Detecting EUV Transients in Near Real Time with ALEXIS

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Abstract. We discuss the ALEXIS automated transient detection system, the statistical approaches used to locate and assess potential transients, and the software tools and databases used to help identify possible counterparts.

1. Introduction

The Array of Low Energy X-ray Imaging Sensors (ALEXIS) experiment consists of a mini-satellite containing six wide angle EUV/ultrasoft X-ray telescopes (Priedhorsky *et al.* 1989, and Bloch *et al.* 1994). Its scientific objective is to map out the sky in three narrow ($\Delta E/E \approx 5\%$) bandpasses around 66, 71, and 93 eV. During each 50 second satellite rotation period the six telescopes, each with a 30° field of view and a spatial resolution of 0.25°, scan most of the anti-solar hemisphere of the sky. The project is a collaborative effort between Los Alamos National Laboratory, Sandia National Laboratory, and the University of California-Berkeley Space Sciences Laboratory. It is controlled entirely from a small ground station located at Los Alamos.

The mission was launched on a Pegasus Air Launched Vehicle on April 25, 1993. An incident at launch delayed our ability to properly analyze the data until November of 1994. In January of 1995, we brought on line automated software to routinely carry out the transient search. After the data is downlinked from the satellite, the software processes and transforms it into sky maps that are automatically searched for new sources. The software then sends the results of these searches by e-mail to the science team within two hours of the downlink. This system has successfully detected the Cataclysmic Variables VW Hyi, U Gem and AR UMa in outburst, and has detected at least two unidentified short duration EUV transients (Roussel-Dupré *et al.* 1995, Roussel-Dupré 1995).

2. Logistical Issues

Because ALEXIS is a spinning satellite, it is an ideal platform with which to study the time variability of the EUV cosmos. The main thrust of this effort is to 1) detect EUV sources at known and unknown locations, 2) provide notification of transients in near real time to enable immediate follow-up from other observatories and 3) create a time history of observed sources for comparison with previously published catalogs to aid in determining long duration variability from EUV sources. Three methods are currently being used to detect EUV transients in the ALEXIS data: 1) daily automated sky map searches, 2) manual inspection of daily sky map and 3) archival search. Details of the search algorithms used are discussed in the next section.

Currently, the 12, 24 and 48 hour accumulation sky maps are searched as a routine part of the post-pass data processing. Eight on-line databases (Einstein Slew, EUVE, ROSAT-2RE, Yale Bright Star, Downes CV, TOAD CV, Gliese, and White Dwarf catalogs) are then automatically cross correlated for likely counterparts. Point source locations, source fit parameters and potential counterpart information are then sent via e-mail to the science team. A recent addition to this effort has been to generate summary tables with this pertinent information and maps for these position which are then made accessible from the ALEXIS web page[1] to the satellite team for evaluation. In the near future, a pager will alert the on-duty scientist to significant transient detections found in the most recent data. Another feature of the web page is that for a list of locations for 1) 40 sources with good potential for detection by ALEXIS spanning a range of system types (i.e. CV's, RS CVn's, ALGOL systems, flare stars, etc), 2) 12 EUV bright sources and 3) associated near-by blank fields as control locations, the count rate if it exceeds a certain threshold in a one degree box and other information about the detection are kept in a database. This can then be searched on-line to provide information about possible long term variablity from these systems as well as use the blank field locations to provide a quick-and-dirty idea about the detection statistics. In addition to the on-line catalogs, we also use SIMBAD to search for likely candidates and the WEB SKYVIEW page to compare with other catalogs and other observations from various experiments.

To determine whether or not a real time detection is viable several critical checks are made. If a source passes all of the credibility tests, we then send out e-mail alerts to variable star observers around the world requesting groundbased observations to help determine the optical counterpart.

3. Software and Statistical Issues

From the downlink to the sky maps, all ALEXIS data is analyzed in-house, using a combination of C and IDL routines (Bloch, Smith and Edwards 1992), as well as a few assorted shell and perl scripts. From the sky maps, which are binned into quarter-degree pixels on an Aitoff projection, two additional routines, both written in IDL, were developed for automated point source detection and characterization.

The routine `lampfind` detects point sources and quantifies the confidence that they are not statistical fluctuations above a background. The background is estimated from the counts in a square annulus of size 13×13 pixels with an inner hole of size 5×5. The source region is the central 3×3 square. We assume

[1] http://nis-www.lanl.gov/nis-projects/alexis

that the effective exposure for the background annulus is approximately equal to that of the central region. The background annulus has area $A_B = 144$ and the central source kernel has $A_S = 9$, so if there are C_B counts (photons) in the background, then the probability of seeing C_S or more counts in the source kernel is given by an explicit formula $p = I_f(C_B, C_S)$ where I_f is the incomplete beta function, and $f = A_S/(A_S + A_B) = 0.0588$. This is taken to be the p-value for that source, and it is computed for every potential source location (essentially, every pixel) in every sky map. Lampton (1994) suggested a table-lookup approach which is efficient when maps are large, count rates are low, the ratio f is constant over the map, and the desired number of significance levels is small. In other regimes of parameter space, direct computation of I_f for each potential source is more efficient. We have implemented a hybrid algorithm which incorporates both methods, using the more efficient of each case. The algorithm is used to create "significance" maps.

These p-values are loosely associated with expected false alarm rates. Since they are computed for every pixel in the map, we require a very low threshold to prevent many false alarms in each map. Although an individual source might report a p-value of 10^{-6} we look at many more than 10^6 potential source locations over the course of a month, and so we expect to see a number of these sources. Further, because 1) our p-value estimates at the individual locations might be inaccurate due to artifacts (such as nonuniform background), and 2) the individual locations are not independent of each other (the source kernels and background annuli overlap in space, and the 24 and 48 hour maps overlap in time), it is difficult to extrapolate reported p-values to a confidence that a given source finding is real.

To calibrate our interpretation of p-value, we performed several Monte-Carlo experiments. We made "fake" sky maps (which by construction did not include true sources), applied `lampfind` to these maps, and kept track of how many "sources" were found, and what their reported p-values were. The actual numbers depended on the details of how the fake sky maps were created, but the overall result was that it was not unusual to see upwards of 100 false alarms per month at the at the $p < 10^{-6}$ level. Currently, we log all sites with p-values less than $10^{-3.5}$, and send e-mail for all sites with p-values less than 10^{-6}, but we don't really raise our eyebrows unless $p < 10^{-7.5}$.

Having identified a candidate source, `cashmin` estimates parameters and confidence intervals for location, source strength, background strength, and width of the point-spread function. This routine uses the approach outlined by Cash (1979) that involves minimizing the statistic $C = 2\sum_{i=1}^{N}(e_i - n_i \ln e_i)$, where n_i is the observed number of counts in the i-th bin (pixel), and e_i is the expected number of counts, according to a model that is parameterized as a gaussian on a flat background.

Although the Cash statistic has a χ^2 distribution, it is not written as a "sum of squares", and therefore the conventional application of the Levenberg-Marquart algorithm does not apply. However, it is possible to modify the L-M algorithm so that it can efficiently minimize the Cash statistic. In particular, let D_{ij} be the partial derivative of e_i with respect to the j-th component. Then, the L-M algorithm can be applied by using curvature matrix $\mathbf{A}$ and data vector

β where

$$A_{jk} = \sum_i (n_i/e_i^2) D_{ij} D_{ik} \tag{1}$$

$$\beta_j = \sum_i (n_i/e_i - 1) D_{ij} \tag{2}$$

Compared to the Powell minimization procedure, the L-M method converges appreciably faster.

Since the detection and characterization of point sources is automated, it is possible for unusual circumstances (the most common occurs when a potential point source is near the edge of the scan path) to give rise to completely nonsensical results. We have implemented a few sanity checks to filter out some of these.

For example, we use the Poisson dispersion index to assess whether the background annulus truly is a Poisson background. We break the annulus into N equal-area "pixels". If n_i is the number of counts in the i-th pixel, then the index

$$\frac{\sum_{i=1}^{N}(n_i - \overline{n})^2}{\overline{n}} \tag{3}$$

where $\overline{n}$ is the average number of counts per pixel, is distributed as a χ^2_ν with $\nu = N - 1$ degrees of freedom. This statistic is computed and reported for every source, and when it is unusually large, we tag it as probably spurious.

Due to features not yet full characterized in the ALEXIS background, the ultimate sanity check is still human.

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