The HAWC experiment at the Parque Nacional Pico de Orizaba

A feasibility study for the HAWC Collaboration

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Abstract

HAWC is a wide angle field of view γ-ray observatory requiring a high altitude site with the required infrastructure. We report on the feasibility to install HAWC in the Parque Nacional Pico de Orizaba. The Parque Nacional Pico de Orizaba, located at 19° latitude North, comprises the 5610 meter Citlaltepetl (Pico de Orizaba) and 4600 meter Tliltepetl (Sierra Negra), host of the Large Millimeter Telescope, together with a $\gtrsim 4000$ meter valley between the two volcanoes. We identified a suitable location for HAWC at 4100 meters where the high energy experiment can benefit of the infrastructure developed for the Large Millimeter Telescope. We also report on possible sources of water and the overall properties of this location.

Chapter 1

The HAWC experiment

HAWC, the High Altitude Water Cerenkov experiment, is a wide field of view monitor for very high energy astronomy. The principal scientific objectives of HAWC comprise mapping most of the celestial γ-ray emission, in particular that from the Galactic plane, and to serve as a monitor for flaring high energy sources, like blazars, gamma-ray bursts and even our Sun. In order to accomplish its science targets, HAWC has to meet design specifications which in turn impose tight constraints on its location. The main specifications to consider are

- the detector size
  HAWC is a water tank with a minimum of 150 × 150 meters instrumented area and 4 meters depth. The site must have a relatively flat area somewhat larger than these dimensions and the availability of up to 120,000 m^3 of water in a period not much longer than six months.

- Altitude
  HAWC will detect the Cerenkov radiation on water of secondary electrons ($e^{\pm}$) produced in electromagnetic and hadronic atmospheric cascades. Secondary photons produce $e^{\pm}$ pairs inside the water, which in turn produce Cerenkov emission. In order to maximize the number of secondary γ-rays and electrons for a given primary energy, HAWC needs to be located at the highest possible altitude. However, the installation and operation require human survival conditions. These two limits point to a site higher than 4000 meters above sea-level, with an upper limit of about 5000 meters.

- Building and facilities
  In order to detect the faint glow of Cerenkov radiation, the water

detector needs to be shielded from daylight, requiring a building or cover as large as the water tank itself. The cover or building has to withstand local weather conditions -wind, rain, snow, ultraviolet radiation- and at the same time allow access to any part of the pond for maintenance. The building also needs to comply with environmental impact restrictions.

  Apart from the shield itself, smaller in-situ constructions are required to host the water purification system, electronics and control computers. These should be located next to the water pond shield.

  Facilities at a lower altitude nearby location would be convenient. The complete HAWC project should include outreach activities reaching local communities.

- <u>Power and communications</u>
  HAWC will have 900 photomultipliers in continuous operation, including the related electronics and support equipment. The total power consumption is estimated to be below but close to 100 kW. Stable power is required to ensure the stable performance of the experiment.

Construction of HAWC should be feasible in approximately six months and at a cost of a few millions US dollars. The purpose of this report is to describe the conditions of the Parque Nacional Pico de Orizaba, in Central Mexico, identified as a potential location for HAWC and to quantify the feasibility of installing this unique experiment in the region.

Chapter 2

Science at the Parque Nacional Pico de Orizaba

2.1 Parque Nacional Pico de Orizaba

The Parque Nacional Pico de Orizaba is a Mexican national park containing the Citlaltepetl, or Pico de Orizaba, the highest Mexican mountain with an estimated altitude of 5685 meters above sea level[1]. Citlaltepetl, "the mountain of the stars" in Nahuatl language, is located in the boundary between the states of Puebla and Veracrúz, 106 km West of the Gulf of Mexico. The second prominent feature within the park is a 4600 meter volcano named Tliltepetl, or Volcán Sierra Negra, whose crater is at slightly less than 7 km distance of the Citlaltepetl crater. The young Citlaltepetl and the old Tliltepetl nowadays constitute a joint geological structure, with a convenient 4000 meter altitude where the HAWC experiment can be located, benefiting from the infrastructure developed in the region. Figure 2.1 shows the location and Google Earth view of the two mountains.

The Parque Nacional Pico de Orizaba was established by a presidential decree of December 16, 1936, signed by Lázaro Cárdenas. The decree names seven geographical points as the vertices of the polygon bounding the park (table 2.1). However, the boundaries of the park are defined approximately, with no exact geographical coordinate values. The value quoted for the area of the park in the website of the Comisión Nacional de Áreas Naturales Protegidas (CONANP - www.conanp.gob.mx) is 19,750 hectares. However, using the data of the Instituto Nacional de Estadística, Geografía e

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[1] there is some debate regarding its height. [1] quotes 5610 meter as a revised value. A significantly higher 5740 m is also frequently quoted.

Figure 2.1: Google Earth images of Mexico (*upper left*), Puebla (*upper right*) and Citlaltepetl (*lower*). For scale, the distance between Mexico City and Puebla is about 103 km. The cone of Citlaltepetl and its snow can be appreciated in the border between the states of Puebla and Veracrúz - inaccurately drawn, as it passes through the volcanic crater. The frame of the image of Citlaltepetl and Sierra Negra has a width of 37 km.

Vertex	Location	Long. Lat.	Ref
Cerro Río Valiente (Tlachichuca, Pue)			
	cerro Cuicatepec	19:09:52, 97:15:10	(2)
Potrero Nuevo (La Perla, Ver)			
	Potreto Nuevo	97:12:00, 19:02:15,	(1)
	(Rancho Nuevo)	97:12:13, 19:00:50	(2)
Cerro Palo Gacho (Calcahualco, Ver)			
	Palo Gacho	97:11:45, 19:06:37	(1)
	(map feature)	97:14:17, 18:59:18	(2)
Tepala o Piedras Blancas			
	(map feature)	97:17:06, 18:58:10	(2)
Texmalaquilla (Atzitzintla, Pue)			
	Texmalaquilla	97:17:14, 18:56:32	(1)
	(South of)	97:17:30, 18:55:32	(2)
Xepestepec (Puebla)			
	(pastorias Chipes?)	97:20:36, 19:00:34	(1)
	(map feature)	97:23:20, 18:59:16	(2)

Table 2.1: The 1936 presidential decree defines Parque Nacional Pico de Orizaba through the locations named here. Their coordinates were found from (1) the archivo histórico de localidades of the INEGI; or (2) INEGI printed map. Vertices measured in the mapa digital agree with (2).

Informática (INEGI - www.inegi.gob.mx), either through their Mapa Digital or in their printed topographic maps, we computed a value of 245 km^2. Both INEGI and the park authorities confirmed the official figure of 197.5 km^2, pointing to inaccuracies in the printed and server maps -which should then be considered as indicative, only. When contacted, the responsible of the park, Héctor Rojas, quoted a value of 19,601 hectares, acknowledging this as a provisional figure, pending on an official GPS definition of the park vertices. He provided us with an "official map", which defines the park through only four vertices (figure 2.2). The park, as many in Mexico, does not have a management plan, which will establish the use of the park and its precise GPS measurements of its vertices. The drafting of management plans for nationals parks in Mexico has been ongoing for the last years.

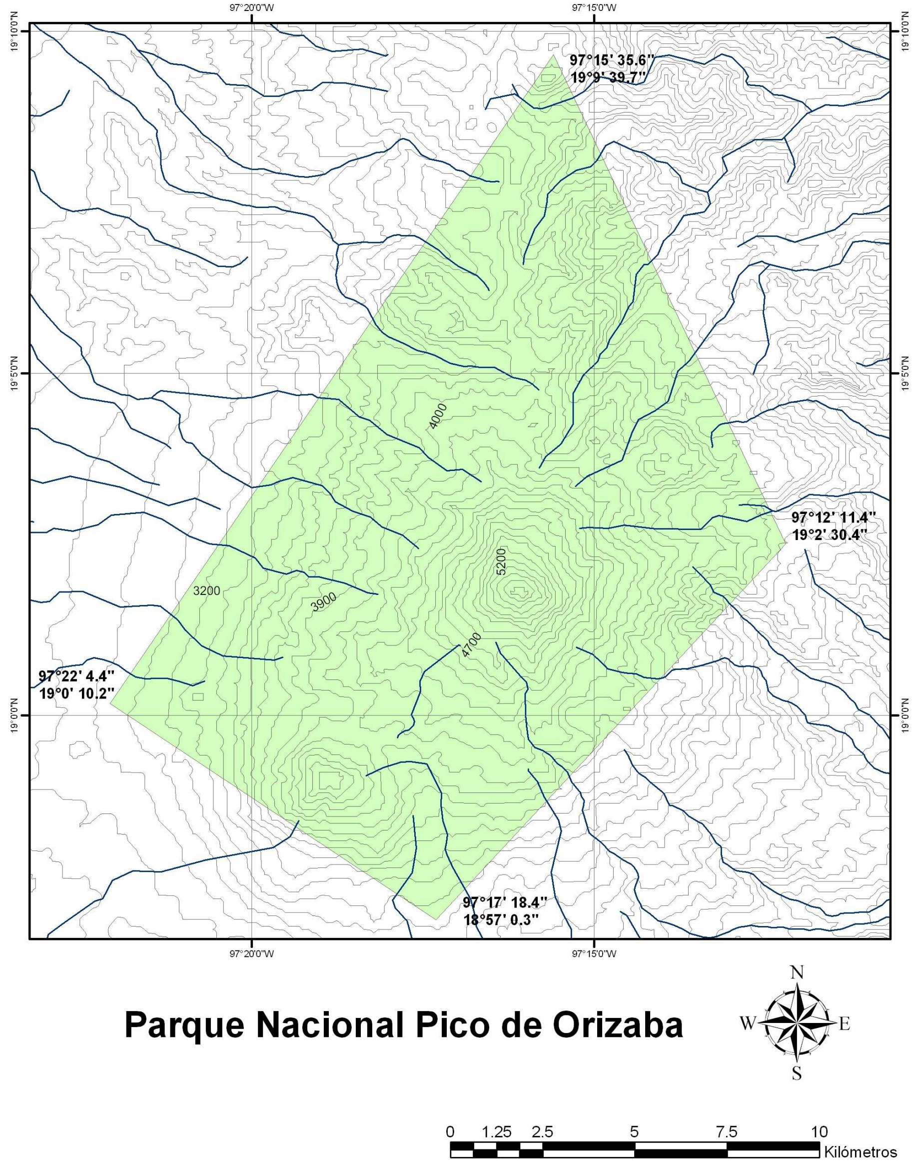


Figure 2.2: Official boundaries of Parque Nacional Pico de Orizaba, as provided by the responsible of the park, Hector Rojas. Note that in this map the park is defined through four, rather than seven, vertices. The location for HAWC identified in this report is inside the park.

2.2 Citlaltepetl and Tliltepetl

2.2.1 Geology

Citlaltepetl, officially named Pico de Orizaba, is the highest mountain in Mexico and the third in altitude in the North American sub-continent. The 100th anniversary volume of the bulletin of the Mexican Geological Society contains a review of the geology and eruptive history of some of the most important Mexican volcanoes, including Pico de Orizaba [2]. A more specific recent work on the geology of Citlaltepetl is contained in the thesis of Andrea Rossotti [3]. Pico de Orizaba is the main peak in the volcanic chain going from Cofre de Perote to Las Cumbres, Pico de Orizaba and Sierra Negra. This chain is part of the Faja Volcánica Transmexicana, a series of volcanic chains in the 2 km high plateau of central Mexico, which itself covers a sizeable fraction of the Mexican territory and population of the country. Citlaltepetl stands some 3 km above this plateau, and over 4 km relative to

Figure 2.3: Aerial view of Citlaltepetl and Tliltepetl. The saddle between both mountains clearly shows above the inversion layer.

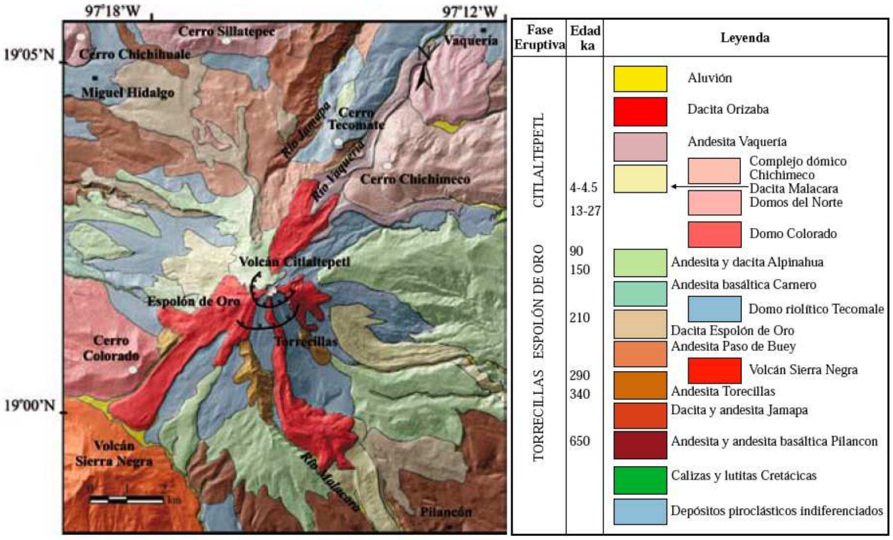


Figure 2.4: Geological map of Citlaltepetl from [2]. The lava tongue descending from Pico de Orizaba towards Sierra Negra, with a deposition of alluvions at its base, is the most noticeable red feature.

the Eastern low lands of Veracrúz.

Citlaltepetl has a complex eruptive history dating back to the formation of the cone of Torrecillas, 650,000 years ago. The present Pico de Orizaba volcano formed about 16,500 years ago inside a previous structure known as Espolón de Oro. Figure 2.4 shows the different structures and their epochs of formation. According to [4] Sierra Negra is an older structure formed through two episodes of activity, the first 600,000 years ago and the second, named the "Orizaba episode", some 240,000 years ago.

Three major explosive events occurring 4,100 years ago are related to the destruction of a mountain dome and the formation of the present crater, formed by a symmetric oval crater of 500m × 400m [2]. An impressive "lava tongue" (labeled "dacita Orizaba" in figure 2.4) spanning 4 km SW in the direction of Sierra Negra is the result of a more recent episode of activity dated 1566. Most recent minor activity episodes occurred in the XVI century, although minor activity has been reported from time to time and the volcano is now considered as active in a period of quietness (table 2.2). Nowadays Citlaltepetl presents weak SO_2 exhalations and low level tremors. Seismological monitoring is performed by station of the CENAPRED (Cen-

Dates	Type of activity	Primary reference
1533-1539	possible series of minor eruptions and exhalations	Códice Teller von Humboldt (1810)
1545	Major eruption	Sahagún (1950-1969)
1559	Eruption	Yarza (1971)
1566	Eruption and prominent lava flow	Böse (1899)
1569-1589	continuous minor eruptions	Sartorius (1961)
1613	Eruption	Böse (1899)
1687	Eruption	Ordoñez (1894)
1846	Eruption	Heller (1853)
1850-1851	Tremors, noise and exhalations	Sartorius (1961)
1864,1866	Tremors, noise and exhalations	Camacho (1922) Sartorius (1966)
1895	Eruption	Revue Cientifique (1895)
1920	Tremors, mud flows	Camacho (1922)
1921	Noise	Friedlaender (1930)
1937	Tremors and ”fire”	Marden (1940)
present	minor fumes, sulfur smell	Rossotti (2005)

Table 2.2: Reported activity of Citlaltepetl in the last 500 years as given and referenced in [3].

tro Nacional de Prevención de Desastres), run by Instituto de Geofísica UNAM, and more recently also by the FI-BUAP seismological station, part of Consorcio Sierra Negra, taking data since late 2006. Estimates of volcanic hazards around active volcanoes in Mexico are represented in ”volcanic hazard maps” [5], which locate the region for HAWC in the edge of zone A, the one with higher risk. This zone can be affected by incandescent flows with a recurrence time of 2000 years; it can also be affected to a lesser extend by minor eruptions with a recurrence of 80 years. More information can also be found in [6, 3].

The valley between Pico de Orizaba and Sierra Negra was formed by the deposition of pyroclastic material composed of sands, ashes, pumices and unconsolidated volcanic trenches. Alluvion deposits are present at 4000 m between the ”lava tongue” and the base of Sierra Negra (fig. 2.4). Basic stratigraphic profiles and compositions are given in [7]. In general the upper first meter or so of ground has a mixture of sand, ashes and small rocks (fig. 2.4). The structure underneath is still permeable until reaching several tens of meters, as described in section §3.3.1.

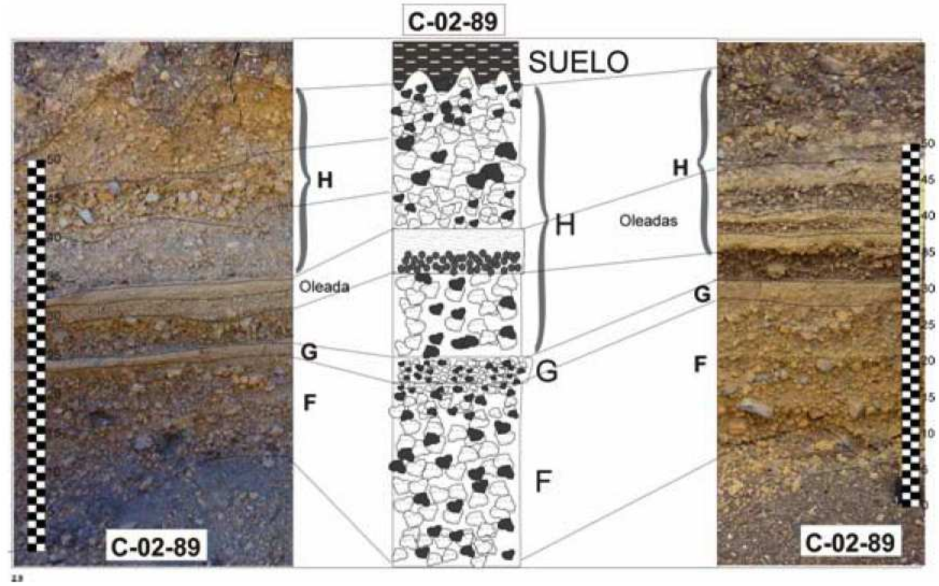


Figure 2.5: Stratigraphic profiles in the Citlaltepetl area. The scale shown with black and white squares indicates 0.5 m in depth. From Rossotti's thesis [3].

2.2.2 Glaciers

The Gran Glaciar Norte, or glaciar de Jamapa, found in the high part of the Northern slope of Citlaltepetl is, with an area of 9 km^2, the largest in Mexico. A relatively recent review of glaciers in Mexico quotes the equilibrium line for the glaciers at Pico de Orizaba as unknown, while those of Popocatepetl and Iztaccihuatl are situated at 4880 m and 4925 m respectively [1]. Most of the Pico de Orizaba glacier is located in the Northern slope, where it is less exposed to direct sunlight. The glacier has a small extension running South, known as Glaciar Suroccidental. This glacier extension departs from the main ice structure at 5250 m, descends on the *Western* side of the lava tongue with a gradient of 200 m/km, to extend down for 1.6 kilometers before ending smoothly at an altitude of 4930 meters [1]. Most of the glacier demelting must run under this slope, close to the HAWC location, but does not seem to be accessible for HAWC. There is firm evidence for the retreat of the Citlaltepetl glacier, driven basically by climate change [8, 9, 10]. Reports from a geoscientist studying the Jamapa glacier for many years

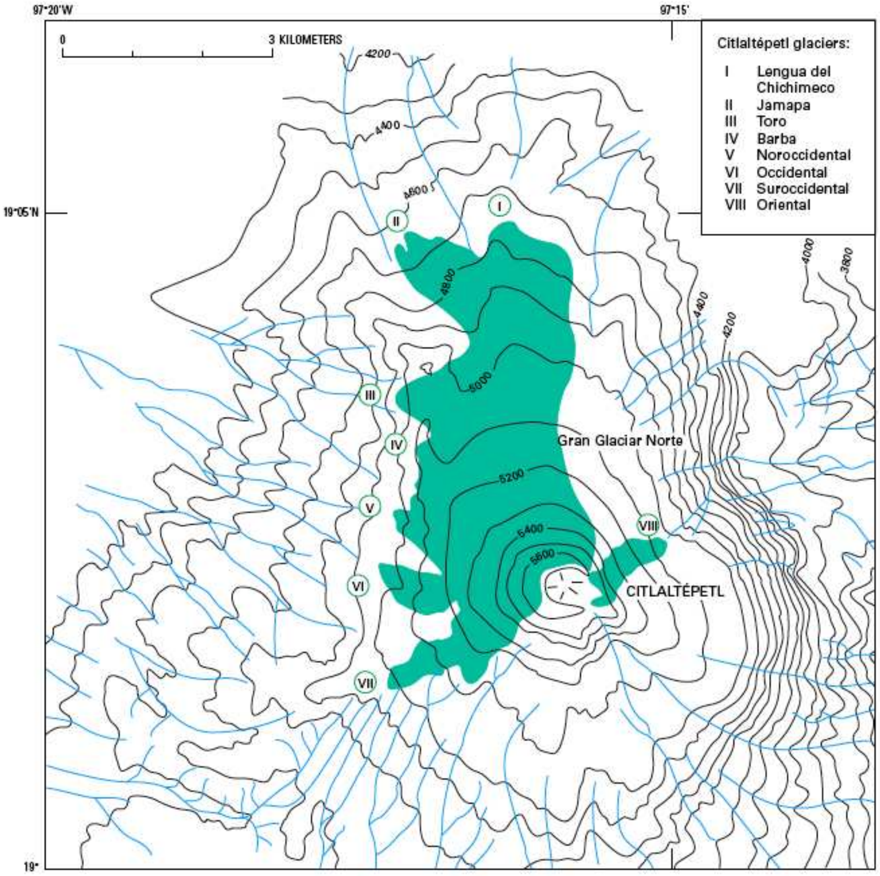


Figure 2.6: The glaciers of Citlaltepetl, shown in green in this map from [1]. The Jamapa Northern glacier is the dominant underlying structure. The SW glacier, marked VII, is the most Southern extension of the Jamapa glacier. The whole glacier structure of Citlaltepetl has been declining such that the SW extension has most probably disappeared by now.

in situ suggest that its shrinkage is likely to be proceeding faster than the worldwide average recession speed for glaciers of 1.5 m/year [11, 12]. This might be particularly true for the smaller glacier extensions.

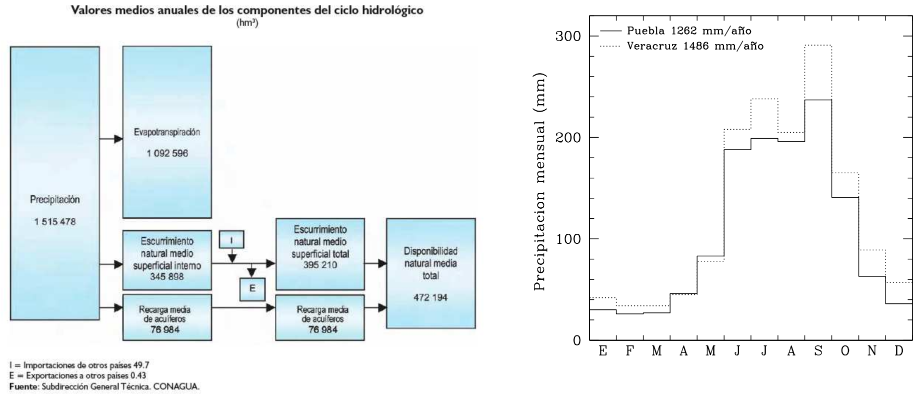
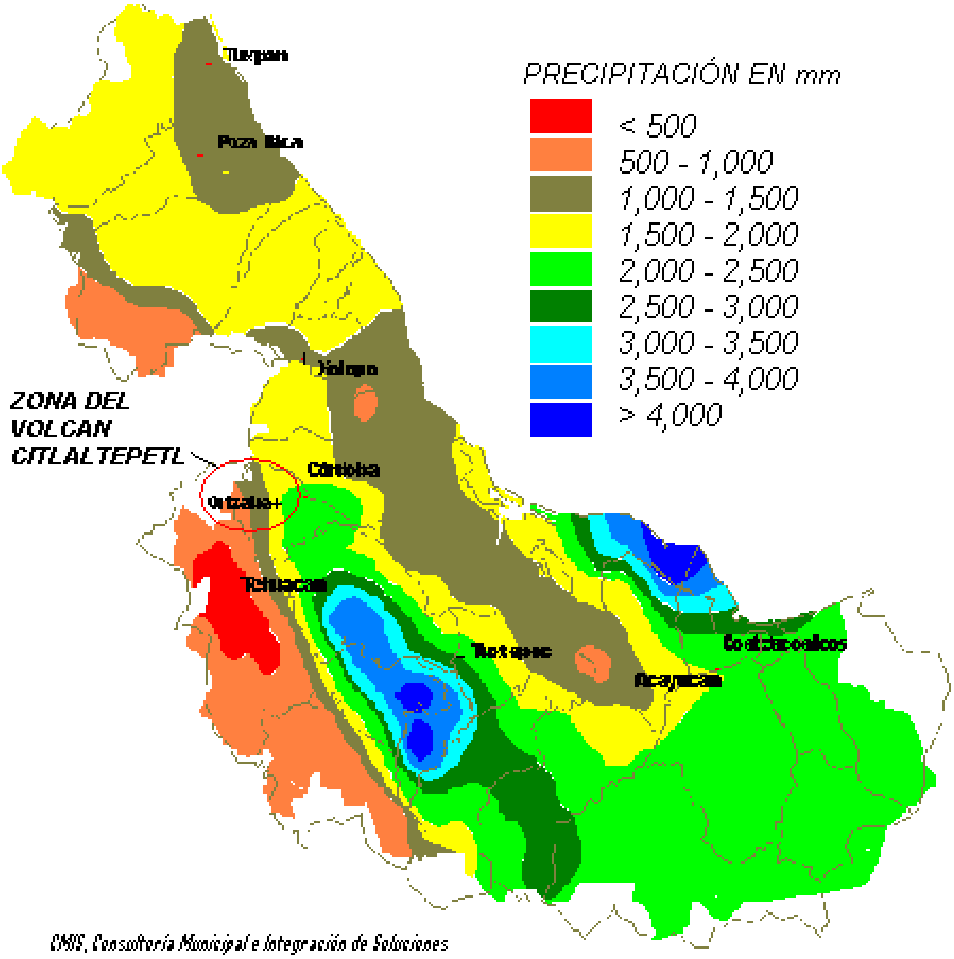


Figure 2.7: *Left:* hydrological cycle of all water precipitation in Mexico, according to the CONAGUA report for 2006. *Right:* monthly modulation of the precipitation in Puebla and Veracrúz. Most of the rain comes in the summer, between May and October.

2.2.3 Hydrology

The Comisión Nacional del Agua, CONAGUA (www.conagua.gob.mx), divides Mexico in about a dozen hydrological regions, with the Parque Nacional Pico de Orizaba located inside the hydrologic region X, "Golfo Centro". This region is further subdivided in six sub-regions, of which Córdoba and Tehuacán are of interest to us. The water precipitation in the region is between 800 and 1000 mm/year, somewhat below the average for the state of Puebla (figure 2.8). According to the hydrological cycle reported by CONAGUA, about 72% of the precipitation returns to the atmosphere as evapotranspiration (fig. 2.7 and ref. [13]). The region is well ranked in terms of "water availability", with a mean availability per capita of 10,932 m^3/person/year and 5% pressure on the demand [13]. According to these numbers, the water required for HAWC is just above the amount available for 10 persons-year in the region.

The precipitation in the area is influenced by the Gulf of Mexico, which introduces a strong summer - winter modulation. The six month period between May and October accounts for 83% of the precipitation (fig. 2.7). The precipitation received by the Parque Nacional Pico de Orizaba gives birth to minor rivers and flows of water which converge to the Papaloapan river, reaching the sea in the Gulf of Mexico, within the state of Veracrúz. Two minor rivers, named Encino and Malacara, are born on the Southern



CMIS, Consultoría Municipal e Integración de Soluciones

Figure 2.8: Precipitation regimes of the state of Veracrúz. The zone of Citlaltepetl, marked by the red circle, corresponds to the transition region between the high altitude dry Western and the low altitude wetter East. The precipitation figure for the Parque Nacional Pico de Orizaba is about 1000 mm/year.

slope of Citlaltepetl and correspond with underground flows of water and precipitation in convergent geological structures which are considered for the water acquisition system of HAWC.

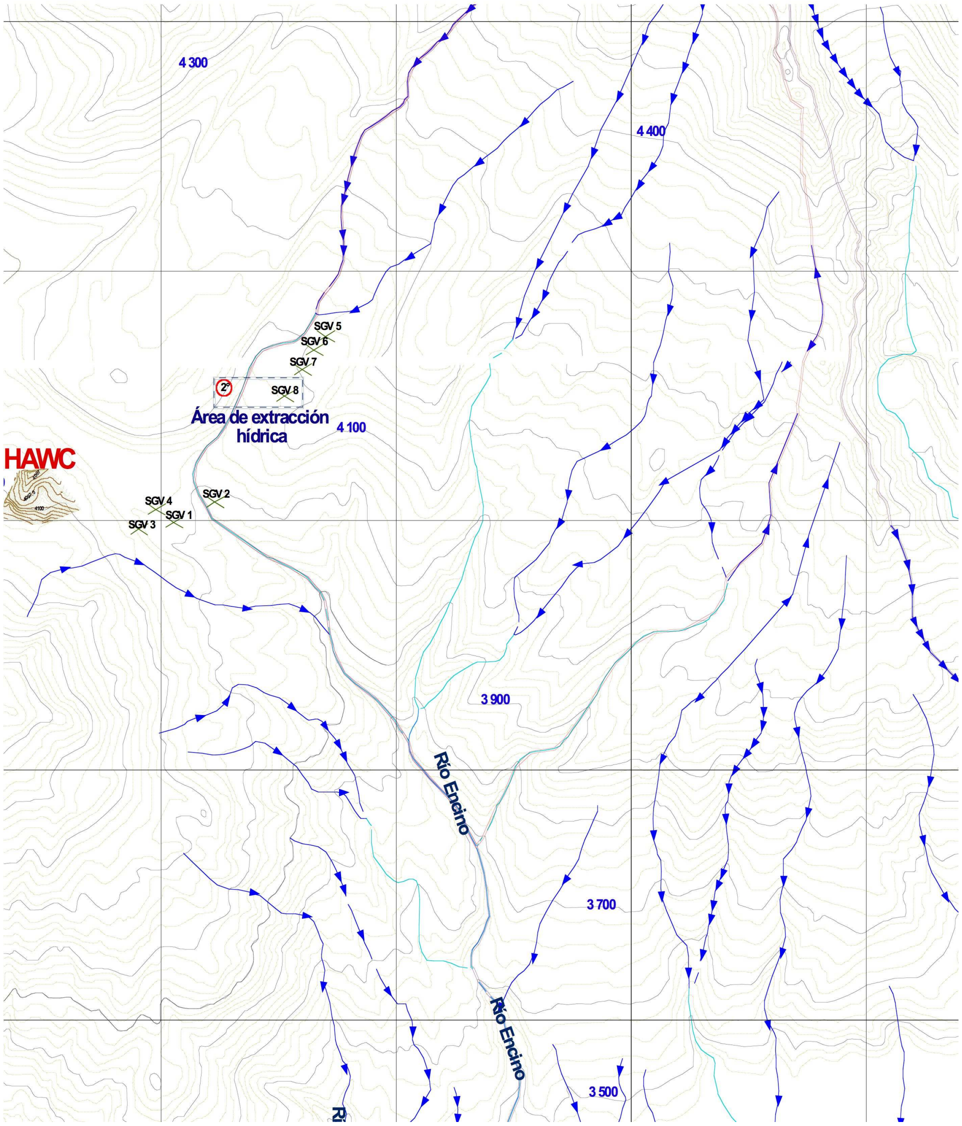


Figure 2.9: Water currents in the region of Citlaltepetl and Tliltepetl. Rivers Encino and Malacara are born at our acquisition points. Encino is marked in the map while Malacara is not shown but runs down East of this map.

2.3 Weather conditions at Sierra Negra

A basic Davis weather station, model Wireless Weather Monitor II, has been operating for over six years some 500 meter NE from the LMT site, close to the HAWC location. A first weather report with almost two years of data was presented in [14], with an updated more complete analysis in preparation [15]. Preliminary analysis of the weather data taken at the top of Sierra Negra from late October 2000 to early February 2007 is summarized in table 2.3. The cumulative histograms are shown in figure 2.10. The first thing to note is that temperature, wind speed and atmospheric pressure at the site do not have large variations. The respective interquartile ranges $q_3 - q_1$ are 2.7°C for temperature, 3.6 m/s for wind speed and 0.8 mbar for atmospheric pressure. The humidity at the summit has the strongest winter to summer variations, together with a less marked night/day contrast. This is better illustrated in figure 2.11.

Extreme temperatures[2] at the summit are -10.6°C and $+9.9$°C; extreme wind speed is 36.2 m/s, corresponding to a five hour interval of winds above 30 m/s on 22/2/2002. We note some coincidence of high winds with hurricanes, but that high winds can occur at any time.

The pressure and temperature at the summit fit a standard atmosphere, defined mainly by a constant temperature gradient $\theta = 6.5$ K/km. The solution of the standard atmosphere is

$$T(z) = T_0 - \theta z, \quad P(z) = P_0(1-\theta z/T_0)^{\alpha}, \quad \rho(z) = \rho_0(1-\theta z/T_0)^{\alpha-1}, \tag{2.1}$$

with $\mu = 28.9644$ the mean molecular weight of the standard atmosphere, $\alpha = \mu m_H g/k\theta \approx 5.256$, and $P_0 = 1013.25$ mbar. The reference temperature T_0 is latitude dependent and can be retrieved from the measurement $T(4.58 \text{ km}) = 1.1^\circ\text{C} = 274.25\,\text{K}$, giving $T_0 = 30.9^\circ\text{C} = 304\,\text{K}$. Using this value for T_0 the predicted pressure at the top of the mountain is $P(4.58 \text{ km}) = 589.7$ mbar, in close to perfect agreement with the measurement of 590.1 mbar. Substituting for 4100 m, the proposed altitude of HAWC, we obtain

$$T(4.1\text{km}) = 4.2^\circ\text{C},\ \rho(4.1\,\text{km}) = 0.786\times 10^{-3}\,\text{g}\,\text{cm}^{-3},\ \text{P}(4.1\,\text{km}) = 625.6\ \text{mbar}\,.$$

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[2] the data has a temperature record of $+11.8^\circ C$ which appears spurious. The same applies to a single datum of wind at 55 m/s.

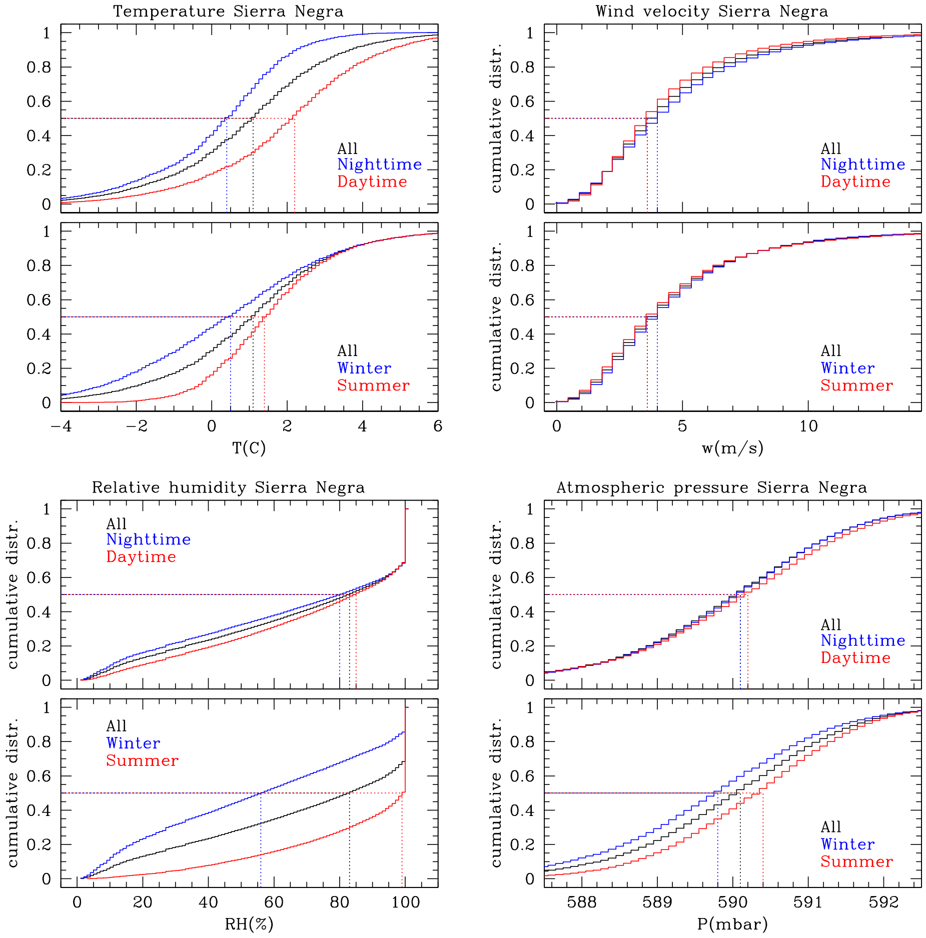


Figure 2.10: Temperature, wind speed and pressure histograms at Sierra Negra. Note the narrow range in the temperature scale and that the distribution of the wind is independent of night, day, summer and winter.

Parameter	Statistic						
Sample	coverage (min)	duty (%)	min	max	q_1	q_2	q_3
Temperature (°C)							
All	2355071	71.43	–10.6	9.9	–0.3	1.1	2.4
Day (8am-6pm)	980813	71.39	–10.4	9.9	0.8	2.2	3.4
Night (8pm-6am)	980777	71.39	–10.2	6.7	–0.8	0.4	1.4
Summer (May-Oct)	1153934	72.52	–4.5	9.8	0.5	1.4	2.6
Winter (Nov-Apr)	1201130	70.39	–10.6	9.9	–1.3	0.5	2.2
Wind speed (m/s)							
All$^{(1)}$	2257986	68.48	0.0	36.2	2.2	3.6	5.8
Day	947966	69.00	0.0	35.8	2.2	3.6	5.4
Night	934365	68.01	0.0	34.4	2.2	4.0	6.2
Summer$^{(1)}$	1106527	69.54	0.0	27.8	2.2	3.6	5.8
Winter	1151459	67.48	0.0	36.2	2.2	4.0	5.8
Relative Humidity (%)							
All	2355071	(*)	1	100	43	83	100
Day	980813	(*)	1	100	50	85	100
Night	980784	(*)	1	100	36	80	100
Summer	1153941	(*)	3	100	76	99	100
Winter	1201130	(*)	1	100	22	56	90
Atmospheric pressure (mbar)							
All	2355071	(*)	567.3	603.3	589.2	590.1	591.0
Day	980813	(*)	575.6	598.0	589.2	590.2	591.1
Night	980784	(*)	567.3	599.9	589.2	590.1	591.0
Summer	1153941	(*)	567.3	597.7	589.5	590.4	591.2
Winter	1201130	(*)	575.3	603.3	588.9	589.8	590.7

Table 2.3: Data coverage and statistics. (*) relative humidity and atmospheric pressure have same coverage as the temperature. (1) a wind record of 55 m/s on 20/6/2001 is not considered as the maximum wind.

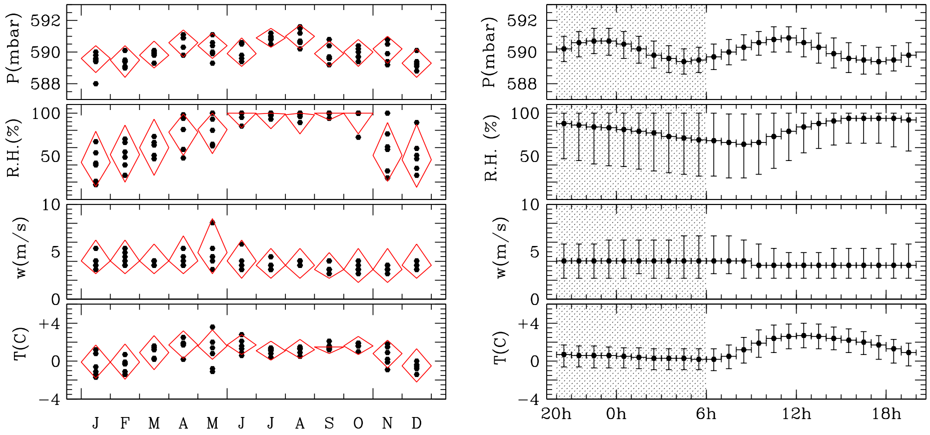


Figure 2.11: *Left:* Monthly statistics of temperature, pressure, humidity and wind. Dots denote quartiles for each of the six years sampled, while diamonds indicate the overall median and lower and upper quartiles. *Right:* hourly statistics of the same quantities, with errorbars going from lower to upper quartiles and using the same vertical scale as in *left*. The shaded zone denotes nighttime.

2.4 The Large Millimeter Telescope

The interest for installing HAWC in the Parque Nacional Pico de Orizaba arose from the development of the Large Millimeter Telescope (LMT). The LMT, shown in figure 2.12, is a 50 meter antenna for astronomical research at wavelengths between 0.8 and 3 mm, built by the INAOE and the University of Massachusetts at Amherst (Umass) after more than ten years of join effort. The project leader is Alfonso Serrano (INAOE) and Peter Schloerb is responsible for UMass. The scientific case of the LMT is the formation of all types of structures in the Universe: planets, stars and galaxies; or even dust grains and the Universe itself. As the largest single dish in the mm-regime it will be an ideal instrument for multiwavelength astronomy. The LMT project and scientific case are summarized in [16]. The LMT, close to enter its commissioning phase, will be a world class astronomical facility and the most powerful tool for Mexican astronomers. The total cost of the telescope is around 110 million USD, making it the most ambitious scientific project in the history of Mexican science.

The LMT is located at the summit of Tliltepetl (volcán Sierra Negra),

Figure 2.12: The Large Millimeter Telescope on inauguration day, Wednesday 22nd of November 2006.

with geographical coordinates $18^\circ 59' 09"$ N; $97^\circ 18' 53"$W, and an elevation of 4580 meters above sea level. The site was chosen in February 1997 based on a monitoring program of the atmospheric content of water vapor in two dozens of Mexican mountains. Tliltepetl was the highest site monitored and altitude showed to be a more relevant factor than latitude for low water vapor atmospheric content, even thought the closeness to the Gulf of Mexico makes the weather more season dependent. Further factors favoring Sierra Negra in the final decision were the good visibility of the Galactic Center and the relative proximity to INAOE. Construction began in 1999, after detailed studies to determine the soil properties. INAOE and UMass have worked together in the development of the LMT and Sierra Negra site infrastructure, including

- the road to the Sierra Negra summit was built by the LMT project (fig. 2.13). The road between Atzitzintla and Texmalaquilla was upgraded by State and Federal Governments as a result of the project, and the road from Texmalaquilla to the saddle has been upgraded mostly by INAOE.

- Electric power installation, including new posts from Texmalaquilla along most of the road, an underground installation for the last 850m and a power station at the top of the mountain. The peak consumption of LMT is of the order of one megawatt.

- An optical fiber connection to internet, which runs in the same posts and conduits as the electricity. Internet was made available for the first time for the Presidential inauguration on November 2006.

- INAOE maintains a temporary base in Atzitzintla. The LMT commissioning and operation plans foresee setting up a larger formal basecamp in the region of Atzitzintla, a task now overdue.

- INAOE has an outreach space, of about 10 m^2, at Casa Magnolia in Ciudad Serdán. Although this is presently the only permanent outreach space in the region, INAOE has participated in several outreach activities in Ciudad Serdán, Atzitzintla and Texmalaquilla.

The installation of LMT required a successful environmental impact declaration, which resulted in the assignment of the top 10.5 hectares of the mountain to INAOE. As a result INAOE can install scientific experiments in that zone without requiring only a formal notification to SEMARNAT.

Figure 2.13: The LMT access road to the Sierra Negra summit. White boxes at the access points to the underground electric line are noticeable.

2.5 The Consorcio Sierra Negra

The Consorcio Sierra Negra is formed by all scientific experiments in the area with the aim of the proper joint operation of such multi-experiment high altitude site. The experiments considered are:

- the Large Millimeter Telescope, already described above.
- RT5, a 5m radiotelescope for solar and interstellar medium studies. This is a collaboration between INAOE (responsible Eduardo Mendoza), the Instituto de Geofísica UNAM (through Alejandro Lara) and the Instituto de Astronomía of UNAM (David Hiriart).
- the Detector de Neutrones Solares (DNS) is an international collaboration with the active participation of the Instituto de Geofísica of UNAM, leaded by José Valdés Galicia. DNS has been operational since 2005 and in September 2006 detected an important solar event [17].
- the Detector de Antineutrones Cósmicos (DAC) is an experiment aimed at detecting antineutrons in cosmic-ray cascades, leaded by Arturo Menchaca of the Instituto de Física of UNAM.
- the Facultad de Ciencias Físico Matemáticas of the Benemérita Universidad Autónoma de Puebla (BUAP) runs a cosmic ray array close to the top of Sierra Negra, formed by small water Cerenkov tanks and a fluorescence detector in construction. The responsible for this experiment is Humberto Salazar.

- the Facultad de Ingeniería of BUAP has recently installed a small seismologic station to monitor the activity of Citlaltepetl (responsible Rogelio Ramos).
- more recently the Climate Institute, represented by Luis Roberto Acosta, approached INAOE to seek the installation of a global warming monitor at Tliltepetl aimed at measuring abundances of greenhouse gases at the site. The installation of this experiment is pending on signing the due agreement.

Aside from these experiments, INAOE has conducted site monitoring programs, including one weather station working without significant interruption since 2000, and an optical seeing study reported in the literature [15, 18]. If HAWC is installed in the Parque Nacional Pico de Orizaba it would not only become a very important partner of the Consorcio Sierra Negra, almost certainly the next after the LMT, while benefiting of coordinated logistic and scientific operation with the other experiments.

Chapter 3

HAWC at the Parque Nacional Pico de Orizaba

3.1 The site

3.1.1 The location for HAWC

HAWC is a detector with $150 \times 150\,\mathrm{m}^2$ instrumented area. Its location requires a fairly flat extension, more like $180 \times 180\,\mathrm{m}^2$ to install the experiment and related infrastructure. Such a flat area at an altitude above 4000 meters constitutes a severe constraint for the site selection. Should HAWC be installed in the Parque Nacional Pico de Orizaba it would benefit not only of the infrastructure effort already made by INAOE for LMT, but also of strategic astronomical properties of the site, namely the visibility of important astronomical objects, like the Crab nebula, the prime γ-ray calibrating source at TeV energies, and the Galactic plane, one of the most interesting objects to survey in the near future.

As mentioned before, the region between the two volcanoes, Pico de Orizaba and Sierra Negra, of approximate coordinates $97^\circ 18'\,\mathrm{W}\, 19^\circ 00'\,\mathrm{N}$, provides the most attractive locations for HAWC. Four possible locations for HAWC have been considered, with the one denoted as "spot A" judged to be the most appropriate because of its relatively easy access, closeness to the LMT road and electricity line, and possibility for expansion. The location of the proposed site is shown in figure 3.1 and a topographic survey of the region is displayed in figure 3.2. The surveyed area covers $251 \times 257\,\mathrm{m}^2$, tilted 22.1° with respect to the NS axis. The mean height of the survey data is 4099 meters with a standard deviation of 6.3 m. The standard de-

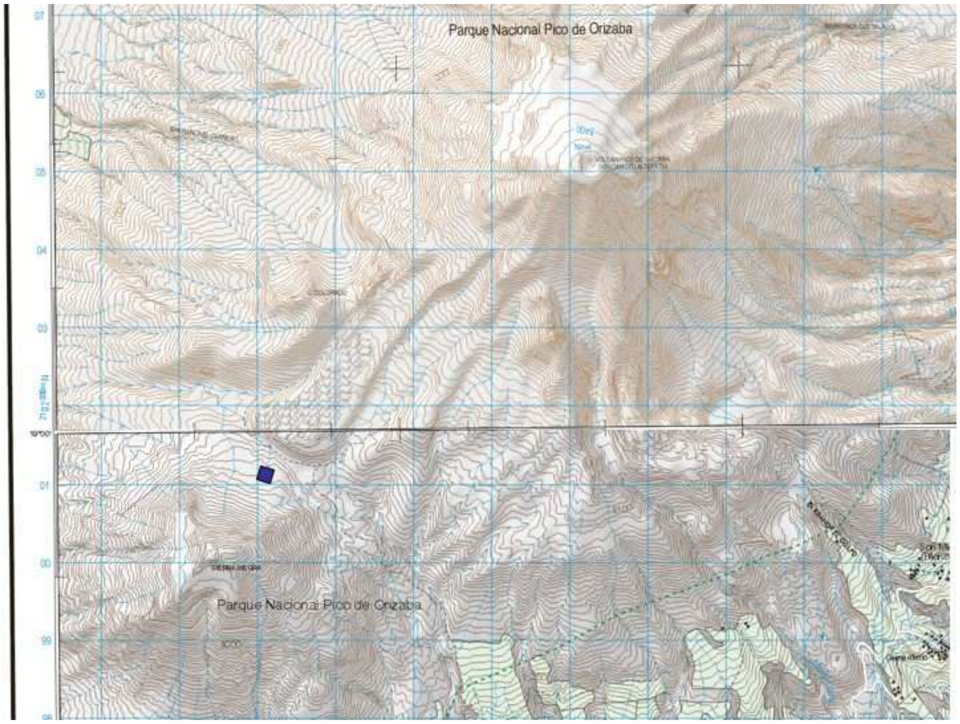


Figure 3.1: Zoom of the INEGI maps between Sierra Negra and Pico de Orizaba. The blue grid has 1 km spacing and marks integer km of UTM coordinates. The small blue square corresponds to the location and dimensions of HAWC, 170 m per side, which we have located with coordinates measured *in situ* rather than with those given in the survey (fig. 3.2). The line between the two maps joined correspond to the parallel of latitude 19°N. Elevation contours are every 20 m.

viation accounts for a slope of 4.8° and an intrinsic dispersion of 2.9 m with respect to the tilted plane. The center of the topographic surveyed area has nominal UTM coordinates $\{x_{utm} = 678144,\ y_{utm} = 2100900\} \rightarrow \{97^\circ 18' 27.7''\,\mathrm{W},\ 18^\circ 59' 34.5''\,\mathrm{N}\}$. A zoom on the nominal location is show in figure 3.2-*left*. We note an inconsistency between the survey coordinates, the INEGI map and GPS measurements made *in situ* on 13-dic-2006. The measured points corresponded to "flat areas" with coordinates $\{678202, 2101116\}$, $\{678112, 2101126\}$ and $\{677795, 2101160\}$, and shown in figure 3.2-*left*. Their locations make us believe that the survey data as an offset $\Delta y \simeq 200\,\mathrm{m}$. Note in figure 3.2 the band spanning close to 1 km West

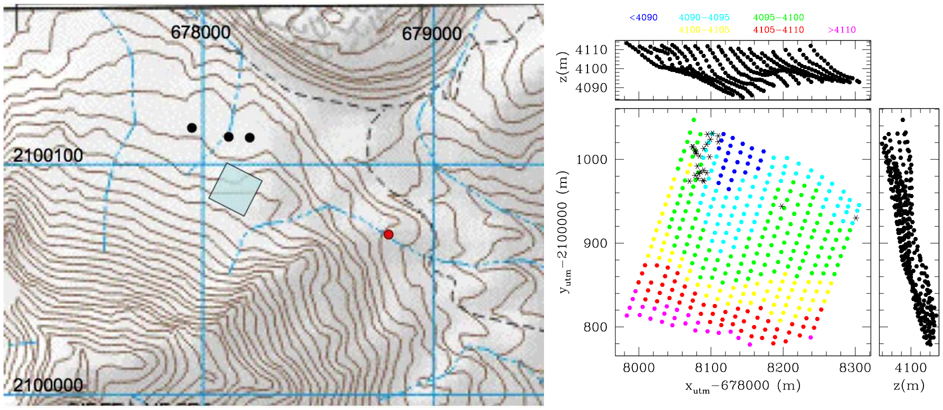


Figure 3.2: *Left:* nominal location of the surveyed zone in the INEGI map, indicated by the blue square. The black circles mark GPS measurements made *in situ* while the red circle -most eastwards- shows the position of the last electricity post and nearest access to the LMT road. *Right:* xy, xz and zy profiles of the survey data. Blue is the lowest z, magenta is the highest. Stars denote the positions of trees. The nominal center is at UTM coordinates (678144, 2100900), which we believe to be offset $\sim$ 200 m South.

from the surveyed. The experiment could be located anywhere in this band and might be expanded in the future.

Of the other three locations surveyed the one labeled "spot B" can be considered a backup. The other two, labeled 1 and 2, have been already discarded. We describe them for completeness:

- spot B (97:16:46, 19:00:12 @ 4320m) is next to half a dozen water tanks which will form the BUAP air shower array. This zone corresponds to pyroclastic deposits, according to fig. 2.4. Spot B is 220 meters higher than spot A, which for the standard atmosphere model gives $T(4.32\,\mathrm{km}) = 2.7°\mathrm{C}$ and $P(4.32\,\mathrm{km}) = 608.8$ mbar, or a grammage 16.8 g/cm^2 (0.45 radiation lengths) lower than at spot A. It is closer to the location of a potentially important water supply point. Its main disadvantage compared to spot A is the larger distance to the electricity/internet connection (3 km approximately) and the need to improve the last 2 km or 2.5 km of the access road, impacting the experiment installation cost.

- spot 1 (97:18:10, 18:59:42 @ 4030m) is the alluvion deposit close to where the road divides between the accesses to Citlaltepetl and to

Figure 3.3: *Left:* Spot A photographed from the LMT site, 400 meter above. The upper feature is the lava tongue, followed South by the alluvion, just visible, and the base of Sierra Negra, with the flat region where HAWC can be located. *Right:* view from the site showing the vegetation.

Sierra Negra, next to a zone where mountaineer groups join. It was the first location considered, due to its flatness, but became discarded in favor of spot A, slightly higher and less visible to the general public.

- spot 2 (97:17:43, 19:00:08 @ 4110m) is part of a rather wide flat valley with a gentle slope running down from Citlaltepetl. It could provide an area larger than $200\times150\,\mathrm{m}^2$ but had to be discarded as the geoelectric studies showed this region to be on top of a former glacier, prone to soil displacement. HAWC would slide downwards and most likely break due to differential motions.

The basic vegetation in the zone is tundra (fig. 3.3), with no prominent plants and trees, a factor easing the environmental demands. In all the terrain the soil is soft and easy to remove. For the same reason it may require a concrete reinforcement and a robust plastic insulation to prevent water losses.

3.1.2 Land availability and permissions

As in any Mexican National Park the owner of the land of the Parque Nacional Pico de Orizaba is the Mexican Federal Government, the sole authority that can grant permissions for using the land. In order to construct HAWC within the national park boundaries an environmental impact declaration (Manifiesto de Impacto Ambiental) has to be submitted to the Secretaría del Medio Ambiente y Recursos Naturales (SEMARNAT -

www.semarnat.gob.mx), the secretary in charge of the environment. HAWC will also require an explicit permit from the Comisión Nacional del Agua (CONAGUA - www.conagua.gob.mx) in order to have access to water in the region.

The submission of a Manifiesto de Impacto Ambiental (MIA) requires SEMARNAT to provide a response within 40 days. The MIA is reviewed by the Comisión Nacional de Áreas Naturales Protegidas (CONANP - www.conanp.gob.mx), the federal agency in charge of National Parks, and by the CONAGUA. The CONANP will in turn ask for the opinion of the Parque Nacional Pico de Orizaba authorities. Examples of points to specify in the Manifiesto de Impacto Ambiental are the water requirements, a comparison with the availability in potential sources and how supplying water to HAWC will impact these; the environmental impact of digging the pong and what will happen with the soil removed; the impact of the presence of the experiment while operating; contributions HAWC may make to the environment of the park; and options for the fate of the installation once the experiment ends. These points are further discussed in §3.4.

INAOE has already been through the process of drafting and submitting a MIA for the Large Millimeter Telescope and is willing to lead the effort for HAWC. In this respect the project has been presented to the Director General de Manejo para la Conservación at CONANP and to the Park Director for their information and advice. Both meetings were productive and the persons in charge of giving the authorization are now familiar with the project. We have approached CONAGUA for consulting the requirements needed for extracting water from the Citlaltepetl, and more recently we meet with the federal CONAGUA authorities to present the project. This meeting was very satisfactory, with the authorities showing to be supportive of our cause. However, CONAGUA officials mentioned that they will require the HAWC project to present a document describing the specific water acquisition project.

3.2 The experiment infrastructure

3.2.1 The reservoir

The stratigraphy of the terrain in the Citlaltepetl surroundings has been studied by the group of Geociencias of UNAM Campus Juriquilla, Queretaro [7]. They show the presence of a top layer of about 1 meter thickness followed by a second layer of pulverized pumice and scoria pyroclastic deposits (fig. 9 in [7]). This translates into a very soft and easy to remove

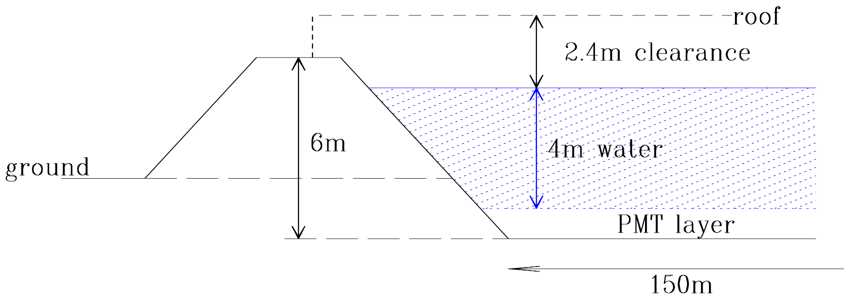


Figure 3.4: Schematic diagram of the lateral structure of HAWC. This diagram assumes a flat terrain while the site has an approximately Northern downwards 5° slope

material with the presence of medium sized rocks below 1-1.5 m. [3, 7] give some general soil parameters (mean diameter, sorting, bulk layer density, compaction...) for the upper layers in the region. This general picture is confirmed by the geoelectrical studies presented here in §3.3.1. Our team is performing soil studies, digging *in situ* and analyzing samples with the Laboratorio de Edafología of BUAP, in order to measure more precisely the soil parameters in the possible locations for HAWC.

The basic design for the vertical structure of HAWC, shown in fig. 3.4, has as a 4m layer of water covering a $\lesssim 1\,\mathrm{m}$ deep layer of photomultipliers. The water is surrounded and contained by a dam whose top is one more meter above the level of the water. The dam contains the water and supports the roof, which is 2.4 m above the level of the water -and 1.4 m above the top of the dam. The soil properties determine the amount of material which needs to be removed to dig the detector pond and, with the same material, make the dam structure holding the water. The advantage of a soft easy removable soil becomes a disadvantage as a relatively large volume of this material is needed to support the water pressure. The stiffness of the dam is directly dependent on the soil properties, although it can be increased with concrete -at a cost. A recent preliminary design presented by "Balcazar Construcciones" includes a layer of concrete 15 cm thick at the bottom and 10 cm thick in the perimeter. The implied volumes of concrete are 764 m^2 and 2250 m^3 respectively, for a total of about 3000 m^3.

In a flat terrain one can calculate the depth h of material to be removed

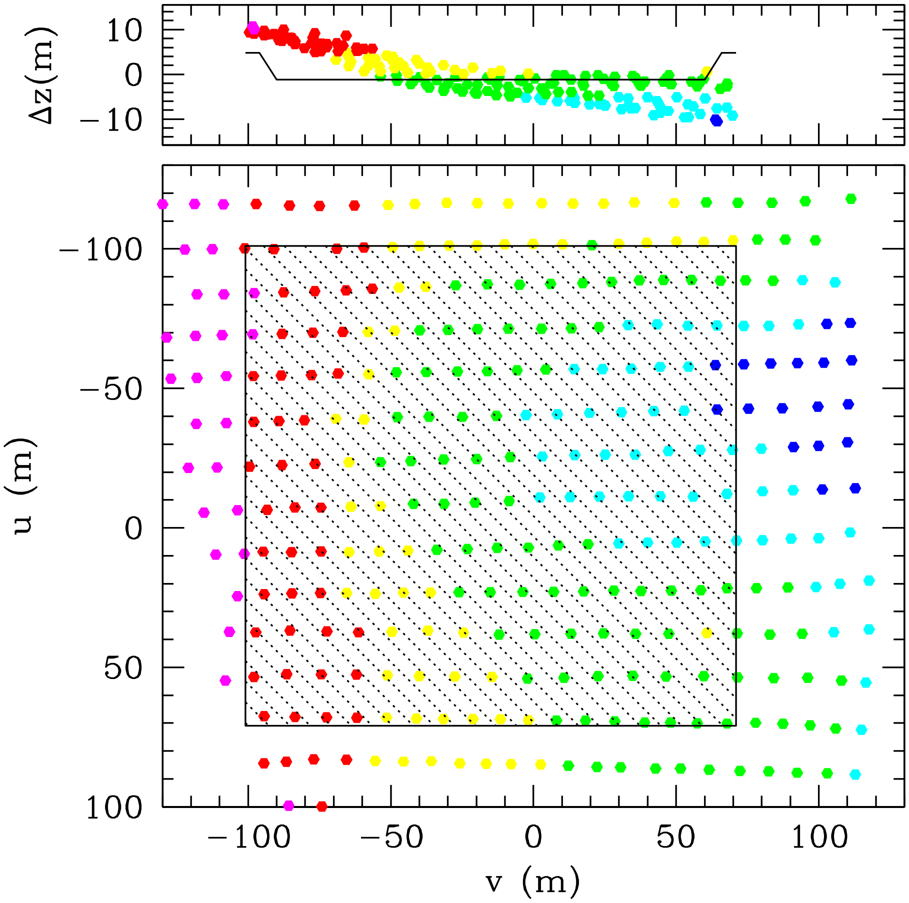


Figure 3.5: A possible configuration for HAWC, indicated by the square of 172 m per side. The upper panel shows the relative heights of the points inside the HAWC area. The colors of the dots denote their heights in 5 m intervals. Building HAWC requires reconciling the dots with the HAWC profile. The construction of the dam structure requires particular care of the lower side of the slope.

considering that this same material makes the dam. With rough assumptions about the friction coefficient, bulk density and compaction of the soil one deduces a depth of about 1.5 meters. However the situation here is that of a 4.6° slope over a $\gtrsim 200 \times 200$ m^2 region, as shown in figure 3.5. Locating HAWC in the (172 m)^2 shaded region at $z_{hawc} = 4098$ m, the volumes above and below the HAWC profile cancel. We took the HAWC profile as 5 m flat at $z_{hawc} + 6$ m, 6 m of slope –1, 150 m flat at z_{hawc}, 6 m of slope +1 and another 5 m flat at $z_{hawc} + 6$ m. The volume of material that has to be moved amounts to about 61,840 m^3, not far from the estimate made by "Balcazar Construcciones" (table 4.1).

The bottom of the pond requires an insulation to prevent water to permeate down through the porous soil. The process involves combining a non permeable PVC geomembrane with a permeable geotextile. A layer of compact clay with bentonite (tricalcium phosphate) between these two layers expands with water creating a seal. A specific type of geomembrane is produced by ALKORPLAN (www.evi.com.mx). It comes in 10×39 m panels of 1.2 mm (0.5 inch) thickness. A geotextile material of 500 g/cm^2 and up to 0.5 m thickness can be provided by UCO. This needs further investigation.

A water circulation system must be installed under the pond in order to transport the liquid to the purification system. There it will be filtered through carbon and is exposed to UV radiation. The specification for HAWC is a flow of 1500 liters per minute, about twice the flow of Milagro. We have not studied this point in here but we presume this not to be a major issue given the experience with the Milagro detector.

3.2.2 The detector

The detector surface of HAWC is to be divided in square cells of 5 m side, forming a 30×30 grid, with a photomultiplier inside each cell (figure 3.6). The division between cells is specified to be opaque and of a material that will not affect the quality of the water and the flow of water inside the detector. An opaque material is preferred in order to avoid delays and time spreads in single signals; however a reflective material could enhance the lateral view of HAWC. While the opaque option is probably the best in terms of detector efficiency, we believe of interest to perform simulations assuming reflective walls and evaluate the lateral performance. This can also be considered as a possible modification in the future. In any case, about 10,800 m^2 of division are required, so the material should also be of low cost in order not to impact the cost of the experiment. The cell structure can accommodate supports for the cover structure, with a 15 m spacing suggested as convenient.

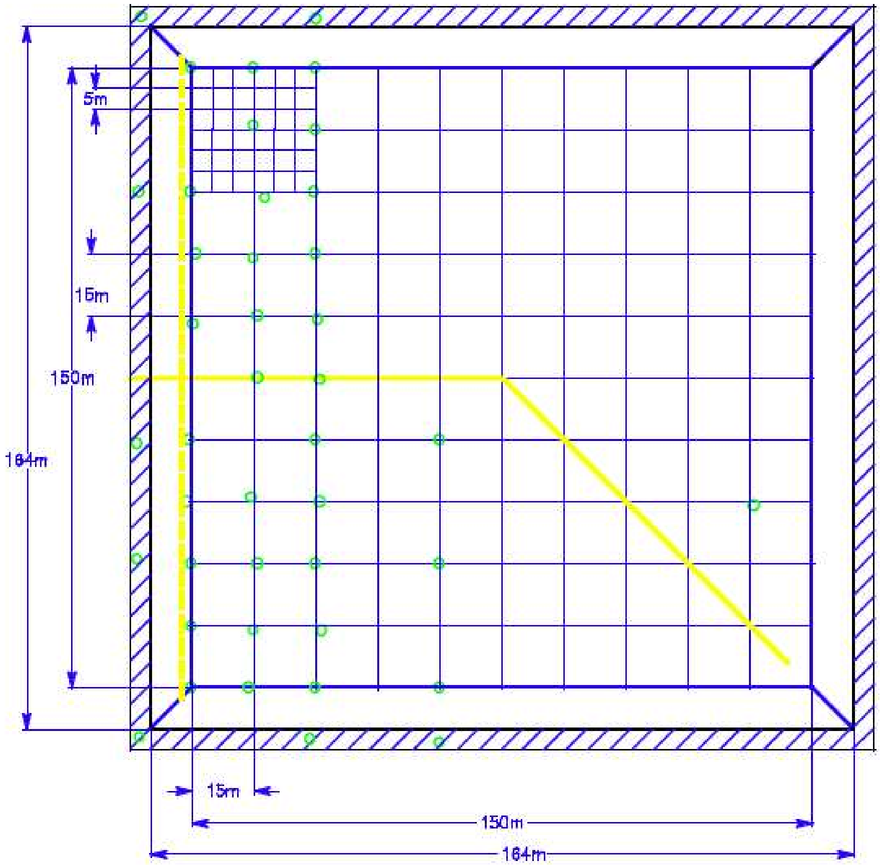
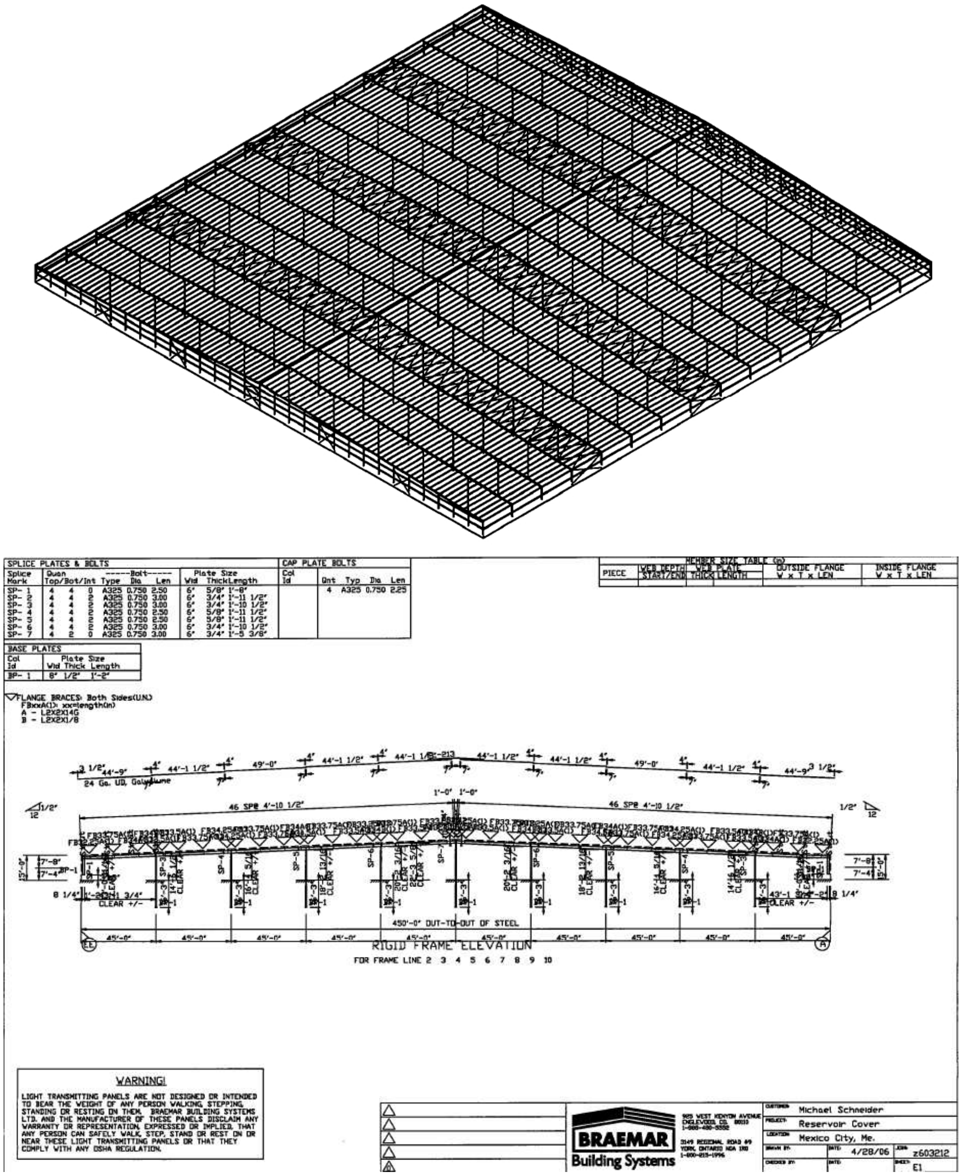


Figure 3.6: Basic layout of the HAWC detector layer. Photomultiplier cells are 5 meter each side. Provisions are considered for supports to the structure every 15 meters. Figure provided by Brenda Dingus.

3.2.3 The building

The main purpose of the structure above the HAWC pond is to shield the water from the ambient light. It is intended to be left empty but it must be possible to access it in order to maintain, repair or improve HAWC. The cover should also protect the experiment from the weather. Milagro uses plastic covers to shield it, but it is considered that the size of HAWC



SPLICE PLATES & BOLTS									
Splice Mark	Quan Top/Bot/Int			Bolt Type	Dia	Len	Plate Size Wid	Thick	Length
SP- 1	4	4	0	A325	0.750	2.50	6"	5/8"	1'-8"
SP- 2	4	4	2	A325	0.750	3.00	6"	3/4"	1'-11 1/2"
SP- 3	4	4	2	A325	0.750	3.00	6"	3/4"	1'-10 1/2"
SP- 4	4	4	2	A325	0.750	2.50	6"	5/8"	1'-11 1/2"
SP- 5	4	4	2	A325	0.750	2.50	6"	5/8"	1'-11 1/2"
SP- 6	4	4	2	A325	0.750	3.00	6"	3/4"	1'-10 1/2"
SP- 7	4	2	0	A325	0.750	3.00	6"	3/4"	1'-5 3/8"

CAP PLATE BOLTS				
Col Id	Qnt	Typ	Dia	Len
	4	A325	0.750	2.25

BASE PLATES			
Col Id	Plate Size Wid	Thick	Length
BP- 1	8"	1/2"	1'-2"

MEMBER SIZE TABLE (in)				
PIECE	WEB DEPTH START/END	WEB PLATE THICK LENGTH	OUTSIDE FLANGE W x T x LEN	INSIDE FLANGE W x T x LEN

FLANGE BRACES: Both Sides(U.N.)
FBxxA(1): xx=length(in)
A - L2X2X14G
B - L2X2X1/8

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PROJECT: Reservoir Cover
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DATE: 4/28/06
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Figure 3.7: *Left:* basic layout of the HAWC detector layer. Photomultiplier cells are 5 meter each side. Provisions are considered for supports to the structure every 15 meters. *Right:* basic design of the HAWC cover building - figures provided by Brenda Dingus.

prevents the use of a plastic cover. The basic design of the cover is a steel structure supporting lighter panels, as shown in figure 3.6. This is included in the quotation 4.1. The design includes anchor bases for the support posts separated every 15 meters.

Apart from the building two smaller constructions are now considered. The water purification system can be accommodated in a $6\,\mathrm{m} \times 4\,\mathrm{m}$ room, while an area of $6\,\mathrm{m} \times 20\,\mathrm{m}$ has been considered for the computer and data storage hardware. Oxygen enrichment might be considered for better human performance, while overpressurising might be preferred to ensure the proper performance of computer hardware - specifically disks.

Due to its large surface and insulating properties, the HAWC cover structure can collect at least 6,000 m^3 of precipitable water per year. A fraction of this water can be used for personnel consumption, making the HAWC experiment independent of in terms of water consumption and an environment friendly experiment. We estimate that to take advantage of this capacity a water reservoir of about 50 m^3 needs to be constructed. With this installation, HAWC can satisfy the human needs of water during operations and contribute to the overall functioning of the Consorcio Sierra Negra by supplying water to the whole Consortium.

3.2.4 Power and communications

The LMT project envisages a significantly larger power consumption than that of HAWC, together with robust communications. The power line to the LMT goes follows the access road from Texmalaquilla up to an elevation of about 4200 m, from where it is canalized underground to the top of Sierra Negra. The closest electricity post to the HAWC site is located at UTM coordinates $\{678811, 2100697\}$, which is at 740 m, 820 m and 974 m

Type	units	Voltage	phases	kW
AC cooling: 5t	3	208	3	50kW
UPS for electronics	10	110	1	15kW
Water system:pumps	2	220	3	15kW
UV system	2	220	1	3kW
Total:				83kW

Table 3.1: Projected power consumption of HAWC. Numbers supplied by Michael Schneider - SLAC.

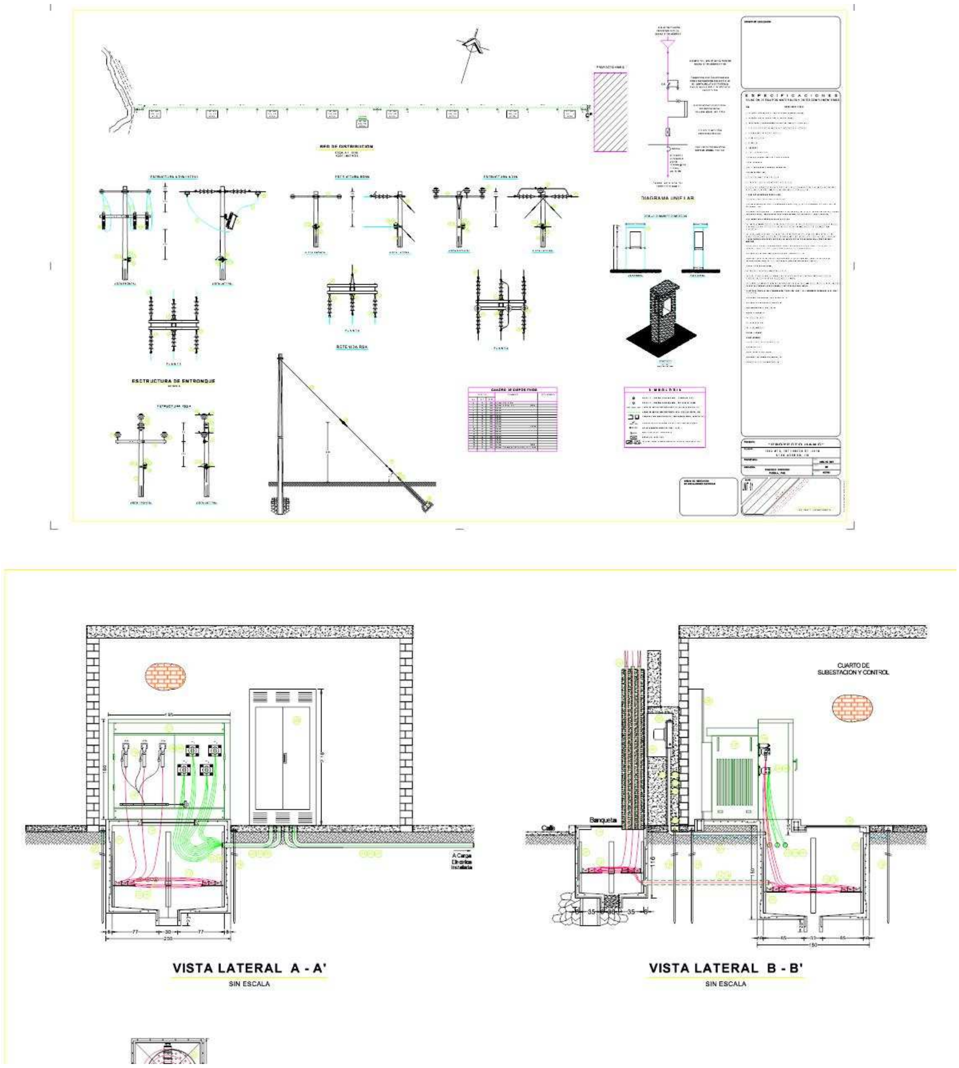

Figure 3.8: *Upper:* design of the electric line supply for HAWC, together with details of some of components involved. *Lower:* front and lateral view of the corresponding electrical station.

from the three "HAWC positions" recorded on the same day (fig. 3.2). The basic needs of HAWC amount to less than 100 kW (table 3.1). A preliminary quotation by the company Dipro Cisem gives an approximate power installation cost of 816,928 pesos. This budget includes 1 km line, posts and related infrastructure, for an aerial transmission line of 34.5 kV and a transformer to 112.5 kVA, including also lightning protection. A design for the electrical installation has been presented by the consulter Daniel Arenas García, consisting of a set of printed and Autocad drawings now available for the HAWC. A few extracted figures are shown in figure 3.8.

3.2.5 Communications

Three aspects of communication need consideration: the access road to HAWC; internet and person to person communications. The distance from the HAWC site to the LMT is the same than to the electricity post, about 1 km. Making this road should require relatively little effort, and is included in the Balcazar budget. Note the possibility to open an alternative access from the NW (figs. 3.1 and 3.2).

The LMT Internet connection was set on time for the LMT presidential inauguration in November 2006. The LMT connection is based on an optical fiber running on the same posts as the power line, so its installation will require 1 km of optical fiber, a connection at the last post and the connection to the HAWC server. For the moment the connection a low capacity but will be expanded to meet the future LMT needs, at several gigabits per second.

The LMT group recommends the use of person to person communications based on cables or the optical fiber. Even though the frequency range of the LMT is outside that of standard radio transmitters, the zone will be functioning as a radio quiet zone and any transmitter will have to be registered and to be granted permission by the LMT group. In practice the permission might be granted once the technical specifications of the transmitter are given and known by the LMT group.

3.3 Water for HAWC

Water is the detector substance of HAWC. The precise amount of water required for HAWC is given by

$$V = \ell^2 h + h/2 \left[(\ell + 2h\tan\theta)^2 - \ell^2\right] = \ell^2 h + 2\ell h^2 \tan\theta + 2h^3 \tan^2\theta,$$

which for $\ell = 150\,\mathrm{m}$, $\theta = 45^\circ$ and $h = 4.8$ m gives $V \simeq 115,000\,\mathrm{m}^3$ -and $118,500$ m^3 for $h = 5$ m. The acquisition of this amount of water within six months translates into an average rate of 7.4 ℓ/s. Here we describe the water availability in the region under consideration and two methods employed to identify potentially important sources of water.

3.3.1 Geoelectrical studies

In one of the first phases of this project we undertook a study seeking for underground water, either from glacier demelting or from filtered precipitation. These geoelectrical studies were performed by the consulter ROCCA. The work consisted in a first sampling of eight points to determine 2D profiles along given directions, with a follow-up sampling in the most promising location -close to the intersecting point of the two sampled axis. These axis were chosen with an *a priori* knowledge of the site. In figure 2.4 one can see the area in blue East of the recent lava flow ("dacita Orizaba"). The intersection of this slope with the alluvion at the base of the "dacita Orizaba", where the terrain flattens, is a region prone to contain underground water. Geoelectrical sampling consists in applying electric potentials to pairs of points on the ground to probe the soil resistivity and to obtain resistivity profiles, which in turn help locating permeable and water saturated underground zones. Measuring at different separations allows to sample different depths. A system of four Schlumberg electrodes of 40 cm length were introduced about 1/4 of their length into the ground and the current circulating between these electrodes was set between 3 and 100 mA.

The first survey was made following two axis intersecting in one point, labeled SGU 2. The first axis ran along the alluvion deposit, roughly in a W→E direction; the second axis ran down the Citlaltepetl slope, roughly N→S direction (table 3.2 and figure 3.9). The general stratigraphy of the zone shows, (i) a superficial layer, just a couple of meters deep, with very high resistivity (above 100,000 Ω/m), (ii) a $\sim 50\,\mathrm{m}$ deep layer of medium resistivity (a few 10,000 Ω/m), (iii) a third layer of low resistivity (below 1000 Ω/m) material typical of water conducting material, down to $\sim$ 100 m below ground, (iv) a high resistivity layer (a few 10,000 Ω/m) below the permeated layer. The EW profile has a cross section indicative of a former glacier structure which must have existed in colder times and which penetrates some 120 meters below the surface, at point SGU 2 (fig. 3.10). The resistivity of the different layers have lower values at this place, suggesting an increased amount of underground water. At present there is no glacier running down in this slope, so the water must originate in precipitation.

The NS profile follows the structure below point SGU 2, with relatively low resistivity values. The important issue in the underground structure is

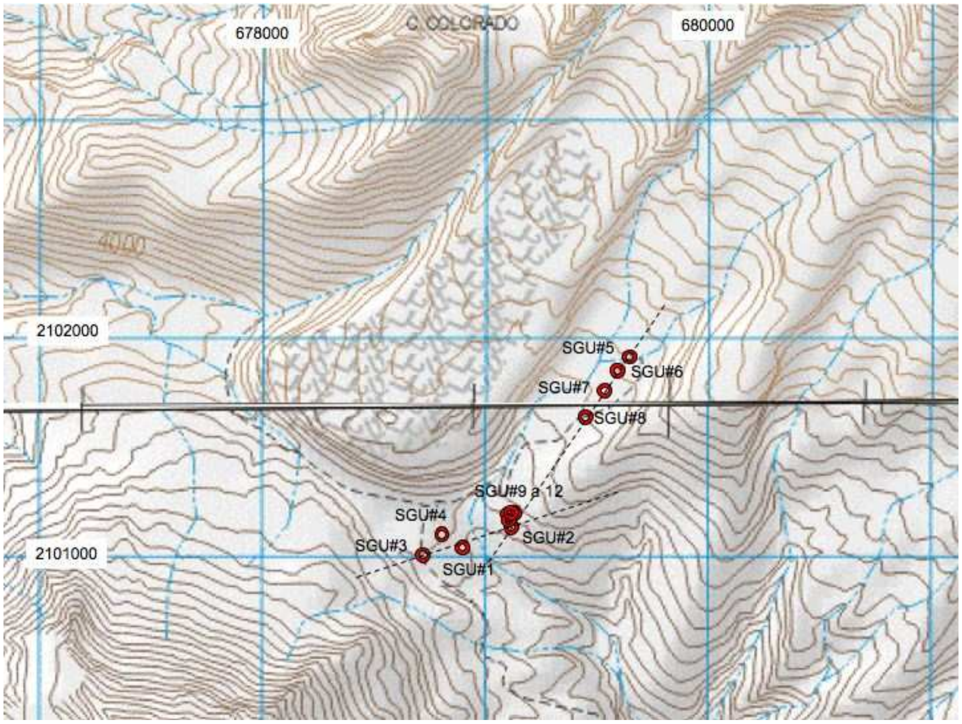

Figure 3.9: Location of geoelectrical sampled points. The two axis are shown, together with the concentration of points near the most promising location.

EW baseline				
Point	SGU 1	SGU 2	SGU 3	SGU 4
Longitude	97:18:02	97:17:55	97:18:08	97:18:05
Latitude	18:59:39	18:59:42	18:59:38	18:59:41
Altitude	4012	4006	4028	4024
NS baseline + SGU 2				
Point	SGU 5	SGU 6	SGU 7	SGU 8
Longitude	97:17:36	97:17:36	97:17:40	97:17:43
Latitude	19:00:07	19:00:05	19:00:02	18:59:58
Altitude	4118	4101	4093	4080

Table 3.2: Geolectrical survey points.

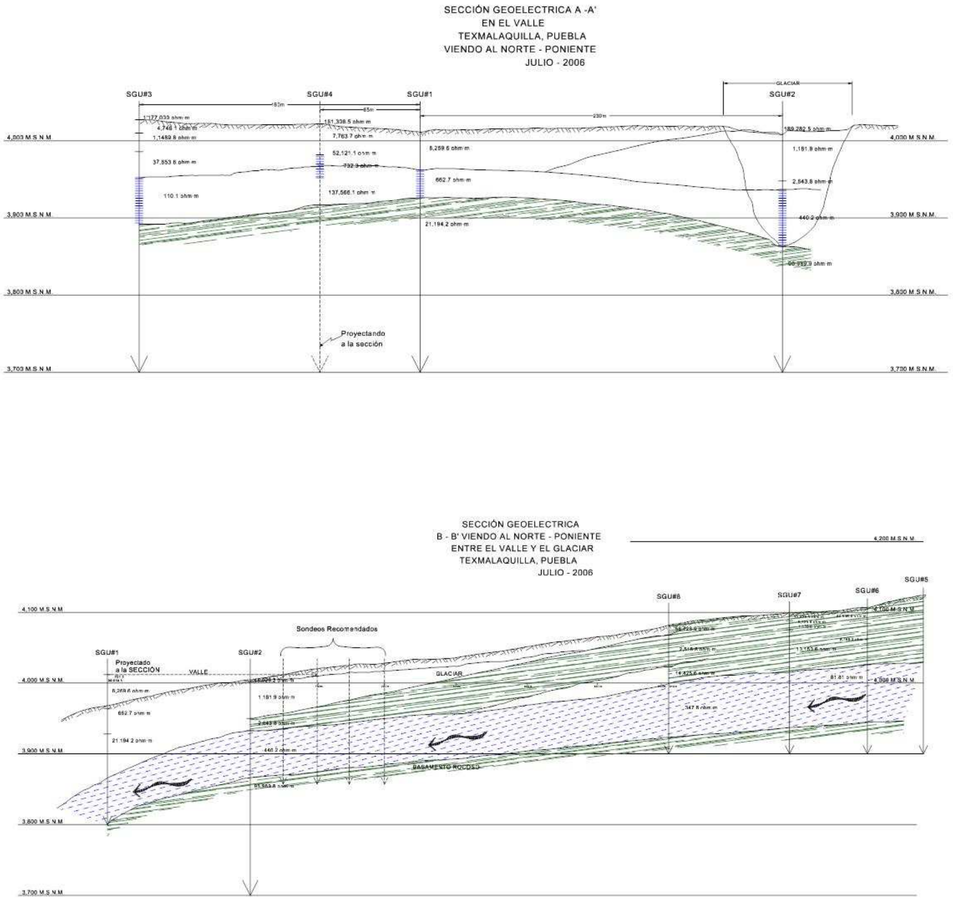

Figure 3.10: The inferred underlying stratigraphy along the EW line (*upper*) and NS slope (*lower*). A former glacier structure is evidenced by the lower resistivities found in the different layers and illustrated on the left side of the upper figure. In the descending slope the resistivity is similar to that found in SGU 2, with its values allowing to estimate the depth of the humid layer. The best place to drill an extraction well is where the slope of the water floor is lowest. Follow up samples were made just above SGU 2. Horizontal lines indicate altitudes of 3700m, 3800m, 3900m and 4000m.

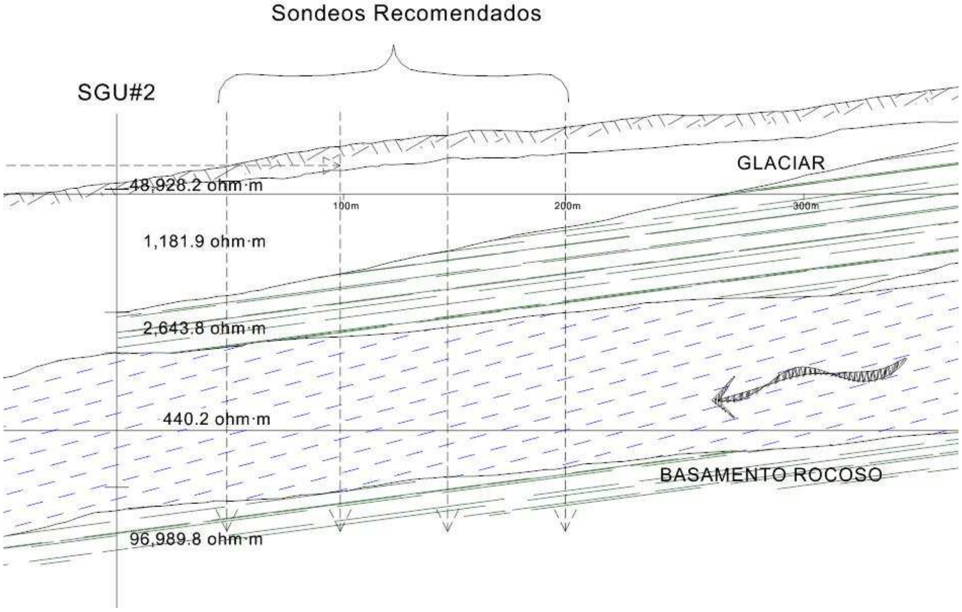

Figure 3.11: Zoom of the zone around SGU 2 where geoelectrical follow-up samples were performed. SGU9 is the points closest to SGU 2.

the determination of the zone of minimum slope, where water might tend to form an underground reservoir and/or be easier to extract. Follow up measurements were made just above SGU 2, as indicated in fig. 3.11, in order to locate approximately the zone of less slope. The follow up studies confirmed that the extraction of water requires drilling a well down to 200 m deep, and pointed to SGU 9 (of geographical coordinates 97:17:55, 18:59:44) as the most promising point for water extraction.

One of the discussion sessions with ROCCA led to the sketch of an extraction well, shown in figure 3.12. It consists of a 12-inch metal pipe surrounded by gravel, contained by a concentric 36-inch pipe. The gravel allows the penetration of water while preventing the inner pipe to be crushed by the overall pressure. The pipes have to enter below the water saturated level, into the less conductive rock, to create a trap from where to pump the water up. The contractor ROCCA gave a rough guess on the cost of the well, based on an estimate of 7,000 to 10,000 pesos per meter drilled and 500 pesos/m^3 of gravel. The amount of gravel needed is below but close to 200 m^3, resulting in 100,000 pesos for this material. Other equipment

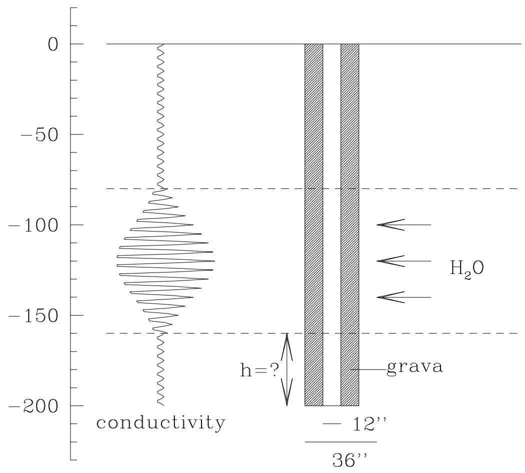

Figure 3.12: Sketch of a design of an extraction well. The well has to penetrate some meters below the non conductive layer to create a trap for the water to enter and be pumped up. An outer cylinder of gravel protects the pipe from the external pressure, allowing the water to flow inside the trap. The pump must be able to extract from a depth of 200 m.

are a 12-inch steel pipe with holes for the water to enter and a 4 to 6 inch pump. The first rough quote for this well is somewhat above one million pesos, although during a meeting at CONAGUA we were told that such a well might be feasible for 600,000 pesos. We are contacting the company "Electromecánica Hidraúlica", based in Puebla, for an alternative quotation and the possibility of an exploration well.

The main concern at this stage is the lack of a quantification on the amount of water that can be obtained through this method. In general consulters use these methods more for qualification than for quantification and are not confident enough to quote the potential flow of water available. Given the uncertainty in whether this method will be able to meet the supply needs of HAWC, we present the results of a different study regarding the capture of water during precipitation events.

3.3.2 Water precipitation: altimetric studies

Citlaltepetl has an area of about 3.5 km^2 above 5000 meters of altitude, making for one million cubic meters of precipitation running down the mountain each year. Altimetric studies seek to find the most important paths and convergence points of water when running down the mountain. These studies, based on 3D modeling of the zone together with *in situ* inspection, were performed by the consulter DIRDAM. Their model is based on the detailed

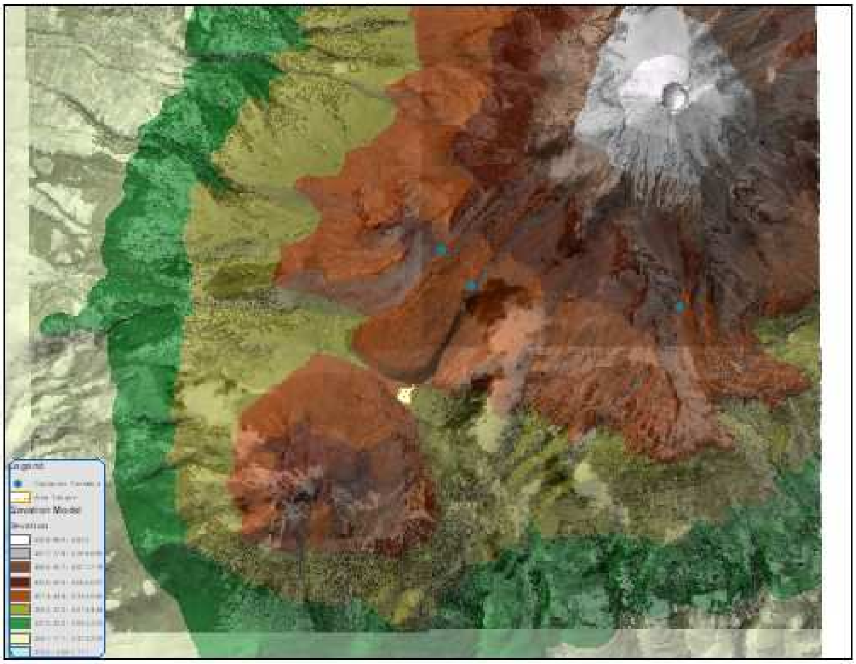

Figure 3.13: Upper view of the altimetric model generated by DIRDAM. Colors indicate altitude levels according to the scale in the bottom left. The blue points indicate the three capture points identified, while the white region is located at spot 1, formerly considered a the site for HAWC.

topographic data from INEGI and aerial photography, without incorporating the permeability of the terrain in a first instance. Direct examination of the soil properties at the site allows to consider them.

Water acquisition points were sought for in the topographic model on the Southern slope of Citlaltepetl at about 4300 m -at the time of the study HAWC was assumed to be in spot 1, at about 4020 m. The transport of water to the site is done through pipes by gravity. Three acquisition points were identified at 4240 meter of altitude, two of them (labeled points 1 and 3) corresponding to highly convergent water flows, while point 2 corresponds to the Eastern rim of the lava tongue described in §2.2.1, where water might flow in the surface and its acquisition is not dependent on the altitude. In addition to the work by DIRDAM, we have examined this rim and found vegetation giving evidence of water flowing down. Point 2 differs from points

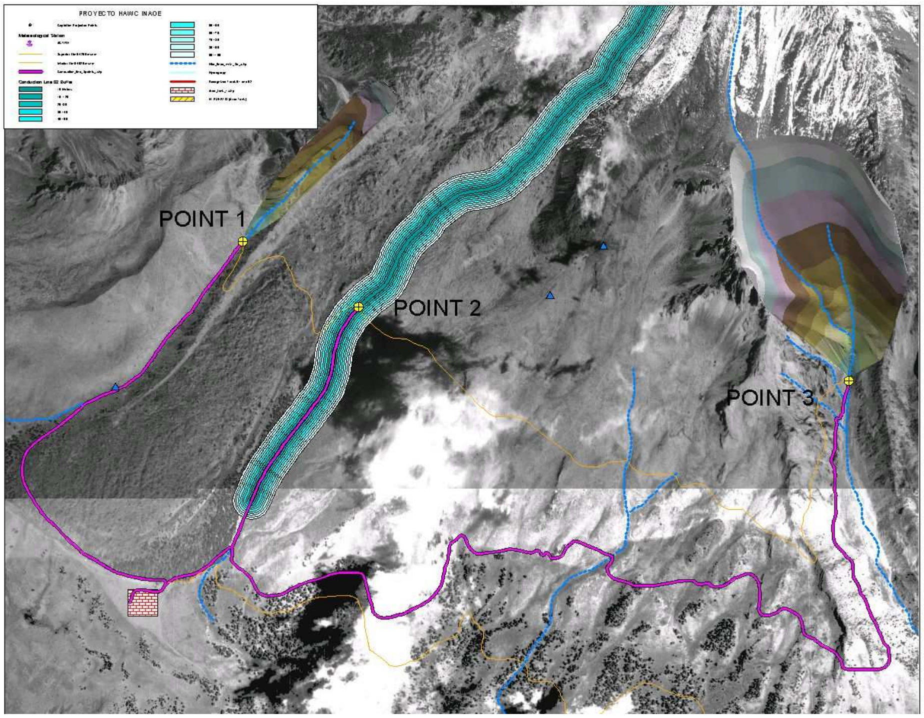

Figure 3.14: Location of the water supply points, marked by the yellow points and denoted 1,2 and 3 from left to right. Magenta lines indicate the piping needed to take water from these points to spot 1, the assumed location of HAWC at the time of the study.

1 and 3 in not been a defined convergence point; water acquisition might be possible all along this rim. Table 3.3 shows the geographical coordinates, estimated area of convergence and volume of the funnel in these points.

Point 1 is located on the West rim of the lava structure. Considering the area it present horizontally, the yearly precipitation and the 30% factor of the hydrological cycle, one would expect at least 52500 m^3 to be flowing through that point annually, insufficient to fill HAWC within a year - but possibly enough to complement the demelting extraction. The piping system required to take the water to spot 1 is 3 km length; spot A is actually nearer to the point and the actual length needed might be slightly reduced. Point 3 is located just East of Espolón de Oro, not far from where BUAP is installing a cosmic-ray experiment. It has a much larger area than point 1 and should be able to provide of the order of 250,000 m^3 of water. The

Point	UTM Coordinates	Total area m^2	Cross section m^2	volume m^3	Length (m)
1	679174, 2103059	211,984	174,867	24,081,198	3030
2	679785, 2102712	....	....	....	2120
3	682371, 2102325	992,097	848,612	263,349,538	7014

Table 3.3: Data of the water capture points identified with the altimetry. The area measures the surface on ground of the region from where water is funneled to the point. The cross section (area planimétrica in the report in Spanish) measures the same area normal to a vertical axis. Length indicates the length of the conduction system, made of pipes, required to take the water from the capture point to HAWC, assumed to be at spot 1.

main issue might be to design a collection system able to stand heavy flows of water. Consulter DIRDAM is presently preparing a preliminary design. The transportation of the captured water to the detector is through pipes and gravity, these two points been 150 meters above the site. PVC pipes with a diameter of 4 inches should suffice.

Complete or at least preliminary designs for the acquisition dams are needed. If these systems work passively they might need to be dismantled once the reservoir is filled.

3.3.3 Quantifying water extraction

The main concern regarding the water supply project is the lack of quantification of the amounts that can be extracted through this methods. Our experience is that contractors are reluctant to go beyond qualitative or semi-quantitative estimates. Even though one can draw figures from the precipitation in the region and the hydrological cycle and get to a baseline 280 mm of water per year, our meeting with the CONAGUA showed us that there are unavoidable uncertainties in the effectiveness of water extraction methods. For example, the existence of an underground body of water below the extraction well can provide a large, but undetermined, amount of water instantly available. Still, in order to have a better understanding of the region and be able to better quantify the proposed extraction methods, we are contacting a hydrogeologist with direct experience in the study of the region of the Parque Nacional Pico de Orizaba.

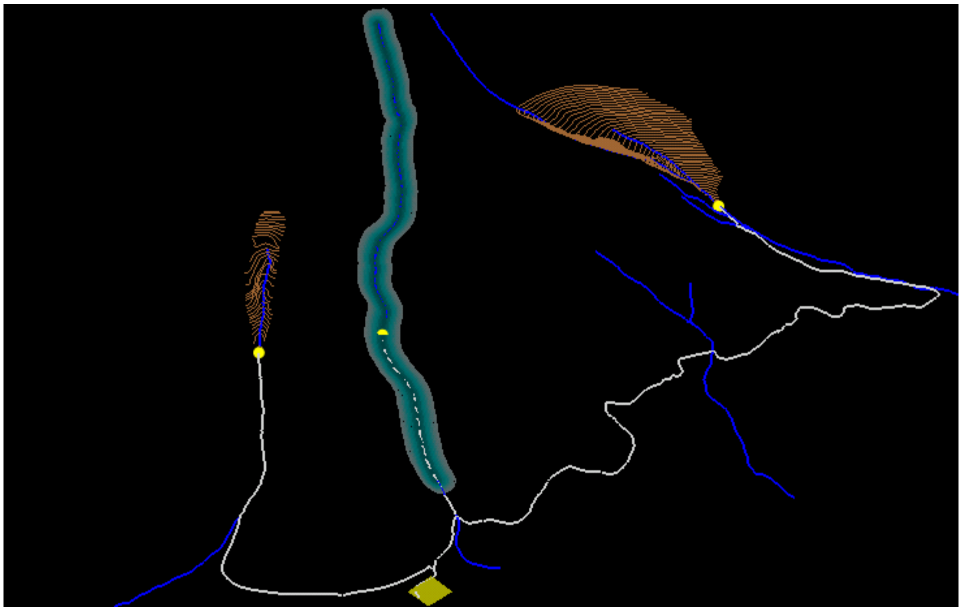

Figure 3.15: Altimetry: three D view of the points and supply system. White lines indicate the pipe systems, while brown shaded area show the volume of influence of the acquisition points.

3.4 Environmental considerations

The permits for the use of the site for HAWC depend mainly in the environmental impact declaration, together with submitting the water acquisition project to the CONAGUA to obtain the permit for acquiring the water. We identified four areas to address in the environmental impact declaration.

3.4.1 The HAWC infrastructure

there are at least five aspects to consider in this point, namely the road, the reservoir, the water circulation system, the cover building and the electricity.

The access road and power line

The start and end points of the access road are fairly well determined so the road can be built anytime soon. The road should be about one kilometer long and six meters wide, to allow transportation of equipment. The road is to start close to the nearest post of the LMT power line. We note that this point is 10 to 20 meters below the height of the terrain, so we need to design a proper interface, taking care of not removing or damaging trees -or to minimize the number of trees to be removed.

We also have to estimate the amount of soil which will be removed, digging one meter deep all along the way gives around 6000 m^3, and mention what we will do with this material. It can be put aside the road or used latter for the HAWC dam.

The power line will run parallel to the access road. The design presented by the contractor Daniel Arenas contemplates installing 17 posts, most of them with 80 meter separation. Posts are about 6 meters tall, should be buried about 1.5 meters into the ground with a concrete or stone reinforcement, and supported with steel wires. Given the scarcity of trees these can be installing without further impact than the removal of the soil and its proper disposal as building material.

The reservoir

We estimated that building the pond requires the removal of the top vegetation layer and close to 70,000 m^3 of soil. The vegetation is scarce in the region so the environmental impact is not severe. The soil removed will be used for the construction, which is also a positive aspect. We note that the slope of the terrain makes the Northern end of the pond a critical point in terms of safety, as any rupture of the pond would translate in water running from there down to Texmalaquilla. This end of the pond needs to have special reinforcement and continuous monitoring of its stiffness.

We have to guarantee that the material of the geoinsulator at the bottom of the pond will not have a negative impact. HAWC will be located at the base of Sierra Negra and it seems unlikely that there are bodies of water just under it. We should confirm this and make sure the geotextile/geoplastic material cannot contaminate water or soil. The water circulation system is buried below the geotextile and has no major environmental impact.

The building and surrounding infrastructure has to be designed such as to fit the landscape. It must consider safety aspects for the park, like not been reflective in order to prevent fires, and to be steady in order not to represent a hazard. For security reasons we might need to fence the area. An environment friendly proposal from the Geociencias group of UNAM is to create a "natural fence"[1] around the experiment. For an outer perimeter of 720 meters we can consider between 100 and 200 trees. These can be very young trees, must be of the species endemic to the region, and can benefit of the water collected by the HAWC cover. We believe this initiative can be beneficial for the local image of the experiment.

3.4.2 Water acquisition

General considerations

We have two strong arguments in our favor in terms of our needs of water. The first is that we will not "use" the water, only retain it for the operation of the experiment. The liquid can be returned to any affected person once the experiment is over, with no degradation on its quality. The second is that the volume involved corresponds to about 11 times the amount available per person-year in the region. Our impact for the overall region is absolutely minimal and very localized both in duration and region. Even in the local scale the amount becomes minimal once we consider the overall duration of the experiment.

We are considering two water acquisition systems: the deep well at the geoelectrical point SGU 9 and two collection dam at the points 1 and 3 defined by the altimetry. From our interviews with authorities the well appears the most environmental friendly system.

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[1] cercado natural is the proper Spanish term.

The well

The well has to reach a depth of about 200 meter with a diameter of about 1 meter, so it requires removal of about 200 m^3 of soil. We need to specify better the infrastructure needed around the well, including one or two pumps, a power supply and a fence. The well can affect the flow of the Encino river, which is not restricted[2] by the CONAGUA. It might not affect it significantly if we have the luck of finding an underground body of water. Transporting the water from the well to the reservoir will probably require a second pump and a system of about 1.5 km of PVC pipes. The trajectory of this pipes needs to be defined. If they are to go buried underground we have to mention the impact of burring them - probably minimal given the scarce vegetation.

The precipitation capture dams

We require at least a preliminary design of the two dam structures related to the precipitation acquisition points, as these will be concrete constructions in the mountain. They might not need to be fenced. We must quantify the effect of water acquisition on the rivers Encino and Malacara, none of them restricted by the CONAGUA. We must make similar considerations for the transportation system.

After water acquisition

We propose to organize one or more meetings with Federal (SEMARNAT, CONANP, PNPO and CONAGUA), State (Puebla and Veracrúz) and local (Municipios de Atzitzintla y Ciudad Serdán) authorities to discuss the fate of the water acquisition system once the water for the experiment is acquired. As mentioned above, we might have to dismantle the acquisition dams to avoid receiving unwanted water once the reservoir is filled. This might be further the case if they have impact on the river. Disposing of the well or donating it to local authorities can be organized.

3.4.3 Operations

HAWC operations will require the average presence of one or two persons on site. This involves the use of water, sewage and disposal of garbage. Mean water consumption in Mexico is quoted as 200 liters per day per person, or 7.3 m^3/year. A sewage system must be implemented, if possible since the

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[2] ”vedado” in Spanish.

construction phase. We also need to organize either the local disposal of garbage or transporting it somewhere else. This can be integrated within the organization of the Consorcio Sierra Negra, which can address the same joint issue for all experiments on site.

If fitted with some extra infrastructure HAWC will be able to collect more than enough water for its human needs during operations and in fact to provide water to the experiments within the Consorcio Sierra Negra. We estimate that a water storage of 50 m^3 would be needed. HAWC can benefit of this setup as part of its contribution to the Consortium.

3.4.4 Post-operations

We are presently considering ten years of operation for the HAWC experiment. If after this term the experiment is finalized, it can be dismantled or donated if required. This concerns the reservoir, cover building and installed infrastructure, while all the electronic and computer hardware must remain property of the participating institutions. We propose to organize discussions regarding the fate of the reservoir with Federal, State and Local authorities once the experiment is declared to be near to finalized.

3.5 Social impact

The LMT project has had an impact on the nearby communities, mainly Atzitzintla, Texmalaquilla and Ciudad Serdán. The local communities are often reticent to outsiders and in particular it is in the town of Atzitzintla where the project has been received less warmly. However outreach activities have been organized in local schools; LMT has also participated in the Ciudad Serdán fair with a stand and has an outreach space available in the Casa Magnolia of Ciudad Serdán. The participation of the HAWC project in outreach activities can be done in coordination with the LMT group, and more general with the whole Consorcio Sierra Negra.

Chapter 4

Operations and science

4.1 Operations

The Mexican HAWC collaboration is presently drafting a proposal for the second phase of a call for "Ideas of Megaprojects" from the Consejo Nacional de Ciencia y Tecnología (CONACyT). This call considers presenting projects requiring up to 1000 million pesos during five years. Based on this CONACyT call we are contemplating a two year plan for building and commissioning HAWC, followed by three years of scientific operation.

The operation of HAWC involves: a relatively small technical staff, mainly from the Mexican institutions with support and advice from the US institutions; consumables, like computer equipment and filters for the purification system; implementation, support and improving the remote monitor system for HAWC; a shared local basecamp in the region of Atzitzintla and Ciudad Serdán -or more generally covering the HAWC share of the Consorcio Sierra Negra, which should provide the local basecamp, security, garbage disposal, road maintenance, security, payment of electricity and internet, and other common operation costs.

4.2 Budget

We provide here an estimate for a five year plan, which considers two years of installation and three year operation. Main installation costs to consider:

- **building the reservoir and related infrastructure**
  The owner of the constructor company "Balcazar construcciones" visited the site in January 2007 and meet the HAWC collaboration in

February 2007 to sketch a possible design for HAWC. He gave a quotation just below 3 million pesos for producing a detailed design for HAWC and a preliminary estimate of the total cost, shown in table 4.1. Depending on the exchange rate this amounts to about 5.6 million USD. The estimate includes also making the access road from the electricity post and a protection fence surrounding the experiment.

Project design		
Topographic survey		
Soil mechanics studies		
Structural calculations		
Architectonic drawings		
Structural drawings		
Detail installation drawings		
Certified register of calculations		
Subtotal		2,923,417
Project construction budget - preliminary		
Item	amount	cost (pesos)
Topographic leveling and tracing	32,400 m^2	129,600
Pond excavation	76,800 m^3	5,836,800
Concrete pond reinforcement (20 cm layer)	6,400 m^3	524,800
Laying excavated material to make the dam	70,000 m^3	2,660,000
Concrete anchors	169 items	1,335,100
Polyethylene piping system	1 circuit	385,315
Concrete bottom slab 3/8 inch thickness	4,260 m^3	15,378,600
Concrete slope	390 m^3	1,521,000
Steel support structure	730,080 kg	19,055,088
Panels 1 inch thick filled with polyurethane	27,225 m^2	8,439,750
Concrete walkway	198 m^3	524,700
Concrete perimetrical facade of 2.2 m height	1500 m^2	969,000
Water purification room (6m × 4 m) and data acquisition, control room (6m × 20 m)	144 m^2	518,400
Subtotal		57,278,153
Total		60,201.570

Table 4.1: Balcazar quotation for the HAWC pond, building and physical infrastructure.

- **The water acquisition systems**
  We do not have a specific quotation for these systems. However the costs related to these systems are (i) the cost of the deep well; (ii) the related water transportation system; (iii) the cost of the two precipitation acquisition points; (iv) the related water transportation systems. We had received quotations for similar work from different companies, which allow us to make an estimate of the cost of the water acquisition system. In particular "Electromecánica hidraúlica" had proposed a system to acquire water from a lower site (at Esperanza, 2000 meters altitude) and transport it some 22 km with 14 intermediate auxiliary pumps. This quotation was fairly detailed in terms of unitary prices. From this and other quotations we have:

  - deep well: PECSA gave to BUAP a quotation for 1.8 million pesos for a well down to 300 meters deep, including the pump, fence, housing installation. Electromecánica hidraúlica quoted 646,000 pesos for drilling a well down to a depth of 170 meters; 233,400 pesos for the extraction pump and accessories; 148,600 pesos for the related electrical installation; and 21,500 pesos for the design drawings and peripheral equipment. This makes a total cost of about 1.05 million pesos, or just below 100,000 USD.
  - water transportation from well to site: given that the well is at a lower altitude than the site an auxiliary pump will be required. Auxiliary pumps were quoted at 170,600 pesos by "Electromecánica hidraúlica", plus 25,300 pesos for peripherals. The cost of a meter of 5-inch PVC pipe was quoted at 77.4 pesos, so for a 1.5 km transportation line we obtain an estimate of 312,000 pesos - about 30,000 USD.
  - the precipitation acquisition system: these are dam structures to collect water flowing during precipitation. At present we do not have an estimate of the cost of these. We will have an interview with the contractor DIRDAM, who made the altimetric studies, to obtain a preliminary design and quotation. We note that the dimensions of the two points are quite different.
  - water transportation from capture points to site: the capture points are above the site so pumping might not be required. The length of the conduct line from point 1 to the former site location (spot 1) is 3030 meters (table 3.3), which results in almost 235,000 pesos of material (22,000 USD); the line from point 3 to

the former site location is 7014 meters long, involving 543,000 pesos (51,000 USD).

Aside from the water capture system the total figure is around 2.14 million pesos. As we do not consider the capture dam to be particularly expensive, so the total cost estimate is probably under 2.5 million pesos, or 240,000 USD - pending our meeting with DIRDAM.

- **Electricity**
  Installing the power line for HAWC has been quoted at 817,000 pesos (§3.2.4).

- **Operations**
  Pending a more accurate estimate, a standard baseline for operation costs is 10% of the installation cost per year, which would mean about 800,000 USD per year or 2.4 million during the first three years of operations.

  Values quoted for Milagro are 100k USD in filters and 100k USD in computing equipment. Technician salaries in Mexico do not make more than 30k USD each. if we include in the operation budget post-doc salaries, travel of the scientific groups, etc... we might reach the 800k USB per year. We consider this figure as conservative, with the possibility of operating with a lower amount.

The sum of installing HAWC and the support infrastructure, filling it and three years of operations is about 88.7 million pesos or 8.5 million USD.

4.3 Scientific input of the Mexican HAWC collaboration

The Mexican HAWC collaboration is a mixture of over thirty astrophysicists, geophysicists and high energy physicists, from the main scientific institutions of Mexico. This includes specialists in interstellar medium (Carrasco, Silich and Tenorio Tagle at INAOE), AGNs (Dultzin at IA-UNAM), GRBs (González and Lee at IAUNAM), compact stars (Page at IAUNAM, Carramiñana at INAOE) and neutrinos (Zepeda at Cinvestav; Delepine at Guanajuato). Members of the Auger collaboration are also involved (Nellen at ICN-UNAM, Villaseñor at UMich), including the group of BUAP who are working in setting-up the cosmic-ray experiments in the Citlaltepetl and Sierra Negra zone (Salazar, Martínez, Álvarez). Both INAOE and UNAM contribute with solar specialists, either astronomers (Mendoza - INAOE) or geophysicists (Lara, Valdés Galicia - Geofísica UNAM). The group of Geociencias of UNAM in Queretaro has expressed peripheral interest in the project, as much as it can provide information of the geology of the region. This follow the line of the proposal by the group of the Instituto de Física UNAM for using muons to map the structure of Citlaltepetl, in an analogous project to the mapping of the pyramid of the Sun in Teotihuacán.

In short we can cite specific scientific advantages of installing HAWC in the Parque Nacional Pico de Orizaba:

- if the instantaneous field of view of HAWC is 35°, it will be able to map all declinations between -14° and $+54^\circ$, i.e. 52% of the celestial sphere, reaching down to longitude 15° in the Galactic plane. This translates in a perfect overlap with the Veritas strip survey and a non-negligeable overlap with the HESS Galactic plane survey.

- the transit zenith angle of the Crab nebula will be 3°, making it possible a precise characterization of the performance of the instrument with zenith angle, together with a prime database of the Crab.

- it will be able to work in a coordinated mode with the two HEGRA telescopes to be installed on top of Sierra Negra and with the LMT in the study of transients like blazars and gamma-ray bursts. The groups of UNAM and INAOE are likely to implement a multiwavelength monitoring program during the operations of GLAST and HAWC.

- located in the Sierra Negra region HAWC will benefit of the solar studies performed with the RT5 solar radiotelescope and the detector de neutrones solares DNS. The groups of INAOE and Instituto de Geofísica UNAM involved in these experiments will also be in the HAWC collaboration and will provide man power to perform data analysis required to expand their solar studies into the HAWC domain.

- the "volcano tomography" proposal to map the interior of Citlaltepetl can become a particularly interesting extension to the scientific potential of HAWC into the geosciences. We note that Citlaltepetl is a particularly interesting volcano due to its youth, dimensions and relation with the other volcanoes in the Faja Volcánica Transmexicana.

- the joint US-Mexican HAWC collaboration will be one of the most important scientific bi-national groups, second in resources to that of the LMT but with a more numerous scientific group.

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