Gamma-Neutrino Coincidence Alerts to GCN

GAMMA_NU Alerts

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AMON

Astrophysical Multimessenger Observatory Network

The Astrophysical Multimessenger Observatory Network

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1.1 Motivation

The Astrophyisical Multimessenger Observatory Network (AMON) [1], will issue public alerts based on gamma rays and neutrino sub-threshold detections. The present documentation focus on the description of the alerts produced by an analysis using data from the HAWC observatory's (see [2]) daily monitoring stream and the IceCube singlet stream [3]. Neutrino coincidences with gamma rays are one of the main probes that we have to look for sources of cosmic rays and neutrinos.[1] The purpose of sending these public alerts is to encourage the astrophysical community to perform follow-up observations of these coincidences. Our plan is to send alerts with a false alarm rate (FAR) of < 4 coincidences per year. This FAR threshold is still within our expectation of random coincidences, so with the help of follow-up observations we can pinpoint the coincidences that could be real. We present a brief summary of the searches and the description of the coincidence alerts that we are sending.

1.2 Data

The HAWC data fed into the analysis consists of significant excess above 2.75, or "hotspot", locations in the sky with a cluster of events above the estimated cosmic-ray background level, identified during one full transit of that sky location above the detector. Most of these events are expected to just be fluctuations from the expected background in HAWC.

The IceCube data, made by the singlet stream, is generated by an online neutrino search that is tuned to select track-like through-going neutrino events. It is dominated by background events, atmospheric neutrino events in the Northern hemisphere, and high-energy atmospheric muons in the Southern hemisphere.

1.3 Description of the alerts

The coincidence analysis is defined by two criteria. First is a temporal one, where we look for neutrinos inside the transit time of the HAWC "hotspot". Second, we select neutrinos that are within a radius of 3.5° from the HAWC "hotspot" localization. After the neutrino events have passed the selection criteria, we calculate a ranking statistic to select the most interesting coincident events. This ranking

[1] A publication describing the analysis is in progress.

statistic is based on Fisher's method, where we combine all the information that we have from the events. It is defined as:

$$\chi^2_{6+2n_\nu} = -2\ln[p_\lambda p_{HAWC} p_{cluster} \prod_i^{\nu} p_{IC,i}], \tag{1.1}$$

where p_λ quantifies the overlap of the spatial uncertainties of the events; p_{HAWC} is the probability of the HAWC event being compatible with a background fluctuation; $p_{cluster}$ is the probability of seeing more than one neutrino from background in the HAWC transit period; and $p_{IC,i}$ is the probability of measuring an energy/BDT score or higher for an Icecube event assuming it is a background event (calculated using the energy/BDT score and zenith angle). The p_λ value is obtained from maximizing a likelihood calculation that measures how much the position of the HAWC event and the IceCube events overlap with each other. This is calculated as

$$\lambda(\vec{x}) = \sum_{i=1}^{N}(ln(S_i(\vec{x})) - ln(B_i)) \tag{1.2}$$

where S corresponds to the uncertainties of the events, assuming Gaussian distributions on the sphere, and B is the spatial background distribution from each detector at the position of the events. This likelihood is maximized by finding the best position of the coincidence $\vec{x}$. A higher λ value means the uncertainties of the events overlap more. This translates into a smaller p_λ. Since during the likelihood the product of the Gaussian distributions leads to another gaussian, we use this to obtain the uncertainty in the position of the coincidence. This leads the uncertainty to be similar in size to the smallest uncertainty which in this case comes from the HAWC "hotspot" ($\mathcal{O}(0.2^\circ)$). We will send 50% and 90% containment radius (1.18σ and 2.15σ for a 2D gaussian).

Due to the fact that we can have more than one neutrino in the time window, this affects the degrees of freedom of equation 1.1. Considering this, we transform the χ^2 to a p-value, with the corresponding number of degrees of freedom, and then calculate the negative logarithm of this quantity. This is represented as

$$\chi^{2'} = -\log p(> \chi^2_{6+2n_\nu}), \tag{1.3}$$

which is the value that we used to rank the coincidences. The false alarm rate (FAR) is a function of this value.

1.4 Rate of coincidence alerts and latency

The analysis methods was run on scrambled datasets. These datasets corresponds to two years of data. The scrambled process was done several times to obtain enough statistics to build the FAR distribution. Figure 1.1 is the FAR as a function of the ranking statistic. The FAR reported will be derived per coincidence based on the ranking statistic value found in Eq. 1.3 and the equation that appears in Fig. 1.1 derived from the scrambled tests.

The rate of alerts that we will sent to GCN is 4 per year, which corresponds to a ranking statistic threshold of 6.48.

Due to the way the HAWC analysis is performed, the location of the sky has to transit above the HAWC detector before the analysis can start. This, depending on the declination, will take at least 6 hours before an alert can be sent. The coincidence analysis inside the AMON servers take less than a minute to run after it receives the alert.

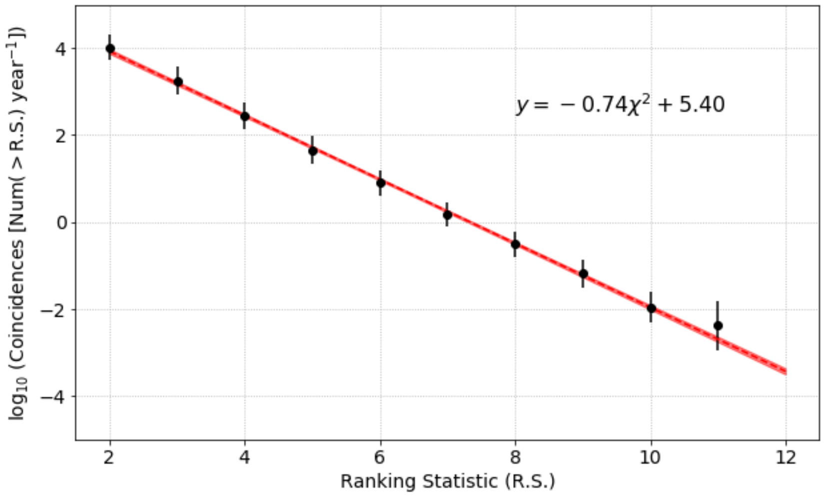

Figure 1.1: False alarm rate as a function of the ranking statistic obtained from the scrambled datasets

1.5 Description of the alert GCN notice content

The GCN notices contain information that should help follow-up observatories decide on following possible multi-messenger sources, specifically the false alarm rate.

- GCN Stream: GCN Socket number. This corresponds to 172 for the Gamma-Nu stream.
- AMON Stream: Number of the AMON analysis stream. For this HAWC-IceCube analysis, the value is 1.
- AMON ID: ID of the coincidence event.
- Revision: Revision of the coincidence.
- Right Ascension and Declination in several epochs (current, J2000 and J1950) with a 50% and 90% containment angular uncertainty.
- Time and date in universal time (UTC): this will correspond to the end of the HAWC transit.
- Time window: this will correspond to the time of the HAWC transit, which depends on the declination. Given in seconds.
- False Alarm Rate: rate of random coincidences expected from the scrambled analysis.
- P-value: This is a default parameter for the Gamma-Nu GCN stream. No value is generated for this analysis, though in general it will be the probability of observing a coincidence ranking statsitic (or higher) assuming the coincidence is fortuitous. For this analysis it will be always 1.

It will also contain more information that is derived by GCN. These can be the position in other coordinate systems, distance to the sun or moon, etc. See the example in the next section.

1.6 Example of alert message

```
//////////////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Sun 24 Feb 19 02:03:33 UT
```

```
NOTICE_TYPE:     GAMMA_NU_COINC
GCN_STREAM:      172
AMON_STREAM:     1
AMON_ID:         29
REVISION:        0
SRC_RA:          220.30d {+14h 41m 13.86s} (J2000),
                 220.5000d {+14h 42m 1.02s} (current),
                 219.8014d {+14h 39m 12.44s} (1950)
SRC_DEC:         36.80d {36d 48' 02"} (J2000),
                 36.72001d {36d 43' 12"} (current),
                 37.01d {37d 00? 49"} (1950)
SRC_ERROR:       0.9 [deg, stat, 90\% containment]
SRC_ERROR50:     0.49 [deg, stat, 50\% containment]
DISCOVERY_DATE:  18538 TJD;  55 DOY; 19/02/24 (yy/mm/dd)
DISCOVERY_TIME:  39689 SOD {11:01:29.00} UT
TIME_WINDOW:     19800[s]
FAR:             0.87 [yr^-1]
P-VALUE:         1
SUN_POSTN:       337.09d {+22h 28m 23s} -9.57d {-9d 34' 34"}
SUN_DIST:        117.09 [deg] Sun_angle= 7.8 [hr] (West of Sun)
MOON_POSTN:      121.73d {+08h 06m 56s} +20.14d {+20d 08' 11"}
MOON_DIST:       98.92 [deg]
GAL_COORDS:      62.46, 64.89 [deg] galactic lon,lat of the event
ECL_COORDS:      201.47,49.08 [deg] ecliptic lon,lat of the event
COMMENTS:        Gamma-Nu Coincidence Alert from Daily Monitoring HAWC and IceCube
```

1.7 Revisions

Due to the way the HAWC algorithm works, once a point in the sky leaves HAWC's field-of-view, the analysis starts. It is possible that the location of the maximum of the hotspot has not finished its transit, so a revision of the alert will be issued, with a typical delay of ∼15 mins. A coincidence alert then might also have a revision accordingly.

1.8 Follow-up Procedure

Any follow-up observatory can send a GCN circular after performing the respective observations. AMON members (collaborations or groups that have signed an MoU with AMON), should also send their follow-up information to the email amon.psu@gmail.com.

Analysis 2

ANTARES Fermi Alerts

2.1 Motivation

The AMON collaboration is planning to send out private real time alerts for coincidences between Fermi-LAT gamma rays and ANTARES neutrinos. The current plan is to send alerts with a false alarm rate (FAR) of ¡ 4 coincidences per year. We present here a brief summary of the searches and the description of the coincidence alerts.

2.2 Description of alert selection

At its core, our analysis is a real-time search for Fermi-LAT gamma rays coincident with neutrinos detected by ANTARES. The ANTARES collaboration sends their neutrino data to AMON in real time over a private stream. Photon data from the LAT is downloaded as it becomes publicly available on the LAT FTP server[1].

Once new LAT data has been downloaded, our analysis first filters the data. We require the photons to have energies between 100 MeV and 300 GeV, a LAT zenith angle of less than 90°, and arrival times within the boundaries of the good time intervals (GTI) provided by the LAT satellite files.

The coincidence search is then carried out on the filtered LAT data and the ANTARES data. A coincidence is defined as any photons arriving within 5° and ± 1000 s of an ANTARES neutrino. For each coincidence, a pseudo-log-likelihood test statistic, λ, is calculated as follows:

$$\lambda = 2 \ln \frac{P_{\nu\gamma}(\vec{x})\, n_\nu!\, n_\gamma!\, \Pi_{\nu,\gamma}\, \tau(\Delta t_i)}{\Pi_\gamma\, B_{\gamma,i}(\vec{x})} + \sum_\nu \ln \frac{1 - p_{c,i}}{p_{c,i}}, \tag{2.1}$$

where $P_{\nu\gamma}$ is the product of the point spread functions (PSF) of each LAT photon and each ANTARES neutrino at the best position, $\vec{x}$, with each PSF normalized to have units of probability per square degree. The n_ν and n_γ terms are respectively the number of neutrinos and gamma rays in the coincidence. The $\Pi_{\nu,\gamma}\, \tau(\Delta t_i)$ term is the product of the temporal weighting function (Fig. 2.1) for each neutrino and gamma ray in the coincidence. For particles within 100 s of the average arrival time, this function is identically one, and it scales as $1/\Delta t$ for times between 100 s and 1000 s. This allows the search to address the possibility of longer-timescale associations (as might result from low-luminosity GRBs) while maintaining a preference for shorter-timescale associations, if and when they are also present.

[1] LAT data located at ftp://legacy.gsfc.nasa.gov/fermi/data/lat/weekly/photon/

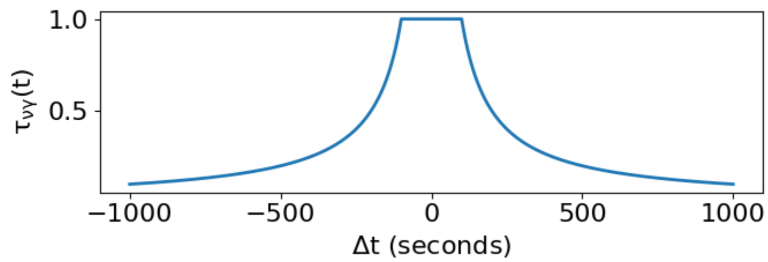

Figure 2.1: Temporal weighting function $\tau(\Delta t)$ used in the analyses. For $|\Delta t|$ <100 s, the function is flat and equal to 1. For $100\,\mathrm{s} < |\Delta t| < 1000\,\mathrm{s}$, the function scales as $1/\Delta t$.

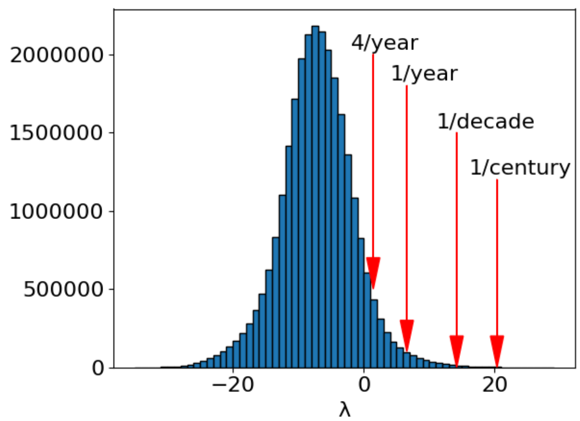

Figure 2.2: Histogram of the null λ distribution. Thresholds marking different false alarm rates are marked in red.

The $\Pi_\gamma\ B_{\gamma,i}(\vec{x})$ term is the product of LAT gamma raybackgrounds for each photon at the coincidence location. Together with the factorial terms, this acts like a Poisson probability of observing n_γ photons from background. The p_c factor is established by the ANTARES Collaboration for each individual neutrino candidate, according to its likelihood to be of astrophysical origin. This factor acts to prefer higher-energy events as more likely astrophysical in origin, with smaller values of p_c indicating a higher energy and a more likely cosmic origin. Overall, larger values of the λ statistic suggest a greater likelihood of a physically associated multiplet from a cosmic source, rather than a coincidence of uncorrelated events.

The best fit position $\vec{x}$ is determined as the location of maximal PSF overlap. As the overlap of a double King function with the interpolated neutrino PSF cannot be solved analytically, the best-fit position is found numerically. For multi-photon coincidences, the event photon multiplicity is determined iteratively: We compare the λ value at maximum multiplicity to that which would result if the photon with the lowest PSF density at the best-fit position were excluded (after recalculating the best-fit position and λ), and iteratively exclude photons until the optimal λ has been computed.

The background is calculated via Monte Carlo simulation. We run 10,000 scrambled versions of the archival ANTARES data are run against the concurrent LAT data to calculate the expected null distribution. Background rates are estimated from the null distribution. Any alert more significant than the 4/year threshold will be sent out via GCN to AMON followup partners.

2.3 Description of alert GCN notice content

The GCN notices contains the following information provided by the AMON collaboration:

- GCN Stream: GCN Socket number. This corresponds to 172 for the Gamma-Nu stream.
- AMON Stream: Number of the AMON analysis stream. For the ANTARES-Fermi analysis, the value is 8 .
- AMON ID: ID of the coincidence event.
- Revision: Revision of the coincidence.
- Time and date in universal time.
- Right Ascension and Declination in several epochs (current, J2000 and J1950) with a $1-\sigma$ (39% containment) angular uncertainty.
- Time window search: the size of the time window for the search.
- False Alarm Rate: rate of background events expected that are "like this alert" observed.
- P-value: This is a default parameter for the Gamma-Nu GCN stream. No value is generated for this analysis, though in general it will be the probability of observing a coincidence ranking statsitic (or higher) assuming the coincidence is fortuitous. For this analysis it will be always 1.

It will also contain more information that it is useful for follow-ups. See the example in the next section.

2.4 Example of alert message

```
//////////////////////////////////////////////////////////////////////
TITLE:           GCN/AMON NOTICE
NOTICE_DATE:     Sun 24 Feb 19 02:03:33 UT
NOTICE_TYPE:     GAMMA_NU_COINC
GCN_STREAM:      170
AMON_STREAM:     8
AMON_ID:         1429625906
REVISION:        0
SRC_RA:          46.181d {+03h 04m 43.37s} (J2000),
                 46.418 {+03h 05m 40.31s} (current),
                 45.569d {+03h 02m 16.65s} (1950)
SRC_DEC:         -8.273d {-08d 16' 26.11''} (J2000),
                 -8.199d {08d 11? 57.5"} (current),
                 -8.468d {08d 28? 03.8"} (1950)
SRC_ERROR:       0.233 [deg, stat, 90\% containment]
SRC_ERROR50:       0.127 [deg, stat, 50\% containment]
DISCOVERY_DATE:  18615 TJD;  132 DOY; 19/05/12 (yy/mm/dd)
DISCOVERY_TIME:  6243 SOD {01:42:52.783} UT
TIME_WINDOW:     364.16[s]
FAR:             0.0613 [yr^-1]
P-VALUE:         1
SUN_POSTN:       48.3375d {+03h 13m 21.3s} 17.9456d {17d 56? 43.7"}
SUN_DIST:        26.3 [deg] Sun_angle= 1.75 [hr] (West of Sun)
MOON_POSTN:      143.7958d {+09h 35m 11.0s} +17.1719d {+17d 10? 19.2"}
MOON_DIST:       99.65 [deg]
```

```
GAL_COORDS:       188.324, -53.279 [deg] galactic lon,lat of the event
ECL_COORDS:       201.47,49.08 [deg] ecliptic lon,lat of the event
COMMENTS:         Gamma-Nu Coincidence Alert from ANTARES Fermi-LAT
```

Bibliography

[1] Hugo A. Ayala Solares, Stephane Couto, Doug F. Cowen, et al. The Astrophysical Multimessenger Observatory Network (AMON): Performance and science program. *Astro. Phys.*, 114:68–76, Jan 2020.

[2] A.U. Abeysekara, A. Albert, R. Alfaro, et al. Observation of the Crab Nebula with the HAWC Gamma-Ray Observatory. *ApJ*, 849:39, 2017.

[3] M. G. Aartsen, M. Ackermann, J. Adams, et al. The IceCube realtime alert system. *Astro. Phys.*, 92:30–41, Jun 2017.