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Fitch, John E., M.S.

Rice University, 1988
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THE DESIGN AND DEVELOPMENT OF PROMETHEUS 1:
RICE UNIVERSITY'S CODED APERTURE FAINT
OBJECT GAMMA RAY TELESCOPE.

by

JOHN E. FITCH

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE
MASTER OF SCIENCE

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ABSTRACT

THE DESIGN AND DEVELOPMENT OF PROMETHEUS 1: RICE UNIVERSITY'S CODED APERTURE FAINT OBJECT GAMMA RAY TELESCOPE.

JOHN E. FITCH

Rice University has been developing a balloon borne gamma ray telescope which is to be used for the detection of spectral gamma ray lines from Type I supernovae within one megaparsec. The telescope is designed to function in the energy range from 100 keV to 10 MeV. The detector is an actively shielded array of 121 0.5" x 0.5" x 2.0" NaI(Tl) crystals. Each crystal is optically separated from the remainder of the array and is to be independently viewed by a 0.375" x 0.375" photomultiplier tube. Inflight calibration of the 121 individual PMTs will be handled by an on board computer in conjunction with LEDs attached to the crystals. The 12 inch thick active shield is constructed of 28 individual blocks of scintillating plastic. Each block is separately viewed by one or more photomultiplier tubes acting in anticoincidence with the central detector, providing excellent isolation of the array from non-source gamma ray detections. The inflight electronics package features a CAMAC crate controlled by an LSI-11/2 microcomputer. The telescope uses a coded aperture approach yielding an overall geometrical spatial resolution of 2.6° x 2.6° FWHM. The energy resolution of the detector is expected to be 12% FWHM at 0.661 MeV. Monte Carlo simulations of the detector/shield assembly yield a projected sensitivity for this instrument of $1 \times 10^{-4}$ photons cm$^{-2}$ sec$^{-1}$ for a 3 sigma detection at 1 MeV.
ACKNOWLEDGMENT

I would like to express my sincerest thanks to Dr. Robert C. Haymes for his role as advisor for this thesis. He has provided the necessary experience and patience needed to develop this instrument and has earned my greatest respect for his knowledge and understanding of the field of gamma ray astronomy. I would also like to thank Dr. Sergey A. Averin for his assistance in developing Prometheus and for introducing me to life in the Soviet Union. Thanks also to Bhaswar Sen for his work and for the numerous discussions on the development of Prometheus. Special thanks to Marie Magee for her patience with our project and to Dr. Ken Smith for the loan of the LSI-11 microcomputer needed to operate this detector.

Without the support and love given by my wife, my parents, my family, and my church over the years, I would not have been able to have accomplished this goal. For that, I am eternally grateful. My parents, Edward and Lillian, thanks. You are by far the best.

I dedicate this thesis to my wonderful wife Elaine for delaying some of her dreams so that I could pursue my own. I love you.
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DEFINITION OF SYMBOLS AND ABBREVIATIONS

$M_\odot = \text{solar mass}$

$\text{Eff.} = \text{efficiency}$

$B# = \text{back section of shield}$

$S# = \text{side section of shield}$

$c# = \text{collimator section of shield}$

$ba# = \text{back angle section of shield}$

$\text{trans} = \text{transmitted through or transmitted from}$
INTRODUCTION

This thesis is intended to be a description of a work in progress. This report will cover all aspects of the design criteria, development, and testing of work completed on Prometheus through 12/31/87. Several portions of the detector have not at this time been fully studied and are therefore presented here only in a preliminary manner.

The detection of discrete gamma ray line emissions from supernovae is of primary importance in establishing supernovae as the site of heavy-element nucleosynthesis. In fact, the recent discovery of gamma ray line emissions from SN1987A tend to confirm this theory (Sandie, et al. 1988, Matz, et al., 1988). Modern theory predicts Type One supernovae to be the brightest sources of MeV gamma rays, primarily from the decay of $^{56}\text{Co}$ to $^{56}\text{Fe}$ (e.g. Woosley et al., 1986). The expected flux from this decay for a Type One supernova is between $3 \times 10^{-3}$ and $9 \times 10^{-3}$ photons cm$^{-2}$ sec$^{-1}$ distance$^{-2}$ (Mpc) (Gehrels et al., 1987). (A brief description of supernova theory is given in the next section.) Given this flux and current optical detection rates of Type One supernovae (Gehrels et al., 1987), a detector sensitivity of $2 \times 10^{-5}$ photons cm$^{-2}$ sec$^{-1}$ is required for an average of 1 detectable event per year. This sensitivity is possible for a detector of modest dimensions, if it has a relatively high efficiency and low systematic errors.

Systematic errors dominate the background of existing actively collimated gamma ray telescopes. These errors include shield leakage, and activation of both the detector and the shield assemblies by neutrons and high energy protons. By introducing new techniques for reducing these errors, Prometheus achieves a sensitivity approaching that which is required for one detectable event per year. Additionally, the methods used for these reductions in background can be easily improved by simply increasing the dimensions of the detector. With this in mind, Prometheus was designed as the first of
two to four sections of a larger detector which would retain the basic features of this instrument.

As an added consideration, the design of Prometheus lends itself easily to the use of coded aperture imaging as a means of obtaining spatial resolution of a gamma ray source. In some situations this would prove a valuable asset including determination of a single galaxy among a cluster of galaxies which is responsible for a gamma ray spectrum. Alternatively, spatial resolution of the central region of the Galaxy would assist in determining the source of MeV gamma ray spectra as either diffuse or discrete.

With these considerations in mind, Rice University has begun the development of Prometheus for use in the near future. It consists of an array of sodium iodide scintillation crystals, actively collimated by thick plastic scintillator. At this time, the detector array has been built and undergone initial testing. The electronics system is approximately 10% complete and the shield assembly is approximately 80% complete. Incorporation of these separate sections into the final flight configuration is underway as well as the development of the on-board software and data analysis packages. It is hoped that the detector will be fully flight ready for the fall of this year or early spring of 1989.
SECTION I - SUPERNOVAE

There are two primary classes of supernova events, historically labeled type I and type II. The type I supernovae are thought to be produced by the nuclear explosion of a white dwarf star when an excess of stellar material is deposited onto the white dwarf by a companion star. Type II supernovae result from the gravitational collapse of a red giant progenitor after the core has become iron. The major radioisotope produced in both type I and type II supernovae is $^{56}$Ni. Additionally, this section will deal with some of the other dominant radioisotopes produced, including $^{26}$Al, $^{57}$Co, and $^{44}$Ti.

Type I supernova:

As stated above, type I supernovae are thought to be the result of mass accretion onto a white dwarf from a companion star. The white dwarf is believed to be a carbon-oxygen star which is of mass less than the mass needed to exceed the Chandrashekhar limit, roughly $1.4M_\odot$. The companion star is thought to deposit mostly hydrogen rich material onto the surface of the white dwarf. If the mass accretion rate is greater than $10^{-9}M_\odot$ per year, hydrogen burning results on the surface of the star, creating a helium layer on the white dwarf. As mass accretion continues, a point is reached when the electron degenerate matter of the white dwarf can no longer support the mass of the star. This creates a thermonuclear runaway starting towards the center of the star and moving outward at subsonic speeds. The propagation time for the nuclear burning front to reach the outer layers of the star is thought to be approximately 1 second (Nomoto et al. 1984).

The nucleosynthetic burning of $^{16}$O yields primarily $^{32}$S through reactions with $\alpha$
particles until a temperature of approximately 2.5 billion degrees is reached. Temperature increases occur as the core collapses, igniting new reactions. At 2.5 billion degrees, $^{32}\text{S}$ begins to photodissociate by the loss of a proton. The resulting nucleus rapidly dissociates to $^{30}\text{Si}$ which in turn decays by two photoneutron reactions to $^{28}\text{Si}$. The reaction scheme is outlined in reaction 1 and results overwhelmingly in the production of $^{28}\text{Si}$ (Clayton 1983).

$$^{32}\text{S} \left( \gamma, p \right) ^{31}\text{P} \left( \gamma, p \right) ^{30}\text{Si} \left( \gamma, n \right) ^{29}\text{Si} \left( \gamma, n \right) ^{28}\text{Si} \quad \text{reaction 1}$$

As the temperature continues to increase, the resulting $^{28}\text{Si}$ begins to burn with the major result being $^{56}\text{Ni}$ at the expected temperature of 4.0 billion degrees. See figures 1.1 and 1.2 (Clayton, 1983). $^{56}\text{Ni}$ is the heaviest isotope with equal numbers of neutrons and protons. It beta decays into $^{56}\text{Co}$ with a 6.8 day half life.

The total mass of $^{56}\text{Ni}$ produced in type I supernovae varies from 0.4$M_\odot$ to 1.4$M_\odot$ depending upon the theories involved. The lower mass limit matches observed late time light curves, and the upper mass limit is set by the total conversion of a star at the Chandrasekhar limit to $^{56}\text{Ni}$.

In addition to $^{56}\text{Ni}$, other radioisotopes are thought to be present from explosive nucleosynthesis in a type I event.

$^{57}\text{Co}$ is produced by the decay of the short lived radioisotope $^{57}\text{Ni}$. The expected production rate is between $10^{-3}$ and $10^{-2} M_\odot$ per type I event. (Nomoto et al, 1984; Woosley et al.,1986) $^{57}\text{Co}$ decays in 270 days to $^{57}\text{Fe}$. This relatively short half life makes it very difficult for the expected gamma rays to escape from the overlying supernova shell. Detection of this isotope would however be very valuable in determining the branching ratios between $^{57}\text{Ni}$ and $^{56}\text{Ni}$ production.

The next most important radioactive product, with respect to expected production
rate, is the radioisotope $^{44}$Ti. As can be seen from figure 1.2, $^{44}$Ti is one of the isotopes produced from silicon burning. The expected production rate of $^{44}$Ti is between $10^{-4} M_{\odot}$ and $8.9 \times 10^{-3} M_{\odot}$ (Woosley et al., 1981, 1986).

Finally, production of the long-lifetime radioisotope $^{26}$Al is expected to be approximately $10^{-6} M_{\odot}$ per type I event. (Woosley et al., 1981) This is extremely weak in comparison to the production of some of the other radioisotopes discussed, however the long lifetime (~$10^6$ years) allows for the build up of considerable amounts of $^{26}$Al in the interstellar medium from several possible sources.

Table 1.1 shows the primary radioisotopes believed to be produced in type I supernovae in order of their production rates.

### Table 1.1 - Major Radioisotopes from Type I Supernovae

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Production</th>
<th>Half-life</th>
<th>Stable Product</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{56}$Ni</td>
<td>0.4 - 1.4 $M_{\odot}$</td>
<td>6.1 days</td>
<td>decays to $^{56}$Co</td>
</tr>
<tr>
<td>$^{56}$Co</td>
<td></td>
<td>77 days</td>
<td>$^{56}$Fe</td>
</tr>
<tr>
<td>$^{57}$Ni</td>
<td>$10^{-3}$ - $10^{-2}$ $M_{\odot}$</td>
<td>36 hours</td>
<td>decays to $^{57}$Co</td>
</tr>
<tr>
<td>$^{57}$Co</td>
<td></td>
<td>270 days</td>
<td>$^{57}$Fe</td>
</tr>
<tr>
<td>$^{44}$Ti</td>
<td>$10^{-4}$ - $8.9 \times 10^{-3}$ $M_{\odot}$</td>
<td>48 years</td>
<td>$^{44}$Sc $\rightarrow$ $^{44}$Ca</td>
</tr>
<tr>
<td>$^{26}$Al</td>
<td>$\sim 10^{-6}$ $M_{\odot}$</td>
<td>7.4 $\times 10^5$ years</td>
<td>$^{26}$Mg</td>
</tr>
</tbody>
</table>

Recent studies by Gehrels, et al. of the historical record of observed supernovae between 1954 and 1985 have resulted in figure 1.3 (Gehrels, et al. 1987). Theoretical
considerations to a relationship between peak magnitude and flux of the 0.847 MeV line developed by Arnett (Arnett, 1979) have been applied to yield a more complete relationship given in equation 1.3 (Gehrels, et al., 1987).

\[
\log_{10} \left( F_{0.847} / 10^{-4} \text{ photons cm}^{-2} \text{ sec}^{-1} \right) \geq 0.4 \left( 11.0 + 0.9 - m_B^{\text{peak}} \right) \tag{1.3}
\]

Here, the relation refers to peak magnitude in the blue band. This relationship suggests that an observed peak magnitude of 11 is necessary to have a flux of $1 \times 10^{-4}$ photons cm$^{-2}$ sec$^{-1}$, and a peak magnitude of 13.5 is necessary for $1 \times 10^{-5}$ photons cm$^{-2}$ sec$^{-1}$. Relating this to figure 1.3, it is noted that the rate of observable type I supernovae per year is 0.05 and 0.6 for flux rates of $1 \times 10^{-4}$ and $1 \times 10^{-5}$ photons cm$^{-2}$ sec$^{-1}$ respectively. Therefore, for the ability to observe one detectable type I event every few years, a gamma ray detector must have a 3σ sensitivity at 0.847 MeV approaching $1 \times 10^{-5}$ photons cm$^{-2}$ sec$^{-1}$.

Figure 1.4 shows a plot of the expected light curve for type I supernovae as a function of time from event. This plot is taken from the summary paper by Gehrels et al, 1987. All models shown in this diagram assume a spherically symmetrical homogenous expansion of the ejected material.

Type II supernova:

As stated previously, the progenitor for a type II supernova event is expected to be a red giant star with total mass greater than 8 $M_\odot$. The process by which the explosion occurs is as follows. The star begins to synthesize material by the fusion of hydrogen into helium, then as the hydrogen burns out, the helium is fused into carbon and oxygen, the carbon into magnesium, the oxygen into silicon, etc. until the core is burning silicon into iron (see figure 1.2). From a plot of the nuclear binding energy per nucleon versus the
mass number (figure 1.5) (Clayton, 1983), it is possible to see that the binding energy per nucleon increases with increasing mass until the iron group is reached. This means that it is energetically favorable to fuse lighter elements into heavier elements until iron is reached, specifically until $^{56}\text{Fe}$ is reached. ($^{56}\text{Fe}$ has the distinct property of having the maximum binding energy per nucleon.)

As the iron core continues to increase in mass beyond 1 M$_{\odot}$, it becomes so massive that it can no longer be supported by the electron degenerate matter and begins to contract. This leads to a temperature increase which begins to photodissociate the iron nuclei into alpha particles by reaction 1.2.

$$\sim 100 \text{ MeV} + ^{56}\text{Fe} \rightarrow 13^4\text{He} + 4n \quad \text{reaction 1.2}$$

The huge amount of energy that is required to fuel this reaction is provided by the continued collapse of the star. The star collapses beyond the electron degeneracy point and continues until the point of nuclear degeneracy is reached. At this point, the stellar matter which has been collapsing in a virtual free fall to speeds approaching the speed of light, encounters a core which will collapse no further, and basically bounces. This creates a shock wave which propagates outward from the core fusing successive envelopes of pre-supernova material. (See figure 1.6) (Clayton, 1983).

As the shock enters the oxygen-silicon rich mantle, the density and pressure increases beyond the point of nuclear burning and explosive nucleosynthesis occurs as in figure 1.2. This burning creates a variety of radioisotopes, but the dominant radioisotope is again expected to be $^{56}\text{Ni}$.

The amount of $^{56}\text{Ni}$ produced is highly uncertain due to the fact that unlike type I events, the optical light curves from type II events do not have a single dominant exponential decay phase. Nonetheless, from some type II events, the observed exponential
decay of the light curve can be explained from the radioactive decay of $^{56}$Co. Studies suggest a range of 0.1 to 0.5 $M_\odot$ of $^{56}$Ni could be produced in a type II event (Arnett, 1980; Weaver and Woosley, 1980; Uomoto and Kirshner, 1986). SN1987A appears to have produced approximately 0.075 $M_\odot$ of $^{56}$Ni.

Figure 1.7 shows the expected light curves for type II supernova for the 0.847 MeV line (Gehrels, et al., 1987). These models are also based on spherically symmetric homogeneous expansion of the supernova ejecta. Recent studies of the hard X-ray emission from SN1987A suggest the possibility of mixing in the outer layers of the ejecta (Ebisuzaki, et al., 1988). Models which include mixing show significant increases in line intensity at times less than 1 year and an advancement of the peak line intensity to an earlier time after core collapse (Shibazaki, et al., 1988).

Assuming for the time being no mixing in the ejecta, a peak flux of $1 \times 10^{-6}$ to $4.0 \times 10^{-5}$ photons cm$^{-2}$ sec$^{-1}$ dMpc$^{-2}$ can be expected from a type II supernova sometime around 500 days from the beginning of the event (Gehrels, et al., 1987). Figure 1.8 shows the expected light curve from SN1987a in the 0.847 MeV line, based on a 15 $M_\odot$ type II supernova (Gehrels, et al., 1987). It can be seen from the curve, that a detector having a 3$\sigma$ sensitivity of $1 \times 10^{-5}$ photons cm$^{-2}$ sec$^{-1}$ at 0.847 MeV could possibly detect gamma rays from SN1987A until the summer of 1990.

From the above considerations, it is desirable to have a gamma ray detector with a 3$\sigma$ sensitivity approaching $1 \times 10^{-5}$ photons cm$^{-2}$ sec$^{-1}$ at 0.847 MeV.
SECTION 2 - THE DETECTOR ASSEMBLY

Due to the background dominated environment in which Prometheus is expected to function, achieving the sensitivity required by section 1 is made possible by finding ways of reducing systematic backgrounds. Figure 2.1 depicts a typical balloon borne gamma ray spectrum and the components thereof for the measured background of a flight of the Low Energy Gamma Ray Spectrometer at Palestine, Texas (Gehrels, 1985). The spectrometer consists of a germanium detector with an active NaI collimator. The background flux is composed of several discrete gamma ray lines superimposed on a continuum. The discrete lines are due to naturally occurring radioisotopes in the instrument, activation of the instrumental materials, and the annihilation of positrons produced in the instrument by atmospheric radiations. Continuum sources include activation of the instrument by high energy neutrons and protons, and atmospheric and cosmic gamma rays which either enter the instrument through the aperture or leak through the shield without being detected.

One of the major components of the overall background counting rate around 1 MeV, is due to $\beta^-$ emissions from spallation products of the heavy isotopes of the material in the detector itself. Appendix 1 (Fishman, 1972), lists the spallation products from NaI which decay with the accompaniment of a $\beta^-$ emission. The summed cross section of these events accounts for $\sim$25% of the total geometrical cross section of all of the spallation products from NaI. They are responsible for the "$\beta$ bulge" seen in the background spectrum of previous gamma ray detectors. Because the range of $\beta^-$ rays in NaI is small in comparison to gamma rays of similar energy, $\beta^-$ rays deposit all of their energy in a relatively localized area of the detector. By dividing the detector into crystals which are large compared to the range of $\beta^-$ rays, but relatively small compared to the mean free path
for gamma rays, it is possible to eliminate the $\beta^-$ emissions by requiring an acceptable event to be non-localized in the detector array.

For gamma rays, the total attenuation length in NaI(Tl) is given in figure 2.2. The attenuation length for $\beta^-$ particles in NaI is shown in figure 2.3 and is approximated by the relationship between linear attenuation coefficient and energy given below.

$$X \ (\text{cm}^{-1}) = 62.139 \ E^{1.141} \ \text{(MeV)} \quad (2.1)$$

The average energy of the $\beta^-$ emissions from the NaI spallation products is 1.18 MeV. From equation 2.1 above, the average linear attenuation length for spallation $\beta^-$ rays in NaI is 51.44 cm$^{-1}$. From figure 2.2, the average linear attenuation length for gamma rays at 1.18 MeV in NaI is 0.2 cm$^{-1}$. From this, we see that unless the average length of a detector element becomes as small as 0.001 cm, all of the emitted $\beta^-$ rays will be confined to a single detector element. Therefore, the smallest detector size greater than 0.001 cm would be desirable so as to limit the number of low energy gamma rays which are misidentified as $\beta^-$ rays. (i.e. Those gamma rays which are confined to a single crystal.)

Discussions with representatives from various firms which produce NaI(Tl) crystals, have suggested that square crystals with cross sectional areas approaching 0.40 cm$^2$ are available. However, for crystals of 5.0 cm in length, the relative strength of the crystal lattice makes a 0.40 cm$^2$ NaI(Tl) crystal highly susceptible to fracture. As this was a major concern, it was decided to limit the cross sectional area of the detector elements to greater than 0.40 cm$^2$. Additionally, as each detector element had to be viewed by an
independent photosensitive device, considerations to available electronics became a factor.

The smallest available photomultipliers have a total cross sectional area of 1.0 cm$^2$. Magnetic and electrostatic shielding of the PMTs are required, suggesting that crystals with cross sectional areas greater than or equal to 1.2 cm$^2$ are necessary. The final decision was based on all of these considerations and resulted in the purchase of 121-1.27 cm x 1.27 cm x 5.0 cm NaI crystals from the Bicron Corporation.

From Monte Carlo simulations done by Dr. Averin at Rice University (described in detail in section 8), it is shown that gamma rays with energies below 0.10 MeV are effectively confined to one crystal element and thus vetoed as $\beta^-$ rays. This suggests that any spallation products which decay with the emission of a gamma ray with energy $\leq$ 0.1 MeV will be vetoed and not add to the detector background. From the spallation cross sections of Na and I we see that this accounts for $\sim$8% of the total geometrical cross sections.

To allow for budgetary considerations, it was decided that the NaI crystals would be compensated and packaged at Rice. As NaI is hygroscopic, it was necessary to accomplish this in a dry atmosphere. With the use of a dry box borrowed from the Materials Science department, the NaI array was constructed as shown in figure 2.4. Methods of compensation and optical separation were carried out as suggested by Mott et al., 1957. These included polishing the individual crystals with 320 grit dry emery paper and coating the lateral surfaces of the crystal with magnesium oxide.

The detector is composed of the 121-0.5" x 0.5" x 2.0" NaI(Tl) crystals arranged in an 11 x 11 array. Each crystal is surrounded by a 3/32" layer of packed magnesium oxide powder to insure optical isolation and total internal reflection. The two ends of each crystal are fastened to the detector's inner housing by placement into an 0.25" aluminum spacing grid, and hermetically sealed by a 0.125" layer of Dow Corning Sylgard
coupling compound. The two end sections of the detector are further sealed by two 0.125" quartz windows which are pressure fit against the Sylguard and sealed with an O-ring type assembly. The entire area of the detector with the exception of the quartz windows is surrounded by a 0.75" layer of lithium fluoride powder packed to an average bulk density of 1.4 gm cm$^{-3}$. An outer housing of aluminum was then attached with another O-ring type seal to provide additional support and protection for the array.

The lithium fluoride powder is used as a shield against slow neutron activation of the detector. The effects of this shielding will be described in more detail in section 8.

Testing of the completed array was carried out under two different programs. The first was an attempt to study the array as a single unit. The second was a crystal by crystal calibration using low energy collimated sources.

To test the array as a whole, single photomultiplier tubes were coupled to the array in various configurations. RCA photomultipliers of various diameters (2", 3", 5") were tested. Due the the large difference in detector area (283 cm$^2$) versus photocathode area (20.2, 45.6, 126.6 cm$^2$ respectively), it was necessary to use a light pipe from the quartz window of the array to the PMT. It quickly became apparent that the energy resolution of the array/single PMT configuration was poor, with the best configuration giving a resolution of 40% FWHM at 0.661 MeV. This figure is misleading for several reasons. The first problem was found from the crystal-by-crystal testing. As will be described below, variations in gain from crystal to crystal are as high as 14%. By viewing the array with a single PMT, these errors can not be corrected and will therefore severely distort the expected photopeak. The second problem arose from the Compton scattering of photons in the areas of the array which were not directly viewed by the photocathode. Any events which were a combination of Compton scatterings from different sections of the detector were therefore severely distorted. As consequence of this, information on energy
resolution could not be obtained by measuring the detector as a whole.

What could be measured was the overall efficiency of the detector as a function of energy, and compared to the efficiencies calculated by Monte Carlo simulations. This was accomplished by using a configuration as shown in figure 2.5. The detector array was coupled to a single RCA 5" PMT with Dow Corning optical coupling grease. (The grease is used to cut down the light losses incurred at the interface of detectors and photosensitive devices.) The array was then radiated with beams of gamma rays of various energies. Integration of the entire background subtracted spectrum provided a counting rate for the interactions in the array. After making corrections for half lives and solid angle subtended by the array, the results are presented in figure 2.6, where they are compared to Monte Carlo calculations of the detector. The large error bars on the experimental data are due to the uncertainty in absolute source strength. Energy calibration sources were used as an alternative to flux-calibrated sources due to the prohibitive cost of the flux-calibrated sources. The overall fit to the Monte Carlo data is still quite good.

Crystal-by-crystal calibration was accomplished with the use of a 0.75" diameter RCA PMT. The PMT was optically coupled to a single crystal which was then radiated as shown in figure 2.7 by a collimated beam of $^{57}$Co gamma rays. The beam was such that the unscattered gamma rays were confined to one individual crystal, and carefully aligned with the center of the crystal being viewed by the PMT. The emission from $^{57}$Co is at 0.122 MeV and has an excellent (98% from Monte Carlo simulations) probability of being confined to a single crystal. By being confined to one crystal, it is possible to get an accurate determination of the energy resolution at that energy. In addition, the variances in gain from crystal to crystal can be studied to determine the extent to which in-flight calibration is necessary. Each crystal was studied in this manner with the results being presented in figures 2.8 to 2.13.
Figures 2.8, 2.9, and 2.10 show the corrected data from the array in three dimensions. The data shows all crystals except row 11, which was not studied in detail. The corresponding two-dimensional plots of the data are shown in figures 2.11, 2.12, and 2.13 respectively. After the data had been analyzed, it was found that the preamp connecting the PMT to the pulse height analyzer was degrading the signal, causing a degradation in the energy resolution calculation. To correct for this, 3 crystals were chosen at random in the array, and recalibrated without the preamp. What was found is presented in figure 2.14. It shows a linear correction factor of \( \sim 7.87\% \) for the energy resolution at 0.122 MeV. This correction factor is included in figures 2.9 and 2.12.

The corrected average energy resolution for the array is 35.9 percent, with a standard deviation of 7.49 percent, at 0.122 MeV. The average value for the peak channel was 84.57, with a standard deviation of 12.35, at 0.122 MeV. The average error in these calculations, as computed by the pulse height analysis software, was 3.55 percent with a standard deviation of 1.07 percent.

From looking at the data for the peak channel, (i.e., figure 2.11) we see a variation in gain from crystal to crystal of plus and minus 14.6 percent. Some of these variations may have been caused by changes in optical coupling. By studying several crystals more than once, changing only the optical coupling, it was seen that this accounted for a small (<3%) variation. The major components of the variations are due to drifts in high voltage supply, and compensation differences from crystal to crystal. This data shows the need for an accurate in-flight calibration system.

Initial ideas for in-flight energy calibration included light emitting diodes (LEDs) attached to the quartz window opposite each PMT. By shining light through each crystal while in energy calibration mode, variations from both compensation and high voltage drift could be corrected. Recent discussions with NASA technichians suggest that stable
LEDs are not readily available, and calibrations using LEDs have not proven reliable. Their suggestion is to use a radioactive source which decays with the emission of two low energy gamma rays. Resolution of the peaks would yield a direct energy calibration for each crystal. Two problems arose with such a suggestion. The first involves the historical use of in-flight calibration sources. Shielding these sources when not calibrating proves to be a problem, increasing the background of the detector. The other problem was trying to calibrate all 121 crystals quickly with a single source.

A solution exists for Prometheus by using a source which emits two γ rays, each with energy less than 100 keV. At 100 keV, the γ ray will be confined to a single crystal, therefore, during normal operation, will be rejected as a β− event. While operating in calibration mode, Prometheus will be programmed to accept only those events which are confined to a single crystal. In such a way, a single source illuminating the entire array will be able to calibrate the array, and will not be seen during normal operation.

From the energy resolution at 0.122 MeV, it is possible to determine some limits for the overall energy resolution of the array as a function of energy. For a typical NaI (Tl) crystal, the energy resolution as a function of the energy $E$, goes as $E^{-0.5}$ (Mott, et al., 1957). This is due to the linear relationship of the light output from the crystal as a function of energy, and the Poisson statistics of the photoelectrons. Typical laboratory scintillators have a single quartz window allowing light to escape from the crystal only into the photocathode of the PMT. Due to the second quartz window on Prometheus, the amount of light reaching the photocathode will be reduced by a factor of two. Thus if all of the light reaching the far end of the crystal, away from the PMT, escapes, the resolution as a function of energy can be expected to fall off as $(E/2)^{-0.5}$. Taking these limits, we can estimate the likely region of resolution versus energy for the calibrated detector. These results are shown in figure 2.15.
It is recognized that these preliminary results are not very meaningful. However the data do tend to support the idea that the detector array is functioning as expected. It is necessary to have the entire array, along with the veto system functioning, in order to provide more accurate data. This is in the process of being accomplished as more of the system becomes operational.
SECTION 3 - THE ACTIVE SHIELD

At an altitude corresponding to an atmospheric depth of 3.5 grams cm\(^{-2}\), Prometheus will be immersed in a sea of ambient gamma and cosmic rays. As a means of preventing interactions in the detector from non-source events, Prometheus is surrounded by a thick active shield. Active shielding is the detection of a non-source event as compared to passive shielding which requires the absorption of non-source events. In addition to providing non-source vetoing, the shield also creates a method for requiring all acceptable events to be totally absorbed in the detector array. That is, if an event only partially deposits its energy in the array and subsequently triggers the shielding, the event is vetoed.

Some of the major concerns in the design of the shielding system were efficiency, lack of activation, and cost effectiveness. Previous gamma ray detectors incorporated NaI(Tl) or CsI(Tl) active shielding. Although this provided sufficient efficiency in a relatively thin shield, large volumes of shielding material were still required. Activation of the large volume of shielding material often decreased the overall detector sensitivity, even when the shield thickness was increased. As can be seen from figure 2.1, leakage through the shield becomes the major concern between 100 keV and 800 keV, and remains a major concern above 2 MeV. Therefore it is necessary to find a way of increasing shield efficiency without sacrificing sensitivity.

With this in mind, Prometheus uses a thick plastic scintillator for an active shield. Scintillating plastic has the desired feature of possessing an extremely low activation cross section, due to the low atomic number elements of which the plastic is composed. In addition, all of the radioisotopes which are produced by activation of the
plastic decay with the accompaniment of a charged particle. Therefore, any radiation produced by the shielding is eliminated from the final spectrum, independent of shield thickness. The major drawback of using plastic scintillator is its inherently low density, which corresponds to a low stopping power for gamma rays. Thus to provide sufficient shielding, i.e. several mean free paths thickness, the shielding volume must be greater than needed by previous higher density inorganic shields.

A study of the gamma ray background spectrum over Palestine Texas at an altitude of 3.5 gm cm\(^{-2}\) yielded the following angular dependence on the differential spectrum (Gehrels et al, 1985).

**Table 3.1 - Best-Fit Differential Energy Spectra at 3.5 gm cm\(^{-2}\) over Palestine Texas.**

<table>
<thead>
<tr>
<th>Zenith angle</th>
<th>Differential Energy Spectrum (Photons cm(^{-2}) s(^{-1}) sr(^{-1}) MeV(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0° - 65°</td>
<td>0.052 E(^{-1.81})</td>
</tr>
<tr>
<td>65° - 95°</td>
<td>0.085 E(^{-1.66})</td>
</tr>
<tr>
<td>95° - 130°</td>
<td>0.14 E(^{-1.50})</td>
</tr>
<tr>
<td>130° - 180°</td>
<td>0.047 E(^{-1.45})</td>
</tr>
</tbody>
</table>

(0° corresponds to pointing straight up; 180° corresponds to downwards pointing.)

Using this flux distribution integrated over solid angle, and the linear attenuation coefficients from figure 3.1, the total shield leakage as a function of energy can be calculated for various shield thicknesses. The results of these calculations are shown in figure 3.2. As expected, it is seen that increasing shield thickness greatly increases the effectiveness of the shielding. From geometrical considerations in the gondola (see section
7), the thickest shield feasible for Prometheus is 12". With these considerations in mind, the design of a 12" thick plastic shield was undertaken.

Plastic scintillator is produced by pouring molten plastic into a form and allowing the ingot to cool. The largest (due to strength considerations) available volume of plastic is produced as a slab measuring 24" x 6" x 64". Because of budgetary considerations, purchasing a single slab of the plastic proved to be the most efficient approach to fabricating the shield. Therefore, a single slab of BC-416 scintillating plastic with the above measurements was supplied by Bicron Corporation.

The plastic was divided into 28 sections (as seen in figure 3.3) by the Rice University Research Support shop, and polished by Mr. Bruce Mast and Ms. Shannon Powers. Due to the low melting point of the plastic, machine polishing was not possible. After machining the plastic surface to ~50μm, 600 and 1000 grit emery paper was applied. This was followed by hand polishing of all of the surfaces with 5μm aluminum oxide compound, and finally with 1μm aluminum oxide compound. The result was a highly polished surface on all sides of the plastic.

In order to efficiently retain the light output from gamma ray interactions in the plastic, the blocks were loosely wrapped in a layer of polished aluminum foil. This allowed for a slight air gap which causes total internal reflection in the plastic. Photomultipliers could now be attached with the aid of Dow Corning optical coupling compound to provide a large isolated gamma ray detector.

The 28 various blocks were arranged in such a way so as to provide the most efficient shielding for the array. Figure 3.4 shows the final configuration.

As can be seen in figure 3.4, the entire shield, including the aperture is to be surrounded by a 1" thick layer of lithium fluoride. As in the case of the lithium fluoride surrounding the detector array, this is to shield against activation of the array from slow
neutrons and will be discussed further in section 8. In addition, a thin active shield is to be placed in the aperture to provide 4π sr protection of the array against charged particles.

To support the shield/detector assembly and to allow for connection to the inner gondola, some type of structure assembly was required. A full scale mockup of this structure was designed and built to allow for laboratory testing of the shielding and detector in the final flight configuration. This structure was made from wood, and is shown in figure 3.5. As of this writing, ~80% by volume of the shielding has been cut, polished, and assembled into the configuration shown in figure 3.4. The shielding electronics have not yet been assembled and are awaiting software development for initial testing.

Individual shield sections have however been studied in detail, including testing of various PMTs, positioning of PMTs, efficiency as a function of energy, minimum threshold experiments and efficiency as a function of position of gamma rays. In studying the plastic scintillator, it is necessary to keep in mind that the dominant interaction between the gamma ray and the scintillator is through Compton scattering in the energy region from 20 keV to > 10 MeV. This means that, except at very low energies, there will be no photopeak in the spectrum from the plastic, but only a Compton edge and shelf.

The initial testing was done by Bruce Mast and compared the counting rate for two configurations of tube positioning. The first configuration used one of the 12″ x 6″ x 6″ blocks which make up the back section of the shield. It had a 3″ diameter RCA PMT optically coupled to one of the 6″ square faces. The second configuration, which used another block of the same dimensions, had two 3″ RCA PMTs attached to one of the 12″ x 6″ surfaces. The results from both tests show an efficiency of approximately 42% at 0.847 MeV. This value has an error of plus or minus 20% due to the uncertainty in the absolute value of the source used. The results are consistent with results which I obtained later.
The main point is that viewing the plastic from a different position yielded no major change in detection efficiency.

The next series of tests attempted to determine the most efficient size of the PMTs which were to view the shield in the final flight configuration. This was accomplished by attaching PMTs of 2", 3", and 5" diameters to the 6" square face of one of the back sections of plastic, and comparing the observed counting rates. At the same time, the source position was varied to provide a study of efficiency versus source position. The results of this test are shown in figure 3.6. The conclusion that can be drawn is that the detection efficiency as a function of PMT size is a constant. Therefore, in order to take advantage of existing hardware and the most cost efficient purchase of additional hardware, 2" diameter PMTs will be used on the active shield of Prometheus.

A more detailed study of efficiency as a function of source position and energy was then carried out. Figures 3.7 and 3.8 show the efficiency of the plastic as a function of source position at 0.122 MeV and 0.847 MeV respectively. The theoretical curve is based on a random emission routine which determines, from the geometry of the test, the number of gamma ray photons whose trajectories intersect the plastic and the distance through the plastic that each photon travels if it remains unscattered. From this information and the total attenuation coefficient, a precise determination of the theoretical efficiency can be made. As a means of checking this program, a plot of the fraction of photons intersecting the plastic as a function of distance from the plastic is compared to a curve of the reciprocal of the distance squared. As the distance from the plastic becomes large, the fraction of photons intersecting the plastic should approach a $1/r^2$ dependency. This can be seen to be true in figure 3.9. As another check, the average distance in the plastic should asymptotically approach the actual dimension of the plastic as the distance from the
plastic becomes large. This is shown in figure 3.10 and except for statistical fluctuations, this is also true. As a final check on the efficiency calculated by the program, we can take the value of the average distance traveled in the plastic and compute the expected efficiency from the total attenuation coefficient. For a source distance of two inches from the plastic, centered on the plastic, the average distance through the plastic is 5.8" giving a efficiency of 89%, 75%, and 61.6% at 0.122 MeV, 0.661 MeV, and 0.834 MeV respectively. The corresponding values calculated from the program are 90.5%,70%, and 70% with a statistical error of plus and minus 8%. Therefore, the values from the program are in good agreement with the efficiencies calculated from the equivalent average thickness of the plastic. Because the efficiency is a function of thickness, the values calculated from the program should differ from those computed by using the average distance through the plastic.

The efficiency of the plastic as a function of energy for a source centered on the plastic at a distance of 2" is shown in figure 3.11. As can be seen from the comparison with the theoretical efficiency as a function of energy, the experimental data are consistently lower. Several statements need to be made to explain this result. The first is a disclaimer for the point at 0.661 MeV. The $^{137}\text{Cs}$ source that was used had a strength of 115 µcuries. In the close proximity necessitated by the light-tight testing area, this produced a counting rate of approximately $1.2 \times 10^5$ counts/sec as detected by the pulse height analyzer. At this rate, the electronics system experienced a dead time of $>50\%$. Thus with the detector almost completely saturated, no real analysis can be expected.

The other two points had counting rates $>100$ times less, placing them in a portion of the dead time curve which showed only a 2-3% deadtime correction. Thus, the counting rates can be expected to be accurate. The difference between the observed efficiency and the experimental efficiency can be explained as an effect due to the Compton
scattering. The great majority of interactions between gamma rays with energies from 20 keV to 10 MeV are through Compton scattering. Thus for a gamma ray to deposit all of its energy into the plastic, the gamma ray must undergo several scatterings, i.e. the plastic must be several mean free paths thick. For a detector which has a non-zero threshold, the possibility exists that some gamma rays may undergo a single Compton interaction and exit from the detector without depositing enough energy to trigger the detector. Therefore, the efficiency of detection should increase with decreasing detector threshold.

A study performed by Gehrels, 1985, shows the dependency of shield leakage versus shield threshold for several energy regions for a NaI shield. This plot is reproduced in figure 3.12. A similar dependency should be seen for plastic shielding.

For the energy regime of 0.63 to 2.5 MeV, a shield threshold of 100 keV produces a decrease in shield efficiency by approximately 34%. This magnitude of decrease is consistent with what is observed in the data shown in figure 3.11. From this analysis, the shield threshold is an important factor in determining the overall efficiency of the the active shield.

In an effort to determine the lowest feasible shield threshold for the plastic scintillator, testing was begun using several low energy sources. The initial results show a lowest possible background-subtracted energy resolution of approximately 40 keV. (\(^{241}\text{Am}\) with a gamma of 60 keV was detectable with a counting rate consistent with a threshold of 40 keV.) These results were obtained by using a great deal of amplification of the PMT pulses. This created low level noise around 40 keV which was several orders of magnitude more intense than the source strength. As the flight configuration uses the plastic scintillator only in anti-coincidence with the detector, all pulses generated by the plastic will cause a veto signal for the array. Therefore for a true 40 keV threshold, the noise from the amplifiers must be considerably reduced to below 40 keV. Design of
various electronics schemes capable of achieving this is underway by qualified individuals (i.e. not myself).

In conclusion, a lower limit shield threshold of approximately 40 keV may be feasible causing a less severe increase in the theoretical shield leakage than what is currently observed.
SECTION 4 - CODED APERTURE IMAGING

Because the detector has been divided into an array of several smaller detectors, a technique known as Coded Aperture Imaging may be used to yield information on the spatial distribution of point sources in the aperture. The technique was first proposed by Dicke in 1968 (Dicke, 1968), and has found general acceptance as a means of imaging x-ray and gamma ray sources. This section will briefly describe two variants of this technique which may be useful on Prometheus. The first deals with a new type of coded aperture which has many useful properties. The second deals with work completed by Dr. Truman P. Kohman at Carnegie-Mellon University who simulated random Coded Apertures with the expected parameters of Prometheus. Dr. Kohman's work differs from the theory of Dicke, and was developed by him to simplify the image reconstruction.

The general theory involves the use of an aperture which is composed of regions which are either transparent or opaque to the incoming radiation. If there is a point source in the field of view of the instrument, it will cast a shadow pattern onto a position sensitive detector plane. By designing an aperture pattern which produces a unique shadow pattern for each position in the aperture, it is possible to reconstruct the aperture image from the detector shadow.

The position sensitive detector may be represented as a two dimensional array $D$. (For Prometheus, this would have dimensions of 11 x 11.) The value of each element in $D$ corresponds to the total number of counts observed in that element from the aperture flux. The aperture can also be represented by a two dimensional array $A$, with values of either 0 or 1 corresponding to opaque and transparent regions respectively. Likewise, the source field is assumed to be a two dimensional array $S$, which is parallel to the aperture and located at a fixed distance from the aperture. The values of $S_{ij}$ correspond to the
amount of radiation coming from the source field position \( ij \) on the sky.

It can be shown (Gottesman, et al., 1986) that the detector plane data is given by equation 4.1 below, where \( * \) is the correlation operator. The array \( B \) is the background flux observed in each detector element.

\[
D = S * A + B \quad (4.1)
\]

Reconstruction of the source is completed by a decoding array function \( R \) such that equation 4.2 holds.

\[
S' = D * R = S * A * R + B * R \quad (4.2)
\]

where \( R \) has the following property.

\[
A * R = N \delta_k \quad (4.3)
\]

In equation 4.3, \( N \) is the number of holes in the aperture pattern, and \( \delta_k \) is the Kronecker delta function. Therefore equation 4.2 reduces to the following.

\[
S' = NS + B * R \quad (4.4)
\]

Gottesman et al., have developed a new class of Coded Apertures which function as described above. This new type of aperture is classified as a PNP (Psuedo-Noise-Product) Coded Aperture and combines several important features for passive coded aperture applications.

The first problem that is encountered in a typical Coded Aperture is the lack of self supporting patterns. This means that for a passive Coded Aperture, supporting the opaque sections of the aperture would require structures crossing the transparent regions of the aperture. This would decrease the transmission coefficient of the transparent regions. Another problem with other types of Coded Apertures is that the noise in the
reconstructed image is dependent upon the initial image distribution.

PNP designs eliminate both of these problems. Typical Coded Aperture patterns are developed with the use of a 1 dimensional Psuedo Noise (PN) sequence. To produce a two dimensional array, this PN sequence is mapped onto a two dimensional plane. For PNP arrays, two independent 1 dimensional PN sequences are used, their direct product being the PNP two dimensional array. By doing this, the new array becomes self supporting, i.e. all opaque sections are interconnected. Additionally, the reconstruction array R, has elements which are either 1 or 0. This means that equation 4.3 is satisfied for all source configurations, and therefore the reconstructed image has a uniform noise distribution regardless of the source field S.

An example of an 11 x 11 PNP array is given in figure 4.1 (Gottesman et al., 1986). This actual aperture is derived by a process of internal mosaicking' as described by Fenimore et al., 1978 (Fenimore et al., 1978). The resulting structure along with its decoding function R, is shown in figure 4.2.

Because of time considerations, very little additional work has been done at Rice University with regards to the imaging capabilities of Prometheus. However, an independent source offered his services in modeling the coded aperture and running computer simulations to determine the performance of such apertures.

Dr. Kohman's work describes the detector count array C as the product of the source fluence array F and the aperture transmission matrix T, plus the addition of a background noise. Thus;

\[ C = TF + B \quad (4.5) \]

For a reconstructed image to be possible, the number of detector elements in C must be greater than or equal to the number of elements in the source field F. This is a
limitation not required in the previous discussion. For a zero noise case, a unique source reconstruction exists for J=K (J is the size of C, K is the size of F). For a non-zero noise term, several solutions exist for J = K, the degeneracy of solutions decreasing as J/K increases. Dr. Kohman eliminates the degeneracy of solutions by comparing the image generated by a potential source field with the observed image and performing a least-squares-fit analysis on all of the potential source fields.

In order to obtain a flat response function over a large portion of the aperture, a second aperture which is completely transparent is required in front of the coded aperture. This is described by Dr. Kohman as a limiter. To obtain the largest overall sensitivity of the detector, an oversized aperture is to be employed. This configuration can be seen in figure 4.3. For this geometry, Dr. Kohman gives the following parameters where CO is the width of the flat central object field, AP is the size of the aperture, IM is the size of the detector, R is the limiter to aperture distance/detector to aperture distance, OB is the size of the source field (Kohman, 1986).

\[
CO = AP - IM + 1 \quad (4.6)
\]

\[
LI = AP + R (AP - IM) \quad (4.7)
\]

\[
OB = AP - IM + 1 + 2 \left\lfloor \frac{IM - 1}{R + 1} \right\rfloor \quad (4.8)
\]

The central object field exceeds AP - IM by 1 due to the fact that an object at the extreme position of the central object field can be seen by the detector. The angular resolution is given by the ratio of the detector size to the distance from the aperture to the detector. For Prometheus, the size of the detector elements are governed by the crystal size plus the surrounding layer of magnesium oxide. The total element size is 1.50 cm.
The detector to aperture distance is 23.75 cm yielding an overall spatial resolution of ~2.6°.

Dr. Kohman used the characteristics of Prometheus to simulate viewing of a source field which contained 8 sources of various intensities, the strongest of which corresponded to the observed flux from the Crab nebula integrated over the energy range of Prometheus. For an integration time of 1 hour, this flux corresponded to 120 units of flux. Also included in the source field was an overall sky background of 10 units per detector element. The detector background, composed of leakage through the shield and radiation incident on the aperture was compared both at 100 units per hour and 1000 units per hour, covering the expected range for Prometheus. The results of the simulation for a detector width of 11, an aperture width of 8, and the ratio of limiter to aperture / aperture to detector distances of 3, is shown in figure 4.4. Each unit in figure 4.4 is equivalent to ~2.6°.

In order to obtain results from coded aperture data, it is necessary to understand where the initial interaction of the incoming gamma ray in the detector occurs. In Dr. Kohman's simulation, it is assumed that the initial interaction site is known to within one detector element. In reality however, this is not necessarily known. The idea behind the β- rejection method used in Prometheus requires an incoming gamma ray to Compton scatter into two or more detector elements. As this occurs in one time window, it is not necessarily known which crystal was the initial interaction site. In order to determine this site, it is assumed that on the average, each Compton scattering will result in the deposition of 1/2 of the gamma rays energy before collision.

To determine if this assumption was correct, a Monte Carlo simulation was carried out by Dr. Averin which provided information on the accuracy of calculating the initial interaction site. The following equation was used to estimate the initial position of the of j-th photon in the X coordinate.
\[ \bar{X}_j = \frac{\sum_{i=1}^{k_j} x_{ij} E_{ij}}{\sum_{i=1}^{k_j} E_{ij}} \]  \hspace{1cm} (4.9)

where \( x_{ij} \) is the coordinate of the \( i \)-th interaction of the \( j \)-th photon, \( k_j \) is the number of interactions for the \( j \)-th photon, and \( E_{ij} \) is the amount of energy deposited by the \( j \)-th photon in the \( i \)-th interaction. A similar expression was used for the \( Y \) coordinate. The dispersion of the data as a function of energy was calculated by equation 4.10.

\[ \delta_E = \sqrt{\frac{\sum (\bar{X}_j - X_0)^2}{N-1}} \]  \hspace{1cm} (4.10)

The results, given in figure 4.5, show the dispersion, due to multiple Compton interactions, to be less than one crystal width, thus confirming the ability of the coded aperture system to perform as shown in figure 4.4.
SECTION 5 - THE ELECTRONICS ASSEMBLY

The electronics system of Prometheus can be separated into two major sections. The first section consists of the electronics which govern data acquisition. The second section is described as 'housekeeping' and includes all balloon controls.

As was mentioned previously, the entire electronics system uses standard CAMAC electronics (IEEE Standards 583 and 596). The flight system includes a 25 slot CAMAC crate directly coupled to ±6, ±12, and ±24 v. This crate is capable of supplying up to 650 W of power when fully loaded. The crate is controlled through the use of a Standard Engineering Corporation MIK-11/2 microprocessor / crate controller generously loaned to us by Dr. Ken Smith of this department. The MIK-11/2 system logic is based on an LSI-11 microprocessor module. The entire control assembly takes up the five highest number slots on the CAMAC crate, leaving 20 slots for other uses.

The data acquisition electronics are schematically illustrated in figure 5.1. The system consists of 121 inputs from the 121 NaI(Tl) crystals, 28 veto inputs from the shield assembly, and various control inputs.

The 121 photomultipliers for the NaI(Tl) crystals are produced by the Hamamatsu corporation, model number R2248. These are 8 stage 3/8" x 3/8" PMTs with a gain of \( \sim 1 \times 10^6 \). A list of pertinent data and a schematic illustration of the tube is shown in figure 5.2. The bleeder string assembly for the R2248 is shown in figure 5.3. The first shipment of 7 of these tubes has just been received, and none have been operated at this time. The expected output from this circuit is an analog pulse with a rise time of \( \sim 250 \) nsec, a 1/e decay time of \( \sim 500 \) nsec, and a peak voltage of between 1 and 10 mV for a gamma ray of 100keV. (Output voltage is based on typical array voltage using a similar RCA PMT.) The power required for each tube operating at 1500 v is \( \sim 1 \) W. The high voltage to each tube is to be supplied by 2 LeCroy Model 1443P high voltage supplies. Each supply has 16 channels capable of supplying 6.25 W / channel. A description of the
HV supplies is given in Appendix 2.

In order to allow for the necessary logic required by the β-ray rejection and calibration modes of operation, these small analog pulses need to be converted to digital pulses capable of triggering logic devices. This is to be accomplished with the use of a LeCroy model TRA1000 low level amplifier in series with a LeCroy MVL407 comparator circuit as shown in figure 5.4.

This circuit combination yields a variable input threshold from ~0.2 mV, making it possible to set the threshold of each crystal to the individual response of the crystal, thereby compensating the threshold for crystal-to-crystal variations in output. In addition to the standard ECL output (logic pulse with $0 = -0.8$ V, $1 = -1.6$ V, ≥10 nsec wide), the above circuit also includes an analog output with gain of up to 5000. Therefore, section 2 of figure 5.1 is completely realized by the above mentioned circuit. Specifications on both the MVL407 and the TRA1000 can be found in appendix 2.

The β-ray rejection method is to be accomplished with four LeCroy model 4532 32 channel Majority Logic Units (or three LeCroy model 4448 48 channel coincidence registers) connected in series. These units produce an output pulse with an amplitude which is proportional to the number of inputs received within a gated time window. The inputs to these units are the 121 logic outputs from the MVL407 circuits. The output is 80 mV/ input terminated into 25 ohms (or -100 mV/input into 50 Ω). This output is supplied to a discriminator which has a threshold that is adjustable from the MIK-11 microprocessor.

The necessity of allowing for inflight adjustment of the discriminator comes from the added ability this gives in changing the operational mode from data acquisition. In β-ray rejection mode, the discriminator will be set to allow for events which are the combination of signals from 2 or more crystals. In the energy calibration mode, each crystal is to be calibrated individually. This requires that one and only one crystal trigger.
Finally, if the source being viewed is strong enough, the β-ray rejection mode can be terminated by requiring ≥ 1 crystal to trigger an event. This could be useful when looking for line emissions in the energy regime from 100 keV to 500 keV where the sensitivity of the detector is degraded by the misidentification of gamma rays as β rays.

The output of the discriminator is input to a Logical Gate Generator (LeCroy model 2323, see appendix 2) where it is checked against the output from the veto circuit to provide a gate pulse to the analog to digital converters, thereby allowing data acquisition.

The veto circuit is similar to the NaI(Tl) circuit in many respects. The PMTs used are RCA 8053 2" diameter 10 stage devices with a gain of ~10^6. Figure 5.5 shows a schematic of the PMT, the bleeder string used for this circuit is similar to figure 5.3. High voltage is to be supplied from the same two LeCroy HV supplies. Because the ratio of the light output from plastic to the light output from NaI(Tl) is about 0.1, the output pulse for a 100 keV gamma ray in the plastic is between 0.1 and 1 mV. This pulse is fed into the same type of MVL407 circuit as described previously, with one of the logical outputs of the comparator being input to an OR gate, and the other pulse supplying the input to one of 28 scalers.

The scalers serve two purposes. The first is to keep track of the total flux of particles integrated over all energies interacting with each section of plastic. Because the shield represents 28 individual detectors, analysis of the interactions in the plastic can lead to a better understanding of the directional dependence of the background flux. In addition timing data from the shield can be used to search for pulsars and transients that are outside of the aperture but above the horizon. This type of analysis is a secondary goal of Prometheus and will be overridden if it in any way compromises the primary goals of Prometheus. The second purpose of the scalers is to monitor the dead time from the shield. This will be used in determining an accurate flux measurement and in allowing for modifications to the veto system in flight if one or more sections of the shield
malfucion.

The ECL pulses from the shield assembly will be input to a LeCroy model 4565 16 to 64 channel OR Logic Unit (see appendix 2 for details). This unit will provide the veto pulse for the Logical Gate Unit (LGU) described previously. If the LGU gets a logical 1 from the Majority Logic Unit, and a logical 0 from the veto system, then a gate pulse for the ADC's is generated allowing for data transfer.

The ADC's are LeCroy model 2249W 12 channel A-to-D converters (see appendix 2 for details). Each ADC will be connected to the analog output from one MVL407 circuit, i.e. the output from one NaI crystal. Upon receiving a gate pulse the ADCs will convert the analog pulse to a digitized output with >1% resolution. The MIK-11/2 will then read the pulses, perform a pulse height analysis of the individual pulses, and a pulse height analysis on the total output from the array, store the data onboard, and transfer the data to the telemetry unit. As soon as the pulses are read, the ADCs will clear and wait for the next event. From initial testing of the ADCs and the transfer rate of data from the MIK-11/2, this system is capable of functioning with counting rates as high as $10^3$ or $10^4$ per second.

The housekeeping electronics of Prometheus closely matches that which was accomplished on previous flights of the Rice University Gamma Ray Astronomical Telescope (RUGRAT). No major work has been done at this time in determining the exact electronics configuration of the gondola, relying instead on previous flights for confidence in our ability to accomplish this task. Descriptions of the current status of the gondola as well as more detailed explanations of gondola devices will be given in section 7.

A list of the electronic devices and their power requirements are given in Table 5.1. The total power required for Prometheus is ~660 W. This is to be supplied by batteries for a total of up to 24 hours.
Heat dissipation becomes an important factor in the design when as much as 660 W is to be dissipated. Most electronic devices can operate satisfactorily at \( \leq 38^\circ \text{C} \). Therefore, it is necessary to dissipate the power at a rate compatible with a 38\(^\circ\) equilibrium temperature. Because Prometheus will be operating in an environment with little or no atmosphere, heat transfer to the environment by convection and conduction will be minimal. Radiation will be the dominant energy transfer mechanism.

**Table 5.1 - Electronics Summary**

<table>
<thead>
<tr>
<th>Device/Name</th>
<th>Number Required</th>
<th>CAMAC slots Required</th>
<th>Total Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4448 Coincidence Register</td>
<td>3</td>
<td>3</td>
<td>41.4</td>
</tr>
<tr>
<td>4415 Programmable Discriminator</td>
<td>1</td>
<td>1</td>
<td>17.58</td>
</tr>
<tr>
<td>2323 Gate Generator</td>
<td>1</td>
<td>2</td>
<td>19.2</td>
</tr>
<tr>
<td>4565 Logical OR</td>
<td>1</td>
<td>1</td>
<td>~20</td>
</tr>
<tr>
<td>2249W ADC</td>
<td>10</td>
<td>10</td>
<td>105.2</td>
</tr>
<tr>
<td>MIK-11/2 Processor</td>
<td>1</td>
<td>3</td>
<td>45.4</td>
</tr>
<tr>
<td>R2248 PMT</td>
<td>121</td>
<td>0</td>
<td>121</td>
</tr>
<tr>
<td>RCA 8054 PMT</td>
<td>28</td>
<td>0</td>
<td>28</td>
</tr>
<tr>
<td>TRA 1000 Preamp</td>
<td>149</td>
<td>0</td>
<td>125</td>
</tr>
<tr>
<td>MVL407 Comparator</td>
<td>38</td>
<td>0</td>
<td>15.96</td>
</tr>
<tr>
<td>Housekeeping</td>
<td>~5</td>
<td>~120</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>25</td>
<td>~660</td>
<td></td>
</tr>
</tbody>
</table>

For a blackbody with a temperature of 38\(^\circ\) C and a radiating material with an
emissivity similar to copper, the area of radiating surface needed to dissipate 660 W of energy is 4.2 m². In order to decrease this surface area, it has been suggested that the electronics should be packaged in a refrigerator type configuration capable of keeping the electronics at 38° C while being surrounded by a volume of much higher temperature. For a radiating surface of 2 m², this outer secondary volume would require a temperature of 100° C. For a Carnot type cycle to transfer 660 W between 38° C and 100° C would require an additional ~400 W (assuming a 33% efficiency in transfer). Therefore, the total power requirement of the entire system, including cooling, is ~ 1kW.
SECTION 6 - THE SOFTWARE PACKAGE

The software being developed for Prometheus can be divided into two sections. The first section deals with the data aquisition and control commands to be used for the balloon flight. The second section deals with data analysis. At this time, only the initial programming and familiarization with the operating system has been undertaken.

The source code used by the MIK-11/2 microprocessor is RT-11 version 5.0 in the single job configuration. As a lack of understanding of Assembly routines for the MIK-11/2 was found, we purchased the crate control subroutines from DSP Technology Corporation. These Assembly code subroutines allow quick access to all of the standard CAMAC commands from a linked Fortran program by means of simple function statements.

The in-flight programming requires several separate routines functioning simultaneously, yielding priority access to data aquisition. The three major sections of the program are data aquisition, housekeeping, and data storage including transmission to ground. The expected non-vetoed (i.e. acceptable events) non-background-subtracted counting rate for the array operating in β rejection mode, is expected to be approximately 3 cnts cm⁻² sec⁻¹ MeV⁻¹ for the energy region from 100 keV to 10 MeV (assuming a downward flux corresponding to table 3.1 and the geometrical considerations mentioned previously for the array and the collimator). The housekeeping data consists of mostly slowly varying DC levels which require updating only every few seconds or even every few minutes. Finally the data storage is handled fairly quickly with data transfer rates of ~500 Kbytes sec⁻¹. (Actual rates may be limited by storage hardware, however transfer to a memory buffer can proceed at the above rate.) With these considerations in mind, data aquisition becomes the dominant time constraint on the programming.

The data aquisition software requires a program which recognizes when data are to
be sampled by the electronics as outlined in section 5. When data are present in any one of the 121 channels of ADCs, (one channel for calibration mode, ≥ two channels for source mode) a Look-at-Me (LAM) signal is generated by the ADC which has the signal. Because it is expected that only between 3 and 5 channels will be triggered for each event, the greatest number of 12 channel ADC modules that will have any signal is likely to be 5. Therefore the greatest number of read and clear commands necessary will be ~60. Reading the ADCs at a rate comparable to rates quoted by DSP Technologies for the MIK-11 with the purchased subroutines, we will be able to access up to ~850 60-channel signals per second, keeping in mind that the counting rate is expected be ~500 per second. If LeCroy model 4532 Majority Logic Units are used, the actual 3 to 5 channels which have a signal can be accessed directly, giving a data aquisition rate of between $10^4$ and $5 \times 10^4$ sec$^{-1}$. (The 4532 has the added feature of telling not only how many channels triggered, but which ones.) After the data is received from the ADCs, a 'block clear' signal will be generated, resetting the ADCs, and leaving the system ready to accept another event.

For the initial flight, as a means of insuring correct data analysis, the raw data will be stored on board and will be telemetered to the ground station. No data analysis of the array will be accomplished in real time. The raw data will consist of a single word per event which contains the following information; the event number, the event time, the position of each crystal which triggered and the signal from each crystal which triggered. From this and the information received from housekeeping, data analysis on every aspect of the flight can be taken into account.

Figure 6.1 shows a block diagram of the expected configuration of the Fortran programming required by Prometheus.

The data analysis package will consist of several pulse height analyzers combined in such a way as to separate out both the total energy and the coded aperture information.
The data will be combined to give the total energy deposited per event, corrected for gain differences between individual crystals. The number of background subtracted events per energy bin (~10 keV / bin) will be displayed as a final output. In addition, the gain corrected energy per crystal will be output to the coded aperture analysis section. Pulse height analysis software will be modeled after the presently used PCA-1000 software purchased from The Nucleus Incorporated (see appendix 3).

The coded aperture analysis will determine the most probable initial interaction position of each event based on the energy distribution of the event in the detector. It is assumed that for the average Compton interaction around 1MeV, approximately 50% of the energy will be deposited. This allows the crystal with the largest energy deposition to be identified as the initial interaction site. Monte Carlo simulations performed by Dr. Averin (figure 4.5) show that the error in identification of initial interaction position using this method is less than 1 crystal width at 1 MeV. Because the resolution given in the coded aperture section only requires determining which crystal was the initial interaction site within 1 crystal width, this analysis is sufficient. Further analysis will proceed as outlined in section 4.

Real time analysis of housekeeping information will be performed by the MIK-11 and used in a feedback cycle with the driving motors and temperature controls to keep Prometheus operating correctly and pointed on source. Housekeeping commands will also be telemetered to the ground station to allow for manual override of any operation.

Finally, the MIK-11 will perform both automatic calibration operations and on-source, off-source pointing variations at set time intervals. These automatic controls will also have the ability of being overridden by commands from the ground.
SECTION 7 - THE GONDOLA

The balloon gondola to be used by Prometheus is the same gondola used on several previous flights (i.e. Hall, 1975), with modifications being made to allow for the geometrical differences of Prometheus. The gondola is composed of two sections, named the inner and outer gondola respectively. The inner gondola provides an equatorial mounting system for Prometheus along with supporting the electronics, magnetometers, altimeters, telemetry and antenna.

When placed in the inner gondola, Prometheus can be independently rotated about the azimuth, declination and right ascension axes. Each of these three rotations is driven by an independent stepping motor controlled by the MIK-11. The polar axis is inclined at a fixed angle corresponding to the latitude of the balloon launch site.

The outer gondola rotates freely about the inner gondola on the azimuth-axis. The outer gondola carries the batteries which supply the power to Prometheus and feeds this power through slip rings on the azimuth-axis shaft. It is attached to the balloon by a single swivel joint connected to the four corners of the gondola. The swivel joint serves to partially decouple the gondola from balloon rotations.

The pointing control of the gondola is determined by the use of three horizontal flux-gate magnetometers (Heliflux Magnetic Aspect Sensors Type Ram-5C) encased in a plastic housing. The output voltage of the magnetometers is proportional to the component of the earth's magnetic field along the magnetometer's axis. Two of the magnetometers are aligned parallel to the horizontal component of the earth's magnetic field when calibrated to 0° azimuth. The third magnetometer is aligned perpendicular to the horizontal component of the earth's magnetic field at 0° azimuth. The magnetometers are isolated from close metal contact by suspension on a boom from the inner gondola. The voltage from the perpendicular magnetometer and one of the parallel magnetometers is
telemetered to the ground station to yield the azimuth angle of Prometheus. The output of
the second parallel magnetometer is used by the MIK-11 to drive the azimuth angle
motor. A null signal indicates an azimuth of geomagnetic north. The geomagnetic
declination at Palestine, Texas is a known angle; Prometheus is offset by this angle so
that the polar axis is aligned parallel to true north. Calibrations of the magnetometers will
be carried out at Palestine just prior to launch.

The altimeter to be used by Prometheus is to be supplied by the National Scientific
Ballooning Facility at Palestine, Texas and is to consist of three MKS Baratron pressure
transducers. A pressure/voltage curve will be established for all three units just before
launch. The system is typically accurate to between 100 and 120 meters at 43 kilometers
(Miller, 1987).

To insure that Prometheus is leveled correctly during flight, a pendulum type
levelometer will be flown. The output from the levelometer will be fed to housekeeping
and monitored by the ground station. Proper understanding of the magnetometer output
requires that the gondola remain level.

The unassembled gondola was received from Marshall Space Flight Center in the
spring of 1986, where it had been in storage from previous flights. It was reassembled at
Rice, including replacement of the azimuth-shaft assembly which had been broken upon
landing on its last flight. The stepping motors were tested and found functional.

At this time, no other work has been completed on the gondola. Preliminary changes
have been studied and are in the process of being implemented. These include changing
the width of the detector housing to accommodate the ~40 inch width of Prometheus, and
totally replacing the former electronics housing with the CAMAC crate and cooling
system.
SECTION 8 - SENSITIVITY

In order to determine the sensitivity of Prometheus, several Monte Carlo simulations have been carried out at Rice University. The most elaborate simulation was performed by Bhaswar Sen, (Sen, 1987) and used the Sandia National Laboratory code ACCEPT (Halbleib, 1979). This program contains the cross section data for all elements up to 1000 MeV, and tracks all generated photons and electrons through various physical processes including Compton and photoelectric interactions, Bremsstrahlung and pair production.

The simulation assumed a single NaI(Tl) detector of dimensions matching those of the array. The detector was shielded by a 12" thick layer of plastic scintillator and was placed in an atmospheric gamma ray spectra similar to what is to be expected over Palestine, Texas (Gehrels, 1985). Additionally it was assumed that there was no activation of the detector to add to the background.

The calculated detector efficiency as a function of energy is shown in figure 8.1, and compares well to similar calculations (Capponi, 1983). A calculation of the flux incident on the detector as a function of angle and as a function of energy is shown in figure 8.2 (Sen, 1987). The total flux leaking through the shield plus the aperture flux is compared to the flux from the aperture in figure 8.3. This can be compared to figure 3.2 which is a straightforward calculation of the shield leakage and aperture flux from cross-section data and backgrounds fluxes from Gehrels et al., 1985. Figure 3.2 does not take into account the geometrical cross section of the detector whereas figure 8.3 does. Figure 8.4 shows the area of the array presented as a function of zenith angle (Sen, 1987). In can be seen that there is a minimum at 90°. In figure 3.2, the maximum leakage comes from the zenith angles between 65° and 130°. Therefore, if we take into account the surface area of the array as a function of angle, figure 3.2 closely resembles figure 8.3. Figure 8.5 shows
the total background flux incident on the array as a function of energy. The best fit of the data between 0.1 MeV and 3.0 MeV is given by equation 8.1.

$$\text{Flux (photons sec}^{-1}\text{MeV}^{-1}) = 0.460 E^{-1.165} (\text{MeV}) \quad (8.1)$$

For an energy resolution of 10% at 1.0 MeV, the total flux (photons sec$^{-1}$) is given by equation 8.2. Because the spectrum is given by a Gaussian distribution, 1.5 times the energy range at FWHM will provide ~90% of the counts in the peak. Therefore the limits of integration are from $1.0\text{MeV} \pm 1.5(0.1)/2$ MeV.

$$\text{Flux (photons sec}^{-1}) = 0.460 \int_{0.925}^{1.075} E^{-1.165} \, dE \quad (8.2)$$

This yields a total of 0.069 photons sec$^{-1}$, or for an expected 6 hour integration time and a 36% efficiency at 1 MeV, a total of 537 counts from the background. On-source, off-source background subtraction eliminates all except the statistical fluctuations of the background. This would be given by the standard deviation of the counts which for a gaussian distribution is the square of the total counts. In this case, this accounts for 23.1 counts. For a statistically significant detection, the generally accepted criteria is that a source must be greater than 3 times the background flux which would be 69.5 counts. Therefore, for a source integration time of 6 hours, and a detector efficiency of 36% at 1.0 MeV, Prometheus has a $3\sigma$ detector sensitivity at 1.0 MeV of approximately $4.6 \times 10^{-5}$ photons cm$^{-2}$ sec$^{-1}$.

This figure does not include background from activation, fast or slow neutron interactions, or the lower efficiency of Prometheus due to the $\beta^-$ rejection method. It is assumed that the activation background is minimal due to both the $\beta^-$ rejection and the use of plastic for the active shield. Corrections due to neutron interaction and efficiency
changes however, do need to be made.

Monte Carlo simulation carried out by Dr. Averin included the 121 separate crystals of Prometheus and calculated several necessary results. The code which he developed included photoelectric interaction, Compton scatterings and pair production. As a means of verifying the code, Dr. Averin simulated a detector for which corresponding experimental data was available (Shafroth, 1967). This comparison is shown in figure 8.6 and shows that the Monte Carlo output is in excellent agreement with experiment. The total efficiency of the combined 121 crystals of Prometheus is shown in figure 8.7. Figure 8.7 also shows the efficiency of the detector as a function of energy when single crystal events are excluded.

At 1.0 Mev, without β rejection, Dr. Averin computed an efficiency of ~33 %, while the figure used by Sen was ~36%. If single crystal events are rejected, the overall sensitivity of Prometheus drops to ~22% at 1.0 MeV. Because the efficiency is decreased by ~39% at 1.0 MeV, the total number of background flux counts will be decreased to ~328 counts for a 6 hour flight. The 3σ sensitivity of Prometheus will also be decreased to ~6 x 10^-5 photons cm^-2 sec^-1.

Atmospheric neutrons also add to the background source and are not included in the previous considerations. As was mentioned previously, Prometheus has a 1" thick layer of lithium fluoride completely surrounding the active shielding. This acts as a slow neutron shield through the reaction \(^6\text{Li} (n,\alpha) ^4\text{He}\). The LiF used has an abundance of ~6% \(^6\text{Li}\). The most important background source which will form by slow neutron capture will be \(^{128}\text{I}\) from \(^{127}\text{I}\). In ~15% of the cases, \(^{128}\text{I}\) will decay with the emission of a 0.44 MeV photon. Because of the rejection of single crystal events, only ~30% of the 0.44 MeV photons will add to the background. This accounts for only \((0.3(0.15)= 0.045)\) 4.5% of the total slow neutrons which reach the detector and interact with the I.

For a thermal neutron flux of 0.05 neutrons cm^-2 sec^-1 expected over Palestine,
Texas (Armstrong, et al., 1973), approximately 1% will leak through the slow neutron shield. The number that interact with the total surface area of the array is 0.26 sec⁻¹ which results in a total flux of 1.17 x 10⁻² 0.44 MeV photons sec⁻¹ incident on the array, or a total increase in the background about 0.44 MeV of ~6.0 x 10⁻⁵ photons sec⁻¹ cm⁻².

In addition, there are spallation reactions in the LiF layer which are shown in Appendix 1. The largest component of the spallation radiation from the shield comes from the decay of ¹⁵O with the accompaniment of a 0.511 MeV gamma. The total cross section for formation of ¹⁵O is 12.8 mbarns. For a neutron flux of 0.05 neutrons cm⁻² sec⁻¹, this translates to the formation of ~6.2 x 10⁻⁴ ¹⁵O nuclei sec⁻¹ cm⁻² from a 3 cm thick LiF shield. At equilibrium and using the half life of ¹⁵O, this would yield a total of ~4.9 x 10⁻⁶ 0.511 MeV photons cm⁻² sec⁻¹ from the LiF shield. These photons are emitted in all directions and the percentage which interact with the array is less than 50%. Therefore, the maximum number of photons interacting the array from the 1.6 x 10⁴ cm² LiF shield would be 0.020 photons sec⁻¹. The shield will be approximately 5.5% transparent at 0.511 MeV, and the array will have an efficiency of detecting the radiation of 35%. This yields a total of 3.85 x 10⁻⁴ 0.511 MeV photons sec⁻¹ on the array, or ~2 x 10⁻⁶ photons sec⁻¹ cm⁻² added to the background.

Finally, fast neutrons may also add to the background. The plastic shield is between 10 and 15 mean free paths in thickness for fast neutrons (Haymes, et al., 1988). Therefore, the recoil protons from fast neutron scattering will generate a veto pulse.

The sensitivity of Prometheus, accounting for most known sources of background radiation should be ~1 x 10⁻⁴ photons sec⁻¹ cm⁻² at 1 MeV, for a 6 hour flight in a background radiation field similar to that described by Gehrels over Palestine, Texas. This represents a factor of ~10 reduction from current balloon borne gamma ray detectors.
SECTION 9 - CONCLUSIONS

Prometheus represents several new techniques for background reduction for balloon borne gamma ray telescopes. Fabrication and testing of Prometheus, both in the laboratory and with computer simulations, have continued to support the theoretical calculations that inspired her. With modest dimensions, Prometheus 1 is capable of improving on current detector sensitivities in the 0.1MeV to 10 MeV energy region by a factor of 10. With fairly simple modifications to the geometry of the detector, it will be possible to continue to improve this sensitivity limit. Due to the generous support of both Rice University and NASA, Prometheus 1 has been given the opportunity to be built and flown. The maiden launch of Prometheus is expected to be in the fall of this year from Palestine Texas, viewing the Crab nebula. If all goes as expected, this flight will herald a new generation of gamma ray telescopes which will not only be able to detect faint source low energy gamma ray objects, but will also be able to resolve them spatially.
REFERENCES

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Halbleib, J.A., Sr., 1979, Sandia National Laboratory publication No. 79-0415.


Shibazaki, N., and Ebisuzaki, T., and 1988, *The Effect on the Gamma Ray lines of Mixing of $^{56}$Ni in the Core*, presented at the January 1988 meeting of the AAS, Austin, Texas.


APPENDIX 1

Spallation cross sections for sodium, iodine, lithium, and fluorine. Only products of sodium and iodine which produce a $\beta^-$ emission are listed.

<table>
<thead>
<tr>
<th>ISOTOPE (MeV)</th>
<th>EFFECTIVE 3 GeV CROSS SECTION (mBarns)</th>
<th>MEAN $\beta^-$ ENERGY</th>
<th>HALF LIFE (MeV)</th>
<th>MAXIMUM $\gamma$ ENERGY LIFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{126}$I</td>
<td>78.6</td>
<td>0.625</td>
<td>13.d</td>
<td>----</td>
</tr>
<tr>
<td>$^{119}$Sb</td>
<td></td>
<td>0.024</td>
<td>45.1</td>
<td>38h</td>
</tr>
<tr>
<td>$^{117}$Sn</td>
<td>51.5</td>
<td>----</td>
<td>14d</td>
<td>0.158</td>
</tr>
<tr>
<td>$^{119}$Sn</td>
<td>50.9</td>
<td>----</td>
<td>250d</td>
<td>0.024</td>
</tr>
<tr>
<td>$^{121}$Sn</td>
<td>27.5</td>
<td>0.19</td>
<td>27h</td>
<td>0.037</td>
</tr>
<tr>
<td>$^{123}$Sn</td>
<td>11.6</td>
<td>0.71</td>
<td>129d</td>
<td>----</td>
</tr>
<tr>
<td>$^{115}$In</td>
<td>51.3</td>
<td>0.25</td>
<td>6x10$^{14}$y</td>
<td>----</td>
</tr>
<tr>
<td>$^{116}$In</td>
<td>44.5</td>
<td>1.67</td>
<td>14s</td>
<td>----</td>
</tr>
<tr>
<td>$^{117}$In</td>
<td>12.6</td>
<td>0.73</td>
<td>1.93h</td>
<td>0.158</td>
</tr>
<tr>
<td>$^{118}$In</td>
<td>20.4</td>
<td>2.1</td>
<td>5s</td>
<td>----</td>
</tr>
<tr>
<td>$^{119}$In</td>
<td>6.3</td>
<td>1.3</td>
<td>18m</td>
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<tr>
<td>$^{120}$In</td>
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<td>2.0</td>
<td>3s</td>
<td>----</td>
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<td>$^{121}$In</td>
<td>5.9</td>
<td>1.8</td>
<td>3m</td>
<td>----</td>
</tr>
<tr>
<td>$^{109}$Cd</td>
<td>13.8</td>
<td>----</td>
<td>453d</td>
<td>0.088</td>
</tr>
<tr>
<td>$^{113}$Cd</td>
<td>35.7</td>
<td>0.14</td>
<td>20m</td>
<td>----</td>
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<tr>
<td>$^{115}$Cd</td>
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<td>0.73</td>
<td>43d</td>
<td>0.028</td>
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<td>0.40</td>
<td>49m</td>
<td>----</td>
</tr>
<tr>
<td>$^{111}$Ag</td>
<td>25.4</td>
<td>0.53</td>
<td>7.5d</td>
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</tr>
<tr>
<td>$^{112}$Ag</td>
<td>19.3</td>
<td>1.97</td>
<td>3.2h</td>
<td>----</td>
</tr>
<tr>
<td>$^{114}$Ag</td>
<td>7.7</td>
<td>2.3</td>
<td>5s</td>
<td>----</td>
</tr>
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<td>$^{115}$Ag</td>
<td>0.8</td>
<td>1.67</td>
<td>20s</td>
<td>----</td>
</tr>
<tr>
<td>$^{100}$Pd</td>
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<td>----</td>
<td>4d</td>
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</tr>
<tr>
<td>$^{103}$Pd</td>
<td>7.3</td>
<td>----</td>
<td>17d</td>
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</tr>
<tr>
<td>$^{107}$Pd</td>
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<td>44s</td>
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<td>1.1</td>
<td>22m</td>
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<tr>
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<td>0.15</td>
<td>3.2h</td>
<td>0.019</td>
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<td>ISOTOPE (MeV)</td>
<td>EFFECTIVE 3 GeV CROSS SECTION (mBarns)</td>
<td>MEAN $\beta^{-}$ ENERGY</td>
<td>HALF $\gamma$ ENERGY LIFE</td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>--------------------------------------</td>
<td>--------------------------</td>
<td>---------------------------</td>
<td></td>
</tr>
<tr>
<td>$^{101}$Rh</td>
<td>4.2</td>
<td>4.5d</td>
<td>0.180</td>
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</tr>
<tr>
<td>$^{104}$Rh</td>
<td>27.8</td>
<td>1.23</td>
<td>43s</td>
<td>0.022</td>
</tr>
<tr>
<td>$^{105}$Rh</td>
<td>17.3</td>
<td>0.287</td>
<td>36h</td>
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</tr>
<tr>
<td>$^{106}$Rh</td>
<td>13.2</td>
<td>1.82</td>
<td>30s</td>
<td>----</td>
</tr>
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<td>$^{107}$Rh</td>
<td>1.1</td>
<td>0.76</td>
<td>22m</td>
<td>0.115</td>
</tr>
<tr>
<td>$^{108}$Rh</td>
<td>3.3</td>
<td>2.2</td>
<td>17s</td>
<td>----</td>
</tr>
<tr>
<td>$^{110}$Rh</td>
<td>1.8</td>
<td>2.8</td>
<td>5s</td>
<td>----</td>
</tr>
<tr>
<td>$^{97}$Ru</td>
<td>3.0</td>
<td>----</td>
<td>2.9d</td>
<td>0.110</td>
</tr>
<tr>
<td>$^{103}$Ru</td>
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<td>0.94</td>
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<td>0.129</td>
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<td>$^{106}$Ru</td>
<td>3.6</td>
<td>0.02</td>
<td>367d</td>
<td>----</td>
</tr>
<tr>
<td>$^{107}$Ru</td>
<td>1.5</td>
<td>1.6</td>
<td>4.2m</td>
<td>----</td>
</tr>
<tr>
<td>$^{108}$Ru</td>
<td>0.8</td>
<td>0.67</td>
<td>4.5m</td>
<td>0.165</td>
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<tr>
<td>$^{97}$Tc</td>
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<td>0.05</td>
<td>2.6x10^6y</td>
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<tr>
<td>$^{98}$Tc</td>
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<td>0.85</td>
<td>1.5x10^6y</td>
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<tr>
<td>$^{99}$Tc</td>
<td>19.7</td>
<td>0.15</td>
<td>2.1x10^5y</td>
<td>0.140</td>
</tr>
<tr>
<td>$^{100}$Tc</td>
<td>15.0</td>
<td>1.7</td>
<td>17s</td>
<td>----</td>
</tr>
<tr>
<td>$^{102}$Tc</td>
<td>6.2</td>
<td>2.2</td>
<td>5s</td>
<td>----</td>
</tr>
<tr>
<td>$^{103}$Tc</td>
<td>3.6</td>
<td>1.2</td>
<td>50s</td>
<td>0.21</td>
</tr>
<tr>
<td>$^{104}$Tc</td>
<td>0.6</td>
<td>2.9</td>
<td>18m</td>
<td>----</td>
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<td>$^{105}$Tc</td>
<td>1.0</td>
<td>1.7</td>
<td>8m</td>
<td>0.110</td>
</tr>
<tr>
<td>$^{93}$Mo</td>
<td>4.9</td>
<td>----</td>
<td>&gt;100y</td>
<td>0.030</td>
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<tr>
<td>$^{99}$Mo</td>
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<td>67h</td>
<td>0.143</td>
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<td>$^{101}$Mo</td>
<td>0.2</td>
<td>1.91</td>
<td>14.6</td>
<td>0.190</td>
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<tr>
<td>$^{20}$F</td>
<td>8.5</td>
<td>3.52</td>
<td>11.4s</td>
<td>----</td>
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<tr>
<td>$^{21}$F</td>
<td>1.7</td>
<td>2.84</td>
<td>4.4s</td>
<td>----</td>
</tr>
<tr>
<td>$^{13}$O</td>
<td>1.2</td>
<td>----</td>
<td>0.0089s</td>
<td>0.51</td>
</tr>
<tr>
<td>$^{14}$O</td>
<td>6.5</td>
<td>----</td>
<td>71s</td>
<td>2.31</td>
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<td>$^{15}$O</td>
<td>12.8</td>
<td>----</td>
<td>125s</td>
<td>0.51</td>
</tr>
<tr>
<td>$^{19}$O</td>
<td>0.4</td>
<td>2.41</td>
<td>29s</td>
<td>0.197</td>
</tr>
<tr>
<td>$^{20}$O</td>
<td>0.1</td>
<td>1.91</td>
<td>14s</td>
<td>----</td>
</tr>
<tr>
<td>$^{12}$N</td>
<td>5.7</td>
<td>----</td>
<td>0.01s</td>
<td>17.9</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>12.5</td>
<td>----</td>
<td>10m</td>
<td>2.72</td>
</tr>
<tr>
<td>$^{16}$N</td>
<td>1.0</td>
<td>5.21</td>
<td>7.2s</td>
<td>----</td>
</tr>
<tr>
<td>ISOTOPE (MeV)</td>
<td>EFFECTIVE 3 GeV CROSS SECTION (mBarns)</td>
<td>MEAN $\beta^-$ ENERGY</td>
<td>HALF (MeV)</td>
<td>MAXIMUM $\gamma$ ENERGY LIFE</td>
</tr>
<tr>
<td>---------------</td>
<td>----------------------------------------</td>
<td>------------------------</td>
<td>------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>$^{10}$C</td>
<td>5.0</td>
<td>----</td>
<td>19s</td>
<td>0.72</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>12.1</td>
<td>----</td>
<td>20m</td>
<td>2.5</td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>2.4</td>
<td>0.08</td>
<td>5730y</td>
<td>----</td>
</tr>
<tr>
<td>$^{15}$C</td>
<td>0.1</td>
<td>4.88</td>
<td>24s</td>
<td>----</td>
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<tr>
<td>$^{8}$B</td>
<td>4.3</td>
<td>----</td>
<td>0.8s</td>
<td>0.51</td>
</tr>
<tr>
<td>$^{7}$Be</td>
<td>10.9</td>
<td>----</td>
<td>53d</td>
<td>0.48</td>
</tr>
</tbody>
</table>
APPENDIX 2

The data for various electronics modules shown in this appendix comes from LeCroy corporation publications, either individual module data sheets, or information taken from the LeCroy corporation 1985 reference manual.

SPECIFICATIONS/Model 1443/12
16-CHANNEL HV MODULE

Channels/Module:

Output Voltage:

Voltage Regulation:
Full Scale:

Programming Step:
Programming Accuracy:

Programming Reproducibility:
Voltage Monitor Accuracy:
Monitor Long-Term Stability:
Output Long-Term Stability:

For Temperature Coefficient:

Output Ripple:

Current Output:
Output Protection:

Output Connector Type:

16.
0 to 2500 V: ≥ 500 V for rated performance. Polarity indicated by N or P suffix.
0.05% of full scale, line and load.
2500 V, 2047 V, 1500 V; 4095 V also available (limited to 2500 V max.) mainframe jumper option.
0.025% of full scale.
< ± (0.5% + 2 V) for demand voltages > 500 V.
< 1 V at a constant load and temperature after 10 minutes warm up.
± (0.1% + 1.5 V) channel-to-channel.
< 1.5 V/wk at constant load and temperature.
< 2 V/wk at constant load and temperature.
Typically 0.005%/ºC.
Max., 0.01%/ºC from 500 V to 2500 V (10ºC to 40ºC ambient).
Typically < 50 mV peak-to-peak;
< 250 mV peak-to-peak maximum.
Up to 2.5 mA per channel.
Fully protected against arcs at load, short circuit and overload.
Multiconductor block-type connectors,
SHV connectors specified by F suffix.
Monolithic Model MVL407
Quad Ultrafast Voltage Comparator

- Low cost
- 400 MHz operation
- 4 Comparators/DIP
- 3.5 nsec propagation delay
- Built-in 4.8 mV hysteresis
- 50 Ω line drive capability
- 100 mW/channel typical power dissipation
- Complementary ECL outputs

GENERAL DESCRIPTION

The MVL407 is a quad voltage comparator designed for applications in which ultra high speed and accurate timing are most important. The device is manufactured using a state-of-the-art high speed bipolar process which results in an extremely short (35 nsec) propagation delay with operation at speeds in excess of 400 MHz.

Each channel provides differential inputs and complementary outputs compatible with the ECL logic family. The outputs can drive 50 Ω loads or 100 Ω twisted pair. (External pull-down resistors are required).

The MVL407 incorporates a unique hysteresis feature for exceptionally clean operation. When the comparator changes state, an internal differential input offset of about 4.8 mV is generated. This positive feedback drives the device quickly through its switching region, greatly reducing the possibility of oscillation or output chatter with small or slowly changing inputs.

The propagation delay is typically 3.5 nsec and changes by only 100 psec for 5 to 100 mV range of overdrive. This very low delay variation makes the MVL407 extremely useful in critical timing applications.

For evaluation and for prototyping purposes, the Model MVL407PK is recommended. It consists of a single MVL407 mounted on a circuit board. Space is provided on the board for user prototyping circuitry. The power and reference voltage are supplied to the MVL407 via a wire pigtail.
Monolithic Model MVL407
QUAD ULTRAFAST VOLTAGE COMPARATOR

| **Absolute** | **Positive Supply Voltage** | + 6 V |
| **Maximum** | **Negative Supply Voltage** | − 6 V |
| **Ratings** | **Input Voltage** | ± 4 V |
| **(Above which MVL407 may be destroyed.)** | **Differential Input Voltage** | ± 4 V |
| | **Output Current** | 30 mA (single output) |
| | **Power Dissipation** | 800 mW |
| | **Operating Temperature** | −20°C to + 70°C |

**Electrical Characteristics**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Units</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{o}$</td>
<td>Input offset current</td>
<td>$−0.5$</td>
<td>$± 0.05$</td>
<td>$+0.5$</td>
<td>$μA$</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>$ΔI_{o}/ΔT$</td>
<td>Average TC of $I_{o}$</td>
<td>$−1.5$</td>
<td>$± 0.5$</td>
<td>$+1.5$</td>
<td>$nA^°C$</td>
<td>See Fig. 1</td>
</tr>
<tr>
<td>$I_{b}$</td>
<td>Input bias current</td>
<td>$3.5$</td>
<td>$5.0$</td>
<td>$7.0$</td>
<td>$μA$</td>
<td>See Fig. 11</td>
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<tr>
<td>$ΔI_{b}/ΔT$</td>
<td>Average TC of $I_{b}$</td>
<td>$−40$</td>
<td>$−20$</td>
<td>$0$</td>
<td>$nA^°C$</td>
<td>See Fig. 11</td>
</tr>
<tr>
<td>$R_{in}$</td>
<td>Input resistance</td>
<td>$20$</td>
<td>$30$</td>
<td>$−$</td>
<td>$KΩ$</td>
<td></td>
</tr>
<tr>
<td>$C_{in}$</td>
<td>Input capacitance</td>
<td>$1.2$</td>
<td>$1.6$</td>
<td>$2.1$</td>
<td>$pF$</td>
<td></td>
</tr>
<tr>
<td>$V_{cm}$</td>
<td>Input voltage range</td>
<td>$−2.0$</td>
<td>$1.7$</td>
<td>$V$</td>
<td></td>
<td>See Figs. 2, 14</td>
</tr>
<tr>
<td>$V_{T_{x}+}$</td>
<td>Threshold for OUT $+$</td>
<td>$−1.0$</td>
<td>$+2.4$</td>
<td>$+5.0$</td>
<td>$mV$</td>
<td>See Fig. 4, Note 4</td>
</tr>
<tr>
<td>$V_{T−}$</td>
<td>Threshold for OUT $−$</td>
<td>$−6.0$</td>
<td>$+2.4$</td>
<td>$0$</td>
<td>$mV$</td>
<td></td>
</tr>
<tr>
<td>$ΔV_{T{x}}/ΔT$</td>
<td>Average TC of $V_{Tx}$</td>
<td>$−10$</td>
<td>$± 5$</td>
<td>$10$</td>
<td>$μV^°C$</td>
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</tr>
<tr>
<td>$V_{H}$</td>
<td>Hysteresis voltage</td>
<td>$4.6$</td>
<td>$4.8$</td>
<td>$5.0$</td>
<td>$mV$</td>
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<tr>
<td>$V_{OL}$</td>
<td>Output low level</td>
<td>$−1.85$</td>
<td>$−1.71$</td>
<td>$−1.63$</td>
<td>$V$</td>
<td></td>
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<tr>
<td>$V_{OH}$</td>
<td>Output high level</td>
<td>$−.96$</td>
<td>$−.84$</td>
<td>$−.80$</td>
<td>$V$</td>
<td>See Fig. 3</td>
</tr>
<tr>
<td>$ΔV_{OH}/ΔT$</td>
<td>Average TC of $V_{OH}$</td>
<td>$−$</td>
<td>$1.5$</td>
<td>$−$</td>
<td>$mV^°C$</td>
<td></td>
</tr>
<tr>
<td>$ΔV_{OL}/ΔT$</td>
<td>Average TC of $V_{OL}$</td>
<td>$−$</td>
<td>$0.6$</td>
<td>$−$</td>
<td>$mV^°C$</td>
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</tr>
<tr>
<td>$I^+$</td>
<td>Positive supply current</td>
<td>$40$</td>
<td>$50$</td>
<td>$mA$</td>
<td></td>
<td>4 channels Without output pulldown resistors, See Fig. 1</td>
</tr>
<tr>
<td>$I^−$</td>
<td>Negative supply current</td>
<td>$37$</td>
<td>$47$</td>
<td>$mA$</td>
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<tr>
<td>PD</td>
<td>Power dissipation</td>
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<td>$494$</td>
<td>$mA$</td>
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**Switching Characteristics**

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<th>Typ</th>
<th>Max</th>
<th>Units</th>
<th>Comments</th>
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<tr>
<td>$t_{pd}$</td>
<td>Propagation delay</td>
<td>$3.0$</td>
<td>$3.5$</td>
<td>$4.0$</td>
<td>$nsec$</td>
<td>See Fig. 3</td>
</tr>
<tr>
<td>$Δt_{pd}/ΔT$</td>
<td>Average TC of propagation delay</td>
<td>$−$</td>
<td>$2$</td>
<td>$−$</td>
<td>$psec^°C$</td>
<td>0 to 70°C</td>
</tr>
<tr>
<td>$t_{r}$, $t_{f}$</td>
<td>Transition time</td>
<td>$1.2$</td>
<td>$1.4$</td>
<td>$nsec$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t_{r}$, $t_{f}$</td>
<td>Transition time</td>
<td>$5.8$</td>
<td>$1.2$</td>
<td>$nsec$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$DPR$</td>
<td>Double pulse resolution</td>
<td>$−$</td>
<td>$2.0$</td>
<td>$−$</td>
<td>$nsec$</td>
<td></td>
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<tr>
<td>$f_{max}$</td>
<td>Max. toggle frequency</td>
<td>$−$</td>
<td>$400$</td>
<td>$−$</td>
<td>$MHz$</td>
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<tr>
<td>$T_{min}$</td>
<td>Min. input width</td>
<td>$−$</td>
<td>$1$</td>
<td>$−$</td>
<td>$nsec$</td>
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**Interchannel Matching**

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<th>Typ</th>
<th>Max</th>
<th>Units</th>
<th>Comments</th>
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<tbody>
<tr>
<td>$ΔV_{H}$</td>
<td>Hysteresis</td>
<td>$± 0.25$</td>
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<td>$mV$</td>
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<td>$ΔV_{Tx}$</td>
<td>Threshold voltage</td>
<td>$± 1.25$</td>
<td>$+$</td>
<td>$mV$</td>
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<td></td>
</tr>
<tr>
<td>$ΔI_{o}$</td>
<td>Input offset current</td>
<td>$± 50$</td>
<td>$nA$</td>
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</tr>
<tr>
<td>$Δt_{pd}$</td>
<td>Propagation delay</td>
<td>$± 125$</td>
<td></td>
<td>$psec$</td>
<td>Unobservable</td>
<td></td>
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<tr>
<td>Cross talk—any channel</td>
<td>$−$</td>
<td>$−$</td>
<td>$−$</td>
<td></td>
<td>Note 1</td>
<td></td>
</tr>
</tbody>
</table>

*Interchannel matching refers to the variation between the channels on any single chip.

NOTES:
1. Cross talk is measured at a threshold of 2 mV.
2. Propagation delays are defined to be the delays between a positive going input and an output transition of either polarity. The input overdrive is 50 mV with the threshold set at 0 mV.
3. Double pulse resolution is defined as the minimum pulse pair spacing at which the MVL407 responds to the second pulse of the pair. The output levels of the second pulse must cross $V_{OH}$ and $V_{OL}$, See Figure 5.
4. See Application Hints.
Monolithic Circuit/Type TRA1000
Charge/Current Pulse Preamplifier

FEATURES

- Low noise
- Low cost
- Low power dissipation
- Versatile configuration flexibility
- Very wide dynamic range
- Monolithic

- Excellent linearity
- >5000 open-loop voltage gain
- Current or charge input modes
- Inverting and non-inverting outputs
- Directly drives twisted pair or 50 Ω cable

Ideal for Wire Chamber Linear Measurements

The LeCroy Model TRA1000 monolithic preamplifier is a versatile, economical, low-noise device which can be used either as a current-to-voltage preamplifier or as a charge-to-voltage preamplifier. The device has been designed for use with negative input signals; however, it may also be configured for operation with positive inputs. The various options are selected through the use of external components.

The TRA1000 has been designed for direct connection to a variety of detectors. Its low noise and low input impedance make it ideal for use with proportional wire chambers even when resistive wire is used for position measurements. The device also finds application with photomultipliers when the economy of low-gain tubes is a factor or dynamic range considerations are important. When used in conjunction with both the last dynode and the anode signals, exceptional dynamic range can be achieved by selecting different gains for the two devices. In this way high- and low-sensitivity channels are configured.

The linearity of the preamplifier is excellent for a wide range of input risetimes and selected gains. The linear range of output is 0 to 1 V, even for 50 Ω loads. In the applications discussed below typical linearity has been measured in conjunction with a LeCroy 2280-Series 12-bit ADC. The result is typically <0.5% of reading, with proper compensation.

The equivalent input noise of the preamplifier is as low as 2 pAV/Hz in some configurations. In the applications documented below noise measurements are quoted in rms pC, referred to the preamplifier input. The LeCroy 2280-Series current-integrating ADC’s, employing a 500 nsec wide gate, were used to characterize the current-to-voltage configurations. For the charge-to-voltage configurations a peak-sensing 2280-Series ADC was used. The output noise in rms mV is also given for each case below.

The low price, compact packaging, and low power dissipation of the Model TRA1000 make it an ideal choice for use in large-scale systems applications. It is particularly suited for use as a current-sensitive preamplifier for MWPC analog position measurements. The Model TRA1000 is a low-cost, high-performance answer to a wide range of charge-sensitive and current-sensitive preamplifier needs.

Model TRA1000T is a printed circuit card allowing prototyping and evaluation of the TRA1000.
**SPECIFICATIONS**

**MONOLITHIC CIRCUIT/TYPE TRA1000**

**CHARGE/CURRENT PREAMPLIFIER**

Gain: >5000 open-loop voltage gain into 50 Ω load. Current-mode and charge-mode gains are determined by external feedback elements.

Linearity: <±0.5% integral, into 50 Ω load.

Rated Output: 1.0 V into 50 Ω load.

Inverted output: 1.8 mA sink current; 20 mA source current.

Non-inverted output: 20 mA sink current; 1.8 mA source current.

Output Impedance: <1 Ω, with R<sub>Fe</sub> = 2.7 kΩ; see specifications below.

Risetime: See specifications below.

Falltime: See specifications below.

Input Noise: See specifications below.

Input Bias Current: <7 μA.

Input Voltage: Quiescently 700 mV.

Temperature Range: 0°C to 70°C.

Power Supply Requirements:

- Rated Voltage, Quiescent Current
  - Standard operation: +12 V @ 6 mA.
  - Two-voltage operation (for FET input stage or with buffered output):
    - +12 V @ 6 mA + FET drain current (~10 mA) and buffer current (~25 mA);
    - -12 V @ -2 mA + buffer current (~26 mA).

Package: 16-pin plastic DIP.

*All specifications are typical at 25°C and the rated supply voltages. Currents flowing into the amplifier are considered to be positive.

ALL SPECIFICATIONS SUBJECT TO CHANGE

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**APPLICATION NOTES**

The TRA1000 input consists of a special geometry low-noise common emitter transistor as part of a cascode stage. The emitter connection is isolated from the power ground and is brought out on pin 2. This input ground must be externally referenced to power ground by the user. A frequency compensation point on the output of the cascode stage is available on pin 16. Compensation may not be required for the highest gain operation. Compensation for each of the example circuits shown in the accompanying schematics is presented only as a guide. Precise component values will depend upon details of the layout, the input source characteristics, etc. Compensation values should be selected to avoid oscillation and to minimize overshoot of the output.

The output stage consists of a single transistor having both collector and emitter external connections, allowing either differential or single-ended outputs to be used. The collector (pin 10) provides the non-inverting output and the emitter (pin 9) provides the inverting output. Due to quiescent DC levels, the outputs must be capacitively coupled. For proper operation the outputs must be loaded symmetrically.

The TRA1000 can operate from a single power supply, as shown in Fig. 1. Pin 8 is connected to the chip substrate and must always be connected to the most negative power supply used. When an input FET or an output buffer is used, two power supplies are required. Power supply ripple should be below 3 mV (peak-to-peak) for low-noise performance. A series inductor of 1 μH with a 6.8 μF capacitor to ground provides excellent rejection of power supply transients. For highest gain operation a negative network should be used. The isolation of input ground and power ground allows for protection against possible noise due to loop grounds or pickup which could feed through to the input stage. For most applications the input ground at Pin 2 can be tied directly to the circuit board ground plane. The power ground, Pin 11, should be tied to the ground plane. A bypass capacitor from Pin 4 to ground is required for all circuit configurations. In many cases a value of 0.01 μF may be used. For critical low noise applications use 0.001 μF.

For optimum performance good wiring techniques are essential. The circuit must be built on a printed circuit board having a continuous ground plane on one side. The input and feedback connections must be kept as short as possible to minimize stray capacitance. If a DIP socket is desired, a low-profile version should be used, and pinplugs are preferable.

The gain of the TRA1000 is determined by the feedback element selected. See Figs. 1 and 2. When a resistor is employed, the TRA1000 becomes a transimpedance amplifier; i.e., a current-to-voltage device. The transfer gain will be determined by the value of the resistor. For example, a 10 KΩ resistor offers 10 mV/μA gain. When used in this mode, the TRA1000 should be driven from a current source such as a photomultiplier anode or an ionization chamber.

When driven from a voltage source, such as an amplifier, a series input resistor is required by the TRA1000. In this case the voltage gain of the TRA1000 is given by R<sub>Fe</sub>/R<sub>e</sub> (R<sub>e</sub> = feedback resistor; R<sub>f</sub> = series input resistor).

When the TRA1000 employs a capacitor as its feedback element, it operates as a current-integrating or charge-sensitive amplifier. Its gain is determined by the value of the capacitor. For example, with 5 pF as the feedback element, the TRA1000 has a gain of 0.5 VpC. In this mode it is necessary to employ a resistor in parallel to the feedback capacitor in order to provide a discharge path for the capacitor and thereby determine the falltime of the amplifier and also maintain necessary DC feedback for proper biasing of the input.

Applications requiring a faster risetime than specified in the cases on the following pages may be accommodated by supplying more current to the TRA1000 input stage. This may be accomplished by inserting a 1.5 KΩ resistor between pins 12 and 13 (labeled points 28 and 29 on the TRA1000). This decreased risetime will be gained at the sacrifice of increased noise. For example, if Case 7 is modified by addition of this 1.5 KΩ resistor then a risetime of 15 nsec may be achieved but the typical noise performance will be about 0.8 IC (HWHM) rather than 0.4 IC.

The input voltage of the TRA1000 is quiescently ±700 mV. When used with an input FET, the quiescent input voltage will be different but also non-zero. As a result, it is often necessary to AC-couple the input, eliminating a DC path to ground. For many applications direct coupling may be possible. When used in conjunction with an ideal current source such as an ionization chamber, a proportional chamber, or a photomultiplier anode, direct coupling may be used as long as any resistance to ground is large compared to the feedback resistance.

The input to the TRA1000 is a virtual ground. In the applications listed below the input impedance is given. In most cases it is less than 20 Ω. As a result, when driven from a transmission line, proper termination requires a series resistance. Choose a value so that when added to the input impedance, proper termination is obtained. For fast edges an RC from the input to ground may be required. Some common mode noise rejection may be achieved if the ground return of the input is tied only to pin 2 rather than to chassis ground. In this case the ground reference of the TRA1000 circuit and the ground of the source must be tied common. Although the input circuit provides some protection against chamber breakdown, it is suggested that the clamp circuit shown in Figure 1 be employed.

The inverting output can swing ±1 V in the positive direction. Since this point is used for feedback, the TRA1000 is ideally suited for negative inputs. For use with positive inputs, an external pnp transistor should be used as a buffer. See Figure 3. A pnp transistor with f<sub>β</sub> = 500 should be used.

The input bias current of the TRA1000 is approximately 5 μA. This value sets an upper limit on the magnitude of the feedback resistance (R<sub>f</sub> ≤ 1 KΩ). For applications requiring high transimpedance gain or current-integrating operation with a large time constant, it is necessary to replace the input transistor with a FET. See Figure 2. Note that pins 2 and 3 are connected to ground. A junction-type n channel FET is recommended. The 1N875 or 2N4453 are common in this application.

The output of the TRA1000 can be used to drive 100 Ω twisted-pair cable. A typical drive circuit is shown in Figure 4. When only the inverting output is to be used, the pull-up resistor and AC-coupling capacitor on the noninverting output may be eliminated. In this case, pin 10 should be connected to +12 V.
CAMAC Model 2323

Programmable Dual Gate and Delay Generator

- No dead time
- Programmable width
- Programmable delayed signal

- Accepts NIM, TTL or ECL inputs
- Range 50 nsec to 10 sec
- Manual or CAMAC control

LeCroy's CAMAC Model 2323 is a fully programmable gate and delay generator packaged with two channels in a double width CAMAC module. Its gate duration is programmable over the range 100 nsec to 10 seconds, covering a dynamic range of eight orders of magnitude. Outputs as short as 50 nsec can be selected at the expense of accuracy and stability. All settings may be programmed under CAMAC control or via front panel switches. Under CAMAC control, settings are overwritten whereas they are incremented under manual control. The Model 2323 offers excellent stability and jitter properties with 0.2% of Full Scale accuracy in the gate setting.

The Model 2323 offers both Start and Stop inputs. This allows the output pulse width to be determined by the Start - Stop time difference in the latched mode or by the internal timer in the preset mode. A Blanking NIM input causes a notch to be taken out of the gate, equal in duration to the blanking input. This is especially useful to gate off data acquisition during spurious periods. Conversely, a NIM OR input causes all outputs to be set to true for the duration of the OR inputs.

The unit offers NIM and NIM outputs equal in duration to the gate width selected. In addition, a DELAY output is produced at the trailing edge of the Gate pulse. The Model 2323 also provides a differential ECL output and a TTL output capable of driving a NIM Bin Gate. Both the ECL and TTL outputs may be driven from either the Gate or Delay circuit. These options are selected by board mounted shorting plugs.

The gate duration and width of the Delayed output are programmable under CAMAC control. Each of the two channels may be set independently. All values which are loaded into the Model 2323 may also be read back via CAMAC. Programming of the delay involves a ten bit “mantissa” and a three bit “characteristic”.

The Start input is normally configured to accept NIM signals. A bridged high impedance input is employed to allow the trigger of more than one channel of 2323. The front end of the Start input consists of a comparator circuit, factory adjusted to trigger at \(-400 \pm 50 \text{ mV}\). A front panel accessed multiple turn potentiometer allows the user to adjust the threshold over the range \(-3 \text{ V to } +3 \text{ V}\). This allows the unit to be triggered by NIM, ECL, TTL or other standard logic signals. A front panel accessed switch selects either the positive-going or negative-going edge as the trigger. The stop input accepts NIM standard pulses.

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SPECIFICATIONS
CAMAC Model 2323
DUAL PROGRAMMABLE GATE AND DELAY GENERATOR

Gate Width
Range: 100 nsec to 10 sec; pulses to 50 nsec at reduced accuracy and stability
Accuracy: ±0.2% of full scale (mantissa)
Temperature Stability: <200 ppm/K
Jitter: <0.2% of setting
Resolution: 0.1% of full scale (mantissa)

Delay Width
Range: 10 nsec to 300 nsec
Width Options: 10 nsec, 30 nsec, 100 nsec, 300 nsec
Accuracy: ±20%

Inputs
START:
Bridged high impedance pair. Lemo-type connectors. Input trigger level adjustable over the range ±3 V via front panel potentiometer. As supplied, the input is set to trigger at -400±50 mV with a negative going edge. Action of the input is to initiate the timing cycle.

STOP:
Standard NIM. Impedance 50 Ω. Lemo-type connectors. Action of the input is to terminate the timing cycle in the latched mode. Active in both latched and preset modes. The delay is <20 nsec.

OR:
Standard NIM input via Lemo-type connector. Input impedance 50 Ω. Produces NIM, NIM, ECL, and TTL outputs as long as the OR signal is asserted.

BLANK:
Standard NIM input via Lemo-type connector. Input impedance 50 Ω. Cancels NIM, NIM, ECL, and TTL outputs as long as the BLANK signal is asserted. Overrides OR input.

Outputs
BUSY LED:
Indicates unit is active; duration stretched to 1 msec minimum.

NIM:
Standard NIM (−16 mA) signal via a Lemo-type connector. Goes low for gate duration. Risetime ≤2 nsec. Falltime ≤2.5 nsec.

NIM:
Standard NIM (−16 mA) signal via a Lemo-type connector. Goes high for gate duration. Risetime ≤2 nsec. Falltime ≤2.5 nsec.

ECL:
One per section. Complementary ECL levels via a 2-pin connector. PC mounted shorting plug allows this output to be logically identical to the GATE or DELAY pulse or their complements.

TTL:
One per section. An FET open drain output (+35 V max, 250 mA, 0.5 W max). PC mounted shorting plug allows this output to be logically identical to the GATE or DELAY pulse or their complements.

DELAY:
Standard NIM (−16 mA). Lemo-type connector. Delayed from start of NIM by the gate width. (Goes low at trailing edge of gate). Programmable for 10, 30, 100 or 300 nsec duration. Risetime ≤2 nsec.

CAMAC COMMANDS
F(1) · A(0)
Read channel A programming word.
F(1) · A(1)
Read channel B programming word.
F(9) · A(0)
Stop channel A gate.
F(9) · A(1)
Stop channel B gate.
F(17) · A(0)
Write channel A programming word.
F(17) · A(1)
Write channel B programming word.
F(25) · A(0)
Start channel A gate.
F(25) · A(1)
Start channel B gate.
C or Z
Stops channels A and B gates.

Programming Word
M = mantissa
C = characteristic
L = latch bit
D = delayed pulse width

Programmable mode:
(L = 0). Duration = M×10⁻⁶ nsec. (For 100 s ≤ M ≤ 10²). Settings of 50 ≤ M ≤ 100 at reduced accuracy and stability.
(L = 1). Duration = time between STOP and START inputs.

Delay Options:

<table>
<thead>
<tr>
<th>D</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>10 nsec</td>
</tr>
<tr>
<td>01</td>
<td>30 nsec</td>
</tr>
<tr>
<td>10</td>
<td>100 nsec</td>
</tr>
<tr>
<td>11</td>
<td>300 nsec</td>
</tr>
</tbody>
</table>

General
Input-Output Delay:
Recovery time:
Packaging:
Power Consumption:

24 nsec (Start input to NIM output).
None. The unit may be retriggered any time after the timing cycle has been completed.

1.8 A @ +6 V
1.3 A @ −6 V
50 mA @ +24 V
75 mA @ −24 V
SPECIFICATIONS
CAMAC ECLine Model 4564
16 TO 64 FOLD OR LOGIC UNIT

INPUT CHARACTERISTICS
Signal Inputs:
64 in four 2 x 17 pin front panel connectors; all inputs accept differential ECL levels; impedance: 110 ohms; minimum input pulse width 6 nsec maximum width DC; maximum input frequency > 100 MHz.

OUTPUT CHARACTERISTICS
Overlap Outputs:
Rear panel 2 x 17 pin connector, out 1 to 12; generate differential ECL levels; the output pulse width corresponds to the input pulse overlap (+2 nsec for the desired logic combination. See logic diagram below for pin allocation to the different logic functions; minimum output width 5 nsec; maximum width DC maximum overlap output frequency > 100 MHz; transit time 12 nsec ± 1 nsec independent from the logic function.

Rear panel connector, out 13 to 16; any of the overlap logic combinations can be connected, via jumper option to any of the four discriminator/shaper included in the unit; these four shaped outputs provide differential ECL levels and the output width is internally adjustable from 15 to 500 nsec; maximum frequency: 50 MHz; double pulse resolution 13 nsec.

NOTE: An option, where all rear panel multipin connector output are at NIM levels, can be provided upon request.

SPECIFICATIONS SUBJECT TO CHANGE

LOGIC DIAGRAM

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>OUTPUT CONNECTOR PIN #</th>
<th>LOGIC FUNCTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>1</td>
<td>A</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>B</td>
</tr>
<tr>
<td>16</td>
<td>3</td>
<td>C</td>
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<td>C·D</td>
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<td>7</td>
<td>A·B</td>
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<td>8</td>
<td>C·D</td>
</tr>
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<td>9</td>
<td>A·B·C·D</td>
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<tr>
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<td>10</td>
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<td>11</td>
<td>(A·B)·(C·D)</td>
</tr>
<tr>
<td>16</td>
<td>12</td>
<td>A·B·C·D</td>
</tr>
</tbody>
</table>
SPECIFICATIONS
CAMAC Model 2249W
12 CHANNEL ANALOG-TO-DIGITAL CONVERTER

Analog Inputs:
12; Lemo type connectors; charge sensitive (current integrating); AC coupled (2 nsec time constant, field changeable); 50 Ω impedance; linear range normally 0 to −2.0 V; protected to ±50 V against 1 nsec transients

Gain:
−0.25 pC/count ± 5%

Full-Scale Range:
Approximately −500 pC (maximum count ≈ 1980)

Integral Non-Linearity:
±0.05% ± (0.5 pC + 0.1%) (1980 total counts)

ADC Resolution:
Better than 0.25% of reading ±0.5 pC/week (at constant temperature)

ADC Isolation:
A 5 V, 20 nsec overload pulse in any one ADC disturbs data in any other ADC by no more than 0.5 pC (2 counts)

Gate Input:
One gate common to all ADC's; Lemo type connector; 50 Ω impedance; −600 mV or greater enables; minimum duration, 30 nsec; maximum recommended duration up to 10 nsec; partial analog input must occur within 0.5 nsec after opening gate to preserve accuracy; effective opening and closing times, 5 nsec; internal delay, 7 nsec

Fast Clear:
One front panel input common to all ADC's Lemo type connector; 50 Ω impedance; −600 mV or greater clears, minimum duration, 50 nsec. Requires additional 2.0 μsec settling time.

Pedestal:
Adjustable over approximately 100 counts via side-panel accessed trimmer capacitor. Somewhat higher for wide gate.

Test Function:
With CAMAC I present, the positive DC level applied to front panel “Test” input (internal high impedance connection to +12 V) or optional rear connector P1, P2, or P5 is connected to output of channel A (25) S2. (With CAMAC I not present, F(25)-S2 will generate the gate only, providing a measure of the pedestal.)

Digitizing Time:
106 μsec

Readout Time:
Readout may proceed at the fastest rate permitted by the CAMAC standard after digitization is complete.

Readout Control:
Ready for readout when LAM signal appears. Refer to ESONE Committee Report EUR4100e and EUR4900e for additional timing details, voltages, logic levels, impedances, and other standards.

Data:
The proper CAMAC function and address command normally gates the 11 binary bits of the selected channel onto the the R1 to R11 (2nd to 21st) Datayway bus lines.

CAMAC Commands:
Z or C: ADC's and LAM are cleared by the CAMAC "Clear" or "Initialize" command; requires S2. Z also disables LAM.

CAMAC Function Codes:
F(0): Read registers; requires N and A; A(0) through A(11) are used for channel address.
F(2): Read registers and Clear module and LAM; requires N and A; (clears on A(11) only)
F(3): Test Look-At-Me; requires N and any A from A(0) to A(1) independent of Disable Look-At-Me.
Q response is generated if LAM is set.
F(5): Clear module and LAM; requires N, S2, and any A from A(0) to A(11). If (Q) response is generated
F(0) or (Q) if A(0) to A(11).
F(10): Clear Look-At-Me; requires N, S2 and any A from A(0) to A(11).
F(24): Disable Look-At-Me; requires N, S2, and any A from A(0) to A(11).
F(25): Test module; requires N, S2 and any A from A(0) to A(11).
F(26): Enable Look-At-Me; requires N, S2 and any A from A(0) to A(11). Remains enabled until Z or
F(24) applied. Caution: the state of the LAM mask will be arbitrary after power turn-on.

Q and LAM Suppression:
Adjustable potentiometer (accessible from side of module) sets count level required (from 0 to 100) before data is considered useful. A module in which all channels contain less than set amount will produce no O-response or LAM and appears during readout as an empty CAMAC slot, thus reducing readout time. A Command Accept response is still generated. The LAM suppress portion can be disabled with a solder jumper option.

Packaging:
In conformance with CAMAC standard for nuclear modules (ESONE Committee Report EUR4100e)
RF shielded CAMAC #1 module.

Current Requirements:
143 mA at +24 V; 75 mA at −24 V; 725 mA at +6 V; 155 mA at −6 V
APPENDIX 3

Information in this appendix concerns the operation of the PCA-1000 pulse height analysis package supplied by The Nucleus Corporation. This is a single 1024 channel pulse height analyzer which interfaces with an IBM PC or compatible. All laboratory data generated by Prometheus was done with the use of this analysis package.

The Nucleus Personal Computer Analyzer (PCA) card is designed physically to be installed in a full length slot of the IBM PC, XT, or AT. It may also be installed in some of the IBM compatibles, e.g. AT&T 6300 and the Compaq.

The PCA card contains a 100 MHz Wilkinson ANALOG TO DIGITAL CONVERTER, (ADC), SINGLE CHANNEL ANALYZER (SCA), MULTICHANNEL SCALER (MCS), and a dual-ported memory. The dual-ported memory allows the operator to exit the PCA program through DOS without interrupting the analysis and storage of data input to the PCA card. The card, along with the standard software, transforms the personal computer into a very powerful Multichannel Analyzer. An input of 0 to 8 volts from a shaping amplifier is the only external signal necessary for pulse height analysis (PHA) operation.

The software utilizes the personal computer functions to transfer data to a printer or to store and load data to the floppy or hard disk. The operating procedures are menu intensive and important parameters are displayed on the monitor with the spectral data.
SECTION TWO - SPECIFICATIONS

2.1 Technical Specifications

Memory

8192 channel acquisition memory. (Optional 1024, 2048, and 4096 channel).

Capacity

\[ 2^{24} \times (16,777,215) \] maximum counts per channel.

Time Base

1 MHz crystal controlled. Preset live and real acquisition time selectable to 999,999 seconds maximum.

Memory Group

Selectable in binary increments 256 channel to 8192 maximum.

ADC

8192 channel, 100 MHz clock frequency Wilkinson type. (Optional 1024, 2048, 4096 channel available). 0 to ±8 volts unipolar or positive leading.

Conversion Gain

Selectable from 256 to 8192 channels in binary increments.

Digital Offset

Selectable in 256 channel blocks to 7936 channels.

Linearity

Integral: \( \pm 0.1\% \) over top 98\% of range
Differential: \( \pm 1\% \) over top 98\% of range

Temperature Stability

Gain: \( \pm 0.01\% /\degree C \)
Zero Level: \( \pm 0.01\% /\degree C \)

Lower Level Discriminator

15-turn screwdriver adjustment (rear panel)
Range: 0.5 to 105\%
Upper Level Discriminator

15-turn screwdriver adjustment (rear panel)
Range: 0.5 to 105%

Zero Level

15-turn screwdriver adjustment (rear panel)
Range: -4 to +8%

Input Polarity

Positive or positive leading bipolar.

Inputs

ADC: 0 to 8.2V nominal, positive pulse
GATE: TTL low gates off ADC
BUSY: TTL low gates off live timer
MCS: TTL positive pulse
MCS DWELL: TTL negative pulse
EXT. SYNC.: TTL positive pulse starts MCS pass

Outputs

ROI: TTL pulse for x-ray mapping (Optional)
SCA: TTL pulse

Power Requirements

+5V  1.2 A.
+12V  65 Ma.
-12V  65 Ma.

Display

A high resolution live display is provided through the personal computer monitor. IBM personal computers require an IBM graphics card #1504910 (or equivalent) for monochrome displays or an IBM Enhanced Graphics Adapter #1501200 (or equivalent) for color displays. All compatible personal computers must have an equivalent graphics card.
The PCA card contains a calibration algorithm to calculate the energy calibration curve. The algorithm allows for a minimum of two and a maximum of fifteen energy calibration points to be defined by the user. The number of points defined by the user would depend on the precision of calibration desired and the linearity of the gamma energy versus pulse height output of the detector. The algorithm incorporates a linear fit between each defined energy point. The FWHM and centroid calculators are an integral part of the Energy Calibration feature.

The method used to compute the centroid of a peak is the weighted arithmetic mean. The calculation is done on the Net Area of the peak. The net area of the peak is determined by averaging the beginning ROI channel contents and the three previous channels and drawing a straight line from there to the average of the ending ROI channel contents and the three following channels. All counts above that line are considered to be Net Area. The formula for the centroid computation is as follows:

\[
CTR = \frac{Y_1*X_1 + Y_2*X_2 + ... + Y_n*X_n}{Y_1 + Y_2 + ... + Y_n}
\]

Where \(X\) is the channel number from the beginning of the ROI and \(Y\) is the Net channel contents of channel \(X\).

The FWHM of a peak is found by first determining the channel with the most net counts. This channel's contents and the contents of the channel before and after are used to compute the theoretical peak value. Next the peak value is divided by two in order to determine the 'half max' value. Two adjacent channels are found on the lower side of the peak whose Net contents are above and below the 'half max' value. A linear interpolation is done between these two channels to determine the fractional channel where the 'half max' value would be. Next two adjacent channels are found on the upper side of the peak whose Net contents are above and below the 'half max' value.
Again, a linear interpolation is done between these two channels to determine the fractional channel where the 'half max' value would be. Finally, the difference (in channels or energy if calibrated) in the upper fractional channel and the lower fractional channel is the FWHM value of the peak.
Fig. 7-12 A schematic diagram of the principal nucleus that results from the burning of silicon. For $T_s > 4$ the burning is so fast that $Z/N = 1$ throughout the burning, leading to a composition dependence upon the temperature like that in Fig. 7-9. The time required for the burning increases markedly as the temperature is decreased, with the result that the relatively slow beta decays lower the value of $Z/N$ during the burning. Near $T_s = 3$ the neutron-rich nucleus Fe$^{56}$ has sufficient time to appear, and at even lower temperatures the beta decays drive the equilibrium to Fe$^{56}$.

Figure 1.1

A typical example of the net flow due to major reactions in the silicon-burning network.

Figure 1.2
Figure 1.3 - Note: 'Balloons' refers to conventional existing balloon borne detectors.
Figure 1.3 - Note: 'Balloons' refers to conventional existing balloon borne detectors.
Fig. 1.5 The binding energy per nucleon of the most stable isobar of atomic weight A. The solid circles represent nuclei having an even number of protons and an even number of neutrons, whereas the crosses represent odd-A nuclei. (M. A. Preston, "Physics of the Nucleus," Addison-Wesley Publishing Company, Inc., Reading, Mass., 1962.)

Figure 1.5

Figure 1.6
Figure 1.7
Figure 1.8- Light curves for the 0.847 MeV γ-ray line for three models. The 1.238 MeV line light curve is shown for the 15 $M_\odot$ model. The 3 $\sigma$ detection sensitivities (assuming 8 keV line widths) for current and new generation high resolution balloon-borne spectrometers are indicated. Prometheus will have a sensitivity equal to the value indicated for new balloons.
Figure 2.1
Figure 2.2
Figure 2.3 - Linear Attenuation Length for Beta Rays in NaI(Tl).
Outer aluminum housing and secondary hermetic seal.

Packed Lithium Fluoride layer acting as slow neutron shield.

Inner aluminum housing and primary hermetic seal.

Layer of Magnesium Oxide surrounding crystals for reflective coating.

121- NaI(Tl) crystals 0.5" x 0.5" x 2.0".

Figure 2.4a - Top View of Detector Array

121- Hamamatsu R2248 PMTs

0.125" Quartz window

Lithium Fluoride

Inner and Outer aluminum housing and seals.

0.125" Quartz window

121- individual calibration LEDs

Figure 2.4b - Cross Section of Detector Array with Photomultipliers and Calibration LEDs attached.
Figure 2.5 - Testing method for energy efficiency.
Figure 2.6 - Efficiency of the Array versus Energy.
Figure 2.7 - Configuration of crystal by crystal calibration.
Figure 2.8 - Peak channel versus crystal at 0.122 MeV.
Figure 2.9 - Percent resolution versus crystal at 0.122MeV.
Figure 2.10 - Percent error versus crystal at 0.122 MeV.
Figure 2.11 - Peak channel versus crystal at 0.122 MeV.
Figure 2.12 - Percent resolution versus crystal at 0.122 MeV.
Figure 2.13 - Percent error versus crystal at 0.122 MeV.
Figure 2.14 - Percent resolution versus crystal with and without faulty preamp.
Figure 2.15 - Extrapolated resolution from $^{57}$Co calibration at 0.122 MeV.
Figure 3.1 - Linear attenuation coefficients for plastic scintillator.
Figure 3.2a - Total flux leaking through shield versus energy.

Figure 3.2b - Flux leakage through 12 inch plastic shield versus zenith angle.
Figure 3.3 - Shield sections cut from purchased slab of plastic scintillator.
Figure 3.4a - Front view of active plastic shield.

Figure 3.4b - Cutaway view of Prometheus 1 from side.
Figure 3.5 - Wooden support structure for active shield assembly.

Scale: 1" = 1'0"
Figure 3.6 - Comparison of 5", 3", and 2" diameter photomultipliers.
Figure 3.7 - Efficiency of plastic scintillator versus source position at 0.122 MeV.
Figure 3.8 - Efficiency of plastic scintillator versus source position at 0.837 MeV.
Figure 3.9 - Comparison of Monte Carlo output versus $r^{-2}$ curve.

Figure 3.10 - Average distance in plastic versus distance from plastic as computed by Monte Carlo simulation.
Figure 3.11 - Efficiency of plastic scintillator versus energy.
Figure 3.12 - Ratio of shield leakage of non-zero threshold versus shield leakage for zero energy threshold, as a function of threshold energy.
Figure 4.1 - 11 x 11 PNP aperture.
Figure 4.2 - PNP aperture for Prometheus.
Figure 4.3 - Geometry of oversized coded aperture with limiter.
Coded Data: Counts per crystal from background subtracted spectrum integrated over all energies from 100 keV to 10 MeV. Integration time: 3 hours.

Figure 4.4a - Coded data from Crab nebula simulation.
Source distribution for coded aperture simulation. The highest point corresponds to a source with an equivalent intensity of the Crab Nebula integrated over Energy from 100 keV to 10 MeV. Integration time 3 hours. Background leakage: 1000 flux units per crystal per hour.

Figure 4.4b - Source field used for simulation of Crab nebula.

Figure 4.4c - Reconstructed source field from coded data for Crab nebula simulation.
Figure 4.5 - Monte Carlo results of estimation of error in misidentifying initial gamma ray interaction site in array.
Figure 5.1 - Schematic diagram of electronics.
Rectangular or Hexagonal Faceplate Types

<table>
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<tr>
<th>Type No.</th>
<th>Remarks</th>
<th>Spectral Response</th>
<th>Maximum Ratings</th>
<th>Average Anode Current</th>
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<td></td>
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<td>(nm)</td>
<td>(nm)</td>
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<td>Silt shape faceplate</td>
<td>400U</td>
<td>185 - 650</td>
<td>420</td>
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<td>R2248</td>
<td>36&quot; x 36&quot; square shape</td>
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**Cathode Sensitivity**

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<td>120</td>
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<tr>
<td>60</td>
<td>85</td>
<td>10.5</td>
<td>82</td>
<td>1250</td>
<td>30</td>
<td>85</td>
<td>8.2 x 10^4</td>
<td>1.0 x 10^4</td>
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</table>

Figure 5.2 - Hamamatsu R2248 photomultiplier

(C-2) Cathode Grounding for Pulse Output
For general scintillation or photon counting applications, 
Cp and Rg are recommended to be 6.005 µF and 1 MΩ.
Care should be taken since a high voltage is applied to these parts.

Figure 5.3 - Typical bleeder string for R2248
CASE 6 For very-high-gain (100 mV/µA) applications with negative inputs.

RESPONSE TO RECTANGULAR INPUT

100 nsec/Horizontal Division
200 mV/Vertical Division

Assume: 30 nsec (10% to 90%)
Falltime: 25 nsec (10% to 90%)
Propagation Delay: 32 nsec
Output Noise: 450 µV rms typical (±175 MHz Bandwidth)
Input Impedance: 20 Ω

Figure 5.4 - Schematics for MVL407 and TRA1000
TEN-STAGE, head-on, flat-faceplate, venetian-blind type having S-11 response. Wavelength of maximum response is 4400 ± 500 angstroms. This type makes use of copper-beryllium dynodes and a flat-circular, cesium-antimony, semitransparent photocathode. Window material is Corning No. 0080 lime glass or equivalent. Tube weighs approximately 7 ounces and has a non-hygrometric base.

DIRECT INTERELECTRODE CAPACITANCES (Approx.):
Anode to Dyode No. 10 .............................................. 7 pf
Anode to All Other Electrodes ................................... 8.6 pf

MAXIMUM RATINGS (Absolute-Maximum Values):
DC Supply Voltage:
   Between anode and cathode ........................................ 2000 max volts
   Between anode and dyode No. 10 ................................ 200 max volts
   Between consecutive dynodes .................................. 250 max volts
   Between dynodes No. 1 and cathode .............................. 600 max volts
   Between focusing electrode and cathode ......................... 600 max volts
Average Anode Current ............................................ 2 max ma
Ambient Temperature .................................................. 75 max °C

TYPICAL CHARACTERISTICS:
DC Supply Voltage* ................................................. 2000 1000 1250 volts
Radiant Sensitivity (at 4400 angstroms)† .......................... 96000 13000 4500 a/w
Cathode Radiant Sensitivity (at 4400 angstroms)‡ .................. 0.055 0.055 0.055 a/w
Luminous Sensitivity§ ................................................ 125 19 6 a/lm
Cathode Luminous Sensitivity ............................... 75 75 75 a/lm
Current Amplification ................................................... 250,000
Equivalent Anode-Dark-Current Input at
22°C at 4400 anstroms ............................... 0.4 0.9 max 0.23 pw
equivalent Noise Input at 4400 anstroms .......................... 0.0053 0.0053 0.00745 pw

*DC supply voltage (E) is connected across a voltage divider which provides voltages as shown in the accompanying table. The focusing-electrode voltage is adjusted to that value between 60 and 100 percent of dynode No. 1 potential (referred to cathode) which provides maximum anode current.
†With light input of 10 microlumens transmitted through blue filter (Corning C.S. 5-54, glass code No. 5113, polished to 1/4 stock thickness), from a tungsten-filament lamp operated at a color temperature of 3300°K
‡Same as (†), but a light input of 0.01 lumen is used; 200 volts applied between the cathode and all other electrodes connected as anode.
§With light input of 10 microlumens from a tungsten-filament lamp operated at a color temperature of 2870°K.

Figure 5.5 - RCA 8053 photomultiplier.
Figure 6.1 - Block diagram of system software.
Figure 8.1 - Total efficiency of array as computed by ACCEPT.
Figure 8.2 - Energy deposited in array as computed by ACCEPT.
Figure 8.3 - Total flux in array versus incident aperture flux.
Figure 8.4 - Geometric factor of array versus zenith angle as computed by ACCEPT.
Figure 8.5 - Best fit of ACCEPT flux data in array.
Figure 8.6 - Verification of in house Monte Carlo simulation.
Figure 8.7 - Results of Monte Carlo simulation of array with and without $\beta$ rejection.