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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 the MAGIC published papers. This document should provide the necessary and sufficient information to interpret the MAGIC FITS data files. In particular, it describes the organization of the information as well as the definition of headers and keywords which are specific for 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 too 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 probably that, historically, the field has been developed by scientists with a background biased towards particle physics rather than towards astronomy, and therefore with a different tradition regarding the data distribution formats. The situation is gradually changing as the field is evolving and maturing, in particular in the 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 is a major task that will most likely be 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 is 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 MAGIC 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 the 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, in a form '*n.m*', where '*n*' refers to the version of the data format it describes, and '*m*' to subversion of this document. 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 always the primary header, which may or may not be followed by a primary data array. In the case of the MAGIC FITS files, the PHDU header usually contains the most general information about the observation. The primary data array may or may not be present. In the case that 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 of type BINTABLE. Extensions can be used to save data from skymaps, alpha/theta² plots, light curves or spectra.

3 Header and Data Units

The MAGIC FITS data files use only three different types of HDU's: the PHDU, IMAGE and BINTABLE extensions. There can be as many HDU extensions of each type as desired.

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

3.1 Skymap

Skymaps can be recorded in the PHDU or as IMAGE extensions. The PHDU is reserved for final skymap (i.e. for showing the number of excess events). However, the PHDU may also consist of the primary header only –with no associated data– describing the data used within 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 are the skymaps for: number of excess events over the background (N_{ex}), total number of recorded gamma-ray candidate events before background subtraction (N_{on}), total number of recorded background events (N_{off}), normalized number of background events (N_{bkg}), upper limits and significance. N_{on} and N_{off} are the number of gamma-ray and background candidate events observed in the field of view, with no further normalization applied. N_{bkg} is the (normalized) number of estimated background events, the normalization factor (k) is defined in such a way that $N_{\text{bkg}} = N_{\text{off}}/k$. The number of excesses is $N_{\text{ex}} = N_{\text{on}} - N_{\text{bkg}}$. The significances are computed using formula 17 of Ref. [6], and the upper limits by using the prescription from Ref. [7].

Skymaps are recorded as 2-dimensional images, where the coordinates may be celestial, galactic or camera. The precision 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 2 fields (columns) and a maximum of 4. The two compulsory fields represent the values of the time (MJD) and measured flux, stored in this order. In the case that 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 fourth one as the error on the flux. The flux may be differential or integral, and the corresponding units are [$\text{ph TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}$] or [$\text{ph cm}^{-2} \text{s}^{-1}$]. If the field corresponding to the flux error is filled with zeros, then the flux values are interpreted as the 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 2 fields (columns) and a maximum of 4. The two compulsory fields represent the values of the energy

(GeV) and the flux, stored in this order. In the case that a third field is present, it is interpreted as the error in the flux. If there are 4 fields present, the third one is interpreted as the half-width of the energy bin and the fourth one as the error on the flux. The flux may be differential or integral, and the corresponding units [$\text{ph TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$] or [$\text{ph cm}^{-2} \text{ s}^{-1}$]. If the field corresponding to the flux error is filled with zeros, then the flux values are interpreted as the upper limits, computed following the method described in Ref. [7].

In the case that the SED is represented, all the rules described above apply, except that the units for the integral and differential fluxes are given as [$\text{ph TeV}^2 \text{ cm}^{-2} \text{ s}^{-1}$] and [$\text{ph TeV cm}^{-2} \text{ s}^{-1}$], respectively.

3.4 Alpha/Theta² plot

Alpha or theta² plots are recorded as BINARY TABLE extensions. The binary data table consists of a minimum 2 fields (columns) and a maximum of 4. The two compulsory 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 that 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 HDUs in which MAGIC data is organized. It is not intended as an exhaustive 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 in the explicitly stated cases. In case of contradicting values between different headers, the secondary HDU will prevail. 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 stated.

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 standard 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...]. 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 zeros 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.'
- **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** [string]: Current version of the FITS file, in a form '*n.p*', '*n*' being the data format version and '*p*' the file 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 hours).
- **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. If not present, it is assumed that no explicit lower zenith angle has been stated in the quoted article.
- **ZMAX** [float]: Maximum zenith angle (in degrees) of the observations. If not present, it is assumed that no explicit upper zenith angle has been stated in the quoted article.
- **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 confidence 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 precision of the bin content, the number of axes and how to transform the 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 precision 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 by 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 of the coordinate represented by axis **n**.
- **CRPIXn** [float]: Location of a reference point along the 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]: Coordinates, along the n-th axis, of the object being observed, irrespectful to the fact wether MAGIC detects it or not. The coordinates must be in the same units expressed by CTYPEn.
- BESTPOSn [float]: Best estimate, along the n-th axis, of the coordinates of MAGIC source (if any) . The coordinates must be in the same units expressed by CTYPEn.
- DESTPOSn [float]: Error on the best estimate of the coordinates 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 content of the image has 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 content of the image has 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, ..., TFIELDS, and for no other value.

- **TFORM n** [string]: String defining the format and precision 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.
- **TUNIT n** [string]: Physical unit of the quantity contained in the field n .

| Value | Data Represented | number of bytes |
|-------|---------------------------------|-----------------|
| L | Logical | 1 |
| X | Bit | * |
| B | Unsigned byte | 1 |
| I | 2-byte integer | 2 |
| J | 4-byte integer | 4 |
| K | 8-byte integer | 8 |
| A | Character | 1 |
| E | Single precision floating point | 4 |
| D | Double precision floating point | 8 |
| C | Single precision complex | 8 |
| M | Double precision complex | 16 |
| P | Array descriptor (32-bit) | 8 |
| Q | Array descriptor (64-bit) | 16 |

Table 3: Interpretation of valid TFORM n 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 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.

- Version [0.0]. November 30th 2009. First release

- Version [0.1]. March 10th 2010. Stating both lower and upper zenith angle is optional
- Version [0.2]. November 05th 2010. SEDs can be added as SPECTRUM extensions

References

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