Preprocessing of Raw Image Data with PixInsight

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Preface

Preprocessing of raw image data, also known as *data reduction*, persues the following main objectives:
- removal of reproducible detractions from raw image data,
- measurement of quality-relevant subframe properties and deriving weighting factors therefrom,
- registration of subframes and
- integration of subframes applying normalization and pixel rejection, taking into account weighting factors.

Correctly performed image acquisition and preprocessing are basic requirements for getting optimal results in astrophotography. Mistakes that happen in these stages normally cannot be corrected anymore in postprocessing. Common causes for suboptimal results or an interrupted preprocessing workflow are:
- poor or inconsistent raw image and calibration data,
- wrong or incomplete metadata in raw data and
- flawed settings or wrong succession of steps in preprocessing.

This guide is intended to introduce astrophotographers to the set of PixInsight's tools needed for recognizing and avoiding such deficiencies. It contains a depiction to the basic function of camera hardware and some tips regarding the control software. Certain properties of the used image sensor/camera are revealed that have critical impact on image calibration results. These relationships have to be taken into account for the acquisition of calibration frames, generation of master calibration files and for the settings used in the calibration workflow. The important role of metadata for the correct processing of raw image data in astrophotography is described.

The following topics are explained in detail: function and acquisition of calibration frames, generation of master calibration files, settings for correct execution of image calibration, inspection and judgement of calibration results using PixInsight's tools. An outline of post-calibration preprocessing steps is given. Finally, automation of preprocessing using PixInsight's WeightedBatchPreprocessing (WBPP) script is treated.

The Appendix contains a section about types of resources for PixInsight, resources for processes and scripts that are mentioned in this guide and the list of abbreviations that are used in this guide.

References are provided in order to facilitate further studies. Endnotes and references are specified in square brackets and are compiled separately at the bottom of this document.

If you feel that an important point is missing in this guide or something is wrong or unclear, please send a private message to me (user bulrichl in the PixInsight forum). If reasonable I will supplement or correct my description.

The up-to-date version of this guide is available in the PixInsight forum:
https://pixinsight.com/forum/index.php?threads/guide-to-preprocessing-of-raw-data-with-pixinsight.11547/

Structure

A Camera Hardware and Control Software

A1 Setup and Properties of Digital Cameras used for Astrophotography

A1.1 General setup of image sensors used in digital cameras

Image sensors of digital cameras are commonly structured as a two-dimensional array of photosites based on the semiconductor material silicon. The photosites include a lightsensitive region (a photodiode). Photons having sufficient energy to overcome the silicon bandgap energy (= 1.14 eV, corresponding to a wavelength of 1100 nm) interact with the silicon and generate electron-hole pairs (photoelectric effect) **[1]**. Silicon therefore is transparent to light of a wavelength > 1100 nm, but is sensitive in the wavelength ranges NIR (1100 - 700 nm), visible light (700 - 400 nm), UV (400 - 10 nm) and in the soft x-ray region (10 nm – 0.1 nm). In silicon devices, **one** electron-hole pair is generated by a single interacting photon of wavelengths in the range of 1100 to 400 nm.

By establishing an electric field within a certain region of the photodiode substrate a "depletion region" is generated which is capable of collecting the generated photoelectrons. Before an exposure is started, a reset is executed by which the charge is removed from all photosites, creating a defined initial state. During exposure time, generated electrons are accumulated per photosite. After exposure, the accumulated electrical charge of each photosite is converted into voltage by an amplifier in the readout process. Each voltage is finally converted into a digital number by an analog-to-digital converter (ADC), generating a two-dimensional array of integer values.

A1.2 Quantum efficiency (QE)

External quantum efficiency QE_{ext} **[2]** is the fraction of incident photon flux that contributes to the photocurrent in a photodetector as a function of wavelength. In case of an OSC image sensor (see section A1.6) it is typically combined with the transmittance of each color filter. External QE can be expressed as the product of internal quantum efficiency QE_{int} and optical efficiency (OE):

$$QE_{ext} = QE_{int} * OE$$

Internal QE is the fraction of photons incident on the photodetector surface that contributes to the photocurrent. It is a function mainly of photodetector geometry and doping concentrations and is always less than one for silicon photodetectors. Optical efficiency is the photon-to-photon efficiency from the pixel surface to the photodetector's surface. The geometric arrangement of the photodetector with respect to other elements of the photosite structure determine OE (shape and size of the aperture; length of the dielectric "tunnel" (see **[2]**, Fig. 7); and position, shape, and size of the photodetector). Experimental evidence shows that OE can have a significant role in determining the resultant external QE.

A1.3 CCD and CMOS image sensors

Charge-Coupled Devices (CCD) and Complementary Metal-Oxide-Semiconductor (CMOS) image sensors (CIS) are commonly utilized for digital cameras. Both technologies use photodiodes as photosensitive elements. Today predominantly an enhanced version, the "pinned photodiode" **[3]** is applied which combines low noise, high quantum yield and low dark current.

The differences between CCD and CIS **[4]** are related mainly to charge transport and readout architecture: in a CCD, the electrical charges are shifted successively across the sensor area to output registers and from there to the output node. Here, the electrical charges are converted by an amplifier into voltages which are outputted serially. A CCD delivers a frame as a sequence of analog pixel values (voltages). A/D conversion is performed time multiplexed by an external ADC in the camera electronics. In a CIS, conversion of electrical charge into voltage and amplification are performed on each individual photosite. The ADCs are located on the chip as well. Different ADC topologies can be implemented in a CIS. In a commonly used approach, each column is equipped with an ADC, and the ADCs operate in parallel, so all pixel values of one row are converted simultaneously. A CIS delivers a frame as digital pixel values.

A1.4 Binning

By binning, pixels are combined into larger pixels. E.g. 2x2 binning means that four pixels in a 2x2 matrix are combined into one pixel. In case of a CCD this process is performed on the sensor before readout, i.e. binning occurs before readout noise is introduced. Binning a CCD improves signal-to-noise ratio (SNR) and reduces the time for frame transmission at the cost of image resolution. In a CIS, binning occurs after readout, that means readout noise has already been introduced to each pixel **[5]**. Furthermore, depending on the design of the sensor, binning a CIS can combine pixels in a lower bit depth, so a SNR improvement possibly is not achieved at all.

A1.5 Controlling amplification of the analog signal of CMOS image sensors

The amplification of the analog signal is controlled by parameters gain and offset: offset shifts the zero point, gain changes the slope of the characteristic curve of the amplifiers. This happens before A/D conversion. In addition certain cameras let the user choose among different readout modes.

A1.5.1 *Conversion gain* and parameter *gain*

ADCs output relative numbers, referred to as Digital Number (DN) or Analog-to-Digital Unit (ADU), that don't have physical relevance. In order to compare the performance of different sensors, Digital Numbers have to be converted to electrons. The metric *conversion gain* G is defined as the Data Number per pixel devided by the number of electrons per photosite:

`G = DN per pixel / number of e⁻ per photosite`

Conversion gain G includes two fundamental signal transfer stages: the charge-to-voltage (V/e-) and the analog-to-digital (DN/V) conversion. Key performance measures of a sensor (conversion gain, readout noise, linearity, uniformity, dark current, full well capacity, etc.) can be determined by applying the photon transfer characterization technique **[6]**, or according to **[7]** or **[8]**. The script BasicCCDParameters uses the procedures described in Ref. **[7]**, chapter 8.2 Basic CCD Testing, see Errata to First Printing 2nd Edition of "The Handbook of Astronomical Image Processing", pages 229 - 234. Unfortunately it produces wrong results for dark current when *optical black level subtraction* (see sections B4.2 and B5.1.2) is performed which is the case for many regular digital cameras and some CMOS sensors **[9]**. A different approach of calculating dark current which works well even when optical black subtraction is performed in the camera is deduced in detail by Alessio Beltrame in Ref. **[10]**. The same approach is used in Mark Shelley's script DSLRSensorParameters, version 0.0.7 **[11]** which therefore is better suited for sensor analysis.

Manufacturers of dedicated astro cameras normally specify the *inverse conversion gain* K for a camera model, and image acquisition applications use the nonstandard FITS keyword `EGAIN` to record this value:

`K = 1/G = number of e⁻ per photosite / DN per pixel`

For dedicated astro cameras utilizing a CCD, the amplification factor of the primary voltage generated in the readout process is a fixed value, i.e. conversion gain cannot be varied. For dedicated astro cameras utilizing a CIS, the amplification factor of the primary voltage generated in the readout process can be adjusted by setting the parameter *gain* in the camera driver or image acquisition software. Image acquisition applications (e.g. SGP, NINA, APT, Ekos, CCDciel, SharpCap) use the nonstandard FITS keyword `GAIN` to record the current value of this parameter in the FITS header. Usually, the correlation between the parameter gain and the metric conversion gain is published by the camera manufacturer. Note that there is no standardized scale for the parameter gain, camera manufacturers are using different scales for it. Also note that the *inverse conversion gain* is used for the FITS keyword `EGAIN`, so a gain value of 0 corresponds to the highest available `EGAIN` value.

For regular digital cameras, *ISO speed* is the parameter that is used for varying conversion gain. Its value is retrieved by the raw decoding software. Image acquisition applications use the FITS keyword `ISO` or `ISOSPEED` to record this value.

A1.5.2 Parameter *offset*

For dedicated astro cameras utilizing a CCD and regular digital cameras, the zero-point of the analog signal normally is a fixed value.

For dedicated astro cameras utilizing a CIS, the zero-point of the analog signal can be adjusted by setting the parameter *offset* in the camera driver or image acquisition software. Image acquisition applications use the nonstandard FITS keyword `OFFSET` (e.g. SGP, NINA, APT, Ekos, CCDciel) or `BLKLEVEL` (e.g. SharpCap) to record the current value in the FITS header if this parameter is settable. Note that the correlation between the parameter offset and the resulting bias shift (in units of DN) in the file differs for different camera models.

Which value should be set if offset is variable? Too small values will cause clipping in the low range, an issue that cannot be repaired after the event. On the other hand, much too large values will confine the dynamic range of subframes. One should check dark frames (captured within the used range of gain and exposure time) for clipping in the low range **[n1]**. If clipping is detected, the offset parameter has to be increased sufficiently. The subject is complicated by the fact that the optimal offset value is different, depending on the gain settings. In my view, however, setting offset appropriately for the highest actually used gain is sufficient, this offset value can be used persistently. This check and correction has to be made once, after image quality is set in the camera, and camera driver, image acquisition software and file format are chosen (see sections A2.1 to A2.3).

A1.5.3 Readout mode

Certain cameras have separately controllable readout modes which affect the performance in terms of full well capacity, noise characteristic and readout noise. ASCOM (see section A2.2) supports the property 'Camera.ReadoutMode'. Provided that camera driver and image acquisition software support this feature, the user can choose the most suitable readout mode, and the used setting is written to the nonstandard FITS keyword (see section A3) `READOUTM`. Please read the corresponding documentation of the camera manufacturer. E.g. the following camera models of make QHY have separately controllable readout modes: QHY411 (IMX411), QHY461 (IMX461), QHY600 (IMX455) and QHY268 (IMX571); QHY's corresponding documentation is given in Ref. **[12]**. The different readout modes of these cameras are supported by QHY's ASCOM camera driver, they are also supported by *direct* camera drivers (see section A2.2) of certain image acquisition applications, e.g. NINA or SharpCap. NINA's *direct* camera driver even allows for changing readout mode, gain and offset within a sequence when its Advanced Sequencer is used **[13]**.

A1.6 Monochrome and OSC image sensors

It is important to differentiate between monochrome and One Shot Color (OSC) image sensors. The photosites of a monochrome image sensor are not equipped with color filters. Usually a filter wheel is used with LRGB and narrowband filters. For each filter, monochrome frames are obtained. The rough workflow in this case is: for each filter, perform image calibration and cosmetic correction, then register and subsequently integrate the frames. The integration results for each filter (monochrome images) have to be combined to a RGB image.

In OSC image sensors, each individual photosite of the sensor is equipped with a color filter. Usually 3 different colors are used for the color filters. Each photosite is exposed only to the light transmitted through its color filter. The different color filters are arranged in a periodic pattern on the sensor, called Color Filter Array (CFA) mosaic pattern, e.g. a Bayer pattern or Fujifilm's X-Trans mosaic pattern. In Bayer patterns, the smallest repeated unit consists of 2x2 elements. 25 % of all photosites detect only red light, 50 % detect only green light, and 25 % detect only blue light (R/G/B = 1:2:1), and green filters occupy diagonal positions. This implies that 4 different Bayer patterns exist, see **Figure 1**.

The smallest repeated unit of Fujifilm's X-Trans mosaic pattern consists of 6x6 elements. 22.2 % of all photosites detect only red light, 55.6 % detect only green light, and 22.2 % detect only blue light (R/G/B = 2:5:2).

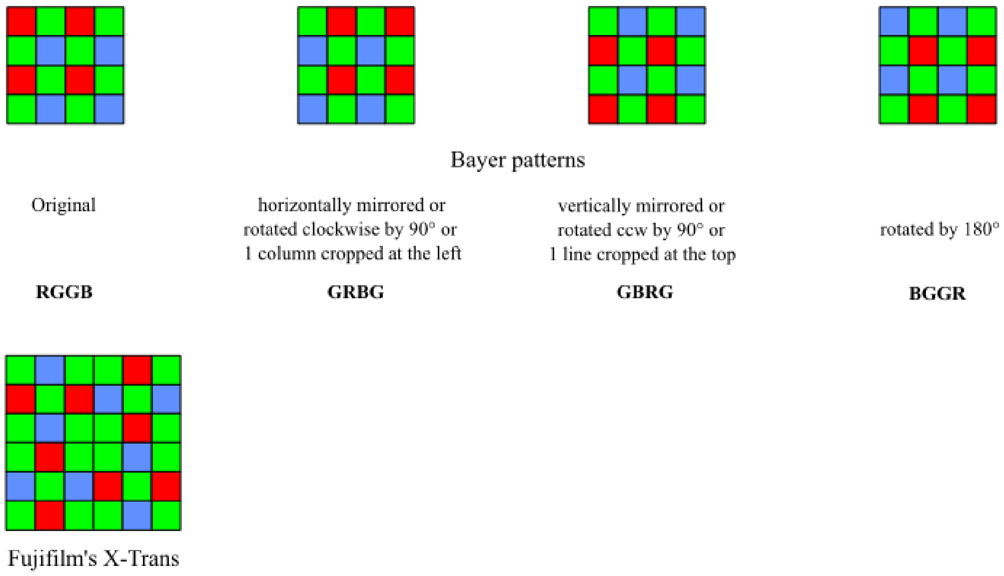

Figure 1: Bayer patterns and Fujifilm's X-Trans mosaic pattern

Thus with an OSC camera, it is possible to gain data for 3 colors simultaneously, in one shot. However, in bayered/mosaiced data (CFA data) the color information is incomplete: only one color information exists for each element of the sensor. The color information missing in CFA data has to be reconstructed by an interpolation algorithm called "Debayering" or, more generally, "Demosaicing". RGB (color) images are generated not before this process has been executed. Therefore CFA data of an OSC camera are not color images. CFA data are classified as 'Gray' in the 'Information' tool bar of PixInsight and are displayed as grayscale images.

Because the assignment of color to pixel value (= intensity) is contained in the pixel coordinates, performing certain geometric operations on CFA data will alter the CFA mosaic pattern. Provided that width and height of the image are even numbers (this is the normal case), an original Bayer pattern 'RGGB' is changed as indicated in the text below the Bayer patterns in **Figure 1** by following geometric operations: mirroring and rotation (→ process FastRotation), cropping (→ process Crop) by an odd number of columns at the left, or cropping by an odd number of lines at the top.

Fujifilm's X-Trans mosaic pattern is invariant regarding rotation. Provided that width and height of an image are divisible by 6, rotation consequently will not alter the color assignment, but mirroring and cropping will.

For bayered frames, PixInsight assigns CFA channel numbers according to the following scheme (numbering of x- and y-coordinates begins with 0):

x	y	CFA channel
even	even	0
even	odd	1
odd	even	2
odd	odd	3

Accordingly, the following assignment to CFA channels results for the pixels in the upper left corner of a bayered frame:

```
0  2
1  3
```

CFA channel numbers are used for bayered frames in the processes SplitCFA and MergeCFA.

When using an OSC camera (be it a regular digital camera or a dedicated astro camera), the entire calibration process has to be performed with raw CFA data. The rough workflow in this case is: perform image calibration and cosmetic correction with raw CFA data. Then the frames have to be debayered. Subsequently the debayered frames are registered and finally integrated.

A1.7 Properties of digital cameras used for astrophotography

In principal both regular digital cameras (e.g. Digital Single-Lens Reflex (DSLR) or Digital Single Lens Mirrorless (DSLM) cameras) and dedicated astro cameras can be used for astrophotography. When choosing a regular digital camera for astrophotography, one should take care that the camera can be set to save the data in a raw file format (see section A2.3.1). However, many models of regular digital cameras manipulate the sensor image data even when the raw file format is set (e.g. applying black point correction, lossy data compression, spatial filters for hot pixel removal, or exhibiting the "star eater" issue) **[14]**. Such camera models are ill-suited for astrophotography.

Regular digital cameras normally are OSC cameras. There are dedicated astro cameras in monochrome and in OSC versions. In order to reduce thermal noise, dedicated astro cameras usually are equipped with a cooling system including temperature control, whereas regular digital cameras normally are not cooled.

A2 Quality Settings, Camera Drivers, Image Acquisition Software and File Formats

A2.1 Camera-internal adjustment of image quality

For astrophotography, it is essential to capture frames that are not preprocessed in the camera regarding black/white point adjustment, stretching, noise reduction, distortion correction or (in case of an OSC camera) white balance setting. Besides, the maximum available bit depth (given by the resolution of the camera's ADC) shall be used. In order that these requirements are met, the following adjustments are necessary:

A2.1.1 Regular digital cameras

If a regular digital camera is used which is able to save the data in a proprietary raw file format (see section A2.3.1), set the camera in the camera menu to use this raw file format. Besides set Manual exposure mode. For Deep Sky astrophotography additionally set Bulb exposure and disable both long exposure noise reduction and (if available) distortion correction in the camera **[15]**.

A2.1.2 Dedicated astro cameras

For dedicated astro cameras adjust the sample format in the camera driver or in the image acquisition software to 16 bit generally (monochrome and OSC cameras). For OSC cameras it is important that CFA data (not RGB data!) will be stored in the file. The proper option is called differently, dependent on the used camera driver/image acquisition software, e.g. RAW16 (= CFA data, sample format of 16 bit).

When using an OSC camera and a *direct* camera driver (see section A2.2) in an image acquisition application, caution is advised: image acquisition applications allow to change the white balance of a displayed color image by multiplying the intensities of the R and B color channels respectively with a factor. In doing so, some image acquisition applications write the altered data to disk in the FITS file. For deep sky astrophotography, this must be avoided because due to the usual data format '16-bit integer', the altered data will contain rounding errors, and clipping of high values will arise by this manipulation. If the image acquisition application is behaving this way, it must be configured to not change the white balance, and this configuration must be saved. Only in this way, the real raw intensities will be saved to disk in the FITS files, see **[16]**. Such a complication cannot happen when an ASCOM camera driver is used.

A2.2 Camera drivers and image acquisition software

Manufacturers of cameras usually provide a software library (Software Development Kit, SDK) which helps software developers create applications that utilize all functionality of the camera. A SDK enables the communication between an application and the device driver of the camera on operating system level. In order to call a function of the SDK directly, the image acquisition application needs to contain an in-app driver which is specific to the camera platform in question. The frequently used term "native" camera driver for such a type of driver is misleading and should be replaced by the term "direct" camera driver, as suggested in **[17.a]** and **[18]**.

Manufacturers of dedicated astro cameras usually also provide an ASCOM camera driver. Its use requires the installation of the ASCOM Platform **[n2]**. An ASCOM driver acts as an abstraction layer on top of the SDK, removing any hardware dependency in the client (here: in the image acquisition application). Via an ASCOM driver, the application can access only a subset of the functionality that is supported by the SDK.

Architectural differences between direct camera driver and ASCOM camera driver are described in detail by Dale Ghent in **[17.a]**, **[17.b]** and **[24.a]**. As a consequence of these differences, a direct camera driver usually has the advantage of faster post-exposure download and larger scope of operation compared to an ASCOM camera driver **[17.a]**, **[18]** and **[24.a]**.

Image acquisition applications can run the camera in two different modes: streaming data (video) mode or single exposure (still) mode. The resulting frames differ depending on the mode that was used **[24.b]**. For deep sky astrophotography, single exposure mode should be used exclusively.

A2.3 File formats for image acquisition

Note that settings of image quality (see section A2.1) do not necessarily define the file format in which the image data are saved to disk. The file format (proprietary raw, FITS or XISF) usually can be set separately in the image acquisition software. If different drivers are available for a camera (e.g. direct and ASCOM driver), the file format may also depend on the camera driver that is selected in the image acquisition software.

Dependent on the chosen file format, the data may differ: proprietary raw file formats contain intensity values in the bit depth of the ADC, e.g. for a 12-bit ADC in the range of 0 to $2^{12} - 1 = 4095$, or for a 14-bit ADC in the range of 0 to $2^{14} - 1 = 16383$. In contrast, the same data in a FITS file usually (dependent on the camera driver) are scaled to 16 bit (range 0 to $2^{16} - 1 = 65535$), by multiplying with a factor (12 bit: by factor 16, 14 bit: by factor 4). Whether scaling of intensity values is performed can be determined by inspecting the histogram of a subframe **[n3]**.

Different behavior regarding scaling of intensity values is one important reason that the use of different file formats for light and calibration frames within one project may lead to severe issues in image calibration. So please follow the advice given in section B.3.

A2.3.1 Proprietary raw file formats of regular digital cameras

Each camera manufacturer has its own proprietary raw file format (e.g. Canon: CR2 or CR3, Nikon: NEF, Sony: ARW, Fujifilm: RAF, Pentax: PEF, Panasonic: RAW or RW2 format, or Adobe's DNG format). The image acquisition application SGP lets you choose whether the data coming from the camera will be saved to disk in proprietary raw file format or in FITS file format (or in both of them). Other image acquisition applications (e.g. NINA, APT or SharpCap) will save the data of regular digital cameras in proprietary raw file format by default. In the latter case, it is possible to save the files in FITS file format by additionally installing and using a third-party ASCOM driver **[25]**, at least for certain camera models of Canon, Nikon, Pentax, Panasonic and Sony.

In proprietary raw formats, the data are encoded and compressed. PixInsight's RAW format support module uses the raw image decoding software 'LibRaw', a successor of 'DCRAW', to perform the task of decoding the data.

A2.3.2 Flexible Image Transport System (FITS) format

Flexible Image Transport System (FITS) is an open standard of a file format for images, spectra and tables that is widely-used in the field of astronomy. The structure of FITS files is defined in Ref. **[26]**.

Byte order is big-endian in FITS files. A FITS file is comprised of segments called *Header and Data Units* (HDUs). FITS files that were written by an image acquisition software normally consist of only one HDU. A HDU is a data structure consisting of a header containing metadata (see chapter A3) and the data (in our case: the image) that are described in the header. Header and data area are constructed of *FITS blocks* that comprise 2880 bytes. A FITS header is constructed of 80-byte keyword records, each of which consists of a name (bytes 1 to 8), a value indicator `'= '` (bytes 9 and 10), a value and optionally a comment (bytes 11 to 80). The primary header must contain the mandatory keywords `SIMPLE = T`, `BITPIX` which specifies the bit width and number format of each element of the data array, and `NAXIS` and `NAXISn` (with `n = 1` to `NAXIS`) which define the data array's dimensionality. The header is completed with the `END` keyword. If necessary, the header or data unit is padded out to the required length with ASCII blanks or NULLs depending on the type of unit.

The keywords `BSCALE` and `BZERO` can be used to linearly scale the pixel values in the data array to transform them into the physical values that they represent according to the following equation:

```
physical_value = BZERO + BSCALE * array_value
```

Default values are 0.0 for `BZERO`, and 1.0 for `BSCALE` (no scaling). According to the FITS standard, 16-bit, 32-bit and 64-bit integer values in the image array are signed (format of representation: two's complement). However, normally the keyword `BZERO` is used for storing unsigned-integer values in the FITS array. In this case, the value of `BZERO` is set to `2^(BITPIX - 1)`, e.g. `BITPIX = 16 -> BZERO = 32768`, and `BSCALE` shall have the default value of 1.0.

Unfortunately the FITS standard does not define an unambiguous vertical orientation of pixel data stored in image arrays. In practice, both of the possible vertical orientations are encountered in FITS files:

Case 1: coordinate origin = lower left corner of the image, hence vertical coordinates grow from bottom to top, **'BOTTOM-UP'**,

Case 2: coordinate origin = upper left corner of the image, hence vertical coordinates grow from top to bottom, **'TOP-DOWN'**.

In PixInsight, the vertical orientation in FITS files is set in section 'Global options', parameter 'FITS orientation' of FITS Format Preferences (accessible from Format Explorer, double click on 'FITS', parameter 'Coordinate origin'), and in the global option 'FITS orientation' of the WeightedBatch Preprocessing (WBPP) script (see chapter D). The value is used for reading and writing FITS files, the default value in FITS Format Preferences being 'Upper left corner (top-down)'. WBPP will use the global setting in FITS Format Preferences if option 'Global Pref' is selected.

It is crucial that one and the same setting for the vertical orientation in FITS files is used for the generation of all master calibration files as well as for light frame calibration, otherwise the calibration result will be wrong. This applies to both monochrome and color cameras and has to be considered generally when master calibration files are intended to be reused.

The correct value for the vertical orientation in a FITS file can be determined by plate solving if the type of telescope is known **[n4]**. If the selected value does not match the actual vertical orientation in an imported FITS file, the row order in the image array will be misinterpreted and, as we have seen in section A1.6, this will effect that the Bayer pattern of CFA data is altered. So the correct selection of the vertical orientation in FITS files is a prerequisite for automatic detection of the correct CFA mosaic pattern.

In order to solve the practical issues that arise from the above described orientation ambiguity in FITS files, the nonstandard FITS keyword `ROWORDER` was proposed **[27]**. This keyword can assume the values 'BOTTOM-UP' or 'TOP-DOWN'. Nowadays this keyword is generated by most image acquisition applications.

PixInsight supports the `ROWORDER` keyword. Opening of FITS files: if option 'Use ROWORDER keywords' is enabled in FITS Format Preferences AND the keyword `ROWORDER` is detected, its value will be used instead of the value of parameter 'Coordinate origin' in FITS Format Preferences, and in WBPP instead of the value of parameter 'FITS orientation'.

The FITS header does not necessarily contain the Bayer pattern for OSC cameras. Most image acquisition applications write the nonstandard FITS keywords `BAYERPAT`, `XBAYROFF` and `YBAYROFF` which are supported by PixInsight as well. If either the FITS keyword `BAYERPAT` is not written to the FITS header or the conventions concerning Bayer offsets are not met by the image acquisition software, the correct Bayer pattern will have to be explicitely specified when executing the ImageCalibration and the Debayer process, or when using the WBPP script. Usually the manufacturer of the camera specifies the correct Bayer pattern. If it is unknown, the correct value can be determined by capturing and analyzing a daylight image **[n5]**.

In PixInsight, FITS format has been deprecated when XISF was introduced as the native file format. In PixInsight v1.8.9-2, the FITS Format Module was updated. FITS files now are considered only as containers for image data and some essential metadata. PixInsight supports FITS format as input format for raw data, but output of files in FITS format is somewhat limited and not intended for production purposes. The changes are described in Ref. **[28.a]**, **[29]**.

A2.3.3 Extensible Image Serialization Format (XISF)

For output, PixInsight uses its native file format, Extensible Image Serialization Format (XISF) **[30]**.

Byte order is little-endian in XISF files. 16-bit and 32-bit integer values in image arrays are unsigned. In XISF files, the vertical orientation of pixel data in image arrays is always 'TOP-DOWN'.

XISF supports astronomical image metadata in a fully standardized and much more structured and rigorous way than FITS file format. The image acquisition applications NINA and Ekos support XISF as output format. Ekos runs with INDI/KStars, using the new libXISF C++ library **[31]**.

A3 Metadata

Besides image data, image files contain metadata that describe properties of the file, properties and settings of used equipment and software, information about environmental conditions, observation site and observed target. In astrophotography, certain metadata are essential for the correct processing of raw image data or for computing exact astrometric solutions. Their importance is often underestimated.

A3.1 Metadata in different file formats

File formats commonly used for astrophotography (proprietary raw file formats of regular digital cameras, FITS file format and PixInsight's native file format XISF) use different standards for storing metadata:

A3.1.1 Metadata in proprietary raw file formats

All proprietary raw file formats of regular digital cameras support the Exchangeable Image File Format (Exif). Only metadata which are relevant for general photography are usually supported. For correct processing of astro images, these metadata are required, but they are insufficient.

When working with data in proprietary raw file formats, ascertain that PixInsight's RAW Format Preferences (Format Explorer, double click on 'RAW') is set to 'Pure Raw'. Proprietary raw file formats contain some metadata that are needed for correctly processing astronomical images: focal length and aperture, timestamp, exposure time, ISO speed, image width and height and the CFA mosaic pattern of an OSC camera. When opening such a file in PixInsight, the raw image decoding software 'LibRaw' that is used by PixInsight's RAW format support module retrieves the metadata and makes them available for processing. Focal length and aperture are transmitted correctly only if a compatible lens was connected to a regular digital camera. When the camera was used with a telescope, the camera is unable to detect values of focal length and aperture and useless default values (e.g. a focal length of 50 mm) are stored in the metadata. PixInsight's RAW format support module therefore provides the options 'Force focal length' and 'Force aperture'. When enabled, either no metadata will be generated for focal length and aperture respectively (when the default value of 0 is left) or the inputted values will be used. If manual image calibration is intended to be used, these options should be applied. However, in case of using the WeightedBatchPreprocssing (WBPP) script, the focal length value should be input in WBPP instead, see section D2.3.4.

A3.1.2 Metadata in FITS files

FITS files contain metadata in the FITS header. Certain FITS keywords **[26]** are defined that store the information in its value. Compared to proprietary raw file formats of regular digital cameras, FITS file format is better suited due to its capability of storing metadata that are relevant for astrophotography (e.g. image type, coordinates of the observation site, name of the observed target, approximate coordinates of the image center, pixel size of the sensor, focus position, etc.).

Unfortunately the original FITS standard was incomplete and inadequate. In 2003, SBIG, a manufacturer of CCD cameras for astronomical observations, published SBFITSEXT **[32]**, a "Set of FITS Standard Extensions for Amateur Astronomical Processing Software Packages" that was implemented in their CCDOPS software. Software Bisque (CCDSoft) and Diffraction Limited (MaximDL) agreed to this Standard Extension and implemented it in their own software, so it became a "quasi-standard". In 2014, Diffraction Limited acquired SBIG. Over the years, different companies and software developers created several nonstandard FITS keywords in an uncoordinated manner. The current situation is complicated by the existence of many nonstandard FITS keywords which partially are redundant or conflicting. It is not surprising that not all of of these nonstandard keywords are supported by image acquisition and processing applications for astro images in equal measure. This situation often poses problems for the correct evaluation of metadata in processing software. In spite of poor standardization, FITS file format still is widely used as output file format in image acquisition applications and as input file format for image processing applications.

A3.1.3 Metadata in XISF files

PixInsight's native file format XISF **[30]** contains the metadata in XISF properties for registered images and following processing stages. For compatibility, it additionally contains relevant metadata in FITS keywords (see Ref. **[29]**) for all processing stages. XISF supports astronomical image metadata in a fully standardized and much more structured and rigorous way than FITS file format does.

A3.2 Metadata required for correct image calibration

In order to ensure a correct calibration result, light and calibration frames processed in an image calibration run must be compatible, see section B3. It happens frequently that image calibration has to be executed differently for certain groups of light frames, e.g. in case of different filters, different exposure times or different values of gain, offset or readout mode for broad- and narrowband filtered frames. In such cases, the raw frames must contain the following metadata:

- width,
- height,
- binning,
- image type,
- filter name,
- gain or ISO speed,
- offset,
- readout mode,
- exposure time (if dark frame optimization is not used),
- CFA mosaic pattern [for OSC cameras] and
- vertical orientation in FITS files [for OSC cameras].

It is preferable for manual and even more important for automated execution of preprocessing that the raw frames contain these metadata.

A3.3 Metadata required for exact computing of astrometric solutions

Other metadata are needed in later stages of image processing: several of PixInsight's tools e.g. PhotometricColorCalibration (PCC) **[33]**, **[34]** and SpectrophotometricColorCalibration (SPCC) **[35], [36]**, **[37.a]**, the scripts CatalogueStarGenerator, AnnotateImage, AlignByCoordinates **[38]**, **[39]** and MosaicByCoordinates **[40]**, **[39]** require the exact computation of astrometric solutions. In order that this can be achieved by the ImageSolver script **[41]**, **[28.b]**, **[42.a]**, **[43]**, light frames preferably should contain all metadata that are starred in **Table 1**:

- UTC observation start time,
- approximate RA coordinates of the image center,
- approximate DEC coordinates of the image center,
- focal length and
- pixel size.

RA and DEC values are used only as rough seed coordinates for plate solving. Focal length and pixel size are needed to compute the pixel scale. From these data and approximate UTC observation start time, PixInsight's ImageSolver then computes accurate International Celestial Reference System (ICRS) or Geocentric Celestial Reference System (GCRS) **[44.a]** coordinates. The CometAlignment tool and the computation of ephemerides of solar system bodies **[44.b]**, **[45]** require correct values of UTC observation start time and additionally geodetic observation site coordinates. If needed metadata are missing in the light frames, these data have to be input manually in the ImageSolverScript.

Editing FITS headers in case of missing or invalid metadata can be considered only as workaround for saving valuable data in particular cases. Many problems with preprocessing can be avoided by ensuring that metadata are correct and exhaustive. Therefore the right choice and correct configuration of the image acquisition application is essential. An appropriate image acquisition application must

- support saving the data in file format FITS and/or XISF,
- include the ability of plate solving in order that the light frames will contain sufficiently accurate coordinates of the image center and
- be capable of writing correct values for all needed metadata **[46]**, specified in valid data formats and units **[47]**.

If your current image acquisition application doesn't have these capabilities, you should look for better software and substitute it. Today these requirements are met even by software at no charge.

For plate solving, for color calibration and for annotating solar system bodies, the use of local databases in PixInsight is recommended/required. Pleiades Astrophoto provide appropriate database files for the ImageSolver script, for the PCC and SPCC processes and for the AnnotateImage script **[n6]**.

Table 1: Metadata required for calculating astrometric solutions

Required	FITS keyword	XISF property	Significance, data format and unit
*	DATE-BEG (DATE-OBS)	Observation:Time:Start	UTC observation start time, in ISO 8601 format: 'YYYY-MM-DDThh:mm:ss.sss'
	DATE-END	Observation:Time:End	UTC observation end time, in ISO 8601 format: 'YYYY-MM-DDThh:mm:ss.sss'
	OBSGEO-L (LONG-OBS, SITELONG)	Observation:Location:Longitude	Longitude of the observation site, OBSGEO-L, LONGOBS: in deg, SITELONG string format: 'DD MM SS.SSS'
	OBSGEO-B (LAT-OBS, SITELAT)	Observation:Location:Latitude	Latitude of the observation site, OBSGEO-B, LAT-OBS: in deg, SITELAT string format: 'DD MM SS.SSS'
	OBSGEO-H (ALT-OBS, SITEELEV)	Observation:Location:Elevation	Elevation of the observation site above sea level in meters
*	RA (OBJCTRA)	Observation:Center:RA	Approx. right ascension of image center, RA: FPN in deg, OBJCTRA: string in 'HH MM SS.SSS' format
*	DEC (OBJCTDEC)	Observation:Center:Dec	Approx. declination of image center, DEC: FPN in deg, OBJCTDEC: string in 'DD MM SS.SSS' format
	RADESYS	Observation:CelestialReferenceSystem	Celestial reference system: ICRS, GCRS or GAPP
	EQUINOX	Observation:Equinox	(deprecated) Equinox in years
	EXPTIME	Instrument:ExposureTime	Total exposure time in seconds, used only to synthesize observation end time when not available
*	FOCALLEN	Instrument:Telescope:FocalLength	Focal length of the telescope in millimeters (XISF property in meters!)
*	XPIXSZ (PIXSIZE)	Instrument:Sensor:XPixelSize	Pixel size in microns including binning

Bracketed keywords are nonstandard keywords. They are supported as input data by PixInsight for the sake of compatibility. PixInsight's astrometry engine gives precedence to standard keywords. This means e.g. if the keywords `RA` and `DEC` are present, `OBJCTRA` and `OBJCTDEC` are ignored.

B Calibration Frames, Master Calibration Files and Image Calibration

B1 Why Do We Perform Image Calibration?

Every now and then the need for correct image calibration is questioned, and shortcuts are proposed which are claimed to be on par with correct image calibration. However, generalizations can be deceptive. You should not blindly follow suggestions for shortcuts in image calibration unless you verified that thereby no degradation of image quality is involved when applying your typical approach for data acquisition using your equipment. In order to take the right measures, it is useful to consider what can be accomplished by correct image calibration.

B1.1 Temporal noise

Definition according to Ref. **[51]**, lecture 6,

Quote:

```
Temporal noise is the temporal variation in pixel output values under constant
illumination due to device noise, supply and substrate noise, and quantization
effects.
```

Temporal noise in the light frames cannot be reduced by image calibration; image calibration will even introduce a slight amount of additional temporal noise from the master calibration files into the calibrated subframes.

B1.2 Fixed pattern nonuniformity (FPN), dithering

Definition according to Ref. **[51]**, lecture 7,

Quote:

```
Fixed Pattern Noise (FPN), also called nonuniformity, is the spatial variation
in pixel output values under uniform illumination due to device and
interconnect parameter variations (mismatches) across the sensor.
```

Fixed Pattern Nonuniformity (FPN) is generated by imperfections of the sensor: the individual photosites of a sensor do not behave ideally. There are pixel-to-pixel variations in bias voltage, dark current and light sensitivity. Some CCD and CMOS image sensors also show a pronounced artifact called "amplifier glow" (see section B2.2). In daylight photography, the effect of FPN may be negligible, but it is crucial in low light photography, particularly in astrophotography. Whereas the visual impression of temporal noise can be reduced by extending the total exposure time, this does not apply to FPN. FPN has to be removed as far as possible, otherwise it will become visible once the integration is stretched decently. This will emerge even more clearly in deeper exposed integrations. FPN is reduced in image calibration, but not removed completely. Remaining patterns (= "correlated noise") will manifest themselves in the integration result either as "walking noise" or as "color mottling" **[52]**, depending on the presence or absence of field drift **[n7]**. In order to decrease these unwanted remaining patterns further, it is strongly recommended to apply a technique called *dithering* **[53]**, **[54.a]** during light frame acquisition. Dithering means: the pointing direction of the telescope is displaced by **random** values between exposures. In image registration, the stars are realigned, thereby misaligning the patterns. As a result, a large portion of the patterns that remained after image calibration can be averaged out or rejected in image integration. The needed dither magnitude for achieving best results depends on the scale of the sensor's patterns. Normally, a random shift of 5 to 8 pixels in the subframes is sufficient.

Sometimes it is claimed that dark frames are not needed when dithering was applied. This generalized statement is wrong: dithering is no replacement for capturing dark frames **[54.b]**, **[54.c]**.

Dithering between light frames and using a MasterDark in image calibration are complementary, so both must be performed in order to obtain the optimal image calibration result.

B1.3 Vignetting and shadowing effects

To make things worse, imperfections of the optics affect the light that hits the photosites: vignetting and shadowing effects caused by dust particles in the light path are common to every telescope.

B1.4 Motivation for performing complete image calibration

All above mentioned effects cause reproducible detractions of raw image data which can be removed to a large extent by correctly performed image calibration. Residual FPN plus residual vignetting/shadowing effects will set a limit beyond that an image cannot be stretched further. So the motivation to perform a complete image calibration is: to reduce FPN, vignetting and shadowing effects **as far as possible**. Since there are additive and multiplicative corrections involved, calibration steps have to be executed in the reverse order of the occurrence of the disruptive effects in image acquisition (also see Ref. **[55]**).

B2 Types of Calibration Frames

B2.1 Bias frames

Bias frames are needed when dark frame scaling (in PixInsight: *dark frame optimization*, see section B5.2) shall be applied. In the normal case, bias frames can also be used for the calibration of flat frames. There are, however, certain cases in which dark frames with exposure time matching the flat frames have to be used for the calibration of flat frames (see section B4.3.1).

The bias signal is composed of the constant offset and the fixed pattern generated in the readout process.

Bias frames are captured with the sensor in complete darkness, at the shortest exposure time that the camera can provide which is achieved by setting an exposure time of 0 s.

Please note: The bias frames of cameras with a Panasonic MN 34230 sensor (e.g. ZWO ASI1600, QHY163 or Atik Horizon) show a varying gradient across the frame and an inconsistent bias level when exposure times < 0.3 s are used **[56]**. With such a camera, it is advisable to use a minimum exposure time of 0.3 s. However, it is not valid to generalize this recommendation for all CMOS sensors: other CMOS sensors usually don't show this anomaly of an inconsistent bias level. The only other exception that I am aware of is the Sony IMX294 sensor.

B2.2 Dark frames

Dark frames are needed for the calibration of light frames and - in certain cases (see section B4.3.1) - for the calibration of flat frames. The term "target frame" is used for the frames that are to be calibrated.

Dark frames contain bias signal plus dark signal. The dark signal is composed of the integrated dark current, the fixed pattern generated thereby and if applicable "amplifier glow".

Dark frames are captured with the sensor in complete darkness, at an exposure time that matches the target frames. In the special case when dark frame optimization (see section B5.2) shall be applied for the calibration of the target frames, the exposure time of the dark frames shall be greater or equal the exposure time of the target frames.

Please note: Well-known examples of sensors that exhibit strong "amplifier glow" are: Sony IMX183, IMX294 and Panasonic MN34230. Some other CMOS and also certain CCD image sensors are affected similarly. Generally it is not recommended to use dark frame optimization with such sensors.

B2.3 Flat frames

Flat frames are needed for the correction of vignetting, of shadowing effects caused by dust particles and of the fixed pattern that is generated by different light sensitivity of individual photosites of a sensor. This step of the calibration process is called "flat field correction".

Flat frames contain bias signal, the information about vignetting/shadowing effects and the pixel-to-pixel variation of light sensitivity. Flat frames have to be calibrated before they are integrated to the MasterFlat. Normally, a MasterBias can be used for calibrating the flat frames. In certain cases, however, is it necessary to use a MasterDark with exposure time matching the flat frames for this purpose (see section B4.3.1).

Flat frames are captured through the telescope or lens, and it is essential that the field is as uniformly illuminated as possible. If a monochrome camera is used, flat frames have to be taken for each filter.

B3 Settings and Conditions for Image Acquisition of Calibration Frames

Light frames and calibration frames that shall be processed in one calibration run must be compatible regarding scaling of intensity values, image dimensions and vertical orientation of pixel data. In order to achieve this compatibility, it is essential to use the same quality settings, the same camera driver, the same image acquisition application and the same file format in image acquisition (see sections A2.1 to A2.3).

B3.1 Camera settings

In case of a regular digital camera, ISO speed, and in case of a dedicated astro camera, binning (see section A1.4), gain and offset (sections A1.5.1 and A1.5.2), and, if applicable, readout mode (section A1.5.3) must be consistent.

In the special case when *dark frame optimization* shall be applied (see section B5.2), the exposure time of the dark frames shall be greater or equal the exposure time of the target frames. When dark frame optimization is not to be applied, dark frames have to be captured at the same exposure time as the target frames.

B3.2 Temperature

For cameras without cooling system: try to take the dark frames at the same ambient temperature as the light frames. For cameras with cooling system: use the same setpoint for all frames. It is important to achieve a **constant** sensor temperature during a session. Therefore two basic conditions must be met:

1. The setpoint must be set so high that the cooling power never exceeds about 75 - 80 % and
2. the setpoint must be set some degrees below the lowest ambient temperature in the particular night.

The first condition must be respected in order not to overcharge the cooling system which would result in the sensor temperature rising above the setpoint. The second condition must be fulfilled in order to avoid that the sensor temperature will drop below the setpoint. Due to limited cooling power, at sites with large seasonal temperature variation, a higher setpoint can be required during summer time than in winter season.

In terms of noise, the desirable setpoint depends on dark current, readout noise and sky brightness **[57]**.

B3.3 Dark frames and bias frames: avoiding of light leaks

Generally, light leaks have to be carefully avoided. Light leaks arising during acquisition of dark frames can even lead to complete failure of image calibration. PixInsight's processes Statistics and HistogramTransformation are well-suited for spot-checking some frames. In order to detect a light leak in your equipment, it is advisable to take a few dark frames with constant exposure time in a bright place with changing external illumination. Compare the statistics and histograms of these dark frames: differences point to the existence of a light leak which has to be localized and remedied. The Blink tool is particularly helpful to analyze the statistics of a whole series of calibration frames. Load the series into the Blink tool, click on the bar graph icon ('Series analysis report'), check option 'Write text file', select the output folder and confirm with 'OK'. The statistics of the whole series is then saved to the text file "Statistics.txt" for further inspection. Instead of the Blink tool the BatchStatistics script can be used as well for this purpose.

Probable candidates for light leaks are all mechanically moving parts in the light path: focuser, camera rotator, filter slider or filter wheel. In Newtonians, light can get in from the primary mirror side through openings for air ventilation that shall facilitate rapid cooling down of the primary mirror. The viewfinder of a DSLR must be capped during capturing. Light leaks at the tilt plate of a camera have been reported **[58]**. Lens caps made of plastic are not necessarily nontransparent for IR light. If your lens cap is not made of metal, wrap additional aluminum foil around it and secure it with a rubber band.

It goes without saying that dark frames and bias frames that shall be used for the generation of master calibration files always shall be captured in a dark place.

B3.4 Flat frames: unchanged light path for image acquisition

For flat frame acquisition it is all-important to have an unaltered light path. If a monochrome camera is used, separate flat frames have to be captured for each filter. Best is not to change anything about the setup and take flat frames directly before or after light frames. That means, one must not change:
- camera orientation (rotating angle),
- aperture,
- focus position,
- flattener or reducer,
- position of filters and
- position of a retractable dew shield.

Often the question is asked whether small changes of focus (due to temperature change) are relevant in this regard. The answer is: no, they are not, but the focus position should be in the same range that was adjusted during light frame acquisition.

B3.5 Flat frames: very short exposure time can cause nonuniformly illuminated field

Flat frames have to be captured through the telescope or lens ensuring that the field is illuminated as uniformly as possible. Too short exposure time for flat frames can cause nonuniform illumination, e.g. when the light source flickers with low frequency (depending on the power source, the illuminant and the use of a dimmer) or when a mechanical shutter of a dedicated astro camera is used. So check with your equipment whether there is a lower limit for flat frame exposure time in terms of uniform illumination.

B3.6 Flat frames: determining appropriate exposure to light

Illumination level and exposure time for flat frames have to be controlled in order that the peak in the histogram is in the region of linear response of the sensor. At first determine the maximum intensity value (in DN) in the histogram of an overexposed frame (= *saturation intensity*). Take 0.5*(saturation intensity + bias level) as the approximate target mean value of a flat frame. The impact of overexposed flat frames on the resulting flat field correction is shown in Ref. **[59]**.

Warning: Most regular digital cameras have a display and can show a histogram of the saved images. This "back of camera" histogram is a support for daylight photography only, usually totally useless for astrophotography. It is not a histogram of the linear data, but shows a histogram of the data after an initial stretch. Don't use this histogram for determining the appropriate exposure time for flat frames, otherwise your flat frames will be severely underexposed **[60.a]**.

For regular digital cameras, aperture priority can be used to capture flat frames. This is especially useful when the illumination level changes rapidly, e.g. when sky flats are captured in twilight. Important: in order to get well exposed flat frames, you will have to adjust exposure compensation to about +2 1/2 to +3. The appropriate value might depend on the camera model and has to be determined once **[60.b]**.

It is important that the number of clipped pixels in the upper intensity range of flat frames is negligible. However, hot/warm pixels are not relevant in this respect. Therefore, the maximum intensity value of a flat frame that is indicated in the Statistics process is not suitable for this assessment. An appropriate way to judge whether a flat frame is clipped too much in the upper intensity range is to take a look at the histogram. Alternatively the following PixelMath expression can be used which counts the number of pixels `n` that have intensity values between `min` and `max` and outputs the result to the process console (disable option 'Generate output' in section 'Destination'):

```
RGB/K:    n += $T <= max/65535 && $T >= min/65535
Symbols: min = ..., max = ..., n = global(+)
```

The values of symbols `min` and `max` must be adjusted appropriately considering the saturation intensity.

For flat frames of OSC cameras there is another aspect: the weakest color channel should have sufficient signal in the lower range **[61]**.

B4 Generation of Master Calibration Files

It is advisable to prepare master calibration files and check them (by inspecting them visually and taking a look at image statistics and histograms) before light frame calibration is executed. In order to minimize additional noise that is introduced by image calibration, the number of calibration frames that is used to prepare a master calibration file matters. The noise reduction ratio of the additionally added noise is proportional to the square root of the number of the calibration frames.

B4.1 MasterBias (MB) and MasterDark (MD)

MB and MD shall be prepared according to Vicent Peris's tutorial **[62]**: simple integration of bias frames and dark frames respectively with the following parameters:

Section 'Image Integration':
Combination: 'Average',
Normalization: 'No normalization',
Weights: 'Don't care (all weights = 1)'
Option 'Subtract pedestals' must be disabled (please read the tooltip for 'Subtract pedestals').

Section 'Pixel Rejection (1)':
Rejection algorithm: 'Winsorized Sigma Clipping',
Normalization: 'No normalization'

With the settings in section 'Pixel Rejection (2)', a fine tuning is achievable in order that only unwanted signal (e.g. *cosmic ray artifacts* **[63]**) is rejected.

Disable option 'Signal and Noise Evaluation'.

When the process is completed, the integration result, the MB and MD respectively, must be saved to disk.

B4.2 Never pre-calibrate dark frames or a MasterDark

Formerly there were tutorials that suggested to calibrate, in a preceding step, either individual dark frames or integrated dark frames with the MasterBias, a procedure that I will denote as "pre-calibration" of the MD. Please don't follow this advice, it is both unnecessary and unfavorable.

Many modern regular digital cameras apply a mechanism (in the hardware) that subtracts the mean intensity of optical black pixels that are situated outside of the image region of the sensor (*optical black level subtraction*). Thus dark frames and bias frames have similar average intensities, almost independent of the exposure time of the dark frames. Subtraction of the MB from the MD (or from a dark subframe) therefore results in negative values for a high fraction of the pixels. If the subtraction of the MD is carried out in a preceding step, all resulting negative values will be truncated, because truncation to the [0,1] range is carried out as the very last step in the calibration task **[64]**. This truncation is necessary in order to preserve a coherent data set. <u>However, the truncated data are lost.</u>

Dedicated astro cameras should not (and normally do not) apply optical black level subtraction, but if (due to cooling and/or modern low-noise sensors) the dark current is very low, dark frames and bias frames again have similar average intensities. Then the impact might be the same as described above. This subject was dicussed already in 2014 in Ref. **[65]**.

I experienced this data loss with a calibrated MD of my Canon EOS 600D (= Rebel T3i), ZWO ASI294MC Pro and ASI071MC Pro. **Figure 2** shows screen sections of the histograms (here: of a Canon EOS 600D = Rebel T3i): on the left side the not pre-calibrated MD, on the right side the pre-calibrated MD in which about half of the peak is truncated (set to zero).

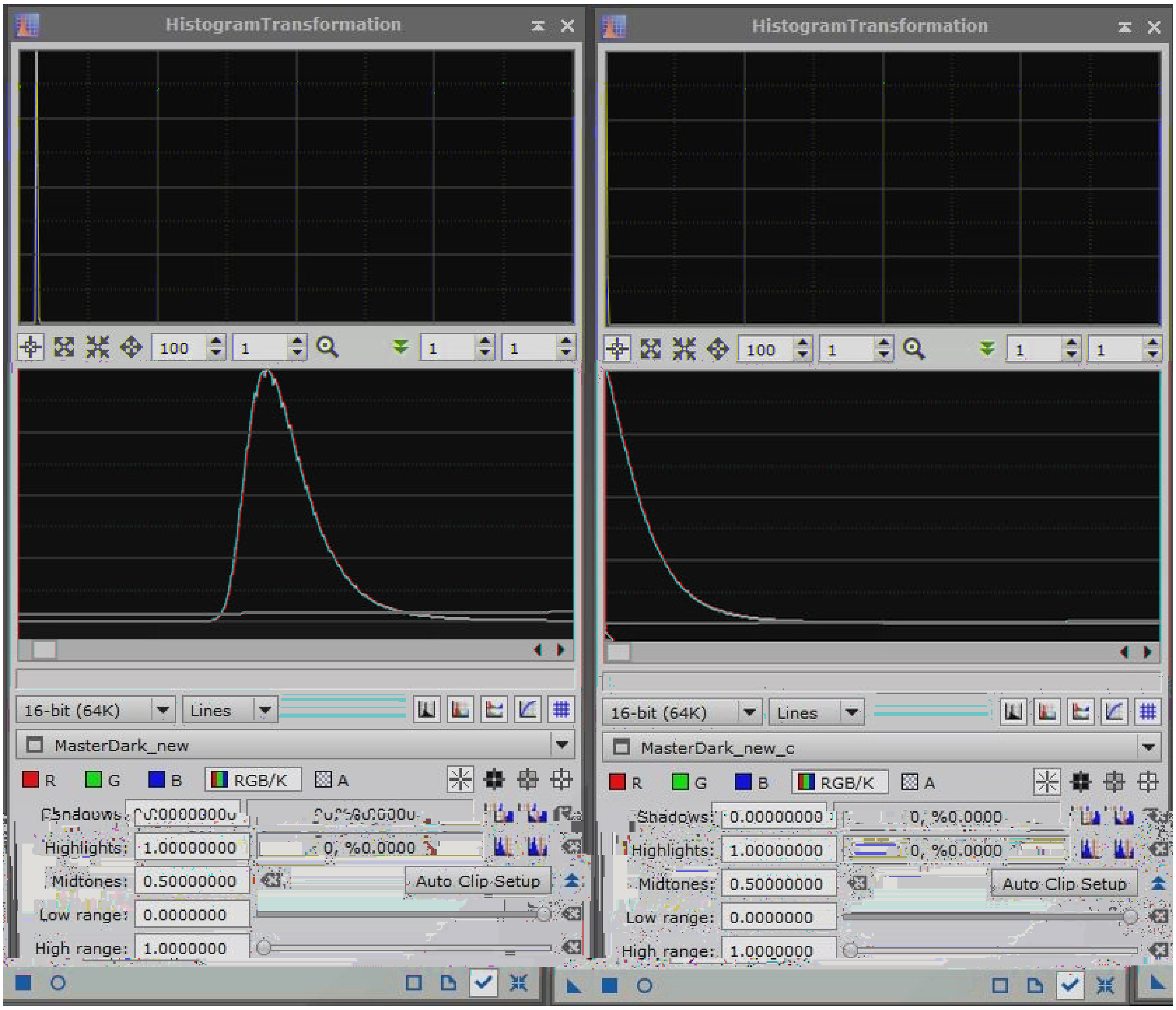

Figure 2: Histograms of MD, left side: not pre-calibrated, right side: pre-calibrated

If such a pre-calibrated, clipped MD is used for light frame calibration, only about half of the pixels in the light frame are calibrated correctly. For the rest of the pixels (in this example: for the other half), the correction for the fixed pattern generated by the integrated dark current is not achieved. One consequence of using such a pre-calibrated, clipped MD will be higher residual fixed pattern in calibrated lights. Another consequence is: due to clipping of negative values, the mean value of a pre-calibrated dark frame or MasterDark will be too large.

In section B5.2 we will see that only one situation exists in which the term (MasterDark - MasterBias) is needed: when dark frame scaling shall be applied. So what can be done to avoid this data loss? It's very easy: PixInsight's ImageCalibration can perform the subtraction during image calibration of the light frames, preserving negative values as intermediate results, thus avoiding this type of clipping completely.

The bottom line from the above therefore is:

NEVER pre-calibrate dark frames, neither individual dark frames nor integrated dark frames. If dark frame scaling shall be applied, use PixInsight's option of calibrating the MD during calibration of light frames instead.

MasterDarks prepared according to section B4.1 by simply integrating the dark frames contain the bias pedestal. We will use them as they are. Note that the compatibility with pre-calibrated MasterDarks has been removed in the WBPP script in v2.5.0.

B4.3 MasterFlat (MF)

The procedure of preparing the MF involves two steps: calibration of individual flat frames and integration of calibrated flat frames to the MF.

If a monochrome camera is used, separate MFs have to be generated for each filter.

B4.3.1 Calibration of flat frames

With sufficiently exposed flat frames, no clipping will arise, so the application of an output pedestal (see section B6.1) is never needed in the calibration of flat frames.

Normally, a MasterBias can be used for the calibration of flat frames. In certain cases, however, it is advisable to capture dark frames with matching exposure time for the calibration of flat frames:

Case 1: if the flat frames contain a non-negligible amount of dark signal,
case 2: if the camera has an inconsistent bias level when exposure times < 0.3 s are used (see section B2.1).

Case 1 may apply e.g. when flat frames for narrowband filters are captured, resulting in a long exposure time. The question whether it is advisable to use bias frames or matched dark frames for the calibration of flat frames was discussed in Ref. **[66.a]**. Jon Rista's contributions to this thread are particularly worth reading. The bottom line is: matched dark frames are only needed if there is non-trivial dark signal in the flat frames. A simple test **[n8]** reveals whether this is the case. If the test result is negative, the additional effort for capturing matched dark frames would be waste, and a MasterBias should be used for calibrating the flat frames.

In case 2 it is advisable to expose the flat frames for ≥ 0.3 s, and a MD generated from dark frames with exposure time matching the flat frames should be used.

Flat frames should be calibrated using either a MB or a MD with exposure time matching the flat frames. If dark frame optimization is not intended to be applied:
- Disable options 'Signal Evaluation' and 'Noise Evaluation'.
- Disable section 'Master Bias'.
- Enable section 'Master Dark', select the MB (or the MD with exposure time matching the flat frames), enable option 'Calibrate' **[n9]**, disable option 'Optimize'.
- Disable section 'Master Flat'.

If dark frame optimization shall be applied:
- Disable options 'Signal Evaluation' and 'Noise Evaluation'.
- Enable section 'Master Bias', select the MB, enable option 'Calibrate' **[n9]**.
- Enable section 'Master Dark', select the MD with exposure time matching the flat frames, enable both options 'Calibrate' and 'Optimize'.
- Disable section 'Master Flat'.

B4.3.2 Integration of calibrated flat frames

Subsequently, the calibrated flat frames are integrated with the following parameters (see Ref. **[62]**):

Section 'Image Integration':
Combination: 'Average',
Normalization: 'Multiplicative',
Weights: 'Don't care (all weights = 1)'

Section 'Pixel Rejection (1)':
Normalization: 'Equalize fluxes'

Which rejection algorithm in section 'Pixel Rejection (1)' is appropriate depends on the number of used frames, see the PixInsight Reference Documentation "ImageIntegration" **[67]** for recommendations.

With the settings in section 'Pixel Rejection (2)', a fine tuning is achievable in order that only outliers are rejected.

Disable option 'Signal and Noise Evaluation'.

When the process is completed, the integration result, the MF, must be saved to disk.

B5 Light Frame Calibration with PixInsight's ImageCalibration Process

Select the ImageCalibration process and load the light frames by 'Add Files'.

For deep-sky non-CFA raw frames, the options 'Signal Evaluation' and 'Noise Evaluation' should always be enabled in ImageCalibration. For CFA data, signal and noise evaluation should be performed by the Debayer process, and hence these options should be disabled in ImageCalibration.

B5.1 Overscan correction

Some cameras suffer from instable bias level. This manifests itself either by a drift of bias level during a capturing session (e.g. due to thermal effects) or by differing bias level values whenever the camera is powered up. PixInsight's overscan correction in the ImageCalibration process is intended for compensating such fluctuations of bias level.

B5.1.1 Including/excluding overscan data

Whether overscan correction is applicable at all depends on the camera. Prerequisites are

- the sensor of the used camera has a region with overscan pixels and
- there is also an option to include or exclude the corresponding data.

For dedicated astro cameras, this option (if present) can be found in the ASCOM camera driver or, when a
mage a9quisition ajplication. For cameras of bλand ⊠fi this option is

[illegible] when a …fie in

[illegible] when the …fie

Case 2: overscan correction is not intended to be used
Option 'Remove Overscan Area' in the camera driver must be enabled for dedicated astro cameras. This will result in files that do not contain the overscan data. For regular digital cameras, option 'No image crop' in PixInsight's 'RAW Format Preferences' has to be disabled. This will effect that overscan data (if present) are removed when a file in proprietary raw format is opened in PixInsight. The rest of section B5.1 is then moot and can be skipped.

B5.1.2 *Optical black* and *overscan* pixels
Some sensors contain regions outside the image region which are not intended to detect light and therefore don't contribute to the image directly. Two types of pixels can be found which have to be differentiated: *optical black* pixels (sometimes called "dark reference" pixels) contain photosites that are covered with opaque material, so their output will be composed of bias + dark signal. By contrast, *overscan* pixels (sometimes called "dummy" or "bias reference" pixels) do not contain photosites but only readout electronics, so their output will be composed of pure bias signal. Only the latter type is appropriate for overscan correction. Overscan pixels provide an *internal standard* of bias level that is recorded simultaneously with the image data.

B5.1.3 Checking the quality of overscan data
Before deciding whether overscan correction shall be used for a given camera, it is important to thoroughly check the quality of the data. Adjust the settings of case 1 in section B5.1.1; as a result dimensions of frames will increase slightly. Capture some light frames and all types of calibration frames. Hartmut Bornemann's script 2DPlot **[n10]** is most suitable for inspecting the data. Ref. **[69]** shows two examples of different sensors and describes criteria that are important:

- uniformity of counts in image and overscan regions of bias frames,
- absence of dark current in the overscan region of dark frames,
- absence of light leakage into the overscan region of flat frames.

For some sensors, it is necessary to determine an **actually useful** portion of the overscan region which contains consistent data.

If, however, this inspection shows that the quality of the data in the overscan region is dubious, please don't apply overscan correction in image calibration, use the settings of case 2 in section B5.1.1 and skip the rest of section 5.1.

B5.1.4 Configuration of section 'Overscan' in ImageCalibration
If one decides to apply overscan correction in image calibration, light frames and all calibration frames must include the overscan data, otherwise image geometry will be incompatible and a corresponding error message will appear in image calibration. Please use the settings of case 1 in section B5.1.1.

In PixInsight's ImageCalibration process, section 'Overscan' has to be enabled and configured correctly. The image region as well as source and target regions for up to 4 overscans can be defined. This is accomplished just as for previews: specify x and y coordinates of the top left pixel (numbering of x and y coordinates begins with '0'), plus width and height of each region. A foolproof method for generating correct data is: open a light or flat frame that contains the Overscan region and generate previews for the regions. If image region and target region are identical (this is usually the case), only two previews will be needed. The preview properties can be viewed and copied using 'Modify Previews...'. Transfer these data to the 'Overscan' section of the ImageCalibration process. The source region shall be restricted to the previously determined **actually useful** portion of the overscan region. Examples of Overscan configuration for camera models QHY600M and QHY268C are given in Ref. **[70]**.

In overscan correction, the median of the pixels in the source region is computed and subtracted from all pixels in the corresponding target region. Subsequently, the image is cropped to the dimensions of the image region. In case of an OSC camera, remember to define **even** x and y coordinates for the top left pixel of the image region, otherwise the bayer pattern will be altered in the cropping step (see section A1.6).

B5.2 Dark frame optimization

Once you decided to not pre-calibrate the MD, things become quite simple. In fact, for light frame calibration there are only two settings left that will lead to a correct subtraction of the bias level: one for calibration with and one for calibration without dark frame optimization.

B5.2.1 Light frame calibration with dark frame optimization enabled

Dark frame scaling means that one MD with long exposure time is used for the calibration of light frames which were captured at less or equal exposure time. Assuming that a camera with temperature control is used at constant temperature, the dark current is constant, and the dark signal (= MD - MB) increases linearly with time. In this case it is possible to scale the dark signal according to the ratio: exposure time(LightFrame) / exposure time(MD). Note, however, that in *dark frame optimization*, PixInsight uses neither temperature nor exposure time to evaluate the dark scaling factor k. The dark frame optimization algorithm in PixInsight is based on variance minimization using the whole area of the target frame, see Ref. **[71]**.

The general form of the calculation applied in the calibration of light frames is represented in equation {1}:

```
Cal1 = ((LightFrame - MB) - k * (MD - MB)) / MF * f         (WITH dark frame optimization) {1}

where k: dark scaling factor,
      f: master flat scaling factor (= mean of MF)
```

(By application of the master flat scaling factor f, the MF is normalized.)

Conclusion: The only problematic term (concerning negative values) in equation {1} is: (MD - MB). When the calibration of the MD is executed only during light frame calibration, the term (MD - MB) is an **intermediate result**, accordingly negative values will not be truncated. The calibrated MD will not be saved to disk.

For the calibration of light frames with dark frame optimization, use the settings in **Figure 3**, right side:
- Enable section 'Master Bias', select the MB, enable option 'Calibrate' **[n9]**.
- Enable section 'Master Dark', select the MD, enable both options 'Calibrate' and 'Optimize'.
- Enable section 'Master Flat', select the MF, disable option 'Calibrate'.

If the dark frame optimization algorithm calculates a value of k < 0.005, the warning

`No correlation between the master dark and target frames (channel 0).`

is outputted to the process console. This means that the dark frames don't match the light frames at all, and it will be necessary to capture new matching dark frames.

The dark frame optimization algorithm implicitely assumes that the dark scaling factor does not change for the whole range of intensity values and for the whole sensor area. For different cameras, these conditions are met in varying degree.

Using dark frame optimization for a camera without temperature control may greatly improve the calibration result. This is because temperature deviations between dark and light frame acquisition are unavoidable in this case. For a camera with temperature control, the benefit of dark frame optimization will be much lower, possibly even not detectable. The application of dark frame optimization for sensors that exhibit "amplifier glow" (see B2.2) is generally not recommended.

Bottom line: The camera model determines whether using dark frame optimization is favorable or not. Dark frame optimization should only be applied when it has been verified that a given camera actually is suitable for its application. Helpful hints for a corresponding checking procedure are given in section 3.4, "How to verify the optimization performance" of the Reference Documentation for the ImageCalibration process.

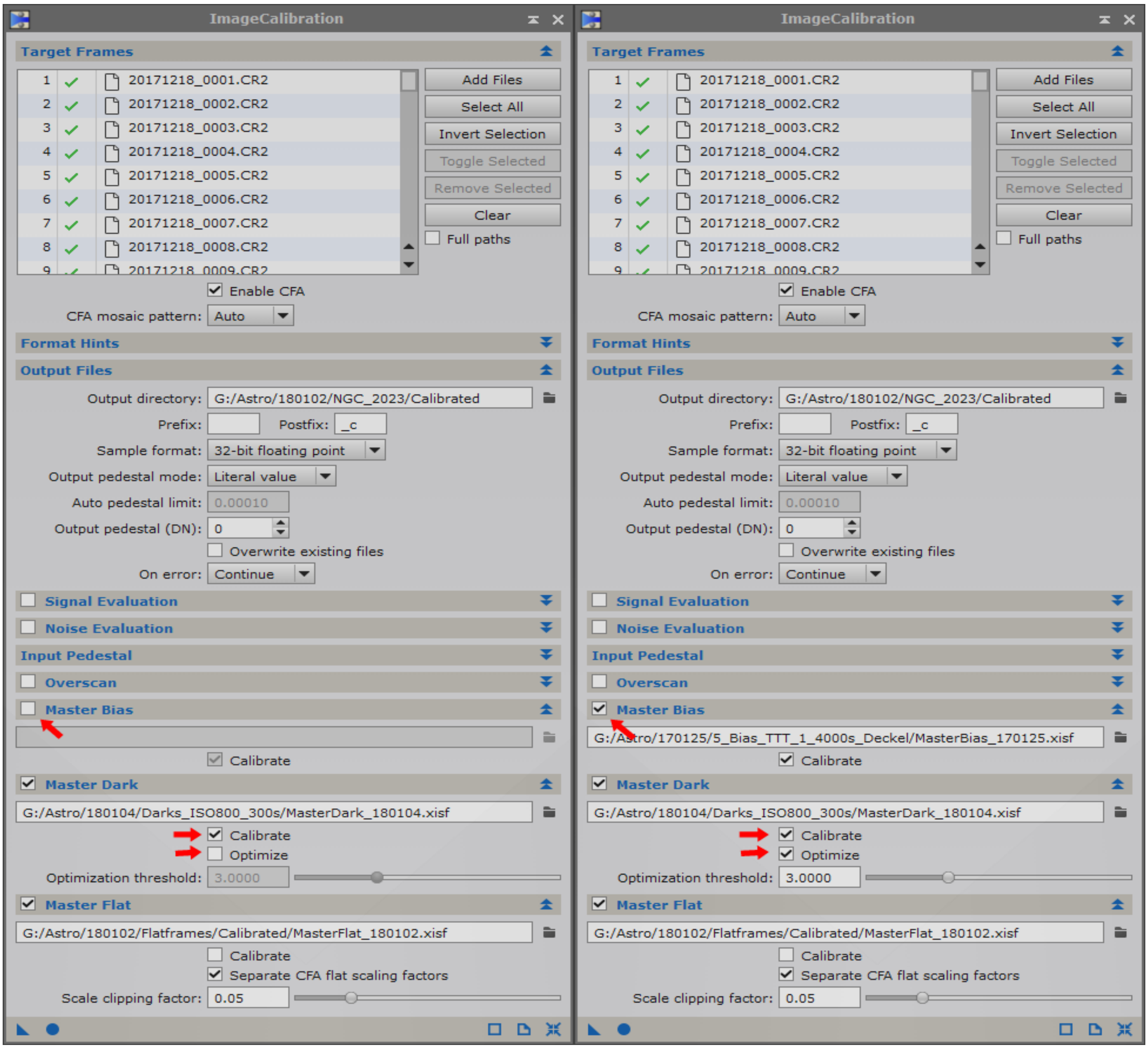

Figure 3: Settings in ImageCalibration, left side: no dark frame optimization, right side: with dark frame optimization **[n9]**

B5.2.2 Light frame calibration with dark frame optimization disabled
Without dark frame optimization, k equals 1.0, therefore **MB is canceled out from equation {1}**. Thus equation {1} is simplified to equation {2}:

```
Cal2 = (LightFrame - MD) / MF * f                    (NO dark frame optimization) {2}
```

Conclusion: The term that could be problematic concerning negative values, (MD - MB), does not appear in equation {2}. For a light frame calibration without dark frame optimization a MB is not needed, in fact a MB must not be applied at all.

For the calibration of light frames without dark frame optimization use the settings in **Figure 3**, left side:

- Disable section 'Master Bias'.
- Enable section 'Master Dark', select the MD, enable option 'Calibrate' **[n9]**, disable option 'Optimize'.
- Enable section 'Master Flat', select the MF, disable option 'Calibrate'.

B5.3 ImageCalibration's output to process console

After having adjusted the necessary settings for light frame calibration, the process can be executed. During or after the execution, observe the output to the process console. The output may look like the following example (extract):

```
* Loading master bias frame: ...
Loading image: w=5202 h=3464 n=1 Gray Float32
1 image property
3616 FITS keyword(s) extracted

* Loading master dark frame: ...
Loading image: w=5202 h=3464 n=1 Gray Float32
1 image property
CFA pattern: GBRG
595 FITS keyword(s) extracted

* Loading master flat frame: ...
Loading image: w=5202 h=3464 n=1 Gray Float32
1 image property
CFA pattern: GBRG
198 FITS keyword(s) extracted

* Applying bias correction: master dark frame.

* Computing dark frame optimization thresholds.
ch 0 : Td = 0.00065573 (135620 px = 3.010%)

* Computing master flat scaling factors.
ch 0 : f = 0.102262                    (1) <==

* Calibration of 1 target frames.
* Loading target calibration frame: ...

...

Reading RAW data: done
* Computing dark frame optimization factors.
Bracketing: done
Optimizing: done
* Performing image calibration.
Calibration range: [-2.212678e-02,3.047908e-01]
* Performing signal and noise evaluation.
Dark scaling factors:
ch 0 : k = 0.776                       (2) <==
PSF signal estimates:
ch 0 : TFlux = 1.2094e+03, TMeanFlux = 1.3503e+01, M* = 2.0243e-04, N* = 2.9608e-04,
2528 PSF fits
Noise estimates:
ch 0 : sigma_n = 2.8551e-04, 53.49% pixels (MRS)
Noise scaling factors:
ch 0 : sigma_low = 1.901665e-04, sigma_high = 7.674687e-04
* Writing output file: ...
```

(1): The master flat scaling factor `f` is the mean of the MF. In case of using the option 'Separate CFA flat scaling factors', a flat scaling factor is computed for each color channel.

(2): (Only when dark frame optimization is enabled) `k` is the dark scaling factor, optimized for lowest variance in the calibration result using the whole area of the target frame.

B5.4 Examples of approved settings for light frame calibration

B5.4.1 Canon EOS 600D = Rebel T3i (no cooling, no "amplifier glow")
Using this DSLR, the result of the light frame calibration was greatly improved by using dark frame optimization. The MB was used for flat frame calibration.

- Take flat frames, dark frames and bias frames,
- prepare the master calibration files according to section B4,
- calibrate the light frames using the settings shown in section B5.2, **Figure 3**, right side.

B5.4.2 ZWO ASI294MC Pro (cooling with temperature control, strong "amplifier glow")
Using this CMOS camera, I did not notice an improvement of the light frame calibration result by using dark frame optimization. The "amplifier glow" tended not to calibrate out completely with dark frame optimization enabled. So I decided not to use it. A MD with exposure time matching the flat frames was used for flat frame calibration.

- Take flat frames and dark frames with matching exposure time for light frames and for flat frames,
- prepare the master calibration files according to section B4,
- calibrate the light frames using the settings shown in section B5.2, **Figure 3**, left side.

B6 Inspection and Judgement of Calibration Results

B6.1 Checking for clipping in the low range, output pedestal

After having performed light frame calibration, some of the resulting calibrated light frames should be tested for clipping in the low range **[n1]**. If extensive low-range clipping is detected in calibrated frames, the calibration result is incorrect. Low-range clipping occurs when negative pixel values result in subtracting the MasterDark from a light frame.

Low range clipping in light frame calibration can be caused by

- using different quality settings, different camera drivers, different acquisition applications or different file formats for the acquisition of light and calibration frames (see sections A2.1 to A2.4)
- not matching dark frames (regarding temperature, ISO speed/gain, offset, readout mode or exposure time, see sections B3.1 and B3.2) or
- light leaks during dark frame acquisition (see section B3.3).

These possible causes for clipping must be checked and fixed in the first place.

If aforementioned causes are excluded, negative pixel values are possibly caused by a too low signal in the light frames (e.g. due to very short exposure time or the usage of narrowband filters and short exposure time): if after subtraction of the MD from the light frame, the noise of the background exceeds the median of the background, some pixels have negative values which will be truncated in the very last step of image calibration.

In this case, it is advisable to add a small positive value (an *output pedestal*) to all pixels. The objective is not, to avoid negative values completely: if the value of an output pedestal is chosen much too large, truncation will occur in the upper range and diminish dynamic range of the calibrated frame. The value of an output pedestal should be chosen that the fraction of negative pixel values is statistically irrelevant, a fraction of 0.01 % seems to be appropriate in most cases.

Adjustment of an output pedestal can be made in ImageCalibration, section 'Output Files'. Two possibilities exist: selecting the Output pedestal mode 'Literal value' enables the user to input for the parameter 'Output pedestal (DN)' a fixed value which will be used for all target frames. In Output pedestal mode 'Automatic', an individual output pedestal value will be computed and applied automatically for each frame. The fraction of clipped pixels can be adjusted by the parameter 'Auto pedestal limit'. When an output pedestal is applied, a FITS keyword `PEDESTAL` is created and the used value is stored.

B6.2 Checking flat field correction: over-/undercorrection

For a successfully achieved flat field correction, both a correct dark-calibration of the flat frames and of the light frames is essential. Otherwise under- or overcorrection of vignetting and shadowing effects caused by dust particles will be the consequence.

Examples (these cases are extremes, intended only for illustrating the tendency):
- If the calibration of the flat frames is omitted, the result of the flat field correction will be undercorrected (= residual vignetting in the calibrated light frames).
- If both the MasterBias and a not pre-calibrated MasterDark are subtracted from the light frames, the result of the flat field correction will be undercorrected.
- If the dark-calibration of the light frames is omitted, the result of the flat field correction will be overcorrected (= "negative vignetting" in the calibrated light frames).

B6.3 Checking flat field correction: dust spots appear embossed

Generally, differing light entrance angles between light and flat frames will produce an embossed appearance of dust spots. This can be effected by different causes:
- Dust motes have moved a little bit between capturing of light and flat frames.
- The camera was rotated a touch, or, if a motorized rotator is used, the position of the rotator doesn't match precisely.
- If a filter wheel is used, the position of the filter doesn't match precisely, either because the filter is not fixed correctly to the filter wheel inset or the rotation is not exact. With some filter wheels, a better precision is obtained when in the filter wheel driver, the movement is set to unidirectional.
- Stray light in the optical train, leading to off-axis light rays that illuminate the sensor. The results may be different with each filter, because this effect is wavelength dependent. In this case, sky flats might give better results. Ref. **[72]** is a good article about special issues with flat field correction that are caused by stray light.

B6.4 Color shift introduced by flat field correction

Calibrated light frames of an OSC camera must be debayered before they can be judged visually. A ScreenTransferFunction (STF) Auto stretch should be applied with option 'Link RGB channels' disabled. For an OSC camera it is normal that the flat field correction will give rise to a color shift if one flat field scaling factor is computed for the MasterFlat in the calibration of the light frames. The reason for this is that the color channels in the flat frames usually are exposed differently, but the master flat scaling factor is computed averaging all channels. Therefore the weakest channel(s) in the flat frames will be increased in the calibrated light frames, and the strongest color channel(s) will be attenuated. However, the resulting color shift is meaningless, because the correct color balance will be adjusted later in the workflow, preferably with SpectrophotometricColorCalibration (SPCC) **[35]**, **[36]**, **[37.a]**. The color shift is also meaningless in terms of SNR. Nevertheless, the ImageCalibration process provides the option 'Separate CFA flat scaling factors' in section 'MasterFlat' **[73]**. If this option is enabled (this is the default setting) and the CFA mosaic pattern is either successfully detected or explicitely set by the user, 3 CFA scaling factors (one for each color channel) are computed for the MasterFlat. In this way the color shift, that occurs with flat field correction when one master flat scaling factor (averaged over the color channels) is used, will be avoided.

C Post-Calibration Preprocessing Steps

The preprocessing steps that follow image calibration are listed in appropriate succession. Please note: not all of the listed processes are needed generally, it depends on the used camera.

C1 Linear Defect Correction (LDC) [Only if linear defects are detected]

CCDs tend to degrade over time, at least sometimes defects are probably caused by cosmic ray artifacts **[54.c]**. Frames acquired with a CCD camera often have some defect columns. If their number amounts to a significant fraction, they cannot be corrected by cosmetic correction. In this case, a reference image has to be created by integrating all subframes prior to registering. The entire and partial line defects are detected in the reference image by the script LinearDefectDetection (LDD). Subsequently, the linear patterns are corrected in the calibrated subframes by the script LinearPatternSubtraction (LPS) **[74]**. The application of LDD + LPS is called Linear Defect Correction (LDC).

Caution: Don't apply LDC without verification that it is advantageous. One should perform the workflow without LDC at first and carefully check the integration result as described in Vicent's tutorial **[74]**. If you don't detect linear artifacts in the integration result, you must not apply LDC. It depends on the sensor whether its usage will improve the integration result. Frames of cameras utilizing modern CMOS sensors usually do not generate linear defects. In such cases, application of LDC might even **produce** linear patterns in the integration result.

C2 Cosmetic Correction

Image calibration usually will leave some hot and warm pixels in the calibrated light frames. This is normal because these pixels strongly deviate from ideal behavior. Deviations caused by hot and warm pixels that remained after image calibration should be corrected with the CosmeticCorrection (CC) process. In case of an OSC camera, uncorrected intensity values of hot and warm pixels do particular damage, because they will be spread into neighboring pixels in the Debayering step. This is undesirable, because it would impede correct pixel rejection in image integration. For OSC cameras, the option 'CFA' has to be enabled in the CC process.

Frequently it was suggested to execute CC, section 'Use auto detect' enabled, with a 'Hot sigma' value of 3.0 (which is the value when the CC tool is reset). This recommendation is oversimplified and needs to be revisited:

When **images of an OSC camera** are intended to be corrected with CC, the result of applying CC must be judged <u>only after debayering</u> **[75]** in order to avoid that faint stars will be eliminated in the course of the correction. When CC is used with section 'Use auto detect', it is crucial to use high enough values for parameter 'Hot sigma'. The following information might serve as a starting point for own investigations: For my equipment (refractor, focal length of 530 mm, OSC camera, pixel size of 3.76 µm, resulting in a pixel scale of 1.5 "/px), a value of 13 proved to be appropriate. Another user (camera lens, focal lengths of 135 mm and 50 mm, OSC camera, pixel size of 3.76 µm, resulting in a pixel scale of 5.7 and 15.5 "/px) determined values of as large as 25 - 30 to be suitable! It is also reasonable to check up the number of corrected pixels (output to the process console and documented in the FITS header of cosmetically corrected frames) for different values of parameter 'Hot sigma'. The proper number of corrected pixels probably will not vary much for a given camera and gain setting.

C3 Debayer [Only for OSC Cameras]

In case of an OSC camera, the calibrated light frames now have to be demosaiced with the Debayer process. If the raw subframes are in FITS file format, the correct CFA mosaic pattern might have to be specified explicitely (see section A2.3.2). The recommended Debayering method for astronomical images is VNG because this algorithm produces fewest colored artifacts **[76]**.

Option 'Output mode' decides on the type of the outputted frames **[77]**: in the default Output mode

'Combined RGB color', a RGB image is generated. Output mode 'Separate RGB channels' will generate three monochrome images (one for each color channel), and Output mode 'RGB color + separate RGB channels' is a combination thereof. The use of option 'Separate RGB channels' allows the independent registration of color channels with distortion correction. This helps to fix misalignments caused by optical defects and differential atmospheric dispersion.

Signal and noise evaluation must be enabled (this is the default).

C4 Blink Tool, Subframe Weighting

When preprocessing is achieved by manually executing PixInsight's processes step by step, at this stage the frames should be checked visually with the Blink process in order to reject obviously bad frames (due to e.g. clouds, guiding error, poor focus, etc.). In some cases, inspection with Blink is essential. Subsequently, for the remaining frames the SubframeSelector (SFS) process can be applied in order to optimize SNR of the resulting integrated image. In SFS, the user can configure expressions for approval of subframes and for subframe weighting. The reference image for the StarAlignment process can be chosen (looking out for low FWHM and low eccentricity) and inspected visually as well. Previous to PixInsight v1.8.9, this was the commonly practiced approach.

The old metric 'SNR', however, always has been a problematic quality estimator: it cannot be used for subframe weighting for sets with differing strong gradients because it interprets strong gradients as signal, and it cannot reject very bright images where the target signal is entirely buried under the noise. This was the main reason that in PixInsight versions before v1.8.9, the user had to execute the SFS tool and give thought to set up appropriate approval and weighting expressions.

The problems with the metric SNR are overcome since version 1.8.9 of PixInsight, in which new subframe weighting metrics are used as quality estimators: the new robust metrics 'PSF Signal Weight', 'PSF SNR' and 'PSF Scale SNR' are based on a hybrid PSF/aperture photometry and multiscale analysis methodology. PSF Signal Weight is now the default weighting metric in the ImageIntegration tool. The new subframe weighting algorithms are explained in detail in a Reference Documentation **[78]**. In section "Examples", data sets obtained with different equipment and under different observation conditions are analyzed in SFS using the new metrics. It is worthwhile taking the time and studying this section thoroughly. Considering one's specific used equipment and observation conditions for choosing the most suitable subframe weighting metrics can improve the results. Summing it up: for preprocessing raw data, SFS is basically superseded by the new weighting methods, but it remains a valuable tool for analyzing data. The Blink tool still is essential for recognizing light frames containing flaws which are not detectable by the new metrics: light frames with certain guiding errors **[79]**, or halos around bright stars due to thin clouds or haze must be sorted out before proceeding with registration, otherwise the flaw might be visible in the master light. The same applies when WBPP (see chapter D) is used.

Please note: when using SFS, it is essential to load calibrated frames (monochrome camera) or calibrated and debayered frames (OSC camera) in order to generate accurate subframe weights. The calculation of PSF Signal Weight has undergone significant modifications since its first introduction in version 1.8.8-10, thus values obtained with versions 1.8.8-10 to -12 are not compatible with version 1.8.9 and following versions. Raw data therefore have to be calibrated and (if applicable) debayered with **current versions** of PixInsight's ImageCalibration and Debayer tools. Depending on the type of raw data, signal and noise evaluation must be carried out by different processes:

- for monochrome raw frames, signal and noise evaluation must be performed by ImageCalibration,
- for mosaiced CFA raw frames, signal and noise evaluation must be performed by the Debayer process.

Probably the most important consequence of the new subframe weighting metrics and the also new LocalNormalization tool (see section C6) is: full automation of the whole preprocessing pipeline is now facilitated (see chapter D).

C5 Registration

Approved images then are registered by the StarAlignment process **[80]** against the reference image. Distortion correction will be applied when one of the Registration models 'Thin Plate Splines' or 'x. Order Surface Splines' **[41]**, **[42.b]** is selected (please read the informative tooltip text for 'Registration model'!).

If the use of drizzle integration is intended, option 'Generate drizzle data' has to be enabled.

When option 'Separate RGB channels' was used in the Debayer process, all resultant monochrome images shall be registered to the same reference image (normally a green channel because of higher SNR than in the other channels). For very low SNR images, it might be necessary to increase the 'Noise reduction' parameter in section 'Star Detection' in order that the star detector is able to find reliable stars.

C6 Local Normalization

The LocalNormalization (LN) tool was completely redesigned and reimplemented in version 1.8.9 of PixInsight **[81]**. Contrary to the old LN tool, the new LN tool is a high-accuracy normalization process which can be fully automated and executed without supervision, so its use after image registration, before image integration is highly recommended.

Local normalization is not removing gradients completely, it tends to reproduce the gradients of the reference image. The application of local normalization can greatly facilitate the removal of gradients from the integration result though. This process requires a reference image, either the best single subframe or a frame that is generated from the best calibrated and registered subframes by image integration, possibly followed by application of Dynamic Background Extraction. The LN process outputs normalization data files (extension: xnml) that shall be used in image integration both for pixel rejection and normalization of the output, and (if applicable) in drizzle integration for normalization of the output.

Note that ImageIntegration and DrizzleIntegration need .xnml files that are generated by the new LN tool, older .xnml files are no longer compatible.

C7 Integration

Finally, the preprocessed light frames are integrated by the ImageIntegration process. Use 'Add Files' for adding registered subframes. The application of local normalization is recommended for both pixel rejection and output. If applicable, local normalization data files (extension: xnml) are added using 'Add L.Norm Files', and drizzle data files (extension: xdrz) using 'Add Drizzle Files'.

The following parameters are recommended:

Section 'Image Integration':
Combination: 'Average',
Normalization: 'LocalNormalization',
Weights: 'PSF signal weight'

In the present case of preprocessed light frames, option 'Subtract pedestals' should only be enabled if a global pixel rejection algorithm is applied (please read the tooltip for 'Subtract pedestals').

Section 'Pixel Rejection (1)':
Normalization: 'LocalNormalization'

Which rejection algorithm in section 'Pixel Rejection (1)' is appropriate depends on the number of used frames, see the PixInsight Reference Documentation "ImageIntegration" **[67]** for recommendations.

With the settings in section 'Pixel Rejection (2)', a fine tuning is achievable in order that only unwanted signal is rejected (e.g. caused by cosmic ray artifacts **[63]**, aeroplanes or satellites). The judgement whether the chosen parameters are appropriate or whether they should be tweaked further is greatly facilitated by comparison of the integration result with the rejection map "rejection_high", see section "Rejection Maps" of Ref. **[67]**.

When option 'Separate RGB channels' was used in the Debayer process and all debayered monochrome images were registered to the same reference image (normally a green channel because of higher SNR than in other channels), the registered monochrome images shall be integrated separately for each channel. This generates three monochrome integration results which have to be recombined to a RGB image with the ChannelCombination process.

C8 Fast Integration

The new tool FastIntegration **[28.c]** was designed for processing a very large number (thousands) of light frames. It comprises the steps image registration and image integration with algorithms that are simplified and optimized for speed. The following compromises have been made: no distortion correction is used in registration, LocalNormalization is not applied, no rating and weighting is applied in the integration, pixel rejection is performed only on limited subsets called batches. Target frames for FastIntegration must be calibrated, cosmetically corrected and in case of data of an OSC camera debayered. FastIntegration requires at least 6 detectable stars. In WBPP, FastIntegration is available as an option for post-calibration groups.

C9 Drizzle Integration [Recommended]

The Drizzle method was developed for the linear reconstruction of monochrome images from undersampled, dithered data **[82]**. In PixInsight, the algorithm is implemented for monochrome images and for images in CFA format.

For undersampled images, an enhancement of resolution can be achieved (for images of both monochrome and OSC cameras) by applying drizzle integration.

For images acquired with an OSC camera, there is another advantage. As we saw in section A1.6, in CFA data for each pixel of the sensor only **one** color information exists. The missing color information in CFA data has to be reconstructed by "Debayering" or "Demosaicing". These interpolation algorithms introduce certain kinds of artifacts that may show up even in the integration result. For OSC cameras, Juan Conejero generally recommended to apply drizzle integration, because thereby interpolation artifacts are avoided completely **[83]**. This advantage can also be utilized when the data are not undersampled. In this case, a 'Scale' of 1 should be used and parameter 'Drop shrink' should be set to 1.0. Of course no enhancement of resolution will be achieved thereby. Also see the discussion on the usefulness of applying drizzle to not undersampled, monochrome images **[84]**.

For a successful application of drizzle integration, a uniform coverage of the drizzle array must be accomplished. The weight map "drizzle_weights" should be judged: it must be uniform **[85]**. Two requirements have to be met in image acquisition in order to achieve this aim:
- the frames must be well-dithered **[86]**,
- the number of frames must be sufficient.

When drizzle integration is intended to be used, the workflow after calibration of the light frames must be modified slightly:

In the steps registration (section C5) and integration (section C7), option 'Generate drizzle data' has to be checked. Before the ImageIntegration process is executed, Drizzle data files (extension: xdrz) have to be added using 'Add Drizzle Files', additionally to the registered files.

Subsequently the DrizzleIntegration process has to be performed. Use 'Add Files' for adding drizzle data files (extension: xdrz). If the CFASourcePath was changed, the new path can be specified in DrizzleIntegration, section 'Format hints', parameter 'Input directory' (see corresponding tooltip). DrizzleIntegration does not perform pixel rejection, so a normalization for pixel rejection is immaterial for this process. However, local normalization should be used for output when local normalization data files (extension xnml) are available. In this case, use 'Add L.Norm Files' for adding the xnml files. Option 'Enable local normalization' is enabled by default in DrizzleIntegration. In case of OSC cameras, option 'Enable CFA drizzle' has to be checked.

When option 'Separate RGB channels' was used in the Debayer process and all debayered monochrome images were registered to the same reference image, drizzle integration shall be performed separately for each channel **[77]**. This generates three monochrome drizzle integration results which have to be recombined to a RGB image with the ChannelCombination process.

C10 Cropping

The result of image integration or drizzle integration should be cropped in order to remove border areas with low signal/low SNR due to dithering or field drift. Appropriate cropping parameters can be determined in the following way:

Open the **low rejection map** of the integration result. Apply a boosted STF Auto Stretch, create a preview and modify the borders of the preview with the mouse in order to exclude the white edges. Then retrieve the parameters `x`, `y`, `w` and `h` from the Preview Properties (select the preview, PREVIEW/Modify Preview...) and set the following parameters to the Crop process (`ws` and `hs` are sensor width and sensor height, respectively):

```
left   = -x              right  = x + w - ws
top    = -y              bottom = y + h - hs
```

Apply the Crop process to the image integration or drizzle integration.

Thereby, preprocessing has been completed.

D Automation of Preprocessing: WeightedBatchPreprocessing (WBPP) Script

In previous chapters of this guide, PixInsight's processes needed for preprocessing were executed manually, step by step. For a beginner it is important to practice preprocessing in this way first in order to become acquainted with the involved processes. Knowing the entire data reduction procedure and understanding how it works at each stage is absolutely necessary if you want to control the procedure, and it is also a prerequisite for automating preprocessing. The universal rule is applicable for preprocessing: **Once you have mastered something manually, then you can automate it for convenience.**

D1 Development of PixInsight's Preprocessing Pipeline

Automating preprocessing comprises compiling and executing a sequence of processing elements in which the output of each element is the input of the next element. In software engineering, such a sequence is called "pipeline" **[87]**. The request of PixInsight users for a preprocessing pipeline can be backtracked to the year 2010 **[88]**. In 2011, a first trial, the script PreProcessPipeline, was released by sjbrown **[89]**. This script was not further developed though. In the same year, the new script CalibrateAlign was released by kwiechen **[90]**. In the aftermath it was further developed by the author and PixInsight staff. In 2012 it was renamed as BatchPreprocessing (BPP) script and included in the official PixInsight distribution. In 2019, its successor, the WeightedBatchPreprocessing (WBPP) script **[91]** - **[108]** was released by Roberto Sartori. This script additionally integrated subframe weighting, a component important for optimizing SNR of the resulting integrated images. Since 2020 WBPP is part of the standard PixInsight distribution. The objective of full automation of preprocessing was still not achievable with PixInsight in 2021, and Juan Conejero at that time advised against using integrated light frames generated by WBPP for production purposes **[109.a]**. Only after substantial progress related to subframe weighting (see section C4), image registration (distortion correction) and local normalization (see section C6) was achieved, the foundations were laid. Along the way, WBPP's development kept pace with these improvements in PixInsight. Also the computation of astrometric solutions was integrated. Since the release of PixInsight v1.8.9 (with WBPP v2.4.0), the preprocessing pipeline can be executed without need for interruption and supervision, and the developers consider integrated light frames generated by WBPP to be appropriate for production purposes **[97]**, posts #17 and #27. It is still advisable to use the Blink tool in order to sort out light frames with certain flaws (see section C4) before starting up WBPP.

Adam Block as well had a share in the further development of WBPP. He created a series of free videos that explain function and usage of the WBPP script extensively, see **[110]**.

In WBPP, the steps of the preprocessing pipeline are called *operations*. WBPP's preprocessing pipeline is composed of the following trackable operations **[111]**:

- Calibration,
- LDD + LPS,
- Cosmetic correction,
- Debayer,
- Measurements,
- Weights generation,
- Bad frames rejection,
- Weights writing,
- Reference frame selection,
- Plate solving,
- Registration,
- Local normalization reference frame selection,
- Local normalization reference frame [interactive],
- Local normalization,
- Image Integration,
- Drizzle integration,
- Autocrop and
- RGB channel recombination.

Before we get into WBPP's mode of operation, its user interface will be described:

D2 WBPP's User Interface: Elements and Structure

The structure of WBPP's user interface is divided into three distinct regions which comprise different functions, see **Figure 4**:
region (1): elements for general configuring,
region (2): buttons for general control, and
region (3): panel for monitoring and specific configuring.

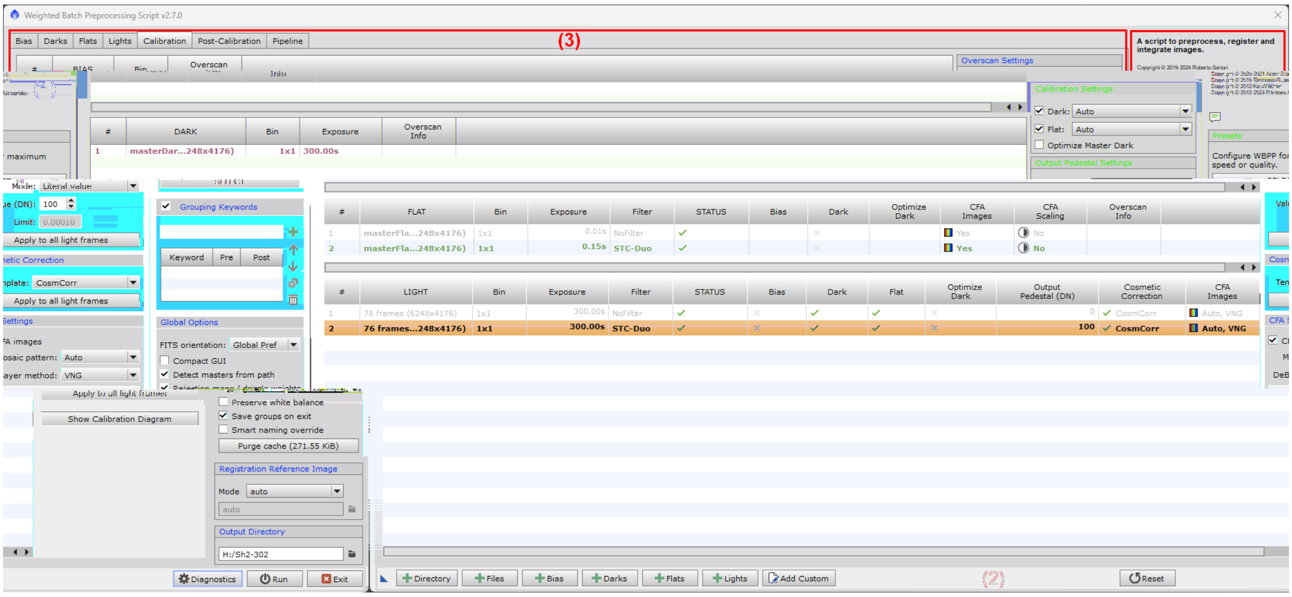

Figure 4: Structure of WBPP's user interface

D2.1 General configuring

The rightmost part of WBPP's main dialog (1) contains elements for general configuring. A document icon shows a quick reference guide in form of a tooltip text. In subjacent sections some general parameters and options can be configured: 'Presets', 'Grouping Keywords', 'Global Options', 'Registration Reference Image' and 'Output Directory'.

D2.1.1 Presets

Presets are intended to facilitate configuring WBPP. The user can choose between three presets that will differ regarding execution time and quality of the preprocessing result:

- 'Maximum quality with no compromises': Local Normalization is enabled with its default maximum number of stars used for scale evaluation, and the PSF type is *Auto*.
- 'Faster with sub-optimal quality results': Local Normalization is enabled with a reduced number of stars used for scale evaluation (500), and the PSF type is *Moffat 4*.
- 'Fastest method with lower quality results': Local Normalization is disabled.

D2.1.2 Grouping keywords

The user can create grouping keywords by typing the identifier into the input field and using the + icon. When several grouping keywords are defined their sequence can be changed by selecting a grouping keyword (it will be highlighted in orange background color) and applying the ↑ or ↓ icons. The gear icon allows to define whether a selected grouping keyword shall be taken into account in calibration ('Pre') and/or in post-calibration stage ('Post'). Press this icon several times in order to rotate through the possible combinations.

D2.1.3 Global options
- Parameter 'FITS orientation' (see section A2.3.2)
  The choices in the dropdown control are 'Global Pref' (this is the default) or explicitely ('top-down', 'bottom-up'). The tooltip text is important:
  Existing ROWORDER keywords will always take precedence over this setting.
- Option 'Compact GUI'
  This control is intended for low resolution screens in order that all elements of WBPP's GUI can be reached. Default: disabled.
- Option 'Detect masters from path'
  When option 'Smart naming override' is enabled AND option 'Detect master from path' is disabled, the path is ignored and only the filename is scanned. Default: enabled.
- Option 'Rejection maps / drizzle weights'
  When enabled, rejection maps and drizzle weights are embedded within generated master files. The autocrop operation needs the low-rejection map in order to work properly. When autocrop is enabled, the low-rejection map will be present in the master light files even when option 'Rejection maps / drizzle weights' is disabled. Default: enabled.
- Option 'Preserve white balance'
  When enabled, loading CFA images will preserve white balance if provided by the file format. Default: disabled.
- Option 'Save groups on exit'
  When enabled, frame groups will be saved before closing the dialog. On next launch of WBPP they will be reloaded. Default: enabled.
- Option 'Smart naming override'
  When enabled, any keyword (syntax: "KEYWORD_value") found in path or filename of the added files will override corresponding metadata stored in the FITS header or XISF properties. Default: disabled.
- Button 'Purge cache'
  When pressed, WBPP's cache is deleted.

D2.1.4 Registration reference image
- Parameter 'Mode'
  Options 'auto' and 'manual' are available. If option 'manual' is selected, the registration reference image has to be selected. If a post-calibration grouping keyword was created by the user, an additional option, 'auto by <keyword>' is offered. If option 'auto' is selected AND a post-calibration grouping keyword was created, the 'Diagnostic Messages' dialog will issue a warning message that advises to consider selecting mode 'auto by <keyword>, otherwise all frames would be aligned on the same reference image. The user should think about which option is intended to be applied, see e.g. Ref. **[94]**, section "New Reference Frame Mode" for an example when 'auto by <keyword>' is appropriate.

D2.1.5 Output directory
An output directory has to be selected before executing WBPP's preprocessing pipeline, otherwise an error message will be issued in the 'Diagnostic Messages' dialog or when the attempt is made to execute the pipeline.

D2.2 General control

At the bottom of WBPP's main dialog (2), the blue triangle icon (New Instance), the buttons for adding files ('+Directory', '+Files', '+Bias', '+Darks', '+Flats', '+Lights' and 'Add Custom'), and the buttons 'Reset', 'Diagnostics', 'Run' and 'Exit' are arranged:
- New Instance

Like most processes and many scripts in PixInsight, WBPP has a blue triangle icon (New Instance).

- +Directory button

The image type is evaluated for each file that is found in a recursive search in the selected root directory and all subdirectories. The files are added to the input file list of the corresponding image-type panel.

- +Files button

The image type is evaluated for each selected file. The files are added to the input file list of the corresponding image-type panel.

- +Bias button

Selected files are forced to be added to the input file list of the Bias panel.

- +Darks button

Selected files are forced to be added to the input file list of the Darks panel.

- +Flats button

Selected files are forced to be added to the input file list of the Flats panel.

- +Lights button

Selected files are forced to be added to the input file list of the Lights panel.

- Add Custom button

The user can input image type, filter name, binning and exposure time. Input data will take preference over metadata in FITS header or XISF properties. The files are added to the input file list of the corresponding image-type panel.

- Reset button

WBPP can be reset. The following options are available:
'Reset all parameters' to *factory values* or
'Reset all parameters' to *settings of the last session*.
Independently, option 'Clear all file lists' can be selected.

- Diagnostics button

When pressed, input data are checked for inconsistencies. There are three message levels: notes, warnings and errors. Additionally, estimated disk space required for each operation and total disk space required for completing all operations are displayed.

- Run button

When pressed, the 'Diagnostic Messages' dialog is displayed. If this dialog is closed, WBPP will return to its main dialog, allowing the user to change settings. If the 'Diagnostic Messages' dialog is acknowledged with the 'OK' button, the preprocessing pipeline will be executed.

- Exit button

When pressed, WBPP will be quit.

D2.3 Monitoring and specific configuring

At the top of WBPP's main dialog, the image-type tabs ('Bias', 'Darks', 'Flats' and 'Lights'), and the tabs 'Calibration', 'Post-Calibration' and 'Pipeline' are arranged. Whereas elements in region (1) and buttons in region (2) of **Figure 4** are invariable, the appearance of the panel in region (3) is variable, it depends on which tab is active. When an image-type tab is active, the list of input files is shown in the left half of the panel: either calibration subframes, master calibration files (the latter marked with a blue star) or light subframes. Input files are grouped, the grouping criteria depend on the image type. In the right half of the panel at the top, buttons 'Clear', 'Remove Selected' and 'Invert Selection' support removing input files. Below these buttons, different parameters and configurable sections are displayed, depending on the active tab:

D2.3.1 Bias panel
The input file list of the Bias panel is grouped according to image dimensions (width x height), binning and (if generated) calibration grouping keywords ('Pre').

The right half contains:
- Section 'Overscan' (see section B5.1)
  Section 'Overscan' can be enabled or disabled. When enabled, pressing button '→Overscan parameters...' will show parameter group 'Overscan'.
- Parameter group 'Image Integration' for bias frames (see section B4.1)

D2.3.2 Darks panel
The input file list of the Darks panel is grouped according to image dimensions (width x height), binning, exposure time and (if generated) calibration grouping keywords ('Pre').

The right half contains:
- Parameter 'Optimization threshold' (for dark frame optimization, see tooltip text)
- Parameter 'Exposure tolerance'
  Dark frames with exposure times differing by less than this value (in seconds) will be grouped into the same master (see section B4.1).
- Parameter group 'Image Integration' for dark frames (see section B4.1)

D2.3.3 Flats panel
The input file list of the Flats panel is grouped according to image dimensions (width x height), binning, filter, exposure time and (if generated) calibration grouping keywords ('Pre').

The right half contains parameter group 'Image Integration' for flat frames (see section B4.3.2).

D2.3.4 Lights panel
The input file list of the Lights panel is grouped according to image dimensions (width x height), binning, filter, exposure time and (if generated) calibration grouping keywords ('Pre'). If available in the files, the metadata 'Observation Start Time', 'Right Ascension', 'Declination', 'Focal Length' and 'Pixel Size' will be displayed additionally for each light frame.

In the right half at the top, the additional button 'Hide Astrometry' is arranged. When this button is pushed, metadata 'Observation Start Time', 'Right Ascension', 'Declination', 'Focal Length' and 'Pixel Size' will be blanked out from the input file list.

Below the buttons, the following parameters and sections are arranged:
- Parameter 'Calibration exposure tolerance'
  Light frames with exposure time differing by less than this value (in seconds) will be grouped together during calibration operation.
- Section 'Linear Defects Correction' (see section C1)
- Section 'Subframe Weighting'
  When enabled, the subframe weighting method can be selected from the dropdown control. 'PSF Signal Weight', 'PSF SNR', 'PSF Scale SNR', 'SNR Estimate' and 'Weighting Formula' are available (see section C4 and tooltip text of the dropdown control). When 'Weighting Formular' is selected, button '→Weighting formular parameters...' is released. When this button is pressed, parameter group 'Weighting Formular Parameters' will be shown.
- Section 'Image Registration' (see section C5)
  When enabled, button '→Registration parameters...' is released. When this button is pressed, parameter group 'Image Registration' will be shown.
- Section 'Astrometric Solution' (see sections A3.1.1 and A3.3)
  The WBPP script will call ImageSolver when option 'Astrometric Solution' is enabled. If metadata needed for computing of astrometric solutions are missing in the light frames, these data have to be input

manually. When option 'Interactive in case of failure' is enabled, it will present at runtime the ImageSolver interface for manual tuning of solver parameters when initial parameters failed to generate an astrometric solution. In order to avoid an interruption of script execution due to missing data, these should be input before letting WBPP execute the preprocessing pipeline. When button '→Image Solver parameters...' is pressed, parameter group 'Image Solver default parameters' which includes an online object search dialog will be shown **[103]**.

- Section 'Local Normalization' (see section C6)
  When option 'Interactive mode' is enabled, the Local Normalization Selector graphical interface for inspection, evaluation and selection of the subset of frames used for generating the local normalization reference image will be used during runtime, see Ref. **[100]**, section "Interactive Local Normalization reference frame selection Guide". When button '→Normalization parameters...' is pressed, parameter group 'Local Normalization' will be shown.
- Section 'Image Integration' (see section C7)
  When option 'Autocrop' is enabled, each generated master light will be cropped automatically. The cropping region will be the largest rectangle fully included within each registered frame. The autocrop operation needs the low-rejection map in order to work properly. When autocrop is enabled, the low-rejection map will be present in the master light files even when option 'Rejection maps / drizzle weights' is disabled. When button '→Integration parameters...' is pressed, parameter group 'Image Integration' will be shown. Parameter P.rangeClipHigh will be set to `false` by WBPP, see Ref. **[109.b]**.

The remaining panels, 'Calibration', 'Post-Calibration' and 'Pipeline' look different from the image-type panels: On the right side, the buttons 'Clear', 'Remove Selected' and 'Invert Selection' are absent because they are not needed. The partitioning between left and right side is changed.

D2.3.5 Calibration panel
On the left side of the Calibration panel, all groups of input files in the vertically arranged sections BIAS, DARK, FLAT and LIGHT are represented. Each section shows the group ID for the respective image type, the number of frames per group, image dimensions (width x height) and binning. Additional information is given depending on the image type:

- in section BIAS:
  'Overscan Info' and calibration grouping keywords ('Pre')
- in section DARK:
  'Exposure', 'Overscan Info' and calibration grouping keywords ('Pre')
- in section FLAT:
  'Exposure', 'Filter', 'Status', 'Bias', 'Dark', 'Optimize Dark', 'CFA Images', 'CFA Scaling', 'Overscan Info' and calibration grouping keywords ('Pre')
- in section LIGHT:
  'Exposure', 'Filter', 'Status', 'Bias', 'Dark', 'Flat', 'Optimize Dark', 'Output Pedestal', 'Cosmetic Correction', 'CFA Images' and calibration grouping keywords ('Pre')

<u>When selecting a group in section FLAT</u> (it will be highlighted in orange background color), the right side of the Calibration panel changes and related information is populated:

- Section 'Calibration Settings'
  Calibration of flat frames with dark frames can be enabled or disabled using control 'Dark'. When this option is enabled, the assignment of calibration files to a group in section FLAT can be selected from the dropdown control, either automatically or manually (group ID, binning and exposure time are displayed). When control 'Dark' is disabled, bias frames (if available) will be used to calibrate flat frames (for details on the used master calibration files, see Ref. **[112]**). If in this case bias frames are missing, a warning is issued below section 'CFA Settings'. Applying dark frame optimization (see section B5.2) can be enabled or disabled using control 'Optimize Master Dark'.

- Section 'CFA Settings'
  When option 'CFA images' is enabled, WBPP will insert a Debayering operation prior to image registration in the preprocessing pipeline. Option 'Separate CFA flat scaling factors' (see section B6.4) can be enabled or disabled. When button 'Apply to all flat frames' is pressed, these settings are applied to all groups in section FLAT. If inconsistencies in the configuration are detected, corresponding warning messages will be displayed below section 'CFA Settings'.
- Button 'Show Calibration Diagram'
  When button 'Show Calibration Diagram' is pressed, the calibration diagram for the selected group in section FLAT is displayed.

<u>When selecting a group in section LIGHT</u> (it will be highlighted in orange background color), the right side of the Calibration panel changes and related information is populated:
- Section 'Calibration Settings'
  Calibration of light frames with dark frames can be enabled or disabled using control 'Dark'. When this option is enabled, the assignment of calibration files to a group in section LIGHT can be selected from the dropdown control, either automatically or manually (group ID, binning and exposure time are displayed). When control 'Dark' is disabled, bias frames (if available) will be used to calibrate light frames (for details on the used master calibration files, see Ref. **[112]**). If in this case bias frames are missing, a warning is issued below section 'CFA Settings'. Applying dark frame optimization (see section B5.2) can be enabled or disabled using control 'Optimize Master Dark'.
  Calibration of light frames with flat frames can be enabled or disabled using control 'Flat'. When this option is enabled, the assignment of calibration files to a group in section LIGHT can be selected from the dropdown control, either automatically or manually (group ID, binning and exposure time are displayed). When this option is disabled, a note will be issued in the 'Diagnostic Messages' dialog.
- Section 'Output Pedestal Settings' (see section B6.1)
  In dropdown control 'Mode', either 'Literal value' or 'Automatic' can be selected. In case of 'Literal value', input field 'Value (DN)', in case of 'Automatic', input field 'Limit' is enabled. When button 'Apply to all light frames' is pressed, these settings are applied to all groups in section LIGHT.
- Section 'Cosmetic Correction' (see section C2)
  CosmeticCorrection process icons can be selected per group in section LIGHT from dropdown control 'Template'. Attention, these process icons must be present before the WBPP script is called! When button 'Apply to all light frames' is pressed, this setting is applied to all groups in section LIGHT.
- Section 'CFA Settings' (see section C3)
  Control 'CFA images' can be enabled or disabled, 'Mosaic pattern' and 'DeBayer method' can be selected from dropdown controls. When button 'Apply to all light frames' is pressed, these settings are applied to all groups in section LIGHT. If inconsistencies in the configuration are detected, corresponding warning messages will be displayed below section 'CFA Settings'.
- Button 'Show Calibration Diagram'
  When button 'Show Calibration Diagram' is pressed, the calibration diagram for the selected group in section LIGHT is displayed.

D2.3.6 Post-Calibration panel

On the left side of the Post-Calibration panel, all post-calibration groups are represented. The number of frames per group, image dimensions (width x height), binning, 'Exposures' (if a post-calibration group contains different exposure times, they are enumerated in this field), 'Filter', 'Color Space', 'Integration Time', 'Drizzle' status, 'Fast Integration' status and 'Status' are shown. Post-calibration grouping keywords ('Post') are displayed as well.

On the right side of the Post-Calibration panel, parameter 'Exposure tolerance' is located. Light frames with exposure times differing by less than this value (in seconds) will be grouped into the same master. When a post-calibration group is selected, related information is populated:

- Section 'Channels Configuration' (see section C3)
  In dropdown control 'Debayer', the *Output Mode* ('Combined RGB', 'Separate RGB channels' or 'RGB color + separate RGB channels') can be selected. Channels that are not needed (e.g. when narrowband data is collected using OSC cameras) can be disabled using the 'Active' controls 'R', 'G' and 'B'. When control 'Recombine RGB' is enabled, WBPP will recombine the channels to a RGB image at the end of the pipeline execution. The latter option is only available when all separated channels are active.
- Section 'Drizzle Configuration' (see section C8)
  Drizzle can be enabled or disabled using control 'Enable'. The parameters 'Scale', 'Drop Shrink', 'Function' and 'Grid Size' can be adjusted. Pressing button 'Reset' will reset the drizzle parameters for the selected group. When button 'Apply to all groups' is pressed, the settings are applied to all groups of light frames.
- Section 'Fast Integration' (see section C9)
  FastIntegration can be enabled or disabled using control 'Enable'. When option 'Save images' is enabled, registered images will be saved.

D2.3.7 Pipeline panel

On the left side of the Pipeline panel, a running number, 'Operation', 'Group details' and 'Est. disk space' is shown. For some operations, data for 'Group details' and 'Est. disk space' are generated not before the operation is executed.

On the right side, the following sections are arranged:
- Section 'Active Steps'
  The operations in the post-calibration stage can be enabled or disabled.
- Section 'Event Script'
  An Event Script **[101]** , **[111]** can be used to retrieve information from WBPP during runtime via the `env` object. It can be enabled (in this case the script has to be selected) or disabled. Some details about the `env` object and its properties, `event, operationsCount, operationIndex, name, status, statusMessage` and - for some operations - `group` are given in Refs. **[111]** and **[108]**.
- Section 'Pipeline builder'
  A Pipeline Builder script **[108]** can be used to customize the WBPP pipeline, see the tooltip text of the file selector. It can be enabled (in this case the script has to be selected) or disabled. The pipeline builder script is a new feature developed to support the requirements of the MARS project **[113]**.

D3 WBPP's Mode of Operation

D3.1 Retrieval of metadata from added files, grouping keywords

Certain metadata are required for both manual preprocessing and usage of the WBPP script in order to ensure that compatible light and calibration frames are processed in groups, yielding correct image calibration results. WBPP retrieves the needed information in the following way:

For each opened file it reads the full list of key-value pairs (typically the contents of the FITS header) and stores this information in a temporary register. If manual forcing is not used for adding files and overruling by option 'Smart naming override' is disabled, this register is scanned for the keys listed in **Table 2**, and additionally for any user-defined **grouping keyword**, see Ref. **[114]** for details.

Table 2: Metadata that are always used by WBPP for preprocessing

FITS keyword	Significance
IMAGETYP	Image type
FILTER (INSFLNAM)	Filter name
XBINNING (BINNING, CCDBINX)	Binning
EXPTIME (EXPOSURE)	Exposure time in seconds
BAYERPAT	Bayer pattern
ROWORDER	Vertical orientation of pixel data in image arrays of FITS files

Bracketed keywords are unusual keywords that are supported as input data by PixInsight for the sake of compatibility.

WBPP will scan these keywords, handle different groups of frames separately, and propagate the FITS keywords to calibrated, (if applicable) debayered and registered frames. Grouping keywords are propagated to the filename of master calibration files, but not to filenames of master light files. Contrary to Ref. **[93]**, grouping keywords are not propagated to the FITS header of master files (dark, flat or light).

Examples:
When different values of gain, offset or readout mode shall be handled correctly in WBPP, the user can create the corresponding grouping keywords (GAIN, OFFSET, READOUTM) in order to keep apart frames captured with different settings.

When the proprietary raw format of a regular digital camera is used, it may be useful to create the grouping keyword ISOSPEED in order that calibration of frames captured with different ISO speed settings is performed correctly.

When generating a master calibration file, WBPP will introduce the word "master" into the value of FITS keyword IMAGETYP, e.g. "master dark". This allows the automatic detection when master calibration files generated by WBPP are reused.

Metadata required for calculating astrometric solutions are treated in section A3.3.

D3.2 Adding files, manual forcing

Adding files can be performed in different ways. The simplest way, applicable when all metadata are provided, is using buttons +Directory or +Files. Already when the user adds files, WBPP begins to compile the preprocessing pipeline. Whenever the configuration is changed, WBPP will adapt the pipeline accordingly. The current preprocessing pipeline can be checked in the Pipeline panel. Adding files by buttons +Bias, +Darks, +Flats or +Lights will force the corresponding image type. When button 'Add Custom' is used, the user can input image type, filter name, binning and exposure time. In these cases, the input data will take preference over metadata in FITS header or XISF properties.

D3.3 Overruling of metadata by "smart naming override"

When option 'Smart naming override' is enabled, any keyword found in path and filename of the added files using the syntax "KEYWORD_value" will override corresponding metadata stored in the FITS header or XISF properties. When option 'Smart naming override' is enabled AND option 'Detect master from path' is disabled, the path is ignored and only the filename is scanned. Attention: Once the file is loaded, the file metadata are frozen and will not change. This means: **If intended to be applied, option 'Smart naming override' must be enabled when the file is added, changing it afterwards has no effect**.

Keywords are case-insensitive, values are case-sensitive. Keyword values will be sanitized by WBPP, i.e. any character out of the set "`-():. a-zA-Z0-9`" will be replaced by "-". Filter names may contain characters "-" and " " see Refs. **[95]** and **[114]**. When creating the frame group folder, character "`:`" will be replaced by "-" because it is incompatible with the file system of certain operating systems, see Ref. **[98]**.

Provided that correct and exhaustive metadata are present in the raw data, there is usually no need to put metadata into paths or filenames. The 'Smart naming override' option should be used exclusively for special cases which otherwise cannot be managed.

D3.4 Grouping of files

In the image-type panels, WBPP will represent the files grouped according to the keywords in **Table 2** plus the generated grouping keywords. In the Calibration panel, the frame groups are sorted in sections according to image type. In the Post-Calibration panel, only light frame groups are displayed. When a grouping keyword is modified in section 'Grouping Keyword' in the general configuring region (1), the groups will be reorganized accordingly. The grouping can be controlled additionally with parameters 'Exposure tolerance' and 'Calibration exposure tolerance':

- Exposure Tolerance (Darks panel):
  Dark frames with exposure times differing by less than this value (in seconds) will be grouped into the same master.
- Calibration Exposure Tolerance (Lights panel):
  Light frames with exposure time differing by less than this value (in seconds) will be grouped together during calibration operations.
- Exposure Tolerance (Post-Calibration panel):
  Light frames with exposure times differing by less than this value (in seconds) will be grouped into the same master.

D3.5 Applying differentiated grouping in calibration and post-calibration stage

By configuring grouping keywords with the gear icon the user defines whether a grouping keyword shall be appplied for grouping in calibration ('Pre') and/or in post-calibration stage ('Post').

An example for differentiating the grouping used in calibration and post-calibration stage is given in Ref. **[94]**, section "Grouping Keywords Modes": the keyword NIGHT is set applicable only for calibration purposes ('Pre'). This will effect that flat field correction is performed with flat frames of each night, but post-calibration operations are executed for all sessions combined.

Different behavior can also be achieved in the registration operation: if a post-calibration grouping keyword was created by the user, an additional option 'auto by <keyword>' is selectable in parameter 'Mode' of section 'Registration Reference Image'. When option 'auto by <keyword>' is selected, a separate registration reference image will be selectable for each <keyword> group (see the tooltip text for option 'Mode' in section 'Registration Reference Image'). This option is useful for handling different panels of a mosaic appropriately, an example is given in Ref. **[94]**, section "New Reference Frame Mode": the grouping keyword PANEL is set applicable only for Post-calibration ('Post'). When option 'Mode' in section 'Registration Reference Image' is set to 'auto by PANEL', a registration reference image will be selectable for each panel group, and the post-calibration operations are performed separately per panel.

D3.6 Checking the configuration

Before executing the pipeline, its consistency should be checked by the user. There are several possibilities:

- Checking calibration diagrams
  Calibration panel, group in section FLAT selected → push button 'Show Calibration Diagram'
  Calibration panel, group in section LIGHT selected → push button 'Show Calibration Diagram'
- Checking the Pipeline panel
  The Pipeline panel lists all operations that will be executed with the current configuration.

- Checking WBPP's notes, warnings and error messages
  Calibration panel, group in section FLAT selected → warning message below section 'CFA Settings' in case of inconsistencies.
  Calibration panel, group in section LIGHT selected → warning message below section 'CFA Settings' in case of inconsistencies.

Button 'Diagnostics' should be pushed for displaying notes, warnings and errors. Also the user can check whether free disk space will be sufficient for completing all operations of the current pipeline. (The 'Diagnostic Messages' dialog is displayed as well when button 'Run' is pressed.)

D3.7 Executing the pipeline, execution monitor, process container script, ouput path structure

When the Run button is pressed, the 'Diagnostic Messages' dialog is displayed. If this dialog is closed, WBPP will return to its main dialog, allowing the user to readjust settings. If the 'Diagnostic Messages' dialog is acknowledged with the 'OK' button, the preprocessing pipeline will be executed.

During execution, the Execution Monitor gives a review about the progress of the procedure: the list of compiled operations, elapsed time for each completed operation, the currently running operation, the status (success, failed, running, cancelling), a note containing additional information and overall elapsed time. A 'Cancel' button for interruption of the procedure is available.

At the end of each execution, WBPP creates the process container script **[101]**, saved in the /logs/ directory, named with the execution timestamp and the string "_ProcessContainer.js". This script can be used to launch a process container that contains all processes executed by WBPP during the correspondent run. The script can be opened from the script editor or simply be dragged into the PixInsight window. Once loaded, you can run it with the Compile & Run button, and the process container will be created.

When finished, a <u>detailed</u> logfile named with the execution timestamp and file extension ".log" will be saved in the directory /logs/. This textfile is very helpful in case of problems in the course of pipeline execution.

WBPP's output path structure is described in Ref. **[94]**.

D3.8 Caching system

An integrated caching system **[101]** allows the re-execution of WBPP after tuning of some parameters without the need to execute the whole preprocessing pipeline again. The caching system will check which data are still valid after modification of parameters and re-use valid data.

D3.9 New instance

By dragging and releasing the blue triangle icon (New Instance) onto the desktop, a WBPP script icon is generated which can be saved and executed afterwards. The cache is also stored inside WBPP script icons. Thus the script icon configuration can be tuned further and executed, also taking advantage of the caching system.

E Appendix

E1 Types of Resources for PixInsight

Pleiades Astrophoto provide different resources that explain concepts, describe function and usage of processes, show workflows and demonstrate specific examples of processing with PixInsight: the 'help' command in the Process Console, Reference Documentations, tool tips, links in menu `RESOURCES`, Video Tutorial Series, Knowledge Capsules and the PixInsight Forum.

- The 'help' command in the Process Console
  A list of internal commands of the PixInsight core application and installed processes with command-line support are listed when the command 'help' is entered in the Process Console. Specific help on commands and installed processes is displayed when 'help <cmd_id>' is entered where <cmd_id> is the identifier of the command or installed process.

- PixInsight Reference Documentations
  In my view, Reference Documentations are PixInsight's most important resources. Reference Documentations describe function, parameters and usage of processes and scripts in text form. They can be displayed either by clicking on the icon 'Browse Documentation' (the sheet of paper icon at the bottom right of the process window) or by calling Process Explorer and choosing the desired process from the select list. Unfortunately Reference Documentations which are linked to the process/script are available for only a few processes. In some cases, somewhat outdated Reference Documentations (which nevertheless contain valuable information) are still available at **[115]**; the correspondent direct links are given in **Appendix E2**. When a Reference Documentation is missing completely, please study PixInsight's tooltip texts which are available for most of the parameters in all processes.

- Menu RESOURCES
  In the menu RESOURCES, several links refer to documentation:

```
RESOURCES > Learning > Online Tutorials
                     > Online Processing Examples
                     > Official PixInsight YouTube Channel
                     > WeDoArt Productions
                     > PixInsight Resources
                     > PixInsight Ambassadors
RESOURCES > Community > PixInsight Website
                      > PixInsight Forum
RESOURCES > Technical Documents > ...
RESOURCES > Development > ...
```

  Selecting such a link displays its contents in the embedded PixInsight Web Browser.

- PixInsight Video Tutorial Series **[116]**
  The website is also directly accessible from the menu `RESOURCES > Learning > Official PixInsight YouTube Channel`. The video tutorials explain general concepts, the user interface and the usage of tools in PixInsight. The videos are short and concise, each having a playing time between 4 and 15 min. Four series of videos are available: Introduction to PixInsight (37 videos), SPCC (5 videos), Workflows (17 videos) and GradientCorrection (7 videos). For the complete list of videos including the topics of each video and the corresponding current times see Ref. **[117]**.

- PixInsight Knowledge Capsules, **[118]**
  This is a new type of advanced learning resource. Knowledge Capsules are PixInsight projects that contain starting images, the used process icons and documentation. The reader can switch seamlessly between reading and executing the process icons without losing the thread, thanks to the Project Documentation Icon "Continue Reading". One is able to directly take a detailed look at what a process effectuates (e.g. view the histogram or the statistics). The pace of the lecture can be defined individually - a big advantage over videos. Currently, two Knowledge Capsules are available free of charge: "Dynamic

Range Management" and "Narrowband". The project data and a PDF file "Knowledge Capsule Start Guide" which explains concept and usage of Knowledge Capsules are downloadable from the PixInsight software distribution system **[49]**. Knowledge capsules are superior to texts and even more to videos when wider context is to be presented.

- PixInsight Forum **[119]**
  The PixInsight Forum is directly accessible from the menu `RESOURCES > Community > PixInsight Forum`. In the forum sections "Announcements" and "Release Information", the developers publish information about new PixInsight versions, technical descriptions and practical usage examples of new and improved tools. In other forum sections, experienced users will help questioners to solve issues. The forum also has a Search function, a fact that seems to be unknown to many forum members. Often a question is not put for the first time and has been answered before.

E2 Resources for Processes and Scripts that Are Mentioned in this Guide

The following list shows resources for processes and scripts that are mentioned in this guide. In case of ambiguity these resources should be consulted. The term "linked RefDoc" indicates a Reference Documentation that is linked to the correspondent process/script and to the Process Explorer, whereas "RefDoc **[xy]**" indicates a direct link to a Reference Documentation that is available only at PixInsight's Reference Documentation website **[115]**.

Processes:	
ImageCalibration	linked RefDoc
CosmeticCorrection	linked RefDoc
Debayer	linked RefDoc
Blink	Video 30 of "Introduction to PixInsight"
SubframeSelector	Video 30 of "Introduction to PixInsight", also RefDoc **[78]**
FastIntegration	linked RefDoc, also **[28.c]** + Videos 9 + 10 of "Workflows"
StarAlignment	RefDoc **[80]**, also **[42.b]** and Tutorial **[41]**
LocalNormalization	linked RefDoc, also **[81]**
ImageIntegration	RefDoc **[67]**
ScreenTransferFunction	linked RefDoc + Videos 6 to 8 of "Introduction to PixInsight"
HistogramTransformation	linked RefDoc
ChannelCombination	linked RefDoc
Crop	linked RefDoc
FastRotation	linked RefDoc
CometAlignment	linked RefDoc
PCC	Tutorial **[33]**, additionally **[34]**
SPCC	RefDoc **[35]**, also **[36]**, **[37.a]** + Video Tutorial Series "SPCC"
Scripts:	
BatchStatistics	linked RefDoc
ImageSolver	Tutorial **[41]**, also **[28.b]**, **[42.a]**, **[43]** + Video 31 of "Introduction to PixInsight"
AlignByCoordinates	RefDoc **[38]**, also **[39]**
MosaicByCoordinates	RefDoc **[40]**, also **[39]**
LDD	**[74]**
LPS	**[74]**
WBPP	**[91]**, **[114]**, **[110]** + Videos 28.1, 28.2 of "Introduction to PixInsight"

No resources are available for the processes Statistics, PixelMath, SplitCFA, MergeCFA, DrizzleIntegration and neither for the scripts BasicCCDParameters, CatalogueStarGenerator and AnnotateImage. The links given in the Reference Documentation website **[115]** for the SubframeSelector script and the ImageSolver script are not working.

E3 List of Abbreviations

ADC	Analog-to-Digital Converter
ADU	Analog-to-Digital Unit
A/D	Analog-to Digital
ASCOM	AStronomy Common Object Model
CC	CosmeticCorrection (process)
CCD	Charge-Coupled Device
CFA	Color Filter Array
CIS	CMOS Image Sensor
CMOS	Complementary Metal-Oxide-Semiconductor
DEC	Declination
DN	Digital Number
DSLM	Digital Single-Lens Mirrorless
DSLR	Digital Single-Lens Reflex
Exif	Exchangeable Image File Format
FITS	Fexible Image Transport System
FPN	Fixed Pattern Nonuniformity
FPN	Floating Point Number
FWHM	Full Width at Half Maximum
GCRS	Geocentric Celestial Reference System
HDU	Header and Data Unit
ICRS	International Celestial Reference System
INDI	Instrument Neutral Distributed Interface
IR	Infrared
LDC	Linear Defect Correction
LDD	LinearDefectDetection (script)
LN	LocalNormalization (process)
LPS	LinearPatternSubtraction (script)
LRGB	Luminance, Red, Green and Blue
MB	MasterBias
MD	MasterDark
MF	MasterFlat
NIR	Near Infrared
OE	Optical Efficiency
OSC	One Shot Color
PCC	PhotometricColorCalibration (process)
PSF	Point Spread Function
QE	Quantum Efficiency
RA	Rectascension
RGB	Red, Green and Blue
SDK	Software Development Kit
SNR	Signal-to-Noise Ratio
SPCC	SpectrophotometricColorCalibration (process)
STF	ScreenTransferFunction (process)
UTC	Coordinated Universal Time
WBPP	WeightedBatchPreprocessing (script)
XISF	Extensible Image Serialization Format

Endnotes

[n1] Checking for clipping in the low range
Clipping the intensity range of data always means data loss. In image acquisition and preprocessing this situation must be avoided absolutely. Clipping in the low range has to be detected and fixed. Adequate analysis tools that PixInsight provides for checking for clipping are HistogramTransformation and PixelMath processes:

HistogramTransformation:
Check the histogram (adjust horizontal zoom that the histogram region around intensity 0 can be inspected carefully, this might be the case at a horizontal zoom of about 50 – 800).

PixelMath expression (in the 'Destination' section disable option 'Generate output'):

```
RGB/K:      clipped_lo += !$T
Symbols:    clipped_lo = global(+)
```

This PixelMath expression counts the number of pixels `clipped_lo` that have intensity value 0. The value of the global variable `clipped_lo` is outputted to the process console.

[n2] ASCOM Platform, INDI and Indigo
ASCOM (an abbreviation for AStronomy Common Object Model) **[19]** is an open initiative to provide a standard interface to a range of astronomy equipment including mounts, focusers and imaging devices, originally applicable only in a Microsoft Windows environment. ASCOM defines a collection of required properties and methods that ASCOM compliant software can use to communicate with an ASCOM compliant device **[20]**. Since 2018 the process of extending ASCOM to interconnectivity and to other operating systems (Linux, Mac OS) is under way (ASCOM remote, ASCOM Alpaca **[21]**).

The ASCOM Platform underwent substantial change and extensions in the last years, so use of an up-to-date ASCOM Platform version and a matched ASCOM driver version is important. Example: the capability of changing the offset value in an application within an image sequence has been added not before ASCOM platform version 6.5. Of course, the used ASCOM camera driver version has to support this feature as well in order that it will work correctly.

Besides ASCOM, other standards for astronomy software development are INDI and Indigo **[22]**. A survey of these developments is beyond the scope of this guide, also see Ref. **[23]**.

[n3] Determining whether the camera driver scales intensity values
Open the FITS file in PixInsight and inspect the histogram in plot resolution '16-bit (64K)', graph style 'Lines' at high horizontal zoom (e.g. 800). If a smooth curve appears, no scaling was applied. If discrete lines are displayed, measure the distance (in DN) between adjacent lines. This value is the factor which was applied for the scaling of the intensity values.

[n4] Determining the correct vertical orientation in a FITS file
Suppose that the FITS header does not contain the FITS keyword `ROWORDER`, and the selected value of the vertical orientation in FITS files is set to the default value, 'top-down' (this is a guess). If the number of mirrors by which the light beam is reflected in the telescope on its way to the sensor is known, the correct vertical orientation can be determined by plate solving with the ImageSolver script:

Telescopes that generate a true sided image (even number of mirrors, e.g. refractors, SCTs, newtonians):
If the 'Rotation' line of the plate solving result in the Process Console contains the comment "(flipped)", the correct vertical orientation in that FITS file is bottom-up, otherwise it is top-down.

Telescopes that generate a mirror-inverted image (odd number of mirrors, e.g. Celestron RASA):
If the 'Rotation' line of the plate solving result in the Process Console contains the comment "(flipped)", the correct vertical orientation in that FITS file is top-down, otherwise it is bottom-up.

Astrometric solutions generated by PixInsight versions < 1.8.9-2 will display a wrong 'flipped' status and wrong rotation value when viewed in versions >= 1.8.9-2. In this case, the image must be solved again in PixInsight >= 1.8.9-2.

[n5] Determining the correct Bayer pattern of an OSC camera
Provided that the correct vertical orientation in FITS files is set, the correct CFA mosaic pattern of a FITS file can easily be determined. Capture a well exposed daylight image. Open the FITS file in PixInsight and debayer it, setting the CFA mosaic pattern to 'RGGB' (this is a guess). Take a look at the histogram:

If red and blue channels differ significantly, the correct CFA mosaic pattern is of type 'XGGY',
if red and blue channels are almost identical, the correct CFA mosaic pattern is of type 'GXYG'.

Now that the G channels are identified unambiguously, only two possibilities are left which differ by exchanged R and B channels. Debayer the FITS file with these two CFA mosaic patterns in question and compare the results. It is obvious which one is correct (e.g. blue sky should be blue, not red).

[n6] Databases for plate solving, for color calibration and for annotating solar system bodies
Valid astrometric solutions generated by the ImageSolver script are required for target images of the processes PhotometricColorCalibration (PCC) and SpectrophotometricColorCalibration (SPCC), and of the AnnotateImage script. For PCC and SPCC, it is recommended to enable distortion correction in ImageSolver (see section 4.3, "Database Search / Star Matching" of Ref. **[35]**). For the annotation of solar system bodies this is mandatory **[48]**.

It is recommended to use local databases for plate solving with the ImageSolver script and for color calibration with either PCC or SPCC. The database files are in XPSD (eXtensible Point Source Database) format, but they are different: the 'Gaia DR3' database contains astrometric data that is needed by ImageSolver. The 'APASS DR9' and 'APASS DR10' database contain spectroscopic data that is used by PCC. The 'Gaia DR3/SP' database contains spectroscopic data that is used by SPCC.

Ephemeris files that are needed for the identification and annotation of solar system bodies with the AnnotateImage script are in XEPH format.

The database files can be downloaded from Software Distribution **[49]**. They should be stored on a fast storage medium, but on no account in the PixInsight application folder - in this case the data would be deleted whenever a new PixInsight version is installed.

- Astrometric data for ImageSolver (XPSD format)

It is recommended to use a local 'Gaia DR3' database for the ImageSolver script. The complete database comprises 16 files of about 2.8 GiB each. For widefield images, the first 3 files (including stars of mag 18), for medium field the first 9 files (including stars of mag 20) are sufficient in most cases. After download, the Gaia process has to be configured once: click on the wrench icon of the Gaia process, set 'Data release' = 'Gaia DR3', select all 'Gaia DR3' files and confirm with OK (also see Video 31 of "Introduction to Pixinsight").

- Photometric data for PCC (XPSD format)

It is recommended to use local database files 'APASS DR9' (1.1 GiB) and 'APASS DR10' (2.4 GiB) for PCC. After download, the APASS process has to be configured once: click on the wrench icon of the APASS process, set 'Data release' = 'APASS DR9', select the 'APASS DR9' file, then set 'Data release' = 'APASS DR10', select the 'APASS DR10' file, and finally confirm with OK.

- Photometric data for SPCC (XPSD format)

SPCC requires the use of a local 'Gaia DR3/SP' database. There is a small (11.1 GiB in 4 files) and a complete data set (63.2 GiB in 20 files). Warning: Never mix XPSD files from the small and complete Gaia DR3/SP sets.

Doing so may lead to incorrect color calibration results due to duplicate database entries **[35]**. After download, the Gaia process has to be configured once: click on the wrench icon of the Gaia process, set 'Data release' = 'Gaia DR3/SP', select all 'Gaia DR3/SP' files and confirm with OK (also see section 3.1.1, "Configuring Gaia DR3/SP Database Files for SPCC" of Ref. **[35]**).

- Ephemeris files for the AnnotateImage script (XEPH format)

Currently 13 files of about 130 MiB each, covering the observation period from November 30, 2023 to May 23, 2025, are provided **[50]**. The database is useable for the specified observation period and must be updated when expired. If annotation of solar system bodies is intended, these files have to be downloaded and installed in the AnnotateImage script: download the XEPH files and store them in a special folder. Select the image to be annotated, run AnnotateImage, push the 'ADD Layer' button (green plus icon), select 'Custom XEPH files' and confirm with OK. Select the 'Custom XEPH Files' layer, choose 'Directory search' and select the folder with the XEPH files. Now the annotation can be configured, previewed and run.

[n7] Field drift
In guided imaging, field drift is the consequence of imperfect polar alignment and/or differential flexure. In unguided imaging, periodic error is another contribution. If no dithering was applied, field drift can be detected and measured by integrating raw subframes (in case of an OSC camera: debayered, but uncalibrated and unregistered subframes). Star trails will arise in the integration result. Their length correponds to the field drift over the duration of the capturing session.

[n8] Determining whether flat frames contain non-trivial dark signal
In Ref. **[66.b]**, Jon Rista describes a simple test how to verify whether a non-trivial dark signal is contained in the flat frames. Summary: Take 30 to 50 dark frames with exposure time matching the flat frames, integrate them to a MasterDark and subtract the MasterBias, adding a pedestal in order to avoid clipping. The test result depends on the used sensor and the conditions for flat frame acquisition. If no meaningful signal is present in this difference frame, the additional effort for capturing matched dark frames would be waste, and a MasterBias should be used for calibrating the flat frames.

[n9] Changed recommendation for setting option 'Calibrate' in ImageCalibration
Compared to previous versions of this guide (before January 2023), the recommended settings for the calibration of light frames have been changed: calibration of MB and MD shall be enabled **always**. The new settings shown in **Figure 3** will work correctly regardless of whether overscan correction is enabled or not.

Together with the removal of compatibility with pre-calibrated MasterDarks in WBPP (see section B4.2) this change allows a standardized workflow for light frame calibration in PixInsight.

[n10] Hartmut Bornemann's scripts
... can be downloaded from Herbert Walter's website, https://www.skypixels.at/ . You can either downlod individual scripts from https://www.skypixels.at/pixinsight_scripts.html or automatically obtain and update Hartmut's scripts by adding https://www.skypixels.at/HVB_Repository/ to the Update Repositories in PixInsight's menu feature `RESOURCES > Updates > Manage Repositories`.

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