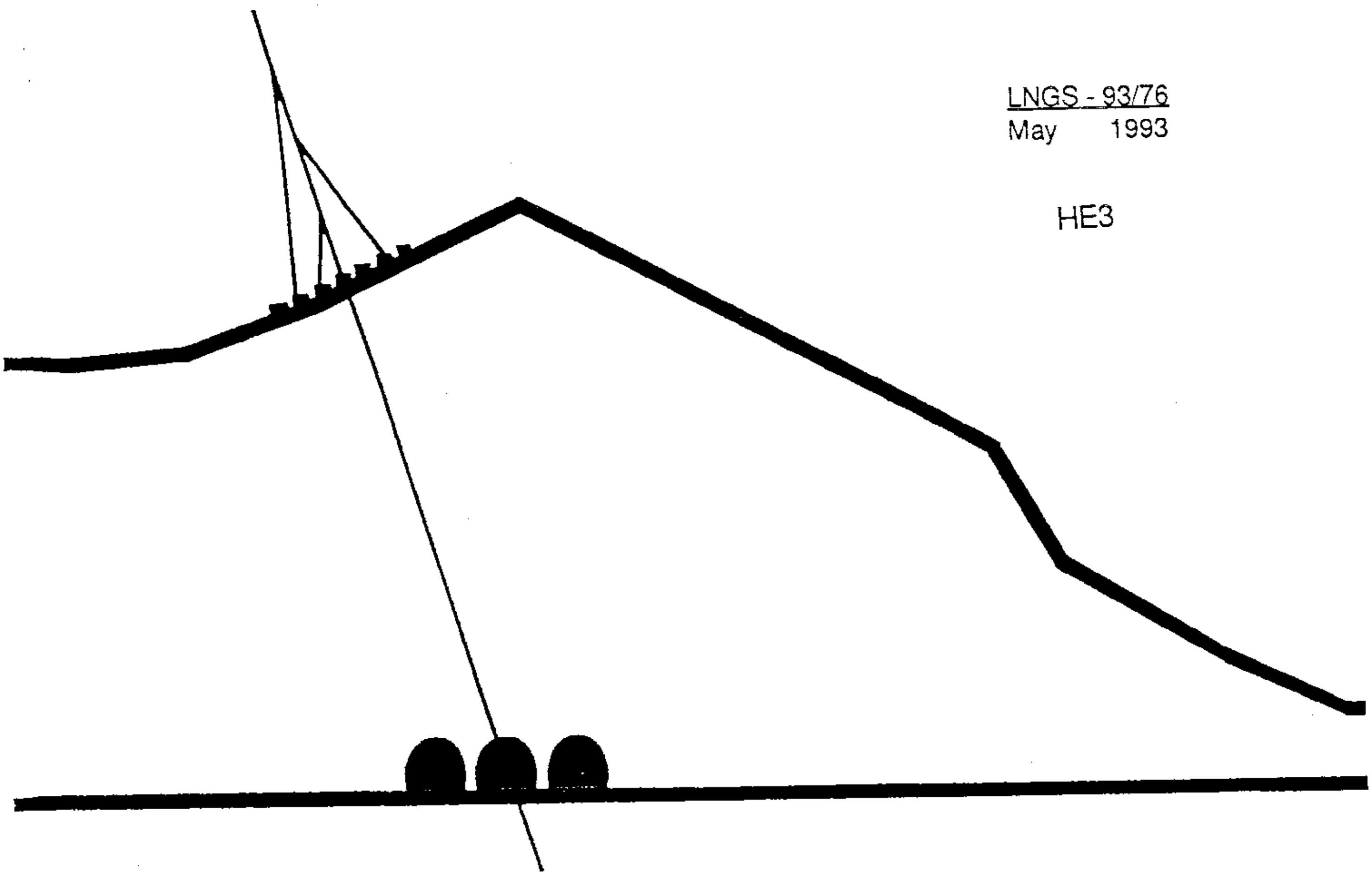

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CONTRIBUTIONS TO THE 23rd ICRC

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M. Ambrosio[12], R. Antolini[7], G. Auriemma[14*], R. Baker[11], A. Baldini[13], B.B. Bam[2], G.C. Barbarino[12], B.C. Barish[4], G. Battistoni[6○], R. Bellotti[1], C. Bemporad[13], P. Bernardini[10], H. Bilokon[6], V. Bisi[16], C. Bloise[6], C. Bower[8], S. Bussino[14], F. Cafagna[1], M. Calicchio[1], D. Campana[12], M. Carboni[6], S. Cecchini[2•], F. Cei[13], V. Chiarella[6], R. Cormack[3], S. Coutu[4], G. DeCataldo[1], H. Dekhissi[2], C. DeMarzo[1], M. De Vincenzi[14••], A. Di Credico[9], E. Diehl[11], O. Erriquez[1], C. Favuzzi[1], C. Forti[6], P. Fusco[1], G. Giacomelli[2], G. Giannini[13⋆], N. Giglietto[1], P. Giubellino[16], M. Grassi[13], P. Green[18], A. Grillo[6], F. Guarino[12], P. Guarnaccia[1] C. Gustavino[7], A. Habig[8], R. Heinz[8], J.T. Hong[4], E. Iarocci[6◇], E. Katsavounidis[4], E. Kearns[3], S. Kyriazopoulou[4], E. Lamanna[14], C. Lane[5], C. Lee[11], D. Levin[11], P. Lipari[14], G. Liu[4], R. Liu[4], M.J. Longo[11], Y.Lu[15], G. Ludlam[3], G. Mancarella[10], G. Mandrioli[2], A. Margiotta-Neri[2], A. Marin[3], A. Marini[6], D. Martello[10], A. Marzari Chiesa[16], M. Masera[16], D.G. Michael[4], S. Mikheyev[7‡], L. Miller[8], M. Mittlebrunn[5], P. Monacelli[9], M. Monteno[16], S. Mufson[8], J. Musser[8], D. Nicoló[13], R. Nolty[4], S. Nutter[11], C. Okada[3], G. Osteria[12], O. Palamara[10], S. Parlati[7], V. Patera[6], L. Patrizii[2], B. Pavesi[2], R. Pazzi[13], C.W. Peck[4], J. Petrakis[17], S. Petrera[10], N.D. Pignatano[4], P. Pistilli[10], F. Predieri[2], L. Ramello[16], J. Reynoldson[7], F. Ronga[6], G. Sanzani[2], A. Sanzgiri[15], C. Satriano[14*], L. Satta[6◇], E. Scapparone[2], K. Scholberg[4], A. Sciubba[14◇], P. Serra Lugaresi[2], M. Severi[14], M. Sitta[16], P. Spinelli[1], M. Spinetti[6], M. Spurio[2], J. Steele[4], R. Steinberg[5], J.L. Stone[3], L.R. Sulak[3], A. Surdo[10], G. Tarlé[11], V. Togo[2], V. Valente[6], C.W. Walter[4], R. Webb[15], W. Worstell[3].

1. Dip. di Fis. dell'Univ. di Bari and INFN, Bari, Italy, 2. Dip. di Fis. dell'Univ. di Bologna and INFN, Bologna, Italy, 3. Phys. Dept., Boston Univ., Boston, MA, USA, 4. Cal. Inst. of Tech., Pasadena, CA, USA, 5. Dept. of Phys., Drexel Univ., Philadelphia, PA, USA, 6. Lab. Naz. di Frascati dell'INFN, Frascati (Roma), Italy, 7. Lab. Naz. del Gran Sasso dell'INFN, Assergi (L'Aquila), Italy, 8. Depts. of Phys. and of Astr., Indiana Univ., Bloomington, IN, USA, 9. Dip. di Fis. dell'Univ. dell'Aquila and INFN, L'Aquila, Italy, 10. Dip. di Fis. dell'Univ. di Lecce and INFN, Lecce, Italy, 11. Dept. of Phys., Univ. of Michigan, Ann Arbor, MI, USA, 12. Dip. di Fis. dell'Univ. di Napoli and INFN, Napoli, Italy, 13. Dip. di Fis. dell'Univ. di Pisa and INFN, Pisa, Italy, 14. Dip. di Fis. dell'Univ. di Roma and INFN, Roma, Italy, 15. Phys. Dept., Texas A&M Univ., College Station, TX, USA, 16. Dip. di Fis. dell'Univ. di Torino and INFN, Torino, Italy, 17. Bartol Res. Inst., Univ. of Delaware, Newark, DE, USA, 18. Sandia Nat. Lab., Albuquerque, NM, USA, * Also Univ. della Basilicata, Potenza, Italy, • Also Ist. TESRE/CNR, Bologna, Italy, •• Also Univ. di Camerino, Camerino, Italy, ⋆ Also Univ. di Trieste and INFN, Trieste, Italy, ◇ Also Dip. di Energetica, Univ. di Roma, Roma, Italy, ‡ Also Inst. for Nucl. Res., Russian Academy of Sciences, Moscow, ○ Also at INFN, Milano, Italy.

The GRACE Collaboration

R. Baker[1], B.C. Barish[3], A. Habig[2], D.S. Levin[1], S. Mufson[2], J. Musser[2], G. Tarlé[1], G. Sembroski[4] M. Kertzman[5].

1. Dept. of Phys., Univ. of Michigan, Ann Arbor, MI, USA, 2. Depts. of Phys. and of Astr., Indiana Univ., Bloomington, IN, USA, 3. Cal. Inst. of Tech., Pasadena, CA, USA, 4. Dept. of Physics, Purdue University, West Lafayette, IN 47907 5. Dept. of Physics, DePauw University, Greencastle, IN 46135.

Coincident Observations of Air Cerenkov Light by a Surface Array with Deep Underground Muon Bundles.

The GRACE and MACRO Collaborations†

Abstract

This paper describes the results of a test to simultaneously observe Cerenkov light and deep underground muons produced in a single cosmic ray cascade. The five element prototype air Cerenkov telescope array was deployed at Campo Imperatore above the Gran Sasso lab for an engineering run completed in the fall of 1992.

1.INTRODUCTION

We have tested a prototype 5 element air Cerenkov telescope array [1] on Campo Imperatore at a slant distance of 3300 meters of water equivalent from the MACRO [2] detector. Our primary objective was to determine the feasibility of operating a large scale array in conjunction with a deep underground muon detector in order to provide a measure of the primary energy in a region below that to which extensive air shower arrays are normally sensitive. To penetrate to MACRO depth, muons have a minimum of 1.5 TeV and thus represent primary cosmic ray energies of several TeV and higher. The simultaneous observation of the air Cerenkov component of the electromagnetic cascade and deep underground muon bundles [3,4] can therefore augment studies of very high energy nucleus-air interactions and cosmic ray elemental composition [1]. We have, in addition, measured the relative arrival times at each of our telescopes and have obtained the direction of cosmic rays producing muons in the underground detector. This information is used to check the pointing capability of the MACRO detector. Air Cerenkov tests have also been done at Gran Sasso by the EASTOP collaboration [3,4].

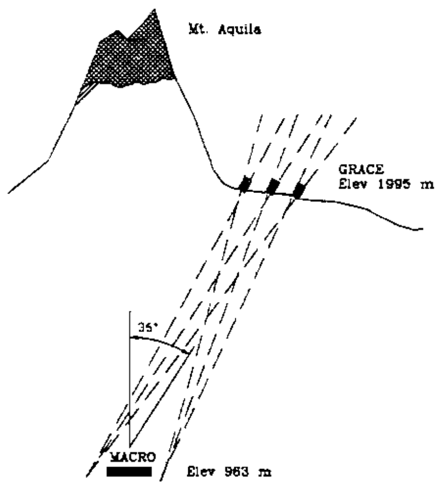

Figure 1. GRACE-MACRO profile.

2. CONFIGURATION

The optical components of our light collectors are a 32 inch diameter, $f \sim .9$ parabolic mirror [5] focusing onto a 20 cm diameter hemispherical EMI phototube. The half opening angle of the aperture is 6°. Four of the telescopes are configured on a square, 80 meters on a side, with the fifth located at the center. They are oriented with their optical axes pointing away from the center of MACRO. In this manner each telescope views a patch of sky overlapping about 4° with its neighbors. The MACRO detector, described in ref. 2, was operated with 6 lower supermodules and presented a projected area in the direction of the Cerenkov array of $\sim 900\mathrm{m}^2$. Fig. 1 shows the profile of this arrangement.

For most runs the data acquisition was triggered by a majority of 2 telescopes generating pulses above a fixed electronic threshold. Trigger rates were nominally about 1 Hz, but could vary widely due to ambient light conditions. Each event trigger latched a clock with a 32μsec least count. MACRO time measurements have a nominal event to event timing jitter of 1 μsec. Our timing resolution over the course of a single night's run was generally limited to ~ 1 msec, but after correction for the smooth thermal drift of the clock, event timing to about 100 μsec was possible. The coincidence events were extracted from the correlation peak in the distributions of event time differences between the surface and underground detectors. The relatively low trigger rates of the two detectors ensured that even with 1 msec timing the background of accidental coincidences was small.

3. DATA SELECTION

We have processed data for a series of 15 runs conducted during moonless nights during the early fall of 1992. These runs yield about 89.2 hours of live time during which the average coincident rate with MACRO was about 2.8 events an hour. The first 13 of these runs employed two-fold telescope triggering in conjunction with the 6 supermodules of the MACRO detector. In the final two runs, a single telescope trigger was used and only 4 MACRO supermodules were operational. The average coincidence rate includes run periods during partially cloudy or hazy skies. An example of our correlation peak for a run during a clear, dark night is shown in Figure 2a in which no data cuts (other than a muon track be present in MACRO) were invoked, and Figure 2B where the shower cores (as determined by the muon tracks) were required to fall within 200 m from the perimeter of GRACE. The maximum coincidence event rate that we have observed is $4.9 \pm 0.8\mathrm{hr}^{-1}$

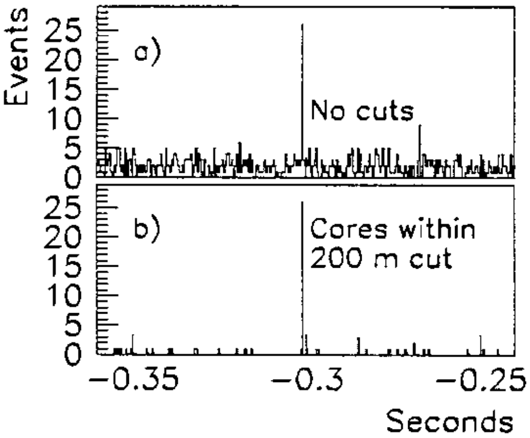

Figure 2a-b. Timing distribution of GRACE-MACRO events.

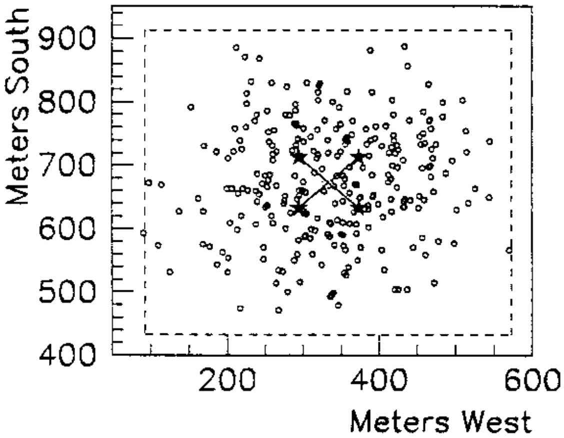

Figure 3. Core locations determined from muon tracks.

In Figure 3 we show the spatial distribution on a level plane through the center of the Cerenkov array of all events that fall under the coincidence peaks. The core positions are determined by extending the underground muon track up to the surface, and the size of the circles corresponds to one half of the error introduced by multiple Coloumb scattering of the muons in their passage through the mountain. The four outer light collectors are represented by stars and the crossed diagonal lines indicate the center of the array. The inner box indicates the centroid of the events which includes a small correction for differential trigger thresholds. The correspondence of the centroid with the array center provides excellent confirmation of the telescopes' positioning and orientation. The outer dotted line indicates a data cut: muon tracks falling outside this line were excluded as GRACE events. We find that a looser data cut (corresponding to a greater fiducial area) doesn't contribute to the coincidence signal. Inspection of Figure 3 demonstrates that most events cluster well within this boundary. After background subtraction, we have a total of 250 events in conjunction with MACRO. Of these over 45 are associated with underground multiple muons.By considering the total number of events passing within a fiducial region 100 meters from the center of GRACE and the rate of MACRO muon tracks through this same region, a relative average trigger efficiency of approximately 23% is obtained. From Monte Carlo calculations based on a parameterization of underground muon rates [6], we estimate our primary energy threshold to be $\sim$ 30 TeV.

A photoelectron distribution from a single GRACE run is shown in Figure 4, where we have fit an inverse power law to the tail. This spectrum is the convolution of several factors. The pulse height for a given energy depends strongly upon the distance of the detector from the shower core. This further implies that for a fixed threshold, higher energy showers are detected at greater distances from the core than lower energy ones. Secondly, photoelectron fluctuations tend to "spill over" from lower to higher counts flattening the spectrum somewhat. We show in Figure 4 a Monte Carlo calculation of the expected photoelectron spectrum where have also considered pedestal fluctuations and trigger threshold. We can also roughly estimate the primary energy threshold from the calculated lateral distribution of air Cerenkov generated photoelectrons [1] in combination with the most probable number of photoelectrons detected. For a 50 photoelectron threshold (pedestal fluctuations introduce some uncertainty into this value) and for a shower core distance of about 80 meters (i.e. the separation between 2 telescopes) this threshold is crossed by Cerenkov light produced by primary protons above 15 TeV.

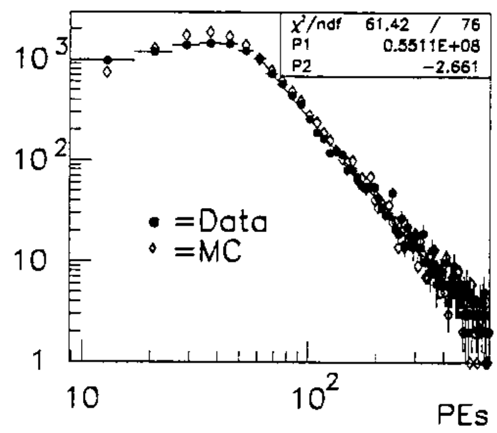

Figure 4. Photoelectron spectrum for non-coincident events.

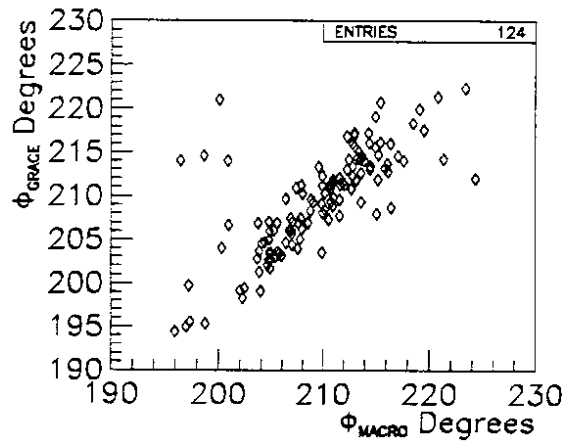

Figure 5. GRACE vs MACRO azimuth.

4. MEASUREMENT OF SHOWER DIRECTION

The relative time of arrival of the Cerenkov light cone at each station can yield the arrival direction of the shower. While Monte Carlo simulations [1] indicate that the angular resolution for single events is limited to about $1-2°$, mainly due to fluctuations in the arriving wavefront, a sample of coincident events can render a measure of the pointing precision of an underground detector. The arrival direction is calculated by chi square minimization of

$$\chi^2 = \sum_j (ct_j + \epsilon_j(\mathbf{r_j}) + \mathbf{n}(\theta,\phi)\cdot\mathbf{s_j})^2$$

where $\mathbf{n}(\theta,\phi)$ is the direction unit vector of the wavefront, t_j and $\mathbf{s_j}$ are the pulse arrival times and location of the station j relative to the origin respectively. ϵ_j is minor correction for the conical shape of the wavefront that depends on the distance from the core $\mathbf{r_c}$. Its exclusion does not significantly alter the angular distribution. In Figure 5 we show the GRACE versus MACRO azimuthal angles. Figure 6a and 6b shows the difference in azimuthal and zenith angles as measured by the two detectors. The known systematic uncertainty in the pointing of the array is $\sim 0.5°$. We conclude that the observed difference of MACRO and GRACE pointing can be accounted for by this systematic uncertainty and a $0.2°$ random error.

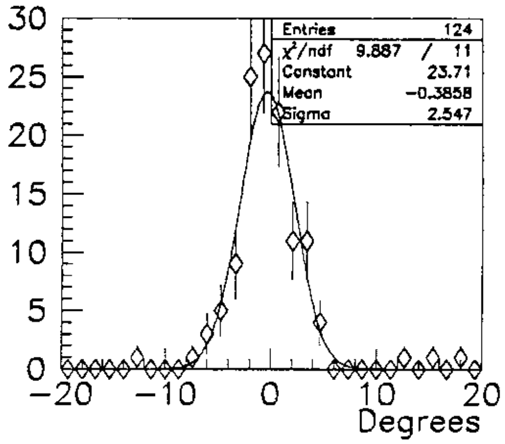

Figure 6a. Azimuth difference.

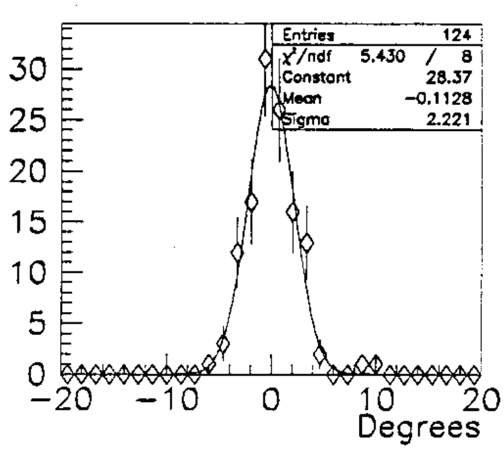

Figure 6b. Zenith difference.

5. CONCLUSION AND ACKNOWLEDGEMENTS

We have demonstrated the operation of a five element Cerenkov array with the MACRO detector. Our 250 event sample includes nearly 20% multiple muons events. These are the first observations of deep underground multiple muons with air Cerenkov radiation in extensive air showers, and are the focus of our continued analysis. We have verified the pointing precision of the MACRO detector to $\pm0.2^\circ$ random and $\pm0.5^\circ$ systematic uncertainties.

We are deeply indebted to the former Gran Sasso Laboratory director Professor E. Bellotti and staff for the extensive cooperation and assistance for this test. We further acknowledge funding provided by the U.S. Department of Energy and the University of Michigan Phoenix Memorial Reactor.

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