FITS file format specifications for HEALPix products

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Abstract

This document describes the requirements on the FITS files containing HEALPix products, and in particular sky maps.

Contents

1   Introduction

The FITS (Flexible Image Transport System) format[1] (Hanisch et al. 2001; FITS Working Group 2016) was chosen by HEALPix[2] (Hierarchical Equal Area Iso Latitude Pixelation of the sphere, Górski et al. (2005)) because of

- the self-documentation of FITS files, thanks to their human readable headers,

- their portability across all types and architectures of computers, and

- the availability of FITS reading and writing routines and libraries in virtually all computer languages.

However, since FITS files can contain any kind of data, and HEALPix can deal with many kinds of simulated or observed data, beyond its original target science of Cosmic Microwave Background (CMB) visualisation and analysis, some requirements have to be put on the FITS file written and read by the various HEALPix-based codes to allow a smooth automated parsing and interpretation of the different files likely to be encountered. Examples of FITS files following the guidelines described in this document, as well as the latest version of this documents, can be found at `https://healpix.sourceforge.io/data/examples`. Note that other format specifications are available, for specific scientific applications, including one for Fermi data[3].

In what follows, the reader is assumed to be familiar with FITS format, and with the HEALPix pixelation of the sphere.

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[1] `https://fits.gsfc.nasa.gov/standard40/fits_standard40aa.pdf`
[2] `https://healpix.sourceforge.io`
[3] `https://gamma-astro-data-formats.readthedocs.io/en/latest/skymaps/healpix/index.html`

2   Formats

The data exchanged includes full sky and partial sky maps, as well as angular power spectra, Spherical Harmonics coefficients, ...

In all cases, the primary unit of the FITS file, which can only accommodate images, is *not* used to store any numerical data, and all information is stored in the other units (or extensions) of the FITS file, in the form of binary or text tables. Therefore, the primary header (generated automatically) should be similar to

```
SIMPLE  =                    T / file does conform to FITS standard
BITPIX  =                   32 / number of bits per data pixel
NAXIS   =                    0 / number of data axes
EXTEND  =                    T / FITS dataset may contain extensions
DATE    = '2099-12-31T23:59:59' / file creation date (YYYY-MM-DDThh:mm:ss UT)
END
```

and can only contain background information on the data contained in the extension(s), like the data release, a reference to a publication, ...

2.1   Sky Maps

Sky maps are stored in extensions of the FITS file, in the form of binary tables. Most FITS generating libraries (such as `cfitsio`[4], or `astro.io.fits`[5]), will automatically generate a baseline header with information similar to

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                    4 / width of table in bytes
NAXIS2  =               196608 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    1 / number of fields in each row
```

Numbers and character strings appearing in *italic* may take a different value in specific FITS files.

2.1.1   Full sky maps

- **Required keywords:**

  PIXTYPE = 'HEALPIX',

  INDXSCHM= 'IMPLICIT'[6] the pixel index is not given, but that p-th data value read correspond to the pixel p (starting at 0),

  ORDERING=   pixel numbering scheme, either 'RING' or 'NESTED' (see https://healpix.sourceforge.io/html/intro.htm),

  NSIDE   =   a power of 2 in $\{1, 2, 4, 8, 16, \ldots, 2^{29}\}$,

  FIRSTPIX= 0   lowest pixel index present (0 based, even in languages using 1-based indices, and even though FITS is 1-based),

  LASTPIX = $12 N_{\mathrm{side}}^2 - 1$ highest pixel index present (0 based),

  BAD_DATA= -1.6375000E+30[7] sentinel value given to missing or bad pixels.

- **Recommended keywords:**

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[4]`cfitsio` C library: https://heasarc.gsfc.nasa.gov/fitsio/

[5]`astro.io.fits` FITS file handling in python: http://docs.astropy.org/en/stable/io/fits/

[6]Some historical FITS data sets, such as WMAP full sky maps (https://lambda.gsfc.nasa.gov/product/map/current/index.cfm) released in 2012 or before, do not contain the INDXSCHM keyword (assumed to be IMPLICIT) nor BAD_DATA (since all pixels were observed and defined) but contain all the other required keywords, and will be read by standard HEALPix routines for legacy reasons. However, all new files must contain each of the required keywords.

[7]This sentinel value BAD_DATA = 1.6375e+30 is hard coded in the HEALPix codes (to recognize missing pixels from NaN occuring because of numerical errors) and can not be changed

```
    OBJECT  = 'FULLSKY',
```

COORDSYS=   currently (v3.50) HEALPix supports `'G'`, `'E'` and `'C'` for Galactic, Ecliptic and
        Celestial/Equatorial respectively.

- **Example header:**
  For instance, a full sky map with $N_{\text{side}} = 128$, containing $N_{\text{pix}} = 12N_{\text{side}}^2 = 196608$ pixels, in Galactic
  coordinates, stored in RING indexing, will have in its header

```
COMMENT  ------------------------------------------
COMMENT  Sky Map Pixelisation Specific Keywords
COMMENT  ------------------------------------------
PIXTYPE = 'HEALPIX '            / HEALPIX Pixelisation
ORDERING= 'RING    '            / Pixel ordering scheme, either RING or NESTED
NSIDE   =                   128 / Resolution parameter for HEALPIX
FIRSTPIX=                     0 / First pixel # (0 based)
LASTPIX =                196607 / Last pixel # (0 based)
COORDSYS= 'G       '            / Pixelisation coordinate system
COMMENT  G = Galactic, E = ecliptic, C = celestial = equatorial
BAD_DATA= -1.637500000000E+30 / Sentinel value given to bad pixels
OBJECT  = 'FULLSKY '
INDXSCHM= 'IMPLICIT'            / Indexing : IMPLICIT or EXPLICIT
```

  The lines starting with `COMMENT`, and the comment strings after the `/` sign, are *not* required, but are
  provided for clarity and for the convenience of the human reader.
  The FITS standard states that keyword values made of strings are to be put between quotes, in
  which the leading blanks are significant while trailing blanks are not. Strings shorter than 8 char-
  acters (like `HEALPIX`, `RING`, `G` and `FULLSKY` in the example above) used to be padded to the right
  with spaces, even though this not required anymore except for the value of the `XTENSION` keyword
  (FITS Working Group 2016).

Historically, since the HEALPix tools initially were designed for the simulation and analysis of WMAP
and Planck CMB data, the sky maps they generate and/or read often contain either

- intensity (= temperature) information (or by analogy any other intensive or extensive scalar quantity
  living on the sphere, like a surface brightness, a column density, a planetary elevation, ...)

- intensity and (linear) polarisation, described by the three I, Q, U Stokes parameters.

Therefore the HEALPix codes are mostly concerned with properly describing and identifying these few
fields among all those that can be present in the FITS files, as described in this document.
Other "ancillary" quantities, such as a measurement of the instrumental noise for observational data (which
for each pixel can take the form of the number of averaged data taking samples or an estimated standard
deviation or (co-)variance of the instrumental noise in I, Q and U, ...) are of course of interest but their mere
existence, their relevance and how they are best used in a given data analysis depend on the kind of data
considered, the algorithm being used and the scientific purpose of the analysis, among other things. As a
consequence the HEALPix tools **do not** attempt to provide nor enforce a single universal scheme to encode
all those extra "ancillary" informations, which are left to the discretion of science projects (see for instance
the Planck sky maps archived at `https://pla.esac.esa.int/pla/#home`) and code developpers.

2.1.1.1 Temperature only:

The binary table has a single column (ie `TFIELDS = 1`)

- **Required keywords:**

```
    POLAR   =          F       no polarisation,
    TTYPE1  = 'TEMPERATURE' .
```

- **Recommended keywords:**

TUNIT1   =   providing the map physical units is highly recommended (eg `'K'` or `'mK'` for Kelvin and milliKelvin respectively),

TEMPTYPE=   `'THERMO'` or `'ANTENNA'` for thermodynamic/CMB or Rayleigh-Jeans temperature fluctuations respectively.

2.1.1.2 Temperature + polarisation:

In that case, the binary table has three columns (ie `TFIELDS = 3`)

- **Required keywords:**

  POLAR   =   T   polarisation is present,

  POLCCONV= `'COSMO'`   either `'COSMO'` or `'IAU'`, see below,

  TTYPE1   = `'TEMPERATURE'`[8],

  TTYPE2   = `'Q_POLARISATION'`[9]

  TTYPE3   = `'U_POLARISATION'`[10]

  > The keyword `POLCCONV` (POLarisation Coordinate CONVention) was introduced by HEALPix and impacts the sign of U Stokes parameter, as described in https://healpix.sourceforge.io/html/intro_HEALPix_conventions.htm. Tools to add or modify this keyword in existing FITS files are listed at the same place.
  > Remember that the choice made in HEALPix (identified as `COSMO`), in line with most of the CMB scientific literature, is different from the one recommended by the International Astronomical Union (`IAU`)!

- **Recommended keywords:**

  TUNIT1   =   see "Temperature only" above,

  TUNIT2   =   must be the same as `TUNIT1`,

  TUNIT3   =   must be the same as `TUNIT1`,

  TEMPTYPE=   see temperature only.

- **Example header:**

  An *IQU* polarized map, will have in its FITS header

  ```
  Sky Map Pixelisation Specific Keywords seen above (page 4)
  COMMENT   ----------------------------------------------
  COMMENT            Data Specific Keywords
  COMMENT   ----------------------------------------------
  TEMPTYPE= 'THERMO  '        / temperature type either THERMO or ANTENNA
  POLAR    =                 T / Polarisation included (True/False)
  TTYPE1   = 'TEMPERATURE'     / Temperature map
  TFORM1   = '1E     '         / data format of field: 4-byte REAL
  TUNIT1   = 'mK     '         / map unit
  COMMENT
  TTYPE2   = 'Q_POLARISATION'  / Q Polarisation map
  TFORM2   = '1E     '         / data format of field: 4-byte REAL
  TUNIT2   = 'mK     '         / map unit
  COMMENT
  TTYPE3   = 'U_POLARISATION'  / U Polarisation map
  TFORM3   = '1E     '         / data format of field: 4-byte REAL
  TUNIT3   = 'mK     '         / map unit
  COMMENT
  POLCCONV= 'COSMO   '         / Coord. convention for polarisation (COSMO/IAU)
  Any other extra information
  END
  ```

---

[8]to be preferred to `'signal'`, `'I_Stokes'` or `'I_STOKES'` found in existing data sets

[9]to be preferred to `'Q-POLARISATION'`, `'Q_POLARIZATION'`, `'Q_Stokes'`, `'Q_STOKES'`, `'Q-pol'`, ...

[10]to be preferred to `'U-POLARISATION'`, `'U_POLARIZATION'`, `'U_Stokes'`, `'U_STOKES'`, `'U-pol'`, ...

Note: when $N_{\text{side}} \geq 16$ and mostly for historical reasons, some HEALPix FITS writing routines can generate files featuring `TFORM* = '1024E'` (where 1024 consecutive values are written at the intersection of a column and a row). This feature is totally transparent to most FITS parsers and does not reduce the portability or compliance of those files.

- **Example FITS files:**
  See https://healpix.sourceforge.io/data/examples/full_TQU.fits.

2.1.2 Partial sky maps

Some observed data sets only cover a small fraction of the sky, and it would be wasteful to store them in full sky maps with all unobserved pixels set to the sentinel value `BAD_DATA`=-1.6375×10^{30}. It makes more sense to store only the pixels which have been actually observed, meaning that the FITS file must contain for each of them, the pixel index, the observed pixel value, and any other relevant information on that pixel.

- **Required keywords:**

  PIXTYPE = 'HEALPIX',

  INDXSCHM= 'EXPLICIT' the pixel index is explicitely given,

  ORDERING=   either 'RING' or 'NESTED',

  NSIDE   =   a power of 2 in $\{1, 2, 4, 8, 16, \ldots, 2^{29}\}$,

  OBS_NPIX=   number of pixels listed in the file,

  BAD_DATA= -1.6375000E+30[11] sentinel value given to missing or bad pixels,

  TTYPE1 = 'PIXEL'   the first column is an integer stating explicitely the (0-based) index of the pixel considered,

  It is important to note that the 'PIXEL' field must be in the first column of the table.

- **Recommended keywords:**

  OBJECT = 'PARTIAL',

  COORDSYS=   can be among 'G', 'E' and 'C' for Galactic, Ecliptic and Celestial/Equatorial respectively,

  TUNIT1 = ''   pixel index,

  TFORM1 = 'J'   4-byte signed integer, (or 'K' for 8-byte signed integer)

A format designed to hold polarized or unpolarized data on a fraction of sky is supported in many flavours of HEALPix (including F90, IDL and python)

2.1.2.1 Partial sky temperature only

For temperature-only data, the binary table has two columns (ie `TFIELDS = 2`), and the following extra keywords

- **Required keywords:**

  POLAR   =   F   no polarisation,

  TTYPE2 = 'TEMPERATURE'   the second column is the temperature,

- **Recommended keywords:**

  TUNIT2 =   physical units of Temperature,

  TFORM2 =   'E' or 'D' 4-byte or 8-byte real,

---

[11]See footnote 7 on page 3

> TEMPTYPE= 'THERMO' or 'ANTENNA' for thermodynamic/CMB or Rayleigh-Jeans temperature fluctuations respectively.

- **Example FITS file:**
  See https://healpix.sourceforge.io/data/examples/partial_T.fits. Note that this file use the Nested pixel ordering.

2.1.2.2 Partial sky polarized data

If data are polarized, the binary table has four columns (ie TFIELDS = 4) instead, and the following extra keywords

- **Required keywords:**

POLAR	=	T	polarisation is present,
POLCCONV=	'COSMO'		either 'COSMO' or 'IAU', see note on POLCCONV on page 5
TTYPE2	=	'TEMPERATURE'	the second column is the temperature,
TTYPE3	=	'Q_POLARISATION'	the third column is the Q Stokes parameter of polarisation,
TTYPE4	=	'U_POLARISATION'	the fourth column is the U Stokes parameter of polarisation,

- **Recommended keywords:**

TUNIT2	=	physical units of Temperature,
TFORM2	=	'E' or 'D' 4-byte or 8-byte real,
TUNIT3	=	physical units of Q (same as TUNIT2)
TFORM3	=	same as TFORM2
TUNIT4	=	physical units of U (same as TUNIT2)
TFORM4	=	same as TFORM2
TEMPTYPE=		see temperature only

- **Example header:**
  In the example of Fig. 1, the FITS file contains a HEALPix NESTED-ordered map at $N_{\text{side}} = 128$ in which only 10% of the pixels are observed

- **Example FITS file:**
  See https://healpix.sourceforge.io/data/examples/partial_TQU.fits

2.1.2.3 Partial sky format for experimental data

Currently a four-column TFIELDS = 4 format is implemented in some flavours of HEALPix (namely in F90 and IDL), to describe data (and their instrumental noise) on a fraction of the sky. In that format, the header of the first extension includes

- **Required keywords:**

PIXTYPE = 'HEALPIX',	
INDXSCHM= 'EXPLICIT'	the pixel index is explicitly given,
ORDERING=	either 'RING' or 'NESTED',
NSIDE =	a power of 2 in $\{1, 2, 4, 8, 16, \ldots, 2^{29}\}$,
OBS_NPIX=	number of pixels listed in the file,

```
COMMENT  ----------------------------------------------
COMMENT  Sky Map Pixelisation Specific Keywords
COMMENT  ----------------------------------------------
PIXTYPE = 'HEALPIX '             / HEALPIX Pixelisation
ORDERING= 'NESTED   '                 / Pixel ordering scheme, either RING or NESTED
NSIDE   =                     128 / Resolution parameter for HEALPIX
COORDSYS= 'G       '              / Pixelisation coordinate system
COMMENT  G = Galactic, E = ecliptic, C = celestial = equatorial
NSIDE   =                     128 / Healpix resolution parameter
OBJECT  = 'PARTIAL '             / Sky coverage, either FULLSKY or PARTIAL
OBS_NPIX=                   19660 / Number of pixel observed and recorded
INDXSCHM= 'EXPLICIT'             / indexing : IMPLICIT or EXPLICIT
BAD_DATA=  -1.637500000000E+30 / Sentinel value given to bad pixels
COMMENT  ----------------------------------------------
COMMENT          Data Specific Keywords
COMMENT  ----------------------------------------------
TFORM1  = '1J      '             / Integer*4 (long integer)
TTYPE1  = 'PIXEL   '             /
TUNIT1  = '        '             /
TFORM2  = '1E      '             / Real*4 (floating point)
TTYPE2  = 'TEMPERATURE  '        /
TUNIT2  = 'K       '             /
TFORM3  = '1E      '             / Real*4 (floating point)
TTYPE3  = 'Q_POLARISATION'       /
TUNIT3  = 'K       '             /
TFORM3  = '1E      '             / Real*4 (floating point)
TTYPE4  = 'U_POLARISATION'       /
TUNIT4  = 'K       '             /
TFORM4  = '1E      '             / Real*4 (floating point)
BAD_DATA=        -1.63750E+30 / Sentinel value given to bad pixels
COORDSYS= 'G       '              / Pixelization coordinate system
COMMENT          G = Galactic, E = ecliptic, C = celestial = equatorial
POLCCONV= 'COSMO   '              / Coord. convention for polarisation (COSMO/IAU)
Any other extra information
END
```

Figure 1: Example of FITS header for a partial TQU map

BAD_DATA= -1.6375000E+30[12] sentinel value given to missing or bad pixels,

TTYPE1 = 'PIXEL'   the first column is an integer stating explicitly the index of the pixel considered,

TTYPE2 = 'SIGNAL'   the second column is the value measured (or simulated) in that pixel,

TTYPE3 = 'N_OBS'   the integer number of observations on which this measure is based,

TTYPE4 = 'SERROR'   the fourth column is an estimate of the error made on the measurement.

It is important to note that the 'PIXEL' field must be in the first column of the table.

- **Recommended keywords:**

    OBJECT = 'PARTIAL',

    COORDSYS=   can be among 'G', 'E' and 'C' for Galactic, Ecliptic and Celestial/Equatorial respectively,

    TUNIT1 = ''   pixel index,

    TFORM1 = 'J' 4-byte integer,

    TUNIT2 =   physical units of signal,

    TFORM2 =   'E' or 'D' 4-byte or 8-byte real,

---

[12]See footnote 7 on page 3

```
TUNIT3   =   ''     hit count,

TFORM3   =   'J'   4-byte integer,

TUNIT4   =      must be the same as TUNIT2,

TFORM4   =     'E' or 'D' 4-byte or 8-byte real.
```

If the last two columns are not known upon writing, they can be replaced by place-holder values of 1 and 0.0 respectively in every pixel, or the 2-column format described in §2.1.2.1 can be used instead.

- **Example header:**
  In this example, the FITS file contains a HEALPix NESTED-ordered map at $N_{\text{side}} = 128$ in which only 10% of the pixels are observed

```
TFORM1  = '1J      '              / Integer*4 (long integer)
TTYPE1  = 'PIXEL   '              /
TUNIT1  = '        '              /
TFORM2  = '1E      '              / Real*4 (floating point)
TTYPE2  = 'SIGNAL  '              /
TUNIT2  = 'K       '              /
TFORM3  = '1J      '              / Integer*4 (long integer)
TTYPE3  = 'N_OBS   '              /
TUNIT3  = '        '              /
TFORM4  = '1E      '              / Real*4 (floating point)
TTYPE4  = 'SERROR  '              /
TUNIT4  = 'K       '              /
PIXTYPE = 'HEALPIX '              / HEALPIX pixelisation
ORDERING= 'NESTED  '               / Pixel ordering scheme, either RING or NESTED
NSIDE   =                     128 / Healpix resolution parameter
OBJECT  = 'PARTIAL '              / Sky coverage, either FULLSKY or PARTIAL
OBS_NPIX=                   19660 / Number of pixel observed and recorded
INDXSCHM= 'EXPLICIT'              / indexing : IMPLICIT or EXPLICIT
BAD_DATA=           -1.63750E+30 / Sentinel value given to bad pixels
COORDSYS= 'G       '              / Pixelization coordinate system
COMMENT           G = Galactic, E = ecliptic, C = celestial = equatorial
Any other extra information
END
```

- **Example FITS file:**
  See https://healpix.sourceforge.io/data/examples/cut_T.fits

The same partial sky format can be applied to polarized data. In that case, the I, Q, U Stokes parameters are each stored in a separate extension of the same FITS file, with similar information provided in each of the header (with the same NSIDE, COORDSYS, ORDERING and OBS_NPIX in each extension), the header of the first extension should also include

```
POLAR   =                     T /
POLCCONV= 'COSMO   '              / Coord. convention for polarisation (COSMO/IAU)
EXTNAME = 'TEMPERATURE'          /
```

the header of the second one:

```
POLAR   =                     T /
POLCCONV= 'COSMO   '              / Coord. convention for polarisation (COSMO/IAU)
EXTNAME = 'Q_POLARISATION'       /
```

and the header of the third extension:

```
POLAR   =                     T /
POLCCONV= 'COSMO   '              / Coord. convention for polarisation (COSMO/IAU)
EXTNAME = 'U_POLARISATION'       /
```

2.1.3   Mixed resolution objects

Not consistently implemented in HEALPix

2.2 $a_{\ell m}$

To be written

2.3 Power Spectra (C_ℓ) and Window Functions (B_ℓ)

To be written

3 Acknowledgment

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4 References

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