Chapter 1

Some Projects Designed to Study High-Energy Cosmic Rays

1.1 EUSO: Extreme Universe Space Observatory

The Extreme Universe Space Observatory (EUSO)[9] was a space mission devoted to the search of Ultra High Energy Cosmic Rays. EUSO was proposed to ESA as a free-flyer mission in January 2000. However, due to an opportunity window, EUSO's installation was redirected to the ISS, on the Columbus Exposed Payload Facility. By December 2000 the study on accommodation of EUSO was finished successfully and the project proceeded to Phase A. Phase A was successfully concluded by mid-2004 and EUSO was considered technically ready to proceed to Phase B. However, due to financial and programmatic issues related to the NASA Space Shuttle program, much affected by the Columbia accident in 2003, EUSO was put on hold. Nowadays two EUSO inspired projects are being considered: JEM-EUSO, a detector similar to EUSO, developed in the context of the Japanese participation in the ISS and Super-EUSO, which has been proposed to the Cosmic Vision program of ESA with a schedule beyond 2015.

The main purpose of EUSO was to collect very large statistics of UHECR at 10^{20} eV, reaching the 10^{21} eV decade, allowing systematic studies on primary cosmic rays composition and origin, while performing an inter-calibration with the Pierre Auger Observatory at energies of 5×10^{19} eV. Searches for highly energetic electron and tau neutrinos could also be performed with EUSO. A secondary objective of EUSO was to study the physical properties of the atmosphere, and related phenomena, including meteors and electrical discharges.

The principle of EUSO, illustrated in figure 1.1, was to observe from space the

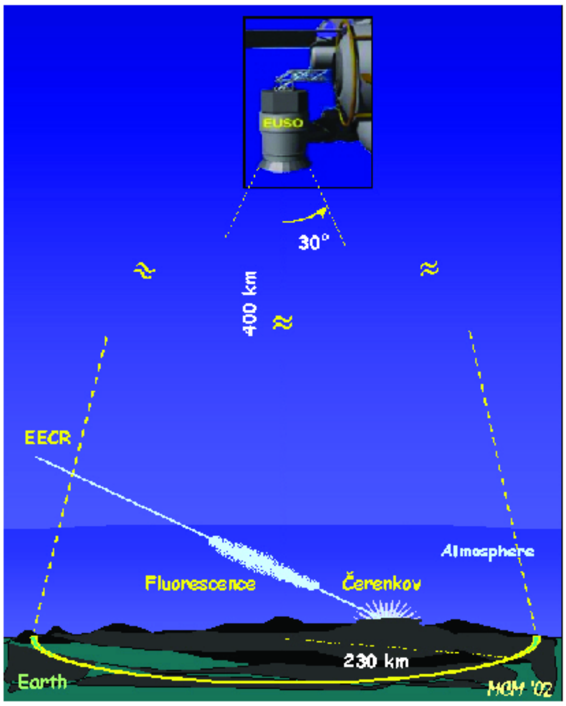


Figure 1.1: The EUSO concept

fluorescence and Cherenkov light produced by EASs in Earth's Atmosphere. The instrument consisted of an UV Telescope to be placed at$\sim$ 400 km height (the ISS altitude) , pointing to the nadir with a full field of view of 60°. With such a design, EUSO would have had an observation area of approximately 200 000 km^2. The ISS, and thus EUSO, have a 51° inclined orbit with respect to the equator, allowing EUSO to observe both hemispheres detecting cosmic rays from all directions in the sky. However, fluorescence telescopes such as EUSO, operate exclusively on moonless nights, which reduces their duty cycle to $\sim$ 10%.

The estimation of the shower energy with EUSO relied on the calorimetric measurement of EAS in the atmosphere. This was accomplished by integrating the detected fluorescence light profile to estimate the energy of the shower. The direction of an EAS can be reconstructed from the fluorescence light distribution on the focal plane and by the timing at which the photons reach the detector. However, being a monocular experiment, there is an ambiguity in the estimation of the height of the EAS in the atmosphere. To solve this ambiguity EUSO relied not only on the detection of the fluorescence light produced by the EAS but also on the measurement of the Cherenkov component reflected from Earth´s surface. The collection of reflected Cherenkov light would also allow for an improved estimation of the location of the EAS core. Thus, the EUSO expected signal, represented in figure 1.2 would

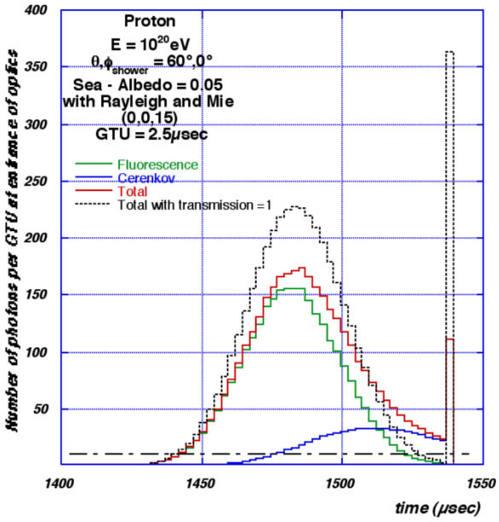


Figure 1.2: Expected signal seen by EUSO

have a fluorescence component followed by a peak of reflected Cherenkov light.

EUSO was designed to have a relative energy resolution of the order of 30%, an angular resolution better than 2° and a resolution of 35 $\mathrm{g\,cm^{-2}}$ in the depth of the shower maximum. Such goals, combined with the limited resources of a space mission installed in the ISS, led to the adoption of a highly pixelated focal surface($\sim 10^5$ pixels), with a high acquisition rate using the Single Photon Counting technique (see chapter **??**).

The EUSO Detector

An exploded view of EUSO is shown in figure 1.3 . EUSO would be composed by an optical system directing the incoming light to a focal surface where it would be collected by photomultiplier tubes. Although the two fundamental systems in EUSO were the optical system and the data acquisition system, additional subsystems associated with a space experiment conducted aboard the ISS were also incorporated in the detector, such as the interface system to the ISS and the thermal conditioning system. EUSO would also be equipped with a LIDAR to perform measurements of important atmospheric parameters.

Although the definitive detector characteristics were to be defined in the project Phase B some of the important parameters of the design were already established in Phase A: the optical system was composed by two double faced Fresnel lenses. The collecting area of the instrument being defined by a first Fresnel lens with a diameter of 2.5 m, followed by a similar lens placed 2 m away, and 1.5 m before the

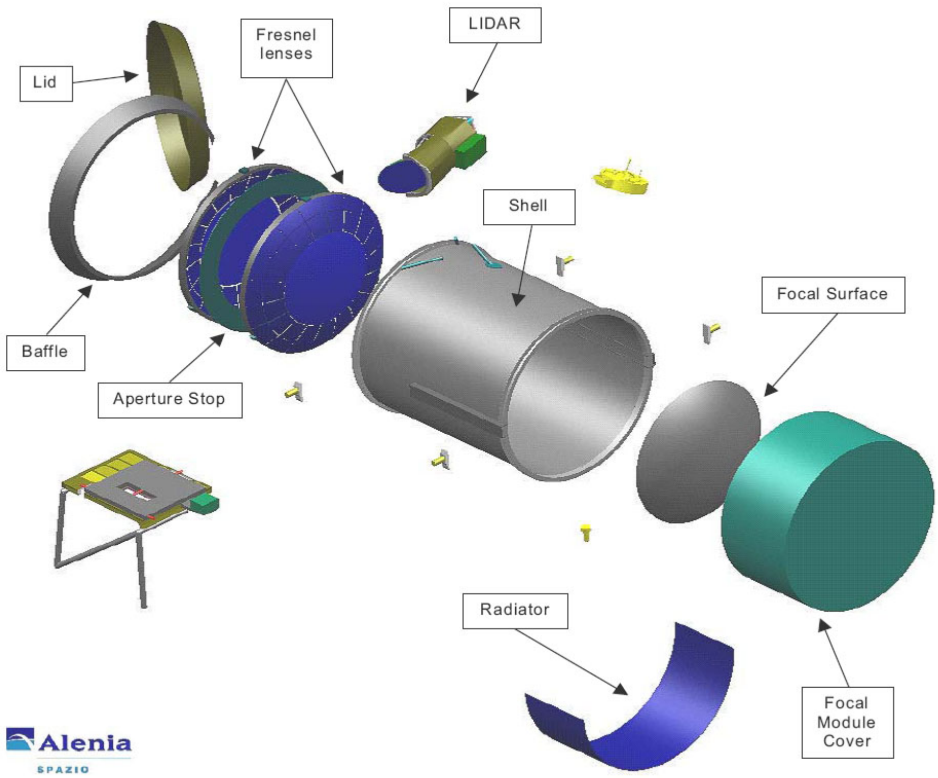


Figure 1.3: The EUSO detector

focal surface. The optical system had to comply with the full field of view of 60° while producing a spot inferior to 5 mm, corresponding to 0.1°. A bandwidth filter was deposited as a coating on the first lens to filter light outside the $300 - 400$ nm wavelength region to remove background.

The focal surface would be instrumented with MAPMTs providing a high density of channels and the DAQ of the system was based in the Single Photon Counting technique to instrument such large number of channels ($\sim 10^4$). This technique employs very simple front-end electronics allowing the reduction of financial, power and mass budgets, in compliance with the requirements of a space experiment. In EUSO the pixel signals would be input to a fast discriminator whose output would feed a counter clock. This part of the system was designed to work with a peak-to-peak resolution of 10 ns. In each Gate Time Unit (of the μs order) the value from the counter would be read and the counter would be reset, corresponding to the acquisition of a number of detected photons per pixel per GTU. The system would saturate in the of case a bunch of photons arriving within the resolving time of the system: in fact all photons arriving within 10 ns would be counted as a single photon. This saturation could be overcome by the digitalisation, through an ADC, of the last dynode signal of a whole PMT (containing 64 pixels).

1.2 The ULTRA experiment

The ULTRA experiment - Ultra violet Light Transmission and Reflection in the Atmosphere - was a support experiment for the EUSO mission with the goal of providing quantitative measurements of the UV light produced by EAS traversing the atmosphere after reflection on the Earth surface. The ULTRA experiment is described in [1] and its achievements are reported in [7].

The main concept of ULTRA, illustrated in figure 1.4, was the use an UV optical detector, the UVScope, to collect the UV light generated by the EAS whose arrival direction, core location and shower size are estimated using the data collected with a conventional ground array of scintillators, the ETScope. The UVScope was typically placed on a high location pointing downward so that its field of view centre coincided with the ETScope central station, and the UV light reflected from the surface upon shower front arrival reached the UVScope where it could be detected. Two wide field of view Cherenkov detectors, "Belenos", were placed in the centre of the array pointing to the zenith and the nadir in order to measure in coincidence the direct and diffused Cherenkov light.

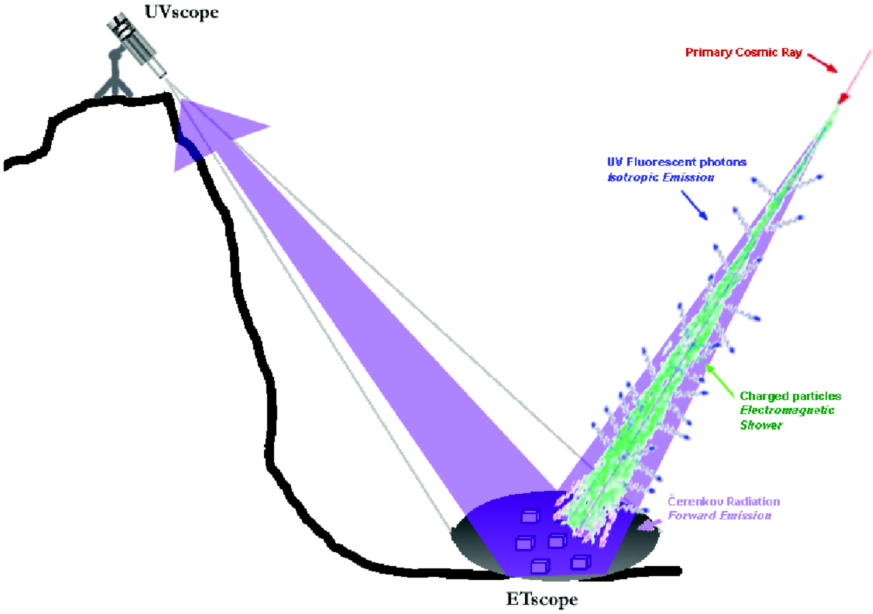


Figure 1.4: The ULTRA operation principle.

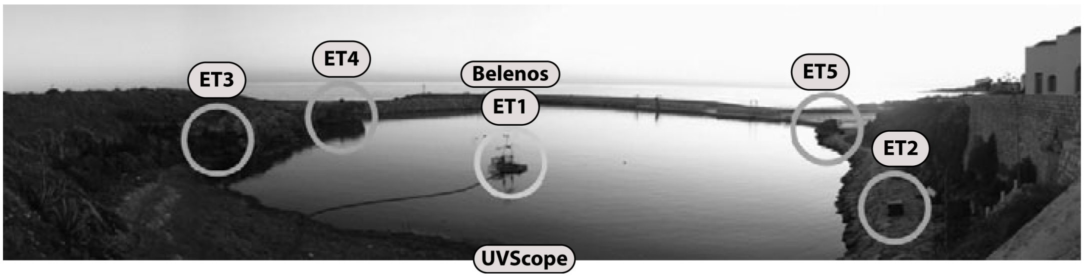


Figure 1.5: View of the ULTRA setup. The ETScope stations are indicated as ET1, ET2, ET3, ET4 and ET5. The station ET1 and the Belenos detector are installed in the center of the array in a raft. The UVScope is at a higher altitude pointing downward. The photo was taken, approximately, from the UVScope position.

The first engineering runs for calibration and optimisation took place at Mont-Cenis and Grenoble, France, and are reported in [4]. In May 2005 ULTRA was installed in Capo Granitola, Sicily, Italy, in a protected small private harbour, providing the conditions to study the reflection of Cherenkov light from EAS on water. The central station was placed on a raft, along with “Belenos”, in the centre of the harbour. The other stations were placed on shore near the coast line of the harbour. Figure 1.5 is a photograph, taken from the UVScope location, where the ETScope stations and Belenos are indicated by circles. The location, in the local coordinate system, of the several detectors of ULTRA is indicated in figure 1.6

The DAQ used in the successful run in Sicily was based on an acquisition board developed at LIP - the LIP-PAD board. This board, as well as its application in

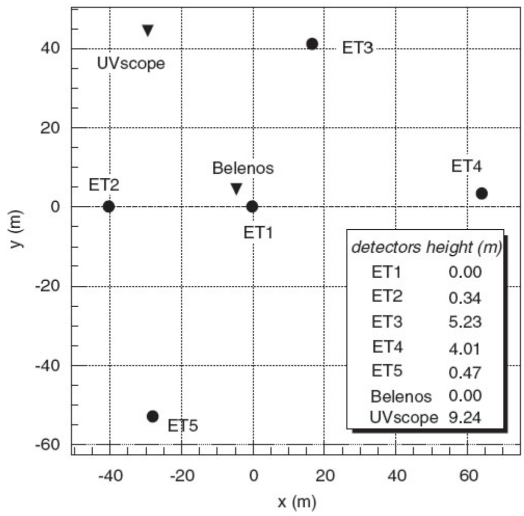


Figure 1.6: The location of the detectors in ULTRA

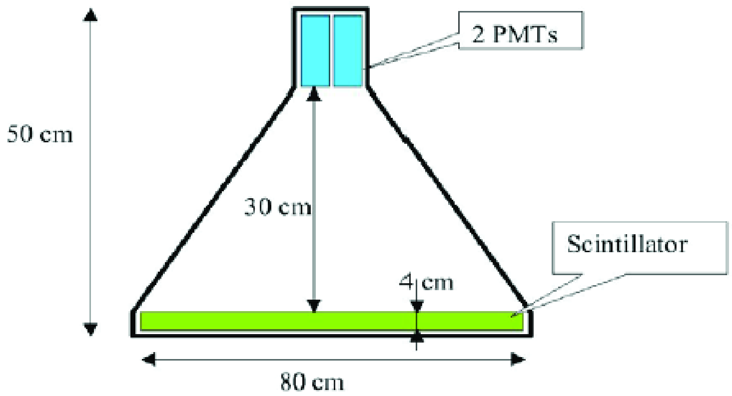
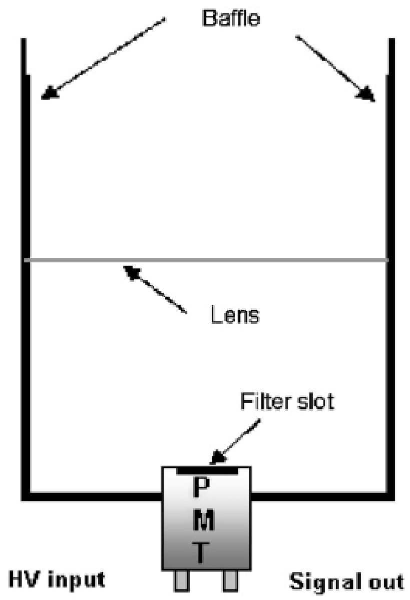


Figure 1.7: Schematic view of one ETScope station

ULTRA, is the subject of chapter **??**. Full simulations of the ETScope and of the UVScope were developed at LIP using the Geant4 simulation toolkit [3, 2].

The ETScope detector

The ETScope was a ground array of scintillators used to detect the electromagnetic component of EAS. Each ETScope station estimated the corresponding particle density as well as the shower front impact time. Figure 1.7 represents a schematic view of one station which consisted of a plastic scintillator, NUCLEAR NE 102A with 80×80 cm^2, 4 cm thick, enclosed in an aluminium pyramidal shaped box internally coated with a white diffusing paint. For protection from environmental conditions, each of these boxes was placed inside a PVC container. At the top of the



(a)

(b)

Figure 1.8: The UVScope detector. Left: scheme of each monocle. Right: The binocular detector at Capo Granitola.

pyramidal box there were two co-located Photomultipliers PHILIPS PHOTONICS XP3462B collecting the light generated in the scintillator by charged particles.

In the presented configuration each PMT received, at the same time, approximately half of the light signal and thus the coincidence between the two PMT signals eliminated uncorrelated noise. In shower acquisitions, a larger dynamic range is needed, and one of the PMTs was set to a lower gain. The High Gain PMT was sensitive to low particle densities in the detector. It had a better response in time and was used to perform the trigger logic and to evaluate the difference in timing between the several stations. The Low Gain PMT was mainly used to estimate the number of particles in a station when the high gain PMT saturated. To enable their cross-calibration, the gain of the PMTs was set in such a way that their dynamic ranges overlapped.

The UVScope detector

The UVScope detected the UV light generated by an EAS and diffusely reflected on ground. The UVScope was a binocular instrument with two monocles mounted side by side overlooking the ETScope array. Each monocle, represented in figure 1.8(a), consisted of a lens and a PMT enclosed inside a metallic cylinder. The lens used was a Fresnel lens made of UV transmitting acrylic with a diameter of 457 mm and an effective focal length of 441.97 mm at $\lambda = 400$ nm. The photocathode of the PMT had a diameter of 68 mm and was placed at the centre of the focal plane defined by the lens. Considering the instrument geometry, its full field of view was estimated to be $\sim 9°$. Figure 1.8(b) is a photograph of the UVScope mounted on a telescope structure in Capo Granitola.

1.3 Gamma Air Watch - GAW

Gamma Air Watch [8, 6] – GAW – is a "path-finder" experiment to test the feasibility of a new generation of Imaging Atmospheric Cherenkov telescopes for the detection and measurement of the Cherenkov light produced by high-energy gamma rays traversing the Earth atmosphere. Traditional Imaging Atmospheric Cherenkov Telescopes (IACT) use large reflective optical systems associated with a PMT camera at the focal surface. These telescopes are designed to search for incoming γ-rays from a given source and have a small field of view (few degrees). Ground based detectors have high field of view and high duty cycle but low sensitivity. Such detectors need acquisitions of several months to detect the Crab Nebula.

GAW adds high flux sensitivity to a large field of view ($24° \times 24°$) capability. In traditional IACT designs the size of the camera necessary to have a large FOV would produce a very large obscuration on the mirror. To overcome this problem GAW uses an innovative approach based on a refractive optical system and a highly pixelated focal surface. In figure 1.9 a schematic view of the GAW telescopes is presented. The refractive optical system is composed by a custom-made 2.13 m diameter Fresnel lens with a focal length of 2.56 m. The lens is designed to have an uniform spatial resolution suitable to meet the Cherenkov imaging requirements up to 12° off-axis. The use of such a system makes it possible to overcome the obscuration problem as well as the optical aberration for large input angles.

The focal surface detector of each telescope consists of a grid of 40×40 Multi-Anode Photomultipliers Tubes (MAPMT). Each MAPMT has 64 anodes, arranged in an 8×8 matrix. The focal surface is operated in single photoelectron counting mode [5] instead of the charge integration method widely used in the IACT experiments. The total array of active channels, 102 400 for each telescope, will record the Cherenkov image as a binary image with high granularity, which is fundamental in order to minimise the probability of photoelectrons pile-up within intervals shorter than the sampling time of 10 ns. In such working mode, the effects of electronics noise and PMT gain differences are kept negligible, allowing the photo-

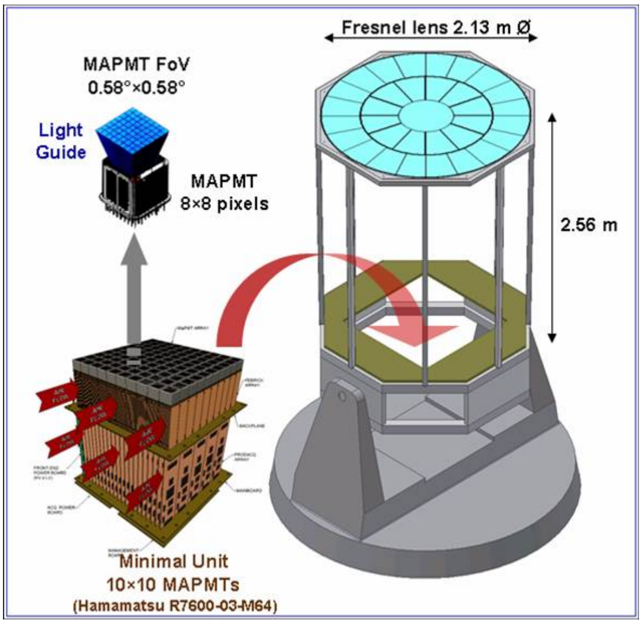


Figure 1.9: Schematic view of one GAW telescope.

electron trigger threshold to be lowered and, as a result, achieving a low telescope energy threshold in spite of the relatively small dimension of the GAW telescope light-collector.

The GAW electronics has been designed to fully match the specific requirements imposed by this new approach. GAW focal surface and acquisition system, including the triggering system are described in more detail in section **??**.

1.4 The Pierre Auger Observatory

The Pierre Auger Observatory is an instrument designed to measure Ultra High Energy Cosmic Rays providing high statistics at the far end of the CR spectrum. The Pierre Auger Observatory is a hybrid detector composed by a surface array and by a set of fluorescence detectors. A southern and a northern site are foreseen to attain full sky coverage.

The southern site is installed near Malargüe, a small town in the province of Mendoza, Argentina. The site, covering $\sim 3\,000\,\text{km}^2$, was completed in 2008 and it is the biggest cosmic ray detector ever built. The northern site is currently being designed and the corresponding proposal is being finalised. The site will be located in Colorado, USA, near the town of Lamar. It is currently foreseen that the detector will cover $\sim 20\,000\,\text{km}^2$. The first local activity will be the installation of a small surface array for R&D in 2009/2010.

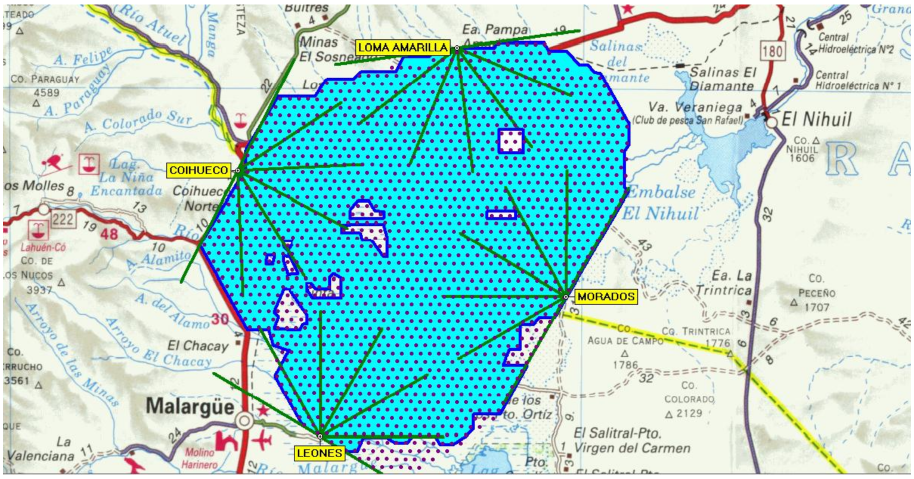
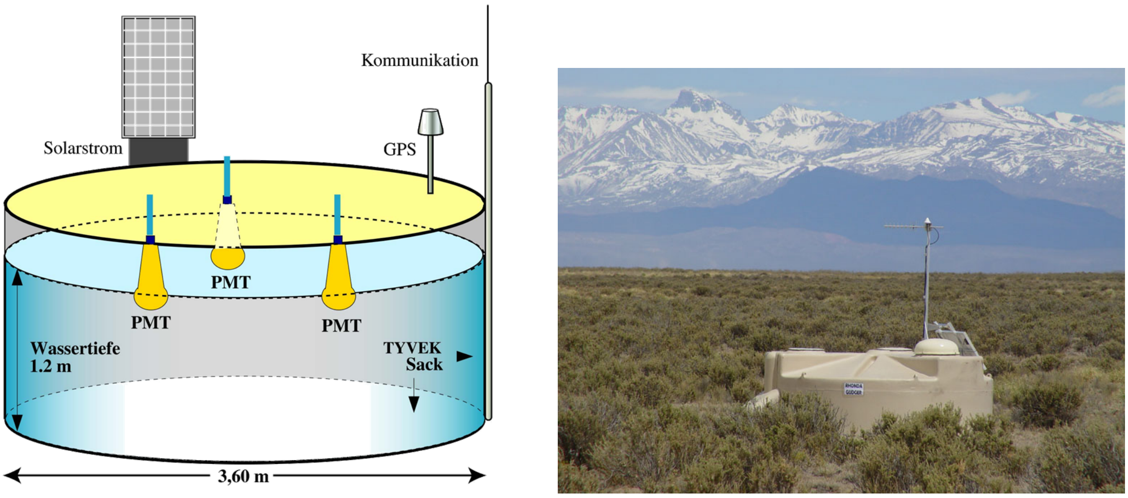


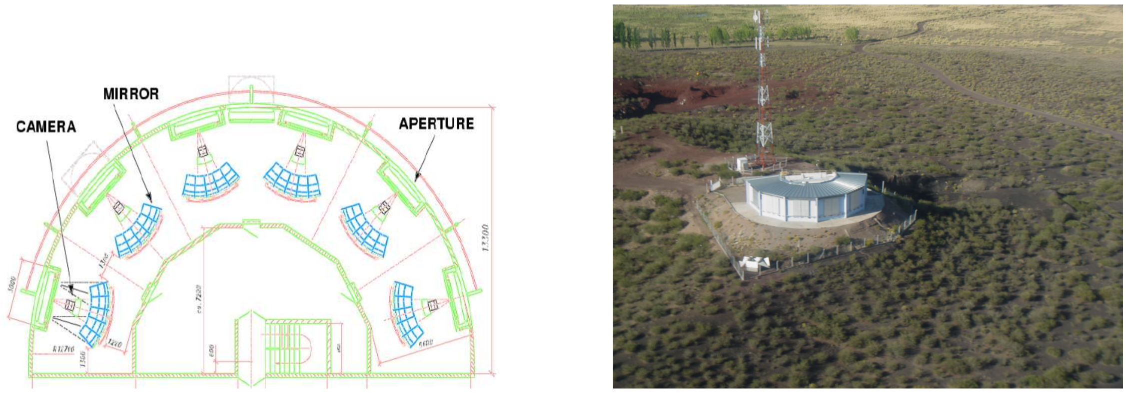
Figure 1.10: The Pierre Auger southern site status in June 11 2008



(a) (b)

Figure 1.11: Scheme and photograph of an Auger water tank

The status of the Auger South detector in 11 June 2008 is shown in figure 1.10 where the water tank layout, each marked by a dot, can be seen, as well as the four fluorescence eyes and the town of Malargüe. The surface detector is composed by $\sim$ 1600 water tanks. A scheme and a photograph of a surface detector water tank are presented in figure 1.11 . Each tank is a plastic container where an inner liner is installed and filled with purified water, in which Cherenkov light is generated by the relativistic shower particles. The liner is coated to diffusely reflect the light which will arrive at the three Photomultipliers placed on top and be processed by an FADC. Data are recorded and time-tagged with the help of a GPS. The data from each tank is transmitted to the nearest FD site and then to the Auger central campus installed in Malargüe. To minimise the bandwidth only information about



(a) (b)

Figure 1.12: Scheme and photograph of an Auger fluorescence eye

the time of the trigger is transmitted in the first step. Using this information, a central trigger decides if there is an interesting event and the involved stations are then requested to transmit the whole information recorded for that event.

The fluorescence detector is composed of four fluorescence eyes overlooking the SD array. Each fluorescence eye, shown in figure 1.12, is composed of six telescopes having a zenithal field of view of $\sim 30°$ and an azimuthal field of view of $180°$. Each telescope, figure 1.13, is composed by an entrance filter, a corrector lens, a spherical mirror and a PMT camera. A detailed description of the fluorescence telescopes is presented in chapter **??**.

The atmospheric conditions influence shower development, fluorescence light production and its propagation to the fluorescence telescopes. Therefore, Auger has a thorough program for atmospheric monitoring, the main atmospheric parameters being constantly monitored by weather stations. Regular launches of atmospheric balloons are also performed to record the dependence of the relevant atmospheric parameters with altitude. Several other apparatus are installed on site to monitor the atmosphere using light: the three main devices are the cloud cameras, the LIDARs and the Central Laser Facility.

The cloud cameras are infrared cameras installed on top of the fluorescence buildings enabling the verification of the cloud coverage for the fluorescence events. The clouds emit more infrared radiation than the cloudless sky, due to the relative temperature difference, appearing white in the cameras. Each camera is mounted on a steerable support and acquires images of small parts of the sky, which are joined, at every 15 minutes, to form an image of the whole sky. The cloud images are correlated to the field of view of each pixel in the fluorescence telescopes and a database is filled with cloud coverage information for each particular pixel.

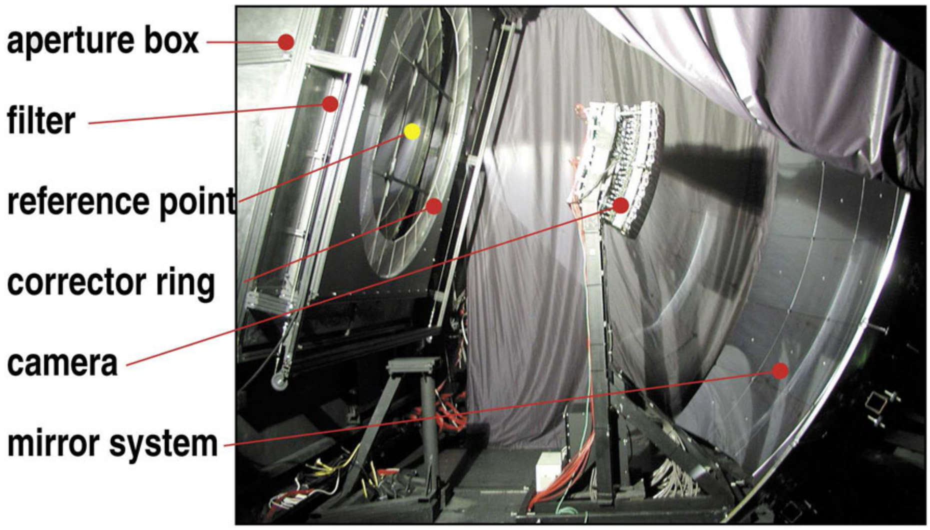


Figure 1.13: The Auger fluorescence telescopes

At the Auger southern site there are four LIDARs, one in each FD site, and a Raman LIDAR installed near "Los Leones" fluorescence detector. The LIDAR uses an UV laser to send short light pulses to the atmosphere which are then scattered. Part of this scattered light reaches the LIDAR station where it is collected using a parabolic mirror and focused into a PMT where it is recorded as a function of time. The LIDAR is mounted on a steerable structure to probe the whole sky. The data collected provide information on the Vertical Atmospheric Depth, aerosol scattering and absorption and can help in the characterisation of the cloud conditions of the sky. Namely, it can provide information on cloud coverage, height, depth and opacity of clouds. The Raman LIDAR is based on inelastic scattering of light and allows more detailed studies on the composition of the atmosphere to be performed. This technique requires a very intense light beam and is only used at twilight when the FD detectors are not operating.

The CLF, Central Laser Facility, is a laser emitter with an energy of 8 mJ placed in the middle of the array, equidistant from three fluorescence eyes ("Los Leones", Los Morados" and "Coihueco"). The laser propagates in the atmosphere suffering Rayleigh and Mie scattering. Some of the scattered light reaches the fluorescence telescopes. The laser energy is measured and it is set in such a way that the signal recorded in a telescope is similar to the signal emitted by an EAS with an energy $\sim 10^{20}$ eV. The CLF main application is the measurement of the attenuation of light in the atmosphere which depends on the atmospheric conditions. However, since the CLF provides a controllable source of light, the so-called laser data can also be used to perform studies of detector performance.

Two new detectors are currently being developed in the Auger southern site. The Auger enhancements are AMIGA that stands for Auger Muons and Infill for the Ground Array and HEAT - High Elevation Auger Telescopes. The AMIGA detector consists of a grid of water tanks - the infill - with half the separation used in the standard array and also of muon detectors be buried 3 m deep. Due to the infill, AMIGA will enable the study of cosmic rays of lower energy ($\sim 10^{17}$ eV) and will also allow to study in detail the muonic component of the showers using the information from buried scintillators. The HEAT enhancement will extend the field of view of the fluorescence detector in one eye ("Coihueco") up to $\sim 60°$.

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