ESO SCIENCE DATA PRODUCTS STANDARD

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Addendum

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APEX Sub-Millimetre Flux Maps

This section defines the image data format for fully reduced, astrometrically registered and flux calibrated sky maps in the sub-millimetre domain, in particular applicable to observations using the bolometer arrays LABOCA and ARTEMIS at the APEX 12-metre telescope.

The image array represents the spectral flux density in units of Jansky per beam or a decimal fraction thereof like milli-Jansky per beam as declared in the `BUNIT` keyword.

`FLUXERR` specifies the uncertainty of the absolute flux calibration including all contributing effects, i.e. the instrumental calibration, atmospheric conditions in terms of the precipitable water (PWV) and stability, and the calibration source.

The effective spatial resolution of the map, given by the keyword `SKY_RES`, accounts for the combined effect of the instrumental beam size and any additional smoothing possibly applied to the data during map synthesis.

The uncertainties of the astrometric registration are quantified using the FITS WCS keywords `CSYERi` and `CRDERi` for the systematic and random parts to the error budget, respectively.

Data Types

The flux map is the primary product and should always be associated with the RMS noise map, or the signal-to-noise ratio map, or both. Noise maps are separate FITS files having the same geometry as the flux map image. Other types of ancillary data may be optionally associated.

Data Type `PRODCATG`	**Description**
`SCIENCE.IMAGE.FLUXMAP`	APEX sub-mm flux map in FITS format. The data array should reside in the primary header data unit (HDU) of the FITS file.[1] FITS header keywords according to Table 1 must be present.

[1] FITS extensions may be present, e.g. to encode the list of original science data files in terms of a FITS table instead of using a list of indexed header keywords (see: Provenance extension, Sect. 2.4.2, Doc. GEN-SPE-ESO-33000-5335, Issue 5)

Data Type ASSOC*i*	Description
ANCILLARY.RMSMAP	RMS noise map. FITS image with the same geometry (NAXIS*i*) and the same physical units (BUNIT) as the flux map. Required unless SNR map is provided (see below).
ANCILLARY.SNRMAP	The signal-to-noise ratio (SNR) map is equal to the arithmetic ratio of flux map and noise map. FITS image with the same geometry (NAXIS*i*) as the flux map. The SNR map is dimensionless, i.e. BUNIT should be set to a blank string. Required unless the RMS noise map is provided.[2]
ANCILLARY.SRCTBL	Catalogue of sources directly detected in the map image (optional). Format: FITS binary table For high-level source catalogues resulting from a survey project, please adopt the SCIENCE.CATALOG format instead (see page 7).
ANCILLARY.RESMAP	Map of residuals after removal of sources (optional). FITS image with the same geometry (NAXIS*i*) and the same physical units (BUNIT) as the flux map.
ANCILLARY.SRCMASK	Sextractor source mask file (optional). FITS image with the same geometry (NAXIS*i*) as the flux map.
ANCILLARY.FILTERED	Multi-scale filtered image used to optimally extract compact sources (optional). FITS image with the same geometry (NAXIS*i*) and the same physical units (BUNIT) as the flux map.

Table 1: Sample FITS header of the APEX sub-millimetre flux map (primary HDU)

```
SIMPLE  =                    T / File does conform to FITS standard
BITPIX  =                  -32 / Bits per pixel
NAXIS   =                    2 / Number of axes
```

[2] The RMS noise map or the SNR map must be associated as file number 1 (ASSOC1/ASSON1).

```
NAXIS1  =                  447 / Axis length
NAXIS2  =                  476 / Axis length
BUNIT   = 'Jy/beam '           / Physical unit of array values
ORIGIN  = 'APEX'               / Facility
DATE    = '2010-02-11T13:19:30' / Date FITS file was generated
TELESCOP= 'APEX-12m'           / Telescope name
INSTRUME= 'APEXBOL'            / Instrument name
FILTER  = '870u'               / Frequency or wave band
WAVELMIN=            7.994E+05 / [nm] Minimum wavelength
WAVELMAX=            9.517E+05 / [nm] Maximum wavelength
OBJECT  = 'CDFS'               / Target designation
RA      =              53.1208 / [deg] Image centre (J2000.0)
DEC     =             -27.8131 / [deg] Image centre (J2000.0)
EQUINOX =               2000.0 / Standard FK5 (years)
RADECSYS= 'FK5'                / Coordinate reference frame
MJD-OBS =        54293.5610800 / Start of observations (days)
MJD-END =        54743.4766700 / End of observations (days)
DATE-OBS= '2007-07-12T13:27:57.3' / Start of observations
TIMESYS = 'TAI'                / Time system for MJD and DATE-OBS
PROG_ID = 'MULTI'              /
PROGID1 = '078.F-9028(A)'      / ESO programme identification
PROGID2 = '079.F-9500(A)'      / ESO programme identification
PROGID3 = '080.A-3023(A)'      / ESO programme identification
PROGID4 = '081.F-9500(A)'      / ESO programme identification
NCOMBINE=                 2497 /# of combined raw science data files
```

List of original science files, either in terms of PROV keywords:

```
PROV1   = 'APEXBOL.2007-07-12T13:27:57.000' / Original science file
PROV2   = 'APEXBOL.2007-07-12T13:40:32.000' / Original science file
PROV3   = 'APEXBOL.2007-07-12T13:46:12.000' / Original science file
```

(truncated)

or, alternatively, using the dedicated FITS binary table extension (see also Table 2*)*

```
PROVXTN =                    T / TRUE if provenance recorded in FITS extension
OBSTECH = 'CONTINUUM'          / Technique of observation
PRODCATG= 'SCIENCE.IMAGE.FLUXMAP' / Data product category
ASSON1  = 'less_laboca_ecdfs_rms_v1.0.fits' / RMS noise map
ASSOC1  = 'ANCILLARY.RMSMAP'   / Category of associated file
ASSON2  = 'less_laboca_ecdfs_sn_v1.0.fits' / Signal-to-noise map
ASSOC2  = 'ANCILLARY.SNRMAP'   / Category of associated file
ASSON3  = 'less_laboca_ecdfs_residual_v1.0.fits' / Residuals map
ASSOC3  = 'ANCILLARY.RESMAP'   / Category of associated file
ASSON4  = 'less_laboca_ecdfs_f5_cat_v1.0.fits' / Source catalogue
ASSOC4  = 'ANCILLARY.SRCTBL'   / Category of associated file
```

```
FLUXCAL = 'ABSOLUTE'           / Certifies the validity of BUNIT
CTYPE1  = 'RA---GLS'           /
CTYPE2  = 'DEC--GLS'           /
CD1_1   =   -1.68725801995E-03 /
CD1_2   =                   0. /
CD2_1   =                   0. /
CD2_2   =    1.68725801995E-03 /
CRPIX1  =    2.24000000000E+02 /
CRPIX2  =    2.38500000007E+02 /
CRVAL1  =    5.31208326761E+01 /
CRVAL2  =   -2.78130552740E+01 /
CUNIT1  = 'deg'                /
CUNIT2  = 'deg'                /
CSYER1  =           0.00222222 / Systematic error
CSYER2  =           0.00222222 / Systematic error
SKY_RES =                  27. / [arcsec] FWHM effective beam size
FLUXERR =                  8.5 / [%] Fractional flux calibration error (RMS)
BNOISE  =               0.0012 / [Jy/beam] Median RMS background noise
MAPMODE = 'SPIRALRAS,OTF'      / APEX mapping mode
FEBE1   = 'LABOCA-ABBA'        / Frontend-backend combination
PROCSOFT= 'BoA 2010-06-24'     / Data reduction software/system
REFERENC= '2009ApJ...707.1201W' / Bibliographic reference
CHECKSUM= '7eAq9b5o7bAo7b3o'   / HDU checksum updated 2010-03-11T13:36:30
DATASUM = '3396496275'         / data unit checksum updated 2010-03-11T13:36:30
END
```

Table 2: Example for encoding the original science files (“provenance”) of APEX sub-millimetre flux maps using the FITS binary table extension

```
XTENSION= 'BINTABLE'           / binary table extension
BITPIX  =                    8 / 8-bit bytes
NAXIS   =                    2 / 2-dimensional binary table
NAXIS1  =                   68 / width of table in bytes
NAXIS2  =                 2497 / 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
EXTNAME = 'PHASE3PROVENANCE'   / name of this binary table extension
TTYPE1  = 'PROV    '           / label for field
TFORM1  = '68A     '           / format of field
CHECKSUM= 'kHnfkFkdkFkdkFkd'   / HDU checksum updated 2015-03-18T10:36:37
DATASUM = '3565490772'         / data unit checksum updated 2015-03-12T10:26:21
```

```
END


Row         1
 APEXBOL.2007-07-12T13:27:57.000

Row         2
 APEXBOL.2007-07-12T13:40:32.000

Row         3
 APEXBOL.2007-07-12T13:46:12.000

                    Remaining records not displayed
```

FITS Keyword Definitions

Type	Keyword	Description
(S)	INSTRUME	Instrument name as defined in the original raw FITS file. `INSTRUME= 'APEXBOL'`
(S)	FILTER	Name of the electromagnetic frequency or wave band. *Definition in the context of APEX sub-millimetre maps:* `FILTER = '870u'` LABOCA 870 micron band `FILTER = '200u'` ARTEMIS 200 micron band `FILTER = '350u'` ARTEMIS 350 micron band `FILTER = '450u'` ARTEMIS 450 micron band
(R)	WAVELMIN WAVELMAX	Electromagnetic wave band coverage in terms of the wavelength interval in units of nanometers (nm). *Definition for the LABOCA 870 micron band:* `WAVELMIN = 7.994E+05` LABOCA 870 micron band `WAVELMAX = 9.517E+05` LABOCA 870 micron band

Type	Keyword	Description

(S)	BUNIT	Physical unit of array values.
		The base unit for sub-millimetre flux maps is Jansky per beam.
		Examples:
		`BUNIT = 'Jy/beam' Jansky per beam`
		`BUNIT = 'mJy/beam' milli-Jansky per beam`

(R)	BNOISE	Point source sensitivity limit due to background noise (1**σ** level) in units of Jansky (Jy). In case of variations across the image, BNOISE refers to the median, i.e. the level reached in at least 50% of the mapped area. BNOISE corresponds to the beam-smoothed RMS noise level (Jy/beam) in case of APEX sub-millimetre flux maps.[3]
(R)	SKY_RES	Effective spatial resolution of the data in terms of the FWHM of the profile of an unresolved source (arcsec). In case of APEX sub-millimetre maps SKY_RES is the FWHM effective beam size of the map including the instrumental beam and possible smoothing applied during map synthesis.
(R)	FLUXERR	Fractional uncertainty of flux calibration (per cent). The FLUXERR estimate includes all contributing effects, in case of sub-millimetre flux maps in particular: the instrumental calibration, atmospheric conditions in terms of PWV and stability, and the calibration source. *Example:* `FLUXERR = 15.` indicates an overall uncertainty of the flux calibration of 15% RMS.
(S)	PROV*i*	List of science files, which were processed to generate this data product. Original raw files must be referenced in terms of the ESO/SAF identifier recorded as ARCFILE in the FITS header, also known as “DP.ID” in the SAF query forms. References to raw files in terms of ORIGFILE must be converted to the corresponding ARCFILE name prior to Phase 3 data submission.[4]

[3] Note: BNOISE has a fixed unit (Jy or Jy/beam) independent of BUNIT.

[4] http://archive.eso.org/wdb/wdb/eso/apex_origfile/form provides a conversion tool from APEX ORIGFILE names to ARCFILE names.

Type	Keyword	Description
(L)	PROVXTN	Flag indicating that original science files are recorded in a dedicated FITS binary table extension of the product file as per GEN-SPE-ESO-33000-5335, Sect. 2.4.2, instead of being listed as PROV*i* keywords.
(S)	MAPMODE	APEX map modes being used. Format: comma-separated list of the following keywords: OTF — On-the-fly mapping SPIRALRAS — Raster of spirals SPIRAL — Single spiral; normally only used for pointings, not for deep maps *Example:* `MAPMODE = 'SPIRALRAS,OTF'`

(S)	FEBE*i*	APEX frontend/backend combination propagated from the original raw FITS file.
		Examples:
		`FEBE*i* = 'LABOCA-ABBA'`
		`FEBE*i* = 'SABOCA-ABBA'`
		`FEBE*i* = 'ARTEMIS200-BEAR2'`
		`FEBE*i* = 'ARTEMIS350-BEAR1'`
		`FEBE*i* = 'ARTEMIS450-ARTBE'`
		`FEBE*i* = 'ARTEMIS450-BEAR1'`

Survey Catalogues

The legacy source catalogue produced by a survey project using the APEX facility should be formatted as a FITS binary table with header keywords according to Table 2.[5]

The catalogue may be based on one or many sub-mm map images depending on the area covered by the survey. Each map image must be referenced in the catalogue file using the PROV*i* keywords *(i=1,..,N)*.

The following keywords should be propagated from the map images to the primary header of the FITS binary table. Median values should be adopted for SKY_RES and BNOISE in case of variations across the survey area:

ORIGIN	TELESCOP	INSTRUME	FILTER
WAVELMIN	WAVELMAX	MJD-OBS	MJD-END

[5] Please also refer to the general requirements for scientific catalogue data to be submitted to the ESO Science Archive Facility as specified in Sect. 5, Doc. GEN-SPE-ESO-33000-5335, Issue 5.

DATE-OBS	TIMESYS	PROG_ID	PROGID*i*
OBSTECH	SKY_RES	BNOISE	MAPMODE
FEBE*i*			

The survey catalogue should include J2000 positional coordinates (decimal degrees) and each source must have a unique name ('identifier').

A given survey may produce more than one source catalogue to allow separate catalogues for instance one for point-like sources another for extended sources using different source extraction techniques optimized according to the type of source.

Table 3: Sample FITS header of the APEX sub-millimetre survey catalogue

```
SIMPLE  =                    T / File does conform to FITS standard
BITPIX  =                    8 / Number of bits per data pixel
NAXIS   =                    0 / Number of data axes
EXTEND  =                    T / Extensions may be present
ORIGIN  = 'APEX'               / Facility
DATE    = '2010-02-11T13:19:30' / Date FITS file was generated
TELESCOP= 'APEX-12m'           / Telescope name
INSTRUME= 'APEXBOL'            / Instrument name
FILTER  = '870u'               / Frequency or wave band
WAVELMIN=            7.994E+05 / [nm] Minimum wavelength
WAVELMAX=            9.517E+05 / [nm] Maximum wavelength
OBJECT  = 'CDFS'               / Target designation
RA      =              53.1208 / [deg] Image centre (J2000.0)
DEC     =             -27.8131 / [deg] Image centre (J2000.0)
EQUINOX =               2000.0 / Standard FK5 (years)
RADECSYS= 'FK5'                / Coordinate reference frame
MJD-OBS =        54293.5610800 / Start of observations (days)
MJD-END =        54743.4766700 / End of observations (days)
DATE-OBS= '2007-07-12T13:27:57.3' / Start of observations
TIMESYS = 'TAI'                / Time system for MJD and DATE-OBS
PROG_ID = 'MULTI'              /
PROGID1 = '078.F-9028(A)'      / ESO programme identification
PROGID2 = '079.F-9500(A)'      / ESO programme identification
PROGID3 = '080.A-3023(A)'      / ESO programme identification
PROGID4 = '081.F-9500(A)'      / ESO programme identification
PROV1   = 'less_laboca_ecdfs_flux_v1.0.fits' / Original science file
OBSTECH = 'CONTINUUM'          / Technique of observation
PRODCATG= 'SCIENCE.CATALOG'    / Data product category
REFERENC= '2009ApJ...707.1201W' / Bibliographic reference
SKY_RES =                  27. / [arcsec] FWHM effective beam size
BNOISE  =              0.0012 / [Jy/beam] Median RMS background noise
```

```
MAPMODE = 'SPIRALRAS,OTF'      / APEX mapping mode
FEBE1   = 'LABOCA-ABBA'        / Frontend-backend combination
CHECKSUM= 'XnMjYkLgXkLgXkLg'   / HDU checksum updated 2010-03-17T14:33:54
DATASUM = '3749781989'         / data unit checksum updated 2010-03-17T14:33:54
END
```

Extension 1

```
XTENSION= 'BINTABLE'           / FITS Extension first keyword
EXTNAME = 'PHASE3CATALOG'      / FITS Extension name
BITPIX  =                    8 / Number of bits per data pixel
NAXIS   =                    2 / 2-dimensional table
NAXIS1  =                   44 / Width of table in bytes
NAXIS2  =                  126 / Number of rows in table
PCOUNT  =                    0 / Parameter count
GCOUNT  =                    1 / Group count
TFIELDS =                    7 / Number of columns in each row
TTYPE1  = 'NAME'               / Label for column 1
TFORM1  = '20A'                / Format for column 1
TCOMM1  = 'Source name'        / Description for column 1
TUNIT1  = ' '                  / Physical unit for column 1
TUCD1   = 'meta.id;meta.main'  / Unified content descriptor for column 1
TINDX1  =                    T / TRUE if database index exists
TTYPE2  = 'RA'                 / Label for column 2
TFORM2  = 'E'                  / Format for column 2
TCOMM2  = 'Right Ascension (J2000)' / Description for column 2
TUNIT2  = 'deg'                / Physical unit for column 2
TUCD2   = 'pos.eq.ra;meta.main' / Unified content descriptor for column 2
TINDX2  =                    T / TRUE if database index exists
TTYPE3  = 'DE'                 / Label for column 3
TFORM3  = 'E'                  / Format for column 3
TCOMM3  = 'Declination (J2000)' / Description for column 3
TUNIT3  = 'deg'                / Physical unit for column 3
TUCD3   = 'pos.eq.dec;meta.main' / Unified content descriptor for column 3
TINDX3  =                    T / TRUE if database index exists
TTYPE4  = 'SOBS'               / Label for column 4
TFORM4  = 'E'                  / Format for column 4
TCOMM4  = 'Observed 870 micron flux density' / Description for column 4
TUNIT4  = 'Jy'                 / Physical unit for column 4
TUCD4   = 'phot.flux.density;em.mm.200-400GHz'  / Unified content descriptor for
TINDX4  =                    T / TRUE if database index exists
TTYPE5  = 'E_SOBS'             / Label for column 5
TFORM5  = 'E'                  / Format for column 5
TCOMM5  = 'Uncertainty in Sobs' / Description for column 5
TUNIT5  = 'Jy'                 / Physical unit for column 5
```

```
TUCD5   = 'stat.error;phot.flux.density' / Unified content descriptor for column
TTYPE6  = 'SNR'                / Label for column 6
TFORM6  = 'E'                  / Format for column 6
TCOMM6  = 'Signal-to-Noise'    / Description for column 6
TUNIT6  = ' '                  / Physical unit for column 6
TUCD6   = 'stat.snr'           / Unified content descriptor for column 6
TTYPE7  = 'FDR'                / Label for column 7
TFORM7  = 'E'                  / Format for column 7
TCOMM7  = 'Expected number of false detections' / Description for column 7
TUNIT7  = ' '                  / Physical unit for column 7
TUCD7   = 'meta.number'        / Unified content descriptor for column 7
END
```