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Cosmic Ray Rejection with NGST

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Abstract. The Next Generation Space Telescope (NGST) will perform wide-field imaging in the high-radiation environment of deep space. Outside any protective magnetic fields, cosmic rays will produce many charged-particle events on the imaging detector, affecting as much as 10% of the field-of-view during a baseline 1000-second obervation. We present an algorithm that identifies cosmic ray events in a series of non-destructive readouts during an observation. Test results, in which over 99% of of the cosmic rays are identified and removed without significant degradation of the accumulated image data, are also presented.

1. Introduction—Why Reject Comic Rays?

The Next Generation Space Telescope (NGST), planned for launch in 2007, will be a large aperture, passively-cooled observatory concentrating on the infrared (IR) part of the spectrum. One of the primary missions of the NGST is to provide infrared deep images of distant (high-redshift) galaxies. As of this writing, the project team's goal is to push the NGST observation bandpass to wavelengths as long as 10 microns and beyond. To do this, the telescope's mirror and optical assembly must be kept extremely cold—on the order of 40 K. In order to achieve this low temperature without expensive and massive active cooling equipment, the telescope must be located in deep space. Therefore, the NGST is planned to be launched into an L2 halo orbit, about 1 million miles from the Earth.

This puts the NGST beyond the protective influence of any planetary magnetic field, exposing it to a large number of cosmic rays. When a cosmic ray passes through the detector, its charge will falsely trigger the detector, ruining the data in that part of the detector. During a baseline 1000-second exposure, we anticipate that 10% of the detector will be hit by a cosmic ray. This high level of data loss will significantly impact NGST's science return.

2. Rejecting Cosmic Rays

By "rejecting" cosmic rays, we are referring to techniques to digitally analyze image data and identify and discard cosmic ray events in the detector, preserving only clean data. We can accomplish this by reading the detector frequently and then identifying cosmic rays as unusual events on the detector.

The NGST detectors will have non-destructive read-out capability. Therefore, we can read the detector multiple times during an observation while keeping the integrated observation data. The detector is assumed to have a 16-bit dynamic range and an intrinsic read noise uncertainty of ± 15 electron units. We unrealistically assume, for now, that there are no systematic errors and that we know the dark field and flat field completely. (We plan to add non-trivial dark field and flat field components in future tests.)

Our cosmic ray identification algorithm involves performing 65 non-destructive reads on the detector. We designate these values S_0, S_1 and so on up to S_{64}. S_0 is performed at the start of the sequence (t=0) and the remaining reads are distributed evenly throughout the 1000-second observation (i.e. $t_i = i * 1000/64$). For the purpose of identifying cosmic rays, we compute the differences $D_0 ... D_{63}$, where $D_i = S_{i+1} - S_i$. We then identify cosmic rays events as being instances where $Abs(D_i - Median(D_i)) > 5 * AbsDev(D_i)$. We use the median and absolute deviation (instead of the more traditional mean and standard deviation) because the former are more robust when the data sample contains outliers (Press et al. 1986). In particular, we discovered that the median and standard deviation failed when a data sample was impacted by multiple cosmic rays (0.6% of the detector will be impacted by multiple cosmic rays). We use the absolute value of the difference to avoid biasing the data; since a few data reads (> 1 in 10^4) will randomly lie more than 5 deviations from the median, we must be careful to discard all of the "natural" outliers in both directions from the mean as well as the cosmic rays.

If a cosmic ray is detected in interval j, we repeat this algorithm for $D_0 ... D_{j-1}$ and for $D_{j+1} ... D_{63}$, and so on until no cosmic ray candidates are found. Since we are looking for events at the 5-deviation level, we expect that fewer than 1 "good" data value in 10^4 data points will be rejected falsely.

3. Finding Flux Values

After rejecting cosmic rays, we have a series of data read values $S_0 ... S_{64}$ and a list of zero or more outliers from the mean for the series, the vast majority of which should be cosmic ray events on the detector. To calculate the value of the flux of the object, we apply the optimum slope-fitting routine to the up-the-ramp data, discarding the outliers. (We are concerned only with the slope—the increase in detector counts over time. The zero-point of the line is not needed for this calculation.)

We use a variant on the linear least-squares fit for each segment of consecutive data reads that are not impacted by cosmic rays. We compute a covariance matrix for the data values $M_{i,j}$, which is a tridiagonal matrix where $M_{i,i} = S_i + 2 * \sigma^2$, ($\sigma$ is the readout noise, ± 15 electron units), $M_{i,i+1} = M_{i,i-1} = -\sigma^2$

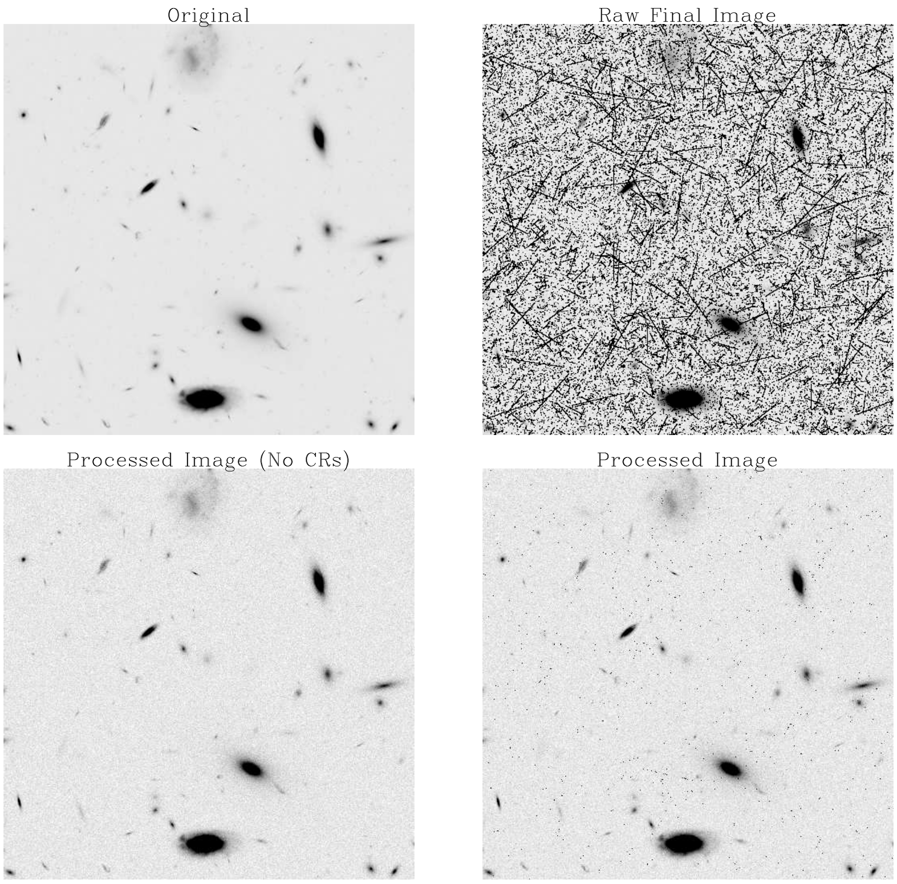

Figure 1. Sample Results using simulated NGST data. Clockwise from upper left: Simulated NGST field of view (Im & Stockman 1998); Simulated FOV as read directly from hypothetical NGST detector (includes noise & detector cosmic ray events, 1000-second exposure); Processed image including cosmic ray removal; Processed image generated from observations with cosmic rays turned off in data simulator.

and $M_{i,j} = 0$ where $j \neq \{i-1, i, i+1\}$. We then compute $C_{i,j} = M_{i,j}^{-1}$, and find the slope of the line $A = \Sigma_{i=0}^{n-1}(S_i * \Sigma_{j=0}^{n-1} C_{i,j})$.

The slope A is computed for each line segment that is not interrupted by a cosmic ray event. Multiple slopes are then combined into a single value using $S_{out} = \frac{\Sigma_{j=1}^{\#segs}[A_j*(N_j)(N_{j-1})(N_{j+1})]}{\Sigma_{j=1}^{\#segs}(N_j)(N_{j-1})(N_{j+1})}$, where A_j is the slope of line segment j and N_j is the number of data reads making up segment j.

4. Results

As seen from Fig. 1, the cosmic ray rejection algorithm removes most of the cosmic ray events from the detector. 114319 cosmic ray events occured on the detector during the 1000-second observation shown here. 1669 cosmic rays, just over 1% of the total, survived the detection and removal process.

If left unremoved, the cosmic ray events in the detector completely ruined 10.3% of the image. The cosmic ray removal process left 1.4% of the image as completely lost, and, because it threw out data reads, reduced the signal-to-noise in 10.2% of the image (including false-positive identifications). The algorithm is still in need of refinement; there were 606 pixels falsely identified as being impacted by cosmic rays along with the 1669 surviving cosmic rays.

4.1. When to reject Cosmic Rays?

Due to financial and communications restrictions, we expect that cosmic ray rejection may have to be done on-board the NGST. We expect the NGST data downlink to be approximately 1.6×10^6 bits per second for 8 hours per day for a total of 5.35GB per day. The near-IR detector alone will contain 64 million 16-bit pixels, for a raw data content of 128MB per data read. For 80 1000-second observations per day, the near-IR camera alone will produce 10GB per day. This requires a data compression ratio of a factor of 2 (Nieto-Santisteban et al. 1999). However, if we wished to perform cosmic ray rejection after downlink, the data from all 65 data reads would have to be downlinked. This would require a communication rate of more than 600 GB per day, requiring a compression ratio of over 100.

5. Conclusion

We can identify and remove 99% of cosmic ray events on the NGST detector. While there is room for improvement, the data quality and information content are largely preserved by this algorithm. This cosmic ray rejection method provides a way to combine 65 images into one, and contributes a significant amount of data compression. This, in turn, loosens one limiting factor on the NIR camera size due to downlink capability. However, this will require significant computer resources to properly handle a full 8k $\times$ 8k pixel detector.

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