Introduction

We propose to enhance the existing Milagro Gamma-Ray Observatory and develop a telescope facility for studying solar phenomena at GeV energies. The proposed facility will be a unique tool for extending solar neutron and proton observations to the multi-GeV regime with only a modest investment to an existing experimental program. The proposed enhancements will, among other things:

- Extend the energy regime for studying Ground Level Events and solar flares to the 5-100 GeV energy regime
- Facilitate the study of both impulsive and extended emission at high-energies with fine time resolution
- Provide both spatial and temporal data for the study of particle isotropy- and spectral-evolution
- Enable unique multi-wavelength, and multi-particle, studies of solar phenomena in collaboration with other instruments
- Enhance our ability to study the nature of particle acceleration at the highest energies

Scientific Motivation

In the last two solar cycles we have obtained a new appreciation of the ability of the Sun to accelerate cosmic rays. Particle acceleration at, or near, the Sun produces energetic protons (and neutrons) both directly and indirectly. Understanding the particle acceleration process is of both fundamental scientific interest and of practical importance because energetic particles can disrupt human activities in space [1]. Since 1956 it has been clear that cosmic rays exceeding 1 GeV could be accelerated in the solar environment [2]. With the neutron and high-energy gamma-ray measurements performed with the Solar Maximum Mission [3, 4, 5] and the Compton Gamma Ray Observatory [6, 7, 8, 9], we have gained a new insight into the solar-flare phenomenon. We now know that GeV ions (including both protons as well as heavier ions) can be accelerated on rapid timescales (< 1 minute) in flares [10], while in some flares, the acceleration process can last for several hours [6, 8].

Figure 1 Aerial view of the Milagro Gamma-Ray Observatory site. Visible are the large covered pond (foreground) and the counting house, pond utility building, and access roads (background)

Both primary and secondary solar cosmic rays have been measured. Primary solar cosmic rays (those that reach us directly from the acceleration site) are in the form of protons, heavier ions, and electrons. Secondary solar cosmic rays arise from the interaction of accelerated particles with the solar atmosphere and lead to a variety of secondary radiations. Although electron bremsstrahlung has been measured up to ~50 MeV, the highest energy secondaries are gamma rays and neutrons arising from nuclear interactions. For example, energetic protons that impact the solar surface produce secondary pions (π^+, π^- and π^o) and neutrons. The π^o particles quickly decay into Doppler-shifted gamma rays that can exceed 1 GeV in energy. These tertiary photons and secondary neutrons, because they are neutral, travel in straight lines, unaffected by the interplanetary magnetic field. In principle, they can then be detected and measured at Earth with greater sensitivity, because their incident direction is known.

Direct measurements of primary solar electrons, protons and heavier ions (at energies up to ~500 MeV/nucleon) are made with instruments on board spacecraft in interplanetary space. These are the particles whose momenta are not large enough to penetrate the Earth's shielding magnetic field. Ions above ~0.6 GV (mostly protons) produce neutrons in the Earth's atmosphere that can be measured indirectly at ground level with a world wide network of neutron monitors [11]. The network of neutron monitors constitutes an elaborate "magnetic spectrometer" given the different magnetic rigidity cutoff of each site. The *proton* rigidity threshold varies from ~0.6 GV (atmospheric cutoff) at the Earth's poles to ~14 GV at the geomagnetic equator.

Since the incident cosmic rays are charged they follow the interplanetary magnetic field lines. Even for the case of a highly anisotropic or focused beam of solar protons, the particles always arrive at the observation point from a direction other than that of the Sun. In addition, diffusive processes in interplanetary space disperse the particle arrival directions. A measurement of the arrival direction, along with the intrinsic spread in arrival directions, can serve as a probe of the interplanetary medium and also provide a measure of the solar cosmic-ray pitch angle distribution.

Although ground-level neutron monitors are sensitive to solar protons above ~500 MeV, they have a limited capability to measure an energy spectrum. The energy of the "most energetic" particle detected by the neutron monitor is estimated from the measured time-of-flight with some assumptions regarding the release time of the parent particle at the Sun and the path length (so there is little energy discrimination above 10 GeV). The data from any single NM must be jointly analyzed with other NM data at different thresholds or spacecraft data to arrive at a particle spectrum. In ground-level neutron monitors count rates can often rise several percent over the quiescent rate. Major (once per decade) solar flares can produce much larger effects, up to factors of 2 or 3. The greatest increase occurred in February 1956 at 3000%.

Evidence for GeV particles accelerated in flares comes from the secondary solar gamma-ray spectrum that has a peak at the π^o rest energy and from the measurement of *solar* neutrons at ground level arriving only moments after the γ-rays. (The solar neutron threshold (~500 MeV) is determined by the neutrons' path length in the atmosphere, i.e., the Sun's local zenith angle and the altitude of the station.) The exact mechanism by which these particles are accelerated to such high energy has not yet been identified. We know only that the energy source for these energetic ions is the coronal magnetic field. How this energy is converted rather efficiently into energetic particles (in addition to other forms of energy) is little more than a matter of conjecture. Competing theories include both first and second order stochastic acceleration and dc electric fields. First-order Fermi (shock) acceleration [12] is known to operate on interplanetary particles and may also operate on ions in the solar corona that in turn produce the gamma-rays and neutrons. These shocks may be dynamic as in a blast wave or may be quasi-static in the region of magnetic reconnection. Second-order Fermi acceleration may take place in the reconnection region to accelerate protons in the impulsive phase of the flare or may take place over large volumes over long time periods [13, 14, 15]. Electric fields arising from magnetic shears or current sheets may be large in magnitude and extend over large distances to accelerate protons to high energies [16, 17, 18, 19]. Our understanding of high-energy solar flare particles was recently reviewed by Hudson and Ryan [20].

The energetic protons that are measured in space, it is now widely believed, originate from interplanetary phenomena, in particular, interplanetary shock waves [21, 22, 23, 24]. This conclusion is firmly based on the measured distribution of ionization states. However, some fraction of these particles (at energies far below what Milagro is sensitive to) carry chemical and ionization signatures of a low corona origin, i.e., the flare region—the likely site of the particles that produce the neutral secondaries. Except for some clear associations of interplanetary particles with shock waves, there is no single theory or model that stands out above the others to explain the nature or the dynamics of the acceleration process [25].

The transient nature of solar proton phenomena, combined with the limited physical size of the acceleration region, suggests that there must exist an effective upper limit to the energy spectrum of particles produced by the Sun, whether they are accelerated in a flare or by an interplanetary shock. Although, solar proton phenomena have regularly amazed researchers by their intensity and energy, we would expect that the "upper limit" often occurs in the broad energy range of a few GeV to above 100 GeV. This corresponds to an energy range over which the modified Milagro would be sensitive. If the spectrum energy limit occurs above 300 GeV, it may be detected with Milagro in its baseline air-shower configuration. This would provide a third integral measure of the spectrum. A far more likely prospect, though, is that the energy upper limit frequently occurs at lower energies. By measuring the spectrum of solar proton emissions at the highest energies, we would be collecting data to aid in restricting the location of the acceleration site (via time or flight) and the mechanism involved (via energy cutoff and spatial distributions). Acceleration models are most severely tested at the extremes and it is the extreme part of the spectrum that we wish to investigate with Milagro.

Other Physics

A number of science tasks can be addressed with the system proposed here. Although the study of high-energy solar flare and interplanetary phenomena are the primary goal, the unique features of the Milagro with the proposed modifications will allow us to probe heliospheric, cosmic-ray, and gamma-ray astrophysics topics.:

- The Galactic Cosmic Ray (GCR) intensity during Forbush decreases and their recoveries. Coronal mass ejections (CMEs) produce Forbush decreases at Earth, dropping the intensity of Galactic cosmic rays at 1 AU. Over the course of several days after the decrease, the intensity usually returns to its previous level. The CMEs are intrinsically inhomogeneous structures that should produce anisotropic changes in the GCR intensity. The anisotropy of the GCR intensity variations above ~15 GV can only be inferred from NM measurements. The directional capabilities of Milagro in the proposed Solar Telescope mode would allow us, with one instrument, to perform anisotropy measurements at high energy that would complement those made with NMs.

- Charged cosmic rays with energies <10 TeV that propagate through interplanetary space and arrive at Earth will be deflected under the influence of magnetic fields. Therefore the cosmic-ray Sun shadow, formed by the occulting of the isotropic cosmic-ray flux, appears deflected from the true solar position and carries important information about interplanetary magnetic field configurations. The interplanetary magnetic field (IMF) forms as a result of solar wind transport of the solar magnetic field. The complete structure, and time variability, of the IMF is unknown and is expected to be modified significantly during periods of solar activity. Long-term monitoring of the cosmic-ray Sun shadow can provide data with which to study the relationship between time variation of the large-scale structure of the solar/interplanetary fields and the solar cycle. Investigations with the Tibet extensive air shower array at energies >10TeV have yielded interesting results suggesting variations in the Sun shadow, and hence the interplanetary magnetic fields, with the solar cycle from 1991-1997. We will attempt to extend these observations to lower energies below 100 GeV.

- Interaction of high-energy cosmic-ray nuclei with matter may also produce detectable signatures. In fact the same mechanisms that produce muons in the Earth's atmosphere can take place on the solar surface. The fluxes of particles (gamma rays, antiprotons, neutrons, etc.) that result from collisions of high-energy Galactic cosmic rays with the solar atmosphere have been estimated [26]. These estimates are sensitive to assumptions about cosmic-ray transport and can be studied in detail over long timescales at GeV energies during the current solar cycle with the proposed detector enhancement.

- Although extensive air showers produced by γ-ray primaries are muon poor, the muon content of showers induced by astrophysical sources of GeV-TeV photons may be sufficient to make them sources observable in muons. The issue of photopion production and its relationship to gamma-ray astronomy has been studied by a number of authors [27, 28]. For example, a multi-TeV air shower will produce a 100 GeV muon with a probability of order 1% [29], which should be sufficient to observe the brightest DC sources or the most intense transients (e.g. Gamma-ray Bursts) in muons. Sensitivity estimates are somewhat speculative, depending on source spectrum, duty-cycle, and integration time. An active galaxy with a hard spectrum extending to 10 TeV might be observable in ~1 year with a significance in excess of 5σ; intense GRBs may also be observable if they have hard spectra (spectral slope ~1.5) and durations of 10 s or more [28]. Measurement of a cosmic event in two Milagro operating modes (solar trigger and air-shower trigger) would provide a unique new measure of the source spectrum. This is particularly important for measuring the spectrum of extragalactic objects, whose gamma-ray flux can, and is, attenuated at high energies due to interaction with the extragalactic infrared radiation field

The Milagro Gamma-Ray Observatory

Milagro is the first water-Cherenkov detector built specifically to study extensive air showers. Its primary science goals are to survey the sky for TeV gamma-ray emission from objects such as active galactic nuclei, supernova remnants, and gamma-ray bursts. Located 2650m above sea level in the Jemez Mountains of New Mexico, Milagro is a covered, light tight 60 m × 80 m × 8 m pond filled with ~5 million gallons of purified water and instrumented with photomultiplier tubes (Fig. 1). Milagro has a number of advantages over previous ground based extensive air shower (EAS) arrays. Milagro's location above sea-level, combined with its ability to detect a large fraction of the shower particles that reach ground level, leads directly to a relatively low energy threshold for air-shower detection (median triggered energy ~2-3 TeV). In addition, its high duty-cycle for observations (~100%) makes it well suited for the study of transients and long-term continuous monitoring of astrophysical sources.

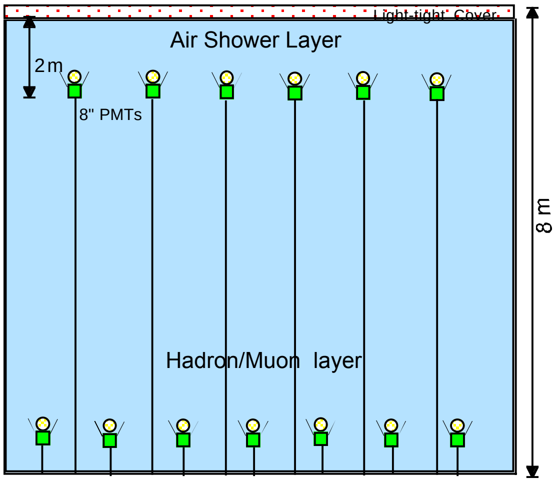


Figure 2 Cross section of the Milagro detector showing two layers of photomultipliers and light tight cover.

Relativistic, charged air-shower particles produce Cherenkov radiation as they traverse a detection medium — in this case water. Here the Cherenkov radiation is emitted in a cone-like pattern with an opening angle of 42^{o}. In addition to charged secondaries, shower photons can also be detected via any pair-produced and/or Compton scattered electrons that are produced in the detector. The water Cherenkov technique allows Milagro to instrument a large area with a sparse spacing of photo-sensors keeping costs low. Techniques such as these have been used for decades in high-energy physics. A total of 723 20-cm photomultiplier tubes (PMTs) arrayed on a 3m grid are used to detect the Cherenkov radiation. Existing electronics provides for the acquisition of both PMT pulse-heights and relative PMT hit times with nanosecond accuracy.

As shown in Figure 2, Milagro has been configured with two planes of PMTs. The first layer of 450 upward-facing tubes, the *air shower layer*, views the top 2-m of water. This layer is used to measure the charged particle air-shower wavefront (via Cherenkov radiation), providing the information needed to reconstruct the primary particle direction. A second layer of 273 upward-facing PMTs, the *muon layer*, is located at a depth of 6.5 m. The layered design of Milagro provides a modest calorimetric measure that may aid the identification of cosmic-ray induced showers, thereby improving the TeV gamma-ray sensitivity of the instrument. The full Milagro instrument was constructed during 1998-1999 and is now operational.

Milagro as a Solar Observatory

The proposed Solar Physics Project will facilitate the study of high-energy solar emission by indirectly detecting solar neutron and proton interactions in the Earth's atmosphere. At high-energies these particles produce cascades that propagate to ground level. However, at energies of interest to solar physics investigations (<100GeV) these particle cascades will, on average, range out via particle decay, interaction, and ionization losses leaving very few particles at ground level. Quite often the only remnant of these low-energy showers is a penetrating muon. The muon events at ground level represent an important probe of solar high-energy phenomena. The background to the solar signature is the large flux of muons associated with cosmic ray induced showers. This large flux requires high-throughput acquisition electronics and event processing to reconstruct individual muon arrival directions, characterize the spatial distributions of solar transients and the cosmic-ray background, and study the temporal evolution of both the spectra and spatial distributions. The Milagro experiment, as it currently exists, is not able to address this physics, since it was designed to measure the global properties of air-showers not individual particles.

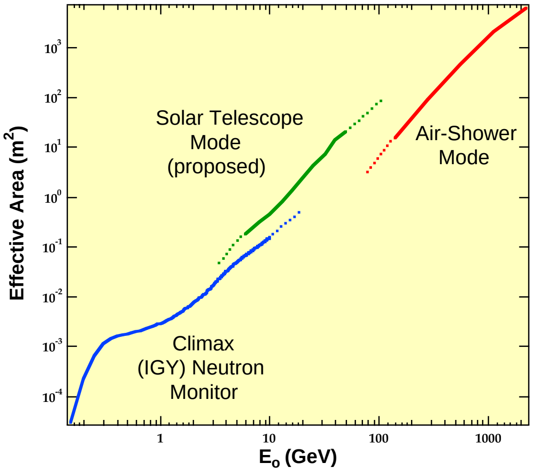


Figure 3 Predicted Milagro effective area to neutrons and protons (green). Also shown are the effective areas for an IGY neutron monitor (blue) and the existing Milagro air-shower trigger mode (red)

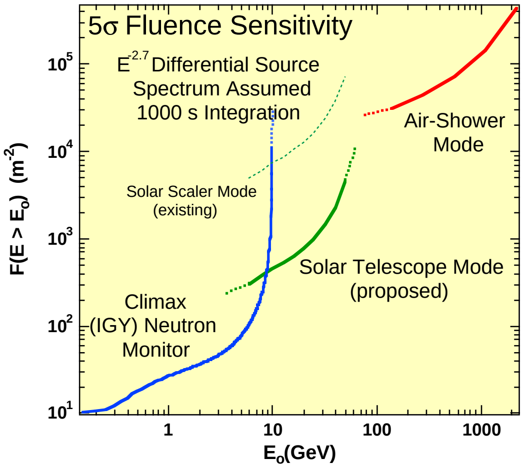


Figure 4 Predicted sensitivity of the proposed Milagro Solar trigger mode. Also shown are the sensitivities for an IGY neutron monitor (blue) and the existing Milagro air-shower trigger mode (red)

GeV particle detection is not a unique capability of Milagro. Neutron Monitors (NMs) routinely monitor the solar-terrestrial neighborhood at similar energies. However these instruments simply measure particle count rates — there is no arrival direction information available on an event-by-event basis. The degree of particle isotropy (pitch angle distributions relative to the magnetic field lines) is determined using event rates measured at different geomagnetic locations around the world.

Milagro is unique since it allows high-energy solar phenomena to be imaged. Imaging is achieved by reconstructing the arrival direction of individual triggered events. Once fit, the solar origin of flare protons and/or neutrons could be established by identifying localized event-rate enhancements and correlating with solar flare measurements at other wavelengths, e.g., optical, radio, or X-ray. The solar origin for neutrons would be directly inferred because they come from the solar direction and would be consistent with the instrumental point spread function. For a beamed component of interplanetary protons the situation is different. Here the reconstructed direction need not point back to the Sun since these particles travel along magnetic field lines. This raises the sensitivity level because of the increased number of degrees of freedom used in the analysis. In addition, a beamed component of protons is unlikely to be consistent with the instrumental point spread function due to intrinsic anisotropies in the pitch angle distributions relative to the field lines. The degree of anisotropy and its evolution with time is an important diagnostic tool. Event reconstruction and source imaging are important and unique features of this instrument that lead directly to a sensitivity improvement by many orders of magnitude, depending on the instrumental angular resolution achieved.

The wide field-of-view and imaging capability of Milagro can significantly aid solar monitoring during outburst periods. The most intense high-energy solar events exhibit 1 GeV gamma-ray and neutron emission for long periods of time, sometimes in excess of 2 hours [30, 31]. Interplanetary particle events are frequently of long duration. Measuring such long solar emissions is difficult in low Earth-orbiting spacecraft because of the satellite occultations every ~90 minutes. Milagro will permit uninterrupted tracking of the Sun across the sky for many hours.

For the proposed Solar Physics Project the trigger criteria will be optimized for low-energy showers dominated by a single muon. At the point where multiple muons strike the pond, or the showers become large, the energy of the primary particle is sufficient to initiate a more traditional air shower, in which case Milagro would trigger in its original air shower mode.

Three different triggering modes are, in principle, available to study solar phenomena in Milagro:

- Air-Shower Mode (AS Mode)
- Scaler Mode
- Solar Mode

The AS mode, currently a simple multiplicity of PMTs on the air-shower layer, is the standard operating mode of Milagro and is optimized for detecting extensive air-showers produced by TeV primaries. The median energy of events meeting the current trigger condition is ~3 TeV. Solar events producing fluxes at such high-energies may be rare, if they occur at all.

The Scaler Mode is a measure of the summed PMT count rates throughout the pond and is analogous to the Neutron Monitor data. This mode exists in the current detector configuration and is sensitive to particle fluxes in the GeV regime, however no spatial information is available thus limiting sensitivity.

To achieve maximum sensitivity at the energies most likely to contain solar particles we propose to develop the Solar Mode. This mode will trigger on, reconstruct, and record the large flux of particles expected at GeV energies. The Solar Mode will bridge a sensitivity gap between the Scaler and AS Modes and improve the sensitivity to multi-GeV primaries. Although there is some overlap in sensitivity and energy response, these three operating modes are maximally sensitive at different energies (see *Expected Performance* below). When combined and applied to the analysis of solar phenomena they will provide a unique measure of the energy spectrum and time variability, capabilities that currently do not exist at these energies with any single instrument.

In addition to independent analyses, Milagro solar physics data can be combined with other instruments for more a complete analysis of a given event. Observations across multiple wavelengths and particle types provide context for data interpretation and model building. Some of the correlated analyses and their science benefits are outlined in Table 1. Many other data comparisons and correlations are possible.

Correlation Study	Instrument(s)	Science Goal
Low energy neutrons/protons	Neutron Monitors (e.g. Climax)	• Anisotropy • Pitch angle distributions • Extend spectrum >10GeV
γ-rays	Compton Observatory YOHKOH HESSI	• Model acceleration & transport processes • π^0 production
X-rays	YOHKOH (SXT)	• Topology/geometry of flare site • HE proton origin (flare vs. CME)
Particle Fluxes	ACE (SEPICA)	• Ion composition at HE
Coronal Activity	SOHO (LASCO) Radio Measurements	• CME geometry & direction • Model proton acceleration at CME

Table 1. Correlation studies possible with the Milagro Solar Physics Project

When used in conjunction with the Climax neutron monitor (500 km to the north) and with the appropriate temperature corrections (see *The Challenges* below), Milagro could serve as a surrogate for a neutron monitor at a different geomagnetic latitude. The scaler rate increases due to solar events can augment the data from the worldwide network of neutron monitors in the same manner as underground muon detectors but with a threshold that is more representative of solar flare particles.

The Benefits of Imaging

If the flux of particles, either solar protons or neutrons, is beam-like we can use the imaging properties of the instrument to reduce background, thereby increasing our sensitivity. The background reduction takes place by restricting the signal to a few square degrees on the sky. Based on Monte Carlo simulations we expect an angular resolution on the order of 5^{o} (see *Expected Performance* below) which translates to roughly 1000 independent bins on the sky. Isolating a potential signal to ~1 such bin reduces the background count rate by a similar factor, increasing the statistical significance of a weak signal over what would have been observed in the scaler mode alone. This improvement in sensitivity is critical because often the solar particle event is initially beam-like, evolving into an isotropic event. Therefore, the first particles in a solar event may suffer only small scattering in interplanetary space and are representative of the early acceleration process. Beams that are not tightly focused will see a smaller improvement in detection sensitivity. Protons above 10 GeV are not deflected significantly when incident on the Milagro site, so the apparent solar direction will not be greatly affected by the geomagnetic field. We will be able to measure not only the count rate of muons from solar protons, but also the intrinsic pitch angle distribution of those protons, providing a direct measure of interplanetary scattering. This is available now with neutron monitors, when the entire global network is combined into a single virtual magnetic spectrometer and the variation of the signal among stations is studied. Milagro will be able to make such a measurement independently and in a different energy range. For neutrons the sensitivity is even greater than it is for protons, since we know that neutrons must come from the solar direction only, reducing the number of trials for detection.

To illustrate the potential benefits of the Milagro Solar Physics Project we can extrapolate experimental results from the flare of 4 June 1991. Data from the Japanese Akeno Giant Air-Shower Array (AGASA) suggest a solar neutron flux of ~2 m^{-2}-s^{-1} above 10 GeV at the top of the atmosphere [32] coincident with this event. Assuming an effective area of 1 m^2 this would produce in Milagro a scaler count rate excess of ~2 event s^{-1}. Assuming this event rate excess was isotropic and similar in duration to a typical GLE (duration of ~1000 s), this would have led to a non-detection. Of course the solar neutrons will point back to the Sun and any secondary muons produced by the neutrons will fall within a region consistent with the instrument point spread function. Scaling the all-sky cosmic-ray background rate to a single 5^o resolution element suggests that Milagro would have observed the neutrons from the flare of 4 June 1991 with a significance in excess of 5σ (Poisson statistics; see Fig. 4). Clearly, in the case of neutrons (always beamed) the imaging capabilities of Milagro allow it to measure far weaker fluxes than that reported by [32]. Because Milagro is at a higher altitude than the AGASA array (750 g-cm^{-2} versus 920 g-cm^{-2}), lower energy particles can reach Milagro, resulting in an increased sensitivity to solar-induced count rate increases. Actual sensitivities are a function of particle species, incident zenith angle, incident energy, and achieved instrumental angular resolution. The degree of localization of the excess over the sky would give a direct measure of the anisotropy and, in turn, a measure of the interplanetary scattering.

The Challenges

Milagro, in its present configuration, is capable of triggering and recording these low-energy events. However, the existing data acquisition system designed to operate at ~1 kHz event rates, is incapable of handling the high muon rates. The experimental challenge is to distinguish single muons, produced by energetic solar particles, from the large number of muons produced by the isotropic background cosmic rays in the atmosphere. Cosmic-ray muons, unrelated to solar emission, will lead to an azimuthally uniform background rate of ~30-100 kHz in the Milagro detector (depending on applied trigger condition). Preliminary results, using Monte Carlo simulations, indicate that Milagro will have an angular resolution of ~5^o for single muons traversing the detector (future tuning of reconstruction algorithms with real-world data should improve this value). This is comparable to the intrinsic uncertainty of the muon direction, a result of the transverse momentum exchange during the pion decay processes. To perform the various science tasks briefly outlined above, a new DAQ must be developed with the following features:

- High event throughput, including event reconstruction
- Minimum deadtime
- Triggering flexibility
- Parallel operation with standard Milagro operations

In the sections that follow we outline a DAQ that meets these requirements and will be able to achieve the high data throughput required for doing physics at the energies of interest.

In addition to the hardware challenges above, the nature of the measurements also poses a challenge. This is because the measurement of secondary atmospheric muons is more difficult than that for secondary atmospheric neutrons. Temperature corrections (related to the atmospheric density profile) are important in relating the muon count rate to the incident proton flux at the top of the atmosphere. Seasonal, diurnal and tropospheric temperature variations affect the survival rate of muons at ground level. This effect is generally much smaller than the correction for barometric pressure, but is on the order of 0.1%/^{o}C. The density profile of the atmosphere affects the balance between pion production and decay at high altitudes. In addition the ionization losses of the muons affect the Lorentz-dilated lifetime of the muon. Pressure and temperature coefficients for muon transport in the atmosphere have existed in the literature for many years, but coefficients particular to our energy range must be re-evaluated based on Milagro data. This work has begun using Milagrito (the Milagro prototype) data and our initial estimates of the temperature and pressure coefficients do not differ markedly from published values. In addition, solar particle events are transient in nature, mitigating some of the problem of precise background corrections.

Expected Performance

Monte Carlo simulations have been used to study reconstruction algorithms, compute effective areas, and estimate flux sensitivities. The complete simulation of the detector response is done in two steps: (1) initial interaction of the primary particle (proton or neutron) with the atmosphere and the subsequent generation of secondary particles, and (2) detector response to the secondary particles reaching the detector level. The CORSIKA air-shower simulation code provides a sophisticated simulation of secondary particle development in the Earth's atmosphere. Electromagnetic interactions are simulated using EGS 4 code. For hadronic interactions the VENUS code was used at high energies and GHEISHA at low energies (<80 GeV). The simulation of the detector itself is based on GEANT.

The effective area and sensitivity estimates of Milagro in the various trigger modes are illustrated in Figures 3 & 4; the effective area and sensitivity of an IGY neutron monitor is also shown for comparison. At the multi-GeV energies of interest here the spectrum of protons or neutrons may be falling rapidly at these energies, however, the increased effective area of Milagro compensates significantly, as does the important imaging capability. To compute plotted sensitivities an angular resolution of 5^o was used for the Solar Mode (see below), while a conservative value of 1^o was assumed for the AS Mode.

We also studied possible trigger criteria. The goal was to identify trigger conditions that maximize the effective area to single muons from primaries incident at the top of the atmosphere. A relatively simple, but effective, trigger condition has been applied to Figures 3 & 4. This condition requires at least 1 muon-layer PMT above the high-threshold AND <10 high-threshold PMTs on the AS-layer. Although this condition is effective, other trigger criteria can be implemented leading to various classes of events. For example, other criteria may lead to events with improved angular resolution (and hence sensitivity) with, however, a reduction in experimental effective area. Details of trigger conditions, and their effects on science return, will be studied with additional simulations and real-world data.

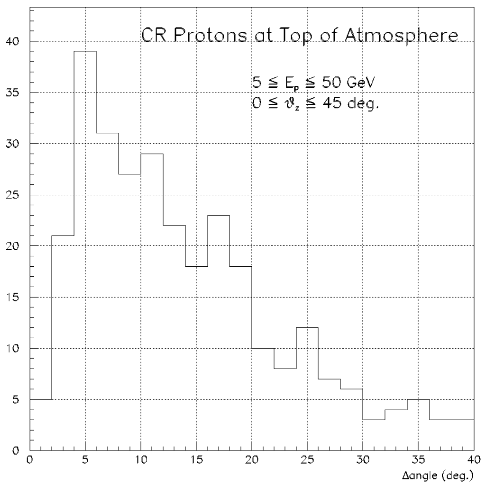


Figure 5 The angular difference between the fitted muon direction and initiating primary particle.

As mentioned above, the simulations have also been used to begin development of event reconstruction algorithms. The principal task of reconstruction is determining directionality. To do this we use a χ^2-minimization applied to PMT pulse-heights and relative timing distributions. Figure 5 shows preliminary results from this effort. The peak in the angular resolution corresponds to $\sim 5^o$, and should represent the width (1σ) of a Gaussian point spread function. The distribution, however, is not the purely the projection of a 2-D Gaussian, but it also has a long tail. Experience with air-shower reconstruction suggests that further improvements (i.e., significant reduction of distribution tail) are expected when PMT pulse-height weighting, iterative fitting algorithms, and other optimizations are incorporated. The purpose of this preliminary algorithm development was to illustrate that muon events can be reconstructed at multi-kHz rates using data from the muon-layer PMTs only.

Efforts aimed at a greater understanding of the instrument response and the further development of reconstruction algorithms are limited by the statistics of simulated events. Because of the relatively low efficiency for secondary particles from GeV primaries to reach the detector level, large numbers of simulated events must be generated. Improving the statistics of the simulated data set is critical for any future studies and the interpretation of observations. In addition, a wider range of energies must be simulated to understand the sensitivity overlaps of various instruments (dashed lines, Figs. 8 & 9).

Milagro Prototype Results

A prototype of the Milagro experiment, "Milagrito," operated from February 1997 to March 1998 [33]. This prototype provided data useful for estimating the expected performance of Milagro and yielded several results on astrophysical sources [34, 35]. Milagrito consisted of a single plane of 228 PMTs, with the same grid spacing as the full-scale detector, covering approximately 2500 m^2. The PMTs were under 1-2 m of water. This configuration produced a trigger rate for air shower events of ~300 Hz

On 6 November 1997, the Sun produced a large X-class solar flare and an associated coronal mass ejection. The event was well observed by LASCO on the SOHO mission. It also produced a large enough flux of solar cosmic-ray protons at high energies to yield ground level events in several neutron monitors, including that at Climax Colorado, several hundred km north of the Milagrito instrument. Within the 3 minute time resolution of the Milagrito counters (limited only by the programmed sampling time of the PMT scalers), Milagrito measured a simultaneous count rate increase in two independent channels, the single-PMT scaler and the 100-PMT air shower trigger starting at about 12:05 UT. Although the Milagrito count rate varies significantly from temperature and barometric changes, we are confident that the count rate increases at Climax and Milagrito arise from the same solar proton flux.

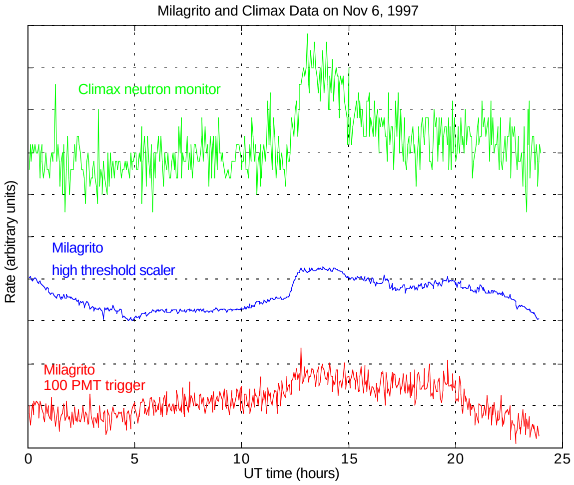


Figure 6Intensity-time profiles for the 6 Nov 1997 GLE. Shown are the Climax neutron monitor data (top, blue), the Milagrito scaler data (middle, green), and the Milagrito air-shower data (bottom, red). Climax data courtesy of C. Lopate, University of Chicago.

The Climax count rate and the Milagrito scaler and 100-PMT trigger rates are shown in Fig. 6. Overlooking the relatively long-term meteorological fluctuations, the events are also of similar duration. Although, these results are preliminary, we estimate the event rate increase in the scaler data due to the CME to be ~0.5%. Conversion of these measurements into a proton flux at the top of the atmosphere is ongoing and requires extensive simulations to determine instrumental effective area (as a function of energy) and an understanding of potential detector systematics.

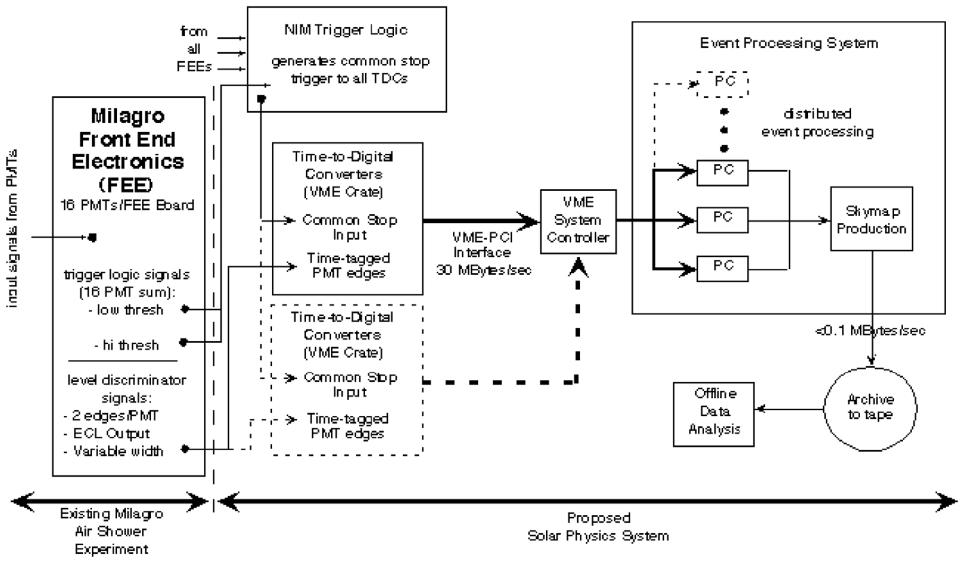
Given that this was a large GLE (5.4%) for Climax, it is no surprise that Milagrito registered a significant signal. More importantly, it indicates that the proton spectrum had a significant high-energy tail. This is confirmed with preliminary spectral modeling of the measurements. No significant roll off in the spectrum occurred between ~2 GeV and 10, or perhaps even 100, GeV. Careful modeling of the emission will constrain the roll over in the spectrum. We are also studying the behavior of the 100-PMT count-rate to ensure that the increase there is solar in origin. If this had been an anisotropic event detected in the Milagro instrument with the proposed modifications, we could have measured this flux with much greater sensitivity, i.e., before the leading edge and for times well after the increase when the scaler mode fell below noise levels. The leading edge of the increase may have been relatively anisotropic based upon recent analyses by Duldig and Humble [36]

Overview of the Proposed System

To perform the proposed solar observations we will develop a new data acquisition and event processing system. This system will be integrated with the existing Milagro detector, but will operate independently from, and in parallel with, the existing Milagro air shower data acquisition system (DAQ). The design goals are to:

- Detect single muons
- Produce real-time skymaps of muon arrival directions
- Identify transient emission of solar energetic particles in real-time
- Archive skymaps for further offline analysis

To accomplish these goals the Solar Physics System will consist of three logical components: a) a high-rate DAQ, b) an event reconstruction and processing system (EPS), and c) data archiving hardware. Figure 7 shows the logical top-level design and data flow for the proposed system.



- *Figure 7 Logical layout of the proposed Solar Physics System including data acquisition (DAQ) and event processing (EPS) sub-systems*

Digitized raw PMT data are first transferred from the DAQ electronics to the system controller CPU. These raw data include, for each event, the trigger time, relative PMT hit times, and time-over-threshold information used to compute PMT pulse-heights. The data rate is minimized by sparsifying the data in the DAQ electronics, i.e., only hit-PMT channels are read out. Once acquired by the system controller event blocks are passed to a cluster of reconstruction nodes (CPUs). This cluster of computers is linked via high-speed networking to the system controller. The multiple compute nodes effectively parallelize the event processing dramatically increasing event throughput. Each reconstruction node will be responsible for calibrating the PMT values (conversion of simple counts to pulse height and timing information) and reconstructing the muon direction. Each reconstructed event direction is subsequently binned into a skymap representing the distribution of muon arrival directions on the sky. The final data product is a series of time-tagged muon skymaps. These skymaps will be archived for further analysis. Due to the large volumes expected at the energies of interest (see *Skymaps* below) it is not possible to save the raw data in a cost-effective manner; it can, however, be recorded with low efficiency during development and operations and used for diagnostic purposes or special studies.

The Solar Physics DAQ

The technical challenge differs from that of the standard Milagro air shower system in that it is driven by the need to handle a the high data rate of single muons. We propose a VME-based data acquisition system that employs off-the-shelf components wherever possible to reduce development time and cost, and to ensure product support. The proposed DAQ consists of the following components:

- PMT front end electronics for signal conditioning (existing part of Milagro experiment)
- NIM trigger electronics
- Time-to-Digital converters
- Event processing/reconstruction infrastructure

To minimize equipment costs we propose to use a standard desktop computer as a VME crate controller. This is feasible since adapters are available that connect the VME bus to the PCI bus that exists in many commercial desktop systems. Hence, this option represents significant cost savings over the purchase of a traditional VME-based single board computer and is expected to reduce system development time. These adapters are available from a number of vendors (*WIENER*, *VMIC*); we have chosen *SBS Connection Products 620 Adapter* because of its data-transfer performance and the availability of software drivers for a variety of computer platforms (including Linux).

Two primary parameters drive the ultimate data throughput requirements of the DAQ: the expected rate of cosmic-ray muons (background) and the expected number of hit PMTs per triggered event. Using Monte Carlo simulations we can convolve these factors to estimate throughput requirements. Figure 8 shows the PMT multiplicity derived from simulations. The simulations were made for protons impinging on the Earth's atmosphere with energies in the range of 5-50 GeV and zenith angles randomly drawn from 0-45°. The U.S. Standard Atmospheric model was included. Simulations show that the mean number of hit muon-layer PMTs will be ~25. The data transfer rate from VME to external CPU has been tested in the lab and found to be 30 Mbytes/s. Combining these parameters with the number of bytes per hit PMT suggests that an average theoretical sustained event rate of ~150 kHz is possible. This estimate includes all CPU overhead associated with transferring data.

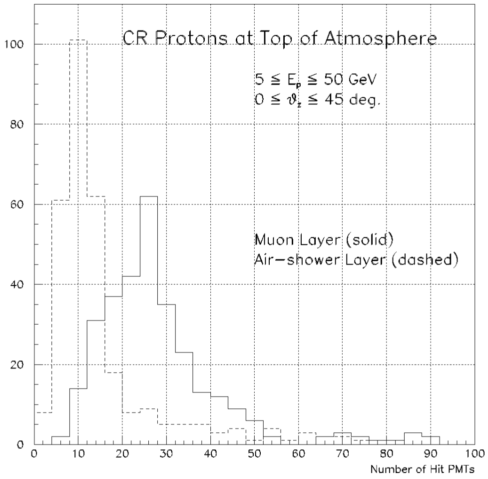


Figure 8 Simulated *PMT multiplicity distributions for the Muon layer (solid) and Air-shower layer (dashed) of Milagro.*

The theoretical event rate capability of the baseline DAQ described briefly above is 5 times the anticipated rate from cosmic-ray single muons. Measurements and simulations suggest that the actual rate of single muons will be on the order of 30 kHz, depending on trigger condition. Therefore, the projected capacity of the DAQ provides ample margin for even the largest solar events. Furthermore, the DAQ design philosophy allows for expandability if real-world rates are significantly higher than achievable with the DAQ electronics contained in a single VME crate. Splitting the TDC channels among two VME crates would easily solve any data rate problems, but complicating somewhat software development and data-flow control. We do not believe this to be a serious impediment to DAQ implementation. As part of the development plan the event rate capability of a single VME crate based system will be tested *in situ* at the Milagro detector. At this time the need to sub-divide the solar DAQ will be made. If sub-dividing the DAQ is required it represents only a small incremental cost to the entire project. It is possible the proposed budget could be reworked to incorporate this option if necessary.

Figure 8 also shows that the majority of information content for these muons events is contained in the muon-layer. Since so few PMTs are hit on the air-shower layer those PMTs provide little useful data for event arrival direction reconstruction. This is confirmed when reconstructing simulated data; the muon-layer provides sufficient timing and pulse-height measurements to achieve good angular resolution. We have therefore decided only to instrument the 273 PMTs of the muon-layer for high-rate data acquisition. This choice significantly reduces costs and has no major impact on data quality or science return.

Milagro Custom Front-End Electronics

Milagro currently employs custom front-end electronics (FEE) designed to pre-process PMT signals. We will use the existing FEE and do not need to develop additional front-end electronics for the proposed Solar Physics Project. The existing FEE provides timing and trigger output signals for each of the 723 PMTs in the detector. The solar physics electronics system proposed here will build upon this existing infrastructure and utilize a set of unused FEE outputs to operate in parallel with the Milagro air shower experiment.

The Milagro PMTs are divided into logical groups of 16 PMTs called "patches." Each patch is serviced by a single set of custom front-end electronics: an "analog" FEE board and a "digital" FEE board. The analog board is used for high-voltage distribution and signal pick-off while the digital board provides signal discrimination and triggering information. The digital FEE board outputs relevant to the solar electronics are 1) a *level discriminator for* each "hit" PMT and 2) 2 *trigger logic* pulses.

Each *level discriminator* signal is a 2-edge ECL signal; the 2 edges correspond to discriminator outputs at both the rising and falling edges of the PMT pulse (Fig. 9). This ECL signal is used to measure both the hit time and the amplitude of each PMT signal. The amplitude of the PMT signal is extracted from a time-over-threshold (TOT) measurement (corresponding to the ECL logic pulse width), while the PMT hit time corresponds to the arrival time of the leading edge. The relative arrival times of all edges (from all hit PMTs) are digitized with time to digital converters (TDC, see below). Calibration conversions from TOT to pulse-height, in addition to timing walk (slewing) and pedestal corrections, will be made during event reconstruction using data from the existing Milagro laser calibration system.

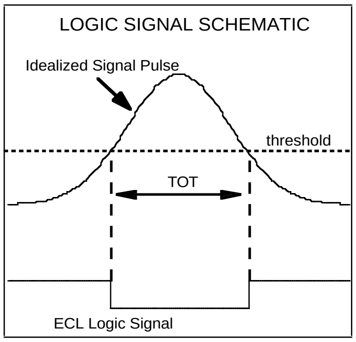


Figure 9 *Timing diagram illustrating the 2-edge ECL logic signal and the Time-Over-Threshold (TOT) concept*

The output voltage of each *trigger logic* signal is proportional to the number of coincident PMTs in each patch with pulse heights above a preset threshold. Two thresholds are provided; one at ~1/4 photoelectrons (PE) and one at 5-6 PEs; *the ability to utilize multiple discriminator thresholds at the trigger level aids dramatically in low-energy background rejection.* The trigger logic signals from all FEE boards are fed to *solar trigger logic* that continuously measure the multiplicity of PMT hits in the detector. A solar physics trigger will be formed when the summed patch pulses match a predetermined trigger condition. The trigger signal will then be fed in parallel to all TDC modules. The time of the solar trigger signal is used as the common reference for determining the relative *hit* times of all triggered PMTs.

Solar Trigger Electronics

An overview of the Solar trigger electronics is shown in Figure 10. This system utilizes off-the-shelf modules (NIM) to produce the common trigger. The configuration of these hardware trigger modules provides a modest degree of pattern recognition thereby improving trigger efficiency to those events most likely to be muons. The inputs to the Solar trigger electronics will be the *trigger logic* outputs from the Milagro FEE boards discussed in the previous section. These FEE outputs provide maximum trigger logic flexibility since they provide both high- and low- threshold summed outputs for trigger. At present simulations indicate that only the high-threshold *trigger logic* outputs need to be used, but this may change as we optimize the system for real data.

Time-to-Digital Converters (TDC)

The DAQ design shown in Fig. 7 incorporates a dedicated TDC channel for each PMT on the detector's muon-layer. Candidate VME-based TDC modules are available from various manufacturers (LeCroy, CAEN). As a baseline, we propose to use the CAEN V673 series *deadtimeless* TDC module that has been specifically designed with high-rate applications in mind. The chief advantage of these TDC modules is their capability for high-speed digital time tagging, and the ability to buffer multiple triggered events, minimizing system deadtime. This TDC also has double pulse resolution (important for the TOT technique) of ~1 ns, and can record up to 16 hits per channel per event. The high channel density of the TDC module (128 channels) keeps per channel costs to a minimum. The ECL outputs from the existing Milagro FEE boards will provide the TDC inputs.

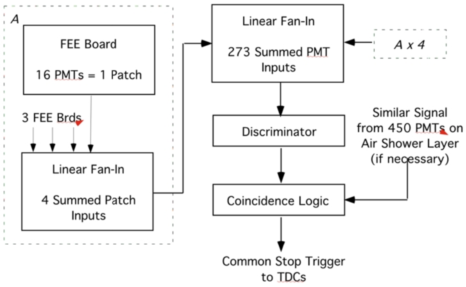


Figure 10 Schematic of NIM trigger logic

The TDCs will operate in *common stop* mode. In this mode acquisition continues until the arrival of a common stop trigger that then latches the relative hit times in each TDC channel. Another advantage of the V673 TDC is its ability to suppress readout of unhit channels and to remove hits outside a predefined acceptance window. These features improve the data throughput performance. The common stop trigger will be generated by the NIM trigger electronics and fed in parallel to all TDC modules.

Solar Physics Event Processing System

The Event Processing System (EPS) must be capable of performing event calibration, event reconstruction, and skymap generation. This represents a computational challenge because of the high event rate expected. The choice of computing platform is important for the success of the proposed research. Three criteria drive the design of the Event Processing System (EPS):

- High event processing throughput
- Expandability
- Cost

We have identified several candidate computing platforms and have defined as a baseline a networked cluster of PCs since this offers the best prospect for ease of development and expandability. Clusters of Linux-based commodity PCs have several advantages over the more traditional high-end computing platforms:

- Low price per CPU
- Free/Open Source Software
- Large User Base
- Expandability

It is likely that as experience is gained with the project the event reconstruction algorithms will change, and the online science tasks may increase. Expandability is therefore a critical design consideration and allows for maximum flexibility. Other computing platforms, in addition to being significantly more expensive, do not offer the same level of expandability.

The PCs (computing nodes) will be configured in a "Beowulf"-style cluster, with high-speed networking providing the intercommunication between processor nodes. The system will operate in a Server/Client configuration with blocks of events passed to individual computing nodes. This pseudo-parallelization will dramatically improve event-processing throughput over a serial approach. The System Controller will act as the server, maintaining communication with and providing data to the Client nodes.

Although computing systems such as the one proposed here can be developed in house, we have chosen to buy a "turn-key" system from a commercial vendor. This choice allows us to concentrate personnel on the other aspects of the proposed project, minimizing development time. A vendor supplied computing platform also ensures hardware/software support. Benchmarks of preliminary event reconstruction software indicate that event reconstruction rates of ~5 kHz can be sustained per CPU (500 MHz Pentium III), therefore we baseline the acquisition of a 20 node system. This number of nodes will be capable of reconstructing events at the average anticipated event rate while also providing sufficient excess computing resources to handle event rate fluctuations and other online analysis.

Data Archiving

Following event processing the reconstructed event directions will provide the necessary information with which to produce skymaps. These skymaps will be archived for later analysis. The archive medium has yet to be established. Although currently the Milagro Gamma-Ray Observatory utilizes DLT tapes, the lower storage requirements of the SPS skymaps may make CDs an attractive alternative. We have baselined a DLT tape archiving system but will revisit this choice using cost, availability, and ease of use as criteria.

The archiving system will be composed of tape (or CD) and disk storage. Data will be buffered to a staging disk for later copying to tape. These tapes will subsequently be sent to the University of New Hampshire for permanent archiving. The off-site archiving facility will consist of DLT tape jukebox, staging disk, and data server. These resources will allow access to 6-8 months (perhaps a full year) of archived data at any one time for detailed analysis.

Solar Physics Sky Maps

The quiescent event rate with the proposed solar physics electronics is expected, conservatively, to translates to a data rate exceeding 1 Tbyte of raw data per day; this much data makes raw data storage prohibitive. To facilitate further analysis of triggered events the reconstructed arrival directions of the low-energy events will be binned into skymaps. The skymaps will be produced at regular time intervals, thereby providing both temporal and spatial distributions of low-energy events. It is anticipated that the skymaps will be produced at 1 second intervals; the skymap spatial resolution will ultimately depend on the single-event angular resolution achievable (predicted to be ~5^o). Saving the data as skymaps reduces the storage requirement to 0.25 Gbytes per day. Further reduction in the storage requirements may be possible with data compression schemes. Table 2 gives a summary of the anticipated skymap parameters.

Table 2
Solar Physics Skymap Characteristics
(Best estimates to date)

Nominal Time-Slice	1 second
Skymap Coverage	$0 < \theta < 90, 0 < \phi < 2\pi$
Spatial Resolution	5^o
Storage Requirement	< 0.25GBytes/day

We currently anticipate writing the archived skymaps in FITS (Flexible Image Transport System) format. This format provides a number of useful features such as standardized file headers and special records and is in common use within the solar physics community. We utilize the FITS skymaps in conjunction with both custom and established data analysis tools such as *SolarSoft*. The *SolarSoft* system is a set of integrated software libraries, databases, and system utilities that provide a common programming and data analysis environment for Solar Physics. It is primarily an *IDL* based system, although customized executables written in other languages can be integrated. The use of FITS, *IDL*, and *SolarSoft* should facilitate data exchange and stimulate coordinated analysis.

Development Plan/Statement of Work

We propose a 12-month Development & Implementation Phase followed by a 24-month Operational Phase for the Milagro Solar Physics Project. This aggressive development schedule is reasonable given maximum use of off-the-shelf components and our experience with the development of the Milagro Gamma-Ray Observatory. All phases associated with the project will be performed in parallel with the operation of the Milagro Gamma-Ray Observatory and will have little or no impact on the TeV astrophysics observations. Development work can be logically divided into two parts: 1) hardware/DAQ, and 2) software development. These will be developed in parallel and later integrated to form the complete system.

Initial system development will be performed at the University of New Hampshire. This will include hardware integration, the development of DAQ control software, and system testing. Once in stable laboratory operation at UNH, the integration of the Event Processing System will begin. This will include developing the appropriate software to facilitate and monitor processing throughput, calibrate raw data, and reconstruct individual events. Finally, once fully tested the completed system will be shipped to and installed at the Milagro experimental site. Final system debugging and tuning, as well as investigations of trigger efficiencies and data rates will occur at this time.

System operation and monitoring will be the primary responsibility of the University of New Hampshire. Operations will include both remote and on-site work. Although the proposed system will be developed for remote operation, frequent site visits for debugging and hardware maintenance will be necessary. Our goal is to electronically transfer data whenever possible from New Mexico to UNH for archiving, which will minimize the need for on-site data storage and site visits. The ability to remotely transfer data ultimately depends on the size of data files. A backup operations plan will include the shipment of data tapes to UNH for archiving.

The Principle Investigator (Ryan) will provide oversight to the entire effort. Co-PI/Project Manager Miller will be responsible for the daily activities, project management, and technical leadership during hardware and software development. Co-PI McConnell will provide hardware and data analysis software development assistance

Throughout all phases of development, implementation, and operation of the Solar Physics Project, the UNH team will support the Milagro Collaboration by participating in instrument development, instrument operations, team meetings and scientific meetings.

Institutional Experience

The University of New Hampshire has a long history of measuring solar neutrons, protons and gamma rays. The neutron monitor on Mt. Washington has been operating since 1956 and is still operated from UNH as part of the worldwide network of neutron monitors. Similarly, we also operate the Durham neutron monitor. At sea level, it provides complementary data to those of Mt. Washington.

The COMPTEL experiment on the Compton Gamma Ray Observatory is operated from UNH. It has been used to measure not only solar flare gamma-ray spectra, but also produced the only image of the Sun in sub-relativistic neutrons. The PI (Ryan) has also performed ground-level cosmic-ray neutron spectroscopic measurements at several latitudes and altitudes to characterize the spectrum for the problem of assessing the impact of neutrons on microelectronics. UNH has experience designing, building and operating a variety of spacecraft and balloon-borne solar high-energy instruments over the past 30 years. These include instruments on the OGO, OSO and Pioneer series as well as the Solar Maximum Mission and the Compton Gamma Ray Observatory.

One of the Co-Investigators (RSM) was the principle developer of the instrument control and DAQ software for the Milagro Gamma-Ray Observatory prototype, in addition to the development of the laser calibration system for the experiment. This experience will facilitate the development of the proposed system.