Guide to Preprocessing of Raw Data with PixInsight

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(revised on January 01, 2023)
This text refers to PixInsight v1.8.9-1 and WBPP v2.5.6, the current versions at the time of writing.

Motivation for Writing this Text

Correctly performed image calibration is a prerequisite for getting the most out of raw data. Inconsistent input data or flawed settings in the ImageCalibration process probably will produce wrong results which normally cannot be corrected anymore in later stages of image processing. In many threads of the PixInsight forum I observed that newcomers often struggled with preprocessing of raw data. Therefore this guide originally (in December 2017) was written with the goal in mind to describe a usage of PixInsight's ImageCalibration process that would work generally, independent of the used camera.

Over the years, the text was developed further. Supplements concerned image calibration in a broader sense, e.g. camera settings, file formats, camera drivers, image acquisition applications, image acquisition of calibration frames, generation of master calibration files and inspection of the calibration result. Latest additions are related to post-calibration preprocessing steps which became more important due to recent further development of PixInsight in this field. So in March 2022 I decided to rename it as "Guide to Preprocessing of Raw Data with PixInsight".

The text is structured in following chapters:

1. Setup and Properties of Digital Cameras used for Astrophotography
2. Metadata, Quality Settings, File Formats, Camera Driver and Image Acquisition Software
3. Why Do We Perform Image Calibration?
4. Types of Calibration Frames
5. Settings and Conditions for Image Acquisition of Calibration Frames
6. Generation of Master Calibration Files
7. Light Frame Calibration with PixInsight's ImageCalibration Process
8. Inspection and Judgement of the Calibration Result
9. Post-Calibration Preprocessing Steps
10. Automation of Preprocessing: WeightedBatchPreprocessing (WBPP) Script

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.

References and endnotes are specified in square brackets and are compiled at the bottom of this document.

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/

1 Setup and Properties of Digital Cameras used for Astrophotography

1.1 General setup of sensors used in digital cameras

Sensors of digital cameras are structured as a 2D array of photosites. The photosites convert incident light to photocurrent which is integrated to electrical charge. After exposure, the generated electrical charge of each photosite is converted to voltage in the readout process. Each primary voltage has to be amplified before the analog-to-digital (A/D) conversion is performed. The amplification is controlled by the parameters gain (related to amplification factor) and offset (related to zero-point adjustment), see section 1.3. Finally, the amplified voltage is converted to a digital number by an analog-to-digital converter (ADC), generating a 2D array of integer pixel values.

1.2 CCD and CMOS sensors

Charge-Coupled Device (CCD) sensors and Complementary Metal-Oxide-Semiconductor (CMOS) sensors are commonly utilized for digital cameras. Both kinds of sensors are quantum detectors based on the semiconductor material silicon which is sensitive to light of wavelengths in the range of about 300 to 1000 nm (UV/VIS and NIR). The differences between these technologies are related to the readout process: in a CCD sensor, a vertical and horizontal transport of electrical charges is effected, then the electrical charges are output serially at one location on the sensor. Conversion to voltage, amplification and A/D conversion are performed outside the sensor, in the camera electronics. In a CMOS sensor, electrical charge to voltage conversion is performed on each individual photosite, and amplification and A/D conversion are performed on the sensor as well. These differences result in different properties of the raw data, and this has to be taken into account in image calibration. The bottom line is: the right approach for image calibration also depends critically on the used sensor and digital camera model.

1.3 Gain and offset

1.3.1 Conversion gain and parameter "gain"

Conversion gain (in e-/DN) is a metric which relates the number of electrons per pixel to the number of counts per pixel, also called Data Numbers (DN) or Analog-to-Digital Units (ADU):

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Conversion gain = number of electrons per pixels / number of counts per pixel
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For dedicated astro cameras utilizing a CCD sensor, conversion gain normally cannot be varied. Some image acquisition applications use the nonstandard FITS keyword (see section 2.1) EGAIN to record this value if the camera reveals it. In this case, the value of the FITS keyword EGAIN is determined by the camera manufacturer for a camera model, the value is not specific for the particular camera.

For dedicated astro cameras utilizing CMOS sensors, the conversion gain can be varied by setting a parameter *gain* in the camera driver or in the image acquisition software. Some image acquisition applications use the nonstandard FITS keyword GAIN to record 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 term "conversion gain" is used in the opposite sense of "gain": a gain value of 0 corresponds to the highest available conversion gain.

For regular digital cameras, ISO is the corresponding parameter that is used for varying conversion gain.

1.3.2 Parameter "offset" and resulting "bias shift"

Offset is the parameter which controls the zero-point adjustment of the analog signal. Regular digital cameras and dedicated astro cameras utilizing CCD sensors normally have a fixed offset value. For dedicated astro cameras utilizing CMOS sensors, the offset value can be varied by setting the value in the camera driver or in the image acquisition software. Some image acquisition applications use the nonstandard FITS keyword OFFSET (e.g. SGP, NINA, Indi) or BLKLEVEL (e.g. SharpCap) to record the actual value of this parameter in the FITS header if offset is variable.

Which offset value should be set if offset is variable? Too small values will cause clipping in the low range which has to be avoided necessarily, because this issue cannot be repaired after the event. On the other hand, offset values that are much too large will confine the dynamic range of subframes. The subject is complicated by the fact that at higher gain settings, a higher offset value will generally be needed as well. In my view, optimizing offset for each gain is not very useful though. Often default values that are preset in the camera driver are reasonable. One should, however, check dark frames (captured within the used range of gain and exposure time) for clipping in the low range [1]. If clipping is detected, the offset parameter has to be increased sufficiently. After suitable image quality is set in the camera, and suitable camera driver, image acquisition software and file format are chosen (see section 2.2 to 2.3), this check and correction has to be made once, because it is mandatory to capture light and all calibration frames of a project with the same offset setting.

Bias shift is the displacement of intensity values (in DN) that results in the FITS file. Dependent on the offset value which is set in the camera driver, a bias voltage is applied that will generate a bias shift of

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bias shift = offset * k * n
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The proportionality factor k is specific for the camera model, and n is the scaling factor (see [2]) which is used in the camera driver for scaling intensity data.

Example:
For the ASI294MC Pro, the proportionality factor k is 16 DN. The scaling factor n is 4, because the sensor has a 14-bit ADC, so the camera driver will scale the data from [0,16383] to [0,65535], i.e. by factor 4. With the default offset setting of 30, a bias shift of 30 * 16 DN * 4 = 1920 DN will result in the FITS file.

1.4 Monochrome and OSC sensors

It is important to differentiate between monochrome and One Shot Color (OSC) sensors. The photosites of a monochrome 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.

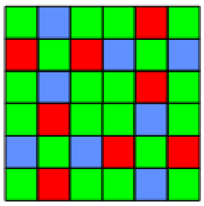
In OSC sensors, each individual photosite of the sensor is equipped with a color filter. Usually 3 different colors are used for the color filters. Each photosite is exposed only to the light transmitted through its color filter. The different colors are arranged in a periodic pattern on the sensor, called Color Filter Array (CFA) mosaic pattern, e.g. a Bayer pattern or Fujifilm's X-Trans mosaic pattern. Thus with an OSC camera, it is possible to gain data for 3 colors simultaneously, in one shot.

The smallest unit of bayered data consists of 2x2 pixels, 25 % of all pixels detect only red light, 25 % detect only blue light, and 50 % detect only green light (R/G/B = 1:2:1). The smallest unit of Fujifilm's X-Trans pattern consists of 6x6 pixel, 22.2 % of all pixels detect only red light, 55.6 % detect only green light, and 22.2 % detect only blue light (R/G/B = 2:5:2). Thus the color information in bayered/mosaiced data (CFA data) is incomplete: 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 an interpolation algorithm called "Debayering" or "Demosaicing". By this process RGB (color) images are generated. 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, caution is to be taken with performing geometric operations on CFA data. Bayered data must not be mirrored, rotated, cropped by odd numbers of columns at the left, or cropped by odd numbers of lines at the top. All of these operations would alter the Bayer pattern, making the color assignment wrong. Fujifilm's X-Trans mosaic pattern is invariant regarding rotation, but mirroring and cropping will alter the color assignment.

Bayer patterns

Original	horizontally mirrored or rotated clockwise by 90° or 1 column cropped at the left	vertically mirrored or rotated ccw by 90° or 1 line cropped at the top	rotated by 180° or 1 column at the left AND 1 line at the top cropped
RGGB	**GRBG**	**GBRG**	**BGGR**



Fujifilm's X-Trans

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.

1.5 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 raw format. However, there are some regular digital cameras that manipulate the data even when the raw format is set (e.g. applying black point correction, applying of spatial filters for hot pixel removal, or the "star eater" issue). Such cameras 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 with temperature control whereas regular digital cameras normally are not cooled.

2 Metadata, Quality Settings, File Formats, Camera Driver and Image Acquisition Software

2.1 Metadata

Together with image data, metadata are saved as well in a file. Metadata describe properties of the file, properties and settings of used equipment and software, information about environmental conditions, observation site and observed target. Some of these metadata are essential for the correct processing of astro images.

File formats commonly used for astrophotography are proprietary raw formats of regular digital cameras, Flexible Image Transport System (FITS) format and PixInsight's native file format Extensible Image Serializing Format (XISF). They use different standards for storing metadata:

Almost all regular digital cameras support the Exchangeable Image File (Exif) Format. Only metadata which are important for general photography (like date and time, focal length, aperture, exposure time, f-number, ISO value, camera and lens model) are usually supported.

The structure of FITS files and the standard FITS keywords are defined in [3]. FITS files contain metadata in the FITS header. Certain FITS keywords are defined that store the information in its value. Unfortunately the original FITS standard was incomplete. This led different organizations and companies to create several nonstandard FITS keywords in an uncoordinated manner. So the current situation is complicated by the existence of many nonstandard FITS keywords, not all of which are supported by image acquisition and processing software for astro images in equal measure. This poses problems for the correct evaluation of metadata in processing software. In spite of poor standardization, FITS format still is widely used as output file format for image acquisition and input format for processing by amateurs and professional astronomers. Compared to proprietary raw formats of regular digital cameras, FITS format is preferable due to its capability of storing metadata that are important for astrophotography (e.g. image type, coordinates of the observation site, name of the observed target, approximate coordinates of the image center, pixel dimensions of the camera, focus position, etc.).

PixInsight's native file format XISF [4] contains the metadata in XISF properties for registered images and following processing stages. For compatibility, it additionally contains the metadata in FITS keywords for all processing stages. XISF supports astronomical image metadata in a fully standardized and much more structured and rigorous way than FITS format. Therefore it would be desirable that more image acquisition applications supported XISF as output format.

Some of PixInsight's tools (e.g. the PhotometricColorCalibration and SpectrophotometricColorCalibration processes or the scripts CatalogueStarGenerator and AnnotateImage) need the exact computation of astrometric solutions. In order that this can be achieved by applying the ImageSolver script or automatically by applying the WBPP script (see chapter 10), light frames are required to contain the metadata that are starred in Table 1:

Table 1: Metadata and astrometric solution

Required	FITS keyword	XISF property	Significance
*	DATE-BEG (DATE-OBS)	Observation:Time:Start	UTC observation time start, ISO 8601 format: YYYY-MM-DDThh:mm:ss.sss
	DATE-END	Observation:Time:End	UTC observation time end, ISO 8601 format: YYYY-MM-DDThh:mm:ss.sss
	OBSGEO-L (LONG-OBS, SITELONG)	Observation:Location:Longitude	Longitude of the image site, in degrees, SITELONG string format: DD MM SS.SSS
	OBSGEO-B (LAT-OBS, SITELAT)	Observation:Location:Latitude	Latitude of the image site, in degrees, SITELAT string format: DD MM SS.SSS
	OBSGEO-H (ALT-OBS, SITEELEV)	Observation:Location:Elevation	Elevation of the image site above sea level in meters.
*	RA (OBJCTRA)	Observation:Center:RA	Approximate right ascension of image center, in degrees, OBJCTRA string format: HH MM SS.SSS
*	DEC (OBJCTDEC)	Observation:Center:Dec	Approximate declination of image center, in degrees, OBJCTDEC string format: DD MM SS.SSS
	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 obs. 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.

Geodetic observer coordinates are used for solar system ephemeris calculations. 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, PixInsight's ImageSolver then computes accurate International Celestial Reference System (ICRS) or Geocentric Celestial Reference System (GCRS) coordinates.

If metadata that are specified as required in Table 1 are missing, the automatic generation of astrometric solution will fail and missing data have to be input manually. This is good reason to avoid saving the data in a proprietary raw format if possible, and to ensure that the needed metadata are correct.

2.2 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 or (in case of an OSC camera) white balance setting. Besides, the maximal bit depth that is available (given by the resolution of the camera's ADC) shall be used. In order that these requirements are met, the following adjustments are necessary:

2.2.1 Regular digital cameras

If a regular digital camera is used which is able to save the data in a proprietary raw format (e.g. Canon: CR2 or CR3, Nikon: NEF, Sony: ARW, Fujifilm: RAF, Pentax: PEF format or Adobe's DNG format), set the camera in the camera menu to use this raw 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 [5] in the camera.

2.2.2 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).

If you use an OSC camera of make ZWO, caution is advised when the 'native' camera driver is used: the ZWO Software Development Kit (SDK) enables the user in the image acquisition software to control settings that influence the white balance of a displayed color image. This is achieved by two parameters, WB_R and WB_B, data range 1 to 100, the default values are WB_R = 52 and WB_B = 95. The intensities of the red channel will be multiplied by WB_R/50 and the intensities of the blue channel by WB_B/50. Unfortunately the results of this multiplication are also written to disk in the FITS file. So it is important to set the values of both parameters to 50 and subsequently apply 'Save Config'; only in this way, the real raw intensities will be saved to disk in the FITS files, see [6]. Since the data coming from the camera are saved in FITS files which usually have the data format '16-bit integer', otherwise rounding errors and clipping of high values will arise. Such a complication is generally avoided when the ASCOM camera driver is used instead of the 'native' camera driver. A related issue with white balance factors also emerges with cameras of make Svbony [7].

2.3 File formats for image acquisition

Note that the above settings of image quality 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. a native and an ASCOM driver), the file format may depend on the camera driver that is selected in the image acquisition software.

2.3.1 Proprietary raw format of regular digital cameras

The image acquisition application SGP lets you choose whether the data coming from the camera will be saved to disk in proprietary raw format or in FITS 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 format by default. By additionally installing and using an ASCOM driver [8] it is possible to save the files in FITS format, at least for certain camera models of Canon, Nikon, Pentax, Panasonic and Sony.

If you decide to let the data coming from the camera be saved to disk in the proprietary raw format, ascertain to set PixInsight's RAW Format Preferences (Format Explorer, double click on 'RAW') to 'Pure Raw'. The proprietary raw format contains the CFA mosaic pattern of an OSC camera. When opening the file in PixInsight, the raw image decoding software 'LibRaw' that is used by PixInsight's RAW format support module detects the CFA mosaic pattern and makes it available for the ImageCalibration and Debayer processes. PixInsight's RAW format support module 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. This is useful when the frames were captured with a telescope, and the camera of course is unable to detect the correct values of focal length and aperture. In this case, the user should enable both options and set the correct values in order to avoid meaningless metadata (e.g. a default focal length of 50 mm).

Due to data compression, the proprietary raw format results in somewhat smaller file size than FITS format or XISF. Dependent on the chosen file format, there is also a difference in the data: the proprietary raw format contains intensity values in the bit depth of the ADC, e.g. 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 are scaled to 16 bit, i.e. they are multiplied by factor 4, the range is 0 to 2^16 - 1 = 65535. This is one important reason that the use of different file formats for one project (light and calibration frames) may lead to severe issues in image calibration. So please follow the advice given in section 2.4.

If you decide to let the data coming from the camera be saved to disk in FITS format, see section 2.3.2.

2.3.2 FITS format

Camera drivers of different dedicated astro camera brands deal differently with raw data: some drivers scale intensity values to the full range of 16 bit, range 0 to 65535, by multiplying with a factor (12 bit: by factor 16, 14 bit: by factor 4). Other drivers leave the intensity values in the range of the ADC's bit depth (12 bit: range 0 to 4095, 14 bit: range 0 to 16383). Whether scaling of intensity values is performed by the driver can be determined by inspecting the histogram of a subframe [2].

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'** and

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 FITS Format Preferences (Format Explorer, double click on 'FITS', parameter 'Coordinate origin'), and in the WBPP script in section 'Global options', parameter 'FITS orientation'. The value is used for import and export of FITS files, the default value in FITS Format Preferences being 'Upper left corner (top-down)'. If the option 'Global Pref' is used in WBPP, the global setting in FITS Format Preferences will be used.

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 [9]. If the selected value does not match the actual vertical orientation in an imported FITS file, the image will be vertically mirrored and, as we have seen in section 1.4, 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 correct debayering results.

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 [10]. This keyword can assume the (case insensitive) values 'BOTTOM-UP' or 'TOP-DOWN'. Nowadays this keyword is generated by a number of image acquisition applications. PixInsight supports the ROWORDER keyword: when the option 'Use ROWORDER keywords' is enabled in FITS Format Preferences AND a ROWORDER keyword is detected, its value will be used to override the value set in FITS Format Preferences and WBPP.

The FITS header does not necessarily contain the Bayer pattern for OSC cameras. Some image acquisition applications write the non-standard 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. Normally 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 [11].

2.3.3 XISF

As far as I know, NINA is currently the only image acquisition application which supports PixInsight's native file format XISF as output format. Hopefully this will change before long.

2.4 Importance of using same camera driver, image acquisition software and file format setting

Some manufacturers of dedicated astro cameras provide two camera drivers: one 'native' driver and one ASCOM driver.

It is essential to use the same camera driver, the same image acquisition software and the same file format for acquisition of light and calibration frames in one project.

If different camera drivers, different image acquisition applications or different file formats are used, it is probable that incompatible results (e.g. regarding scaling of intensity values, image dimensions or vertical orientation of pixel data) are produced. This will invariably cause image calibration to either produce wrong results or even fail completely.

Informative contributions about camera drivers can be found in [12].

3 Why Do We Perform Image Calibration?

3.1 Temporal noise

Definition according to [13], lecture 6,

Quote:

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

3.2 Fixed pattern nonuniformity (FPN), dithering

Definition according to [13], lecture 7,

Quote:

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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.
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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 sensors also show a pronounced artifact called "amplifier glow". In daylight photography, the effect of FPN may be negligible, but it is crucial in low light photography, particularly in astrophotography. Whereas temporal noise can be reduced by extending the total exposure time, FPN cannot be reduced in this way. On the contrary, 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. In practice, correct image calibration will remove "amplifier glow". Other sorts of FPN are 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" [14], depending on the presence or absence of field drift [15]. In order to decrease these unwanted remaining patterns further, it is strongly recommended to apply a technique called "dithering" 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 a correct image calibration (with dark frames) is not needed when dithering was applied. This statement is wrong. Dithering between light frames AND correct image calibration are complementary, so both should be performed. The topic of dithering is discussed in [16].

3.3 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.

3.4 Motivation for performing a correct image calibration

All above mentioned effects cause reproducible detractions of the raw 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 correct 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 occurence of the disruptive effects in image acquisition (also see [17]).

4 Types of Calibration Frames

4.1 Bias frames

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. The bias signal contains only the constant offset and the fixed pattern generated in the readout process.

Bias frames are needed when **dark frame scaling** (in PixInsight: **dark frame optimization**) shall be applied (see section 7.2). Bias frames are also needed for the calibration of shortly exposed flat frames which don't contain a significant amount of dark signal.

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 < 0.2 s are used [18]. With such a camera, it is not advisable to use bias frames at all. 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.

4.2 Dark frames

Dark frames are captured with the sensor in complete darkness, at an exposure time that matches the frames they are intended to calibrate (the target frames). In the special case when dark frame optimization (see section 7.2) 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. Dark frames contain bias signal plus dark signal. The dark signal consists of the integrated dark current, the fixed pattern generated thereby and "amplifier glow".

4.3 Flat-darks

Flat-darks are dark frames for the calibration of flat frames. They are captured with the sensor in complete darkness, at the same exposure time as the flat frames.

If the flat frames contain a non-negligible amount of dark signal, flat-darks have to be used instead of bias frames for the calibration of flat frames. This case 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 flat-darks for the calibration of flat frames was discussed in [19]. Jon Rista's contributions to this thread are particularly worth reading. The bottom line is: flat-darks are only needed if there is non-trivial dark signal in the flat frames. In posts #160, #163 and #169 a simple test is described how to verify whether a non-trivial dark signal is contained in the flat frames. The result depends critically on the used sensor and the conditions for flat frame acquisition. If the test result is negative, the additional effort for capturing matched flat-darks would be waste, and the flat frames should be calibrated with a MasterBias instead. Sole exception: cameras with a Panasonic MN 34230 sensor (bias level instability, see section 4.1).

4.4 Flat frames

Flat frames are captured through the telescope or lens, and it is essential that the field is as uniformly illuminated as possible. Flat frames contain bias signal, the information about vignetting / shadowing effects and the pixel-to-pixel variation of light sensitivity. In certain cases, there may be also a non-negligible amount of dark signal, see section 4.3. Flat frames have to be calibrated before they are integrated to the MasterFlat which then is applied to the dark-calibrated light frames during image calibration.

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".

5 Settings and Conditions for Image Acquisition of Calibration Frames

5.1 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 set value for all frames.

5.2 Camera settings

Light frames and calibration frames that shall be processed in one image calibration run are required to be compatible with each other. In case of a regular digital camera, the ISO setting, and in case of a dedicated astro camera, binning, gain and offset (see section 1.3), if applicable "USB traffic", and readout mode (e.g. for cameras QHY268, QHY600) must be consistent.

In the special case when dark frame optimization shall be applied (see section 7.2), the exposure time of the dark frames shall be greater or equal the exposure time of the light frames. When dark frame optimization is not to be applied, dark frames have to be captured at the same exposure time as the light frames. The exposure time of flat-darks should match the exposure time of the corresponding flat frames.

5.3 Dark frames, bias frames and flat-darks: 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. 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, bias frames and flat-darks that shall be used for the generation of master calibration files always shall be captured in a dark place.

5.4 Flat frames: unchanged light path for image acquisition

For flat frame acquisition it is all-important to have an unaltered light path. The setup should be the same as used for light frame acquisition. That means, one must not change:
- camera orientation (rotating angle),
- 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.

If a monochrome camera is used, separate flat frames have to be captured for each filter. Best is not to change anything and take flat frames directly before or after light frames. With refractors it is usually possible to use one MasterFlat for some longer time.

5.5 Flat frames: very short exposure time can cause nonuniformly illuminated field

Flat frames have to be captured through the telescope or lens applying an uniformly illuminated field 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.

5.6 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 [20].

Warning: Most DSLR 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. Also see [21].

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: 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) in order to get well exposed flat frames.

It is important that the number of clipped pixels in the upper intensity range 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. Or (even better), apply the following PixelMath expression (in the 'Destination' section disable option 'Generate output'; min and max values can be varied):

```
RGB/K:   n += $T < max/65536 && $T >= min/65536
Symbols: min = 60000, max = 65535, n = global(+)
```

This PixelMath expression counts the number of pixels n that have intensity values between min and max. The value of the global variable n is outputted to the process console.

For flat frames of OSC cameras there is an additional aspect: the weakest color channel should have sufficient signal in the lower range.

6 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.

6.1 MasterBias (MB), MasterDark (MD) and MasterFlatDark (MFD)

MB, MD and MFD shall be prepared according to Vicent Peris's tutorial [22]: simple integration of the dark frames, bias frames and flat-darks 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") is rejected.

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

6.2 Never pre-calibrate dark frames or a MasterDark

Unfortunately there are tutorials (e.g. [23]) that suggest to calibrate, in a preceding step, either the individual dark frames or the 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.

Modern regular digital cameras apply a dark current suppression mechanism (in the hardware) that subtracts the mean of optic black pixels that are situated outside of the image region of the sensor. 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 frame) 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 (see [24], post #3). This truncation is necessary in order to preserve a coherent data set. <u>However, the truncated data are lost.</u>

Dedicated astro cameras don't apply such a dark current suppression, 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 [25].

I experienced this data loss with a calibrated MD of my Canon EOS 600D (= Rebel T3i), ZWO ASI294MC Pro and ASI071MC Pro. **Figure 1** 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).

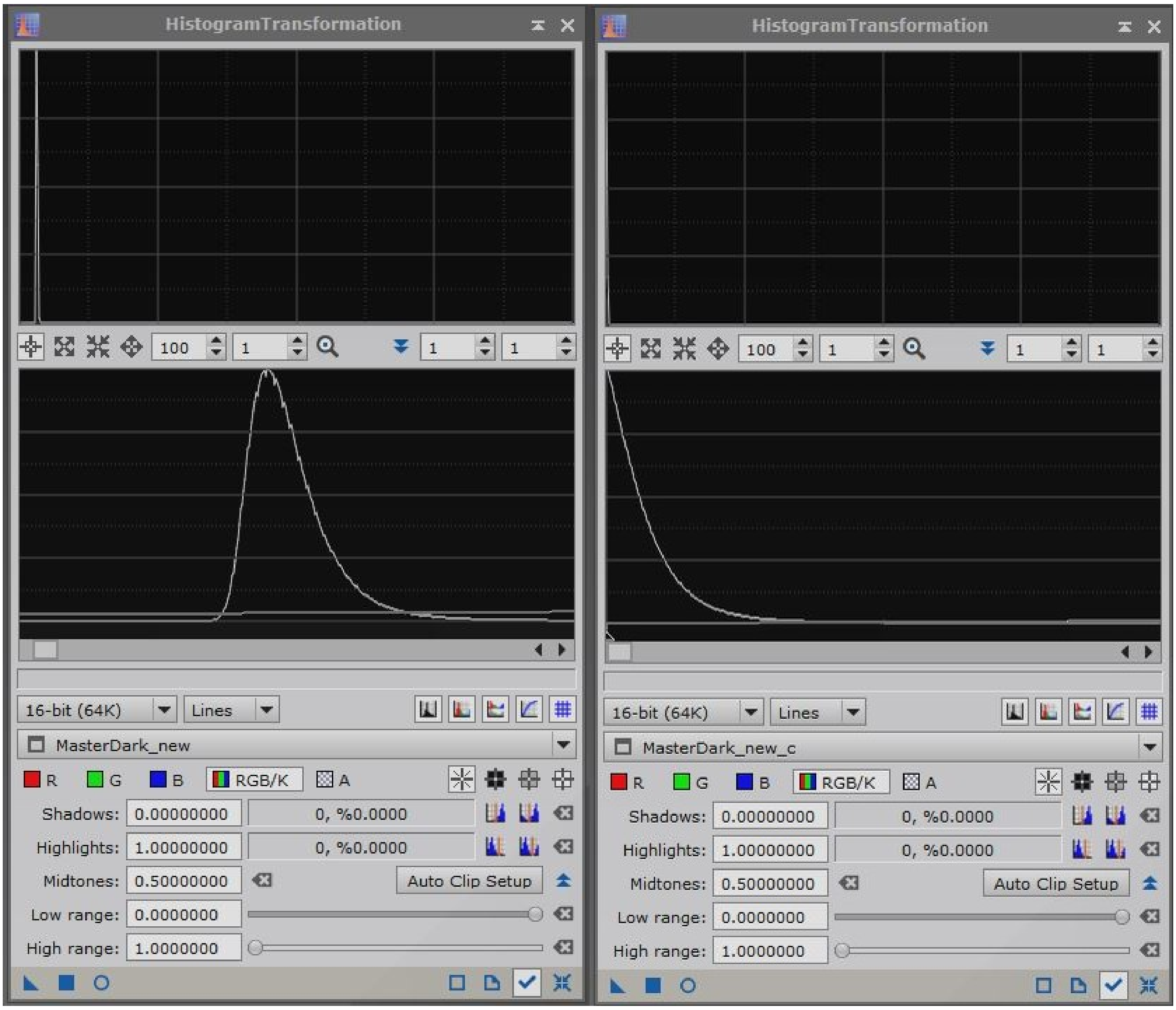

Figure 1: Histograms of MD, left side: not pre-calibrated, right side: pre-calibrated

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 term (dark current * exposure time) is not achieved. The consequence of using such a pre-calibrated, clipped MD is higher residual fixed pattern in the calibrated lights.

In section 7.2 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 your dark frames, neither the individual dark frames nor the integrated dark frames. If dark frame scaling shall be applied, use instead PixInsight's option of calibrating the MD during calibration of the light frames.

MasterDarks prepared according to section 6.1 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.

6.3 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 you use a monochrome camera, separate MFs have to be generated for each filter.

6.3.1 Calibration of flat frames

With sufficiently exposed flat frames, no clipping will arise, so the application of an output pedestal (see section 8.1) is never needed in the calibration of flat frames.

Options 'Signal Evaluation' and 'Noise Evaluation' should be disabled.

Flat frames should be calibrated using either only a MB or only a MFD (no dark frame optimization):
- Disable section 'Master Bias'.
- Enable section 'Master Dark', select the MB (or the MFD), enable option 'Calibrate' [24], disable option 'Optimize'.
- Disable section 'Master Flat'.

The procedure that was described initially in [22] (calibration with the regular MD and MB using dark frame optimization) is not recommended for the calibration of flat frames.

6.3.2 Integration of calibrated flat frames

Subsequently, the calibrated flat frames are integrated to the MF with the following parameters (see [22]):

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" [27] for recommendations.

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

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

7 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.

7.1 Overscan correction

Some cameras suffer from instable bias level. This manifests itself either by a drift of bias level during the 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.

Whether overscan correction is applicable or beneficial depends on the camera. Prerequisite for the utilization of overscan correction is: the sensor of the used camera has a region with overscan pixels, and the camera driver can be configured to output the corresponding data (= overscan enabled). If this prerequisite is not met, overscan correction cannot be used. If an instable bias level is not observed at all, make sure that the camera driver is configured to exclude the overscan region in the output (= overscan disabled), and don't use overscan correction in image calibration, it would be wasted effort.

A word of warning: it is important to ensure that the overscan area is removed in the calibrated frames in either case, otherwise strange artifacts will be generated in the LocalNormalization operation.
- If overscan correction is used, the overscan region is removed in the image calibration operation provided that overscan parameters are configured correctly.
- If overscan correction is not used, set the camera driver to exclude the overscan region (either directly in the ASCOM driver or in the image acquisition application when a native driver is used). In this case, the rest of section 7.1 is moot and can be skipped.

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: "optic black" pixels (sometimes called "dark reference" pixels) contain photosites that are covered with opaque material, so their output will contain 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 contain 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. The procedure for compensation of bias level fluctuations is called "overscan correction".

Before deciding whether overscan correction shall be used for a given camera, it is important to thoroughly check the quality of the data:

Enable overscan in the camera driver. As a result dimensions of frames will increase slightly. Capture some light frames and all types of calibration frames. Hartmut Bornemann's script 2DPlot [28] is most suitable for inspecting the data. Reference [29] 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.

Besides, the location of the **actually useful** portion of the overscan region which contains consistent data has to be determined.

If this inspection shows that the quality of the data in the overscan region is dubious, disable overscan in the camera driver, and don't use overscan correction in image calibration.

If one decides to apply overscan correction in image calibration, light frames and all calibration frames have to be captured with overscan enabled in the camera driver, otherwise image geometry will be incompatible and a corresponding error message will appear in image calibration.

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 (x and y coordinates start 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 [30].

In overscan correction, the median of the pixels in the source region is calculated 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.

7.2 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. These are the two cases which have to be differentiated:

<u>Case 1: Calibration WITH dark frame optimization</u>
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 [31].

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 the light frames with dark frame optimization, use the settings in **Figure 2**, right side [26]:

- Enable section 'Master Bias', select the MB, enable option 'Calibrate'.
- 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 the dark frame optimization algorithm calculates a 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.

However, if the sensor shows "amplifier glow", this might not be calibrated out completely with dark frame optimization enabled.

In cases of a not temperature-controlled camera with "amplifier glow" it's worthwhile to accurately compare the results of both settings (compare the final integration results after image calibration, (if applicable) debayering, and registration of the light frames).

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 varified that a given camera actually is suitable for its application. Helpful hints for a corresponding checking procedure are given in the Reference Documentation [27] for the ImageCalibration process in section '3.4 How to verify the optimization performance'.

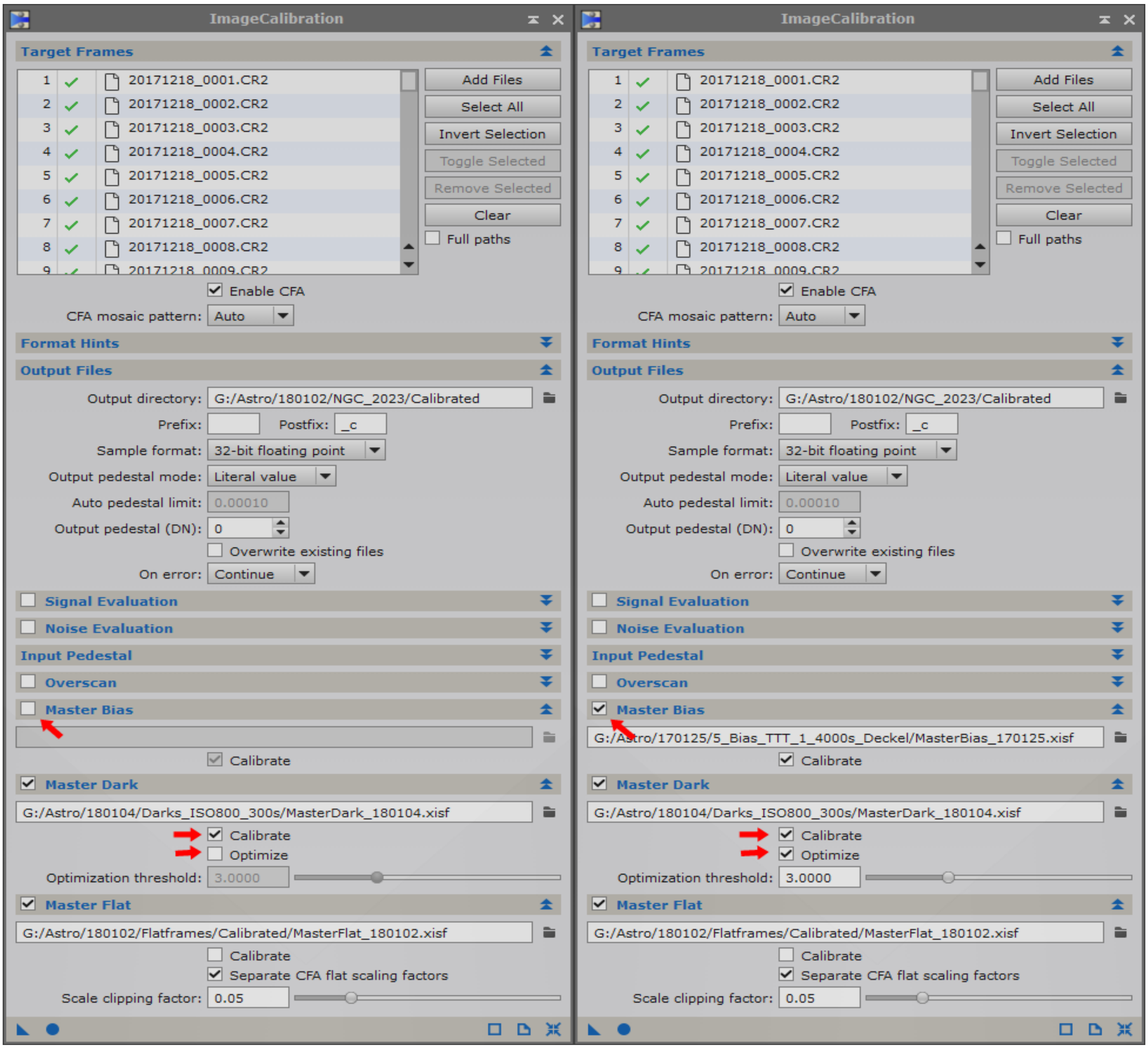

Figure 2: Settings in ImageCalibration, left side: no dark frame optimization, right side: with dark frame optimization [26]

Case 2: Calibration WITHOUT dark frame optimization

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 at all.

For the calibration of light frames without dark frame optimization use the settings in **Figure 2**, left side [26]:

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

7.3 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.

7.4 Examples of approved settings for light frame calibration

7.4.1 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 dark frames, bias frames and flat frames,
- prepare the master calibration files according to section 6,
- calibrate the light frames using the settings shown in section 7.2, **Figure 2**, right side.

7.4.2 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 MFD was used for flat frame calibration.

- Take dark frames, flat-darks and flat frames,
- prepare the master calibration files according to section 6,
- calibrate the light frames using the settings shown in section 7.2, **Figure 2**, left side.

8 Inspection and Judgement of the Calibration Result

8.1 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 [1]. If extensive low-range clipping is detected in calibrated frames, the calibration result is incorrect. Low-range clipping is caused by negative pixel values that result during subtraction of the MasterDark.

Negative pixel values can be caused by
- not matching dark frames (regarding ISO / gain, offset, readout mode, exposure time or temperature, see section 5.2),
- light leaks during dark frame acquisition (see section 5.3) or
- using different camera driver, different acquisition software or different file format for the acquisition of light and calibration frames (see sections 2.3 and 2.4).

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.

8.2 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).

Calibrated light frames of an OSC camera must be debayered before they can be judged. 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 calculated 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. The resulting color shift is meaningless in terms of signal-to-noise ratio. The correct color balance will be adjusted later in the workflow, preferably with the SpectrophotometricColorCalibration (SPCC) process. The ImageCalibration process provides the option 'Separate CFA flat scaling factors' in section 'MasterFlat' [32]. If this option is enabled 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.

8.3 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. Also it is advisable to equip all positions of the filter wheel with filters in order to avoid unbalance.
- 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. Reference [33] is a good article about special issues with flat field correction that are caused by stray light.

9 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.

9.1 Linear defect detection (LDD) / Linear pattern subtraction (LPS) (only for CCD cameras)

Frames acquired with a CCD sensor 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. Subsequently, the linear patterns are corrected in the calibrated subframes by the script LinearPatternSubtraction [34].

9.2 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. Remaining hot and warm pixels should be corrected with the CosmeticCorrection process after image calibration (and an optionally performed linear pattern correction). 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 CosmeticCorrection process.

9.3 Debayer (only for OSC cameras)

In case of an OSC camera, the calibrated light frames have to be debayered now. If the raw subframes are in FITS format, the correct CFA mosaic pattern might have to be specified explicitely (see section 2.3.2).

Option 'Output mode' decides on the type of the outputted frames [35]: 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 should be enabled (this is the default).

9.4 Subframe weighting with SubframeSelector

When preprocessing is achieved by manually executing PixInsight's processes step by step, at this stage the frames can be checked visually with the Blink process in order to reject obviously bad frames (due to e.g. clouds, guiding error, poor focus, etc.). Subsequently, for the remaining frames the SubframeSelector process can be applied which allows for approval of subframes and subframe weighting, configurable by the user. The reference image for the StarAlignment process can be chosen (looking out for low FWHM and low eccentricity) and inspected visually as well. This is the hitherto commonly practiced approach.

The old metric 'SNR', however, always has been a problematic quality estimator: it cannot be used for image 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 one of the main reasons that in PixInsight versions before v1.8.9, calibrated and (if applicable) debayered subframes had to be blinked and the SubframeSelector tool had to be supervised.

These problems are overcome since version 1.8.9 of PixInsight, in which new image 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 an informative article, Juan Conejero explains the new image weighting algorithms in detail [36]. In section "Examples", data sets obtained with different equipment and under different observation conditions are analyzed in SubframeSelector using the new metrics. It is worthwhile taking the time and studying this chapter thoroughly. Considering one's specific used equipment and observation conditions for choosing the most suited image weighting metrics can improve the results. Summing it up: for preprocessing raw data, SubframeSelector is basically superseded by the new weighting methods, but it remains a valuable tool for analyzing data.

Probably the most important consequence of the new image weighting metrics and the also new LocalNormalization tool (see section 9.6) is: full automation of the whole preprocessing pipeline is now facilitated (see section 10).

Note that the computation of PSF Signal Weight has undergone significant modifications since its first introduction in v1.8.8-10, thus values obtained with v1.8.8-10 to -12 are not compatible with v1.8.9 and following versions. Raw data therefore have to be calibrated and 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 the ImageCalibration process,
- for mosaiced CFA raw frames, signal and noise evaluation must be performed by the Debayer process.

9.5 Registration

Approved images then are registered by the StarAlignment process against the reference image. Option 'Distortion correction' (please read the tooltip text!) is only available when the Registration model 'Thin Plate Splines' is selected. 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). In this case thin plate splines and distortion correction shall be enabled, and local distortion normally should be disabled [35]. 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.

9.6 Local normalization

The LocalNormalization (LN) tool was completely redesigned and reimplemented in v1.8.9 of PixInsight [37]. 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.

9.7 Integration

Finally, the preprocessed light frames are integrated by the ImageIntegration process. Use 'Add Files' for adding registered subframes. 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" [27] 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, 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 2.8 "Rejection Maps" of the PixInsight Reference Document "ImageIntegration" [27].

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 th 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.

9.8 Drizzle integration (optional)

For undersampled images, an enhancement of resolution can be achieved (for 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 1.4, 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 [38]. 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.

For a successful application of drizzle integration, two requirements have to be met:
1. the frames must be well dithered,
2. 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 9.5) and integration (section 9.7), 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 applicable, local normalization data files (extension: xnml) are added using 'Add L.Norm Files'.

The following parameters are recommended for DrizzleIntegration:

If local normalization was used in ImageIntegration, option 'Enable local normalization' shall be checked. Then local normalization will be used for the normalization of the output. 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 [35]. This generates three monochrome drizzle integration results which have to be recombined to a RGB image with the ChannelCombination process.

Thereby, data reduction has been completed.

10 Automation of Preprocessing: WeightedBatchPreprocessing (WBPP) Script

In the above description, the whole preprocessing was achieved by manually executing PixInsight's processes, step by step. In my view, this practice is important for a beginner in order to become acquainted with the individual involved processes. Knowing the entire data reduction process and understanding how it works at each stage is absoutely necessary if you want to control your data and is also a prerequisite for automating preprocessing. The universal rule is also applicable for preprocessing:

Once you have mastered something manually, then you can automate it for convenience.

The WeightedBatchPreprocessing (WBPP) script (see [39]), which is part of the standard PixInsight distribution, provides the opportunity to fully automate preprocessing. With WBPP the procedure is fully configurable and, if configured correctly, there is no need for interruption and supervision. The use of WBPP is therefore highly recommended to users who are familiar with the individual steps of preprocessing.

The topic of how WBPP retrieves the metadata that are needed for the correct preprocessing of light and calibration files (e.g. type of exposure, binning, exposure time, filter name, color space, bayer/mosaic pattern, grouping keywords, etc.) is outlined by the creator of the script, Roberto Sartori [40]. Complete understanding of this process is required for taking advantage of WBPP's full potential. Therefore I warmly recommend to read this reference!

For the last versions of WBPP, major concern was that generated integrations contain the correct astrometric solution in the metadata. In order that this important information will not be lost again by cropping the image at the beginning of manual processing, the new operation 'Autocrop' was incorporated into v2.5.4.

WBPP will manage the whole pipeline for data reduction consisting of the following operations:
- Preparation of the master calibration files,
- Calibration of light frames,
- (if applicable) Linear defect correction (LDC) [41],
- Cosmetic correction,
- (if applicable) Debayer,
- Measurements,
- Generation of weights,
- Rejection of bad frames,
- Writing of weights,
- Selection of reference frames for registration,
- Plate solving of reference frames,
- Registration,
- Generation of reference frames for local normalization,
- Local normalization,
- Integration,
- (if applicable) Drizzle integration,
- Autocrop and
- (if applicable) RGB channel recombination.

In case of issues, the detailed logfile which is generated by WBPP and saved in the logs directory will be very helpful for trouble-shooting.

Adam Block has created a series of free videos that explain function and usage of the WBPP script extensively, see [42].

References and Endnotes:

[1] 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 Statistics 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) and

Statistics (option 'Unclipped' must be disabled, this is the default): check 'count (%)', it should be very near 100 %. The fraction of clipped pixels equals (100 % - count (%)).

[2] 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.

[3] "FITS Standard Document", https://fits.gsfc.nasa.gov/fits_standard.html ,
"FITS Documentation", https://fits.gsfc.nasa.gov/fits_documentation.html

[4] "Extensible Image Serialization Format (XISF)", https://pixinsight.com/xisf/index.html

[5] "This happens when you forget to disable lens corrections – Sony", https://www.cloudynights.com/topic/854488-this-happens-when-you-forget-to-disable-lens-corrections-sony/

[6] "ZWO ASI294MC Pro - Bad calibration frames", https://stargazerslounge.com/topic/347561-zwo-asi294mc-pro-bad-calibration-frames/ ,
"Strange bias frames with ASI294MC Pro (under Astroberry)", https://indilib.org/forum/ccds-dslrs/6368-strange-bias-frames-with-asi294mc-pro-under-astroberry.html#51097 and
"ASI533MC Pro weird color balance", https://www.cloudynights.com/topic/708880-asi533mc-pro-weird-color-balance/

[7] "WBPP: Master Light image is tinted incorrectly", https://pixinsight.com/forum/index.php?threads/wbpp-master-light-image-is-tinted-incorrectly.19025/

[8] "ASCOM.DSLR" is an ASCOM driver for Canon, Nikon and Pentax cameras, https://github.com/vtorkalo/ASCOM.DSLR ,
"LumixCameraAscomDriver" is an ASCOM driver for some Panasonic Lumix camers, https://github.com/totoantibes/LumixCameraAscomDriver and
"ASCOMSonyCameraDriver" is an ASCOM driver for some Sony cameras, https://github.com/dougforpres/ASCOMSonyCameraDriver/

[9] Determining the correct vertical orientation in a FITS file
A nonstandard FITS keyword 'FLIPPED' might be present in the FITS header, if plate solving was applied by the image acquisition software. However, PixInsight does not evaluate this keyword.

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:

Case 1: even number of mirrors (e.g. refractors, SCTs, newtons, etc.)
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.

Case 2: odd number of mirrors (e.g. a Celestron RASA telescope)
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.

[10] "Orientation of FITS Images", https://free-astro.org/index.php?title=Siril:FITS_orientation

[11] 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:

Case 1: if red and blue channels differ significantly, the correct CFA mosaic pattern is of type 'XGGY',

Case 2: 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).

[12] Dale Ghent in "Native or ASCOM and Why?", https://www.cloudynights.com/topic/761967-native-or-ascom-and-why/ , posts #20, #25 and #27.

[13] Abbas El Gamal, "EE392B: Introduction to Image Sensors and Digital Cameras", http://isl.stanford.edu/~abbas/aeglect392b.php

[14] Jon Rista in "Walking Noise: What is it?", post #3, https://www.cloudynights.com/topic/749810-walking-noise-what-is-it/

[15] 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 (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.

[16] Jon Rista in "Dithering a "Must" ?", posts #19, #20, #24, #25, #29, #40 and #42, https://www.cloudynights.com/topic/572363-dithering-a-must/

[17] Bart Dierickx, Caeleste, "Imperfections of high-performance image sensors", chapter "Calibration" (pp. 38 - 50), https://www.researchgate.net/publication/273538329_Imperfections_of_high-performance_image_sensors

[18] Jon Rista in "QHY183M & Flats = Frustration", posts #57 and #63, https://www.cloudynights.com/topic/676574-qhy183m-flats-frustration/page-3

[19] Jon Rista in "Should we just stop talking about bias frames?", posts #54, #80, #160, #163 and #169, https://www.cloudynights.com/topic/709822-should-we-just-stop-talking-about-bias-frames/

[20] "persistent dust mote?", https://pixinsight.com/forum/index.php?threads/persistent-dust-mote.19327/

[21] "Nikon Z6, overexposed image, "Statistics" max. only at 25%??", https://pixinsight.com/forum/index.php?threads/nikon-z6-overexposed-image-statistics-max-only-at-25.16594/page-2 , post #29 (Comparison of a "back of camera" histogram to a linear histogram in PixInsight) and post #33 (How to use Av automatic operation of a regular digital camera for capturing of daylight or twilight sky flat frames).

[22] Vicent Peris, "Master Calibration Frames: Acquisition and Processing", https://www.pixinsight.com/tutorials/master-frames/

[23] Kayron Mercieca, "2. Generating a Master Superbias and a Master Dark" and "4. Calibrating Lights and Correcting Hot and Cold Pixels", http://www.lightvortexastronomy.com/tutorial-pre-processing-calibrating-and-stacking-images-in-pixinsight.html#Section2

[24] "Image Calibration and negative values (KAF 8300)", https://pixinsight.com/forum/index.php?threads/imagecalibration-and-negative-values-kaf-8300.6593/

[25] "Preprocessing Canon DSLR frames - a different approach", https://pixinsight.com/forum/index.php?threads/preprocessing-canon-dslr-frames-a-different-approach.6773/
(The correct URL of the link in post #1 is: "Canon 1000D EXIF temperature vs Cooling", https://pixinsight.com/forum/index.php?threads/canon-1000d-exif-temperature-vs-cooling.6842/), "Bias frames - pixel rejection - temperature regulated DSLR", https://pixinsight.com/forum/index.php?threads/bias-frames-pixel-rejection-temperature-regulated-dslr.6747/

[26] 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 2 will work correctly regardless of overscan correction is enabled or not.

[27] PixInsight Reference Documentation
PixInsight Reference Documentation is available for many but not all of the processes. 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.

In connection with Preprocessing, the following Reference Documentations exist, and should be consulted in case of ambiguity: ImageCalibration, CosmeticCorrection, Debayer, SubframeSelector, StarAlignment*, ImageIntegration*, ScreenTransferFunction, HistogramTransformation. The documentation for the starred processes is outdated and currently only available at https://pixinsight.com/doc/ .

There are processes for which a Reference Documentation does not yet exist. In this case please study the tooltip texts that are available for most of the parameters in all processes.

[28] 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'.

[29] Matt Craig and Lauren Chambers, "CCD Data Reduction Guide", chapter 1.6, https://www.astropy.org/ccd-reduction-and-photometry-guide/v/dev/notebooks/01-08-Overscan.html

[30] "ImageCalibration and Overscan area procedure" https://pixinsight.com/forum/index.php?threads/imagecalibration-and-overscan-area-procedure.14469/

[31] Juan Conejero, "Dark Frame Optimization Algorithm", https://pixinsight.com/forum/index.php?threads/dark-frame-optimization-algorithm.8529/ ,
Juan Conejero, "PixInsight 1.8.8-10 Released", https://pixinsight.com/forum/index.php?threads/pixinsight-1-8-8-10-released.17471/ , quoted from section "Other Important Improvements and Bug Fixes":
"Fixed a serious performance regression [see: https://pixinsight.com/forum/index.php?threads/trouble-with-latest-release-1-8-8-9-on-my-mac.17386/] caused by the suppression of the dark frame optimization window parameter of ImageCalibration. The dark frame optimization algorithm is now based on variance minimization instead of noise evaluation. It is now much faster and more accurate."

[32] "PixInsight 1.8.8-6 Released", https://pixinsight.com/forum/index.php?threads/pixinsight-1-8-8-6-released.15028/

[33] Alan Holmes, Blog of March 8, 2013: "Flat Fields and Stray Light in Amateur Telescopes", https://diffractionlimited.com/flat-fields-stray-light-amateur-telescopes/

[34] "Pattern Subtraction Scripts", https://pixinsight.com/forum/index.php?threads/pattern-subtraction-scripts.13083/ ,
Vicent Peris, "Correcting Defective Lines in PixInsight", https://pixinsight.com/tutorials/LDD-LPS/index.html

[35] "PixInsight 1.8.8-9 Released", https://pixinsight.com/forum/index.php?threads/pixinsight-1-8-8-9-released.17106/

[36] "New Image Weighting Algorithms in PixInsight", https://pixinsight.com/doc/docs/ImageWeighting/ImageWeighting.html

[37] "PixInsight 1.8.9 Released", https://pixinsight.com/forum/index.php?threads/pixinsight-1-8-9-released.18148/

[38] "Bayer drizzle instead of de-Bayering with OSC", https://pixinsight.com/forum/index.php?threads/bayer-drizzle-instead-of-de-bayering-with-osc.12996/ and "Additional Interpolation Methods in Debayer Module", https://pixinsight.com/forum/index.php?threads/additional-interpolation-methods-in-debayer-module.13040/#post-80816

[39] "WBPP 2.0 released", https://pixinsight.com/forum/index.php?threads/wbpp-2-0-released.16123/ ,
"WBPP v2.1 Released", https://pixinsight.com/forum/index.php?threads/wbpp-v2-1-released.16638/ ,
"WBPP v2.2 Released", https://pixinsight.com/forum/index.php?threads/wbpp-v2-2-released.17109/ ,
"WBPP 2.3.0 Released", https://pixinsight.com/forum/index.php?threads/wbpp-2-3-0-released.17476/ ,
"WBPP 2.4.0 Released", https://pixinsight.com/forum/index.php?threads/wbpp-2-4-0-released.18182/ ,
"WBPP 2.4.3 Released", https://pixinsight.com/forum/index.php?threads/wbpp-2-4-3-released.18530/ ,
"WBPP 2.4.4Released", https://pixinsight.com/forum/index.php?threads/wbpp2-4-4-released.18569/ ,
"WBPP 2.4.5 Released", https://pixinsight.com/forum/index.php?threads/wbpp-2-4-5-released.18642/ ,
"WBPP 2.5.0 Released", https://pixinsight.com/forum/index.php?threads/wbpp-2-5-0-released.19112/ and
"WBPP 2.5.4 Released", https://pixinsight.com/forum/index.php?threads/wbpp-2-5-4-released.19604/

[40] "How WBPP 2.4.5 retrieves the information of files in the session", https://pixinsight.com/forum/index.php?threads/how-wbpp-2-4-5-retrieves-the-information-of-files-in-the-session.18806/ and
"Truth Table for Matching Bias, Darks, Flats in WBPP and Other Processes", https://pixinsight.com/forum/index.php?threads/truth-table-for-matching-bias-darks-flats-in-wbpp-and-other-processes.19503/ , post #4

[41] Linear defect correction (LDC) is the application of the scripts LinearDefectDetection (LDD) + LinearPatternCorrection (LPS) in WBPP.

[42] "The Definite Guide to WBPP in PixInsight", https://www.youtube.com/playlist?list=PLAzMa9eIVQkBmzPneF8hCgqwkrxsk7CDn