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## Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
1.1	Scope and Contents of this Document . . . . .	3
1.2	Reference Documents . . . . .	3
1.3	Contacts . . . . .	3
<b>2</b>	<b>Installation procedure</b>	<b>3</b>
<b>3</b>	<b>Basic concepts</b>	<b>3</b>
3.1	Introduction . . . . .	3
3.2	Analysis environment . . . . .	4
<b>4</b>	<b>The Exposure Map Generator Task</b>	<b>5</b>
<b>5</b>	<b>The Counts Map Generator Task</b>	<b>10</b>
<b>6</b>	<b>The Intensity Map Generator Task</b>	<b>14</b>
<b>7</b>	<b>The Diffuse Map Generator Task</b>	<b>17</b>
<b>8</b>	<b>Source Detection and Location</b>	<b>21</b>
8.1	Introduction . . . . .	21
8.2	Getting started . . . . .	22
8.3	The Command Line . . . . .	22
8.4	The Map List . . . . .	23
8.5	The Source List . . . . .	24
8.5.1	Spectral models . . . . .	25
8.5.2	Example with Power Law spectral model . . . . .	26
8.6	Calibration Files . . . . .	26
8.7	Output . . . . .	27
8.8	HTML output . . . . .	29
8.9	The Ellipse . . . . .	29

# 1 Introduction

## 1.1 Scope and Contents of this Document

This document provides an abbreviated user manual for the following packages:

1. Scientific Analysis Counts Map Generator
2. Scientific Analysis Exposure Map Generator
3. Scientific Analysis Intensity Map Generator
4. Scientific Analysis Diffuse Map Generator
5. Scientific Analysis Likelihood Analysis -- Multiple Source Location Detection

which pertain to the AGILE-GRID Scientific Analysis subsystems described in **RD[1]**.

## 1.2 Reference Documents

**RD[1]** : *Scientific Ground Segment Software Requirements and Architecture*, AGILE-IFC-SA-001, Issue 2.0

**RD[2]**: *GRID Standard Analysis User Manual and Test Procedures*, AGILE-IFC-OP-008, 16/5/2005

**RD[3]**: *GRID Correction and Standard Analysis User Manual*, AGILE-IFC-OP-010, 26/1/2006

## 1.3 Contacts

The reference person at INAF/OAS Bologna for this document is:

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The packages described in this Document have been developed at IASF-MI by A. Giuliani, A. Pellizzoni, A. Chen, A. Trois, S. Vercellone, and T. Contessi and by A. Bulgarelli, A. Zoli, L. Baroncelli, N. Parmiggiani at IASF/OAS Bologna. S. Mereghetti acts as the IASF-MI software working group coordinator and A. Bulgarelli acts as the Software Manager of the AGILE Team. See also **RD[1]** for a detailed description of the developer list.

# 2 Installation procedure

# 3 Basic concepts

## 3.1 Introduction

AGILE is an ASI (Italian Space Agency) Small Scientific Mission dedicated to high-energy astrophysics which was successfully launched on April 23, 2007. The AGILE instrument is

composed of three main detectors: a Tungsten-Silicon Tracker designed to detect and image photons in the 30 MeV-50 GeV energy band, an X-ray imager called Super-AGILE operating in the 18-60 keV energy band, and a Mini-Calorimeter that detects gamma-rays and charged particles energy deposits between 300 keV and 100 MeV. The instrument is surrounded by an anti-coincidence (AC) system. The main purpose of the Silicon Tracker is to provide a compact imager for gamma-ray photons of energy above 30 MeV. The Tracker converts the gamma-rays in heavy-Z material layers (245  $\mu\text{m}$  of Tungsten,  $0.07 X_0$ ), where the gamma-ray interacts producing an electron/positron pair of Minimum Ionizing Particles (MIP, corresponding to a most probable value of 110  $\text{keV}$ ) in the detector, and records the electron/positron tracks through a sophisticated combination of Silicon microstrip detectors and associated readout. A GRID event is a collection of all the electron/positron interactions in microstrip detector (called clusters) with additional information from energy deposits in the MCAL bars and the configuration of the AC plastic scintillators if present. A complete representation of the event topology allows the reconstruction of the incoming direction and energy of the gamma-ray.

A set of different on-board triggers enables the discrimination of background events (mainly cosmic rays in the AGILE Low Earth Orbit) from gamma-ray events. AGILE raw data are down-linked every  $\sim 100$  min to the ASI Malindi ground station in Kenya, and transmitted first to the Telespazio Mission Control Center at Fucino, and then to the AGILE Data Center (ADC), which is part of the ASI Space Science Data Center (SSDC, previously known as ASDC). The ADC processes the GRID events with additional on-ground filters and provides a classification of each event:

P : events classified as a charged particle and rejected

G : events classified as gamma-ray photons. This is the most useful class for the analysis

S : events classified as single-track: this is a special class of events with no separation between the electron and positron tracks

L : limbo events, not clearly classified.

The AGILE data are organized as lists of photons from the start of the mission until the last released data. For the scientific analysis of a source it is necessary to select events from a given time range and spatial region including not only the source of interest, but also nearby sources within 10-20 degree in radius. The list of photons is provided in the event files (EVT). All the auxiliary information needed to know where AGILE is pointing at a given time and when the spacecraft operates nominally are in the so-called LOG files provided. The scientific tools take the EVT and LOG files as basic input for the analysis.

The events provided in the EVT files are of type G, S, and L. The AGILE team recommends to use the G class for scientific analysis. Only for gamma-ray bursts or other short transient events, and for pulsar timing analysis the G, S and L classes should be used together.

## 3.2 Analysis environment

The AGILE Science Tools are written in C++ and are based on the ROOT (CERN) and CFITSIO (NASA) libraries. All the tools can be run from the command line.

The Science Tools use the Parameter Interface Library (PIL), developed by the ISDC, for parameter input, allowing a variety of input methods:

1. the user can input all or some of the parameters on the command line, in the same order as the provided parameter file;
2. the user can start the tool, which then asks for the values of some parameters interactively on the console;
3. by adding 'mode=h' on the command line, the user can accept all the defaults (the last values used) for parameter values not explicitly provided on the command line

The input and output files are in FITS format. FITS files consist of a series of units, each containing a header and data. Each header contains a list of 'keywords' and their values, which describe the format of the data. The first unit is the 'primary' unit and may or may not contain data. The subsequent units are called 'extensions.'

FITS files can be read and modified by standard tools such as `fv` and the output maps generated by the tools can be displayed with the `ds9` tool.

## 4 The Exposure Map Generator Task

Exposure maps are generated by the procedure `AG_expmapgen` found in the subdirectory: `$AGILE/bin/`. The task `AG_expmapgen` reads the log files listed in the GRID LOG index, integrates the exposure between `tmin` and `tmax`, and outputs a FITS exposure image file. The image is a two-dimensional array in either the ARC or AIT projection. The projection, size and resolution, and center and rotation of the map in Galactic coordinates, `tmin`, `tmax`, `emin`, `emax`, and `index` are specified in the `AG_expmapgen.par` parameter file, along with various integration parameters (`fovrad`, `albrad`, `y_tol`, `roll_tol`, `earth_tol`, `phasecode`), and an interpolation step size (`binstep`).

The interpolation procedure is a linear interpolation method in which only one bin each  $N$  is calculated (where  $N$  is the `step` size parameter). For a bin size of 0.5 deg or 0.25 deg with a step size of  $N = 4$  it is possible to get a good approximation of the exposure map.

The version number of the data is the value of the keyword `OBSW_VER` in the FITS header of the EVT files, e.g:

```
OBSW_VER= '5_21.1_22_27' / OB SW version: PipeOB_B-SCIB-STD_B-COR
```

means that the SSDC pipe version is 5, the scientific analysis version integrated into the SSDC pipeline is 21.1, and the version of the standard analysis that has produced the data is 22 (this is the number that is necessary to check). The last number is the version of the Correction software.

inputs:

AG\_expmapgen.par :

```

outfile,s,ql,"map.exp",,, "Enter output file name"
logfile,s,ql,"LOG.index",,, "Enter GRID log index file name"
sarFileName,s,hl,"${AGILE}/model/scientific.analysis/data/AG-GRID.G0017-SFMG-I0025.sar.gz",,, "Enter effective area file name"
edpFileName,s,hl,"${AGILE}/model/scientific.analysis/data/AG-GRID.G0017-SFMG-I0025.edp.gz",,, "Enter energy dispersion file name"
maplist,s,hl,"None",,, "Maplist file name"
timelist,s,hl,"None",,, "Time intervals file name"
la,r,ql,90,, "Enter Longitude of map center (galactic)"
ba,r,ql,-40,, "Enter Latitude of map center (galactic)"
mdim,r,ql,50,, "Enter size of map (degrees)"
mres,r,ql,0.5,, "Enter bin size (degrees)"
binstep,r,ql,2,, "Enter map bin step size ( 1/mres)"
tmin,r,ql,144590400,, "Enter initial time (sec)"
tmax,r,ql,145886400,, "Enter final time (sec)"
emin,r,ql,100,, "Enter minimum energy (MeV)"
emax,r,ql,50000,, "Enter maximum energy (MeV)"
index,r,ql,2.1,, "Enter spectral index"
fovradmin,r,ql,0,, "Enter min radius of field of view (degrees)"
fovradmax,r,ql,60,, "Enter max radius of field of view (degrees)"
albrad,r,ql,90,, "Enter radius of Earth albedo (degrees)"
phasecode,i,ql,6,, "Orbital phase code"
projection,s,ql,"ARC",,, "Enter map projection (ARC or AIT)"
timestep,i,h,160,, "Enter LOG file step size"
lonpole,r,h,180,, "Rotation of map (degrees)"
y.tol,r,h,0.5,, "Enter boresight movement tolerance (degrees)"
roll.tol,r,h,360,, "Enter roll tolerance (degrees)"
earth.tol,r,h,5.0,, "Earth tolerance (degrees)"

```

Sample grid log index file:

```
LOG/GridLog_0.log 0.000000 32400.000000 LOG
```

Each row of the index file is a grid log file followed by the minimum and maximum times contained in the grid log file. The index file may list multiple grid log files.

outputs:

Screen output (example):

```

You can type the command AG_expmapgen at the command line and insert the requested parameters or insert the parameters as arguments of the procedure: test_dataset_6.0>~/AGILE/bin/AG_expmapgen
logfile=@OB27200_Velatest.LOG.index la=263.59
ba=-2.84 outfile=OB27200_Velatest.EXP
sarFileName=${AGILE}/model/scientific.analysis/data/AG-GRID_G0017-SFMG-I0025.sar.gz
edpFileName=${AGILE}/model/scientific.analysis/data/AG-GRID_G0017-SFMG-I0025.edp.gz
index=2.1 albrad=90 phasecode=6 mdim=30. mres=0.3 binstep=3. tmin=433857532.
tmax=434030332. emin=100. emax=50000. fovradmin=0. fovradmax=50. projection=ARC

```

```

#####
### AG_expmapgen B25 v1.3.0 - A.C. T.C. A.T. A.B. A.Z. ###
#####

```

INPUT PARAMETERS:

```

Output file name:  OB27200_Velatest.EXP
Grid log index file name:  @OB27200_Velatest.LOG.index
Effective area file name:
${AGILE}/model/scientific.analysis/data/AG-GRID_G0017-SFMG-I0025.sar.gz
Energy dispersion file name:
${AGILE}/model/scientific.analysis/data/AG-GRID_G0017-SFMG-I0025.edp.gz

```

```

Maplist file name:  None
Time intervals file name:  None
Size of Map (degrees):  30
Bin size (degrees):  0.3
Longitude of map center (galactic):  263.59
Latitude of map center (galactic):  -2.84
Rotation of map (degrees):  180
Radius of earth albedo (degrees):  90
Boresight movement tolerance (degrees):  0.5
Roll tolerance (degrees):  360
Earth tolerance (degrees):  5
Orbital phase code:  6
Projection (ARC or AIT):  ARC
Bin step size:  3
LOG file step size:  160
Spectral index:  2.1
Initial time (sec):  433857532
Final time (sec):  434030332
Minimum energy:  100
Maximum energy:  50000
Min radius of field of view (degrees):  0
Max radius of field of view (degrees):  50
INTERVALS N=1:
433857532.000000 434030332.000000
Selecting the events..
MakeSelection intervals:
433857532.000000 434030332.000000
Selecting from:  LOG/ag-433857532_STD1.LOG.gz
Selecting from:  LOG/ag-433943932_STD1.LOG.gz
Skipped 3 files.
Selected 8613 rows.
Dimension of m_aeffgrid:  8 19 16
Dimension of m_avgValues:  8 19
MakeGridAverage2:  100 20000
Dimension of m_edpgrid:  8 19 16 16
MakeGridAverage2:  100 20000
Beginning interpolation..
Creating file OB27200_Velatest.EXP
Created file OB27200_Velatest.EXP
Creating image in OB27200_Velatest.EXP
Closing OB27200_Velatest.EXP
#####
### AG_expmapgen B25 exiting .....###
#####

```

sarFileName should be set to `AG_GRID_G0017_SFMM_I0025.sar.gz` if events of type G are selected in the counts map (`filtercode=5`).

FITS file listed in parameter file. Sample header:



```

SIMPLE = T / file does conform to FITS standard
BITPIX = -64 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = 134 / length of data axis 1
NAXIS2 = 134 / length of data axis 2
EXTEND = T / FITS dataset may contain extensions
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A
CRVAL1 = 263.
CRVAL2 = -2.6
CTYPE1 = 'GLON-ARC'
CTYPE2 = 'GLAT-ARC'
CRPIX1 = 67.1666666666667
CRPIX2 = 67.1666666666667
CDELTA1 = -0.3
CDELTA2 = 0.3
CUNIT1 = 'deg '
CUNIT2 = 'deg '
RADESYS = 'FK5 '
EQUINOX = 2000.
LONPOLE = 180.
TSTART = 111412735. / [OBT]first event time
TSTOP = 112363135. / [OBT]last event time
TIMESYS = 'TT '
TIMEUNIT= 's '
MJDREFI = 53005.
MJDREFF = 0.00235444444444444444
TIMEZERO= 0. / TT
DATE-OBS= '2007-07-13T12:00:00' / start date and time of the observation(TT)
DATE-END= '2007-07-24T12:00:00' / end date and time of the observation(TT)
MINENG = 100.
MAXENG = 50000.
TELESCOP= 'AGILE '
INSTRUME= 'GRID '
PIXCENT = 'T '
YTOL = 0.5 / Pointing direction tolerance (deg)
ROLLTOL = 360. / Roll angle tolerance (deg)
EARTOL = 5. / Pointing direction tolerance (deg)
STEP = 2 / Interpolation step size
BUNIT = 'cm**2 s sr'
FOV = 70. / Radius of field of view (deg)
FOVMIN = 0. / Minimum off-axis angle (deg) ALBEDO = 80. / Earth zenith angle (deg)
PHASECOD= 18 / Orbital phase code
INDEX = -2.1
SC-Z-LII= 287.305239941523
SC-Z-BII= -0.237547573935354

```

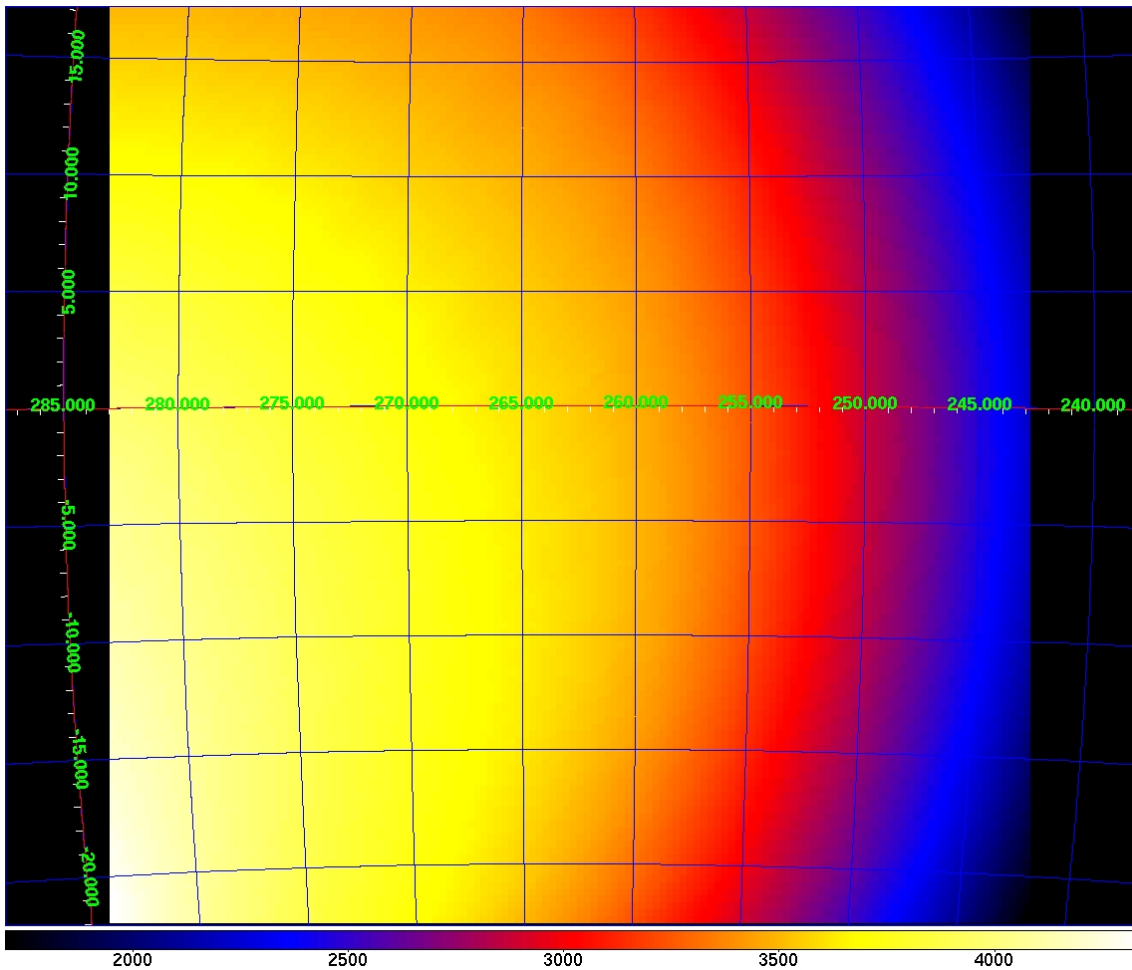


Figure 1: DS9 image of an exposure map produced by AG\_expmapgen.

All are standard FITS keywords except for SC-Z-LII, SC-Z-BII, and SC-LONPL, which indicate the pointing direction and rotation of the spacecraft.

Figure 1 shows the image produced by DS9 for an exposure map generated by AG\_expmapgen, with Galactic coordinate axes displayed.

## 5 The Counts Map Generator Task

Counts maps are generated by the procedure AG\_ctsmapgen found in `$ADC/scientific_analysis/bin/`. AG\_ctsmapgen reads the event files listed in the event file index, bins the counts between tmin and tmax, and outputs a FITS image file. The image is a two-dimensional array in the ARC or AIT projection. The projection, size and resolution, the center and rotation of the map in Galactic coordinates, tmin, tmax, emin, and emax are specified in the AG\_ctsmapgen.par parameter file, along with various integration parameters (fovrad, fovradmin, albrad, phasecode)

and a filter code (`filtercode`). `filtercode=5` correspond to events classified as gamma (G).

Note: In this build `lonpole` must be set = 180.

inputs:

AG\_ctsmapgen.par:

```

evtfile,s,ql,"${ADC}/INDEX/GridEvGen.index",,,"Enter event file index file name"
outfile,s,ql,"",,,"Enter output file name"
mdim,r,ql,120.5,,,"Size of Map(degrees)"
mres,r,ql,0.5,,,"Bin size(degrees)"
la,r,ql,101.45,,,"Longitude of map center(Galactic)"
ba,r,ql,-0.81,,,"Latitude of map center(Galactic)"
lonpole,r,ql,180,,,"Rotation of map(degrees)"
tmin,r,ql,0,,,"Enter initial time(sec)"
tmax,r,ql,32400,,,"Enter final time(sec)"
emin,r,ql,100,,,"Enter min energy"
emax,r,ql,50000,,,"Enter max energy"
fovrad,r,l,180.00,,,"Enter max off-axis angle (degrees)"
fovradmin,r,l,0.00,,,"Enter min off-axis angle (degrees)" albrad,r,l,0.00,,,"Enter r
lonpole,r,l,180,,,"Rotation of map(degrees)"
phasecode,i,l,0,,,"Orbital phase code"
filtercode,i,l,0,,,"Event filter code"
projection,s,,,"ARC",,,"Enter projection (ARC or AIT)"

```

Sample event file index :

```

${ADC}/EVT/SIM000001_1.3901.001.evt 0.000000 32397.000000 EVT

```

Each row of the index file is an event file followed by the minimum and maximum times contained in the event file. The index file may list multiple event files.

outputs:

Screen output (example):

You can type the command `AG_ctsmapgen` at the command line and insert the parameters or insert the parameters as arguments of the procedure.

```

/home/adc/G0_test_dataset>~/ADC/scientific_analysis/bin/AG_ctsmapgen
evtfile=A01_0B1000_r2_ID0_Velatest.EVT.index
outfile=VELA.cts.gz mdim=40 mres=0.3 la=263. ba=-2.60 tmin=111412735.000000 tmax=112363
emin=100 emax=50000 fovrad=60 fovradmin=0 albrad=80 lonpole=180 phasecode=18 filtercode=
projection=ARC

```

```

#####
### Task AG_ctsmapgen B25 v1.3.0 - A.C. T.C. A.T. A.B. A.Z.#####
#####

```

```
#####
```

INPUT PARAMETERS:

```
Input index file name = A01_OB1000_r2_ID0_Velatest.EVT.index
Output file name = VELA.cts.gz
map dimension [deg] : 40.00
map resolution [deg] :0.30
map centroid G.long. [deg] : 263.00
map centroid G.lat. [deg] : -2.60
TMIN [s] : 111412735.000000
TMAX [s] : 112363135.000000
MIN ENERGY [MeV] : 100.0
MAX ENERGY [MeV] : 50000.0
maximum off-axis angle [deg] : 60.00 minimum off-axis angle [deg] : 0.00 radius
of earth albedo [deg] : 80.00
Orbital Phase Code: 18
Filter code: 5
AG_ctsmapgen.....starting

AG_ctsmapgen.....adding events files
AG_ctsmapgen.....addfile exiting STATUS : 0

4990
creating Counts Map.....
writing Counts Map.....
writing header.....

AG_ctsmapgen..... exiting
```

```
#####
##### Task AG_ctsmapgen..... exiting #####
#####
```

FITS file listed in parameter file. Sample header:

```
SIMPLE = T / file does conform to FITS standard
BITPIX = 16 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = 134 / length of data axis 1
NAXIS2 = 134 / length of data axis 2
EXTEND = T / FITS dataset may contain extensions
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A
BZERO = 32768 / offset data range to that of unsigned short
BSCALE = 1 / default scaling factor
CRVAL1 = 263.
CRVAL2 = -2.6
CTYPE1 = 'GLON-ARC'
CTYPE2 = 'GLAT-ARC'
CRPIX1 = 67.16666666666667
CRPIX2 = 67.16666666666667
CDELTA1 = -0.3
CDELTA2 = 0.3
CUNIT1 = 'deg '
CUNIT2 = 'deg '
RAESYS = 'FK5 '
EQUINOX = 2000.
LONPOLE = 180.
TSTART = 111412735. / [OBT]first event time
TSTOP = 112363135. / [OBT]last event time
TIMESYS = 'TT '
TIMEUNIT= 's '
MJDREFI = 53005.
MJDREFF = 0.00235444444444444444
TIMEZERO= 0. / TT
DATE-OBS= '2007-07-13T12:00:00' / start date and time of the observation(TT)
DATE-END= '2007-07-24T12:00:00' / end date and time of the observation(TT)
MINENG = 100.
MAXENG = 50000.
TELESCOP= 'AGILE '
INSTRUME= 'GRID '
PIXCENT = 'T '
BUNIT = ' '
FOV = 60. / Maximum off-axis angle (deg)
FOVMIN = 0. / Minimum off-axis angle (deg) ALBEDO = 80. / Earth zenith angle (deg)
PHASECOD= 18 / Orbital phase code
FILTERCO= 5 / Event filter code
END
```

Figure 2 shows the image produced by DS9 for the counts map generated above, with Galactic

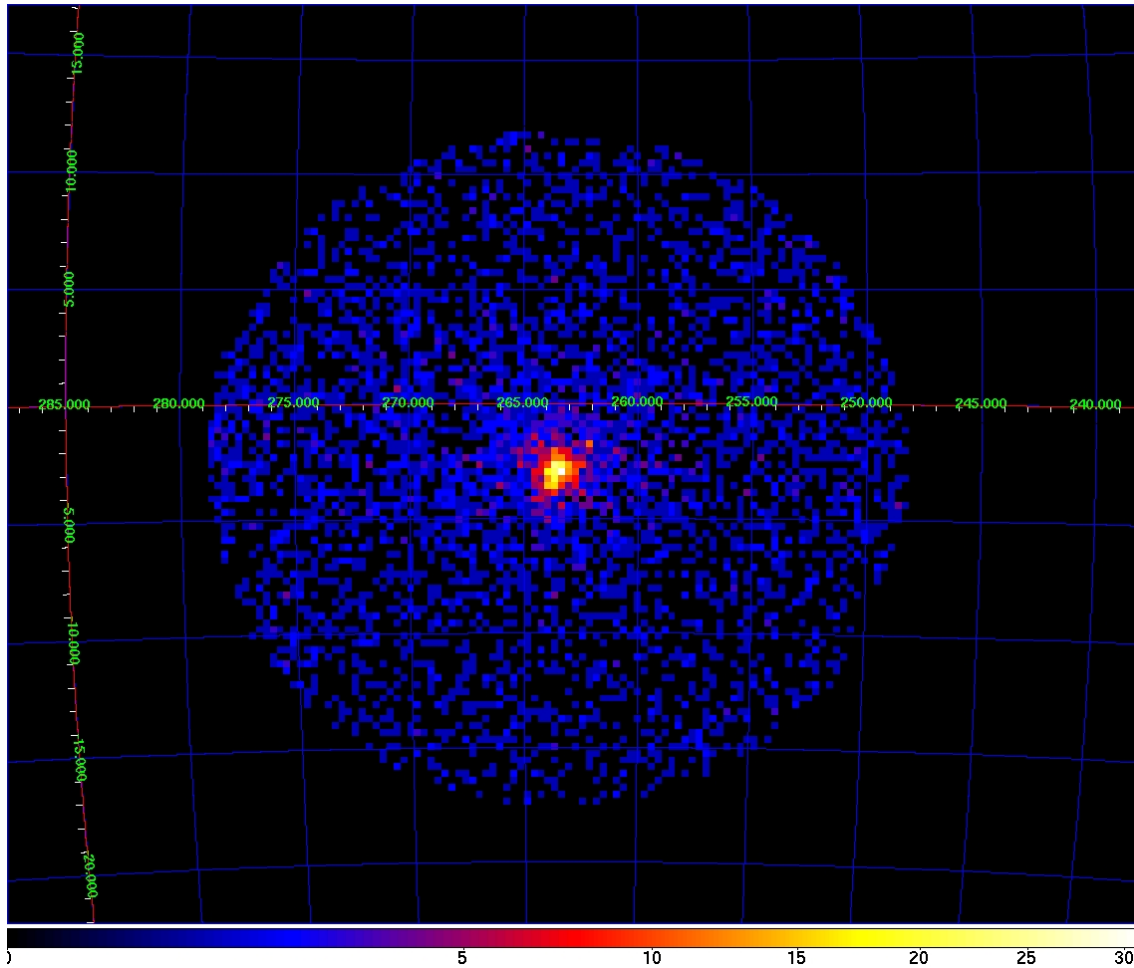


Figure 2: DS9 image of a counts map produced by `AG_ctsmapgen`.

coordinate axes displayed.

## 6 The Intensity Map Generator Task

Intensity maps are generated by the procedure `AG_intmapgen` found in `$ADC/scientific_analysis/bin/`. `AG_intmapgen` reads an exposure map produced by `AG_expmapgen` and a counts map produced by `AG_ctsmapgen` and outputs a FITS image file, in the same format as the exposure map, in which each pixel contains the intensity in that pixel. The image is a square array in the ARC projection. The two input maps should have been produced using the same set of parameters. The intensity map is not used in the scientific analysis; it is useful solely as a visualization tool.

inputs:

`AG_intmapgen.par`:

```

expfile,s,ql,"VELA.exp.gz",,,"Enter exposure file name"
outfile,s,ql,"VELA.int.gz",,,"Enter output file name"
ctsfile,s,ql,"VELA.cts.gz",,,"Enter counts map file name"

```

outputs:

Screen output (example):

You can type the command `AG_intmapgen` at the command line and insert the requested parameters or insert the parameters as arguments of the procedure.

```
/home/adc/GO_test_dataset>~/ADC/scientific_analysis/bin/AG_intmapgen
```

```
expfile=VELA.exp.gz
```

```
outfile=VELA.int.gz
```

```
ctsfile=VELA.gas.gz
```

```

#####
##### AG_intmapgen B25 v1.2.0 - A.B. #####
#####
#####

```

INPUT PARAMETERS:

```
Enter exposure file name = VELA.exp.gz
```

```
Enter output file name = VELA.gas.gz
```

```
Enter counts map file name = VELA.cts.gz
```

```
AG_intmapgen.....starting
```

```
AG_intmapgen..... exiting
```

```

#####
##### Task AG_intmapgen..... exiting #####
#####

```

FITS file listed in parameter file. Sample header:

```

SIMPLE = T / file does conform to FITS standard
BITPIX = -64 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = 134 / length of data axis 1
NAXIS2 = 134 / length of data axis 2
EXTEND = T / FITS dataset may contain extensions
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A
CRVAL1 = 263.
CRVAL2 = -2.6
CTYPE1 = 'GLON-ARC'
CTYPE2 = 'GLAT-ARC'
CRPIX1 = 67.1666666666667
CRPIX2 = 67.1666666666667
CDELTA1 = -0.3
CDELTA2 = 0.3
CUNIT1 = 'deg '
CUNIT2 = 'deg '
RADESYS = 'FK5 '
EQUINOX = 2000.
LONPOLE = 180.
TSTART = 111748135. / [OBT]first event time
TSTOP = 112363135. / [OBT]last event time
TIMESYS = 'TT '
TIMEUNIT= 's '
MJDREFI = 53005.
MJDREFF = 0.00235444444444444444
TIMEZERO= 0. / TT
DATE-OBS= '2007-07-13T12:00:00' / start date and time of the observation(TT)
DATE-END= '2007-07-24T12:00:00' / end date and time of the observation(TT)
MINENG = 100.
MAXENG = 50000.
TELESCOP= 'AGILE '
INSTRUME= 'GRID '
PIXCENT = 'T '
YTOL = 0.5 / Pointing direction tolerance (deg)
ROLTOL = 360. / Roll angle tolerance (deg)
EARTOL = 5. / Pointing direction tolerance (deg)
STEP = 2 / Interpolation step size
TIMESTEP= 16 / Log file step size BUNIT = (cm**2 s sr)**(-1)
FOV = 60. / Radius of field of view (deg)
FOVMIN = 0. / Minimum off-axis angle (deg) ALBEDO = 80. / Earth zenith angle (deg)
PHASECOD= 18 / Orbital phase code
INDEX = -2.1
SC-Z-LII= 287.305239941523
SC-Z-BII= -0.237547573935354

```



Figure 4 shows the image produced by DS9 for a diffuse emission map generated by `AG_intmapgen`, with Galactic coordinate axes displayed.

## 7 The Diffuse Map Generator Task

Diffuse emission maps are generated by the procedure `AG_gasmapgen` found in `$ADC/scientific_analysis/bin/`. `AG_gasmapgen` reads an exposure map produced by `AG_expmapgen` and the master diffuse emission map and outputs a FITS image file, in the same format as the exposure map, in which each pixel contains the diffuse emission in that pixel. The image is a square array in the ARC projection.

The input files should have the extension `SFMG_I0025.disp.conv.sky.gz`. These maps contain models of the diffuse emission convolved with the energy-dependent point spread function and combined into predefined observed energy ranges according to the appropriate energy dispersion function for G events using the FM background filter.

The diffuse emission map should be selected based on the energy range of the analysis. If the analysis is performed between 100 MeV and 50 GeV, select the file `100_50000.0.5.SFMG_I0025.conv.sky.gz` for the `diffusefile` parameter and `100_50000.0.1.SFMG_I0025.conv.sky.gz` for the `hiresdiffusefile` parameter. The first number in the file name is the minimum energy and the second number is the maximum energy. It is possible to add together the files to get different energy ranges. 0.1 degrees is the bin size of the diffuse emission map at low latitudes, while 0.5 degrees is the bin size of the diffuse emission map at high latitudes.

inputs:

```
AG_gasmapgen.par:
  expfile,s,ql,"",,, "Enter exposure file name"
  outfile,s,ql,"s",,, "Enter output file name"
  diffusefile,s,ql,"~/ADC/scientific_analysis/data/100_50000.0.5.SFMG_I0025.conv.sky.gz"
  hiresdiffusefile,s,ql,"~/ADC/scientific_analysis/data/100_50000.0.1.SFMG_I0025.conv.
    "Enter diffuse model file name"
```

outputs:

Screen output (example):

You can type the command `AG_gasmapgen` at the command line and insert the requested parameters or insert the parameters as arguments of the procedure.

```
/home/adc/GO_test_dataset>~/ADC/scientific_analysis/bin/AG_gasmapgen
expfile=VELA.exp.gz
outfile=VELA.gas.gz
diffusefile=~/ADC/scientific_analysis/data/100_50000.0.5.SFMG_I0025.conv.sky.gz
hiresdiffusefile=~/ADC/scientific_analysis/data/100_50000.0.1.SFMG_I0025.conv.sky.gz
```

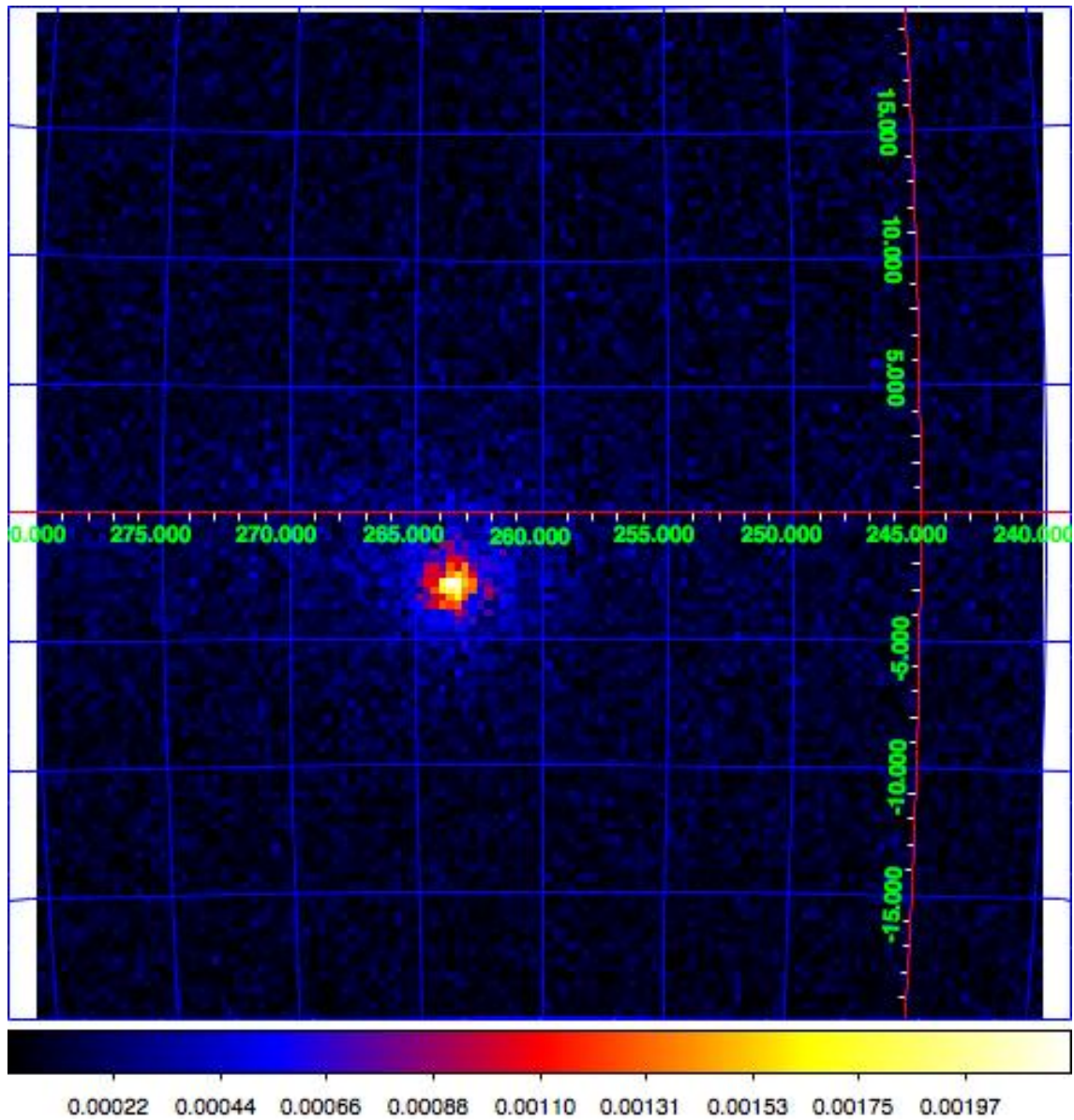


Figure 3: DS9 image of the diffuse emission map produced by AG\_intmapgen with the listed parameter file.

```
#####
#####AG_gasmapgen B25 v1.3.0 - A.C. A.P. A.T. A.B. A.Z. #####
#####
#####
```

INPUT PARAMETERS:

```
Enter exposure file name = VELA.exp.gz
Enter output file name = VELA.gas.gz
Enter diffuse model file name = ~/ADC/scientific_analysis/data/100_50000.0.5.SFMG_I0025.
Enter high res diffuse model file name = ~/ADC/scientific_analysis/data/100_50000.0.1.SFMG_I0025.
```

```
AG_gasmapgen.....starting
```

```
AG_gasmapgen..... exiting
```

```
#####
##### Task AG_gasmapgen..... exiting #####
#####
```

FITS file listed in parameter file. Sample header:

```

SIMPLE = T / file does conform to FITS standard
BITPIX = -64 / number of bits per data pixel
NAXIS = 2 / number of data axes
NAXIS1 = 134 / length of data axis 1
NAXIS2 = 134 / length of data axis 2
EXTEND = T / FITS dataset may contain extensions
COMMENT FITS (Flexible Image Transport System) format is defined in 'Astronomy
COMMENT and Astrophysics', volume 376, page 359; bibcode: 2001A
CRVAL1 = 263.
CRVAL2 = -2.6
CTYPE1 = 'GLON-ARC'
CTYPE2 = 'GLAT-ARC'
CRPIX1 = 67.1666666666667
CRPIX2 = 67.1666666666667
CDELTA1 = -0.3
CDELTA2 = 0.3
CUNIT1 = 'deg '
CUNIT2 = 'deg '
RADESYS = 'FK5 '
EQUINOX = 2000.
LONPOLE = 180.
TSTART = 111748135. / [OBT]first event time
TSTOP = 112363135. / [OBT]last event time
TIMESYS = 'TT '
TIMEUNIT= 's '
MJDREFI = 53005.
MJDREFF = 0.00235444444444444444
TIMEZERO= 0. / TT
DATE-OBS= '2007-07-13T12:00:00' / start date and time of the observation(TT)
DATE-END= '2007-07-24T12:00:00' / end date and time of the observation(TT)
MINENG = 100.
MAXENG = 50000.
TELESCOP= 'AGILE '
INSTRUME= 'GRID '
PIXCENT = 'T '
YTOL = 0.5 / Pointing direction tolerance (deg)
ROLTOL = 360. / Roll angle tolerance (deg)
EARTOL = 5. / Pointing direction tolerance (deg)
STEP = 2 / Interpolation step size
TIMESTEP= 16 / Log file step size BUNIT = (cm**2 s sr)**(-1)
FOV = 60. / Radius of field of view (deg)
FOVMIN = 0. / Minimum off-axis angle (deg) ALBEDO = 80. / Earth zenith angle (deg)
PHASECOD= 18 / Orbital phase code
INDEX = -2.1
SC-Z-LII= 287.305239941523
SC-Z-BII= -0.237547573935354

```

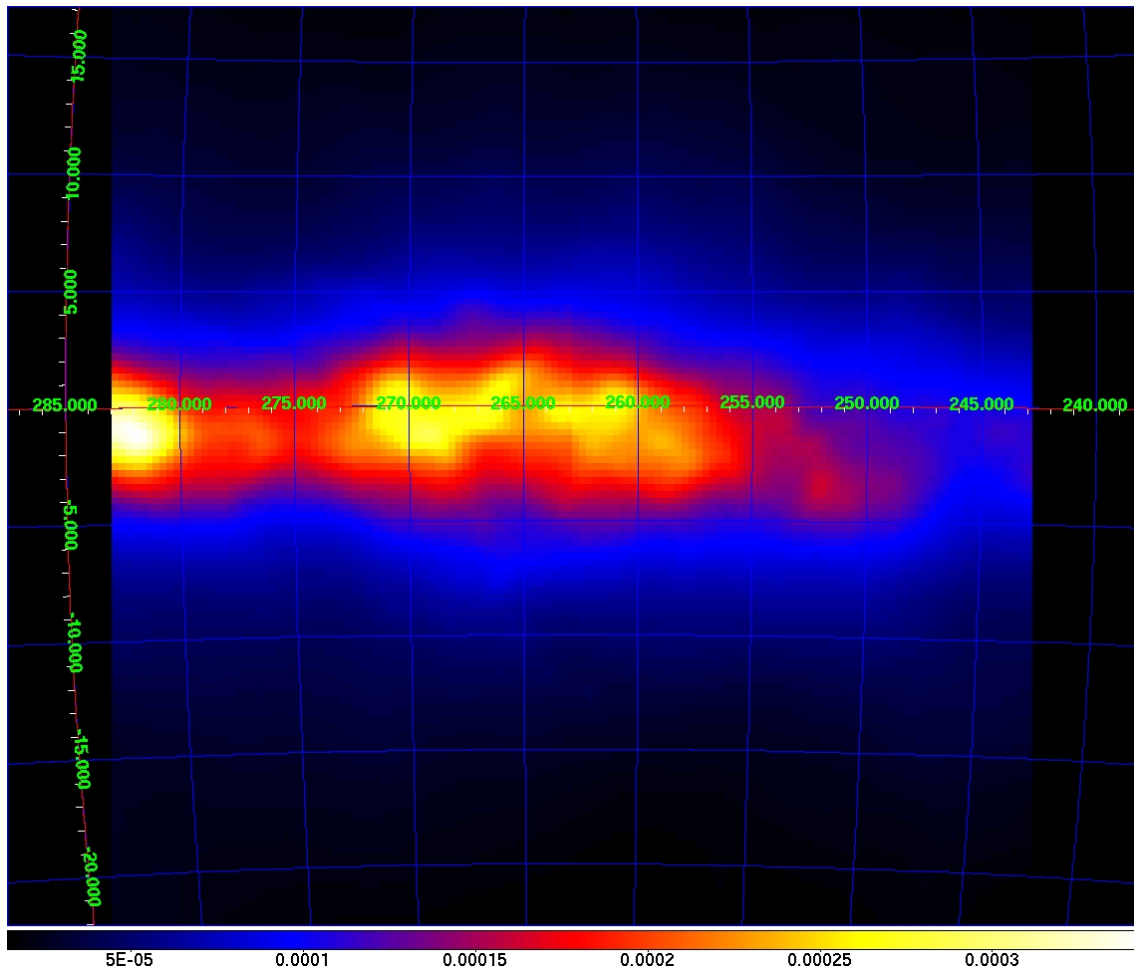


Figure 4: DS9 image of the diffuse emission map produced by AG\_gasmagpen with the listed parameter file.

Figure 4 shows the image produced by DS9 for a diffuse emission map generated by AG\_gasmagpen, with Galactic coordinate axes displayed.

## 8 Source Detection and Location

### 8.1 Introduction

This section describes how to use AG\_multi, the latest version of the source detection and location task using the maximum likelihood method.

## 8.2 Getting started

`AG_multi` is a command line application running under 64-bits Linux or Mac OS X. The aim of this application is to find the best values for the flux, the position and/or the spectral index of a list of gamma ray sources to explain a set of experimental data. The user will provide a list of maps containing maps of photons detected by the AGILE satellite during one or a series of observations, together with maps of the instrument exposure during those observations and the corresponding Galactic diffuse emission models. The user will also provide a list of sources that may explain the photons detected, giving a guess for the flux, position and spectral index of those sources. `AG_multi` will find the best values for the sources to fit the data using the method of maximum likelihood, estimating the improved likelihood due to the presence of each source in the list. The user has a variety of options to influence the process as explained in the following.

## 8.3 The Command Line

The command line is internally managed by the parameter interface library (PIL) developed by the INTEGRAL Science Data Center (ISDC). Each command line option is described by a `.par` file, `AG_multi.par` in this case, a sample of which comes with the distribution. The environment variable `PFILES` should be defined in your account, pointing to the directory where the file `AG_multi.par` resides. The user has two ways to specify the option values in the command line. One is to specify the option name and its value (in any order), the other is to give just the option values in the order they appear in the `.par` file. For example `AG_multi option1=value1 option2=value2 option3=value3...` or `AG_multi value1 value2 value3...`

If any of the command line options are missing, `AG_multi` will prompt the user to either confirm the previously used value or to provide a new one. The values used in the current session will be stored and used in the next session. This behaviour depends on the `.par` file that comes with the distribution, which the user may change. Refer to the PIL library online documentation for all the details.

This is the list of the program options required, in the order they are expected. Each option can be a number or a string.

string maplist

name of a text file containing the the list of the maps. An explanation of this file and its syntax is given below.

string sarfile

One of three calibration files required. This file contains the effective area of AGILE-GRID for a given filter and event type, as a function of energy and direction in instrument coordinates.

string edpfile

One of three calibration files required. This file, for a given filter and event type, contains the energy dispersion function, the distribution of observed energies for measurements of photons of a given true energy, as a function of direction in instrument coordinates.

string psdfile

One of three calibration files required. This file, for a given filter and event type, contains the point spread dispersion function, the distribution of observed offsets from the true photon direction as a function of energy and direction in instrument coordinates.

number ranal

The analysis radius in degrees. When considering a given source, only the photons falling inside the radius will be considered, and the flux, location, and spectral index of sources outside of the analysis region will be fixed.

number galMode

number isoMode

These two numbers, ranging from 0 to 3, tell `AG_multi` how to handle the Galactic and isotropic diffuse components. Refer to the `maplist` section for details.

string srclist

The name of a text file containing the the list of the gamma ray sources to fit to the list of maps above.

string outfile

The name of the main text output file, the title of the HTML output, and the prefix of the other output file names.

number ulcl

Sources for which a flux optimization is requested will have a flux upper limit calculated (in addition to the best-fit flux and error where possible). This parameter specifies the confidence level for the flux upper limits (=1 for 1 sigma, =2 for two sigma, etc.)

number loccl

This parameter specifies the confidence limit of the source location contour for sources for which a source location optimization is requested. It is expressed as a difference in test statistic, distributed according to chi-squared with two degrees of freedom (e.g. 1.38629 = 50%, 2.29575 = 68%, 5.99147 = 95%, 9.21034 = 99%).

## 8.4 The Map List

The map list is a text file listing containing at least one line of text. Each line of text describes one set of maps and it is possible to include empty lines or comment lines. The comment lines begin with an exclamation mark. Each set of maps is described by a line containing space separated values, in the following order:

```
<cts file> <exp file> <gas file> <off axis angle in degrees> <galCoeff> <isoCoeff>
```

The file names may contain absolute or relative path information. However, because the values in each line are separated from one another by a space, they may not themselves contain a space.

The `cts`, `exp` and `gas` files are produced from experimental data by the procedures `AG_ctsmapgen`, `AG_expmapgen`, and `AG_gasmmapgen`. They contain the photon counts, the instrument exposure, and the Galactic diffuse emission model respectively, collected in a given period of time, falling in a given energy interval and detected with a given angle of incidence, among other selection criteria (see the appropriate manual for further details).

The selection criteria affect the shape of the point spread function of the instrument, which `AG_multi` uses the calibration files to calculate. Most of the parameters (energy, phase code etc.) are already contained in the FITS headers of the input files; however, the off-axis angle must be specified explicitly. In general, a separate set of maps should be generated for each range of off-axis angles. In this case, the off-axis angle specified for each set of maps should be consistent with the off-axis angle range from which they were generated. For example, a value of 20 degrees would be an appropriate choice for a set of maps generated for off-axis angles between 10 and 30 degrees.

`galCoeff` and `isoCoeff` are the coefficients for the Galactic and isotropic diffuse emission components respectively. The values may be fixed during the fitting process or some or all of them may be optimized by allowing them to vary. Positive values are considered fixed, while negative values are free to vary starting from their absolute values. These coefficients are affected by the `galMode` and `isoMode` you have given in the command line, according to the following table:

mode = 0: all the coefficients are fixed to their initial absolute values

mode = 1: all the positive coefficients are fixed, while the negative ones are variable (normal behaviour as explained above)

mode = 2: all the coefficients are variable, regardless of their sign

mode = 3: all the coefficients are variable, but their relative proportion is fixed according to their initial values. For example, if two maps have -1 and 2 as initial values of `isoCoeff`, and `isoMode` = 3, the final coefficient may have final values of 3 and 6, maintaining a fixed ratio of 1:2.

## 8.5 The Source List

The source list is a text file listing at least one source. Each line of text describes one source and it is possible to include empty lines or comment lines. The comment lines begin with an exclamation mark. Each source is described by a line containing space separated values, in the following order:

```
<flux> <1> <b> <spectral index> <fixFlag> <minSqrt(TS)> <name> [location limitation]
```

Because the values in each line are separated from one another by a space, they may not themselves contain a space.

The first 4 values, flux in  $\text{cm}^{-2} \text{s}^{-1}$ , galactic longitude and latitude in degrees, and spectral index of each source, represent the initial estimates of the values for that source. According to the fix flag some or all of those values will be optimized by being allowed to vary. The flux



estimates are relevant in the fitting process, as the sources are considered one by one starting with the one with the brightest initial flux value, regardless of the order they are given in the source file. The fix flag is a bit mask, each bit indicating whether the corresponding value is to be allowed to vary. 1 indicates the flux, 2 the position and 4 the spectral index. The user may combine these values, but the flux will always be allowed to vary if at least one of the other values are. Examples:

fixFlag = 0: everything is fixed. This is for known sources which must be included in order to search for other nearby sources.

fixFlag = 3: flux and position variable, index fixed

fixFlag = 5: flux and index variable, position fixed

fixFlag = 7: flux, position and index variable

and also

fixFlag = 2: only the position is variable, but `AG_multi` will let the flux vary too, so this is equivalent to 3.

`minSqrt(TS)` is the minimum acceptable value for the square root of TS: if the optimized significance of a source lies below this value, the source is considered undetected and will be ignored (set to flux = 0) when considering the other sources.

After the name of the source (which should not contain a space), an optional value for the location limitation in degrees may be provided. If this value is present and not zero, the longitude and latitude of the source will not be allowed to vary by more than this value from its initial position.

### 8.5.1 Spectral models

A full energy band spectral fit of the data is performed with different spectral model. The spectral representations used in the BUILD25 are PL, exponential cut-off PL, super-exponential cut-off PL, and log parabola (LP). More details are reported in bulgarelli19

The PL spectral model is used for all sources that are not significantly curved and have low exposure, i.e.

$$\frac{dN}{dE} = N_0 E^{-\alpha}, \quad (1)$$

where  $N_0$  is the prefactor and alpha is the index explicitly evaluated by the MLE method. Our MLE spectral fitting does not explicitly output the prefactor value, which is internally calculated by the numerical procedure.

The majority of the AGILE sources are described by a PL.

The exponential cut-off PL spectral model (PC) is

$$\frac{dN}{dE} = N_0 E^{-\alpha} \exp\left(-\frac{E}{E_c}\right), \quad (2)$$

where  $N_0$  is the prefactor,  $\alpha$  is the index, and  $E_c$  is the cut-off energy. The values  $E_c$  and  $\alpha$  are explicitly provided by the MLE method. The super exponential cut-off PL spectral model (PS) is

$$\frac{dN}{dE} = N_0 E^{-\alpha} \exp\left(-\left(\frac{E}{E_c}\right)^\beta\right), \quad (3)$$

where  $N_0$  is the prefactor,  $\alpha$  is the first index,  $\beta$  the second index, and  $E_c$  is the cut-off energy. The parameters  $\alpha$ ,  $E_c$ , and  $\beta$  are explicitly provided by the MLE method.

The LP spectral model is

$$\frac{dN}{dE} = N_0 E^{-\alpha - \beta \ln(E/E_c)}, \quad (4)$$

where  $N_0$  is the prefactor,  $E_c$  is the pivot energy,  $\alpha$  is the first index,  $\beta$  the curvature. The parameters  $\alpha$ ,  $E_c$ , and  $\beta$  are explicitly provided by the MLE method.

The selection of curved spectra followed the acceptance criteria described in bulgarelli19. Briefly, a source is considered significantly curved if  $TS_{\text{curved}} > 16$ , where  $TS_{\text{curved}} = 2 \times (\log L(\text{curved spectrum}) - \log L(\text{power law}))$ , where  $L$  is the likelihood function obtained changing only the spectral representation of that source and refitting all free parameters.

**SM:** Spectral model. PL indicates power-law fit to the energy spectrum; PC indicates power-law with exponential cutoff fit to the energy spectrum; PS indicates power-law with super exponential cut-off fit to the energy spectrum; LP indicates log-parabola fit to the energy spectrum

**Index= $\alpha$ :** Spectral index for PL, PC, and PS spectral models, first index for LP spectral model, in the energy range 100 MeV – 10 GeV;

$\Delta\alpha$ : Statistical  $1\sigma$  uncertainty of  $\alpha$ , in the energy range 100 MeV – 10 GeV

**par2 =  $E_c$  (MeV):** Cut-off energy for PC and PS spectral models, pivot energy for LP spectral model, in the energy range 100 MeV – 10 GeV;

$\Delta E_c$  (MeV): Statistical  $1\sigma$  uncertainty of  $E_c$ , in the energy range 100 MeV – 10 GeV

**par3 =  $\beta$ :** Second index for PS spectral models, curvature for LP spectral model, in the energy range 100 MeV – 10 GeV

$\Delta\beta$ : Statistical  $1\sigma$  uncertainty of  $\beta$ , in the energy range 100 MeV – 10 GeV

### 8.5.2 Example with Power Law spectral model

As example of input source list, we display here the source list used for the analysis of the Vela pulsar with the test dataset provided along with this release:

!Flux	LII	BII	SpecInd	Fixflag	minsqrTS	NAME	loclimit
9.7e-06	263.590	-2.840	1.71	3	2.0	VelaPSR	2

## 8.6 Calibration Files

The parameters sarfile, edpfile, and psdfile provide the names of the three calibration files. These files are described in detail in other documents, and are provided with the distribution. They are FITS files whose common prefix specifies the filter and event type used and whose suffixes are .sar.gz, .edp.gz and .psd.gz, respectively. Ordinarily, they should not be changed by

the user. The parameter `expcorrfile` provides a correction factor as a function of off-axis angle for older calibration files. It should not be changed by the user. Analysis parameters

The parameters `ulcl` and `loccl` will typically have the values 2.0 (2 sigma upper limits) and 5.99147 (95% confidence contour), respectively, but may be changed by the user for use in, for example, light curves (e.g. `ulcl` = 1) or cases in which the 95% contour cannot be calculated (e.g. `loccl` = 2.29575).

The parameter `ranal` should be the smallest value consistent with 1) the angular extent of the point spread function in the given energy range and 2) the distance to nearby strong sources. In most cases, no more than 10 degrees will be required, and in many cases it is possible to use a smaller value such as 5 degrees.

As we have seen above, during the fitting process some values are fixed and others are variable, depending on the values of the flags. The execution time strongly depends on the number of the variable parameters. It is not possible to predict how long the fitting process will last or how it depends on the number of parameters, but the dependence is not linear. If all the diffuse coefficients are variable and all the fix flags are set to 7, for  $M$  maps and  $S$  sources the number of variable parameters will be  $2M+4S$ . In the case of many maps and many sources, this may lead to a very long execution time.

The fitting process takes place in two steps, according to the method of Maximum Likelihood. During each step all the sources are considered one by one, and several fitting attempts are performed by invoking the function `TH1D::Fit()` provided by the ROOT library, developed by CERN. The user will see on the screen the output printed by that function, and will find the related documentation on the CERN web site.

## 8.7 Output

`AG_multi` prints most of its messages to the standard output, and at the end of each execution it produces 2 main files and another set of files for each source in the source list.

Looking at the screen output one can follow each step of the fitting process. Most messages are sent to the standard output, while the error and warning messages will go to the standard error. Some errors are fatal, and the application will stop in this case. Most fatal errors are about an inconsistent set of input values.

At the end of the fitting process `AG_multi` generates two main files, describing the most relevant results for all the sources, and a set of source-specific files containing more detailed data about that source.

One of the two main files is in HTML format, and it includes both the input and output data grouped in tables. Having a look at this file the user should quickly understand the outcome of the fitting process and its main results. The next section describes the HTML output in more detail.

The second of the two main files contains the same data printed in the HTML file, but in text format, making it is easy to pass it as input to another application for further processing. This file is divided in two sections. The first contains one line for each diffuse component and the second one line for each source. The first line of each section begins with an exclamation mark (a comment line for many applications) labeling the values printed beneath. In each line the values are separated by a space. This is an example of the text output of the analysis of

the Vela pulsar with the test dataset provided. For this analysis, only one set of maps and one source (Vela) is used. The diffuse components coefficients are allowed to vary freely for each set of maps. The symmetric, positive, and negative errors are provided. The flux and position of the source are allowed to vary, while the spectral index is fixed. The name, significance of the source detection, position, source counts with error, source flux with error, and spectral index with error are provided. Because the source spectral index is fixed, its error is set to zero.

```
! DiffName, Flux, Err, +Err, -Err
Galactic 0.575512 0.29238 0.296404 -0.289301
Isotropic 5.43242 3.45244 3.59646 -3.34218
! SrcName, sqrt(TS), L_peak, B_peak, Counts, Err, Flux, Err, Index, Err, Par2, Par2Err,
VelaPSR 9.74211 263.568 -2.7676 64.4601 10.8679 1.85549e-05 3.12832e-06 1.71 0 0 0 0 0 0
```

**index, par2, par3 and related errors depend by the spectral mode used. See Sect. 8.5.1 for more details.**

For each source an additional text file is generated and, when possible, two additional files describing the source contour. The text file contains some comment-like lines (first character is an exclamation mark) labeling the values printed beneath. This is an example of text output, consistent with the example given above:

```
! Label, Fix, index, UL conf. level, srcloc conf. level
! sqrt(TS)
! L_peak, B_peak
! L, B, r, a, b, phi
! Counts, Err, +Err, -Err, UL
! Flux, Err, +Err, -Err, UL, Exp
! Index, Err
1AGL_J0835-4509 3 1.66 2 5.99147
149.957
263.574 -2.84422
263.574 -2.84126 0.0127191 0.0101623 0.0160235 -35.4372
71782 858.393 861.055 -855.729 1727.97
6.05223e-06 7.23747e-08 7.25991e-08 -7.21501e-08 1.45692e-07 1.18604e+10
1.66 0
```

The values `L_peak` and `B_peak` set to the initial values in the source location is fixed. If it is allowed to vary then they are set to the position for which the TS is maximized. If a confidence contour was found, the parameters on the following line describe the best-fit ellipse of the contour, described in detail below. The counts and fluxes are provided, as well as their symmetric, positive, and negative errors if the flux is allowed to vary. For convenience, the exposure of the source, used to calculate the source counts from the flux, is also provided. Finally, the spectral index and its error, if applicable, are provided.

If source location was requested for a given source and a source location contour was found, then three additional files are generated for that source. These files are written using galactic coordinates in degrees and can be loaded by applications such as `ds9` and overlaid on the maps

provided as input to `AG_multi` to visualize the source location contours. One of the three files, with extension `.con`, contains the source contour as found by the `ROOT` functions, expressed as a list of galactic coordinates, one point per line, where the last line is a repetition of the first. It may depict any shape. The other two files describe the ellipse that best fits the contour. One has extension `.ellipse.con` and represents the ellipse as a contour in a format analogous to that of the `.con` file. The other has extension `.reg` and describes same ellipse by its axes and orientation. See the section about the ellipse for more details.

## 8.8 HTML output

The HTML output file is divided into two sections, input and output.

The input section contains three subsections: the command line options, the map list and the source list contents. The command line options are listed in two tables, one with the names of the PSD, SAR and EDP files, the other with the rest of the command line. The maplist subsection also contains two tables. The first lists the mapfile contents and the second contains the data from the map files themselves. This table contains one map per row, and each column contains one value only if it is the same for all the maps. The last table of the input section contains the source list contents.

The output section is also divided into three subsections. The first is a table showing the Galactic and isotropic coefficients and their errors. Also in this table some cells may be grouped together when the values are all the same. The second is a table showing the fit results for the sources and their errors. One of the listed values is the contour equivalent radius, explained in the next section. The last table shows the source flux per energy channel, and it is present only when different energy channels are considered. This table has one row for each source and one column for each energy channel.

## 8.9 The Ellipse

If `AG_multi` was able to find a source contour, an ellipse is fit to the contour. The source contour is a list of points which defines a polygon by connecting each point sequentially. The value of Radius found in the HTML output is the radius in degrees of a circle with the same area as the polygon. `AG_multi` determines the ellipse which best fits the contour. This ellipse will have the same area as the polygon, and the distance between each contour point and the intersection between the ellipse and the line connecting that point to the centre will be minimized. The ellipse is completely described by three parameters: the two axes and the rotation (in degrees) of the first axis around the centre, as expected by the `ds9` application. If the ellipse is a circle, its axes will both be equal to the Radius found in the HTML output. The ellipse is described by two files that are readable by `ds9`: one is a `.reg` file which contains the centre, the axes and the rotation of the ellipse, while the other describes the same ellipse as a list of points in galactic coordinates, thus using the same syntax of a contour file, and has extension `.ellipse.con`. This is an example of ellipse `.reg` file:

```
galactic
ellipse(263.579,-2.8398,0.0167177,0.0205552,22.3895)
```