Chandra monitoring, trending, and response

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ABSTRACT

The *Chandra X-ray Observatory* was launched in July, 1999 and has yielded extraordinary scientific results. Behind the scenes, our Monitoring and Trends Analysis (MTA) system has proven to be a valuable resource. With three years worth of on-orbit data, we have available a vast array of both telescope diagnostic information and analysis of scientific data to access Observatory performance. As part of *Chandra's* Science Operations Team (SOT), the primary goal of MTA is to provide tools for effective decision making leading to the most efficient production of quality science output from the Observatory. We occupy a middle ground between flight operations, chiefly concerned with the health and safety of the spacecraft, and validation and verification, concerned with the scientific validity of the data taken and whether or not they fulfill the observer's requirements. In that role we provide and receive support from systems engineers, instrument experts, operations managers, and scientific users. MTA tools, products, and services include real-time monitoring and alert generation for the most mission critical components, long term trending of all spacecraft systems, detailed analysis of various subsystems for life expectancy or anomaly resolution, and creating and maintaining a large SQL database of relevant information. This is accomplished through the use of a wide variety of input data sources and flexible, accessible programming and analysis techniques. This paper will discuss the overall design of the system, its evolution and the resources available.

Keywords: Chandra, real-time systems, trending

1. INTRODUCTION

The MTA subdivision within the SOT is charged with providing an overview of telescope performance as it affects the science quality and efficiency of the Observatory. The group often serves as a clearinghouse of data and analysis tools in concert with the engineers, instrument experts, and scientists. In the following sections we discuss the inputs, processes, and outputs of the MTA system. Section 5 gives several examples of our work, followed by a short summary of future developments.

A summary of the major spacecraft systems and our monitoring categories is given in Table 1. With the philosophy that any subsystem component, from solar array currents to HRMA and ACIS temperatures, could potentially impact the wholly scientific objectives of the mission, the MTA project offers a novel approach to developing and maintaining the processes that correlate trends within and between *Chandra's* state-of-the-art systems. This paradigm easily facilitates the exchange of information between MTA, systems engineers, instrument experts, and the scientific community.

The MTA team makes fervent use of the World Wide Web. We maintain literally thousands of dynamic web pages on a daily basis. The home page with links to all of the products described below, as well as to many other MTA and *Chandra X-ray Center* (CXC) resources is http://cxc.harvard.edu/mta/sot.html.

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Table 1. Main MTA monitoring categories (*Chandra* subsystems).

ACIS	Advanced CCD Imaging Spectrometer - CCD science instrument
HRC	High Resolution Camera - Micro-channel plate science instrument
EPHIN	Electron, Proton, Helium Instrument - on-board radiation detector
HRMA	High Resolution Mirror Assembly
OBA	Optical Bench Assembly
SIM	Science Instrument Module
OTG	Transmission grating (HETG/LETG) mechanisms
HETG	High Energy Transmission Grating (contains High Energy Grating (HEG) and Medium Energy Grating (MEG))
LETG	Low Energy Transmission Grating
PCAD	Pointing Control and Aspect Determination
ACA	Aspect Camera
CCDM	Command and Control Module
SPC	Spacecraft/Solar Array temperatures and electronics
EPS	Electrical and Propulsion Systems
COMP	Ground computed psuedo-msids (eg. total power)
GRAD	Ground computed temperature gradients

2. INPUTS

The MTA system is designed to use a variety of interchangeable inputs. New data arrives at the CXC approximately every eight hours. Communication with the telescope takes place through the shared resource of NASA's Deep Space Network so continuous contact is not possible. Rather, data is stored on-board and dumped during our one hour supports, roughly three times a day. During real-time contacts live data feeds are sent directly to the CXC. Dumped data generally arrives within five hours via the Jet Propulsion Laboratory.

For raw telemetry decommutation a C++ software package called ACORN[?] (A Comprehensive object-ORiented Necessity) was produced in-house. ACORN is capable of reading from both the real-time telemetry stream through a UDP port or from several types of archived dump files. *Chandra* telemetry is coded in over 11,000 MSIDs (mnemonic string identifiers). Each spacecraft meter, sensor, thermistor, boolean value, etc. is identified and tracked with an unique MSID. Standard MTA processing currently uses about 900 MSIDs. ACORN decodes the telemetry stream and provides times, MSIDs, and values to either the standard output or to a tab-delimited file for MTA tools to use as input. There is also a GUI interface for a quick review of the data.

Input data is also obtained from CXC standard processing pipeline products. We frequently use files from all levels of available processing. Level 0 are essentially the raw telemetry dump data in FITS format, organized by subsystem. Level 1 are aspect corrected science products for each OBSID (observation identification number) such as event lists used for calculations of total dose maps for each of the detectors. Level 2 files are further cleaned events lists and scientific analysis such as source files, which we use to track detected source characteristics to draw conclusions about instrument quantum efficiency, mirror alignment, focus, etc. All of these standard products are easily accessible from the *Chandra* data archive in FITS format.

There are many cases when the above two inputs are not sufficiently convenient or complete. Often RDB format or otherwise delimited ASCII files are used. These types of files are simple to read and write and allow easy access to data from many sources or customizations of data originally in other formats.

In addition to handcrafted and standard CXC products, the MTA system gathers data from outside sources using lynx and anonymous ftp commands. This method is used especially to obtain data from other space missions for radiation monitoring.

3. PROCESSES

The standard MTA data processing pipeline was written in C++ by CXC Data Systems (CXCDS) programmers who continue to provide generous support on complex, object-oriented, Java, or other higher order implementations. The pipeline is run by CXCDS operators who handle all standard data processing and reprocessing tasks. Two modes of operation exist: custom (manual) processing and automated processing. Custom processing occurs on the arrival of each data set to obtain a quick overview of the data and any potential problems. Latency on custom processing is generally just a few hours. Automated processing lags 1-2 days behind, but provides consistent, archive-quality output.

For more customized applications, there is an effort among the MTA group to create simple, yet sophisticated and powerful processes. This allows for rapid software development by MTA data aides. Our programming tools of choice are UNIX shell scripts, PERL, IDL, and HTML. Often a single task is accomplished by a combination of programs. Shell scripts call PERL programs which generate and execute IDL batch files then create or modify an HTML file, for instance. Shell commands are simple and natural to implement and test for many cleaning and maintenance tasks (moving or removing files more than ten days old, for instance). Shell scripts are also handy ways to write wrapper tools around *Chandra's* suite of data analysis programs (CIAO *). For more complicated jobs, PERL provides a readily available platform with all the looping and number crunching capability we have found necessary. PERL has also been utilized in CGI codes, making for interactive, user friendly web pages. Finally, we use IDL for graphical and analytically intense applications.

Programming is almost always approached with the intent of eventual automation of the task at hand. We rely heavily on the UNIX time daemon (cron) to autonomously run jobs at various times of the day, updating data files and web pages and monitoring processing status and telemetry. MTA's crontab consists of over 50 periodic tasks.

All MTA jobs are divided among three UNIX machines, all running Solaris 5.8. The main real-time analysis and standard processing occurs on a Sun Ultra10/440, with a completely independent real-time flow on an UltraE450 for redundancy. A separate UltraE450 handles daily tasks and individual cron jobs.

4. OUTPUTS

MTA data and analysis is provided to the community in essentially three forms. Time- and mission-critical alerts are send via e-mail, standard and custom presentations are posted on the world wide web, and all monitored values are archived in a database.

4.1. Alerts

We have created a number of e-mail aliases to which alert messages can be sent when spacecraft state violations or other problems are detected. Namely, sot_red_alert links to mail accounts and pagers for the most urgent messages, while sot_yellow_alert exists for less urgent or informational notices. MSIDs are monitored in both real-time and processed, near real-time modes as described below.

4.1.1. Real-time alerts

During each real-time support, MTA runs PERL scripts which create a dynamic web page known as the *Chandra* Snapshot (see Sect. 4.2.1). The PERL code incorporates selected limit checks to color code the display, indicating any state violations. In addition, these limit checks will generate messages to sot_red_alert if either of the conditions listed below are found:

- SCS107 is DISABLED (Science instrument safing procedure has run)

*http://cxc.harvard.edu/ciao/documents.html

- FMT (telemetry format) is 5 (*Chandra* is in safe mode)

As a safeguard against false notification, the violation must persist for three minutes before an alert is triggered. Once a message is sent, a semaphore is created which prevents further alerts for the same violations. This semaphore is autonomously removed when the condition subsides for three minutes.

Due to the susceptibility of the ACIS detector to CTI degradation caused by low energy protons, MTA also plays a key role in monitoring the radiation environment. E-mail and pager messages are issued when warranted by data monitored from other spacecraft and models. In particular, we gather ACE, GOES-8, GOES-10, and the Costello Kp index data from solar.sec.noaa.gov. An ACE P3 (112-187 keV) integrated fluence greater than 3.6e8 particles/cm^2/steradian/MeV within two hours triggers a sot_red_alert. For more information on radiation monitoring see (Cameron, 2002).[?]

4.1.2. Near real-time alerts

Our decommutation software[?] provides the capability to send e-mail and/or pager alerts to the responsible scientists for a given subsystem when limit violations are detected. In addition, we have developed a more robust and customizable PERL-based package called *config_mon*. This software autonomously receives spacecraft dump data within a few hours of the completion of each communications pass. This data contains the record of spacecraft state for the time period between the last two real-time contacts. The values are reviewed and compared against expected, as-planned values and operational limits using output products from mission planning and a limits database. When violations are found, e-mails and pages are directed as appropriate. *Config_mon* currently monitors science instrument (SIM) position, focus position, pointing (right ascension, declination, roll), and gratings positions, reporting violations to sot_yellow_alert. We have not yet triggered any erroneous alerts. In all cases thus far, messages sent have been the result of a miscalculated expected state or a previously identified configuration mismatch (usually following an SCS107 activation, where the SIM is stowed and observing has stopped). The latter type of false alert is now prevented by linking the real-time semaphores (Sect. 4.1.1) to *config_mon*. In addition to the sot_yellow alerts, *config_mon* is easily extensible. It currently also monitors reaction wheel rates for the PCAD team and several instrument temperature MSIDS for the ACIS team.

4.2. World Wide Web

Our main vehicle for data dissemination is the world wide web. We maintain a large suite of dynamic web pages, presenting real-time data feeds, standard processing displays, customized studies, and weekly and monthly reports. As much as possible these pages are updated automatically on timescales from one minute to one month.

We are also experimenting with emerging WAP (Wireless Application Protocol) technologies to provide anytime, anywhere access to the most important mission-critical and decision-making data via web-enabled cellular phones or other wireless devices. Currently available on the wireless site [†] are a version of the Snapshot (see Sect. 4.2.1), ACE data, *Chandra* Radiation Model (CRM) data, the real-time contact schedule, and the current week's observing schedule. This has proven to be a valuable quick-look resource and development is ongoing.

4.2.1. Real-time web pages

As mentioned in Sect. 4.1.1, the capstone of our real-time web pages is the *Chandra* Snapshot [‡], which provides easy access to the most relevant information from the most recent telemetry. The page is run using a dedicated ACORN feed and underlying PERL code to format the ASCII output and color code (Table 2) particular items of interest. A cron job checks for new data and updates the values once per minute during real-time contacts. The CGI allows users to review "snapshots" from the past three days and incorporates the latest non-spacecraft

[†]http://cxc.harvard.edu/mta/WL/sot.wml, on a WAP-enabled device
[‡]http://cxc.harvard.edu/cgi-gen/mta/Snap/snap.cgi

Table 2. *Chandra* Snapshot color scheme.

Color	Indication
white	unchecked
green	within limits/matches expected state
yellow	warning limit/suspicious state
red	limit violation/does not match expected state
blue	unchecked (for quantities that are usually checked, for instance RA, Dec, and Roll may not be checked in NMAN mode, and EPHIN rates are not checked in the radiation zones)
purple	stale data (value is more than 15 minutes old, usually means quantity is unavailable in current telemetry format)

data such as ephemeris and radiation environment information. We also provide a text only version for faster access from remote or dial-up connections.

A more comprehensive, but less sophisticated real-time display of MSIDs was created for the Flight Operations Team engineers [§]. Known as the State of Health, there are nine pages covering 1011 MSIDs. Pages exist for PCAD, CCDM, EPS, Thermal, Propulsion, SIM/OTG Mechanisms, a configuration summary, overall summary (top level), and a safe mode summary for quick assessments of telescope health. The design and implementation is similar to that of the Snapshot, with two dedicated ACORN feeds and nine parallel PERL scripts (one for each page) updating every minute during live contacts. There is only limited state checking on the top level and configuration pages and no capability for browsing to earlier epochs.

4.2.2. Standard web pages

Spacecraft subsystem monitoring pages are produced each day as part of the standard data processing pipeline. Plots and statistics are displayed for each mnemonic and values are highlighted according to a green-yellow-red color scheme similar to that shown in Table 2. These plots are reviewed by the MTA team and violations or other concerns are reported each week. Also part of the standard pipeline are automated science analyses. We provide quick-look images and statistics of all observations. Gratings observations are further processed using MIT's HAK (HETG Analysis Kit) code[?] both automatically and manually. CTI observations (Sect. 5.3) are further processed in the pipeline to display the appropriate centroid and pulse height information.

Although not part of the processing pipeline, we have been working to revamp and standardize our trending tools. Using IDL and extracting values from the MTA databases (Sect. 4.3), we provide plots and statistics for all the monitored MSIDs. Three iterations are performed on each datum: five minute average values, daily minimum values, and daily maximum values. The system attempts to predict the next six months' behavior by estimating a first and second derivative. The first derivative is simply a first order (linear) fit to the data. The second derivative is a first order fit to the slopes between smoothed data points. Past, current, or predicted future limit violations are highlighted with the green-yellow-red color scheme (Table 2). Figure 1 shows an example of the trend page output.

4.2.3. Custom web pages

The flexibility of the web, PERL, and IDL, and the easy access to MTA data allows for the timely creation and presentation of customized studies called for by various teams based on current spacecraft needs or anomalies. Many of these investigations become new monitoring and trending tasks with the addition of automated scripts and cron jobs. A few examples of the types of customized studies we have done are: a listing of OBSIDs and simple metrics for calibration observations, tracking ACIS corner pixel, rejected events, and bad pixel trends,

[§]http://cxc.harvard.edu/cgi-gen/mta/SOH/soh.html

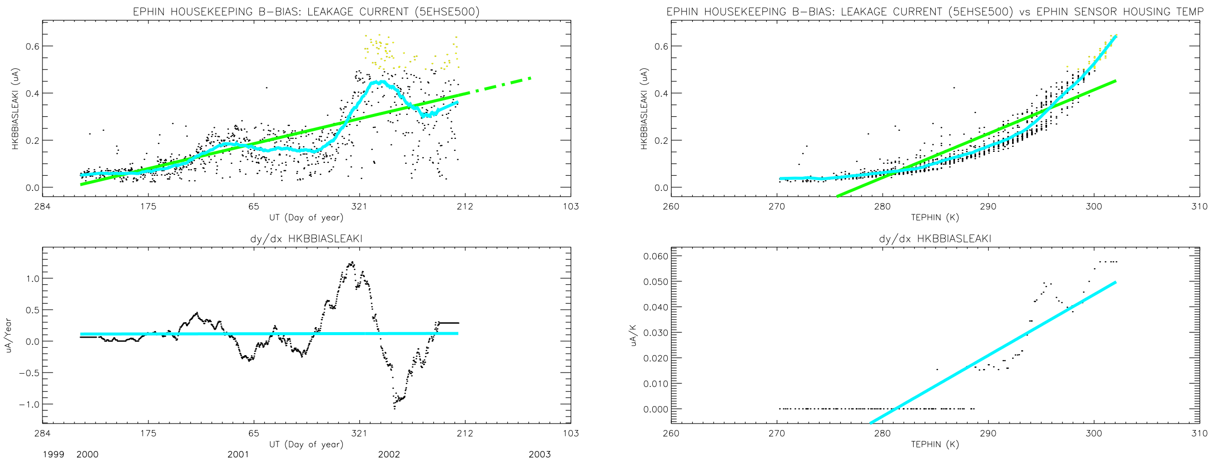

Figure 1. Examples of trending plots from the EPHIN subsystem. The IDL code permits plots of MSID versus time (left) or MSID versus another MSID (right). The top panel in each shows the 5-minute averaged data, a linear fit line, and a smoothed curve. The bottom panels show the slopes between adjacent points on the smoothed curve and a linear fit, that is the second derivative.

timing, position, and voltage requirements for each HETG and LETG insertion and retraction, and PCAD gyro drift rates. Other examples are further explained in Sect. 5.

4.3. Database

At the end of the standard data processing pipeline, a five minute average and standard deviation is computed for each monitored MSID and ingested into an SQL database. Currently there are eight databases and 43 individual tables, divided by subsystem. See (Wolk, 2002)[?] for a complete description. The first phase of the databases are currently being backfilled to the beginning of the mission with completion expected by the fall of 2002. These tables contain engineering-type data (temperatures, voltages, currents, and bi-level, ON/OFF mnemonics). The next phases will expand the databases to include higher processed data. We will add tables such as detected source characteristics for use in HRMA and detector response trending, gratings observation line analyses, science instrument background rates, and CTI measurements.

The CXC Data Systems programming team has developed an extremely handy tool called DataSeeker to extract and merge tables from the MTA databases. This tool is available with either a web interface or command line mode, which makes it convenient for casual users or incorporation into automated scripts. See (Overbeck, 2002)[?] for details on the design and implementation. DataSeeker seamlessly merges data from different tables, keying on time. While most MTA studies have looked at changes over time, we can now investigate other correlations such as temperature versus EPHIN rates or pitch angle versus power consumption. Another important feature of the tool is the ability to incorporate outside tables on the fly. DataSeeker will merge users' RDB files with existing database tables, again keying on time. This has proven valuable as we test the implementation of the next generation of tables and as users have requested data that was not included in the first phase.

5. APPLICATIONS

The MTA system is designed for convenient, efficient data access and flexible analysis. In response to current anomalies and spacecraft concerns, we strive to quickly gather and organize relevant information and post analyses to web pages. In most cases we then attempt to automate updates as the mission progresses and the pages become a part of the daily, weekly, or monthly monitoring and trending regimen. Below are four examples from different areas that have evolved in this way. The SOT home page provides links to these and many others.

5.1. Flight dynamics - Radiation environment

As mentioned previously here and elsewhere, the monitoring and modeling of *Chandra's* radiation environment is a key focus of MTA and the entire SOT. To that end, we created a project to combine all of our radiation information in one place, on one timescale. The ACIS Radiation Correlations page is updated three times a day with the latest data from *Chandra* and other missions. The top level page displays a stacked four panel plot of count rates in various channels and a six panel strip plot of spacecraft configuration for the past week. There are links to the same plots on monthly, yearly, and mission timescales.

The count rate plots are compiled from varied sources. Current GOES-8 (3 channels, 0.8-4, 4-9, 40-80 keV) and ACE (5 channels, 47-65, 112-187, 310-580, 761-1220,1060-1910 keV) rates are obtained via anonymous ftp from solar.sel.noaa.gov, concatenated with previous data and saved locally for longer-term trending. EPHIN values from channels E1300, P4GM, and P41GM are pulled from standard data processing, pipeline produced level 1 files. The raw SCA00 values are then extracted from the MTA databases and scaled to fit on the same plot. Finally, ACIS count rates on CCDs 5, 6, and 7 are added from level 1 event files.

The configuration representation is similarly cobbled from disparate sources. Gratings use, detector use, RADMON (times when autonomous safing is disabled due to radiation belt passage or SCS107 activation), and format (FMT) intervals are determined using output from a local daily comprehensive state summary. Time intervals when *Chandra* is in the radiation zone are computed as periods when any of the three level 1 EPHIN channels are above 1/3 of the RADMON trip threshold, while the indicated SCA00 SAT intervals are defined as periods when the EPHIN SCA00 channel is saturated. Intervals of CTI observations are taken from the CTI trending pages (Sect. 5.3). Spacecraft altitude is read from NASA ranging files and scaled to fit on the plot. Finally, outputs from the *Chandra* Radiation Model are incorporated to show when *Chandra* encounters solar wind, magnetosheath, or magnetosphere conditions.

This analysis has helped in validating many decisions on whether to stop observations due to high radiation. We also see that our current ACE alert and autonomous safing levels are appropriate as ACE, GOES, EPHIN, and ACIS count rates coincide. A closer look at the timing intervals (time between RADMON DISABLE and perigee pass, for instance) justifies the present mission planning practice of "padding" the radiation zones. Thus, lost science time is minimized while protecting ACIS from damage.

5.2. Mechanical performance - SIM

A sudden inability to translate between *Chandra's* science detectors could end the mission. In light of that, we carefully monitor and trend the performance of the mechanical Science Instrument Module (SIM) translation table. There are four nominal aimpoint positions along the Z-axis of the spacecraft which can be selected and adjusted for science observations. The translation table can also be shifted up or down (along the X-axis) to adjust the telescope focus. The expectation is that the SIM may slow down over time as lubricant and mechanical parts wear out. Total life expectancy of the translation table is on the order of 10,000 moves (we've done about 1200 so far). Our SIM pages track three MSIDs: TSCPOS (translation table position, in motor steps), FAPOS (focus position, in motor steps), and MRMMXMV (the maximum motor voltage applied for the most recent move in either X or Z directions).

As the *Chandra* dump data is processed as part of our near real-time monitoring, an auxiliary output is a record of SIM position. The IDL-based SIM trending tool runs once per day and first condenses this list, saving only time and position entries just before and after each move. We define ranges for each of the four instrument arrays and compare the times it takes to translate between each combination. Average move times and standard deviations are computed for each combination. The position information is only available once per major frame in the telemetry which yields a resolution of 32 seconds. This is a longer time that it takes to translate between the two ACIS arrays, so moves between ACIS-I and ACIS-S are not included in general trend statistics. We also make simple position versus time plots and use mission planning output products to check and plot the as-planned and as-flown instrument positions (always within one motor step, unless a safing action has occurred). The maximum motor voltage values are plotted versus time and never exceed 10V. Three iterations of the web pages exist. One showing the above metrics and plots for the entire mission, then zooming in to show the details for the past week, and again for the past 24 hours.

Total mission trends are displayed on a separate page. Here we track TSCPOS and FAPOS cumulative number of moves and cumulative distance moved (in motor steps). There is also a computation of average monthly seconds/motor step. Plotted versus time, we see a constant rate of 0.00137 s/step and no change in the move rate over the course of the mission thus far.

5.3. Instrument performance - CTI

During the first few orbits of the Observatory in 1999, the front-illuminated CCD chips of ACIS were unexpectedly damaged by low energy protons within Earth's Van Allen radiation belts. The damage is manifested as a deterioration of the charge transfer inefficiency (CTI) which results in decreased energy resolution as a function of distance from the readout nodes. Standard operating procedure is now to stop observations and move ACIS from the focal plane during belt transit. Just before and after belt passage on each orbit an observation is obtained using *Chandra's* internal calibration source. The source produces Al Kα, Ti Kα, and Mn Kα emission which is independently analyzed by several groups to monitor and trend further degradation.

MTA's standard processing pipeline produces a comprehensive analysis of all individual CTI measurements. A histogram of the calibration signal ADU values is plotted as seen at each of 160 chip locations across the ACIS array (10 chips $\times$ 4 nodes/chip $\times$ 4 row locations/node). Our CTI metric for each node is defined as the slope/intercept of a linear fit to peak ADU versus row number. Customized MTA PERL scripts collect the latest individual metrics on a daily basis, apply a detrending algorithm to eliminate biases due to the outside radiation environment, and create postscript plots of CTI metric versus time for each node. Combining four nodes, averages are also calculated for each CCD and linear fits are made to all. Each weekly MTA report cites the average detrended ΔCTI/day (~1e-8) for MnKα across the entire ACIS-I array. The monthly report presents ΔCTI/day values for each node and plots the monthly mean CTI versus time.

While continued deterioration of the CTI is inevitable, a decrease in the rate of change is evident. This indicates a success for our radiation zone safing routine, again justifying the sacrifice of some observing time in exchange for a prolonged, productive use of a key science instrument. Work continues among the SOT and ACIS experts to develop pre- and post- exposure schemes to mitigate the CTI effect.

5.4. Science quality - Gratings observations

The ultimate goal of the MTA project is to ensure the highest quality, most efficient science output. One of the ways this is accomplished is through a consistent analysis of all gratings observations. This has been a manual process, but through continuous improvement in the underlying HAK code,[?] it is becoming more automated. The original MTA task list included several elements in this area including monitoring zero order locations, dispersion angles, resolving power (E/ΔE), and line fits. These tasks and others are handled nicely by HAK, so we simply create a covering web page to display the HAK output for each observation.

The standard data processing pipeline produces a level 1.5 events file for gratings observations. This is generally output within two days following the observation, then is used as input to HAK. The IDL-based code produces HTML and RDB output displaying grade and energy filtered events. The analysis continues with finding the zero order location. With the zero order determined, HAK computes the FWHM of the zero order image and of the readout streak (for ACIS), which MTA uses as a metric of HRMA focus. HAK also measures the dispersion angles of the HEG, MEG, and LEG spectra as appropriate, compares the grating's dispersed spectra with the pulse height determined spectra of the zero order image (for ACIS), and fits any detected lines in the dispersed spectra. A line analysis RDB table is created for each arm of the spectra, with columns for energy, FWHM, and E/ΔE.

This process also facilitates easy trending. Data from each individual observation are compiled for zero order location, zero order PSF, E/ΔE, and dispersion angle, then plotted versus time. Currently, there is a manual filtering step to sort point sources from extended sources and to eliminate bad quality data. Zero order positions and dispersion angles appear consistent throughout the mission. No significant change is seen in the telescope focus. The on-orbit energy resolution falls within expectations for HEG and MEG combinations, but appears slightly below predicted values for LEG observations. These compiled gratings metrics will become part of the MTA databases in a future phase.

6. FUTURE WORK

The MTA system continues to evolve with the addition of new data sources, improved software and processes, and enhanced, more user friendly outputs. By using automation as much as possible we are able to continually expand our offerings instead of constantly maintaining and updating the current work. The near future will see a more sophisticated trending package, increasing our ability to predict upcoming problems or limit violations. We hope to replace our current linear fits with higher order analyses. The MTA databases have made many new types of investigations easily and quickly possible, and will continue to do so for both the MTA group and all other users. They will be expanded to include higher level data such as point source characteristics, spectral line characteristics, CTI data, and science instrument background rates. Meanwhile, MTA will proceed to respond to spacecraft issues and anomalies as requested by flight directors, engineers, or instrument teams with custom reports to aid in the optimized, efficient operation of the *Chandra X-ray Observatory*.

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