FITS file format for HEALPix products
Version 0.1

E. Hivon on behalf of the HEALPix collaboration

June 13, 2018

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 (Hanisch et al. 2001) was chosen by HEALPix[1] (Górski et al. 2005) because of

- the portability of the FITS files,
- the availability of FITS reading and writing routines and libraries in virtually all computer languages,
- the self-documentation of FITS files, thanks to their human readable headers.

However, since FITS files can contain any kind of data, and HEALPix can deal with many kinds of simulated or observed data, 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.

Note that other format specifications are available, for specific scientific applications, including one for Fermi data[2]

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

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 accomodate 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
```

[1] http://healpix.sourceforge.net

[2] https://gamma-astro-data-formats.readthedocs.io/en/latest/skymaps/healpix/index.html

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`, or `astro.io.fits`), 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  =                12288 / width of table in bytes
NAXIS2  =                  192 / number of rows in table
PCOUNT  =                    0 / size of special data area
GCOUNT  =                    1 / one data group (required keyword)
TFIELDS =                    3 / 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'` the pixel index is not given, but that p-th data value read correspond to the pixel p (starting at 0)
  - `ORDERING=` either `'RING'` or `'NESTED'`
  - `NSIDE =` a power of 2 in $\{1, 2, 4, 8, 16, \ldots, 2^{29}\}$
  - `FIRSTPIX= 0` lowest pixel index present (0 based)
  - `LASTPIX =` $12N_{\rm side}^2 - 1$ highest pixel index present (0 based)
  - `BAD_DATA= -1.6375000E+30` sentinel value given to missing or bad pixels
- **Recommended keywords:**
  - `OBJECT = 'FULLSKY '`
  - `COORDSYS=` can be among `'G'`, `'E'` and `'C'` for Galactic, Ecliptic and Celestial/Equatorial respectively.
- **Example:** For instance, a full sky map with $N_{\rm side} = 128$, containing $N_{\rm pix} = 12N_{\rm side}^2 = 196608$ 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.

Historically, since the HEALPix tools initially were designed for the simulation and analysis of Planck CMB data, the sky maps they generate and/or read often contain either intensity (= temperature) information, or intensity and (linear) polarisation, described by the three I, Q, U Stokes parameters.

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

Temperature + polarisation: In that case, the binary table has three columns (ie TFIELDS = 3)

- **Required keywords:**
  - POLAR = T polarisation is present
  - POLCCONV= 'COSMO '
  - TTYPE1 = 'TEMPERATURE'[3]
  - TTYPE2 = 'Q_POLARISATION'[4]
  - TTYPE3 = 'U_POLARISATION'[5]

  The keyword POLCCONV (POLarisation Coordinate CONVention) was introduced by HEALPix and impacts the sign of U Stokes parameter, as described in http://healpix.sourceforge.net/html/intro.htm. Remember that the choice made in HEALPix (identified as COSMO) 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:** An IQU polarized map, will have in its FITS header

```
Sky Map Pixelisation Specific Keywords seen above
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
```

2.1.2 Cut 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.

Currently a four-column format is implemented TFIELDS = 4, in which the header of the first extension includes

- **Required keywords:**

[3] to be preferred to 'signal', 'I_Stokes' or 'I_STOKES' found in existing data sets
[4] to be preferred to 'Q-POLARISATION', 'Q_POLARIZATION', 'Q_Stokes', 'Q_STOKES', 'Q-pol', ...
[5] to be preferred to 'U-POLARISATION', 'U_POLARIZATION', 'U_Stokes', 'U_STOKES', 'U-pol', ...

  - 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 sentinel value given to missing or bad pixels
  - TTYPE1 = 'PIXEL ' the first column is an integer stating explicitely 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.
- **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
  - 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.
- **Example:** In this example, the FITS file contains a HEALPix NESTED-ordered map at $N_{\rm side} = 128$ 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
```

The same cut sky field 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

2.2 $a_{\ell m}$

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

References

Górski, K. M., Hivon, E., Banday, A. J., et al., HEALPix: A Framework for High-Resolution Discretization and Fast Analysis of Data Distributed on the Sphere. 2005, The Astrophysical Journal, 622, 759 1

Hanisch, R. J., Farris, A., Greisen, E. W., et al., Definition of the Flexible Image Transport System (FITS). 2001, Astronomy and Astrophysics, 376, 359 1