Fermi-LAT 8-year Source List

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ABSTRACT

We distribute a preliminary *Fermi* Large Area Telescope list of sources (FL8Y) meant to help in writing 2018 NASA *Fermi* Guest Investigator proposals. Based on the first eight years of science data from the *Fermi Gamma-ray Space Telescope* mission and the 100 MeV–1 TeV range, it is the deepest yet in this energy range. Relative to the 3FGL catalog, the FL8Y source list has twice as much exposure as well as a number of analysis improvements, but is lacking an updated model for Galactic diffuse γ-ray emission. The FL8Y source list includes 5524 sources above 4σ significance, with source location regions and spectral properties. Fifty-eight sources are modeled explicitly as spatially extended, and overall 300 sources are considered as identified based on angular extent or correlated variability (periodic or otherwise) observed at other wavelengths. For 2131 sources we have not found plausible counterparts at other wavelengths. More than 2900 of the identified or associated sources are active galaxies of the blazar class, 218 are pulsars.

This source list is meant to be replaced within a few months by the official 4FGL catalog which will benefit from an improved model of diffuse emission.

1. Introduction

This document presents a preliminary list of high-energy γ-ray sources detected in the first eight years of the *Fermi Gamma-ray Space Telescope* mission by the Large Area Telescope (LAT). It is not yet a full-fledged official catalog; therefore we call it FL8Y (for *Fermi*-LAT 8-Year). As in the Third LAT Source Catalog (hereafter 3FGL, Acero et al. 2015) sources are included based on the statistical significance of their detection considered over the entire time period of the analysis. For this reason the FL8Y source list does not contain transient γ-ray sources which are significant over a short duration (such as γ-ray bursts).

The FL8Y source list benefits from a number of improvements with respect to 3FGL, besides the twice longer exposure:

1. Pass 8 data[1] are now used (§ 2.2). The principal difference relative to the P7Rep data used for 3FGL is larger acceptance by about 20% at all energies and improved angular resolution above 3 GeV.
2. We introduce weights in the maximum likelihood analysis (§ 3.2) in order to mitigate the effect of systematic errors due to our imperfect knowledge of the diffuse emission.
3. We explicitly model 58 sources as extended emission regions (§ 3.4), up from 25 in 3FGL.
4. For studying the associations of LAT sources with counterparts at other wavelengths, we have updated several of the catalogs used for counterpart searches, and correspondingly recalibrated the association procedure.

The 4FGL catalog will make use of the same methods, but will adopt an improved diffuse emission model. It will also contain, like 3FGL, spectral energy distributions in broad bins and light curves, which are not provided with FL8Y.

Section 2 describes the LAT, the data and the models for the diffuse backgrounds, celestial and otherwise. Section 3 describes how the catalog is constructed, with emphasis on what has changed since the analysis for the 3FGL catalog. We provide appendices with technical details of the analysis and of the format of the electronic version of the catalog.

2. Instrument & Background

2.1. The Large Area Telescope

The LAT detects γ rays in the energy range 20 MeV to more than 1 TeV, measuring their arrival times, energies, and directions. The LAT is also an efficient detector of the intense background of charged particles from cosmic rays and trapped radiation at the orbit of the *Fermi* satellite. Accounting for γ rays lost in filtering charged particles from the data, the effective collecting area is $\sim$8000 cm^2 at 1 GeV at normal incidence (for the P8R3_SOURCE_V2 event selection used here; see below). The live time is nearly 76%, limited primarily by interruptions of data taking when *Fermi* is passing through the South Atlantic Anomaly ($\sim$13%) and readout dead-time fraction ($\sim$9%). The field of view of the LAT is 2.4 sr at 1 GeV. The per-photon angular resolution (point-spread function, PSF,

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[1] See http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Pass8_usage.html.

68% containment radius) is ∼ 5° at 100 MeV, decreasing to 0.°8 at 1 GeV (averaged over the acceptance of the LAT), varying with energy approximately as $E^{-0.8}$ and asymptoting at ∼ 0.°1 above 20 GeV. The tracking section of the LAT has 36 layers of silicon strip detectors interleaved with 16 layers of tungsten foil (12 thin layers, 0.03 radiation length, at the top or *Front* of the instrument, followed by 4 thick layers, 0.18 radiation length, in the *Back* section). The silicon strips track charged particles, and the tungsten foils facilitate conversion of γ rays to positron-electron pairs. Beneath the tracker is a calorimeter composed of an 8-layer array of CsI crystals (∼8.5 total radiation lengths) to determine the γ-ray energy. A segmented charged-particle anticoincidence detector (plastic scintillators read out by photomultiplier tubes) around the tracker is used to reject charged-particle background events. More information about the LAT is provided in Atwood et al. (2009), and the in-flight calibration of the LAT is described in Abdo et al. (2009c), Ackermann et al. (2012a) and Ackermann et al. (2012b).

2.2. The LAT Data

The data for the FL8Y source list were taken during the period 2008 August 4 (15:43 UTC) to 2016 August 2 (5:44 UTC) covering close to eight years. Intervals around 30 bright GRBs were excised. Solar flares were excised as well, as for 3FGL. Overall about two days were excised due to solar flares, and 39 ks due to GRBs. The precise time intervals corresponding to selected events are recorded in the `GTI` extension of the FITS file (App. B). The maximum acceptance (4.5×10^{11} cm^2 s at 1 GeV) is reached at the North celestial pole. The minimum acceptance (2.7×10^{11} cm^2 s at 1 GeV) is reached at the celestial equator.

The current version of the LAT data is Pass 8 P302 (Atwood et al. 2013). It offers 20% more acceptance than P7Rep and a narrower PSF at high energies. Both aspects are very useful to source detection and localization (Ajello et al. 2017). We used the Source class event selection. The lower bound of the energy range was left at 100 MeV, but the upper bound was raised to 1 TeV. This is because as the source-to-background ratio decreases, the sensitivity curve (Figure 18 of Abdo et al. 2010b, 1FGL) shifts to higher energies.

A residual non-isotropic instrumental background component is apparent in the P302 data at all energies, peaking in a broad ring around the ecliptic equator. The LAT collaboration has recently understood that this background was arising from electrons and positrons leaking through the scintillating ribbons between the anticoincidence tiles. That leakage is most pronounced perpendicular to the tiles, and the ecliptic axis of symmetry is due to the orientation of the solar panels toward the Sun. Since we do not have a good model of this instrumental background, we chose to reduce it to a negligible level (< 1% of the astrophysical background) by cutting harder on the ribbon-related reconstruction variables. That data set is called P305, and the associated calibration is P8R3_SOURCE_V2. The effective area is within 1% of the official P8R2_SOURCE_V6 at all energies, so the acceptance loss is very small.

2.3. Model for the Diffuse Gamma-Ray Background

2.3.1. Diffuse emission of the Milky Way

An update to the Galactic diffuse emission model is in preparation and will be used in 4FGL, but for FL8Y we used the 3FGL model (Acero et al. 2016a) adapted to the Pass 8 data[2]. This is the major limitation of the FL8Y source list.

2.3.2. Isotropic background

The isotropic diffuse background was derived from all-sky fits of the four-year data set using the Galactic diffuse emission model described above and the 3FGL source list. The diffuse background includes charged particles misclassified as γ rays. We implicitly assume that the acceptance for these residual charged particles is the same as for γ rays in treating these diffuse background components together. For the analysis we derived the contributions to the isotropic background separately for all event types.

2.3.3. Solar and lunar template

The quiescent Sun and the Moon are fairly bright γ-ray sources. The Sun moves in the ecliptic but the solar γ-ray emission is extended because of cosmic-ray interactions with the solar radiation field; detectable emission from inverse Compton scattering of cosmic-ray electrons on the radiation field of the Sun extends several degrees from the Sun (Abdo et al. 2011). The Moon is not an extended source in this way but the lunar orbit is inclined somewhat relative to the ecliptic and the Moon moves through a larger fraction of the sky than the Sun. Averaged over time, the γ-ray emission from the Sun and Moon trace a region around the ecliptic.

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[2] The model is available as `gll_iem_v06.fit` from the FSSC.

The Sun and Moon emission are modulated by the solar magnetic field which deflects cosmic rays more (and therefore reduces γ-ray emission) when the Sun is at maximum activity. For that reason the model used in 3FGL (based on the first 18 months of data when the Sun was near minimum) was not adequate for 8 years. We used the improved model of the Moon (Ackermann et al. 2016a) and a similar model of the solar disk (S. Raino, private communication). We did not change the model of inverse Compton scattering on the solar light.

We combined those models with calculations of their motions and of the exposure of the observations by the LAT to make templates for the equivalent diffuse component for the 3FGL analysis using *gtsuntemp* (Johannesson et al. 2013). We reduced the pixel size used to compute the emission from the solar and lunar disks to $0\overset{\circ}{.}125$ in order to follow their paths accurately. As for 3FGL those components have no free parameter.

2.3.4. Residual Earth limb template

For 3FGL we reduced the low-energy Earth limb emission by selecting zenith angles less than 100°, and modeled the residual contamination approximately. For FL8Y (except in § 3.1 which used the same approach as 3FGL) we chose to reject it by cutting harder on zenith angle at low energies and selecting event types with the best PSF. The zenith angle cut was set such that the contribution of the Earth limb at that zenith angle was less than 10% of the total background. Integrated over all zenith angles, the residual Earth limb contamination is less than 1%. We kept PSF2 and PSF3 event types with zenith angles less than 90° between 100 and 300 MeV, and PSF1, PSF2 and PSF3 event types with zenith angles less than 100° between 300 MeV and 1 GeV. Above 1 GeV we kept all events with zenith angles less than 105°.

Selecting on zenith angle applies a kind of time selection (which depends on direction in the sky). This means that the effective time selection at low energy is not exactly the same as at high energy. That time selection is mostly on time scales (at orbit level) shorter than the variability time scales of astrophysical sources. There remains however a modulation due to the precession of the spacecraft orbit on longer time scales (two months) over which blazars can vary. This is not a problem for a catalog (it can at most appear as a spectral effect, and should average out when considering statistical properties) but it should be kept in mind when extracting spectral parameters of individual variable sources. We used the same zenith angle cut for all event types in a given energy interval in order to reduce systematics due to that time selection.

Because the data are limited by systematics at low energies everywhere in the sky (App. A) rejecting half of the data below 300 MeV does not impact the sensitivity (if we had kept this data, the weights would have been lower).

3. Construction of the Catalog

The procedure used to construct the FL8Y source list has a number of improvements relative to what was implemented for the 3FGL catalog. In this section we review the procedure, with an emphasis on what is being done differently. The significances (§ 3.2) and spectral parameters (§ 3.3) of all catalog sources were obtained using the standard *pyLikelihood* framework (Python analog of *gtlike*) in the LAT Science Tools[3] (version v11r7p0). The localization procedure (§ 3.1), which relies on *pointlike*, provided the source positions, the starting point for the spectral fitting, and a comparison for estimating the reliability of the results (§ 3.5.2). Throughout the text we use the Test Statistic $TS = 2\Delta \log \mathcal{L}$ to quantify how significantly a source emerges from the background, comparing the maximum value of the likelihood function $\mathcal{L}$ with and without that source.

3.1. Detection and Localization

This section describes the generation of a list of candidate sources, with locations and initial spectral fits, for processing by the standard LAT science analysis tools, especially *gtlike* to compute the likelihood (§ 3.2). This initial stage uses instead *pointlike* (Kerr 2010). Compared with the *gtlike*-based analysis described in § 3.2 to 3.5, it uses the same data, exposure, and IRFs, but the partitioning of the sky, the computation of the likelihood function, and its optimization, are independent. Since this version of the computation of the likelihood function is used for localization, it needs to represent a valid estimate of the probability of observing a point source with the assumed spectral function.

The process started with an initial set of sources from the 3FGL analysis, not just those reported in that catalog, but also including all candidates failing the significance threshold (i.e., with $TS < 25$). It also used the same list of 58 spatially extended source (§ 3.4), and the three-source representation of the Crab (§ 3.3). The same spectral models were considered for each source as in § 3.3, but the favored model (power law or curved) was not necessarily the same.

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[3] See http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/.

Many details of the processing were identical to the 3FGL procedure: using HEALPix[4] (Górski et al. 2005) with $N_{\rm side} = 12$, to tile the sky, resulting in 1728 tiles of $\sim$25 deg^2 area; optimizing spectral parameters for the sources within each tile, for the data in a cone of 5° radius about the center of the tile; and including the contributions of all sources within 10° of the center. The tiles are of course discrete, but the regions, which we refer to as RoIs, for Regions of Interest, are overlapping and not independent. The data were binned in energy (16 energy bands from 100 MeV to 1 TeV) and position, where the spatial bin size (the bins also defined using HEALPix) was set to be small compared with the PSF for each energy, and event type. The parameter optimization was performed by maximizing the logarithm of the likelihood, expressed as a sum over each energy band and each of the *Front* and *Back* event types, independently for each RoI. Correlations between sources in neighboring RoIs were then accounted for by iterating all 1728 fits until the changes in the log likelihoods for all RoIs were less than 10.

After a set of iterations had converged, the localization procedure was applied, and source positions updated for a new set of iterations. At this stage, new sources were occasionally added using the residual TS procedure described below. The detection and localization process resulted in $\sim$ 13300 candidate point sources with $TS > 10$. The fit validation, Galactic diffuse renormalization and likelihood weighting were done as in 3FGL.

3.1.1. Detection of additional sources

We used the *pointlike* definition of likelihood itself to detect sources that needed to be added to the model of the sky. Using HEALPix with $N_{\rm side} = 512$, we defined 3.2 M pixels in the sky, separated by $\simeq 0\overset{\circ}{.}15$, then evaluated the improvement in the likelihood from adding a new point source at the center of each.

An improvement with respect to 3FGL is that we considered four different possible spectral shapes:

- a power-law spectrum with photon index 2.1
- a harder power-law spectrum with photon index 1.7
- a softer power-law spectrum with photon index 2.4
- a pulsar-like spectrum (Eq. 2) with $\Gamma = 1.7$, $a = 3.33 \times 10^{-4}$ MeV^{-1} and $b = 1$.

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[4] http://healpix.sourceforge.net.

The TS value for each attempt, assigned to the pixel, defines a residual TS map of the sky. Next we performed a cluster analysis for all pixels with $TS > 10$, determining the number of pixels, the maximum TS, and the TS-weighted centroid. All such clusters with at least two pixels were added to a list of seeds. Then each seed was reanalyzed, now allowing the spectral index to vary, with a full optimization in the respective RoI, and then localized. The last step was to add all such refit seeds, if the fits to the spectrum and the position were successful, and $TS > 10$, as new sources, for a final optimization of the full sky.

3.1.2. Localization

The position of each source was determined by maximizing the likelihood with respect to its position only. That is, all other parameters are kept fixed. The possibility that a shifted position would affect the spectral models or positions of nearby sources is accounted for by iteration. Ideally the log likelihood is a quadratic form in any pair of angular variables, assuming small angular offsets. We define LTS, for Localization Test Statistic, to be twice the log of the likelihood ratio of any position with respect to the maximum; the LTS evaluated for a grid of positions is called an LTS map. We fit the distribution of LTS to a quadratic form to determine the uncertainty ellipse, the major and minor axes and orientation. We also define a measure, the localization quality (LQ), of how well the actual LTS distribution matches this expectation by reporting the sum of the squares of the deviations of eight points evaluated from the fit at a circle of radius corresponding to twice the geometric mean of the two Gaussian sigmas.

We flagged apparently significant sources that do not have good localization fits (LQ > 8) with Flag 9 (Table 3) and for them estimated the position and uncertainty by performing a moment analysis of the LTS function instead of fitting a quadratic form. Some sources that did not have a well-defined peak in the likelihood were discarded by hand, on the consideration that they were most likely related to residual diffuse emission. Another possibility is that two adjacent sources produce a dumbbell-like shape; for some of these cases we added a new source by hand.

As in 3FGL, we checked the brightest sources spatially associated with likely multiwavelength counterparts, comparing their localizations with the well-measured positions of the counterparts. The smaller statistical source localization errors in FL8Y allowed estimating the absolute precision more accurately to $\sim 0\overset{\circ}{.}0075$ at the 95% confidence level, up from $\sim 0\overset{\circ}{.}005$ in 3FGL. The systematic factor was the same 1.05 as in 3FGL. Consequently, we multiplied all error estimates by 1.05 and added $0\overset{\circ}{.}0075$ in quadrature to both 95% ellipse axes.

3.2. Significance and Thresholding

The framework for this stage of the analysis is inherited from the 3FGL catalog. It splits the sky into RoIs, varying typically half a dozen sources near the center of the RoI at the same time. There were 2363 RoIs for FL8Y, listed in the `ROIs` extension of the catalog (App. B). The global best fit is reached iteratively, injecting the spectra of sources in the outer parts of the RoI from the previous step or iteration. In this approach the diffuse emission model (§ 2.3) is taken from the global templates (including the spectrum, unlike what is done with *pointlike* in § 3.1) but it is modulated in each RoI by three parameters: normalization and small corrective slope of the Galactic component and normalization of the isotropic component.

Among more than 13,000 seeds coming from the localization stage, we keep only sources at $TS > 25$ with the power-law model, corresponding to a significance of just over 4σ evaluated from the χ^2 distribution with 4 degrees of freedom (position and spectral parameters, Mattox et al. 1996). The model for the current RoI is readjusted after removing each seed below threshold, so that the final model fits the full data. The low-energy flux of the seeds below threshold (a fraction of which are real sources) can be absorbed by neighboring sources closer than the PSF radius.

As in 3FGL we manually added known pulsars that could not be localized by the automatic procedure without phase selection. Only one was considered significant and appears in FL8Y with a fixed position (no error ellipse). This is PSR J1410−6132 at $TS = 30$ inside the extended source FGES J1409.1−6121 (Ackermann et al. 2017).

We introduced a number of improvements with respect to 3FGL (by decreasing order of importance):

1. In 3FGL we had already noted that systematic errors due to an imperfect modeling of diffuse emission were larger than statistical errors in the Galactic plane, and at the same level over the entire sky. With a twice longer exposure and improved effective area at low energy with Pass 8, the effect is now dominant. The approach adopted in 3FGL (comparing runs with different diffuse models) allowed characterizing the effect globally and flagging the worst offenders, but left purely statistical errors on source parameters. In FL8Y we introduce weights in the maximum likelihood approach (App. A). This allows obtaining directly (although in an approximate way) smaller TS and larger parameter errors, reflecting the level of systematic uncertainties. We estimated the systematic level from the spatial and spectral residuals in the Galactic plane where the diffuse emission is strongest. The resulting $\epsilon \sim 3\%$ was used to compute the weights. This is by far the most important improvement, which avoids reporting many dubious

soft sources.

2. The automatic iteration procedure at the next-to-last step of the process was improved. There are now two iteration levels. In a standard iteration the sources and source models are fixed and only the parameters are free. An RoI and all its neighbors are run again until $\log \mathcal{L}$ does not change by more than 10 from the previous iteration. Around that we introduce another iteration level (superiterations). At the first iteration of a given superiteration we reenter all seeds and remove (one by one) those with $TS < 16$. We also systematically check curvature significance (§ 3.3) at this first iteration, and allow sources to switch to a curved spectral shape if $TS_{\rm curv} > 16$ or force them back to power law if $TS_{\rm curv} < 16$. At the end of a superiteration an RoI (and its neighbors) enters the next superiteration until $\log \mathcal{L}$ does not change by more than 10 from the last iteration of the previous superiteration. This procedure stabilizes the spectral shapes, particularly in the Galactic plane. Seven superiterations were required to reach full convergence.

3. The fits are now performed up to 1 TeV, and the overall significances (`Signif_Avg`) as well as the spectral parameters refer to the full 100 MeV to 1 TeV band. The photon and energy fluxes, on the other hand, are still reported up to 100 GeV, because for hard sources with photon index less than 2 integrating up to 1 TeV results in much larger uncertainties.

4. We considered the effect of energy dispersion, in the approximate way implemented in the Science Tools. The effect of energy dispersion is calculated globally for each source, and applied to the whole 3D model of that source, rather than accounting for energy dispersion separately in each pixel. This approximate method captures the main effect at a very minor computational cost. The effect of energy dispersion on the spectra is relatively small. It tends to increase the energy flux (by 4% on average), to reduce the width of the power-law index distribution (by making hard sources softer and soft sources harder, but changing the index by less than 0.02), and to make spectra more curved (because energy dispersion acts as a convolution) but increasing β by only 0.01 on average. In evaluating the likelihood function the effects of energy dispersion were not applied to the diffuse backgrounds whose spectra were obtained from the data without considering energy dispersion.

5. We used smaller RoIs at higher energy because we are interested in the core region only, which contains the sources whose parameters come from that RoI (sources in the outer parts of the RoI are entered only as background). The core region is the same for all energy intervals, and the RoI is obtained by adding a ring to that core region, whose width adapts to the PSF and therefore decreases with energy (Table 1). This does not

Energy interval (GeV)	NBins	ZMax (deg)	Ring width (deg)	Pixel size (deg)				
				PSF0	PSF1	PSF2	PSF3	All
0.1 – 0.3	5	90	7			0.6	0.6	
0.3 – 1	6	100	5		0.4	0.3	0.2	
1 – 3	5	105	4	0.4	0.15	0.1	0.1	
3 – 10	6	105	3	0.25	0.1	0.05	0.04	
10 – 1000	10	105	2					0.04

Table 1: The table describes the 14 components (all in binned mode) of the Summed Likelihood approach used in FL8Y. Components in a given energy interval share the same number of energy bins, the same zenith angle selection and the same RoI size, but have different pixel sizes in order to adapt to the PSF width. Each filled entry under Pixel size corresponds to one component of the summed likelihood. NBins is the number of energy bins in the interval, ZMax is the zenith angle cut, Ring width refers to the difference between the RoI core and the extraction region, as explained in item 5 of § 3.2.

affect the result because the outer parts of the RoI would not have been correlated to the inner sources at high energy anyway, but saves memory and CPU time.

6. At the last step of the fitting procedure we tested all spectral shapes described in § 3.3 (including log-normal for pulsars and cutoff power law for other sources), readjusting the parameters (but not the spectral shapes) of neighboring sources.

We used only binned likelihood analysis in FL8Y because unbinned mode is much more CPU intensive, and does not support weights or energy dispersion. We split the data into fourteen components, selected according to PSF event type and described in Table 1. As explained in § 2.3.4 we kept only the best event types at low energy. Each event type selection has its own isotropic diffuse template (because it includes residual charged-particle background, which depends on event type).

A known inconsistency in acceptance exists between Pass 8 PSF event types. It is easy to see on bright sources or the entire RoI spectrum and peaks at the level of 10% between PSF0 (positive residuals, underestimated effective area) and PSF3 (negative residuals, overestimated effective area) at a few GeV. In that range all event types were considered so the effect on source spectra should be minor. Below 1 GeV the PSF0 event type was discarded so the inconsistency could introduce a downward bias (appearing as slightly too hard spectra) but the discrepancy is lower at low energy. The bias on power-law index is estimated to be ~ -0.01.

3.3. Spectral Shapes

The spectral representation of sources largely follows what was done in 3FGL, considering three spectral models (power law, power law with subexponential cutoff, log-normal). We changed two important things in the way we use the cutoff power law:

- The cutoff energy was replaced by an exponential factor (a in Eq. 2) which is allowed to be positive. This makes the simple power law a special case of the cutoff power law and allows fitting that model to all sources.
- We set the exponential index (b in Eq. 2) to 2/3 (instead of 1) for all pulsars that are too faint for it to be left free. This recognizes the fact that $b < 1$ (subexponential) in all bright pulsars. Among the six brightest pulsars, three have $b \sim 0.55$ and three have $b \sim 0.75$). We chose 2/3 as a simple intermediate value.

Therefore the spectral representations which can be found in FL8Y are:

- a log-normal representation (`LogParabola` in the tables) for all significantly curved spectra except pulsars and 3C 454.3:

  $$\frac{\mathrm{d}N}{\mathrm{d}E} = K \left(\frac{E}{E_0}\right)^{-\alpha-\beta\log(E/E_0)} \qquad (1)$$

  where log is the natural logarithm. The reference energy E_0 is set to `Pivot_Energy` in the tables. The parameters K, α (spectral slope at E_0) and the curvature β appear as `Flux_Density`, `LP_Index` and `LP_beta` in the tables, respectively. No significantly negative β (spectrum curved upwards) was found. The maximum allowed β was set to 1 as in 3FGL.

- a subexponentially cutoff power law for all significantly curved pulsars (`PLSuperExpCutoff` in the tables):

  $$\frac{\mathrm{d}N}{\mathrm{d}E} = K \left(\frac{E}{E_0}\right)^{-\Gamma} \exp\left(a\left(E_0^b - E^b\right)\right) \qquad (2)$$

  where E_0 and E in the exponential are expressed in MeV. The reference energy E_0 is set to `Pivot_Energy` in the tables and the parameters K, Γ (low-energy spectral slope), a (exponential factor) and b (exponential index) appear as `Flux_Density`, `PLEC_Index`, `PLEC_Expfactor` and `PLEC_Exp_Index` in the tables, respectively. Note that in the Science Tools that spectral shape is called `PLSuperExpCutoff2` and no E_0^b term appears in the exponential, so the error on K in the tables was obtained from the covariance matrix. The minimum Γ was set to 0 (in 3FGL it was set to 0.5, but a smaller b results in a smaller Γ).

- a simple power-law form (Eq. 2 without the exponential term) for all sources not significantly curved.

As in 3FGL, a source is considered significantly curved if $TS_{\rm curv} > 16$ where $TS_{\rm curv} = 2\log(\mathcal{L}(\text{curved spectrum})/\mathcal{L}(\text{power-law}))$. The curvature significance is reported as `LP_SigCurv` or `PLEC_SigCurv`.

One more pulsar (PSR J1057−5226) was fit with a free exponential index, besides the six sources modeled in this way in 3FGL. The Crab was modeled with three spectral components as in 3FGL, but the inverse Compton emission of the nebula was represented as a log-normal law instead of a simple power law. The parameters of that component were fixed to $\alpha = 1.75$, $\beta = 0.08$, $K = 5.5 \times 10^{-13}$ ph/cm^2/MeV/s at 10 GeV, mimicking the broken power-law fit by Buehler et al. (2012). They were unstable (too much correlation with the pulsar) without phase selection. Four other sources had fixed parameters in 3FGL. These were freed in FL8Y.

Overall in FL8Y seven sources (the six brightest pulsars and 3C 454.3) were fit as `PLSuperExpCutoff` with free b (Eq. 2), 176 pulsars were fit as `PLSuperExpCutoff` with $b = 2/3$, the Small Magellanic Cloud was fit as `PLSuperExpCutoff` with $b = 1$, 660 sources were fit as `LogParabola` (including the fixed inverse Compton component of the Crab and 22 extended sources) and the rest were represented as power laws.

The way the parameters are reported has changed as well:

- The spectral shape parameters are now explicitly associated to the spectral model they come from. They are reported as Shape_Param where Shape is one of PL (power law), PLEC (exponentially cutoff power law) or LP (log-normal) and Param is the parameter name. They replace `Spectral_Index` which was ambiguous.

- All sources were fit with the three spectral shapes, so all fields are filled. The curvature significance is also calculated twice by comparing power law with both log-normal and exponentially cutoff power law (although only one is actually used to switch to the curved shape in the global model, depending on whether the source is a pulsar or not).

This representation allows comparing unassociated sources with either pulsars or blazars using the same spectral shape. The preferred spectral shape (reported as `SpectrumType`) remains what is used when the source is part of the background (i.e., when fitting the other sources). It is also what is used to derive the fluxes, their uncertainties and the significance.

3.4. Extended Sources

As for the 3FGL catalog, we explicitly model as spatially extended those LAT sources that have been shown in dedicated analyses to be resolved by the LAT. The catalog process does not involve looking for new extended sources, testing possible extension of sources detected as point-like, nor refitting the spatial shapes of known extended sources. Most templates are geometrical, so they are not perfect matches to the data and the source detection often finds residuals on top of extended sources, which are then converted into additional point sources. In FL8Y those additional point sources were left in the model (this differs from what was done in 3FGL). This can reduce the flux of the extended sources compared to previous catalogs.

The latest compilation is the 55 extended sources entered in the 3FHL catalog (Ajello et al. 2017), which includes the result of the systematic search for new sources in the Galactic plane above 10 GeV (FGES, Ackermann et al. 2017). Two of those were not propagated to FL8Y:

- FGES J1800.5−2343 was replaced by the W 28 template from 3FGL, and the nearby excesses (Hanabata et al. 2014) were left to be modeled as point sources.
- FGES J0537.6+2751 was replaced by the radio template of S 147 used in 3FGL, which fits better than the disk used in the FGES paper (S 147 is a soft source, so it was barely detected above 10 GeV).

Three sources were added, resulting in 58 extended sources in FL8Y:

- The Rosette nebula and Monoceros SNR (too soft to be detected above 10 GeV) were characterized by Katagiri et al. (2016b). We used the same templates.
- We added back the W 30 SNR on top of FGES J1804.7−2144 (coincident with HESS J1804−216). The two overlap but the best localization clearly moves with energy from W 30 to HESS J1804−216.

Table 2 lists the source name, origin, spatial template and the reference for the dedicated analysis. These sources are tabulated with the point sources, with the only distinction being that no position uncertainties are reported and their names end in `e` (see App. B). Unidentified point sources inside extended ones are indicated as “xxx field” in the `ASSOC2` column of the catalog.

Table 2. Extended Sources Modeled in the FL8Y Analysis

FL8Y Name	Extended Source	Origin	Spatial Form	Extent [deg]	Reference
J0058.0−7245e	SMC Galaxy	Updated	Map	1.5	Caputo et al. (2016)
J0221.4+6241e	HB 3	New	Disk	0.8	Katagiri et al. (2016a)
J0222.4+6156e	W 3	New	Map	0.6	Katagiri et al. (2016a)
J0322.6−3712e	Fornax A	3FHL	Map	0.35	Ackermann et al. (2016c)
J0427.2+5533e	SNR G150.3+4.5	3FHL	Disk	1.515	Ackermann et al. (2017)
J0500.3+4639e	HB 9	New	Map	1.0	Araya (2014)
J0500.9−6945e	LMC FarWest	3FHL	Map^{a}	0.9	Ackermann et al. (2016d)
J0519.9−6845e	LMC Galaxy	New	Map^{a}	3.0	Ackermann et al. (2016d)
J0530.0−6900e	LMC 30DorWest	3FHL	Map^{a}	0.9	Ackermann et al. (2016d)
J0531.8−6639e	LMC North	3FHL	Map^{a}	0.6	Ackermann et al. (2016d)
J0540.3+2756e	S 147	3FGL	Disk	1.5	Katsuta et al. (2012)
J0617.2+2234e	IC 443	2FGL	Gaussian	0.27	Abdo et al. (2010f)
J0634.2+0436e	Rosette	New	Map	(1.5, 0.875)	Katagiri et al. (2016b)
J0639.4+0655e	Monoceros	New	Gaussian	3.47	Katagiri et al. (2016b)
J0822.1−4253e	Puppis A	3FHL	Disk	0.443	Ackermann et al. (2017)
J0833.1−4511e	Vela X	2FGL	Disk	0.91	Abdo et al. (2010d)
J0851.9−4620e	Vela Junior	3FHL	Disk	0.978	Ackermann et al. (2017)
J1023.3−5747e	Westerlund 2	3FHL	Disk	0.278	Ackermann et al. (2017)
J1036.3−5833e	FGES J1036.3−5833	3FHL	Disk	2.465	Ackermann et al. (2017)
J1109.4−6115e	FGES J1109.4−6115	3FHL	Disk	1.267	Ackermann et al. (2017)
J1208.5−5243e	SNR G296.5+10.0	3FHL	Disk	0.76	Acero et al. (2016b)
J1213.3−6240e	FGES J1213.3−6240	3FHL	Disk	0.332	Ackermann et al. (2017)
J1303.0−6312e	HESS J1303−631	3FGL	Gaussian	0.24	Aharonian et al. (2005)
J1324.0−4330e	Centaurus A (lobes)	2FGL	Map	(2.5, 1.0)	Abdo et al. (2010a)
J1355.1−6420e	HESS J1356−645	3FHL	Disk	0.405	Ackermann et al. (2017)
J1409.1−6121e	FGES J1409.1−6121	3FHL	Disk	0.733	Ackermann et al. (2017)
J1420.3−6046e	HESS J1420−607	3FHL	Disk	0.123	Ackermann et al. (2017)
J1443.0−6227e	RCW 86	3FHL	Map	0.3	Ajello et al. (2016)
J1507.9−6228e	HESS J1507−622	3FHL	Disk	0.362	Ackermann et al. (2017)
J1514.2−5909e	MSH 15−52	3FHL	Disk	0.243	Ackermann et al. (2017)
J1552.7−5611e	MSH 15−56	3FHL	Disk	0.21	Acero et al. (2016b)
J1553.8−5325e	FGES J1553.8−5325	3FHL	Disk	0.523	Ackermann et al. (2017)
J1615.3−5146e	HESS J1614−518	3FGL	Disk	0.42	Lande et al. (2012)
J1616.2−5054e	HESS J1616−508	3FGL	Disk	0.32	Lande et al. (2012)
J1631.6−4756e	FGES J1631.6−4756	3FHL	Disk	0.256	Ackermann et al. (2017)
J1633.0−4746e	FGES J1633.0−4746	3FHL	Disk	0.61	Ackermann et al. (2017)
J1636.3−4731e	SNR G337.0−0.1	3FHL	Disk	0.139	Ackermann et al. (2017)
J1652.2−4633e	FGES J1652.2−4633	3FHL	Disk	0.718	Ackermann et al. (2017)
J1655.5−4737e	FGES J1655.5−4737	3FHL	Disk	0.334	Ackermann et al. (2017)
J1713.5−3945e	RX J1713.7−3946	3FHL	Map	0.56	Abdalla et al. (2017)
J1745.8−3028e	FGES J1745.8−3028	3FHL	Disk	0.528	Ackermann et al. (2017)
J1801.3−2326e	W 28	2FGL	Disk	0.39	Abdo et al. (2010c)
J1804.7−2144e	HESS J1804−216	3FHL	Disk	0.378	Ackermann et al. (2017)
J1805.6−2136e	W 30	2FGL	Disk	0.37	Ajello et al. (2012)
J1824.5−1351e	HESS J1825−137	2FGL	Gaussian	0.75	Grondin et al. (2011)
J1834.1−0706e	SNR G24.7+0.6	3FHL	Disk	0.214	Ackermann et al. (2017)

3.5. Limitations and Systematic Uncertainties

3.5.1. Diffuse emission model

The model of diffuse emission is the main source of uncertainties for faint sources. Contrary to the effective area, it does not affect all sources equally: its effects are smaller outside the Galactic plane where the diffuse emission is fainter and varying on larger angular scales. It is also less of a concern at high energy (> 3 GeV) where the core of the PSF is narrow enough that the sources dominate the background under the PSF. But it is a serious concern inside the Galactic plane at low energy (< 1 GeV) and particularly inside the Galactic ridge ($|l| < 60°$) where the diffuse emission is strongest and very structured, following the molecular cloud distribution. It is not easy to assess precisely how large the uncertainties are, because they relate to uncertainties in the distributions of interstellar gas, the interstellar radiation field, and cosmic rays, which depend in detail on position on the sky.

The FL8Y source list uses the same diffuse emission model as 3FGL. This is a major limitation and the main reason why this source list is not the 4FGL catalog, which will be based on an improved interstellar emission model, making use of better H I data, a *Planck*-based dust map and fitting emissivities over 8 years of Pass 8 data.

We estimate, from the residuals over the entire Galactic plane, that the systematics are at the 3% level. This is already an achievement, but the statistical Poisson errors corresponding to the diffuse emission integrated over the PSF (as described in App. A) are much smaller than this. Integrating all energies above the current one in the Galactic ridge, the statistical precision is 0.2, 0.4, 1, 2, 5% above 100, 200, 500 MeV, 1, 2 GeV respectively.

The weights are able to mitigate the systematic effects globally, but cannot correct the model locally. In particular underestimating the mass of an interstellar cloud will always tend to create spurious sources on top of it, and overestimating diffuse emission at a particular place tends to make the sources on top of it harder than they should be (because the model creates negative residuals there, and those are felt mostly at low energy).

3.5.2. Analysis method

As in 3FGL, we use the *pointlike*-based method described in § 3.1 to estimate systematic errors due to the way the main *gtlike*-based method (§ 3.2) is set up in detail. Many aspects differ between the two methods: the code, the weights implementation, the RoIs, the Earth limb representation. The *pointlike*-based method does not remove faint sources (with $TS < 25$) from the model. The model for diffuse emission is the same spatially but it was rescaled spectrally in each energy bin. Even the data differ, since the *pointlike*-based method uses *Front* and *Back* event types whereas the *gtlike*-based method uses PSF event types with a different zenith angle cut, and rejects a fraction of the events below 1 GeV.

Because of all those differences, we expect that comparing the results of the two methods source by source can provide an estimate of the sensitivity of the source list to details of the analysis. In particular we use it to flag sources whose spectral characterization differs a lot with the two methods (Flags 1 and 3 in Table 3).

3.5.3. Analysis Flags

As in 3FGL we identified a number of conditions that should be considered cautionary regarding the reality of a source or the magnitude of the systematic uncertainties of its measured properties. They are described in Table 3. Because this is a preliminary source list a number of flags are unfilled (4, 5, 6, 7, 11). Flags 1 and 3 account for the comparison with the other analysis method, but not with another diffuse model.

In FL8Y 554 sources are flagged (about 10%). No source was flagged with flag 1, 362 were flagged with flag 3 (different result with *pointlike*), 119 with flag 9 (bad localization), 50 with flag 10 (bad spectral representation) and 53 with flag 12 (highly curved).

4. Source Association-Classification

Table 2—Continued

FL8Y Name	Extended Source	Origin	Spatial Form	Extent [deg]	Reference
J1834.5−0846e	W 41	3FHL	Gaussian	0.23	Abramowski et al. (2015)
J1836.5−0651e	FGES J1836.5−0651	3FHL	Disk	0.535	Ackermann et al. (2017)
J1838.9−0704e	FGES J1838.9−0704	3FHL	Disk	0.523	Ackermann et al. (2017)
J1840.9−0532e	HESS J1841−055	3FGL	2D Gaussian	(0.62, 0.38)	Aharonian et al. (2008)
J1855.9+0121e	W 44	2FGL	2D Ring	(0.30, 0.19)	Abdo et al. (2010e)
J1857.7+0246e	HESS J1857+026	3FHL	Disk	0.613	Ackermann et al. (2017)
J1923.2+1408e	W 51C	2FGL	2D Disk	(0.375, 0.26)	Abdo et al. (2009a)
J2021.0+4031e	γ-Cygni	3FGL	Disk	0.63	Lande et al. (2012)
J2028.6+4110e	Cygnus X cocoon	3FGL	Gaussian	3.0	Ackermann et al. (2011a)
J2045.2+5026e	HB 21	3FGL	Disk	1.19	Pivato et al. (2013)
J2051.0+3040e	Cygnus Loop	2FGL	Ring	1.65	Katagiri et al. (2011)
J2301.9+5855e	CTB 109	3FHL	Disk	0.249	Ackermann et al. (2017)

[a] Emissivity model.

Note. — List of all sources that have been modeled as spatially extended. The Origin column gives the name of the *Fermi*-LAT catalog in which that spatial template was introduced. The Extent column indicates the radius for Disk (flat disk) sources, the 68% containment radius for Gaussian sources, the outer radius for Ring (flat annulus) sources, and an approximate radius for Map (external template) sources. The 2D shapes are elliptical; each pair of parameters (a, b) represents the semi-major (a) and semi-minor (b) axes.

Table 3. Definitions of the Analysis Flags

Flag[a]	Meaning
1	Source with $TS > 35$ which went to $TS < 25$ when changing the analysis method (§ 3.5.2). Sources with $TS \leq 35$ are not flagged with this bit because normal statistical fluctuations can push them to $TS < 25$.
2	Not used.
3	Flux (> 1 GeV) or energy flux (> 100 MeV) changed by more than 3σ when changing the analysis method. Requires also that the flux change by more than 35% (to not flag strong sources).
4	Not used.
5	Not used.
6	Not used.
7	Not used.
8	Not used.
9	Localization Quality > 8 in *pointlike* (§ 3.1) or long axis of 95% ellipse > $0\overset{\circ}{.}25$.
10	Spectral Fit Quality > 30 in *pointlike*.
11	Not used.
12	Highly curved spectrum; `LP_beta` fixed to 1 or `PLEC_Index` fixed to 0 (see § 3.3).

[a] In the FITS version (Table 6 in App. B) the values are encoded as individual bits in a single column, with Flag n having value $2^{(n-1)}$.

Table 4. Catalogs Used for the Automatic Source Association Methods

Name	Objects[a]	Ref.
High $\dot{E}/d^2$ pulsars	313	Manchester et al. (2005)[b]
Other normal pulsars	2248	Manchester et al. (2005)[b]
Millisecond pulsars	240	Manchester et al. (2005)[b]
Pulsar wind nebulae	69	Collaboration internal
High-mass X-ray binaries	137	Chaty et al. (2018)
Low-mass X-ray binaries	187	Liu et al. (2007)
Point-like SNR	295	Green (2009)[c]
Extended SNR[†]	274	Green (2009)[c]
O stars	378	Maíz-Apellániz et al. (2004)
WR stars	226	van der Hucht (2001)
LBV stars	35	Clark et al. (2005)
Open clusters	2140	Dias et al. (2002)
Globular clusters	160	Harris (1996)
Dwarf galaxies[†]	100	McConnachie (2012)
Nearby galaxies	276	Schmidt et al. (1993)
IRAS bright galaxies	82	Sanders et al. (2003)
BZCAT (Blazars)	3561	Massaro et al. (2009)
Supplement to BZCAT	102	Alvarez-Crespo & Massaro (2017)
BL Lac	1371	Véron-Cetty & Véron (2010)
AGN	10066	Véron-Cetty & Véron (2010)
QSO	129,853	Véron-Cetty & Véron (2010)
Seyfert galaxies	27651	Véron-Cetty & Véron (2010)
Radio loud Seyfert galaxies	29	Collaboration internal
Radio-loud Seyfert galaxies	556	Rakshit et al. (2017)
FRICAT (Radio galaxies)	233	Capetti, A. et al. (2017a)
FRIICAT (Radio galaxies)	123	Capetti, A. et al. (2017b)
Giant Radio Sources	1616	Proctor (2016)
2WHSP	1691	Chang et al. (2017)
WISE blazar catalog	12319	D'Abrusco et al. (2014)
Radio Fundamental Catalog	14786	http://astrogeo.org/rfc
CGRaBS	1625	Healey et al. (2008)
CRATES	11499	Healey et al. (2007)
VLBA Calibrator Source List	5776	http://www.vlba.nrao.edu/astro/calib/
ATCA 20 GHz southern sky survey	5890	Murphy et al. (2010)
ATCA follow up of 2FGL unassociated sources	424	Petrov et al. (2013)
70-month BAT catalog	1092	Baumgartner et al. (2013)
IBIS catalog of soft gamma-ray sources	939	Bird et al. (2016)
1st AGILE catalog[*]	47	Pittori et al. (2009)
3rd EGRET catalog[*]	271	Hartman et al. (1999)
EGR catalog[*]	189	Casandjian & Grenier (2008)
0FGL list[*]	205	Abdo et al. (2009b, 0FGL)
1FGL catalog[*]	1451	Abdo et al. (2010b, 1FGL)
2FGL catalog[*]	1873	Nolan et al. (2012, 2FGL)
3FGL catalog[*]	3033	Acero et al. (2015, 3FGL)
1FHL catalog[*]	514	Ackermann et al. (2013, 1FHL)
2FHL catalog[*]	360	Ackermann et al. (2016b, 1FHL)

The same association procedure previously used in 3FGL is adopted here. The Bayesian method (Abdo et al. 2010b) is applied using the set of potential-counterpart catalogs listed in Table 4. The priors are recalibrated via Monte-Carlo simulations to enable a proper estimate of the association probabilities and in turn of the false association rates. These rates indeed depend on the sizes of the error ellipses of the sources. A total of 3393 associations with posterior probabilities greater than 0.80 are found via this method, with an estimated number of false positives of $\sim$41. Note that 22 sources have changed associations between 3FGL and FL8Y. In FL8Y, we did not make use of the Likelihood-Ratio (LR) method (Ackermann et al. 2011b, 2015), which provided supplementary associations with blazar candidates in previous LAT catalogs (62 associations in 3FGL). We thus dropped the “unknown” class introduced in 3FHL, corresponding to associated sources in the ROSAT X-ray survey with spectral energy distributions not consistent with those expected from blazars.

The fraction of associated sources is close to 60%, down from 65% obtained in 3FGL with the same method. This trend calls for deeper counterpart catalogs and surveys than those currently available. We list blazar classes in terms of Flat-Spectrum Radio Quasars (FSRQs), BL Lac type objects (BLL) and blazars of undetermined type (BCU). The BCU sources represent more than 40% of the blazars. However, note that a thorough search for optical spectra in the literature has not been completed yet, which will improve the classification rate in terms of optical classes.

The results of the association procedure are summarized in Table 5. Designations shown in capital letters are firm identifications based on correlated variability (periodic or otherwise) reported at other wavelengths or angular extent; lower case letters indicate associations.

Associations with γ-ray sources reported in earlier LAT catalogs are established by requiring an overlap of their respective 99.9% error ellipses (assuming axes lengths 1.52 times their 95% values). A total of 3155 FL8Y sources were reported in previous FGL catalogs. It is found that 292 3FGL sources are missing in FL8Y. The great majority of them had TS values close to the detection threshold. Some of the missing sources have been split up in multiple FL8Y sources. Similarly, 21 3FHL sources are missing in FL8Y.

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Facilities: Fermi.

Table 4—Continued

Name	Objects[a]	Ref.
3FHL catalog*	1556	Ajello et al. (2017, 1FHL)
TeV point-like source catalog*	108	http://tevcat.uchicago.edu/
TeV extended source catalog†	72	http://tevcat.uchicago.edu/
LAT pulsars	209	Collaboration internal
LAT identified	143	Collaboration internal

[a] Number of objects in the catalog.

[b] version 1.56, http://www.atnf.csiro.au/research/pulsar/psrcat

[c] Green D. A., 2017, 'A Catalogue of Galactic Supernova Remnants (2017 June version)', Cavendish Laboratory, Cambridge, United Kingdom (available at "http://www.mrao.cam.ac.uk/surveys/snrs/")

Table 5. LAT FL8Y Source Classes

Description	Identified		Associated	
	Designator	Number	Designator	Number
Pulsar, identified by pulsations	PSR	184	···	···
Pulsar, no pulsations seen in LAT yet	···	···	psr	34
Pulsar wind nebula	PWN	8	pwn	11
Supernova remnant	SNR	22	snr	17
Supernova remnant / Pulsar wind nebula	···	···	spp	96
Globular cluster	GLC	0	glc	28
High-mass binary	HMB	4	hmb	2
Binary	BIN	1	bin	1
Nova	NOV	1	nov	0
Star-forming region	SFR	1	sfr	1
Compact Steep Spectrum Quasar	CSS	0	css	1
BL Lac type of blazar	BLL	22	bll	1008
FSRQ type of blazar	FSRQ	42	fsrq	618
Non-blazar active galaxy	AGN	0	agn	16
Radio galaxy	RDG	5	rdg	16
Seyfert galaxy	SEY	0	sey	1
Blazar candidate of uncertain type	BCU	5	bcu	1229
Normal galaxy (or part)	GAL	2	gal	3
Starburst galaxy	SBG	0	sbg	4
Narrow line Seyfert 1	NLSY1	3	nlsy1	6
Soft spectrum radio quasar	SSRQ	0	ssrq	1
Total	···	300	···	3093
Unassociated	···	···	···	2131

Note. — The designation 'spp' indicates potential association with SNR or PWN. Designations shown in capital letters are firm identifications; lower case letters indicate associations. In the case of AGN, many of the associations have high confidence.

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A. Weighted log-likelihood

In 3FGL we introduced a first attempt at accounting for systematic errors in the maximum likelihood process itself, at the source detection level. It was not used in the source characterization, however, for lack of a suitable framework. The standard way to account for systematic errors (for example in $XSPEC$[5]) is to define them as a fraction ϵ of the signal and add them to the statistical errors in quadrature, in a χ^2 formalism. This can be adapted to the maximum likelihood framework by introducing weights $w_i < 1$ (Hu & Zidek 2002) as

$$\log \mathcal{L} = \sum_i w_i (n_i \log M_i - M_i) \tag{A1}$$

where M_i and n_i are the model and observed counts in each bin, and the sum runs over all bins in space and energy. The source significance can then be quantified in the same way,

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[5] https://heasarc.gsfc.nasa.gov/xanadu/xspec/

via the Test Statistic $TS = 2\log(\mathcal{L}/\mathcal{L}_0)$ in which $\mathcal{L}$ and $\mathcal{L}_0$ are the (weighted) likelihood with and without the source of interest, respectively.

Since the statistical variance in Poisson statistics is the signal itself, a first guess for the weights could be

$$w_i = \frac{M_i}{M_i + (\epsilon M_i)^2} = \frac{1}{1+\epsilon^2 M_i} \tag{A2}$$

However, that formulation has a serious flaw, which is that it is not stable to rebinning. If one splits the bins in half, then M_i is split in half while ϵ stays the same (it is defined externally). In the limit of very small bins, obviously the weights will all tend to 1 and the $\log\mathcal{L}$ formula will tend to the unweighted one, even though nothing has changed in the underlying data or the model.

The solution we propose, originally presented in Ballet et al. (2015), is to define a suitable integral over energy (E) and space ($\mathbf{r}$) $N(\mathbf{r}, E)$ which does not depend on binning. M_i in the weight formula is then replaced by $N(\mathbf{r}_i, E_i)$ taken at the event's coordinates. For the integral over space, since the catalog mostly deals with point sources, the logical solution is to integrate the background under the PSF, i.e., convolve the model with the PSF $P(\mathbf{r}, E)$, normalized to 1 at the peak (this is equivalent, for a flat diffuse emission, to multiplying by the PSF solid angle). Note that the model already contains the PSF, so this amounts to applying a double convolution to the sky model.

For the energy integral the choice is less obvious. The source spectrum is not a narrow line, so convolving with the energy dispersion (similar to what is done for space) is not justified. An integral over the full energy range would give the same weight to all energies, which is clearly not what we want (there is no reason to downplay the few high-energy events). The option we adopt here is to integrate over all energies above the current one.

$$w_i = \frac{1}{1+\epsilon^2 N(\mathbf{r}_i, E_i)} \tag{A3}$$

$$N(\mathbf{r}_i, E_i) = \int_{E_i}^{E_{\max}} S(\mathbf{r}_i, E)\, dE \tag{A4}$$

$$S(\mathbf{r}, E) = \frac{dM}{dE}(\mathbf{r}, E) * P(\mathbf{r}, E) \tag{A5}$$

where dM/dE is the differential model. As energy increases, the spectra (in counts) decrease and the LAT PSF gets narrower so the convolution makes S even steeper than dM/dE. As a result, the integral giving N is dominated by the lowest energies, so the exact upper bound $E_{\max}$ is not important.

There are two possibilities to define dM/dE. Since the main origin of the systematic error is the diffuse emission, we can restrict dM/dE to the diffuse emission model only (we call the result model-based weights). On the other hand there are also systematic uncertainties on sources due to PSF calibration and our imperfect spectral representation, so another option is to enter the full model (or the data themselves) into dM/dE (we call the result data-based weights). That second choice limits spurious sources next to bright sources. There is of course no reason why the level of systematics ϵ should be the same for the diffuse emission model and the sources, but in practice it is a reasonable approximation.

Another important point, for the procedure to be stable, is that the weights should not change with the model parameters. So dM/dE must be defined beforehand (for example from a previous fit). In this work we use data-based weights computed from the data themselves, with a common ϵ. The data are not as smooth as the model, but this is not a problem in the regime of large counts where weights play a role.

We assume here that ϵ is a true constant (it depends neither on space nor on energy). For a given ϵ the weights are close to 1 at high energy and decrease toward low energy. At a given energy the weights are smallest where the model is largest (in the Galactic ridge). Considering all event types (not what we do in FL8Y), for 8 years and $\epsilon = 3\%$, at 100 MeV the weights are everywhere less than 12%. They reach 50% at high latitude at 250 MeV, and 90% at 500 MeV. In the Galactic ridge, the weights are 0.5% at 100 MeV, 1.5% at 250 MeV, 5% at 500 MeV, 20% at 1 GeV, 60% at 2 GeV and reach 90% at 4.5 GeV.

There remains a specific difficulty, due to the fact that at a given energy we split the data into several components, each corresponding to a particular event type (with a different PSF). Since the systematics play in the same way on all components, the weights must be computed globally (i.e., weights must be lower when using PSF2 and PSF3 events than when using PSF3 alone). On the other hand, the resulting uncertainties with two components should be smaller than those with a single component (adding a second one adds information). In this work, we started by computing weights w_k individually for each component k (the dependence on E and $\mathbf{r}$ is left implicit). Then we assumed that the final weights are simply proportional to the original ones, with a factor $\alpha < 1$ (α depends on E and $\mathbf{r}$ as well). A reasonable solution is then

$$N_{\rm min} = \min_k N_k \tag{A6}$$

$$K_{\rm tot} = \sum_k \left(\frac{N_{\rm min}}{N_k}\right)^2 \tag{A7}$$

$$\alpha = \frac{1+\epsilon^2 N_{\rm min}}{1+\epsilon^2 N_{\rm min} K_{\rm tot}} \tag{A8}$$

$$w_k = \frac{\alpha}{1+\epsilon^2 N_k} \tag{A9}$$

$K_{\rm tot}$ and α are 1 if one component dominates over the others, and $K_{\rm tot}$ is the number of components if they are all similar.

B. Description of the FITS version of the FL8Y source list

The FITS format version of the FL8Y source list has five binary table extensions. The extension `LAT_Point_Source_Catalog Extension` has all of the information about the sources. Its format is described in Table 6.

The extension `GTI` is a standard Good-Time Interval listing the precise time intervals (start and stop in Mission Elapsed Time) included in the data analysis. The number of intervals is fairly large because on most orbits (∼95 min) *Fermi* passes through the South Atlantic Anomaly (SAA), and science data taking is stopped during these times. In addition, data taking is briefly interrupted on each non-SAA-crossing orbit, as *Fermi* crosses the ascending node. Filtering of time intervals with large rocking angles, gamma-ray bursts, solar flares, data gaps, or operation in non-standard configurations introduces some more entries. The GTI is provided for reference and would be useful, e.g., for reconstructing the precise data set that was used for the analysis.

The extension `ExtendedSources` (format unchanged since 2FGL) contains information about the 58 spatially extended sources that are modeled in the FL8Y source list, including locations and shapes. The extended sources are indicated by an e appended to their names in the main table.

The extension `ROIs` contains information about the 2363 RoIs over which the analysis ran. In particular it reports the best-fit background parameters. Its format is very close to that in 3FGL, with one exception. The `RADIUS` column is replaced by `CoreRadius` which reports the radius of the RoI core (in which the sources which belong to the RoI are located). The RoI radius (half-width in binned mode) depends on the component, and is given by the core radius plus `RingWidth`, where the latter is given in the `Components` extension.

The extension `Components` is new to FL8Y. It reports the settings of each individual component (14 in all) whose sum forms the entire data set for the SummedLikelihood approach, as described in Table 1. Its format is given by Table 7.

Table 6. LAT FL8Y FITS Format: LAT_Point_Source_Catalog Extension

Column	Format	Unit	Description
Source_Name	18A	···	Source name FL8Y JHHMM.m+DDMM
RAJ2000	E	deg	Right Ascension
DEJ2000	E	deg	Declination
GLON	E	deg	Galactic Longitude
GLAT	E	deg	Galactic Latitude
Conf_95_SemiMajor	E	deg	Long radius of error ellipse at 95% confidence
Conf_95_SemiMinor	E	deg	Short radius of error ellipse at 95% confidence
Conf_95_PosAng	E	deg	Position angle (eastward) of the long axis from celestial North
ROI_num	I	···	RoI number (cross-reference to ROIs extension)
Extended_Source_Name	18A	···	Cross-reference to the ExtendedSources extension
Signif_Avg	E	···	Source significance in σ units over the 100 MeV to 1 TeV band
Pivot_Energy	E	MeV	Energy at which error on differential flux is minimal
Flux_Density	E	$\mathrm{cm^{-2}\ MeV^{-1}\ s^{-1}}$	Differential flux at Pivot_Energy
Unc_Flux_Density	E	$\mathrm{cm^{-2}\ MeV^{-1}\ s^{-1}}$	1σ error on differential flux at Pivot_Energy
Flux1000	E	$\mathrm{cm^{-2}\ s^{-1}}$	Integral photon flux from 1 to 100 GeV
Unc_Flux1000	E	$\mathrm{cm^{-2}\ s^{-1}}$	1σ error on integral photon flux from 1 to 100 GeV
Energy_Flux100	E	$\mathrm{erg\ cm^{-2}\ s^{-1}}$	Energy flux from 100 MeV to 100 GeV obtained by spectral fitting
Unc_Energy_Flux100	E	$\mathrm{erg\ cm^{-2}\ s^{-1}}$	1σ error on energy flux from 100 MeV to 100 GeV
SpectrumType	18A	···	Spectral type (PowerLaw, LogParabola, PLSuperExpCutoff)
PL_Index	E	···	Photon index when fitting with PowerLaw
Unc_PL_Index	E	···	1σ error on PL_Index
LP_SigCurv	E	···	Significance (in σ units) of the fit improvement between PowerLaw and LogParabola. A value greater than 4 indicates significant curvature
LP_Index	E	···	Photon index at Pivot_Energy (α of Eq. 1) when fitting with LogParabola
Unc_LP_Index	E	···	1σ error on LP_Index
LP_beta	E	···	Curvature parameter (β of Eq. 1) when fitting with LogParabola
Unc_LP_beta	E	···	1σ error on LP_beta
PLEC_SigCurv	E	···	Same as LP_SigCurv for PLSuperExpCutoff model
PLEC_Index	E	···	Low-energy photon index (Γ of Eq. 2) when fitting with PLSuperExpCutoff
Unc_PLEC_Index	E	···	1σ error on PLEC_Index
PLEC_Expfactor	E	···	Exponential factor (a of Eq. 2) when fitting with PLSuperExpCutoff
Unc_PLEC_Expfactor	E	···	1σ error on PLEC_Expfactor
PLEC_Exp_Index	E	···	Exponential index (b of Eq. 2) when fitting with PLSuperExpCutoff
Unc_PLEC_Exp_Index	E	···	1σ error on PLEC_Exp_Index
Npred	E	···	Predicted number of events in the model
ASSOC_GAM	18A	···	Correspondence to previous γ-ray source catalog[a]
TEVCAT_FLAG	A	···	P if positional association with non-extended source in TeVCat E if associated with an extended source in TeVCat, N if no TeV association
ASSOC_TEV	24A	···	Name of likely corresponding TeV source from TeVCat, if any
CLASS	7A	···	Class designation for associated source; see Table 5
ASSOC1	26A	···	Name of identified or likely associated source
ASSOC2	26A	···	Alternate name or indicates whether the source is inside an extended source
ASSOC_PROB_BAY	E	···	Probability of association according to the Bayesian method

[a] in the order 3FHL > 3FGL > 2FHL > 1FHL > 2FGL > 1FGL > 0FGL.

Table 7. LAT FL8Y FITS Format: Components Extension

Column	Format	Unit	Description
Emin	E	MeV	Lower bound of component's energy interval
Emax	E	MeV	Upper bound of component's energy interval
ENumBins	I	···	Number of bins inside energy interval
EvType	I	···	Event type selection for this component
ZenithCut	E	deg	Maximum zenith angle for this component
RingWidth	E	deg	Difference between RoI radius and core radius
PixelSize	E	deg	Pixel size for this component (of exposure map in unbinned mode)
BinnedMode	I	···	0=Unbinned, 1=Binned
Weighted	I	···	1 if weights were applied to this component