

The History of Air Fluorescence

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Abstract. I describe the history of the use of the air-fluorescence technique in UHECR physics.

1 Introduction

This article is a brief review of the history of the use of atmospheric air-fluorescence in the study of Ultra-high Energy Cosmic Rays. This review is very much centered on the work of US groups, both because of the historical importance of the Utah detectors and because of my own involvement. This is not in any way to diminish the very significant early work in the Soviet Union and Japan and the many essential later improvements to the technique by the Pierre Auger collaboration. Since many essential elements of air-fluorescence detectors were developed in the Fly's Eye and HiRes era, I treat these in some detail. The Auger and TA upgrades are the state of the art whose details can be found elsewhere in many contemporary reviews.

2 Pre-history: First Ideas

It is difficult to assign a single person or group to the original idea of using atmospheric air fluorescence to detect and study extensive air showers (EAS) produced by cosmic rays in the UHE range. Between the mid-1950's and the early 1960's, three groups in the Soviet Union, Japan and the US were considering the possibility. Publications by K. Greisen[1], G. Tanahashi, K. Suga, Oda et al.[2] and A. E. Chudakov[3] date to between 1960 and 1962, but there is anecdotal evidence of discussions at earlier cosmic ray conferences. Chudakov was mainly concerned with the development of the Cherenkov technique for gamma-ray astronomy. Here air-fluorescence would be a background which needed to be estimated. The first attempts at building detectors specifically to observe air-fluorescence from EAS were in the US and Japan.

3 Snakes in the Haystack: Early Attempts at Detection

The US effort centered on the K. Greisen's Cornell University group, which built a prototype detector using Fresnel lenses to focus the EAS light on an array of photomultipliers [4]. The instrument was housed in a plywood

"Bucky-dome". Greisen's group worked out all the basic elements of air fluorescence detectors - optics, light collection, phototubes, and fast electronics. They also developed the basic ideas of geometrical shower reconstruction using relative phototube signal timing. Another lasting contribution from this group was a compilation of information on the air-fluorescence efficiency in A. Bunner's Ph.D. Thesis [5]. While they failed to observe any air-fluorescence events, primarily due to the infelicitous Ithaca atmosphere and poor signal to noise, the conceptual design they developed has stood the test of time. The subsequent 50 years of development has rather been a matter of refinement of technique.

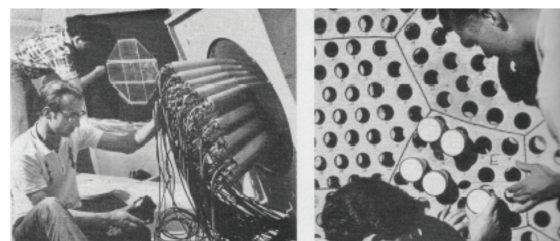


Figure 1. Greisen group prototype air-fluorescence detector.

The Japanese group independently developed a similar design also using Fresnel lenses. The detector was set up at the University of Tokyo's Dodaira Observatory. While most of the events that triggered their detector were attributed to Cherenkov light production, one event with energy near 10^{19} eV was very likely seen in air-fluorescence[6].

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Figure 2. Japanese air-fluorescence prototype building. On the left is Prof. Nagano.

The next attempt at detecting cosmic rays using air fluorescence was of a different nature. By the early to mid 1970's a number of ground arrays were collecting data. These used either plastic scintillation (Volcano Ranch) or water Cherenkov detectors (Haverah Park) and covered areas of 1 to 10 sq km. It was clear that a flux of UHECR up to and beyond 10^{19} eV existed. Could such arrays be used to trigger an air-fluorescence detector?

A group at the University of Utah became interested in pursuing this idea. The group grew out of a long established research program in underground cosmic ray physics established by J. Keuffel. Keuffel together with H. Bergeson and others had built an underground muon detector in the Silver King Mine in Park City, Utah to study neutrino interactions. In 1970, they observed an anomaly in the atmospheric muon flux which some interpreted as due to W boson production. This was dubbed "the Utah effect" and generated much attention. As it turned out, the effect was due to an error in the analysis, but Keuffel's complete honesty in disclosing the problems earned him great respect in the community.

In the aftermath, Keuffel became interested in Greissen's work at Cornell and brought several Cornell physicists to Utah. George Cassiday and Gene Loh became instrumental in the design of a new prototype air fluorescence detector. After Keuffel's untimely death in 1974, Cassiday, Bergeson and Loh established a collaboration with John Linsley of the University of New Mexico,

whose Volcano Ranch plastic scintillation array had been operating for some years in the New Mexico desert.

It was decided to build a small three-mirror prototype and move it to the Volcano Ranch site [7]. The Utah prototype differed from Greissen's or the Japanese prototypes in several respects. Coated spherical mirrors were used, which produced sharper spot sizes than Fresnel mirrors. The front end of the sample and hold electronics were triggered using discriminator circuits equipped with filters which were optimized to reduce sky noise while passing thru the expected pulse width from an EAS travelling with nearly the speed of light. And, of course, the ground array could confirm that an actual EAS had passed through the atmosphere.

Conditions at Volcano Ranch were primitive. Linsley used hay to cover the plastic scintillation counters so that they would be at least partially thermally insulated. A constant danger to the experimenters was the presence of rattle-snakes who would curl up in this insulation and needed to be poked out when any maintenance was performed. The three-mirror Utah prototype was hauled out to the remote location notwithstanding muddy dirt roads. In the end, the run produced 15 well-reconstructed coincident events.

After comparison with expectations, based on air-fluorescence efficiency calculations from Bunner's thesis, it was clear that these were the first events clearly detected using air-fluorescence light. Of particular importance in proving this was the ability to show that the air-fluorescence contribution to the phototube signals could be separated from the air-Cherenkov signal. The signal's angular dependence with respect to the shower axis showed a rapid drop from zero to 30 degrees, followed by a flat tail independent of emission angle. This was a clear signature of fluorescence. A crude estimate of the EAS energy also tallied reasonably with the more traditional surface detector energy estimates.

Much of the analysis software of this and the subsequent full Fly's Eye experiment was based on the detailed work of J. Elbert, a research professor with the Utah group. The September 1977 issue of PRL featured a paper entitled "Measurement of Light Emission from Remote Cosmic Ray Showers" [8]. The era of air-fluorescence as a practical methodology for the study of UHECR had begun.

4 Desert dreams: the Utah Fly's Eye

Not long after the PRL publication, the Utah group, now led by George Cassiday and Eugene Loh, made a proposal to the NSF to build a full scale, 2π solid angle air-fluorescence detector dubbed the "Fly's Eye". The detector site was selected to be on Five Mile Hill at Dugway Proving Ground, a remote Army testing facility several hours drive from Salt Lake City. The site was chosen because of its remoteness from light pollution, clear skies and dry climate, and the safety and security provided by the surrounding base.

Funding was approved and construction was essentially complete by 1981 [9]. The original Fly's Eye con-



Figure 3. Utah air-fluorescence prototype detector. H. Bergeson (L) and G. Cassiday (R) reflected in mirror.

sisted of 67 1.6 m diameter mirrors placed in ingeniously designed galvanized metal cans that rotated down during the day. Each mirror had a camera consisting of 14 3.5 inch diameter round PMT's coupled to individual hexagonal Winston light cones. The PMT signal was fed into a sample and hold integration circuit which was triggered by any one of four different discriminator channel settings. Each discriminator channel had a different filter chosen to maximize signal to noise for a wide range of signal pulse widths corresponding to the expected range of cosmic ray energy and shower distances.

After some initial turn-on difficulties, the Fly's Eye took data, with essentially the same configuration, for more than a decade. Of great assistance to this effort was the work of an impressive series of Australian post-docs from the University of Adelaide: Peter Gerhardy, Bruce Dawson, Dave Liebing, and Dave Bird as well as Brian Fick who joined from Virginia Tech. Academic staff additionally included R. Baltrusaitis, M. Salamon and P. Sokolsky. Software for the on-line PDP-11 computer was developed and maintained by David Steck who worked closely with Cassiday.

Considerable effort was spent in the first few years developing event reconstruction and analysis programs. The lead in this effort was J. Elbert who adapted and further developed ideas from the Cornell group's work. The geometry of each event was determined by a plane fit to the direction of the triggered phototubes followed by a non-linear fit to the arrival times in the event-detector plane. While this monocular reconstruction worked well for long tracks that exhibited significant time-angle curvature, it generated biases for shorter and more linear tracks. Reconstruction of well surveyed Xenon flasher tracks showed that geometrical reconstruction was not well enough understood. To fully understand reconstruction biases an additional detector was required.

Beginning in 1983, a second partial Fly's Eye was constructed at a site 3.5 km from the first. It had identical mirrors and electronics and events that triggered both detectors could be reconstructed using a stereo technique. The geometry of such an event was simply determined from the intersection of the two shower-detector planes. This

method was largely free from the monocular timing biases and was used to fully understand FE I monocular reconstruction. By 1985 a sufficient number of new mirrors were added to FE2 to be able to do real physics with the increased aperture. The development of FE2 hardware and analysis was led by Pierre Sokolsky, who had joined the group in 1982, with the assistance of postdoc Y. Mizumoto.

The Fly's Eye produced the first real physics results that were based on the use of air-fluorescence. Earliest publications included the first limit on cosmic electron-neutrino fluxes (using the LPM effect in the Earth)(1983)[10], a measurement of the p-Air inelastic cross section(1984)[11], and a first attempt at measuring the UHECR spectrum, titled "Evidence for an Ultra-high Energy Cosmic Ray Spectrum with no sign of"(1985)[12]. The low-bias stereo data allowed the Utah group to produce the first fluorescence based EAS elongation rate measurements as well as studies of the EAS Xmax distribution. Comparison with the relatively crude hadronic interaction models that then existed already showed that the mass composition in the 10^{17} - 10^{18} energy range was changing from heavy to light in apparent correspondence with the appearance of an ankle in the stereo cosmic ray spectrum in this energy region[13].

In 1991 FE 1 detected an event which generated a great deal of attention. First reported by H. Dai and carefully analyzed by him and P. Sommers, it was a very well reconstructed EAS with an energy of 3.6×10^{20} eV. This was far beyond the expected GZK with no sign of in the spectrum[14]. Dubbed the "Oh My God Particle" by the news media, it added a mystery to our understanding of cosmic rays since the FE1 monocular spectrum was already showing evidence for a with no sign of at or near the predicted GZK energy of 6×10^{19} eV.

Meanwhile, spectra measured by ground arrays such as Haverah Park, Akeno and AGASA seemed to show a continuing spectrum with no hint of a with no sign of. Now the "Oh My God" particle seemed to indicate possible new physics as well. The time was ripe for proposing larger and better detectors.



Figure 4. The Utah Fly's Eye detector (L). G. Cassiday at the control terminal. The display behind him was a unique planetarium dome with LED's representing each tube's pointing direction. Events were displayed as they came in with the relative timing slowed down so the human eye could see the track development.



Figure 5. P. Gerhardy checking a phototube base.(L); B. Fick, B.Dawson, D. Liebing on 5 Mile Hill, the FE 1 site. One of the many 4w drive vehicles used up over the course of the experiment to access 5 Mile Hill, the F.E. 1 site.

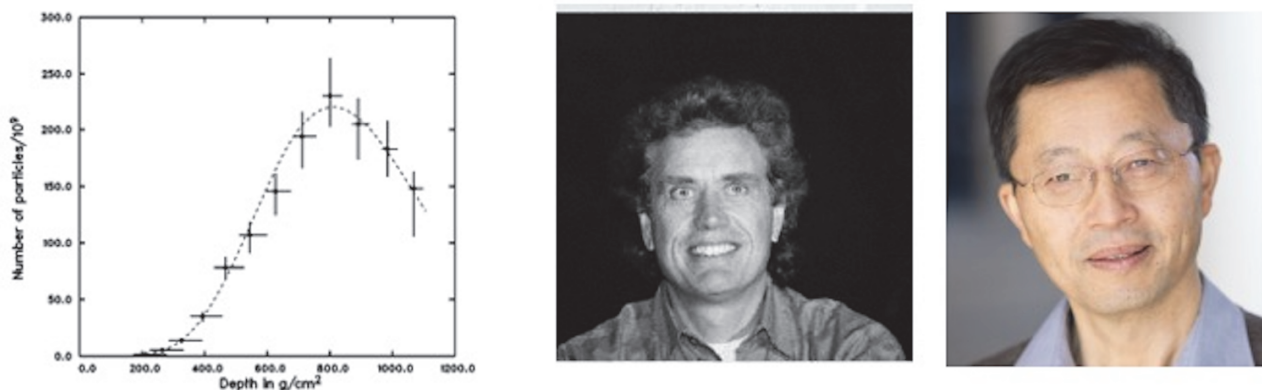


Figure 6. “Oh My God Particle” profile (L), P. Sommers and H. Dai

5 Funding Follies: The Battle For High Resolution

It was clear from the Fly’s Eye experience that the next generation detector should have smaller pixel size. The 3.5” diameter phototubes used in the Fly’s Eye subtended a 5 deg by 5 deg solid angle on the sky. This limited the number of track samples for distant EAS tracks making reconstruction difficult. Additionally, since fluctuations in sky noise determine the signal to noise, reducing the tube aperture would allow triggering on more distant tracks. After a number of studies, a 1 degree by 1 degree tube aperture was found to be optimal. Newer hexagonal phototubes from EMI and Hamamatsu made it possible to close-pack tubes without having to use Winston cones. The basic design of the new detector, to be called HiRes (for High Resolution Fly’s Eye) was settled. It included larger 2 m spherical mirrors to be manufactured in Utah. Gene Loh and engineer Stan Thomas had developed an ingenious vacuum slumping technique to form plate glass into a spherical shape. This was followed by surface aluminization and the application of a novel hard coating to maintain reflectivity in the dusty desert environment.

Several initial proposals for funding to the NSF were unsuccessful. Review committees were moderately encouraging but strongly suggested increasing the size of the group and enlarging the collaboration. The Utah group which at this point was led by Gene Loh and Pierre Sokolsky and included Mike Solomon and Dave Kieda was then joined by Tom O’Halloran from the University of Illinois and Wonyong Lee and Bruce Knapp from Columbia University. The NSF then provided sufficient funds for the construction of the HiRes Prototype detector, consisting of 14 mirrors, each with 256 phototubes with 1 degree by 1 degree solid angle. The Prototype was built at the location of FE 1 overlooking the University of Chicago CASA gamma-ray astronomy array 3.5 km distant.

The CASA detector[15] was a 1 km by 1 km array of closely spaced plastic scintillation detectors whose purpose was to study gamma rays from Cyg X-3 and other astrophysical objects. It included an underground muon

array built by the University of Michigan (MIA). Jim Cronin, who led this group, was beginning to be interested in UHE cosmic rays and the idea of combining CASA-MIA and HiRes prototype data to enlarge the scope of CASA-MIA became attractive. While each detector was independently triggered, a light signal from HiRes prototype flagged CASA-MIA data in time coincidence for future joint analysis. This became the first hybrid cosmic ray detector[16], combining shower Xmax determination with a measure of muon multiplicity from the underground detectors (the surface detector was saturated for most of the coincident data).

While the small area of the CASA array prevented the gathering of statistics much beyond 10^{18} eV, results on the spectrum and composition from below 10^{17} to just above 10^{18} eV were published, showing evidence for a second knee in the spectrum. The muon elongation rate measurement using this data was probably the first indication that EAS models could not reproduce the muon multiplicity, even for a very heavy composition. The Xmax data confirmed the stereo Fly’s Eye result: the composition was changing from heavy to light in this energy region[17]. Analysis of this data was largely done by B. Fick and Z. Cao who were postdocs at the time.

6 The High Resolution Fly’s Eye

After successful demonstrations of the HiRes prototype detector, the group resubmitted the HiRes proposal. A difficulty arose because of the project cost, which would require approval by the National Science Board to move forward. In a stroke of luck, the minimum threshold for NSB approval was moved upwards and the NSF program manager W. Chinowsky was able to authorize funding for the full HiRes. However, only two of the three proposed stations were approved[18].

The final HiRes proposal envisaged stations spaced 12 km apart, so that a substantial fraction of triggered events could be reconstructed in stereo. The funded stations included HiRes I at Five Mile Hill (site of the original FE and the HiRes prototype) and HiRes II at Camels

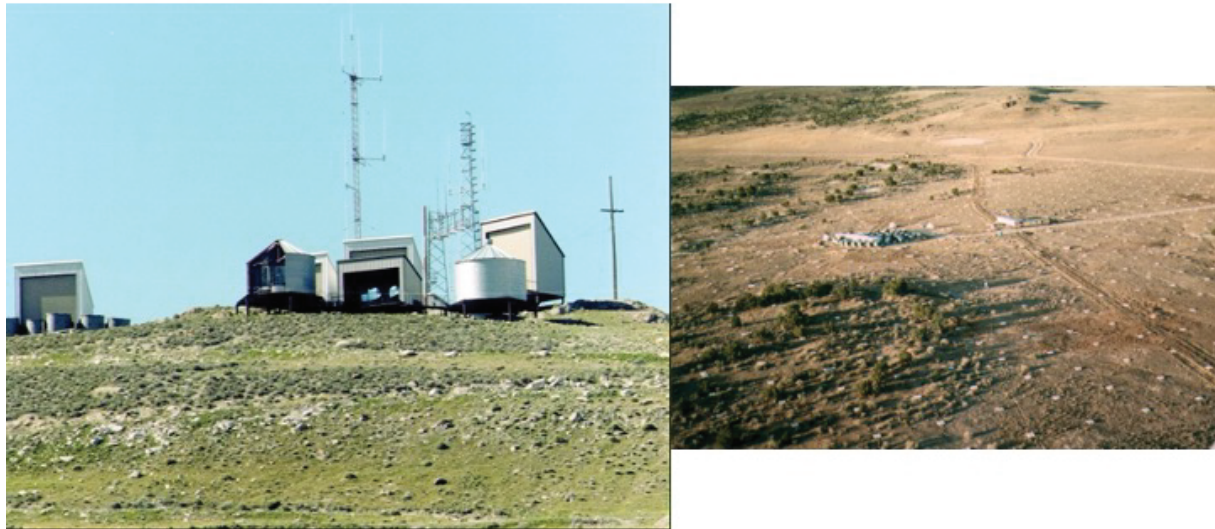


Figure 7. HiRes Prototype detector on 5 Mile Hill [L], CASA/MIA array with FE2 at the center [R]

Back Mountain. The detector had a total of 66 mirrors, each with 256 phototubes covering a 1 deg by 1 deg solid angle. The data acquisition electronics at HiRes I were sample and hold while HiRes II used a FADC system designed by Bill Sippach and Bruce Knapp at Columbia University's Nevis Labs. The expanded HiRes collaboration grew to include groups from Rutgers University (led by Gordon Thomson), University of New Mexico (John A.J. Matthews), Los Alamos National Laboratory (G. Sinis) and Montana State (J. Belz). The University of Tokyo built several CTA-type steerable telescopes for gamma ray astronomy at a nearby site at Dugway. This group was led by M. Teshima. The spokesman for HiRes was Pierre Sokolsky. The scale of the project required a project manager. John Matthews was hired and continued on to manage all the Utah-based projects, including the Telescope Array (which he is currently co-spokesman of).

A substantial effort, led by Lawrence Wiencke, was devoted to understanding atmospheric transmission. A linear array of vertical Xenon flashers spaced one km apart was installed between HiRes I and HiRes II. In addition, a steerable YAG laser system at HiRes II swept over the fiducial volume of the experiment on a regular basis. A nightly database of atmospheric transmission and cloud obscuration in the fiducial volume was maintained. Episodic manned hot air balloon flights carrying a Xenon flasher were performed to check the optical response of the detector to a point light source at various distances in the atmosphere. This was the first systematic attempt at understanding the impact of atmospheric variations on air fluorescence data[19]. The HiRes detector took data for eleven years, shutting down in 2006. It even survived the closure of Dugway Proving Grounds to non-military personnel after 9-11. The experiment was subsequently run by collab-

orators and volunteers from Los Alamos for nearly a year. They had national security clearances and were acceptable to the Army.

The most important physics results from HiRes included: the first > 5 sigma observation of a cut-off in the UHE spectrum at 6×10^{19} eV, consistent with the GZK prediction[20] (soon after confirmed by Auger[21]) and the study of the $X_{\max}$ distribution using well reconstructed stereo events[22]. The resultant elongation rate measured from 10^{18} to above 10^{19} eV was entirely consistent with a light composition (as interpreted by early versions of hadronic model simulations QGSjet and Sybill).

Under the direction of G. Thomson, the HiRes group also pioneered the detailed simulation of the response of the detector to EAS, enabling a comparison between $X_{\max}$ data and predictions from hadronic models for varying compositions. The methods used were based on the successful simulation of detector response in High Energy Physics experiments. The shape of the $X_{\max}$ distribution in the 10^{18} to 10^{19} eV region was found to be consistent with predictions for a primary proton flux by several hadronic interaction models.

7 Snake Array, Northern Auger

After the publication of the HiRes spectrum with no sign of result, a major controversy arose with the Japanese AGASA experiment. AGASA surface detector results pointed to a continuing flux beyond 10^{20} eV with no sign of a cutoff. A series of debates at various physics meetings were held but there was no sign of a resolution. In the event, members of the AGASA group began to work with HiRes on plans for a future, larger aperture and possibly hybrid detector. This grew out of the realization that

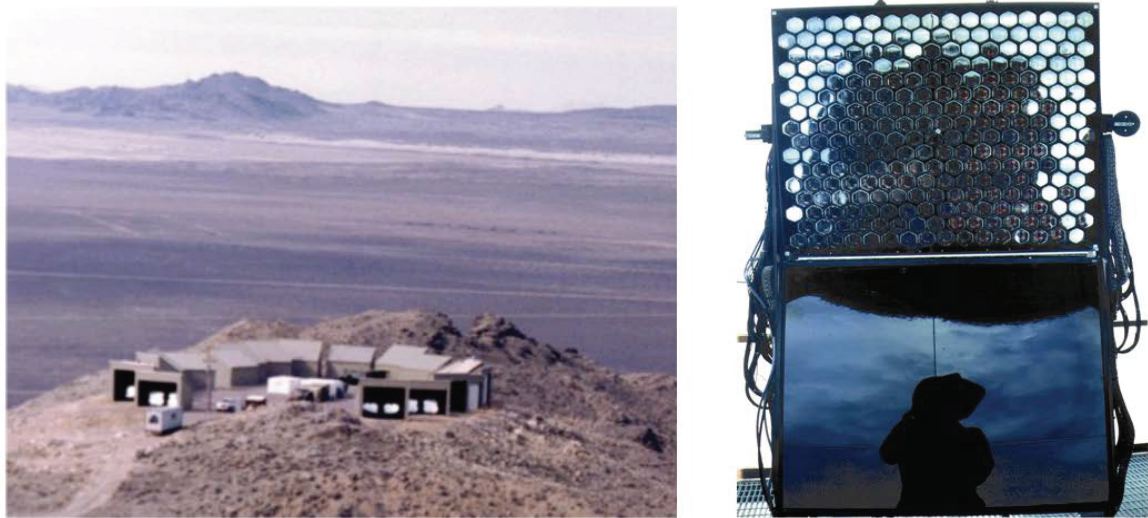


Figure 8. HiRes Camel's Back detectors (L); HiRes pmt array and optical filter panel (R).

had HiRes and AGASA been co-sited, important checks on systematics and energy scale uncertainties could have been performed.

However, the first idea considered was an HiRes-like purely air-fluorescence detector that was to extend in a long chain resulting in a total stereo aperture 10x larger than HiRes. Dubbed the "Snake Array", significant work was done in finding 10 to 12 sites in NW Utah along the remote Snake Valley bordering Nevada. The site surveys were done by Lawrence Wiencke and Shigeru Yoshida from the University of Tokyo.

In a significant development, Jim Cronin convened the six month giant air shower array study at Fermilab in 1995. Cronin was focused on resolving the issue of the possible violation of the GZK cutoff (if the AGASA results were correct and the "Oh My God Particle" was not a fluke). The initial plans that emerged from the study were for a surface array at least 10x larger than AGASA. Cronin was persuaded by Paul Sommers and others to add an air-fluorescence detector making the energy scale estimation much less dependent on hadronic model simulation. Planning for the new Pierre Auger hybrid observatory began. It was to have complete sky coverage with a southern and northern site.

The HiRes group and the AGASA group were working together now on new ideas and a collaboration with Auger was proposed. The Northern site was to be chosen either at a new Millard County, Utah site favored by the HiRes/AGASA group, or at a site in Colorado. After considerable study of both sites, the Auger collaboration, meeting at Fermilab in 2000, chose the Colorado site for

Northern Auger. This eventually led to a split with the HiRes/AGASA group which had already done preparatory work for the site in Millard County. Northern Auger was never funded by the NSF. Instead J. Cronin and A. Watson were able to put together a large international collaboration to build the southern site. Construction began on the PAO site in Malargue, Argentina in 2002 [23]. The PAO detector would have water Cherenkov detectors covering a 3000 km² surface area and four HiRes-like air fluorescence stations overlooking the array. The fluorescence stations had important detailed differences and improvements.

At the same time a Japanese group, now led by M. Fukushima from the University of Tokyo, was successful in getting funding for what was to be called the Telescope Array. Japanese funding provided plastic surface detectors covering 700 km² and two air-fluorescence stations with new mechanical design by Mitsui Engineering including segmented spherical mirrors. US groups, led by Utah were funded by the NSF to relocate refurbished parts of the HiRes detector to the new TA site thus adding a third air-fluorescence detector for full hybrid coverage. Construction on the new site began in earnest in 2003 and data taking began in 2006 [24]. The TA collaboration eventually included institutions from Japan (led by the ICRR of the University of Tokyo), Korea, Belgium (The Free University of Brussels), Russia (INS) and the United States. The first spokesmen for the experiment were M. Fukushima and P.Sokolsky.

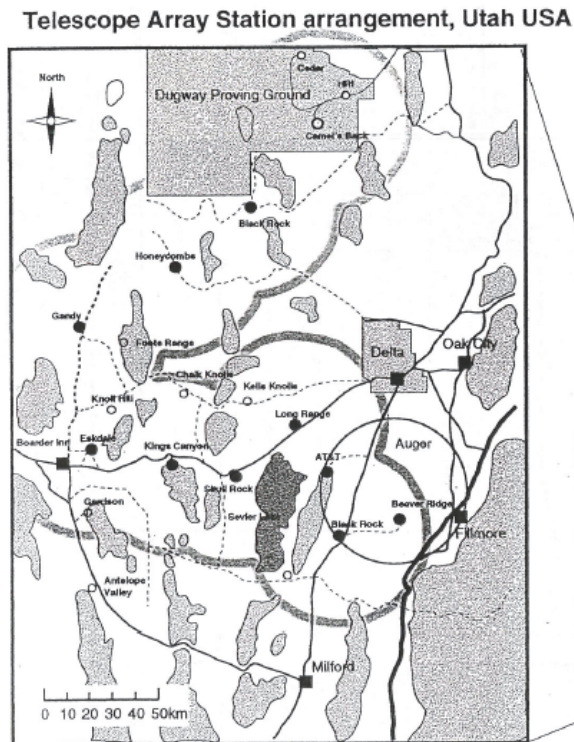


Figure 9. Proposed Snake Array cites in NW Utah.

8 TA and Auger

While the details of experimental design are different between Auger and TA, the basic hybrid detector triggering and event reconstruction are similar, so that together, these two detectors conform to the original idea of a global N-S coverage envisaged by Cronin. The original TA had less than a third of Auger's surface aperture and began taking data at a later date, so statistics in the North were smaller than in the South. Regardless, TA surface data showed, among other results, an interesting possible medium scale anisotropy dubbed the "Hot Spot"[25]. More statistics would be necessary to actually claim a discovery, however. To facilitate this, the TAx4 proposal was developed and funded. A significant fraction of the final 3000 km² surface array was added in 2021. Two additional HiRes-like air fluorescence stations overlooking the new parts of the array were completed by the Utah group. Above 10¹⁹ eV Auger and TA now have roughly similar apertures and the search for anisotropies, global or local is proceeding apace. Of particular interest is the discovery of a large scale dipole anisotropy by the Auger collaboration[26].

9 The Future of the Past

Where does one go from here? While the obvious way forward is increased detector area and sensitivity to the highest UHE cosmic rays, looking to lower energies is also growing in importance. The HiRes prototype-CASA experiment showed how to move to exploring lower en-

ergy cosmic rays. Since the fluorescence light is proportional to deposited energy in the atmosphere, signal to noise becomes problematic below 10^{17} eV. However, the Cherenkov component, which is emitted at angles up to 20 degrees from the EAS axis, is much stronger and can be used both to trigger the detector and to reconstruct the shower profile. Until fairly recently, events with a strong Cherenkov component to the signal were discarded from analysis. In this instance, the detailed and well-vetted Cherenkov light simulation programs developed by gamma ray astronomers have made it possible to understand the EAS shower light production as a mixture of Cherenkov and air-fluorescence light, down to almost 10^{15} eV. The whole range of the cosmic ray spectrum from the first knee to the GZK cutoff can now be measured with a consistent energy scale.

The first steps in this direction were made by the Utah group, led by C. Jui. They built the TALE detector [27] adjacent to the Utah TA site. Expanding on the HiRes prototype idea, they increased the azimuthal and elevation angle acceptance of the HiRes-like detector. TALE was able to extend the spectrum measurement to near 10^{16} eV using events with a mixture of Cherenkov and air-fluorescence light. Further refinements in the analysis of events completely dominated by Cherenkov light extend the measurement to near 10^{15} eV. Much of the success of this analysis is due to the meticulous work of T. Abu-Zayyad, a research professor at Utah. An infill surface array near the detector was deployed to allow hybrid measurements of these events as well.

A similar set of detectors at the Auger site called HEAT and AMIGA [28] also extended the range of the Auger spectrum and composition measurement to below 10^{17} eV. Results from this foray into low energies have been very interesting. The spectrum exhibits three features: the first knee, a broad dip, a second knee, an ankle structure and finally a flattening, followed by the GZK like feature. Many of these individual features have been previously seen in surface detector experiments, but never in one experiment with over five decades of energy range[29].

For the highest energies, there are several paths for the air-fluorescence technique: more of the same but on a larger scale (Snake Array), reducing the cost and increasing reliability and stability of mirrors/phototubes/electronics so that they can cover huge areas and run semi-autonomously (FAST) [30], or placing a downward looking detector into space, either on the ISS or as one or more free-flyers (EUSO, POEMMA) [31]. Radio detection is increasingly competitive, in terms of ability to reconstruct shower profile and energy but requires a much higher detector density on the ground. It remains to be seen what the international cosmic ray community will decide is the appropriate mix of detectors to increase apertures 10 to 100x beyond Auger and TA. It is very likely that air-fluorescence will continue to play an important role because of its nearly model independent energy scale determination and well-understood systematics.



Figure 10. [Top L] BR air-fluorescence detector station for TA, [Top R] Middle Drum detector station for TA; Bottom [L] Auger mirror and pmt array [R] Auger detector housing.

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