Analysis of Data from the Balloon Borne Gamma RAy Polarimeter Experiment (GRAPE)

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The Gamma Ray Polarimeter Experiment (GRAPE), a balloon borne polarimeter for 50~300 keV gamma rays, successfully flew in 2011 and 2014. The main goal of these balloon flights was to measure the gamma ray polarization of the Crab Nebula. Analysis of data from the first two balloon flights of GRAPE has been challenging due to significant changes in the background level during each flight. We have developed a technique based on the Principle Component Analysis (PCA) to estimate the background for the Crab observation. We found that the background depended mostly on the atmospheric depth, pointing zenith angle and instrument temperatures. Incorporating Anti-coincidence shield data (which served as a surrogate for the background) was also found to improve the analysis. Here, we present the calibration data and describe the analysis done on the GRAPE 2014 flight data.

GRAPE

The Gamma RAy Polarimeter Experiment (GRAPE) is a balloon borne Compton polarimeter optimized for 50-300 keV gamma rays. GRAPE was flown initially in 2011. An improved version (improved shielding and larger detector arrays) was flown in 2014.

The configuration flown in 2014 had 24 detector modules (Figure 1). Each module consists of 36 plastic and 28 CsI(Tl) scintillator elements mounted on a multi-anode photo-multiplier tube (MAPMT). PC events are defined as events that interact in one plastic element and one CsI(Tl) element. Ideally, these are events in which a photon scatters from the plastic to the CsI(Tl). These are the events that carry with them the signature of polarization. The module array is completely enclosed by both active shielding (plastic scintillator) and passive lead shielding (Figure 2). Lead collimators are used to define a 20° FoV. This instrument assembly is inside a pressure vessel that is maintained at 1 atm pressure and can be moved in elevation. An inertia wheel assembly is used to point the entire gondola in azimuth.

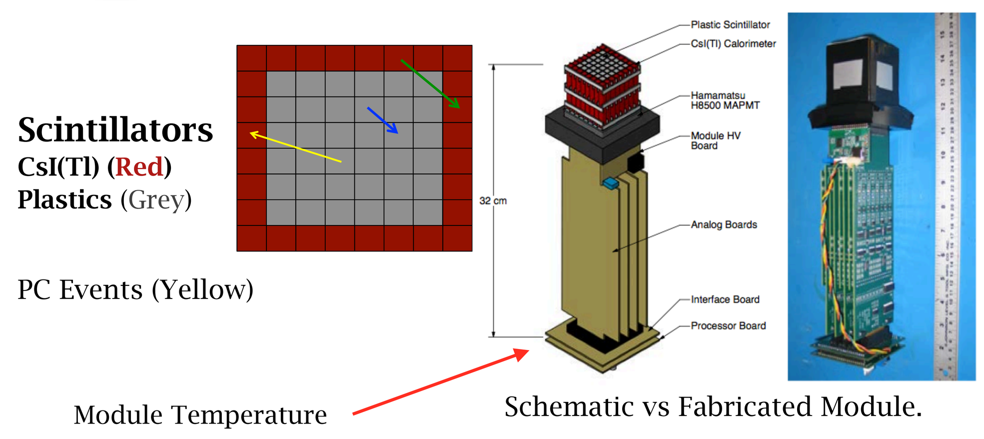


Figure 1: Module and the scintillator array.

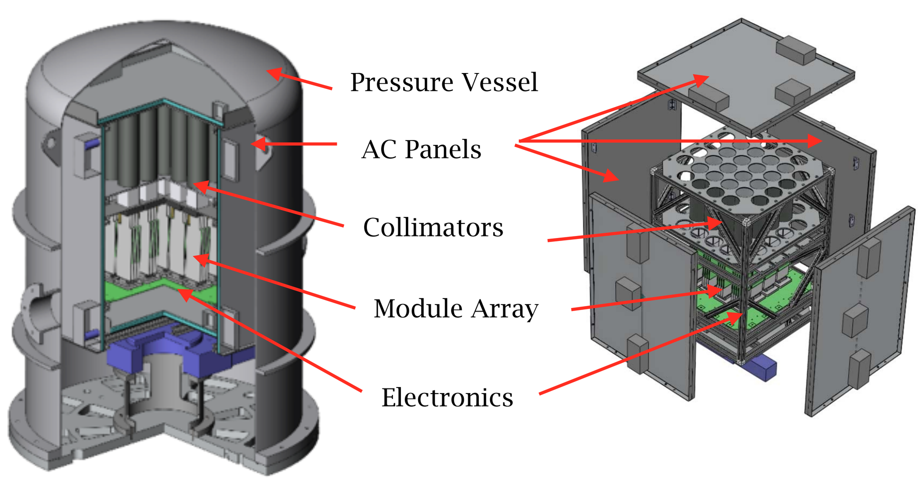


Figure 2: Pressure vessel, collimators and AC panels

Calibration

GRAPE is a Compton polarimeter which works on the principle of Compton scattering, where the photons prefer to scatter at right angles to the incident electric field vectors.

Figure 3 shows a typical ideal azimuthal scattering from polarized source. We define a modulation factor (μ) and the fractional polarization (Π) by the following equations:

$$\mu = \frac{C_{\max} - C_{\min}}{C_{\max} + C_{\min}} \qquad \prod = \frac{\mu}{\mu_{100}}$$

Here $C_{\max}$ and $C_{\min}$ are the maximum and minimum counts as shown in *Figure3*. μ_{100} is the modulation factor for a 100% polarized source typically obtained from simulations. We obtained a value of 0.63 ± 0.02 [3]

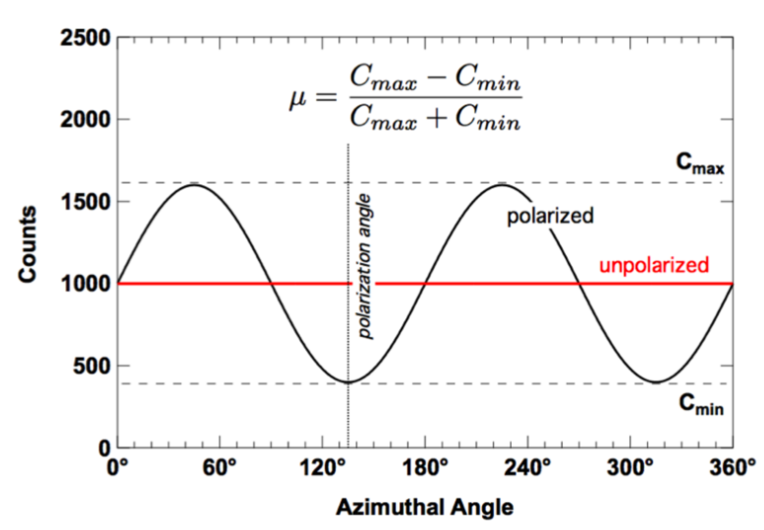
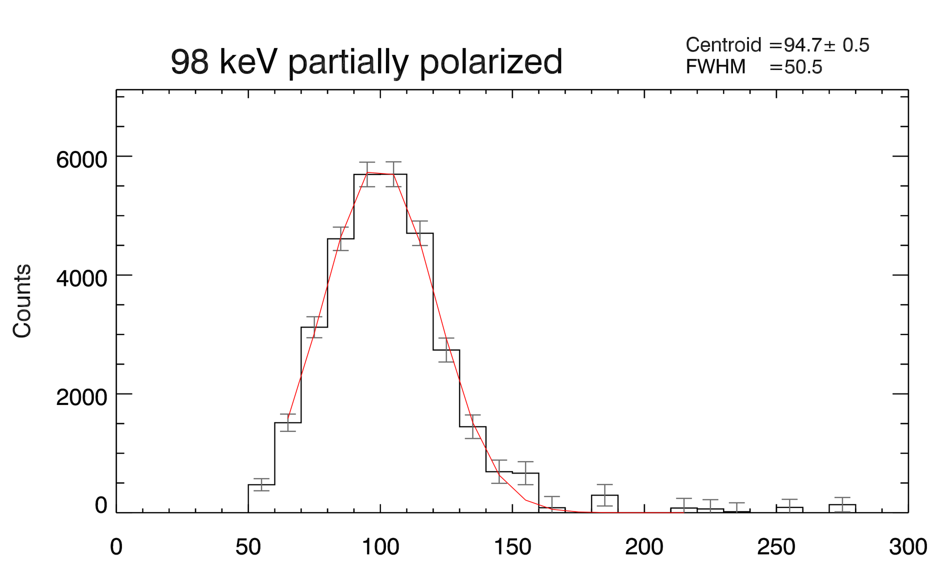


Figure 3: A typical ideal azimuthal distribution from a polarized source.



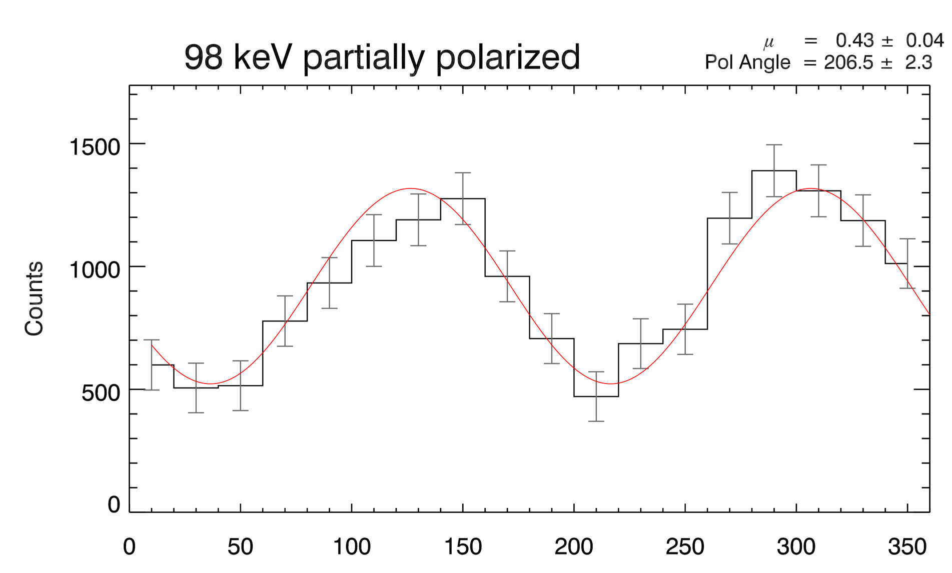


Figure 4a (left) : Energy loss spectrum of a sample 98 keV partially polarized source. The partially polarized source is created by scattering a 122 keV ^{57}Co at 90 deg.
Figure 4b (Right): Azimuthal distribution of the sample 98 keV partially polarized source and the respective polarization angle and modulation factor.

2014 Flight Data

The GRAPE payload was launched on September 26th, 2014 from Fort Sumner, New Mexico. During the flight, GRAPE observed the Sun, Cygnus X-1 and the Crab, along with two background regions in the sky that we refer to as BGD2 and BGD4 . The background regions were regions in the sky that did not have known sources above our sensitivity threshold. During the flight, the Sun was not active and Cygnus X-1 was at a low intensity state (as determined from Fermi-GBM data). So these data could also be used for estimating the background during the Crab observation (our primary scientific target). The payload spent 14.4 hours at float. The Crab was observed for only 1.8 hours. Our flight plan had included 8 hours of data on the Crab, but the flight was terminated before all of the data could be collected. The variation of PC rate with time for various observations is shown in Figure 5.

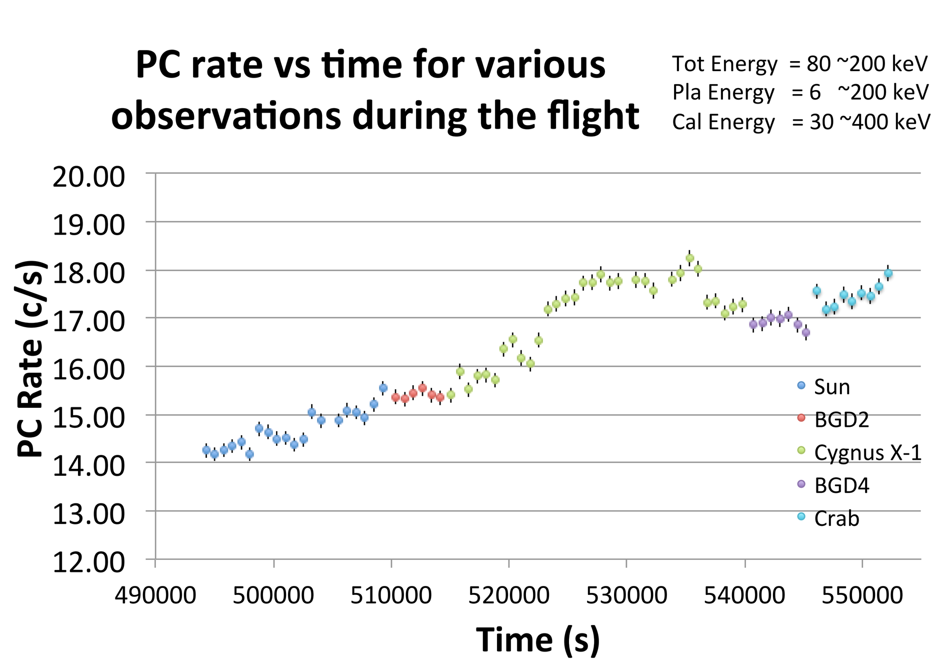


Figure 5: Counting rate vs time during float. PC events carry the polarization signature with them.

2014 Flight Data contd.

Estimating the background for the Crab observation is a challenging task. The background is influenced by various instrumental parameters like atmospheric depth, pointing zenith angle, temperatures, etc. The counting rates of the active anti-coincidence (AC) shield panels provide a measure of the charged flux, which is also linked to the instrumental background. We have addressed the problem of background estimation using Principle Component Analysis (PCA).

In Figure 6 we show some of the instrumental housekeeping parameters that could be related to the instrumental background. The zenith angle is the angle between zenith and the pointed elevation. The average module temperature is the average of the temperatures associated with the module electronics. The scintillator air temperature is the temperature of the air near the scintillator elements. The total AC rates are the summed rate of each of the individual AC panels. Parameters such as these have been used as input to the PCA algorithm. The goal of the PCA is to estimate the instrument al background rate (for PC events) in terms of the various housekeeping parameters.

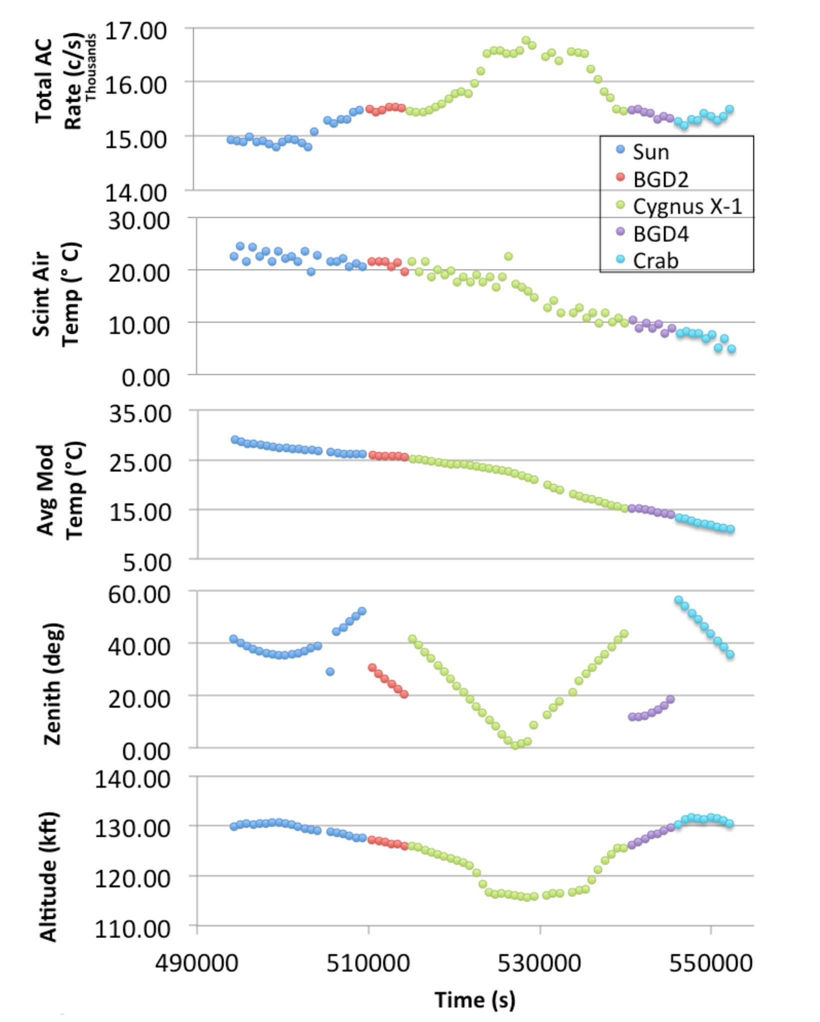


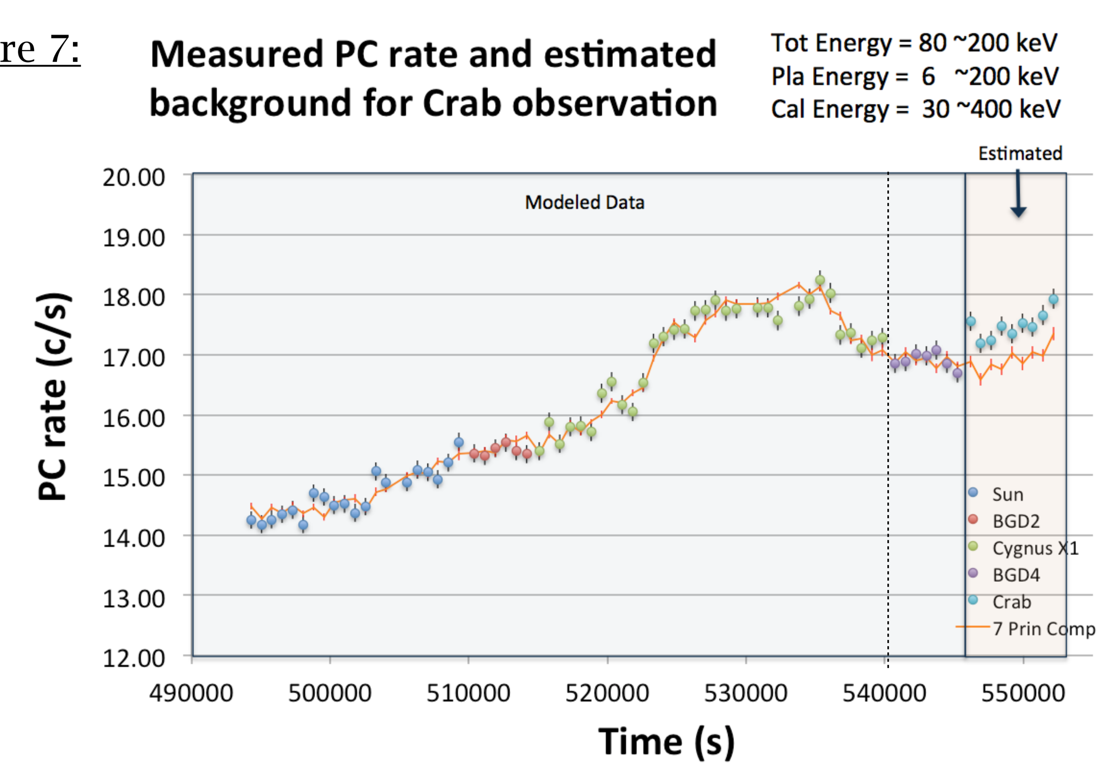
Figure 6: Various instrumental parameters during flight.

Principle Component Analysis

PCA uses a linear combination of the input parameters to define a new set of parameters called principle components. Each of the principle components is associated with an eigenvalue of the correlation matrix of the input parameters. These eigenvalues define the variation present in the data. The relative magnitude of the eigenvalue is a measure of how much that principle component contributes to a description of the data. Principle components associated with smaller eigenvalues contribute very little to an accurate description of the data. In this way, one can select a limited number of principle components (that is typically less than the number of input parameters) to provide a sufficiently precise description of the data. We choose 99% variation to define the number of significant principle components. The first 7 principle components covers 99% of the variation. We fit the data as a linear combination of these 7 principle components (new set of parameters) and use this model to predict the background level during the observation of interest.

To verify the PCA approach, we first used data from observations of the Sun, BGD2 and Cygnus X-1 to estimate the background counting rate for BGD4 data. The difference between the measured counting rate and estimated counting rate for BGD4 is **(0.27 ± 0.58) c/s.** This result validates the use of PCA for estimating the background counting rate.

Figure 7:



Next we extended the analysis to estimate the background counting rate for the Crab observation using data from the Sun, Cygnus X-1 and the two background regions. The difference between the measured counting rate and estimated background counting rate is **(5.06 ± 0.58) c/s.** This represents clear evidence for a signal from the Crab.

Summary

Using the estimated source and background counting rates for the Crab observation, we can determine the corresponding minimum detectable polarization (MDP). The 99% confidence level MDP (a measure of the polarization sensitivity) is given by the equation shown on right. For the limited 1.8 hour Crab observation (all of which was at large zenith angles), the MDP for the integrated Crab flux (integrated over all pulse phases) is 79%. If we consider only the off-pulse phase period of the pulsar, we get an MDP > 100%, indicating that there was insufficient data collected during this flight to make a meaningful polarization measurement for the off-pulse data. Had we measured the Crab for a full transit, our polarization sensitivity levels would likely have been sufficient to measure a polarization at the level reported by Dean et al. (2008) [2] and Chauvin et al. (2016)[4] .

$$MDP_{99} = \frac{4.29}{\mu_{100} C_S}\sqrt{C_S + C_B} \quad [1]$$

Minimum Detectable Polarization. Here, C_S is the source counts, C_B is the background counts and μ is the modulation factor of the instrument for a 100% polarized source (typically obtained via simulations).

[1] Weisskopf, M. C. , Elsner, R. F. , Hanna, D. , Kaspi, V. M. , O'Dell, S. L. et al. The Prospects for X-ray Polarimetry and its Potential use for Understanding Neutron Stars. *In Neutron Stars and Pulsars: About 40 Years After the Discovery: 363rd Heraeus Seminar*, 2006.
[2] Dean, A. J. , Clark, D. J. , Stephen, J. B. , McBride, V. A. , Bassani, L. et al. Polarized Gamma-Ray Emission from the Crab. *Science,* 2008.
[3] Connor, T. . EXAMINING CELESTIAL POLARIZATION WITHTHE GAMMA RAY POLARIMETER EXPERIMENT (GRAPE). PhD thesis, University of New Hampshire, 2012.
[4] Chauvin, M. et al. Observation of polarized hard X-ray emission from the Crab by the PoGOLite Pathfinder. **MNRAS 456, L84–L88** (2016)

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