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FITS format for MAGIC data¹

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Abstract

This document describes the format of the FITS files used by the MAGIC Collaboration for releasing high-level public (published) data. This includes skymaps of different quantities, 1-D histograms, spectra, light curves and, in general, any set of data included in MAGIC published papers. This document should provide the necessary and sufficient information to interpret MAGIC FITS data files. In particular it describes the organization of the information as well as the definion of headers and keywords which are specific of the MAGIC FITS data files.

¹The latest version of this document and the data files are available at http://magic.pic.es/pub/fits/

1 Introduction

Astronomical data sets are traditionally distributed in FITS format[1] files. This practice is not very much spread within the VHE Astronomy community, particularly among the international collaborations operating Cherenkov telescopes (Cangaroo [2], H.E.S.S. [3], MAGIC [4] and VERITAS [5]). One of the main reasons is problably that, historically, the field has been developed by scientists with a background biased rather towards particle physics than towards astronomy, and therefore with a different tradition regarding data distribution formats. The situation is gradually changing as the field is evolving and maturing, and in particular in view of the projected construction of the next generation VHE observatory: CTA, which is intended to work as a "standard" astronomical observatory. Standard VHE *low-level* data formats, which can represent lists of photon candidates with their properties, need to be defined and implemented. This a major task which would be most likely carried out within the CTA framework. In the meantime, the different Cherenkov telescopes have independently developed simple and fast ways to make their public data available to the scientific community. This refers, in all cases known to us, to *high-level* analysis products (i.e. skymaps, lightcurves and spectra) rather than low-level data ones.

This note describes the format of the FITS files containing MAGIC public data. We intend to provide necessary and sufficient information to interpret MAGIC FITS data files. It assumed that the reader has a sufficient knowledge on the FITS format, described elsewhere [1].

The label "public" can be directly translated by "published" in the case of MAGIC data. We provide one FITS file associated to each paper published in a refereed international journal, containing all the data presented in the paper. This normally includes all tables and plots provided in the article, normally detection plots, spectra, lightcurves and skymaps.

The latest version of MAGIC FITS data files are available at http://magic.pic.es/pub/fits/, together with the corresponding version of this document. The version of the document is expressed by two numbers, e.g. 1.2, the first of which refers to the version of the data it describes. We expect questions, comments and feedback from the end-users, which might cause some evolution of the data format which will be, in any case, documented here.

2 MAGIC FITS file structure

FITS files are composed of one or several Header and Data Units (HDUs), out of which there is a Primary HDU (PHDU) and extensions. All HDUs (including the primary one) consist of a set of header records in ASCII text, which may be followed by an integer number of binary data records.

The first component of a FITS file is be the primary header, which may or may not be followed by a primary data array. In the case of MAGIC FITS files, the PHDU header usually contains the most general information about the observation. The primary data array may or not be present. In case it is present, it is reserved for skymaps of excess events (see Section 3).

The PHDU may be followed by an unlimited number of extension HDUs, which can either be of type IMAGE or BINTABLE. Extensions can be used to save data from skymaps, alpha/theta² plots, light curves or spectra

3 Header and Data Units

MAGIC FITS data files use only three different types of HDU's, namely: the PHDU, IMAGE and BINTABLE extensions. They can be used to save data from skymaps, alpha/theta² plots, lightcurves or spectra.

All floating point values are stored in double precission (8 bytes)

There can be as many HDU's of each type as desired.

3.1 Skymap

Skymaps can be recorded in the PHDU or as IMAGE extension. The PHDU is reserved for final skymaps (i.e. showing number of excess events). However, the PHDU may also consist of the primary header only –with no associated data– describing the data used along the file using the appropriate keywords (see Section 4.1). In such a case, the final skymap can be alternatively recorded as an IMAGE extension (see Section 4.2).

Supported skymaps are for: number of excess events over the background $(N_{\rm ex})$, total number of recorded gamma-ray candidate events before background subtraction $(N_{\rm on})$, total number of recorded background events $(N_{\rm off})$, normalized number of background events $(N_{\rm bkg})$, upper limits and significance. $N_{\rm on}$ and $N_{\rm off}$ are the number of gamma-ray and background candidate events observed in the field of view, with no further normalization applied. $N_{\rm bkg}$ is the (normalized) number of estimated background events, the normalization factor (k) is defined such that $N_{\rm bkg} = N_{\rm off}/k$. The number of excesses is $N_{\rm ex} = N_{\rm on} - N_{\rm bkg}$. The significances are computed using formula 17 of Ref. [6], and the upper limits the prescription from Ref. [7].

Skymaps are recorded as 2-dimensional images, where the coordinates may be celestial, galactic or camera. The precission of the image pixel, boundaries of the image, smearing procedure, etc are specified through the corresponding header keywords (see Section 4.2).

3.2 Lightcurve

Lightcurves are recorded as BINARY TABLE extensions. The binary data table consists of a minimum of 2 fields (columns) and a maximum of 4. The two compulsary fields represent the values of the time (MJD) and measured flux, stored in this order. In case a third field is present, it is interpreted as the error in the measured flux. If there are 4 fields present, the third one is interpreted as the half-width of the time bin and the forth one as the error on the flux. The flux may be differential or integral, and the corresponding units ph TeV⁻¹ cm⁻² s⁻¹ or ph cm⁻² s⁻¹. If the field corresponding to the flux error is filled with zeros, then the flux values are interpreted as upper limits, computed following the method described in Ref. [7].

For periodic sources, lightcurves can be given as a function of the phase (defined between 0 and 1), instead of the absolute time. This is indicated by the presence of the keywords TZERO and PERIOD in the HDU.

Alternatively, instead of the flux, another magnitude can be used, with its units defined by the user and explained in the data file.

3.3 Spectrum

Spectra are recorded as BINARY TABLE extensions. The binary data table consists of a minimum of 2 fields (columns) and a maximum of 4. The two compulsary fields represent the values of the energy (GeV) and measured flux, stored in this order. In case a third field is present, it is interpreted as the error in the measured flux. If there are 4 fields present, the third one is interpreted as the half-width of the energy bin and the forth one as the error on the flux. The flux may be differential or integral, and the corresponding units ph TeV⁻¹ cm⁻² s⁻¹ or ph cm⁻² s⁻¹. If the field corresponding to the flux error is filled with zero, then the flux values are interpreted as upper limits, computed following the method described in Ref. [7].

3.4 Alpha/Theta² plot

Alpha or theta² plots are recorded as BINARY TABLE extensions. The binary data table consists of a minimum of 2 fields (columns) and a maximum of 4. The two compulsary fields represent the values of alpha or theta² (deg) and number of ON events, stored in this order. In case that three fields are present, the second field is the number of excess events and the third is the error in the number of excess events. In the case there are four fields, second field is the number of ON events, third field is the number of OFF events and the fourth field is interpreted as the error in the number of background events. The number of ON events are recorded as integer numbers, and the rest as floating point numbers.

4 Keywords

This section provides a summary of the keywords used in the different HDU in which MAGIC data is organized. It is not intended as an exahustive list of all defined FITS standard keywords, but nevertheless some of the most important ones are included in the following lists. Also note that some of the standard keywords must appear in a well-defined order within the header. For a complete description of the FITS standard keywords see Ref. [1].

4.1 General Keywords

The following lists summarize the keywords available for the general description of a data file or an HDU (primary or extension). They can be written to any header, except for the explicitely stated cases. In case of contradicting values between different headers, the secondary HDU will prevale. In this way, values defined in the PHDU apply to all the extension HDU's, except for those cases where a different value is explicitly estated in the former.

This first list shows the keywords from the FITS standard. Some of them are compulsory and must appear in a very well defined order (see Ref. [1] for the details).

• EXTNAME [string]: only for extension HDU's (not PHDU). It defines the kind of information contained in the HDU. The recognized values are summarized in Table 1. This naming convention is not FITS standards but MAGIC specific. When more than one extension of the same type (i.e. containing the same type of information) are present, the string "_n" is added to the extension name, starting from n=1 for the second extension. For instance if two different lightcurves are present, the first one has EXTNAME='LIGHTCURVE' and the second EXTNAME='LIGHTCURVE_1'. In

this case, the keywords and further comments included in the file should clarify the difference between the different extensions.

- DATE [string]: Date/Time corresponding to the file generation in the format 'YYYY-MM-DDThh:mm:ss'. The value shall contain a character string giving the date on which the HDU was created, in the form YYYY-MM-DD, or the date and time when the HDU was created, in the form YYYY-MM-DDThh:mm:ss[.sss...], where YYYY shall be the four-digit calendar year number. When both date and time are given, the literal T shall separate the date and time. The number of seconds may be followed by an optional fraction. No fields may be defaulted and no leading zeroes omitted. The value of the DATE keyword shall always be expressed in UTC.
- DATE-OBS [string]: The format of the value field for DATE-OBS keywords shall follow the prescriptions for the DATE keyword. This keyword is used to report the start of the observation.
- ORIGIN [string]: Name of the organization responsible for the FITS file generation. The default value is 'MAGIC'.
- TELESCOP [string]: Name of the telescope(s) used to acquire the data. The possible values are 'MAGIC-I', 'MAGIC-II' (for single-telescope observations) and 'MAGIC-SYSTEM' (for observations obtained by both telescopes operated in coincidence).
- AUTHOR [string]: Author of the FITS file. The default value is 'MAGIC Coll.'
- VERSION [string]: Current version of the FITS file, in a form 'n.m', 'n' being the format version and 'm' file version.
- OBJECT [string]: Name of the observed source (e.g. 'Crab Nebula').

Value	Data Represented
SKYMAP	Number of excess skymap
ONMAP	Number of ON events skymap
OFFMAP	Number of OFF events skymap
BKGMAP	Estimated background skymap
SIGMAMAP	Map containing excess significances
ULMAP	Map containing flux upper limits
THETA2PLOT	Theta ² histogram
ALPHAPLOT	Alpha histogram
SPECTRUM	Energy spectrum
LIGHTCUR	Light curve

Table 1: Accepted values of the EXTNAME keyword to describe the kind of data present in a given HDU extension

The following list summarizes the keywords defined by MAGIC to describe the content of a given extension:

- VERSION [int]: Number of data version. Files produced with version n of the data are described in versions n.m of this document. The latest versions of data and document are available at http://magic.pic.es/pub/fits/. The list of changes introduced in the different versions are shown in Section 5.
- **REFPAPER** [string]: Reference of the paper where the results shown in the HDU are published, if any.

- TOBS [float]: Total effective observation time (in minutes).
- EMIN [float]: Energy lower cut (in GeV). If not present, it is assumed that no explicit lower energy cut has been applied.
- EMAX [float]: Energy upper cut (in GeV). If not present, it is assumed that no explicit upper energy cut has been applied.
- SIZEMIN [float]: Size lower cut (in phe). If not present, it is assumed that no explicit lower size cut has been applied.
- SIZEMAX [float]: Size upper cut (in phe). If not present, it is assumed that no explicit upper size cut has been applied.
- ZMIN [float]: Minimum zenith angle (in degrees) of the observations.
- ZMAX [float]: Maximum zenith angle (in degrees) of the observations.
- TZERO [float]: For periodic sources, reference time (in MJD) used to compute the ephemeris.
- PERIOD [float]: For periodic sources, period of the modulation (in days).
- PHIMIN [float]: For periodic sources, minimum phase of the observation (ranging from 0 to 1).
- PHIMAX [float]: For periodic sources, maximum phase of the observation (ranging from 0 to 1).
- EFFICIEN [float]: Average efficiency of the gamma/hadron separation cut(s) (in %).
- CONFLEVE [float]: Upper limit condifence level (in %).

4.2 Image Keywords

The following lists summarize the keywords available for the description of an image HDU (primary or extension), i.e. of type SKYMAP, ONMAP, OFFMAP, SIGMAMAP or ULMAP.

The first list shows the keywords defined within the FITS standard. They basically describe the precission of the bin content, the number of axes and how to transform between bin coordinates into physical coordinates for the different axis. Some of them are compulsory and must appear in a very well defined order (see Ref. [1] for the details).

- XTENSION [string]: must be 'IMAGE'.
- BITPIX [int]: Defines the precission of the image pixels. The possible values and their meaning are summarized in table 2.
- NAXIS [int]: Number of axes defining the image (up to 999). In the cases defined in MAGIC. standard, only 2D images are meaningful and thus NAXIS should be 2.
- NAXISn [int]: Number of elements (pixels) along the axis n. It must be present for n = 1, ..., NAXIS, and for no other value.
- CTYPEn [string]: Name or the coordinate represented by axis n.
- CRPIXn [float]: Location of a reference point along axis n. The value is based upon a counter that runs from 1 to NAXISn with an increment of 1 per pixel.

- CRVALn [float]: Value, in the coordinates specified by CTYPEn, corresponding to the point specified by CRPIXn.
- CDELTn [float]: Value, in the coordinates specified by CTYPEn, corresponding to an increment of 1 pixel in axis NAXISn.
- EQUINOX [float]: Equinox, in years, in which celestial coordinates are expressed.

Value	Data Represented
8	Character or 1-byte integer (char)
16	2-byte integer (short)
32	4-byte integer (int)
64	8-byte integer (long)
-32	4-byte floating point (float)
-64	8-byte floating point (double)

Table 2: Interpretation of valid BITPIX values

The following list summarizes the keywords defined by MAGIC to describe the content of the image

- SRCPOSn [float]: Coordinate, along the n-th axis, of the object being observed irrespectful to the fact that MAGIC detects it or not. The coordinate must be in the same units expressed by CTYPEn.
- BESTPOSn [float]: Best estimate, along the n-th axis, of the coordinate of MAGIC source (if any). The coordinate must be in the same units expressed by CTYPEn.
- DESTPOSn [float]: Error on the best estimate of the coordinate of the MAGIC source (if any) along the n-th axis. The error must be in the same units expressed by CTYPEn.
- SMEARGAU [float]: Add this keyword if the contents of the image have been smeared using a gaussian smearing, the float value being the sigma of the used Gaussian function, in degrees.
- SMEARFLA [float]: Add this keyword if the contents of the image have been smeared using a flat-top smearing (circular step function), the float value being the radius of the flat-top area, in degrees.

4.3 Binary Extension Keywords

The following list of keywords is an extract of the standard FITS keywords available to describe the data contained in a Binary Extension HDU. Some of them are compulsory and must appear in a well defined order (see Ref. [1] for the details).

- XTENSION [string]: must be 'BINTABLE'.
- NAXIS1 [int]: Total number of bytes needed to store all the fields for a given entry (row) of the binary table
- NAXIS2 [int]: Total number of entries (rows) of the binary table
- TFIELDS [int]: Total number of fields (column) for each entry of the binary table

- TTYPEn [string]: Name of the field n. It must be present for $n = 1, \ldots$, TFIELDS, and for no other value.
- TFORMn [string]: String defining the format and precission of field n. It must have the form rT where r is an integer specifying the number of elements in the field n, and T a character defining the type. The possible values of T are summarized in Table 3.
- TUNITn [string]: Physical unit of the quantity contained in the field n.

Value	Data Represented	number of bytes
\mathbf{L}	Logical	1
Х	Bit	*
В	Unsigned byte	1
Ι	2-byte integer	2
J	4-byte integer	4
Κ	8-byte integer	8
А	Character	1
\mathbf{E}	Single precission floating point	4
D	Double precission floating point	8
\mathbf{C}	Single precission complex	8
Μ	Double precission complex	16
Р	Array descriptor (32-bit)	8
\mathbf{Q}	Array descriptor (64-bit)	16

Table 3: Interpretation of valid TFORMn values

4.4 Spectrum Keywords

• ISINTEGR [bool]: Set to 'T' if the data represented are integral fluxes or 'F' if they are differential ones.

4.5 Lightcurve Keywords

• ISINTEGR [bool]: Set to 'T' if the data represented are integral fluxes or 'F' if they are differential ones.

4.6 Alpha/Theta² plots Keywords

• ISINTEGR [bool]: Set to 'T' if the data represented are integral fluxes or 'F' if they are differential ones.

5 Version

The version number of a particular data file is noted by the VERSION keyword of the PHDU. Files produced in version n of the data are described in versions n.m of this document. The version number of the document can be found at its front page. This section includes the list of changes from version to version.

 $0.0\,$. November 30 2009. First release

References

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