The observations of the very-high-energy gamma-ray sky by HAWC

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Abstract. The High Altitude Water Cherenkov (HAWC) observatory is an air shower detector designed to study very-high-energy gamma rays. In this proceeding we report the most recent scientific results by HAWC that include the detection of 39, point and extended, gamma-ray sources (already known and new) as well as their physical properties. Also HAWC monitors the flux from the Crab Nebula and two nearby active galactic nuclei, Markarian 421 and Markarian 501, every day as well as searching for transient on various timescales from other sources.

1. HAWC observatory
The HAWC observatory is an instrument designed to be sensitive to gamma rays and cosmic rays between the energies of 100 GeV and 100 TeV. It consists of an array of 300 water Cherenkov detectors (WCDs) deployed in a surface of 22 000 m$^2$ at 4100 m above sea level, in the slopes of the volcano Sierra Negra, Mexico. Each WCD is made up of a cylindrical structure of steel with 7.3 m of diameter and 4.5 m high, with a light-tight bladder inside of it storing 200 000 l of highly purified water. At the bottom of the bladder there are four photomultiplier tubes (PMTs), three (8-in photocathode) forming an equilateral triangle with side length of 3.2 m, centered around the fourth one (10-in photocathode) located at the center of the WCD.

The detection technique is based in the detection of the secondary particles of the extended air showers (EAS) produced by very energetic gamma rays and cosmic rays hitting Earth atmosphere. These particles traveling at relativistic speeds will produce Cherenkov light in the water. By registering the time in which the particles hit the WCDs and the intensity of the light that they produce, it is possible to estimate the direction and the energy of the primary gamma-ray. This detection technique allows HAWC to have a wide field of view of 2 sr and a duty cycle $> 95\%$, which makes it the best instrument in current operation for an almost continuous monitoring of the gamma-ray sky.

2. HAWC sensitivity
The Crab Pulsar Wind Nebula (Crab Nebula) is the brightest source in the Northern sky at TeV energies. It is generally accepted that it is a steady source of TeV photons [1, 2, 3] and can be used to calibrate and verify the performance of a TeV gamma-ray instrument.

In order to assess the performance of the HAWC observatory, 507 days of data taken between 2014 November 26 and 2016 June 2 were selected [4]. The data was fitted using a likelihood procedure [5, 6] and using a log-parabola function $\phi(E) = \phi_0 (E/E_0)^{-\alpha-\beta \ln(E/E_0)}$ as model for
Figure 1. Crab Nebula spectrum measured by HAWC compared with measurements from other instruments [7, 8, 9, 10, 3]. The red band is the $1\sigma$ uncertainty and the light red band indicates the systematic uncertainty [4].

Figure 2. The quasi-differential sensitivity of HAWC as function of photon energy, compared to other instruments [7, 11]. The 507-day observation of HAWC correspond to $\sim 3000$ hours of a source at a declination of $22^\circ$ [4].

the differential spectrum. The de-correlation energy $E_0$ was fixed at $E_0 = 7$ TeV, and the maximum of the likelihood occurs at $\alpha = 2.69 \pm 0.03$, $\beta = 0.15 \pm 0.03$ and $\log_{10}(\phi_0 \text{ cm}^2 \text{ s TeV}) = -12.60 \pm 0.02$. The test statistic (TS) compared to the background-only hypothesis yields a detection significance of more than $100\sigma$ [4].

Figure 1 shows the Crab Nebula spectrum measured by HAWC compared by the spectrum reported from other instruments. It can be seen that the spectrum is compatible with prior measurements within systematic uncertainties. The observation of Crab nebula validates the HAWC analysis for other sources in the sky.

Figure 2 shows the computed differential sensitivity of HAWC to sources at the declination of the Crab Nebula with differential photon spectrum of $E^{-2.63}$. Each bin shows the required flux to be detected at $5\sigma$ 50% of the time. The lines for each bin are shown with a width corresponding to the width required to contain 68% of the events under the $E^{-2.63}$ hypothesis. A correction is made to adjust the bin separation to a quarter decade in true energy, and the result is fitted.

3. HAWC gamma-ray sources catalog

The HAWC Collaboration produced a new catalog of TeV gamma-ray sources with 507 days of data collected between 2014 November 26 and 2016 June 2 observed by the HAWC observatory. For the analysis of the data the maximum likelihood framework was used. The sources were modelled with the following assumptions: a point source or a uniform disk of fixed radius, and a power law energy spectrum [12]. For the analysis of sources considered as pointlike, the spectral index was fixed at -2.7, whereas for the sources considered as extended the spectral index was fixed at -2.0. Also for the extended sources, three hypothesis regarding the extension were considered: radius of 0.5°, 1.0° and 2.0° in the sky. A total of 39 sources were found, 4 of which are extended, according to the search procedure. Out of these 39 sources, 16 are more than a degree away from known TeV sources listed in the TeVCat [13]. Figure 3 shows the test-statistic map for point sources with index -2.7 in equatorial coordinates. The sources Markarian 501 (Mrk501), Makarian 421 (Mrk421) and the Crab Nebula are clearly seen. Figure 4 shows the region around Geminga for the two kinds of analysis. The left map shows the point source
Figure 3. Equatorial full-sky test-statistic map, for a point source hypothesis with a spectral index -2.7 [12].

Figure 4. Region around Geminga in Galactic coordinates. Left: test-statistic map for a point source with spectral index -2.7. Right: test-statistic map for an extended source [12].

4. Daily monitoring of bright sources seen by HAWC

The HAWC observatory with its wide field of view and a high duty cycle is able to monitor any source over two-thirds of the sky for up to 6 hours per day. With 17 months of data between 2014 November and 2016 April, the HAWC Collaboration produced light-curves with single-transit intervals for the brightest objects in the gamma-ray sky: Mrk421, Mrk501 and the Crab Nebula [14]. For each transit, the flux and spectral analysis was performed using the standard HAWC maximum-likelihood method [6]. The three objects were modeled as point sources. To assess the variability of the light curves two different approaches were used. One was the maximum-likelihood in which the flux of each transit for each source was compared with the hypothesis of
Figure 5. Light curve for Mrk421 for 471 transits. The blue lines show the distinct flux states identified via the Bayesian blocks [14].

Figure 6. Light curve for Mrk501 for 479 transits. The blue lines show the distinct flux states identified via the Bayesian blocks [14].

a constant flux. The other approach was the Bayesian block algorithm [15], in which the light curve is divided in regions in which the flux are well represented by a constant flux.

For the analysis the Crab Nebula spectrum was modeled a power law with fixed at $\Gamma = 2.63$, leaving the flux normalisation as a free parameter. The maximum-likelihood analysis of the variability showed a probability of 0.292 of being compatible with a constant flux, whereas the Bayesian block analysis revealed no change points [14]. This result is in agreement with the observations of other TeV instruments.

Figure 5 shows the light curve for Mrk421 with 1-transit intervals. The flux of each point was computed modelling the spectrum as a power law with exponential cut-off, with photon index at $\Gamma = 2.21$ and the cut-off at $E_0 = 5.4$ TeV. The likelihood variability test showed a probability of $4.40 \times 10^{-54}$ of being compatible with a constant flux. The Bayesian block analysis corresponding to a false positive of 5% identified 18 change points in the light curve [14].

Figure 6 shows the light curve for Mrk501 with 1-transit intervals. The spectrum of this source was modelled as Mrk421, with photon index was fixed at $\Gamma = 1.6$ and the cut-off at $E_0 = 5.7$ TeV. The likelihood test showed a probability of $9.18 \times 10^{48}$ and the Bayesian block analysis revealed 13 change points [14].

5. HAWC search for transient events

One of HAWC’s most promising capabilities is the detection of transient events. The HAWC Collaboration has analysed the data coincidental in time and location with 64 gamma-ray burst (GRBs) observed by Swift and Fermi satellites [16]. The analysis was performed using
a classical ON/OFF method in which a circle is defined around the GRB position determining the background events that appear in it, and then computing the number of events above the background. Since the duration of GRBs are variable, different time durations for the search around the time of the event were taken into account. None of the GRBs analysed yielded a significant detection. However upper limits for the very-high energy emission were set [16].

The HAWC collaboration has also implemented a real-time monitor for rapid detection of transient events on timescales lasting from 2 minutes to 10 hours [17]. A total of 187 targets are monitored based on their high probability to produce very-high-energy gamma rays: 46 from TeVCat [13] and 141 from the Fermi-LAT catalog [18]. The monitor is fully operational January 2017 and its capabilities has been tested having positive detection in archival HAWC data of high-confidence flares of Mrk421 and Mrk501 [17].

Acknowledgments
We acknowledge the support from: the US National Science Foundation (NSF); the US Department of Energy Office of High-Energy Physics; the Laboratory Directed Research and Development (LDRD) program of Los Alamos National Laboratory; Consejo Nacional de Ciencia y Tecnología (CONACyT), México (grants 271051, 232656, 260378, 179588, 239762, 254964, 271737, 258865, 243290, 132197, 281653), Laboratorio Nacional HAWC de rayos gamma; L’OREAL Fellowship for Women in Science 2014; Red HAWC, México; DGAPA-UNAM (grants IG100317, IN111315, IN111716-3, IA102715, 109916, IA102917); VIEP-BUAP; PIFI 2012, 2013, PROFOCIE 2014, 2015;the University of Wisconsin Alumni Research Foundation; the Institute of Geophysics, Planetary Physics, and Signatures at Los Alamos National Laboratory; Polish Science Centre grant DEC-2014/13/B/ST9/945; Coordinación de la Investigación Científica de la Universidad Michoacana. Thanks to Luciano Díaz and Eduardo Murrieta for technical support.

References
[1] Abramowski, A. et al., Astronomy and Astrophysics, 562, L4.
[2] Aliu, E. et al., ApJL, 2014, 14, L11.
[3] Bartoli, B., ApJ, 2015, 798, 119.
[4] Abeysekara, A. U. et al., ApJ, 2017, 843, 39.
[5] Albert, S. S., Ann. Math. Statist, 1938, 9, 60.
[6] Younk, P., PoS, ICRC2015, 1042.
[7] Eldik, C. et al., PoS, ICRC2015, 847.
[8] Aleksić, J. et al., JHEAP, 2015, 5, 30.
[9] Meagher, K., PoS, ICRC2015, 792.
[10] Amenomori, M. et al., ApJ, 2015, 813, 98.
[11] Aleksić, J. et al., Astroparticle Physics, 2016, 72, 76.
[12] Abeysekara, A.U. et al., ApJ, 2017, 843, 40.
[13] Wakely S. P. and Doran D., ICRC, 2008, 3, 1341.
[14] Abeysekara, A. U. et al., ApJ, 2017, 841, 100.
[15] Scargle, J. D., Norris, J. P., Jackson, B., Chiang, J., ApJ, 2017, 764, 167.
[16] Alfaro, R. et al., ApJ, 2017, 843, 88.
[17] Abeysekara, A. U. et al., ApJ, 2017, 843, 116.
[18] Ackermann, M. et al., ApJS, 2016, 222, 5.