Performance of the Orbiting Wide-angle Light collector (OWL/AirWatch) Experiment via Monte Carlo Simulation

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Abstract

The OWL/AirWatch collaboration is currently studying and developing missions to image, from low Earth orbit, the air fluorescence signal from giant airshowers induced by the ultra-high energy (E $>$ few $\times 10^{19}$ eV) component of the cosmic radiation. Several Monte Carlo simulations have been developed by various members of the collaboration in order to understand the response of a baseline instrument. We report on the status of a detailed Monte Carlo simulation which has been constructed at GSFC to be used as a tool in instrument definition and to understand the sensitivity to the underlying interaction physics of the possible components of the cosmic radiation. A description of the modeling employed by the simulation is discussed and a preliminary aperture to the acceptance on ultra-high energy proton induced air showers is presented. More complete results including the ability of OWL/AirWatch to detect ultra-high energy neutrino interactions are planned to be completed by the time of the conference.

1 Introduction:

The observation of cosmic rays with energies $> 10^{20}$ eV, which are above the Greisen-Zatsepin-Kuzmin (GZK) cutoff (Greisen, 1966; Zatsepin & Kuzmin, 1966), by a variety of ground based experiments has led to a keen interest in developing a next generation of experiments to measure this component of the cosmic radiation with large statistics (Cronin, 1999). The rarity of events at this energy scale requires these new experiments to have sufficiently large collecting aperture to perform this task.

The OWL/AirWatch collaboration has been examining the possibility of observing from space the air fluorescence signals from airshowers induced by ultra-high energy cosmic rays (Linsley, 1979; Krizmanic, Ormes & Streitmatter, 1998). In order to design and understand the response of an instrument capable of such observations, detailed Monte Carlo simulations are a necessity. The simulations must model the generation of airshowers along with the inherent fluctuations, the generation of fluorescent and Cherenkov light, the scattering and absorption caused by the atmosphere, and the response to the signal by the instrument. The curvature of the Earth must also be properly considered. The simulation must be able to handle the possibility of using multiple satellites at a range of orientations and must make simultaneous measurements of airshowers. Furthermore, the simulation must be written such that it can be easily modified as more detailed or alternative experimental methodologies are developed. The simulation also must evolve as the scientific understanding of the underlying interaction physics and nature of the components of the cosmic rays increase. A group at NASA/GSFC and The Johns Hopkins University have been developing a Monte Carlo simulation ‘from the ground up’. This paper details the modeling used by this simulation.

2 Air Shower Event Generator:

The first stage of the simulation is to generate an airshower. The default shower generator is based upon a methodology specifically developed for observing airshowers from space (Mikulski, 1999). Assuming that the signal observed from space is insensitive to the lateral profile, the generator quickly and efficiently yields individual, fully fluctuated airshowers for a specific energy and as a function of grammage. The underlying hadronic interaction model is a variation of the Hillas splitting algorithm (Hillas, 1981). Modifications are employed to reproduce data at accelerator energies and reasonably extrapolate these results to the ultra-high

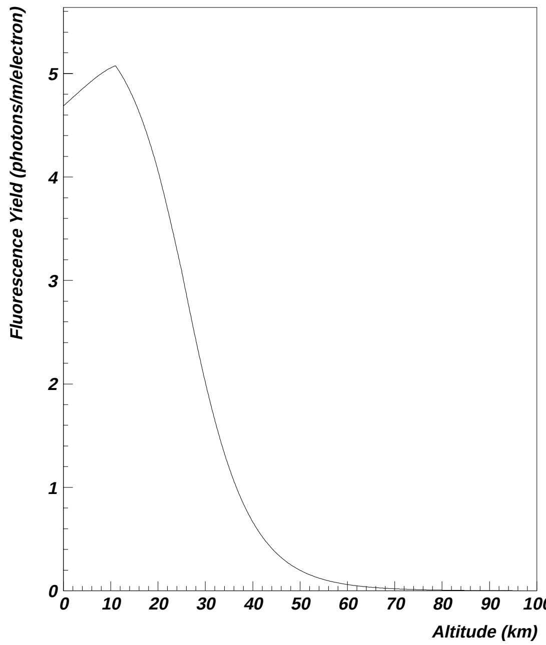

Figure 1: The air fluorescence yield used in the simulation as a function of altitude.

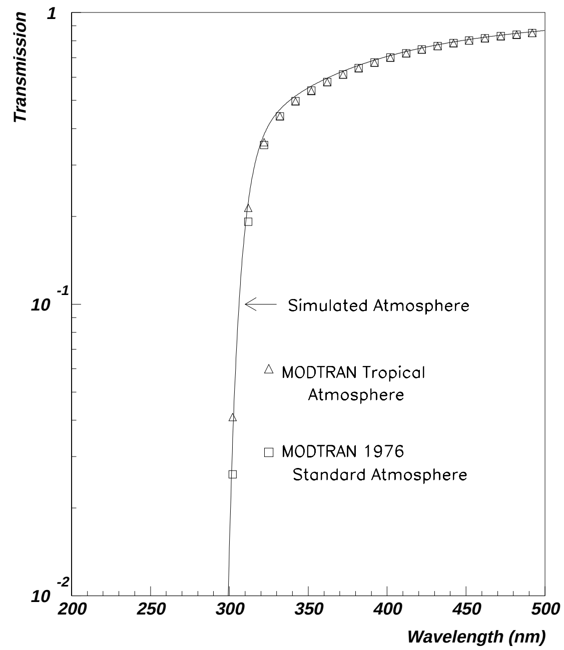

Figure 2: The transmission of light through the atmosphere employed in the simulation compared to the results of the MODTRAN model for a vertical column from sea level to space.

energies under consideration. Effects due to starting point fluctuations, shower development fluctuations. charged pion decay, neutral pion re-interaction, and a parameterization of the Landau-Pomeranchuk-Migdal effect (Landau & Pomeranchuk, 1953; Migdal, 1956) are included. Each generated shower is characterized by a 4-parameter Gaisser-Hillas function. The generation methodology uses airshower parameterizations to evolve the shower in a specified time step, δt, and develop the airshower in the atmosphere from the initial starting point until it reaches the Earth's surface or passes beyond the orbit of the instrument(s). Various topologies are allowed with an isotropic flux uniformly impinging the atmosphere as the default condition, and the effects of the Earth's curvature are taken into account. Unfluctuated Greisen (LaPointe, 1970) or Gaisser-Hillas (Gaisser & Hillas, 1977) parametizations can be chosen and are used as diagnostics. Currently, the generator models any nuclei of arbitrary A.

3 Air Fluorescence Modeling:

Once an airshower is generated for a particular event topology, the next step is to generate an air fluorescence signal. The fluorescence signal is wavelength-dependent and in the near-ultraviolet (Bunner, 1964; Davidson & O'Neil, 1964). The fluorescence yields of Bunner and Davidson & O'Neil are in good agreement, except that the smallest wavelength presented in the measurements of Davidson & O'Neil is 328.5 nm. As the response of an instrument can in principal be non-negligible below this wavelength, the wavelength-dependent fluorescence yields of Bunner are used in the simulation.

The next effect to consider is the pressure- and temperature-dependence of the air fluorescence yield (Kakimoto et al., 1995). The grammage, pressure, and density of the atmosphere in the simulation is described by the Shibata parameterization (Gaisser, 1990). Using this and the temperature-dependence described by the

1976 U.S. Standard Atmosphere (Minzner, 1976), the air fluorescence yield integrated over wavelength can be obtained and is shown as a function of altitude in Figure 1.

4 Atmospheric Modeling:

After a wavelength-dependent light signal is generated, it must be propagated through the atmosphere to the instrument. There are several processes to consider: Rayleigh scattering, absorption by the ozone layer, aerosol (Mie) scattering, and the effects of clouds. The last two are not presently considered, but the effects due to aerosol scattering should be small as the aerosol scale height is $\approx$ 1.2 km (Sokolsky, 1989). The amount of Rayleigh scattered light from a beam of N_γ photons at a air density ρ is given by (Sokolsky, 1989) $dN_\gamma/dx = -\rho(N_\gamma/X_R)(\frac{400}{\lambda})^4$ where $X_R = 2974$ g/cm^2 and λ is the wavelength in nm.

The absorption of ultraviolet light by the Earth's ozone layer depends strongly on the light's wavelength. A model was developed using the measurements of the Total Ozone Mapping Spectrometer (TOMS) experiment aboard the Nimbus-7 Satellite (McPeters et al., 1996). An exponential, wavelength-dependent extinction is assumed with an extinction coefficient $\kappa = 10^{110.5-44.21 \log\lambda}$ (atm-cm)$^{-1}$ and λ in (nm). As the OWL/AirWatch orbit is planned to be at small inclinations, i.e. near equatorial, a 325 milliatm-cm, low-latitude (15°) ozone profile is assumed.

The wavelength-dependent transmission predicted by the model used in the simulation was compared to that obtained using the U.S. Air Force's MODTRAN atmospheric model (Berk et al., 1989). The transmission through a vertical column of atmosphere from sea level to space is shown in Figure 2 for MODTRAN and the model used in the simulation and demonstrates excellent agreement.

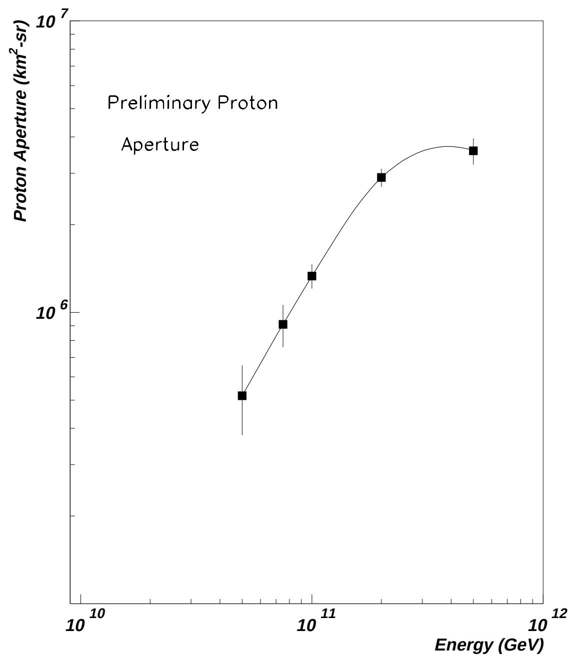

Figure 3: The aperture for proton primaries simulated for the OWL/AirWatch experiment assuming two satellites at an orbit of 640 km and separated by 2000 km.

5 Instrument Modeling:

At this point, the photons from a fluorescence signal have been generated and propagated to outside the Earth's atmosphere. The baseline OWL/AirWatch instrument is defined to use Fresnel optics, a wideband UV filter, and a focal plane with an appropriate photocathode. The properties of the Fresnel optics system developed (Lamb et al., 1998; 1999) yield an acceptance of a light signal up to 30° off-axis (60° full field-of-view) albeit with a reduction in transmission off-axis due to vignetting. This has been modeled and fits well to the parameterization $T(\theta) = 0.842 - 0.817\theta^2 - 1.87\theta^4$ with θ expressed in radians. The resultant optical transmission is further reduced by 5% to account for absorption losses. The wavelength-dependent signal next is convoluted with the response of a BG-1 filter. Finally, the signal is convoluted with the wavelength-dependent response of a bi-alkali photocathode (Philips, 1990). The response of the photo-cathode is parameterized via a wavelength-dependent double-Gaussian response function: $Q(\lambda) = a_1 \exp -0.5((\lambda - a_2)/a_3)^2$ with $a_1 = 0.318$, $a_2 = 349.3$ nm, $a_3 = 130.7$ nm for $\lambda < 450$ nm and $a_1 = 0.288$, $a_2 = 400.1$ nm, $a_3 = 77.83$ nm for $\lambda \geq 450$ nm.

The resultant photo-electron prediction is combined with that for a constant, dark-sky background. The sum is then Poisson fluctuated to obtain an integer photo-electron signal for the particular time step δt. A trigger is then defined by requiring n contiguous time steps above a threshold of m photo-electrons/step.

6 Results:

As a first example of the Monte Carlo, Figure 3 illustrates a preliminary aperture for accepting ultra-high energy proton induced airshowers for two satellites at an orbit of 640 km. Each satellite is assumed to have an optical collection area of 4.9 m^2 and integrate light signals in time steps of 1 μs. The satellites are separated by 2000 km and tilted by 41.8° in the respective direction to view a common area. The inherent $\approx 10\%$ observation efficiency has not been included. The aperture characterized in the figure requires at least 3 photo-electrons in a minimum of 5 contiguous time steps in each satellite for an event to be accepted. This result is consistent that obtained via a separate Monte Carlo for similar experimental assumptions (Dai, Loh, & Sokolsky, 1998). The aperture presented in Figure 3 should be treated as an intermediate result. The effects due to accepting scattered Cherenkov light and non-negligible pixel dead area are not included. These will counteract each other to some level when combined, but still need to be properly modeled. These effects are currently being implemented into the simulation.

References

Berk, A. et al., 1989, GL-TR-89-0122
Bunner,A.N. 1964, Ph.D. Thesis, Cornell University
Cronin, J. 1999, Rev. Mod. Phys. 71, No. 2, S165
Dai, H.Y., Loh, E.C., & Sokolsky, P. 1998, AIP Conf. Proc. 433, 382
Davidson, G. & O'Neil, R. 1964, J. Chem. Phys. 41, 1946
Gaisser, T.K. & Hillas, A.M. 1977, Proc. 15th ICRC (Plavdiv, 1977), 8-353
Gaisser, T.K. 1990, Cosmic Rays and Particle Physics, (Reading: Cambridge University Press)
Hillas, A.M. 1981, Proc. 17th ICRC (Paris, 1981), 8-193
Kakimoto, F. et al., 1995, ICRR-Report-346-95-12, Univ. Utah preprint UUHEP 95/10
Krizmanic, J.F., Ormes, J.F., Streitmatter, R.E. 1998, AIP Conf. Proc. 433
Lamb, D.J. et al., 1998, AIP Conf. Proc. 433, 434
Lamb, D.J. et al, 1999, unpublished
Landau, L.D. & Pomeranchuk, I.J. 1953, Dokl. Akad. Nauk. SSSR 92, 535
LaPointe, M. 1970, NASA SP-243
Linsley, J. 1979, Astronomy Survey Committee (Field Committee) Report
McPeters et al. 1996, NASA RP-1384
Migdal, A.B. 1956, Rhes. Rev. 103, 1811
Mikulski, P. 1999, Proc. 26rd ICRC (Salt Lake City, 1999) HE.2.5.12
Mitzer, R.A. (editor) 1976, NASA SP-398
Philips 1990, Photomultiplier Data Handbook, PC04
Sokoksky, P. 1989, Introduction to Ultrahigh Energy Cosmic Ray Physics (Reading: Addison-Wesley)