety limits, it was expected that certain MSIDs would violate their nominal operating range for certain well-known cases. For instance, it is expected that the cold radiators on sides A and B (MSID: `1CRAT` and `1CRBT`, respectively) would enter its "yellow regime" during perigee transit at certain times of the year as the instrument tends to warm-up during this point in the *Chandra* orbit. Since the "red" and "yellow" limits are designed to bracket this MSID's nominal operating temperature range, we expect a violation to occur at perigee transit. Please see Figure 3 for an example of what this alert looks like. Nevertheless, since this is a known condition and since science operation is suspended when the CXO enters the Van Allen radiation belts, the email alerts that would be spawned by `limitpager_v1-4.pl` due to "yellow" violations by `1CRAT` and `1CBAT` are now suppressed when *Chandra* is entering, at, or exiting from perigee transit.

Secondly, as was mentioned in Section 2.2, the spectral resolution of the front-side CCDs was found to have been significantly reduced early in the mission. It is believed that the primary mechanism for this damage is the

Date: Fri, 19 Apr 2002 10:25:54 −0400 (EDT)
From: <author>
To: <distribution list>
Subject: ACIS LIMIT TRIP!

ACIS ALERT During Current COMM Pass!
YELLOW_LO limit tripped 2 times!
MSID: 1DPICACU
Last Violation Value: 0.80
****
Current OBSID: 2953
Current Altitude / Direction: 135915 / A
Date and Time: Fri Apr 19 14:25:52 GMT 2002
Check http://asc.harvard.edu/mta/RT/acis/www/acis−mean.html for latest info.

Figure 4. Email Alert Example: An example of what an email alert looks like when the MSID `1DPICACU` breaches its "yellow limit".

result of 100-200 keV protons scattering off *Chandra*'s mirrors and impacting the CCDs while ACIS was in the focal plane during perigee transit very early in the mission.[13,16,17] To prevent further damage to the ACIS CCDs, a prevention scheme was implemented by the Science Operations Team of the CXC.[18] One aspect of this scheme has been to limit the orbital proton fluence and flux as measured by the proton monitors on-board the ACE and GOES-8 satellites. One way in which the low energy proton populations can become highly elevated occurs when the Sun unleashes a coronal mass ejection (CME).[19] Once the orbital fluence has reached its threshold value,[18] or if one of the EPHIN channels exceeds its threshold value,[18] *Chandra* science may be suspended by ground intervention (in the case of the former) or autonomously by the spacecraft (in the case of the latter). When this occurs, the ACIS front-end processors are powered down and the Digital Processing Assembly's (DPA) input currents decrease such that a "yellow" violation occurs for `1DPICACU` and `1DPICBCU`. The email alerts generated by this violation serve as a confirmation that *Chandra* has indeed suspended science operations because of such an event. Figure 4 illustrates what this email alert looks like when `1DPICACU` has violated its "yellow" limit. Since the ACIS Engineering Data web page makes extensive use of color and includes various images, an example is not included in this paper (although the URL is presented in Figures 3 and 4).

5.1.2. Peripheral Issues

Lastly, there are some peripheral issues that need to be addressed in order to demonstrate the robustness of the health and safety monitoring. The first issue is one of redundancy. If the machine that hosts the CRON task were to shut down either because of an electrical power failure or due to problems local to that host, the scripts would not run, the web page would not be produced, and the limit-checking would not be performed. To solve this problem, we run these PERL scripts and produce the ACIS Engineering Data web page on two different hosts so that we are not prone to a single-point failure. One host, which produces and performs the "primary" web page and limit-checking, is part of a "mission-critical" suite of SUN work-stations. Should this machine go down for any reason, at any time of the day, the Smithsonian Astrophysical Observatory's computer system group is tasked with the responsibility of solving whatever problem may afflict the host as soon as possible. The second host, the "back-up", is run on an ACIS group SUN work-station. Secondly, two additional PERL scripts have been written that deletes old, obsolete ACORN files as well as ensuring that the ACORN process is active on the CPU. If the ACORN process is not found on the CPU, another process is launched. Both of these PERL scripts are also a part of the CRON task that runs on both hosts. Since these have been the primary ways in which the web page may not have been always up-to-date thus far in the mission, we believe we have now developed a scheme of PERL scripts that is robust to a single-point failure and is one that can be relied upon to monitor the health and safety of the ACIS at all times.

ACIS Process Monitor, Wed Jul 31 03:04:10 2002

OBSID: 2572	**ACIS Monitor**	Bilevels: 01100101	Sent: 2002-212Z07:04:10

VCDU: 127295:104	BEP: 7d8a8817	Fmt: 2	Seq: 13726	SCET: 2002-212T07:04:08

2002-212T07:04:06 : BIAS ERROR THRESHOLD EXCEEDED BY FEP_3

Serial Command	CmdID	Result Code	Bytes	Boot:

Run: 3	Slot: 4	ID: 002a6034	Quad: FULL	Start 2002-211T19:23:08

Mode: TE/FAINT	Exp: 3.2 sec	Rows: 1024	Row1: 0	Sum: 1x1	Win: 0

OBSID: 3724	FEP0: S0		FEP1: S3		FEP2: S1		FEP3: S2		FEP4: S4		FEP5: S5	
Exposure		5366		5366		5366		5366		5366		5366
Thresholds		9706		303		412		12610		14291		7639
Filtered		282		41		47		375		596		593
Events		16		13		19		13		15		41
Tot Events		14082		17903		18923		14075		16240		13437
TimeStamp		0183298e		0183298e		0183298e		0183298e		0183298e		0183298e
Oclk A +-	0	-1	0	+1	0	+1	0	+1	0	-2	0	-1
Oclk B +-	0	+1	0	+2	0	+2	0	+1	0	-1	0	+1
Oclk C +-	0	+1	0	+2	0	+1	0	+2	0	-1	0	+1
Oclk D +-	0	+1	0	+1	0	-1	0	-1	0	-1	0	+1
Bias Errs		0		0		0	********			0		0

SciReport Run:	OBSID:	Start:	Bias:
Exps:	Sent:	FEP:	CCD:

Software Housekeeping				DEA Interface Housekeeping	
2002-212T06:51:09	SWVER	1	30	2002-212T07:04:02	00001024
TIMERCB_INVOKE		640	0	RELAY	0x001f
2002-212T06:52:17	SWVER	1	30	ADC_TMP_BEP_PCB	15.3 C
TIMERCB_INVOKE		640	0	ADC_TMP_BEP_OSC	13.4 C
2002-212T06:53:24	SWVER	1	30	ADC_TMP_FEP0_MONG	20.1 C
TIMERCB_INVOKE		640	0	ADC_TMP_FEP0_PCB	16.8 C
2002-212T06:54:30	SWVER	1	30	ADC_TMP_FEP0_ACTEL	20.0 C
TIMERCB_INVOKE		640	0	ADC_TMP_FEP0_RAM	18.6 C
2002-212T06:55:37	SWVER	1	30	ADC_TMP_FEP0_FB	14.2 C
TIMERCB_INVOKE		640	0	ADC_TMP_FEP1_MONG	21.0 C
2002-212T06:56:43	SWVER	1	30	ADC_TMP_FEP1_PCB	17.8 C
TIMERCB_INVOKE		640	0	ADC_TMP_FEP1_ACTEL	20.9 C
2002-212T06:57:51	SWVER	1	30	ADC_TMP_FEP1_RAM	19.9 C
TIMERCB_INVOKE		640	0	ADC_TMP_FEP1_FB	14.4 C
2002-212T06:58:56	SWVER	1	30	ADC_FPTEMP_12	-248.7 C
TIMERCB_INVOKE		640	0	ADC_FPTEMP_11	-119.7 C
2002-212T07:00:04	SWVER	1	30	ADC_DPAGNDREF1	-0.15 V
TIMERCB_INVOKE		640	0	ADC_DPA5VHKA	5.04 V
2002-212T07:01:10	SWVER	1	30	ADC_DPAGNDREF2	-0.15 V
TIMERCB_INVOKE		640	0	ADC_DPA5VHKB	5.06 V
2002-212T07:02:17	SWVER	1	30	ADC_DEA28VDCA	30.56 V
TIMERCB_INVOKE		640	0	ADC_DEA24VDCA	25.06 V
2002-212T07:03:23	SWVER	1	30	ADC_DEAM15VDCA	-16.66 V
TIMERCB_INVOKE		640	0	ADC_DEAP15VDCA	16.11 V
				ADC_DEAM6VDCA	-6.41 V
				ADC_DEAP6VDCA	6.04 V
				ADC_RAD_PCB_A	0.05 m
				ADC_GND_1	-0.00 V

Figure 5. ACIS PMON Web Page: The monitor receives Chandra telemetry from real-time contacts, extracts ACIS fields, and writes an HTML file.

5.2. Monitoring the ACIS Flight Software Science Telemetry

The second method by which the health and safety status of the ACIS instrument is monitored each and every DSN communication pass is via the ACIS Real-Time Process Monitor (PMON).

The ACIS PMON also receives *Chandra* telemetry during each real-time contact via a UDP port. A series of shell scripts has been written that decommutates the raw telemetry, extracts ACIS science fields, and produces an HTML file that displays these data. This HTML file presents information that is relevant to the ACIS science run currently in progress. Information such as which CCDs are in use, the number of x-ray "events" found in a given exposure frame, the overclock values for each node amplifier on a given CCD, *etc.*, are displayed. A PMON HTML example is presented in Figure 5.

When PMON receives fresh telemetry, it writes an HTML file every 30 seconds. Like the ACIS Engineering Data web page, the headers in the PMON HTML page instruct the user's browser to ask for a new version of the page once every 30 seconds. However, when not in real-time contact, or in a non-ACIS telemetry format, some of the displayed values may be very out-of-date. The user, normally ACIS operations personnel, must inspect the relevant time fields to determine whether the data are still useful. As is the case for the scripts used in monitoring the ACIS house-keeping electronics and temperatures, a PERL script has been written that checks to see if the PMON process is active on the CPU. If it is not, another PMON process is launched. This PERL script is run every 5 mins via another CRON task.

Date: Wed, 31 Jul 2002 03:03:49 −0400 (EDT)
From: <author>
To: <distribution list>

PMON error reported by xcanuck at Wed Jul 31 03:03:49 EDT 2002
Spacecraft Time: 2002−212T07:03:39
Error Message: OBSID 2572 BIAS ERROR THRESHOLD EXCEEDED BY FEP_3
Check http://asc.harvard.edu/acis/RT/acisrt.html for latest info.

Figure 6. PMON Pager Alert: This is an example of a recent in-flight anomaly determined via the ACIS PMON and the pager alert issued to ACIS personnel to announce its discovery.

Over the course of three years of successful flight operations, there have been three issues that the ACIS Operations team (combining personnel from the CXC as well as the MIT/IPI team) have had to solve with regards to issues of ACIS science operation. One, on a few seemingly random occassions, the ACIS bias maps have been interleaved with ACIS science data. The effect of which is to compromise the science data for that particular CCD and unless corrected, the condition will persist. Since this anomaly was diagnosed, changes to the way in which ACIS is commanded via the weekly load have been made such that we have not seen a repeat of this anomaly, the cause of which is still unknown. The second issue is one where the bias map reports a large number of parity errors. The cause of this anomaly is also not known, however, we have not seen this condition since November of 1999 and it may have been the result of a single-event upset. The last issue is one in which a fatal error is reported by the back-end processor on ACIS. This causes software patches to the ACIS flight software to be lost from memory and requires ground intervention by the ACIS Operations team to resolve. Since all three of these anomalies can be determined via the ACIS PMON, a shell script was written that spawns a pager alert (since immediate attention is required) if one of these anomalies were to occur during a real-time contact . An example of this type of alert is presented in Figure 6 and a comment announcing one of these errors can also be seen on the PMON HTML page (the third line from the top in Figure 5).

6. CONCLUSIONS

The ACIS instrument on-board the *Chandra X-ray Observatory* has returned some of the most exquisite, dramatic, and detailed images of the x-ray universe ever seen. The information returned, and the knowledge gained from these ACIS observations, has allowed us to explore another wavelength in rich detail that will undoubtedly propel astronomy forward in this new millenium. However, the continued success of *Chandra*, and ACIS in particular, is dependent upon diligent operation of the spacecraft as well as the prompt notification, and hopefully resolution, of any anomalies encountered in-flight. In this paper, we have presented two distinct methods by which the telemetry from ACIS during *each and every* real-time contact is monitored, and in the event of an anomaly, how alerts are quickly dispatched to key ACIS personnel. As new anomalies are discovered in-flight, we will endeavour to find ways to incorporate their monitoring within our current scheme. After three years of highly successful flight operations, we believe we have developed a very robust and reliable suite of PERL and HTML scripts that will help ensure ACIS' continued success.

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