DOCUMENT TYPE:	Software User Manual
TITLE:	GRID SCIENTIFIC ANALYSIS **USER MANUAL**
DOC. REF.:	AGILE-IFC-OP-09
N. of PAGES:	
ISSUE:	Build-21
DATE:	16 November 2011
PREPARED BY:	A. CHEN, A. BULGARELLI, T. CONTESSI, A. GIULIANI, S. MEREGHETTI, A. PELLIZZONI, A. TROIS, S. VERCELLONE
CHECKED BY:	P. SANTOLAMAZZA, C. PITTORI
APPROVED BY:	
SOFTWARE MANAGER:	A. BULGARELLI
SUBSYSTEM LEADER:	S. MEREGHETTI
PRINCIPAL INVESTIGATOR:	M. TAVANI

Contents

1 Introduction

1.1 Scope and Contents of this Document

This document provides   a 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 IASF-Milano for this document is:
Andrew Chen
`chen@iasf-milano.inaf.it`
02-23699343

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 at IASF-BO as AGILE Team software manager. S. Mereghetti acts as the IASF-MI software working group coordinator. The software has been tested and debugged with the support of the AGILE Data Center Team at ASDC. See also RD[1] for a detailed description of the developer list.

2 Basic concepts

2.1 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 particle 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 μm of Tungsten, 0.07 X_0), into an electron/positron pair of Minimum Ionizing Particles (MIP, corresponding to a most probable value of 110 keV) in the detector, and records the electron/positron tracks through a combination of Silicon microstrip detectors and associated readout.

A GRID event is a collection of all the electron/positron interactions in the 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.

2.2   Event classification and standard data format

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. These data are sent to Earth, where the AGILE Data Center (ADC), hosted at the ASI Science Data Center (ASDC), processes these GRID events with an additional on-ground filter 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 : event not classified

The AGILE data are organized as lists of photons from the start of the mission until the last released data. The list of photons is provided in the event files (EVT). The events provided within the event files are G, S, L. Normally, the AGILE team use the G class for the analysis. Only for gamma-ray bursts and pulsar timing analysis are the G, S and L classes used.

To know where AGILE is pointed at a given time and when the spacecraft operates nominally the auxiliary "LOG" files are provided. The scientific tools take the events and LOG files as basic input for the analysis.

The event and LOG 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.'

The version number of the AGILE data processing is the value of the keyword OBSW_VER in the FITS header of the EVT files, e.g:
OBSW_VER= '3_18_17_16' / OB SW version: PipeOB_B-SCI_B-STD_B-COR
means the version of the ADC pipe is 3, the version of scientific analysis integrated into the

ADC pipeline is 18 and the version of the standard analysis that has produced the data is 17. The last number is the version of correction software.

2.3   AGILE Science Tools

The AGILE Science Tools are written in C++ and use 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 start the tool, which then asks for the values of some parameters interactively on the console;

2. the user can input all or some of the parameter values   on the command line, in the same order as the provided parameter file;

3. the user can input all or some of the parameter values   on the command line, in any order, writing parameter names explicitly as `pname=value`.

In all methods the user can accept the defaults (stored in each task parameter file, if the task was already run defaults are the last values used)   for parameter values not explicitly provided   by adding 'mode=h' on the command line.

Some task input parameters are text files of "index" type, reporting in each row an input file name followed by the minimum and maximum times contained in the file and the file type. The parameter, when specified on the command line, must be preceeded by a @. See examples in the task sections.

AGILE Science Tools use the calibration files in `$ADC/scientific_analysis/data/`. The corresponding parameter in each task parameter file is set to a deafult value suitable for a standard analysis of events of type G in a full energy band 100-50000 MeV. To perform a different analysis the user can change the parameter explicitly providing it on the command line.   The input and output files are in FITS format.   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.

3   The `Exposure Map Generator` Task

Exposure maps are generated by the procedure `AG_expmapgen`, the executable can be   found in `$ADC/scientific_analysis/bin/`. `AG_expmapgen` reads the auxiliary LOG files listed in the *GRID* `LOG` index, integrates the exposure between `tmin` and `tmax`, and outputs a FITS image file. 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.

Sample *GRID* `LOG` index file:
`agstd_GridLog.log 0.000000 32400.000000 LOG`
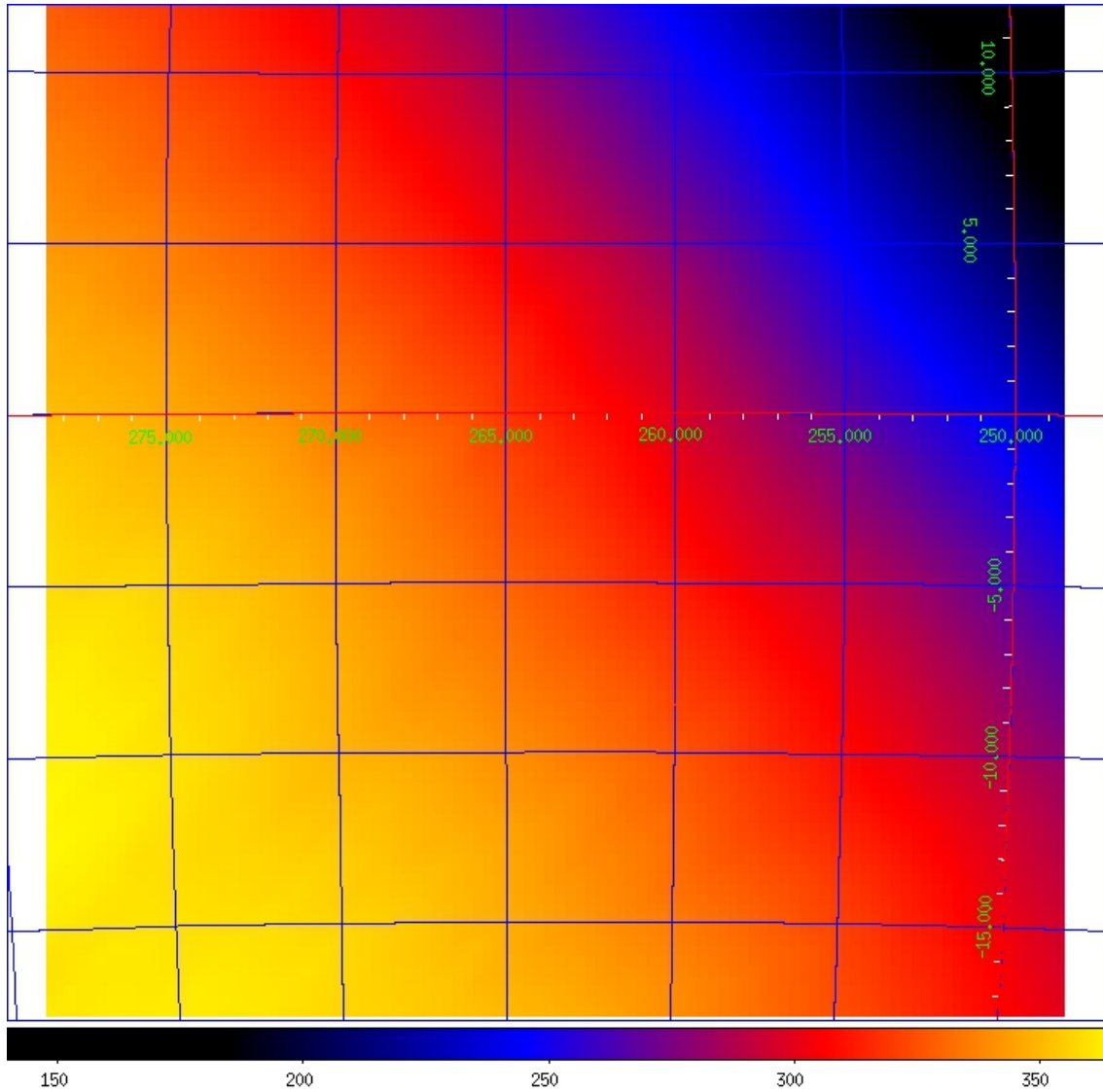
Figure 1: DS9 image of an exposure map produced by AG_expmapgen.

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 `spectral index` are specified in the `AG_expmapgen.par` parameter file, along with various integration parameters (`fovrad, fovradmin, albrad, y_tol, roll_tol, earth_tol, phasecode`), and spatial and temporal interpolation step sizes (`step, timestep`). The interpolation procedure is a linear interpolation method in which only one bin each N is calculated (where N is the `step` size parameter). A spatial interpolation width of $2°$ is sufficient for a good approximation of the exposure map, implying `step`=4 for a bin size of $0.5°$ or `step`=8 for a bin size of $0.25°$. Figure 1 shows the image produced by DS9 for an exposure map generated by `AG_expmapgen`, with Galactic coordinate axes displayed.

inputs:

    AG_expmapgen.par:

    logfile,s,ql,"Log.index",,,"Enter grid log index file name"
outfile,s,ql,"map.exp",,,"Enter output file name"
raeffFileName,s,hl,"AG_GRID_G0017_SFMG_I0023.sar.gz",,,"Enter effective area 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,hl,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 minimum energy"
emax,r,ql,50000,,,"Enter maximum energy"
index,r,ql,-2.1,,,"Enter spectral index"
fovrad,r,ql,50,,,"Enter max off-axis angle (degrees)"
fovradmin,r,ql,0,,,"Enter min off-axis angle (degrees)"
albrad,r,hl,90,,,"Enter radius of earth albedo (degrees)"
y_tol,r,hl,0.5,,,"Enter boresight movement tolerance (degrees)"
roll_tol,r,hl,360,,,''Enter roll tolerance (degrees)''
earth_tol,r,hl,5.0,,,"Enter roll tolerance (degrees)"
keepmono,b,hl,no,,,"Keep monochromatic exposure maps? (yes or no)"
phasecode,i,hl,2,,,"Orbital phase code"
projection,s,ql,"ARC",,,"Enter projection (ARC or AIT)"
step,r,ql,4,,,"Enter step size"
timestep,r,ql,160,,,"Enter LOG file step size"

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.
Here we provide an example of command line:
/home/adc/GO_test_dataset> AG_expmapgen logfile=@LOG_test_5.0.index outfile=map.exp
raeffFileName=$ADC/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.sar.gz mdim=30
mres=0.3 la=263.55 ba=-2.787 lonpole=180 tmin=111844735 tmax=112103935 emin=100
emax=50000 index=-2.1 fovrad=50 fovradmin=0 albrad=90 y_tol=0.5 roll_tol=360.0
earth_tol=5.0 keepmono=NO phasecode=2 projection=ARC step=2 timestep=160

outputs:

    Screen output:

```
###############################################################################
###### AG_expmapgen.cpp V2.2 - 31/07/2009 - A.C., A.T., A.B., T.C. ####
###############################################################################
###############################################################################
```

INPUT PARAMETERS:

Input index file name = @LOG_test_5.0.index
Output file name = map.exp
map dimension [deg] : 30.00
map resolution [deg] :0.30
map centroid G.long. [deg] : 263.55
map centroid G.lat. [deg] : -2.79
TMIN [s] : 111844735.000000
TMAX [s] : 112103935.000000
MIN ENERGY [MeV] : 100.0
MAX ENERGY [MeV] : 50000.0
maximum off-axis angle [deg] : 50.00
minimum off-axis angle [deg] : 0.00
radius of earth albedo [deg] : 90.00
Orbital Phase Code: 2
Pointing direction tolerance [deg] : 0.50
Roll angle tolerance [deg] : 360.00
Earth direction tolerance [deg] : 5.00
raeffFileName = /home/ADC/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.sar.gz
SPECTRAL INDEX : -2.10
map bin step : 2
projection : ARC
time step : 160

AG_expmapgen...............................starting
image read OK
Upper bound greater than the last channel, treated as infinity

AG_expmapgen...................................addfile starting
TIME >= 111844735.000000 && TIME <= 112103935.000000 && LIVETIME ¿ 0 && LOG_STATUS == 0 &&
MODE == 2 && PHASE .NE. 1 && ((#ROW == 1) —— (#ROW == (#ROW/160) *160))
AG_expmapgen...................................addfile exiting STATUS : 0

AG_expmapgen............................. exiting

##
########## Task AG_expmapgen........... exiting ##########
##

Exposure Map 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 = 100 / length of data axis 1
NAXIS2 = 100 / 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&A...376..359H
CRVAL1 = 263.55
CRVAL2 = -2.787
CTYPE1 = 'GLON-ARC'
CTYPE2 = 'GLAT-ARC'
CRPIX1 = 50.5
CRPIX2 = 50.5
CDELT1 = -0.3
CDELT2 = 0.3
CUNIT1 = 'deg '
CUNIT2 = 'deg '
RADESYS = 'FK5 '
EQUINOX = 2000.
LONPOLE = 180.
TSTART = 111844735.  / [OBT]first event time
TSTOP = 112103935.  / [OBT]last event time
TIMESYS = 'TT '
TIMEUNIT= 's '
DATE-OBS= '2007-07-18T12:00:00' / start date and time of the observation(TT)
DATE-END= '2007-07-21T12:00:00' / end date and time of the observation(TT)
TIMEZERO= 0.  / TT
MJDREFI = 53005.
MJDREFF = 0.000754444444444444
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 / Map interpolation step size
TIMESTEP= 160 / Log file step size
BUNIT = 'cm**2 s sr'
FOV = 50.  / Radius of field of view (deg)
FOVMIN = 0.  / Minimum off-axis angle (deg)
ALBEDO = 90.  / Earth zenith angle (deg)
PHASECOD= 2 / Orbital phase code
INDEX = -2.1
SC-Z-LII= 289.698417511038
SC-Z-BII= -0.718600555009459
SC-LONPL= 0.
END
```

All header keywords   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.

4   The `Counts Map Generator` Task

Counts maps are generated by the procedure `AG_ctsmapgen`, the executable can be 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. 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.

Sample *GRID* EVT index file:
`agstd_Grid.EVT 0.000000 32397.000000 EVT`

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). Figure 2 shows the image produced by DS9 for the counts map generated above, with Galactic coordinate axes displayed.

inputs:

```
AG_ctsmapgen.par:
evtfile,s,ql,"Evt.index",,,"Enter event file index file name"
outfile,s,ql,"map.counts",,,"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)"
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,ql,50.00,,,"Enter max off-axis angle (degrees)"
fovradmin,r,ql,0.00,,,"Enter min off-axis angle (degrees)"
albrad,r,hl,90.00,,,"Enter radius of earth albedo (degrees)"
lonpole,r,hl,180,,,"Rotation of map(degrees)"
phasecode,i,hl,2,,,"Orbital phase code"
filtercode,i,hl,5,,,"Event filter code"
projection,s,ql,"ARC",,,"Enter projection (ARC or AIT)"
```

You can type the command AG_ctsmapgen at the command line and insert the parameters or insert the parameters as arguments of the procedure.
Here we provide an example of command line:
`/home/adc/GO_test_dataset> AG_ctsmapgen evtfile=@Evt.index outfile=map.counts mdim=30`

```
mres=0.3 la=263.55 ba=-2.787 tmin=111844735 tmax=112103935 emin=100 emax=50000 fovrad=50
fovradmin=0 albrad=90 lonpole=180 phasecode=2 filtercode=5 projection=ARC
```

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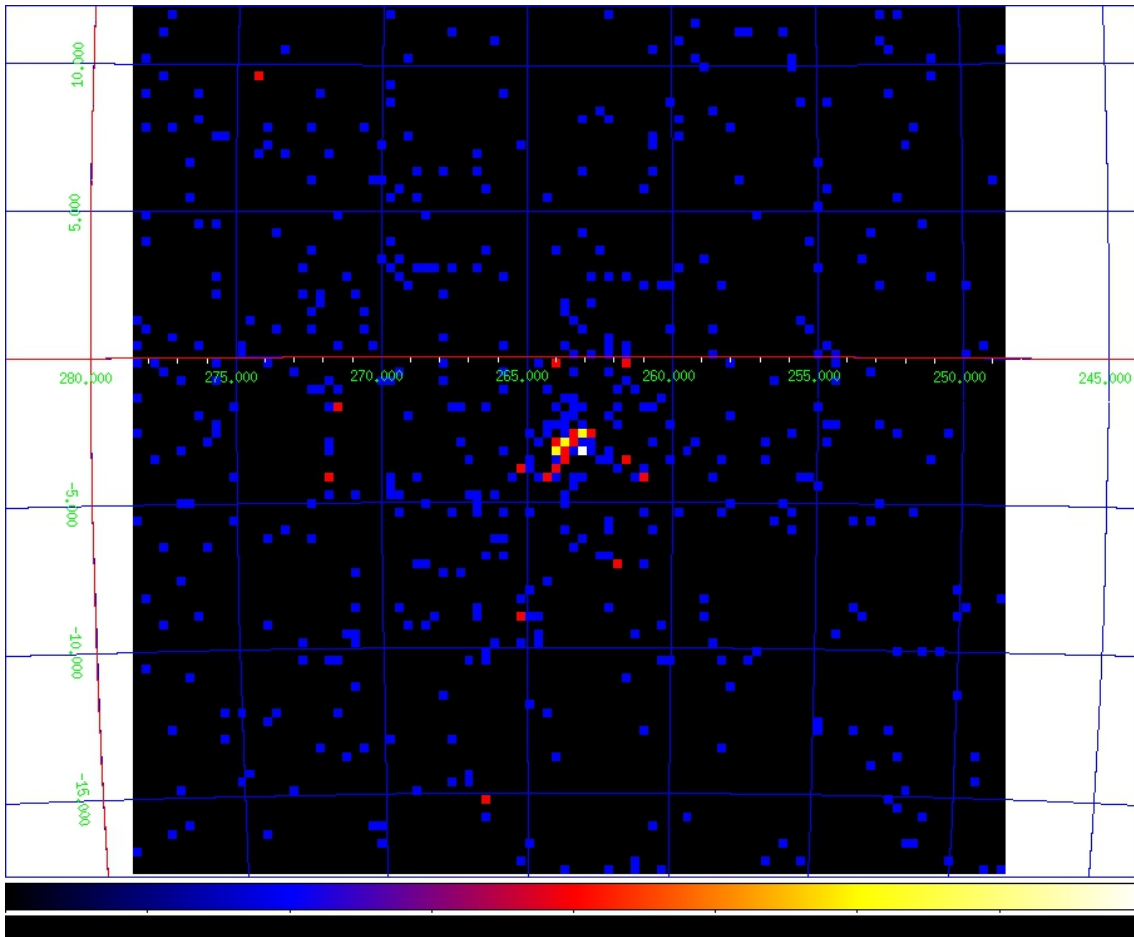
Figure 2: DS9 image of a counts map produced by `AG_ctsmapgen`.

Screen output:

```
##################################################################################
########## AG_ctsmapgen.cpp v.0 - 19/12/05 - A.C., A.T. ##########
##################################################################################
##################################################################################
```

INPUT PARAMETERS:

Input index file name = @OB1000_Velatest.EVT.index
Output file name = map.counts

map dimension [deg] : 30.00

map resolution [deg] :0.30

map centroid G.long. [deg] : 263.55

map centroid G.lat. [deg] : -2.79

TMIN [s] : 111844735.000000

TMAX [s] : 112103935.000000

MIN ENERGY [MeV] : 100.0

MAX ENERGY [MeV] : 50000.0

maximum off-axis angle [deg] : 50.00

minimum off-axis angle [deg] : 0.00

radius of earth albedo [deg] : 90.00

Orbital Phase Code: 2

Filter code: 5

AG_ctsmapgen..............................starting

AG_ctsmapgen...................................adding events files

AG_ctsmapgen...................................addfile exiting STATUS : 0

1389

creating Counts Map...................................

writing Counts Map...................................

writing header......................................

AG_ctsmapgen.............................. exiting

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

Counts Map 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 = 100 / length of data axis 1
NAXIS2 = 100 / 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&A...376..359H
BZERO = 32768 / offset data range to that of unsigned short
BSCALE = 1 / default scaling factor
CRVAL1 = 263.55
```

```
CRVAL2 = -2.787
CTYPE1 = 'GLON-ARC'
CTYPE2 = 'GLAT-ARC'
CRPIX1 = 50.5
CRPIX2 = 50.5
CDELT1 = -0.3
CDELT2 = 0.3
CUNIT1 = 'deg '
CUNIT2 = 'deg '
RADESYS = 'FK5 '
EQUINOX = 2000.
LONPOLE = 180.
TSTART = 111844735.  / [OBT]first event time
TSTOP = 112103935.  / [OBT]last event time
TIMESYS = 'TT '
TIMEUNIT= 's '
DATE-OBS= '2007-07-18T12:00:00' / start date and time of the observation(TT)
DATE-END= '2007-07-21T12:00:00' / end date and time of the observation(TT)
TIMEZERO= 0.  / TT
MJDREFI = 53005.
MJDREFF = 0.000754444444444444
MINENG = 100.
MAXENG = 50000.
TELESCOP= 'AGILE '
INSTRUME= 'GRID '
PIXCENT = 'T '
BUNIT = ' '
FOV = 50.  / Maximum off-axis angle (deg)
FOVMIN = 0.  / Minimum off-axis angle (deg)
ALBEDO = 90.  / Earth zenith angle (deg)
PHASECOD= 2 / Orbital phase code
FILTERCO= 5 / Event filter code
END
```

5   The Intensity Map Generator Task

Intensity maps are generated by the procedure `AG_intmapgen`, the executable can be 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.

Figure 3 shows the image produced by DS9 for an intensity map generated by `AG_intmapgen`, with Galactic coordinate axes displayed.
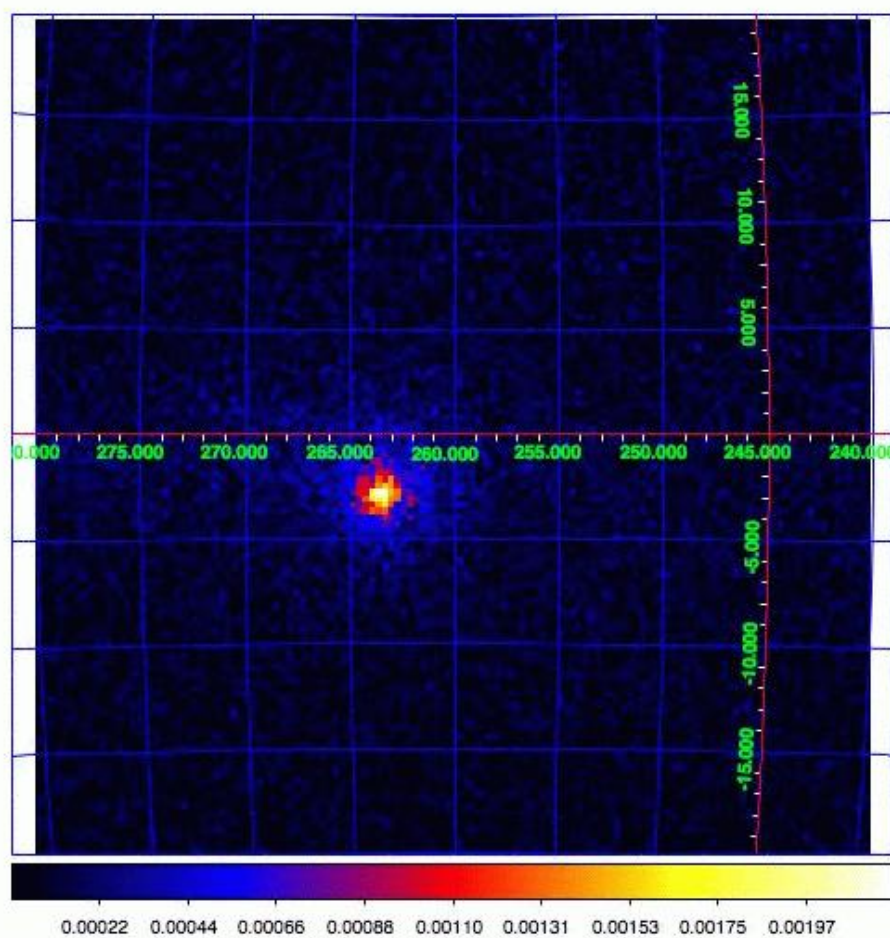

Figure 3: DS9 image of an intensity map produced by `AG_intmapgen` with the listed parameter file.

inputs:

```
AG_intmapgen.par:


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

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.

Here we provide an example of command line:

/home/adc/GO_test_dataset> AG_intmapgen expfile=map.exp outfile=map.int ctsfile=map.counts

outputs:

Screen output:

```
####################################################################
########## AG_intmapgen.cpp v.0 - 19/12/05 - A.C., A.T. ########
####################################################################
####################################################################


INPUT PARAMETERS:

Enter exposure file name = map.exp
Enter output file name = map.int
Enter counts map file name = map.counts



AG_intmapgen..............................starting

AG_intmapgen..............................  exiting



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

Intensity Map 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&A...376..359H
CRVAL1 = 263.
CRVAL2 = -2.6
CTYPE1 = 'GLON-ARC'
CTYPE2 = 'GLAT-ARC'
CRPIX1 = 67.1666666666667
CRPIX2 = 67.1666666666667
CDELT1 = -0.3
CDELT2 = 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 = 0.0023544444444444444
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
SC-LONPL= 0.
END
```

6   The `Diffuse Map Generator` Task

Diffuse emission maps are generated by the procedure `AG_gasmapgen2`, the executable can be found in `$ADC/scientific_analysis/bin/`. `AG_gasmapgen2` 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. Figure 4 shows the image produced by DS9 for a diffuse emission map generated by `AG_gasmapgen2`, with Galactic coordinate axes displayed.
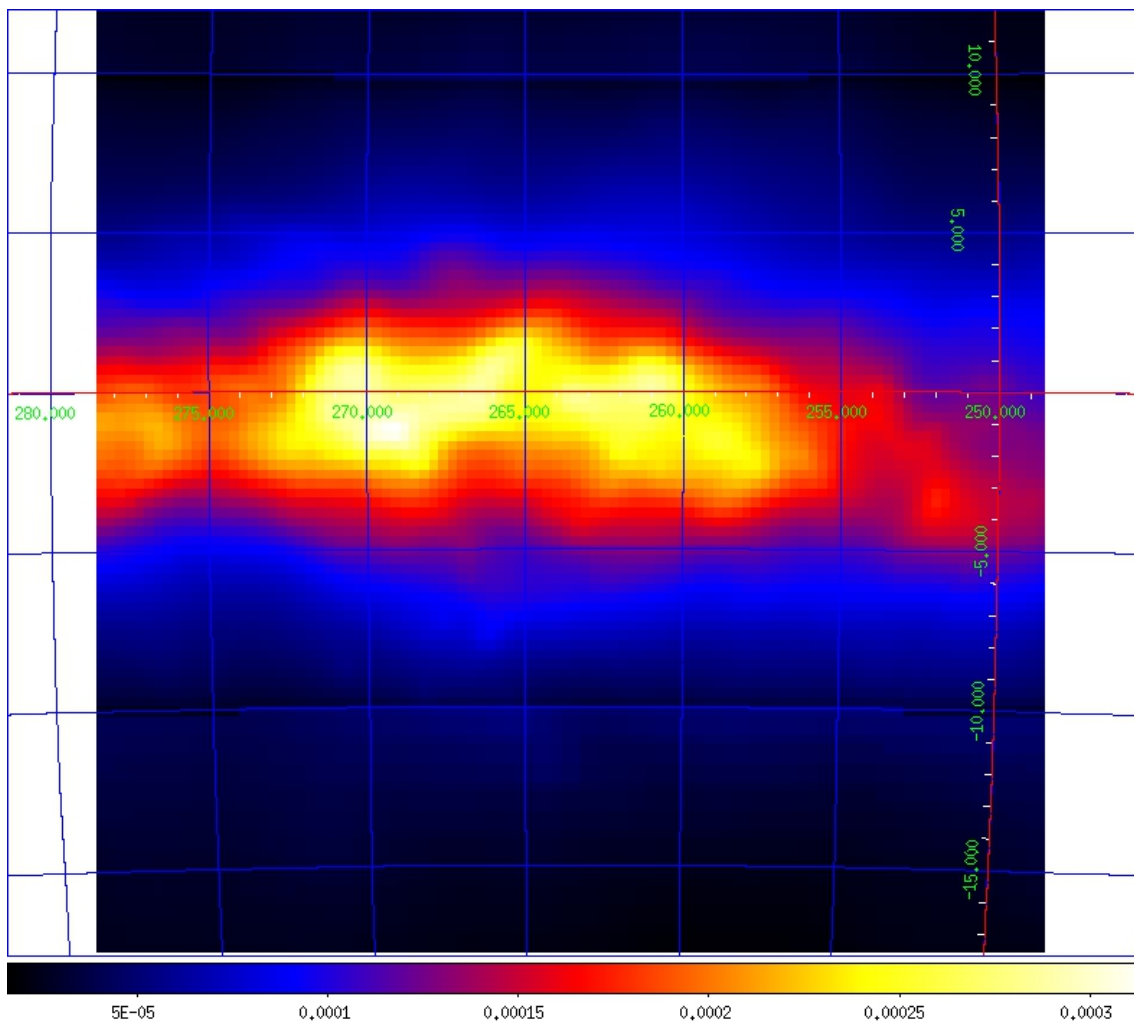
Figure 4: DS9 image of the diffuse emission map produced by AG_gasmapgen2 with the listed parameter file.

The input calibration files should have the extension `SFMG_I0023.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_I0023.disp.conv.sky.gz for the `diffusefile` parameter and 100_50000.0.1.SFMG_I0023.disp.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. Note that 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_gasmapgen2.par:`

```
expfile,s,ql,"map.exp",,,"Enter exposure file name"
outfile,s,ql,"map.gas",,,"Enter output file name"
diffusefile,s,ql,"100_50000.0.5.SFMG_I0023.disp.conv.sky.gz",,,"Enter diffuse model file name"
hiresdiffusefile,s,ql,"100_50000.0.1.SFMG_I0023.disp.conv.sky.gz",,,"Enter high res diffuse model
file name"
```

You can type the command AG_gasmapgen2 at the command line and insert the requested parameters or insert the parameters as arguments of the procedure.

Here we provide an example of command line:

```
/home/adc/GO_test_dataset> AG_gasmapgen expfile=map.exp outfile=map.gas
diffusefile=100_50000.0.5.SFMG_I0023.disp.conv.sky.gz
hiresdiffusefile=100_50000.0.1.SFMG_I0023.disp.conv.sky.gz
```

outputs:

Screen output:

```
######################################################################
########## AG_gasmapgen2.cpp v.2 - 10/10/10 - A.C., A.T. ##########
######################################################################
######################################################################
```

INPUT PARAMETERS:

Enter exposure file name = VELA.exp.gz
Enter output file name = VELA.gas.gz
Enter diffuse model file name = 100_50000.0.5.SFMG_I0023.disp.conv.sky.gz
Enter high res diffuse model file name = 100_50000.0.1.SFMG_I0023.disp.conv.sky.gz

AG_gasmapgen2..............................starting

AG_gasmapgen2.............................. exiting

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

Diffuse Map 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&A...376..359H
CRVAL1 = 263.
CRVAL2 = -2.6
CTYPE1 = 'GLON-ARC'
CTYPE2 = 'GLAT-ARC'
CRPIX1 = 67.1666666666667
CRPIX2 = 67.1666666666667
CDELT1 = -0.3
CDELT2 = 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 = 0.002354444444444444
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
SC-LONPL= 0.
EXTNAME = 'GAS '
DH_CONF_= 'GO017 ' / GRID - DHSim configuration ID
STAN_CON= 'SFMG ' / GRID - Standard an.  configuration ID
FILE_ID = 'I0023 ' / File Identification Number/Issue
END
```

7 Source Detection and Location

7.1 Introduction

This section describes how to use `AG_multi4`, the latest version of the source detection and location task using the maximum likelihood method. This version comes after version 2 (version 3 was not released) and is very similar in many respects.

7.2 Getting started

`AG_multi4` is a command line application running under Linux 32 or 64 bits 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 in order   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_multi4` 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 application also calculates the test statistic and significance for each source.

The user has a variety of options to influence the process as explained in the following.

7.3 The AG_multi4 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 de-

scribed by a `.par` file, `AG_multi4.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_multi4.par` resides. The user may specify the option values on the command line in two ways. 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_multi4 option1=value1 option2=value2 option3=value3...` or `AG_multi4 value1 value2 value3...` Otherwise, if any of the command line options are missing, `AG_multi4` 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 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 observed energy distribution   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.

string expcorrfile
An optional file containing corrections to the effective area as a function of off-axis angle. Provided with the distribution, it should not be changed by the user.

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, wich range from 0 to 3, tell `AG_multi4` 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 list of the gamma ray sources to fit to the list of maps above. Refer to the srclist section for details.

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 a 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. $1.38629 = 50\%$, $2.29575 = 68\%$, $4.60517 = 90\%$, $5.99147 = 95\%$, $9.21034 = 99\%$).

7.4   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> <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_gasmapgen2`. 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 sections about map generation   for further details).

The selection criteria affect the shape of the point spread function of the instrument, calculated by `AG_multi4` using   the calibration files. 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 the mean value in the range in degrees. 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.

The 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)

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.

7.5   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> <l> <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 cm^{-2} 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_multi4` 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.

7.6   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.

7.7   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.

7.8   Task execution

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.

inputs:

```
    AG_multi4.par:
maplist,s,ql,"list.txt",,,"Enter maps file name"
sarfile,s,hl,"AG_GRID_G0017_SFMG_I0023.sar.gz",,,"Enter SAR file name"
edpfile,s,hl,"AG_GRID_G0017_SFMG_I0023.edp.gz",,,"Enter EDP file name"
psdfile,s,hl,"AG_GRID_G0017_SFMG_I0023.psd.gz",,,"Enter PSD file name"
expcorrfile,s,hl," $ADC/scientific_analysis/data/expcorr.fits.gz",,,"Enter Exposure Correction
file name"
ranal,r,ql,10,,,"Enter radius of analysis region"
galmode,i,ql,1,0,3,"Enter diffuse emission mode"
isomode,i,ql,1,0,3,"Enter isotropic emission mode"
srclist,s,ql,"src_list.txt",,,"Enter sources list"
outfile,s,ql,"my2src.out",,,"Enter output file name"
ulcl,r,ql,2.0,,,"Enter upper limit confidence level"
loccl,r,ql,5.99,,,"Enter source location contour confidence level"
```

You can type the command AG_multi4 at the command line and insert the requested parameters or insert the parameters as arguments of the procedure.
Here we provide an example of command line:

```
/home/adc/GO_test_dataset> AG_multi4 maplist=list.txt sarfile=AG_GRID_G0017_SFMG_I0023.sar
edpfile=AG_GRID_G0017_SFMG_I0023.edp.gz psdfile=AG_GRID_G0017_SFMG_I0023.psd.gz ranal=10
galmode=1 isomode=1 srclist=src_list.txt outfile=mysrc.out ulcl=2.0 loccl=5.99
```

`AG_multi4` prints most of its messages to the standard output. 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.

Screen output:
```
#################################################################
###### AG_multi4 v.1.2 - 15/03/2011 - A.C., T.C., A.T. #########
#################################################################
#################################################################
```

INPUT PARAMETERS:

Map file name = list.txt
SAR file name : AG_GRID_G0017_SFMG_I0023.sar.gz
EDP file name : AG_GRID_G0017_SFMG_I0023.edp.gz
PSD file name : AG_GRID_G0017_SFMG_I0023.psd.gz
Exposure Correction file name : expcorr.fits.gz
Radius of analysis : 10
Galactic parameter mode : 1 (from file)
Isotropic parameter mode : 1 (from file)
Sources list : src_list.txt
Output file name prefix : my2src.out

7 - 3EGJ0859-4257_f: 2.8e-07 free
8 - 3EGJ0859-4257_x: 2 fixed
9 - 3EGJ0859-4257_l: 264.64 fixed
10 - 3EGJ0859-4257_b: 2.02 fixed

Begin first loop

Considering source 1: VelaPSR
Source 1: VelaPSR: Flux free, position and index fixed
Fitting of source 1 Flux free
FCN=1850.56 FROM IMProve STATUS=RESET 8 CALLS 119 TOTAL
EDM=1.70305e-11 STRATEGY= 1 ERROR MATRIX UNCERTAINTY 50.0 per cent
EXT PARAMETER APPROXIMATE STEP FIRST
NO. NAME VALUE ERROR SIZE DERIVATIVE
1 Galactic 4.45914e-01 2.08769e-01 2.08769e-03 -2.91695e+05
2 Isotropic 1.99151e+00 4.55797e-01 4.55797e-03 -2.30105e+05
3 VelaPSR_f 8.06342e+00 1.11869e+00 1.11869e-02 -1.10773e+08
4 VelaPSR_x 1.70000e+00 fixed
5 VelaPSR_l 2.63550e+02 fixed
6 VelaPSR_b -2.79000e+00 fixed
7 3EGJ0859-4257_f 0.00000e+00 fixed
8 3EGJ0859-4257_x 2.00000e+00 fixed
9 3EGJ0859-4257_l 2.64640e+02 fixed
10 3EGJ0859-4257_b 2.02000e+00 fixed
Fitting done in 120 iteration. Result=4000

.... omissis ....

Fitting done in 666 iteration. Result=4000

0.440086 1.97711 8.14638 1.7 263.545 -3.03356 1.35525e-12 2 264.64 2.02
SrcCount=2, m_galParCount=1, m_isoParCount=1
Source 1: 0 1 1 1
Source 2: 0 0 1 1
m_binCount=3484
Source 1 with
1 0
2 1
3 8.08533
4 1.7
5 263.545
6 -3.03356
7 1.35525e-12
8 2
9 264.64
10 2.02

likeWith 966.498
likeWithoutVar 1201.46
Source 1 without, fixed
1 1
2 1
3 0

4 1.7
5 263.545
6 -3.03356
7 1.35525e-12
8 2
9 264.64
10 2.02

likeWithoutFixed 996.14

TS 21.6775 0
TSf 7.69958 0
##
########### Task AG_Multi4........... exiting ###################
##

7.9 Output

At the end of the fitting process `AG_multi4` 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 text output in which three sets of maps and one source are 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. In this case, because the   source spectral index is fixed, its error is set to zero.

```
! DiffName, Coeff, Err, +Err, -Err
Galactic_1 1.0497 0.0293663 0.0293867 -0.0293513
Galactic_2 0.903874 0.0309914 0.0310404 -0.0309524
Galactic_3 0.445709 0.0403257 0.040476 -0.0401969
Isotropic_1 6.19155 0.17882 0.17929 -0.178379
Isotropic_2 1.61033 0.0750936 0.0754122 -0.0747974
Isotropic_3 0.599942 0.0449255 0.0452161 -0.0446586
! SrcName, sqrt(TS), L, B, Counts, Err, Flux, Err, Index, Err
1AGL_J0835-4509 149.957 263.574 -2.84422 71782 858.393 6.05223e-06 7.23747e-08 1.66 0
```

For each source an additional text file is generated and, when possible, 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` are set to the initial values if 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_multi4` 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.

7.10   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. 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.

7.11 Ellipse fit to source location contour

If `AG_multi4` 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_multi4` 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)
```

Figure 5 shows a smoothed counts map of Vela with the ellipse fit to the 95 % confidence contour level. The image was generated by DS9 superimposing an output file of type .ellipse.con generated by `AG_multi4`.

8 Analysis procedure

8.1 Example 1: Isolated extragalactic point source

For sources far from the galactic plane and isolated sources, analysis is relatively straightforward. In `AG_multi4` one can use a source list with one line, starting from the position, where the position may be a known counterpart or a peak in the counts or TS map. Set the flux to any positive value, spectral index to -2.0. Make sure to insert a label.

Note that for sources far from the Galactic plane, it is inadvisable to allow both the Galactic and isotropic coefficients to be left free to vary, because the two components are degenerate. One can fix the Galactic coefficient to 0.7 and let the isotropic coefficient vary.
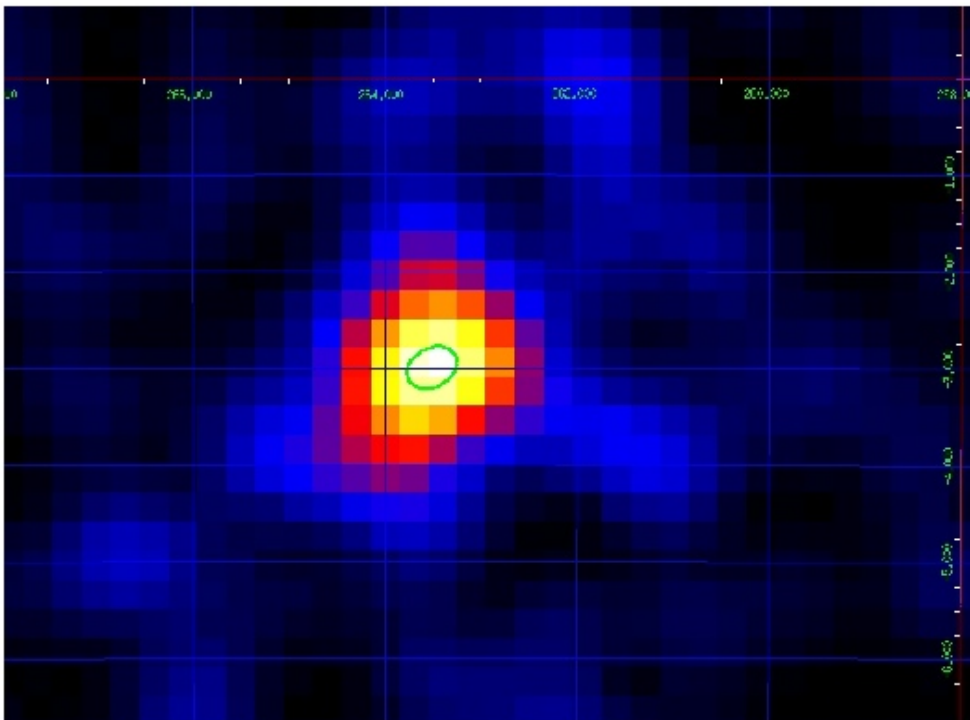
Figure 5: DS9 image of a smoothed counts map of Vela with the ellipse fit to the 95 % confidence contour level.

Unless the source has been previously identified due to correlated variability at other wavelengths (e.g. a pulsar with known ephemeris or a variable AGN), it is advisable to let the

source position vary to check whether the candidate counterpart lies within the 95% confidence contour.

8.2   Example 2: Point source in the presence of other point sources

For sources along the galactic plane or near other sources, the situation is a little more complicated. In principle, one should use an iterative process. Find and optimize the most significant source, by itself. Then, find the next most significant source in the region and write a list with the first source and this additional source. Continue until no new sources are above the significance threshold.

With a pre-defined list of sources, AG_multi4 tries to mimic this process internally; instead of immediately fitting all sources on the list simultaneously, it performs the following steps:

1. Add the fix=0 sources immediately.

2. Set the fluxes of the fix≥1 sources to 0.

3. Fixing the position, optimize the flux of the source with the highest initial flux guess.

4. If fix=2 and the significance is high enough, optimize the position

5. If the significance is not high enough, set the flux to zero for subsequent sources, otherwise set it to the optimized flux level but leave it free to vary

6. Follow steps 3-5 for the remaining sources in order. For each source, fix the flux of sources outside the corresponding region of interest during the analysis.

7. Repeat steps 3-6, this time calculating upper limits and contours. Calculate errors and upper limits even for sources with fix≥1 whose fluxes have been set to zero.

8. Write output files

In the Galactic plane it is almost always advisable to use a predefined list of nearby sources.

8.3   Example 3: Light curve

To find the light curve of a source over a given time period, first perform an analysis over the whole time interval, letting the diffuse coefficients (isotropic for high-latitude sources, both Galactic and isotropic for low-latitude sources) and, if desired, the position vary. Then perform the analysis for each time bin, fixing both the diffuse coefficients and the position to the values found over the longer integration. This will allow the short time interval analyses to proceed even with low statistics.

8.4 Example 4: Spectra

A similar procedure can be used for spectral analysis. Perform an analysis over the entire energy range to determine the Galactic coefficient (if the source is low-latitude) and the position. Then fix those values and perform a simultaneous analysis of multiple maps, one for each energy band, keeping the position and Galactic coefficient fixed to the values found over the whole energy range. Note that, because the isotropic component depends on the instrumental cosmic-ray background, the coefficients of the isotropic component in each energy band must be allowed to vary and cannot be determined through an analysis over the entire energy range.

8.5 Example 5: Dependence on off-axis angle

For strong sources, a more accurate determination of flux and possibly spectra may be obtained by producing separate counts and exposure maps using thin rings of off-axis angle, where (fovradmin, fovrad) take on the values of (0,10),(10,20),(20,30)...(50,60), and are then analyzed simultaneously. Here again the isotropic coefficients must be allowed to vary independently as they are a strong and unpredictable function of off-axis angle.

9 Obsolete Likelihood Analysis Procedures

We strongly suggest to use only the task AG_multi4 for the scientific analysis. The task `AG_multi2` has been provided only for backward compatibility.

9.1 The `Source Detection and Location` Task: Multiple Source Location Detection

This task is performed by the procedure AG_multi2 found in `$ADC/scientific_analysis/bin/`. AG_multi2 reads an exposure map produced by AG_expmapgen, a counts map produced by AG_ctsmapgen, and a diffuse emission map produced by AG_gasmapgen2, spectral index, and energy range, as well as a text file containing a source list, listed in the parameter file. It calculates the test statistic, significance, counts and flux of each of the point sources starting from a given positions in the presence of simultaneously optimized fluxes of all nearby sources in the list, and outputs the results to text files. The main purpose is to optmize both the flux and position of the sources given as input.

inputs:
```
AG_multi2.par:
expfile,s,ql,"VELA.exp.gz",,,"Enter exposure file name"
ctsfile,s,ql,"VELA.cts.gz",,,"Enter counts file name"
gasfile,s,ql,"VELA.gas.gz",,,"Enter diffuse map file name"
sarfile,s,l,"${ADC}/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.sar.gz",,, "Enter SAR file
name"
edpfile,s,l,"${ADC}/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.edp.gz",,, "Enter EDP file
name"
```

```
psdfile,s,l,"${ADC}/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.psd.gz",,,"Enter PSD file
name"
expcorrfile,s,ql,"${ADC}/scientific_analysis/data/expcorr.fits.gz",,, "Enter Exposure Correction
file name"
Emin,r,ql,100.0,,,"Enter minimum energy"
Emax,r,ql,50000,,,"Enter maximum energy"
ranal,r,ql,10.0,,,"Enter radius of analysis region"
gascoeff,r,ql,-999,,,"Enter diffuse emission coefficient"
isocoeff,r,ql,-999,,,"Enter isotropic coefficient"
srclist,s,ql,"Vela_multi.det",,,"Enter source list"
outfile,s,ql,"Vela_multi.res",,,"Enter output file name"
ulcl,r,ql,2.0,,,"Enter upper limit confidence level"
loccl,r,ql,5.9914659,,,"Enter source location contour confidence level"
lpoint,r,l,-999,,,"Enter galactic longitude of instrument
    pointing direction (-999 for undefined)"
bpoint,r,l,-999,,,"Enter galactic latitude of instrument
    pointing direction (-999 for undefined)"
```

The first six parameters should be familiar. The expcorrfile parameter specify a file that contains the correction of the flux based on the off-axis angle.

Note that gascoeff and/or isocoeff may be set to a fixed value or set to -999 to find the optimum non-negative value, srclist is a new input parameter, while the remaining three are new output parameters.

The *outfile* parameter is a string which is both the name of an output file and the prefix for other output files.

The *ulcl* parameter is the confidence level for flux upper limits. These upper limits are calculated for all sources with fix$\geq$1, no matter what their significance level. Like minTS, it is expressed as sqrt(TS). Set this value to 2.0 for upper limits at the same level that AG_srctest_fixed writes in output.

The *loccl* parameter is the deltaTS for the position confidence contours. Set this parameter to 5.9914659, corrisponding to a confidence level of 95%, for contours at the same confidence level as the output of AG_srcloc. A future revision of the software will replace this parameter with the confidence level expressed as a probability (i.e. 0.95 instead of 5.9914659).

lpoint and *bpoint* specifies the AGILE pointing for each observation block. See the ASDC web site for the list of observation blocks.

The srclist parameter is the name of a text file whose format is similar, but not identical, to the format of the input of AG_srclist . Here is a sample srclist for AG_multi2:

Example of source list file:

```
    !  Field Name :
    !  Instrument :  AGILE GRID
    !  flux lii bii index fix minTS label

  0.00E-06 263.65 -2.95 2.1 2 2.0 21
  0.00E-06 260.35 0.35 2.1 2 2.0 22
  0.00E-06 270.55 0.36 2.1 2 2.0 23
  0.00E-06 268.46 -4.14 2.1 2 2.0 24
  0.00E-06 267.56 -4.74 2.1 2 2.0 25
  0.00E-06 261.53 -11.65 2.1 2 2.0 31
```

The lines beginning with "!" are comments and are ignored. Each of the remaining lines is an input source. The columns are as follows:

1 flux ($photons/cm^2/s$) If fix=0 this flux is fixed, otherwise a new optimum is found

2 l (deg) : Galactic latitude

3 b (deg) : Galactic longitude. Note that this parameter suffers from the bug noted in section "Known Issue"

4 spectral index : spectral index of the source, used to calculate the PSF

5 fix : 0 = leave fixed both the flux and position of the source; 1 = optimize the flux of the source while leaving the position fixed; 2 = optimize both the flux and the position of the source. Note that the initial TS of the source must be above both $(min(TS))^2$ and loccl in order for the position to be optimized.

6 minTS : if the $\sqrt{(TS)}$ of the source is initially below this value and fix≥1, its flux will be set to zero during the analysis of the other sources

7 label : A unique string without spaces. It will be used as part of an output filename.

Note that minTS is expressed as sqrt(TS), as is the case for outputs on the screen and in output files.

outputs:

You can type the command AG_multi2 at the command line and insert the requested parameters or insert the parameters as arguments of the procedure.

```
/home/adc/GO_test_dataset> AG_multi2

Enter exposure file name [VELA.exp.gz] :
Enter counts file name [VELA.cts.gz] :
Enter diffuse map file name [VELA.gas.gz] :
Exposure Correction file name [~/ADC/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.expcorr.gz]
:
Enter source list [vela.multi] :
Enter output file name [vela.res] :
Enter minimum energy [100] :
```

```
Enter maximum energy [50000] :
Enter radius of analysis region [10] :
Enter diffuse emission coefficient [-999] :
Enter isotropic coefficient [-999] :
Enter upper limit confidence level [2.0] :
Enter source location contour confidence level [5.9914659] :
Galactic longitude of instrument pointing direction [-999] :
Galactic latitude of instrument pointing direction [-999] :


Screen output:

##################################################################
########## AG_multi2.cpp B18 - 22/04/2009 - A.C., T.C., A.T. #######
##################################################################
##################################################################


INPUT PARAMETERS:

Exposure file name = VELA.exp.gz
counts file name = VELA.cts.gz
diffuse map file name = VELA.cts.gz
SAR file name :  ~/ADC/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.sar.gz
EDP file name :  ~/ADC/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.edp.gz
PSD file name :  ~/ADC/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.psd.gz
Exposure Correction file name :  ~/ADC/scientific_analysis/data/AG_GRID_G0017_SFMG_I0023.expcorr.gz
minimum energy :  100
maximum energy :  50000
Radius of analysis :  10
Diffuse emission coefficient :  -999
Isotropic coefficient :  -999
Upper limit confidence level:  2
Location contour confidence level:  5.99147
Pointing direction:  (-999, -999)
source list :  vela.multi
Output file name prefix :  vela.res
Galactic longitude of instrument pointing direction :  286.419
Galactic latitude of instrument pointing direction :  -1.896


image read OK
Source creation Parameters
0 263.65 -2.95 2.1 2 2 21
0 260.35 0.35 2.1 2 2 22
0 270.55 0.36 2.1 2 2 23
0 268.46 -4.14 2.1 2 2 24
```

```
0 267.56 -4.74 2.1 2 2 25
0 261.53 -11.65 2.1 2 2 31
Diff Component #0 fixflag = 1, param #0 released, max set to 100
, param #0 set to 1
Diff Component #1 fixflag = 1, param #1 released, max set to 100
, param #1 set to 1


...



####################################################################
######### Task Multi.......... exiting ################
####################################################################
```

Output File:

`AG_multi2` writes its output to a text file whose name is specified by the `outfile` parameter in the parameter file.
Example:

```
 ! Gascoeff:  Coeff, Err, +Err, -Err
0.742128 0.065269 0.0654482 -0.0651016
 ! Isocoeff:  Coeff, Err, +Err, -Err
5.17523 0.779803 0.786474 -0.773244
 ! 21:  sqrt(TS), L, B, Counts, Err, Flux, Err
 ! 22:  sqrt(TS), L, B, Counts, Err, Flux, Err
 ! 23:  sqrt(TS), L, B, Counts, Err, Flux, Err
 ! 24:  sqrt(TS), L, B, Counts, Err, Flux, Err
 ! 25:  sqrt(TS), L, B, Counts, Err, Flux, Err
 ! 31:  sqrt(TS), L, B, Counts, Err, Flux, Err
21 40.6372 263.523 -2.90138 1183.54 48.5613 9.0413e-06 3.70971e-07
22 1.40721 260.35 0.35 22.7524 17.4484 1.79216e-07 1.37437e-07
23 1.92633 270.55 0.36 33.4577 19.2379 2.45517e-07 1.4117e-07
24 2.32719 268.24 -4.19059 35.8519 17.489 2.64166e-07 1.28864e-07
25 0.874173 267.56 -4.74 17.098 20.5399 1.26528e-07 1.51999e-07
31 3.79917 261.676 -11.809 40.8257 14.0467 3.15587e-07 1.08583e-07
```

The lines beginning with "!" are comments in order to help the reader. Gascoeff and Isocoeff are set to the last values to emerge from the analysis, which may not be the most useful values. Check the screen output to see the values that emerge depending on the source and region of interest being analyzed. Note that errors, both symmetric and asymmetric, are now provided. Each source has its significance, position, counts, counts error, flux, and flux errors listed.

For convenience, only the symmetric errors are printed in the main output file, but each source with fix≥1 also has its own output file the name of which is the output prefix, followed by "_", followed by the name of the source as listed in the srclist input file. For example, if the output prefix is "vela.res" and the name of the source is "VELA", the source output file would be named vela.res_VELA. If fix=2 for this source and its significance is above both minTS and

loccl, additional output files are written:

- a file with suffix ".con" containing the confidence contour (in ds9 format);

- a file with suffix ".ellipse.con" that is the fit with an ellipse of the confidence contour level of the previous point (in ds9 format);

- a ds9 region file with the ellipse of the previous point. Use this file only for display purpose.

Example of additional output file for each source:

```
!  Label, Fix, index, UL conf.  level, srcloc conf.  level
!  sqrt(TS)
!  L, B
!  Counts, Err, +Err, -Err, UL
!  Flux, Err, +Err, -Err, UL
21 2 2.1 2 5.99147
40.6372
263.523 -2.90138
1183.54 48.5613 49.0616 -48.063 1282.66
9.0413e-06 3.70971e-07 3.74793e-07 -3.67164e-07 9.79849e-06
```

As before, the lines beginning with "!" are comments to aid the reader. The first line gives the name of the source, followed by some input parameters (fixflag, spectral index, upper limit confidence level, source location confidence level). The second line is the sqrt(TS). The third line give the galactic coordinate of the source. The fourth line gives the counts with errors, and the fifth line gives the flux with errors. Note that in every case, the symmetric and asymmetric errors and the upper limits are provided.