Chapter 3

CCD Reductions

3.1 Introduction

This chapter describes the design and the philosophy of the CCD package, its main features, and how to use the tools most efficiently.

With the installation of new instruments on the La Silla Telescopes in addition to the availability of CCDs offering large pixel areas and higher quantum efficiency, the variety of observing modes has grown and, as an obvious consequence, the amount and the diversity of data taken have dramatically increased. It is clear that the MIDAS CCD reduction software should be able to cope with these improvements and hence requires compatibility with the hardware as it is offered to the community.

When designing the basic layout of the CCD software the following basic requirements were kept in mind:

- it should be robust;
- it should be user friendly, easy to use;
- it should offer processing possibilities for a large variety of instruments;
- it should be able to operate both in an automatic mode (to handle large quantities of data) as well as in single command mode (for single image analysis);
- it should offer flexible reduction procedures;
- it should be intelligent.

How intelligent the system is depends on the capabilities of other parts in the data acquisition, archiving, and reduction systems. In this respect the development of the CCD package took place at the right time: the MIDAS Data Organizer package offers the possibility to quickly create a MIDAS table containing the science frames to be reduced and their associated calibration frames. The CCD package uses this facility that is based on selection criteria, similar to the ones that are used for the MIDAS table file system. Also, the ESO Archive project has accomplished that a number of telescope and instrument specifications, needed to come to a (partially) automated CCD reduction, can be retrieved from the frame descriptors.

In order not to re-invent the wheel, existing CCD packages have been consulted, and, when useful, ideas have been implemented in the MIDAS CCD software. Its design has largely profited from the IRAF CCDRED package written by Frank Valdes. Parts of its documentation are used for this manual. Also, discussions with Peter Draper, the author of the STARLINK CCDPACK package, are acknowledged.

The document is split into several sections. They describe in detail the various steps in the CCD reduction, starting from reading in the science and calibration frames and ending with the final cosmetic fix up of the final calibrated frames. Some background information about CCD detectors can be found in the MIDAS Users' Guide, Volume B, Appendix B. Additional information about the CCD commands can be obtained from their help descriptions.

The emphasis of the CCD package is on direct imaging. However, since the first processing steps for spectral data are rather similar to direct imaging major parts of its functionality can also be used for processing these data.

***** WARNING *****

The MIDAS CCDRED context is partly based on the current status of the ESO Archiving project as well as the Data Organizer Context, in particular with regard to exposure types and naming of files. Since both projects may be subject to changes in the future, and because of user experiences and suggestions for improvements, the CCDRED context may undergo adjustments accordingly.

3.2 Nature of CCD Output

The nominal output X_{ij} of a CCD–element to a quantum of light I_{ij} can be given as

$$X_{ij} = M_{ij} \times I_{ij} + A_{ij} + F_{ij}(I_{ij}) \tag{3.1}$$

where the additive contribution A_{ij} is caused by the dark current, by pre-flashing, by charge that may have skimmed from columns having a deferred charge (skim) and by bias added to the output electronically to avoid problems with digitizing values near zero. Quantum and transfer efficiency of the optical system enter into the multiplicative term M. The term I consist of various components: object, sky and the photons emitted from the telescope structure. It is known that the response of a CCD can show non-linear effects that can be as large as 5-10%. These effects are represented by the term F_{ij}.

In the following we ignore the pre-flash and skim term, and hence only take the bias and dark frames into account. The objective in reducing CCD frames is to determine the relative intensity I_{ij} of a science data frame. In order to do this, at least two more frames are required in addition to the science frame, namely:

- dark frames to describe the term A_{ij}, and
- flat frames to determine the term M_{ij}.

The dark current *dark* is measured in absence of any external input signal. By considering a number of dark exposures a medium $< dark >$ can be determined:

$$\langle \mathrm{dark(i,j)} \rangle = \mathrm{dark(i,j) + bias} \tag{3.2}$$

The method to correct the frame for multiplicative spatial systematics is know as flat fielding. Flat fields are made by illuminating the CCD with a uniformly emitting source. The flat field then describes the sensitivity over the CCD which is not uniform. A mean flat field frame with a higher S/N ratio can be obtained buy combining a number of flat exposures. The mean flat field and the science frame can be described by:

$$\overline{\mathrm{flat(i,j)}} = \mathrm{M(i,j) \times icons + dark(i,j) + bias} \tag{3.3}$$

$$science(i,j) = M(i,j) \times intens(i,j) + dark(i,j) + bias \tag{3.4}$$

where $intens(i,j)$ represents the intensity distribition on the sky, and *icons* a brightness distribution from a uniform source. If set to the average signal of the dark corrected flat frame or a subimage thereof:

$$\mathrm{icons} = \langle \mathrm{flat - dark} \rangle \tag{3.5}$$

then the reduced intensity frame *intens* will have similar data values as the original science frame *science*.

Combining Eqs.(3.2), (3.3) and (3.4) we isolate:

$$\mathrm{intens(i,j)} = \frac{\mathrm{science(i,j)} - \langle \mathrm{dark(i,j)} \rangle}{\overline{\mathrm{flat(i,j)}} - \langle \mathrm{dark(i,j)_F} \rangle} \times \mathrm{icons} \tag{3.6}$$

Here *icons* can be any number, and term $\langle dark(i,j) \rangle$ now denotes a dark frame obtained by *e.g.* applying a local median over a stack of single dark frames. The subscript in $\langle dark(i,j)_F \rangle$ denotes that this dark exposures may necessarily be the same frame used to subtract the additive spatial systematics from the raw science frame.

The mean absolute error of $intens(i,j)$ yields with $icons = 1$ (only the first letter is used for abbreviations):

$$(\Delta I)^2 = \left(\frac{\partial I}{\partial S}\right)^2 (\Delta S)^2 + \left(\frac{\partial I}{\partial D}\right)^2 (\Delta D)^2 + \left(\frac{\partial I}{\partial F}\right)^2 (\Delta F)^2 \tag{3.7}$$

Computing the partial derivatives we get

$$(\Delta I)^2 = \frac{(F-D)^2(\Delta S)^2 + (S-F)^2(\Delta D)^2 + (S-D)^2(\Delta F)^2}{(F-D)^4} \tag{3.8}$$

A small error ΔI is obtained if ΔS, ΔD and ΔF are kept small. This is achieved by averaging Dark, Flat and Science frames. ΔI is further reduced if $S = F$, then Equation (3.8) simplifies to

$$(\Delta I)^2 = \frac{(\Delta S)^2 + (\Delta F)^2}{(F-D)^2} \tag{3.9}$$

This equation holds only at levels near the sky–background and is relevant for detection of low–brightness emission. In practice however it is difficult to get a similar exposure level for the *flatfrm* and *science* since the flats are usually measured inside the dome. From this point of view it is desirable to measure the empty sky (adjacent to the object) just before or after the object observations. In the case of infrared observations this is certainly advisable because of variations of the sky on short time scales.

3.3 General Overview of the package

The CCDRED package provides a set of basic commands that perform the various calibration steps. These are the combination of calibration frames, subtraction of the bias level (determined from the overscan area or from a separate bias frame), correction for dark current, division by the flat field, correction for illumination, and correction for the fringe pattern. Also, tools are provided for trimming the frame, and for correction of bad pixels. By combining these basic reduction steps a complete reduction pipeline procedure is built, that enables the user to execute a complete automatic reduction of all science frames.

When the context `CCDRED` enabled, a keyword structure is created which contains the parameters for the calibration steps and to control these. These parameters determine which and how the available reduction steps will be executed. Obviously, in order to get the desired result, these keywords should be correctly filled. Other keywords contain general information, *e.g.* about the telescope/instrument being used. Finally, keywords are created to contain the names of important frame descriptors, like the standard MIDAS descriptor for the exposure time (`O_TIME`). In case information is absent sensible defaults will be used in mostly. Finally, a number of keywords contain information about the status of the reduction.

All operations on a frame that are successfully executed are recorded in its descriptors. This facility, which includes updating the HISTORY descriptor, avoids repetition of reduction sequences, and provides the user with information about what has been done to the data.

Apart from commands that do the actual work, a number of commands will help the user to manage keywords and descriptors and their contents/values. Basically, this means displaying and changing parameters. Also, commands exist to store the current parameter settings and to retrieve these after a session is restarted.

Most of this manual is geared towards the "automatic approach", meaning that it is assumed that the user will use the intelligence that has been built into the system. However, the manual also includes documentation about how to execute single basic steps.

The MIDAS CCD package works in combination with the MIDAS Data Organizer which generates, using a set of selection rules, a MIDAS table containing the science frames and their associated calibration frames. Within this chapter this table is referred to the **Association Table**. This table is important for the package: a number of the commands will only work if the table exists: pipe line processing is only possible with the Association Table. The MIDAS Data Organizer is extensively documented elsewhere in this MIDAS User's Guide.

3.4 Setting, Saving, and Retrieving CCD Keywords

Since the number of parameters involved in a complete CCD reduction is quite large, most command parameters have default values. These defaults are taken from the CCD keyword structure. So, after the data have been read in and organized, you can set the CCD keywords to control the CCD reduction process. Basically, one can divide the CCD keywords in three categories:

- general keywords e.g. for telescope, instrument/detector specifications (which CCD has been used; what is the useful area on the chip; what is the read-out noise, its gain; what is the overscan area) and the entries, needed for the various steps in the calibration sequence. Most of the keywords are filled by the `LOAD/CCD` command (see below).

- calibration keywords related to the handling of calibration data, like fitting of the overscan area, the creation of master calibration frames, the method of bad pixel correction, the creation of illumination and fringe frames. For combining the calibration frames in master calibration frames the system is provided with a set of keywords for each exposure type (see below);

- reduction keywords for controlling the reduction of the science frame(s). Examples are: should the overscan area be used to determine the bias; should we correct for bad pixels; is dark current to be subtracted.

Most of the CCD commands get their input parameters mainly from the CCD keywords. However, most commands also accept a limited number of input parameters on the command line. These parameters will supersede the corresponding keywords. However, apart from a few cases the keyword setting itself is not modified: principally, keywords can only be changed by the `SET/CCD` command. For handling all these keywords the CCDRED package in equipped with five commands: `HELP/CCD`, `SHOW/CCD`, `SET/CCD`, `SAVE/CCD` and `INIT/CCD`.

`HELP/CCD` without parameters gives an overview of all CCD commands available. With an existing CCD keyword as parameter the command will show the present values of that keyword and a short explanation of it use.

`SHOW/CCD` returns you the current CCD keyword contents. Given the number of keywords, to display the information the keywords are grouped and displayed according to their functionality:

- **GE** keywords concerning general information;

- **BS** keywords for combining bias frames;

- **DK** keywords for combining the dark frames;

- **FF** keywords for combining the flat fields;

- **SK** keywords for combining the sky frames;

- **OT** keywords for combining other exposure types;
- **OV** keywords for fitting the overscan region;
- **MO** keywords for the mosaicing commands;
- **FX** keywords for the bad pixel correction;
- **IL** keywords for the creation of an illumination frame;
- **FR** keywords for the creation of a fringe frame;
- **SC** keywords for control of the actual reduction sequence.

With `SET/CCD` a maximum of 8 keywords in the CCD context can be changed in one go.

After (partially) having finished a CCD reduction the user may want to store the current keyword setting. This can be done using the command `SAVE/CCD sav_table`. The command will store the keywords in descriptors of a CCD save table with descriptor information only. The keyword setting can be restored by the command `INIT/CCD sav_table`, where `sav_table` is the table containing the CCD keyword setting, previously saved.

3.5 Calibration Frames and Naming Convention

The CCD package is based on so-called data sets. A data set contains a science frame, all its associated raw calibration frames and the master calibration frames created by combining and processing the raw calibration frames. Depending on the processing to be done on the science frame one or more master calibration frames are to be created.

Basically, the creation of a master calibration frame can be done in two ways. Either one creates a MIDAS catalogue which contains the names of all single calibration frames to be combined in to the master frame, or, in the case of pipe line reduction, one use the Association Table. Since the first method is straightforward we concentrate on the use of the Association Table.

In order to achieve a maximum of efficiency and to interface the package with the Data Organizer, the naming convention for master calibration frames is identical to the naming convention for the naming of the master calibration frames in the latter package. Here the name of a master calibration frame is a composition of the generic prefix and all frame numbers of the calibration frames to be used and therefore selection in the DO context. *E.g.* the master calibration frame `susi_12_123_1245` is a combination of the frames `susi0012`, `susi0123`, and `susi1245`.

After the association process by the DO, the name of the master calibration frame is stored in a separate column in the Association Table. The name of this frame is defined as described above. The names of single calibration frames are however also available in the Association Table. This obviously offers the possibility of simply combining all single raw calibration frames in a master one. To execute this brute force combining the column for the master frame should contain an asterisk `*`. The name of the master will then be a composition of the name of the science frame to which the master calibration frame is associated plus the postfix `_exp`. Here, `exp` is the exposure type, stored in a MIDAS frame descriptor (`EXP_TYPE`), and the name of the column with this exposure type in the Association Table and containing the names of the raw calibration frames. *E.g.* the master calibration frame `susi0100_bias` is created by combining all bias frames associated to the science frame `susi0100` and stored in the Association Table.

Currently, the following exposure types are supported:

- `bias` - bias frames:
  These are zero second integration exposures obtained with the same pre-flash (if any) you have used for your scientific exposures. The bias frame will correct for the small positive voltage added to the true signal from the CCD and determines the photometric zero point of the electronic system.

- `dk` - dark current frames:
  These are long exposures taken with the shutter closed. Dark emission can be caused by several sources (*e.g.* overall background emission, luminescence form source on the CCD) and will add charge linearly with exposure time.

- `ff`, `ff-dome`, `ff-screen` - flat field frames:
  These are used to remove the pixel-to-pixel variations across the chip. In some cases dome flats (exposure of an illuminated screen) or projection flats (exposures of a quartz lamp illuminating the spectrograph slit) will be sufficient to remove the chip variations.

- `ff-sky` - blank sky exposures:
  As an alternative to the dome or projector flats many observers doing direct imaging try exposures of blank sky field(s). A clear advantage is that the sky field to be obtained from the blank sky exposures have exactly the colour of the night sky. However, this method of flat field can only be used in absence of fringing and low telescope background emission.

Other calibration frames that can be used in the calibration process are:

- illumination frames:
  This calibration frame may be used to correct for the fact that the flat field calibration frame do not have the same illumination pattern as the observations of the sky. If this is the case, applying the flat field correction may cause a gradient in the sky background.

- fringe frames:
  It may happen that using a (thinned) CCD a fringe pattern becomes apparent in the frame. The pattern is caused by interference of monochromatic light (*e.g.* night sky lines) falling on the chip and are not removed by other calibration and correction steps. To correct one needs to construct needs a really blank sky frame.

*** **WARNING** ***

In principle, the CCD package allows the use of any name for the calibration frames. However, to make the reduction of CCD frames as easy as possible it is recommended to use the above described naming scheme. It is highly recommended to use it. Using different names may, under particular circumstances, lead to complications, in particular in the case of pipe line reduction.

3.6 Setting up the Reduction Procedure

3.6.1 Loading the Telescope and Instrument Specifications

For reducing data from ESO instrumentation it is assumed that the FITS headers conform the standards set by the document "ESO Archive, Data Interface Requirements". In particular, the ESO specific parameters are stored in a special set of FITS keywords (the ESO hierarchical keywords). Using this standard, while reading in the data FITS keywords are stored in well defined MIDAS descriptors of the MIDAS frames.

As an example, in the ESO case the exposure type is stored in the ESO hierarchical FITS keyword 'HIERARCH ESO GEN EXPO TYPE'. The ESO-MIDAS FITS reader converts that keyword into the MIDAS descriptor _EGE_TYPE. Among the valid exposure types are (according the ESO Archive document): `bias`, `ff`, `ff-dome`, `ff-screen`, `ff-sky`, `dk`, `sci`. Therefore, when the CCD context is started or after executing the command `INIT/CCD` links are created between the frame descriptors and the corresponding CCD keyword. With these links the CCD package knows which exposure types are used and which frame descriptor contains the exposure type.

To fill the CCD keywords with these descriptor names a separate procedure is used: `eso_descr.prg`. A copy of this procedure is put in your working directory. If you need to change one or more descriptor names (*e.g.* the descriptor name of the exposure time), make the modification(s) and run the modified procedure, using `@@ eso_descr`.

The CCD package has been developed to reduce CCD data coming from ESO's telescopes on La Silla. However, some flexibility has been built-in to enable the reduction of data coming from non-ESO telescope/instrument combinations, cases in which the telescope and instrument parameters are different. To fill the CCD keywords with the telescope and instrument setup parameters, like name of the telescope, CCD used, read-out noise, frame size, etc. the command `LOAD/CCD` can be used. This command reads these parameters for the MIDAS table `eso_specs.tbl` that, in case it is not present in your working directory, will be created. At initialization of the CCD context a copy of this table is put in the user's directory. In case non-ESO observing facilities have been used, or you want to modify or append the table with your own setup parameters, you can use the standard table commands *e.g.* `EDIT/TABLE`.

3.6.2 Data Retrieval and Organization

The first step in the CCD reduction is the storage of the data on disk. The MIDAS FITS reader `INTAPE/FITS` provides this functionality. The data probably will contain frames of different exposure type (biases, darks, flat fields, science frames, etc), and possibly

SCI	BIAS	...	QUAL_BIAS	BIAS_MASTER
susi0097.bdf	susi0124.bdf	...		susi_124_125.bdf
susi0098.bdf	susi0124.bdf	...		susi_124_125.bdf
susi0099.bdf	susi0126.bdf	...		susi_124_125_126.bdf
susi0100.bdf	susi0124.bdf	...		susi_125_126_127.bdf

Table 3.1: Example of an Association Table

obtained with different filters. After the `INTAPE/FITS` command these different frames are stored on disk.

3.6.3 The Association Table

The second step is to inspect the data, to define a set of criteria to select the science frames and their associated calibration frames, and to use the MIDAS Data Organizer to do the selection and to create the Association Table. Typically, the Association Table looks as displayed in Table 3.1. Depending on available exposure types and on the selection, like for the bias exposure additional columns for darks and flats can be present in the table. The ... represent the three dimensional character of the Association Table, where in this case, the single bias frames are stored in the third dimension of column `BIAS`.

After inspecting the master calibration frame, the user may decide that this is not what (s)he wants and that using another master calibration frame would be better. For example, one can require that in the calibration process of frame `susi0099.bdf` the master bias `susi_124_125.bdf` is to be used, *i.e.* the bias frames associated with the science frames `susi0097.bdf` and `susi0098.bdf`. The change can either be made by running the DO package once more with slightly different selection rules, or by using the command `EDIT/TABLE`.

In addition to the standard naming convention three other input formats can be used in the Association Table. The first one is the use of non-standard name(s) (*i.e.* frame names that are not related to a data set), *e.g.* `stdbias.bdf` instead of `susi_124_125.bdf`. In this case the system requires that the master bias `stdbias.bdf` already exists. A second possibility is to have an asterisk `*`, indicating that all single raw calibration frame associated with a particular science frame are to be combined. In that case the names of the single frames will be retrieved for the Association Table. The third possibility is to store constants in the Association Table, *e.g.* `294` instead of `susi_124_125.bdf`.

An example of these three input possibilities is given in Table 3.2. Here, for the reduction of the frame `susi0097.bdf` a constant bias value of `294` is used while the frame `susi0099.bdf` will be calibrated using all available single bias frames associated with that science frame. Frame `susi0100.bdf` will be reduced with the standard bias frame `stdbias.bdf` that is assumed to be present in the working directory.

SCI	BIAS	...	QUAL_BIAS	BIAS_MASTER
susi0097.bdf	susi0124.bdf	...		295
susi0098.bdf	susi0124.bdf	...		susi_124_125.bdf
susi0099.bdf	susi0126.bdf	...		*
susi0100.bdf	susi0124.bdf	...		stdbias.bdf

Table 3.2: Example of a manually modified Association Table

3.7 Basic Reduction Steps

The software available in the CCD package takes care of the relative calibrations of the pixel intensities, of averaging, and of cleaning frames. Cleaning in this context means removal of the instrumental signature and other defects from the frames.

A full reduction of CCD data involves the steps outlined below:

- fit and subtract a readout bias given by the overscan strip;
- trim the frame of the overscan strip and other irrelevant columns and/or rows;
- combine the bias, dark, and flat calibration frames (if taken);
- subtract the average bias frame;
- remove the defects from the average dark frame;
- scale the average dark frame and subtract;
- remove the defects from the average flat frame;
- prepare the final flat (subtract dark and normalize; possibly apply illumination correction);
- divide by the flat field;
- fix the bad pixels in the output frame;
- correct for fringe pattern;
- combine science frames.

Some of these steps are optional and depend on the kind of data you have taken. In addition to the operations described here, MIDAS contains a number of other operations like removing of cosmic rays. As indicated above, all steps can be executed in an automatic (batch) mode provided the keyword settings have been done correctly.

In the automatic procedure, the highest level of processing is the loop over all science frames selected in the Association Table. If, for whatever reason, the processing of a frame fails, this frame is skipped and the processing is continued with the next one.

The CCD package system provides a single command for doing the entire calibration of the CCD frames: `REDUCE/CCD`. The command is a composition of a number of lower level procedures, each of them taking care of a particular part of the calibration procedure, and executable via a separate MIDAS command. These components are: overscan correction, trimming, combining, bias correction, dark subtraction, flat fielding, illumination correction, and fringe correction.

Whether you want one or more calibration steps be executed depends on the settings for the various options. Therefore, before starting be sure that the keywords for the reduction are set correctly. These keywords and their meaning are listed in Table 3.3. Also, the keywords for combining calibration frames should be checked. Furthermore, fill the keyword `CCDASSOC` with the name of the Association Table, and check that this table is correct. All keywords can be filled and displayed with the commands `SET/CCD` and `SHOW/CCD`.

Keyword	**Content**	Default	**Description**
`CCD_IN`	name	?	input frame or table
`SC_TYP`	exp. type	*	exposure type of input frame
`SC_PROC`	yes|no	no	list processing only
`SC_SCAN`	yes|no	no	applied overscan offset correction
`SC_TRIM`	yes|no	no	trim the frame from overscan area
`SC_FXPIX`	yes|no	no	bad pixel correction
`SC_BSCOR`	yes|no	yes	bias correction
`SC_DKCOR`	yes|no	yes	dark current correction
`SC_FFCOR`	yes|no	yes	flat field correction
`SC_ILCOR`	yes|no	no	illumination correction
`SC_FRCOR`	yes|no	no	fringing correction
`SC_BSFRM`	name		bias calibration frame
`SC_DKFRM`	name		dark current calibration frame
`SC_FFFRM`	name		flat field calibration frame
`SC_ILFRM`	name		illumination calibration frame
`SC_FRFRM`	name		fringing calibration frame

Table 3.3: Keywords for setting the reduction process

3.8 Preparing Your Calibration Frames

Before the actual processing can start, multiple calibration frames have to be combined into a master. The command that takes care of combining the calibration frames in the CCD package is `COMBINE/CCD`. It provides various methods to improve the S/N statistics in the resulting output frame. Depending on the actual parameter settings, the command can take into account the exposure times in the combining process, and can adjust for a (variable) sky background.

3.8.1 Input and Output

The `COMBINE/CCD` command offers the possibility to combine a number of input images using different combining methods. `COMBINE/CCD` takes three input parameters at maximum: the exposure type of the images to be combined, the input frames themselves and and output frame. The various command options can be chosen by setting a number of specific keywords.

The first input parameter should contain the exposure type of the images to be combined. Possible choices are: BS (for bias); FF (for flat fields), DK (for dark), SK (for sky images), and OT (for others). The combining options the command offers are controlled by a set of exposure type dependent keywords, all starting with this two letter identification that has been given as the first input parameter. These keywords control various combining methods, scaling and offset corrections, as well as weighting (see below).

The second input parameter is the input frames to combine. The input can be provided in different ways:

1. by a list of images; e.g. `frame01,frame02,frame03`;
2. by a MIDAS catalogue; e.g. `framecat.cat`;
3. by a MIDAS Data Organizer (DO) output table (with the extension `.tbl`), the Association Table (see Section 3.6.3).

The parameter for the output frame is required in case the input for the second parameter is a catalogue or a string of input frames. In the case of DO input (association) table, from the name of the output calibration frame in the table the command extracts the names of all requested single calibration frames and combines these frames in the output frame. The name of the output master frame can be indicated with an asterisk, meaning that all associated single calibration frames have to be combined. In that case the names of these single frames are taken for the calibration column in the Association Table, *e.g.* `BIAS`, `DK`, etc. See also Section 3.6.3. By default, the input is taken from the keyword `CCD_IN`.

In addition to the output calibration frame the combined sigma frame can be generated. This frame is the standard deviation of the input frames about the output frame.

Before the actual combining is done the exposure type descriptors of the input frames are compared with the descriptor type stored in the keyword `'exp'_TYP`. In case this keyword is filled with '*' or '?' all exposure types are allowed. Else, a fatal error will follow if the keyword content is not equal to the exposure type(s) of one or more input frames.

3.8.2 Combining Methods

Except for summing the frames together, combining frames may require correcting for variations between the frames due to different exposure times, sky backgrounds, extinctions, and positions. Currently, scaling and shifting corrections are included. The scaling corrections may be done by exposure times or by using statistics in each frame over a selected part of the image. The statistics can reveal (depending on the keyword `'exp'_STA`) setting, (where `'exp'` is the exposure type) for each image the mean, median, or the mode. In the following we refer to the value by MMM. Additive shifting is also done by computing the statistics in the frames.

The region of the frames in which the statistics is computed can be specified by the keyword `'exp'_SEC`. By default the whole frame is used. A scaling correction is used when the flux level or sensitivity is varying. The offset correction is used when the sky brightness is varying independently of the object brightness. If the frames are not scaled then special routines combine the frames more efficiently.

Below follows a simple overview how the weighting, scaling and offset parameters are determined. All obviously depend on the settings of the keywords `'exp'_SCA` `'exp'_OFF`, `'exp'_WEI`, and `'exp'_EXP`. The overview makes clear that offset corrections will only be applied if the scaling correction is switched off. The same is true for applying an exposure time correction.

```
==========================================================================
  o_i = 0.0
  w_i = 1.0
  s_i = 1.0

  exp_SCA=yes
     s_i = M_i
     exp_WEI=yes
        w_i = sqrt(N*s_i)

  exp_SCA=no
     exp_EXP=yes
        s_i = e_i
        exp_WEI=yes
           w_i = sqrt(N*s_i)

     exp_OFF=yes
        o_i = M_i/s_i
        exp_WEI=yes
           w_i = sqrt(N*s_i/o_i)

  s_i = s_i/s_mean
  o_i = (o_i - o_mean) * s_mean
  w_i = w_i/w_sum
```

```
--------------------------------------------------------------------------
  key: o_i:    offset for frame i
       o_mean: mean offset over all input frames
       s_i:    scale factor for frame i
       s_mean: mean scale factor over all input frames
       w_i:    weight factor for frame i
       w_sum:  sum over all weight factors of all input frames
       e_i:    exposure time of frame i
       M_i:    MMM of frame i
       N:      number of of frames previously combined
==========================================================================
```

In the combining no checks are done on the reduction status of the input frames and no attempts are made for any calibration correction like for bias or dark. Hence, in more complicated reduction sequences the user should be sure not to combine *e.g.* flat fields that have been corrected for bias and dark with flats fields that are not corrected.

Except for medianing and summing, the frames are combined by averaging. The average may be weighted by

$$weight = (N * scale) * *1/2 \tag{3.10}$$

where N is the number of frames previously combined (the command records the number of frames combined in the frame descriptor), *scale* is the scale factor depending on the keyword settings listed above (`s_i` or `s_i/o_i`). In most of the applications $N = 1$, *i.e.* the input calibration frames are the original ones and not the result of previous combinings.

There are a number of algorithms which may be used as well as applying statistical weights. The algorithms are used to detect and reject deviant pixels, such as cosmic rays. The choice of algorithm depends on the data, the number of frames, and the importance of rejecting cosmic rays. The more complex the algorithm the more time consuming the operation. For every method pixels above and below specified thresholds can be rejected. These thresholds are stored in the keyword `'exp'_MET`. If used the input frames are combined with pixels above and below the specified threshold values (before scaling) excluded. The sigma frame, if requested, will also have the rejected pixels excluded.

The following list summarizes the algorithms. Further algorithms are available elsewhere in MIDAS (see `COMPUTE/...`, `AVERAGE/...`), or may be added in time.

- Sum - sum the input frames.
  The input frames are combined by summing. Summing is the only algorithm in which scaling and weighting are not used. Also no sigma frame is produced.

- Average - average the input frames.
  The input frames are combined by averaging. The frames may be scaled and weighted. There is no pixel rejection. A sigma frame is produced if more than one frame is combined.

- Median, MMedian - (mean) median the input frames.
  The input frames are combined by medianing each pixel. Unless the frames are at the same exposure level they should be scaled. The sigma frame is based on all input frames and is only a first approximation of the standard deviations in the median estimates. The second method does an averaging around the found median in a certain interval in order to take into account the distribution of the values near the median. This is in effect the same what `AVERAGE/IMAGE` also does using the parameter setting 'options = median,low,high'. The required data interval has to be defined by the `exp_CLP` keyword and is assumed to specify relative limits to the determined median – same as in `AVERAGE/IMAGE` (both limits positive).

- Minreject, maxreject, minmaxreject - reject extreme pixels.
  At each pixel after scaling the minimum, maximum, or both are excluded from the average. The frames should be scaled and the average may be weighted. The sigma frame requires at least two pixels after rejection of the extreme values. These are relatively fast algorithms and are a good choice if there are many frames (>15).

- Sigclip - apply a sigma clipping algorithm to each pixel.
  The input frames are combined by applying a sigma clipping algorithm at each pixel. The frames should be scaled. This only rejects highly deviant points and so includes more of the data than the median or minimum and maximum algorithms. It requires many frames (>10-15) to work effectively. Otherwise the bad pixels bias the sigma significantly. The mean used to determine the sigmas is based on the "minmaxrej" algorithm to eliminate the effects of bad pixels on the mean. Only one iteration is performed and at most one pixel is rejected at each point in the output image. After the deviant pixels are rejected the final mean is computed from all the data. The sigma frame excludes the rejected pixels.

- Avsigclip - apply a sigma clipping algorithm to each pixel.
  The input frames are combined with a variant of the sigma clipping algorithm which works well with only a few frames. The images should be scaled. For each line the mean is first estimated using the "minmaxrej" algorithm. The sigmas at each point in the line are scaled by the square root of the mean, that is a Poisson scaling of the noise is assumed. These sigmas are averaged to get a line estimate of the sigma. Then the sigma at each point in the line is estimated by multiplying the line sigma by the square root of the mean at that point. As with the sigma clipping algorithm only one iteration is performed and at most one pixel is rejected at each point. After the deviant pixels are rejected the file mean is computed from all the data. The sigma frame excludes the rejected pixels.

The "avsigclip" algorithm is the best algorithm for rejecting cosmic rays, especially with a small number of frames, but it is also the most time consuming. With many frames (>10-15) it might be advisable to use one of the other algorithms ("maxreject", "median", "minmaxrej") because of their greater speed.

The choice of the most optimal combining algorithm will clearly depend on the nature of the data and on the exposure type. Therefore, for every supported exposure type the

CCD context contains a default combining setup. Currently, there are five combining setups stored in the CCD keywords, all starting with a specific two letter prefix: for bias BS_, dark DK_, dome flats FF_, sky flats SK_, and for all other exposure types OT_. At initialization these keywords are filled with sensible defaults. Below we will shortly comment on combining the various calibration frames and list the default keywords settings.

3.8.3 Combining Bias Frames

Combination of the bias frames is straight forward: filters used and integration times do not play a role, and in most cases the bias frames can be treated with the same weight. The default keyword setting for the bias combining is displayed in Table 3.4.

Keyword	Content	Default	Description
CCD_IN	input name	?	table of input frames
BS_TYP	descriptor value	*	exposure type to check, if any
BS_SIG	yes|no	no	create sigma image
BS_MET	comb. method	maxrej	type of combining operation
BS_DEL	yes|no	no	delete cal. frames afterwards
BS_STA	mean|median|mode	mode	correct. by Mode/Median/Mean
BS_EXP	yes|no	no	scale by exposure time
BS_SCA	yes|no	no	scale by MMM
BS_OFF	yes|no	no	add offset from MMM
BS_WEI	yes|no	yes	use a weighted average
BS_SEC	area	[<,<:>,>]	area for finding MMM
BS_RAN	real,real	-99999,99999	valid pixel range
BS_CLP	real	3.,3.	low/high sigma clipping factor
BS_NUL	real	NULL(2)	value for rejections

Table 3.4: Keywords for combining bias calibration frames

3.8.4 Combining Dark Frames

Similarly to the bias combination one can obtain an average dark current frame. However, one should consider whether the dark correction should really be applied: one needs a reasonable number of dark frames in order not to degrade the S/N, and obviously this takes telescope time. Because the dark level depends on the exposure time, weighting the input dark frames should be considered. Another possibility would be simply to take the average dark value and to scale that number with the exposure time. Filter type is not important. Table 3.5 shows the default setting for combining dark frames.

If the bias is stable enough to allow taking averages, one might argue that it is not really needed. In that case, provided a good linearity of the CCD, one could do with the subtraction of an average dark frame. If the bias is unstable, one should be careful with

Keyword	Content	Default	Description
CCD_IN	input name	?	table of input frames
DK_TYP	descriptor value	*	exposure type to check, if any
DK_SIG	yes|no	no	create sigma image
DK_MET	comb. method	avsigcl	type of combining operation
DK_DEL	yes|no	no	delete cal. frames afterwards
DK_STA	mean|median|mode	mode	correct. by Mode/Median/Mean
DK_EXP	yes|no	yes	scale by exposure time
DK_SCA	yes|no	no	scale by MMM
DK_OFF	yes|no	no	add offset obtained from MMM
DK_WEI	yes|no	yes	use a weighted average
DK_SEC	area	[<,<:>,>]	area for computing MMM
DK_RAN	real,real	-99999,99999	valid pixel range
DK_CLP	real	3.,3.	low/high sigma clipping factor
DK_NUL	real	NULL(2)	value for rejections

Table 3.5: Keywords for combining dark calibration frames

simply combining bias frames. In that case the better solution might be an average of two bias frames, taken just before and after each flat or sky exposure.

3.8.5 Combining Flat Fields

In combining the flat field frames the filter type is of importance. Hence, the combining command will check for consistency of the keyword containing the filter type. The combining input parameters can be set up in the flat parameter table, similar to the dark frames. Table 3.6 show the default keyword settings.

3.8.6 Combining Sky Frames

The procedure is similar to the flat field combining procedure, except that you may want to scale the sky level using the mean, median or the mode of the intensity distribution or taking into account the exposure time. Hence, in the combining, like in the case of combining flat fields, correct weighting of the frame is important. Combining should be done filter by filter. See Table 3.7 for the keywords.

3.8.7 Combine Example

As an example of the use of a Association Table similar to the one displayed in Table 3.1. Let us create a master flat frame to be used for the reduction of the science frame `susi0100.bdf`. Suppose the Association Table contains the name of the master flat to be created: `susi_140_142_143.bdf`. Hence, three flats have to be combined, namely

Keyword	Content	Default	Description
CCD_IN	input name	?	table of input frames
FF_TYP	descriptor value	*	exposure type to check, if any
FF_SIG	yes|no	no	create sigma image
FF_MET	comb. method	avsigcl	type of combining operation
FF_DEL	yes|no	no	delete cal. frames afterwards
FF_STA	mean|median|mode	mode	correct. by Mode/Median/Mean
FF_EXP	yes|no	yes	scale by exposure time
FF_SCA	yes|no	no	scale by MMM
FF_OFF	yes|no	no	add offset obtained from MMM
FF_WEI	yes|no	yes	use a weighted average
FF_SEC	area	[<,<:>,>]	area for computing MMM
FF_RAN	real,real	-99999,99999	valid pixel range
FF_CLP	real	3.,3.	low/high sigma clipping factor
FF_NUL	real	NULL(2)	value for rejections

Table 3.6: Keywords for combining flat field calibration frames

susi0140.bdf, susi0142.bdf, and susi0143.bdf. To combine these frames into the master flat field we enter:

```
SELECT/TABLE asso_tbl
COMBINE/CCD FF asso_tbl
```

The command will go the Association Table, checks the output name for the flat to be created for science frame susi0100, makes a list of single flats to be combined and does the combining. The output on the screen and stored in the MIDAS log file will look like (VERBOSE=YES):

```
Combining FLAT frames: Input=asso_tbl.tbl; output=susi_140_142_143.bdf

Statistics of frame no. 0:
area [@60,@10:@1070,@1020] of frame
minimum, maximum:                 5.560000e+02   8.654000e+03
mean, standard_deviation:         6.101316e+03   1.913127e+02

Statistics of frame no. 1:
area [@60,@10:@1070,@1020] of frame
minimum, maximum:                 8.390000e+02   1.276900e+04
mean, standard_deviation:         8.313817e+03   2.569877e+02

Statistics of frame no. 2:
area [@60,@10:@1070,@1020] of frame
minimum, maximum:                 4.220000e+02   1.046500e+04
```

Keyword	Content	Default	Description
CCD_IN	input name	?	table of input frames
SK_TYP	descriptor value	*	exposure type to check, if any
SK_SIG	yes|no	no	create sigma image
SK_MET	comb. method	avsigcl	type of combining operation
SK_DEL	yes|no	no	delete cal. frames afterwards
SK_STA	mean|median|mode	mode	correct. by Mode/Median/Mean
SK_EXP	yes|no	yes	scale by exposure time
SK_SCA	yes|no	no	scale by MMM
SK_OFF	yes|no	no	add offset obtained from MMM
SK_WEI	yes|no	yes	use a weighted average
SK_SEC	area	[<,<:>,>]	area for computing MMM
SK_RAN	real,real	-99999,99999	valid pixel range
SK_CLP	real	3.,3.	low/high sigma clipping factor
SK_NUL	real	NULL(2)	value for rejections

Table 3.7: Keywords for combining sky calibration frames

```
mean, standard_deviation:          5.622723e+03   1.722370e+02

Method=avsigclip, low=  0.00, high=  0.00
lowclip=  3.00, highclip=  3.00
    frame #        Ncomb   Exp_time   Mode    Scale    Offset   Weight
susi0140.bdf         1       1.00 571.878   1.093        -0    0.333
susi0142.bdf         1       5.00 862.392   0.725        -0    0.333
susi0143.bdf         1       5.00 441.692   1.416        -0    0.333
---------------------------------------------------------------------
Statistics of output frame susi_140_142_143.bdf:
area [@60,@10:@1070,@1020] of frame
minimum, maximum:                  6.045866e+02   1.023942e+04
mean, standard_deviation:          6.886717e+03   2.060752e+02

                   Ncomb   Exp_time   Mean    Mode  N_undef
susi0100_ff          3      3.933 6886.72 623.478       0
Undefined pixels, set to 'null value' (=     0.000000)
---------------------------------------------------------------------
```

3.9 Processing the Data

Having obtained some background, let us now start to process the input frames according to the scheme in Section 3.7. As indicated in that section the reduction sequence consists, in a simplified version, of the following steps:

1. determine overscan correction and trim area;
2. preparing calibration frames;
3. do the corrections;
4. apply the bad pixel corrections.

3.9.1 How the Data is Processed

Before any processing on the input frame is done, the `REDUCE/CCD` command will first collect all resources needed for the calibration of the science frame(s). These include the master calibration frames, the overscan offset, and scaling parameters. So, at this point no operations are done yet. This is done for efficiency reasons: all standard calibration arithmetic on the input frame is done in one go. As an example, suppose the science frame is supposed to be corrected for dark current and to be flat fielded. From the Association Table the command first identifies the names of the master dark and flat frames, and checks for their existence. If they are not present they will be created. Next, the master dark and flat field will be checked on their processing status. If they have not been processed yet, that will first be do by another (recursive) run of the `REDUCE/CCD` command. In this second run also the scaling factors (*i.e.* exposure times and the mean of the flat field frame) will be determined.

The standard calibration operation is done by a large `COMPUTE/IMAGE` with the following input:

$$out = (in - scan - biasfrm - darkscale * darkfrm) * flatscale/flatfrm \tag{3.11}$$

Here, out is the output frame, in is the input frame, $scan$ is the overscan bias value or frame, $biasfrm$ is the master bias, $darkfrm$ and $darkscale$ are the master dark frame and scaling factor, and $flatfrm$ and $flatscale$ are the master flat field and the mean value of the flat field. In the `COMPUTE` $biasfrm$ and $darkfrm$ can also be constants.

3.9.2 Running `REDUCE/CCD`

The command `REDUCE/CCD` can process one or more science frames automatically provided that:

- the association table correctly describes the associations between the science frames and the calibration frames;
- the CCD reduction table or the `SC_...` keywords contains the correct names of the master calibration frames;
- the keywords for creating the calibration frames are correctly set.

The standard default calibration procedure involves the following processing: overscan subtraction, trimming, bias and dark subtraction, and flat fielding. The keywords to be set for controlling these options are listed in Table 3.3. Below we describe how the command will try to correct your data.

REDUCE/CCD will first identify the Association Table. From this table it gets the names of the input science frames. Next, it will try to find the master calibration frames listed in the table, and will create these if they do not exist yet. After having collected all required calibration data the input frame is checked for its exposure type. Obviously, a dark frame should not be flat fielded and hence the processing options for the dark exposures should be set differently than for the science frames. After having determined the processing options the actual processing starts.

Overscan correction and trimming

If the keyword SC_SCAN is set the first action will be to determine the bias offset. For that you can use the overscan region on the chip. This possibility is certainly helpful in case you did not obtain separate bias calibration frames or in case you want to determine the bias offset for each science frame individually.

At initialization, keywords are created to contain the overscan and image areas: OV_SEC and IM_SEC, respectively. However they are not filled yet. You can find these numbers using a number of standard MIDAS core commands to display one or more frames, or to plot a number of lines or columns. Then use the command SET/CCD to fill in or to adjust the keywords.

The basic command that does the overscan fitting is called OVERSCAN/CCD. It needs at least two input parameters: the input and output frame. A third parameter, the overscan area, may be added. If absent it will be taken from the CCD keyword OV_SEC. To determine the bias offset a number of CCD keywords, all starting with 'OV_' will be read, and hence have to be filled correctly. They are displayed in the Table 3.8

Keyword	**Options**	**Default**	**Description**
OV_SEC	coord.	?	area to be used for fitting
OV_IMODE	yes|no	yes	interactive fitting?
OV_FUNCT	lin|pol	lin	type of function to fit
OV_ORDER	integer	3	order of fit (polyn. fit only)
OV_AVER	integer	1	number of points to combine
OV_ITER	integer	1	max. number of iterations
OV_REJEC	real	3	low/high rejection factor

Table 3.8: CCD keywords for overscan fitting

Depending on the readout direction of the CCD (keyword DIRECT) the command will average the data in the overscan region, and fit these values as a function of line-number (*i.e.* average in the 'x' direction within the overscan region, and fit these as function of 'y'). The fit will be subtracted from each column (row) in your frame. In case of a zero order fit the correction is a simple constant. In the other case it will be one dimensional array.

After an interactive fit has been completed the command will ask you if you want to fit the next frame interactively as well, or if you want to apply the overscan correction to all subsequent frames. In the latter case the overscan correction will be stored as a separate calibration frame or, in case a zero order fit has been used, a single constant.

After the overscan correction is determined, the frames can be trimmed to keep only those parts of the frames that contain valid data. Obviously, this action will speed up the data processing of the subsequent reduction steps. The relevant keyword is `SC_TRIM` (default value `yes`) and `IM_SEC`, containing the data section of the frame.

Bias, Dark and Flat Field Correction

This part has already been discussed in Section 3.8. Depending on the keywords `SC_BSCOR`, `SC_DKCOR`, and `SC_FFCOR` the calibration procedure checks for the availability of the master bias, dark, and flat field calibration frames. If they can not be found they will be created using the input frames listed in the Association Table, and according to the keyword setting for combining.

The next step after having obtained the calibration frames is to process these frames. For example, after the flat is created/found it will be checked for its processing status. If it has not been processed any on-going calibration (*i.e.* of a science frame) will be interrupted, and the flat field will be processed. After this has been completed processing of the science frame will continue.

3.10 Additional Processing

3.10.1 Sky Illumination Corrections

The flat field calibration frame may not have the same illumination pattern as the observations of the sky. In this case when the field field correction is applied to the sky data, instead of being flat there will be gradients in the background. You can check this by plotting several lines over the reduced sky frame. In case of no clear variation you can continue with the correction of your science frame(s) using the standard flat. In some cases the application of the simple flat field correction does not do a good job, and there may be an illumination problem. If such deviations are present one can try to correct for these by applying an illumination correction.

The illumination correction is made by smoothing the reduced blank sky frame heavily. The illumination frame is then divided into the frames during processing to correct for the illumination difference between the flat field and the objects. Like the flat field frames, the illumination correction frames may be data set dependent and hence there should be an illumination frame for each data set.

The smoothing algorithm is a moving average over a two dimensional box. The algorithm uses a box size that is not fixed. The box size is increased from the specified minimum at the edges to the maximum in the middle of the frame. This permits a better estimate of the background at the edges, while retaining the very large scale smoothing in the center of the frame. Other tools in MIDAS can also be used for smoothing, but this may need more of the user and may take more processing time.

Blank sky frames may not be completely blank, so a sigma clipping algorithm may be used to detect and exclude objects from the illumination pattern. This is done by computing the rms of the frame lines relative to the smoothed background and excluding points exceeding the specified threshold factors times the rms. This is done before each frame line is added to the moving average, except for the first few lines where an iterative process is used. If this approach is not successful manual removal of objects (stars) is required.

Keyword	**Value**	**Description**
`CCD_IN`	name	input sky frame
`IL_TYP`	SKY	exposure type
`IL_XBOX`	5.0,0.25	smoothing box in x
`IL_YBOX`	5.0,0.25	smoothing box in y
`IL_CLIP`	yes	clipping the input pixels
`IL_SIGMA`	2.5,2.5	low and high clipping sigma

Table 3.9: Keywords for making the illumination frame

Both in the pipe line reduction and in the manual reduction the illumination corrections to the science frames will be done provided the keyword `SC_ILCOR` is set to 'yes'. In both cases it is assumed that the illumination frames are available. In addition, in the case of pipe line processing the names of the illumination corrections must be stored in the Association Table. If an illumination correction frame is absent an error message will be issued and the illumination correction for the associated science frame will not be done.

3.10.2 Creation of Sky Correction Frames

For creation of one or more sky illumination correction frames the command (`SKYCOR/CCD`) is available. Similar to other corrections, sky frames will first be processed according to the processing keywords (`SC_SCAN`, `SC_TRIM`, `SC_PXFIX`, `SC_BSCOR`, `SC_DKCOR`, `SC_FFCOR`). After this calibration step, the command will smooth the reduced sky frame(s) to create the final sky illumination frame(s).

Input for the command can be either a single sky frame, or the Association Table containing a column with the names of the master sky frames. In the first case the output is, obviously, a single illumination frame. In case the Association Table is given as input the name of the output frame names will be the names of the input frames extended with '`_ill`'. In addition, the illumination frames will be stored in an illumination column in the Association Table. This column can be used in the pipe line processing of the science frame. Default input is taken for the keyword `CCD_IN`. Smoothing parameters are taken from the the `IL_...` keywords, which are listed in Table 3.9.

After the illumination frame has been created, one can multiply the original flat field by the illumination frame, resulting in an adjusted flat field. This approach clearly has the advantage of speeding up the calibration process since it requires one calibration frame and two computations (scaling and dividing the illumination correction) less. The output frame is called sky flat. It is the flat field that has been corrected to yield a flat sky when applied to the observations.

Having done this, this sky flat can be used as the final one. How good this new flat field is can be checked by correcting the blank sky once more, using this sky flat. If the result is not satisfactory one can try to play with the smoothing parameters, or else ask for help of an experienced observer.

To create the sky flat fields the command SKYFLAT/CCD is available. As input it takes the blank master sky frame, processes it if needed, and creates the output sky flat from the smoothed processed sky and the appropriate flat field. The smoothing parameters are stored in the keywords displayed in Table 3.9. The way the command works is identical to the command SKYCOR/CCD. The default names of output sky flats are the same of the original master flat field frames. Hence, the input master flat fields, use to flat the master sky frame, will be overwritten.

3.10.3 Illumination Corrected Flat Fields

A second method to account for illumination problems in the flat fields is to remove the large scale pattern from the flat field itself. This is useful if there are no reasonable blank sky calibration frames and the astronomical exposures are evenly illuminated but the flat fields are not. This is done by smoothing the flat field frames instead of blank sky frames. As with using the sky frames there are two methods, creating an illumination correction to be applied as a separate step or fixing the original flat field. The smoothing algorithm is the same as that used in the other illumination commands. The commands to make these types of corrections are ILLCOR/CCD and ILLFLAT/CCD. The usage is virtually identical to the previous sky illumination correction commands. Obviously, after having obtained the illumination corrected flat field it is reasonable to replace the original flat fields by the corrected flat fields in the reduction table. Like is the case of SKYCOR/CCD, by default the command ILLFLAT/CCD will replace the original flat field by the illumination corrected one.

3.10.4 Fringe correction

The fringe correction should be made from regions of really empty sky. For that the sky frames should be combined such that cosmic rays and faint stars are eliminated. Hereafter, by smoothing the frame determine the average intensity level and subtract this value for the frame. After all objects have been removed from this sky frame the frame is essentially zero except for the fringe pattern. The frame is scaled to the same exposure time as the science frame and then subtracted. Because the night sky lines are variable, matching the fringe amplitude to the one in the science frame may not be as straightforward as expected, but should be possible with robust estimation.

3.10.5 Bad Pixel Correction

The CCD package includes possibilities, before doing the actual calibration step(s), to correct for bad pixels in the CCD calibration frames. This correction is applied via the command `FIXPIX/CCD` and based on existing `MODIFY` commands. Except for the input and output frame the `FIXPIX/CCD` command accepts two more parameters in the command line: the correction method to be applied and the MIDAS table containing the bad pixel(s) of bad pixel areas(s). Default value for these two parameters are stored in the keywords `FX_METH` and `FX_FILE`. In addition to these keywords three other keywords exist to control the correction procedure: `FX_FACT`, `FX_FPAR`, and `FX_NOISE`. The use of these keywords depends on the correction method applied.

Currently, the required format of the table file depends on the correction method to be applied. Below you can find a listing of the method available and with `FX_` keywords involved.

- method `area` (MIDAS commands `MODIFY/AREA`):
  parameter `degree` taken from keyword `FX_FPAR(1)`;
  parameter `constant=0`.
- method `pixel` (MIDAS command `MODIFY/PIX`):
  parameter `arfacts` taken from keyword `FX_FACT`;
  parameter `xdeg,ydeg,niter` taken from keyword `FX_FPAR`;
  parameter `noise` taken from keyword `FX_NOISE`.
- method `column` (MIDAS command `MODIFY/COLUMN`):
  parameter `col_type=V`.
- method `row` (MIDAS command `MODIFY/ROW`):
  parameter `row_type=V`.

3.11 Mosaicing of Frames

In particular in the IR range of the spectrum but also in the optical the user may want to combine several reduced science frames into a mosaic. To support this, the CCDRED context contains five mosaicing commands.

In order to align or match a number of images the user first has to run the command `CREATE/MOSAIC`. This command creates a master frame containing all input frames to be aligned and intensity matched as sub rasters. The order in which the sub rasters are put in the mosaic image is determined by a number of keywords all starting with `'MO_'`. *E.g.* the keyword `MO_CORN` determines the origin of the mosaic. Apart from the mosaic image, `CREATE/MOSAIC` also creates a MIDAS table containing all relevant information about the subrasters in the mosaic image and the ways it was created.

Using the mosaic frame and the database table, one can now do the alignment or alignment and matching of the sub raster. The alignment can be done by the command `ALIGN/MOSAIC`, the matching by two commands: `MATCH/MOSAIC` and `FIT/MOSAIC`. To be successful these commands need additional information were the images have to be glued together. The commands ALIGN/MOSAIC and MATCH/MOSAIC accept that information in three different formats: a fixed shift, a table with the x and y shifts for each subraster, or a table of common objects. The command FIT/MOSAIC only needs the database table that should contain the shifts per subraster.

The command SHIFT/MOSAIC is created in order to support the selection of common objects in adjacent subrasters. This command can be used to create a MIDAS table containing these objects and that can be used as input for the commands ALIGN/MOSAIC and MATCH/MOSAIC.

The keyword setting for the mosaicing can be inspected by the command SHOW/CCD MO. Changes can be done by the SET/CCD command. Below follows an overview of the mosaicing keywords and their default settings. The help files of the five commands give the full details.

Keyword	**Options**	**Default**	**Description**
MO_SEC	coord.	[<,<:>,>]	section for statistics
MO_SUBT	yes|no	no	subtraction option?
MO_CORN	ll|lr|ul|ur	ll	type of function to fit
MO_DIREC	row|column	row	add subraster row/column wise
MO_RAST	yes|no	no	add in raster pattern
MO_OVER	integer	1,1	space between adj. frames
MO_INTER	interpolant	lin	interpolation method
MO_MNPX	integer	0	minimal number of pixels
MO_TRIM	integer	1,1,1,1	trim columns and rows
MO_NUL	real	NULL(2)	value for rejections

Table 3.10: CCD keywords for mosaicing

3.12 Miscellaneous

Besides the standard product described in the previous sections, a number of additional commands is implemented or will be considered and implemented later. E.g. within MIDAS a command to remove cosmic rays already exists. Hence, this command can be implemented in the standard CCD pipeline procedure.

After the data have been calibrated, one might need to combine a number of science frames into a combined frame. A tool for doing this should correct for possible differences in sky background, exposure time, positions, etc. In a previous version of the CCD context such a tool did exist. We might consider porting this tool to the new CCD context.

3.13 Commands in the CCD package

Below follows a brief summary of the CCD commands and parameters for reference. Except for the already existing command `FILTER/COSMIC`, the commands in Table 3.11 are initialized by enabling the CCD context with the MIDAS command `SET/CONTEXT CCDRED`. Parameters will generally obtained from the CCD keywords; however some of the keyword settings can be overruled by specifying them on the command line.

HELP/CCD	[keyword]
	provide help information for a CCD keyword
INITIAL/CCD	[name]
	initialize the ccd package
LOAD/CCD	[instr]
	load telescope/instrument specific default
SET/CCD	keyw=value [...]
	set the CCD keywords
SAVE/CCD	name
	save the keyword settings
SHOW/CCD	[subject]
	show the CCD keyword setup

Table 3.11: CCD commands

REDUCE/CCD	[in_spec] [out_frm] [proc_opt]
	(partial) calibration of one or more science frames
COMBINE/CCD	exp_type [in_spec] [out_fram]
	combine CCD frames using catalogue input
OVERSCAN/CCD	in_fram out_fram [sc_area] [mode]
	fit bias offset in the overscan region and correct
TRIM/CCD	in_fram out_fram [im_sec] [del_flg]
	extract the useful data fro the ccd frame
FIXPIX/CCD	in_fram out_fram [fix_file] [fix_meth]
	correct bad pixels using a pixel file
BIAS/CCD	in_fram out_fram bs_fram
	correct input frame for the additive bias offset
DARK/CCD	in_fram out_fram dk_fram
	correct the input frame for additive dark offset
FLAT/CCD	in_fram out_fram ff_fram
	do a flat fielding of the input frame
ILLUM/CCD	in_fram out_fram il_fram]
	do an illumination correction of the input frame
FRINGE/CCD	in_fram out_fram fr_fram
	do a fringe correction of the input frame
FRCORR/CCD	[in_spec] [out_spec] [xboxmn,xboxmx] [yboxmn,yboxmx] [clip] [losig,hisig]
	make fringe frame
ILLCORR/CCD	[in_spec] [out_fram] [xboxmn,xboxmx] [yboxmn,yboxmx] [clip] [losig,hisig]
	make flat field illumination correction frame(s) (TBD)
ILLFLAT/CCD	[in_spec] [out_fram] [xboxmn,xboxmx] [yboxmn,yboxmx] [clip] [losig,hisig]
	make illumination corrected flat field frames (TBD)
SKYCORR/CCD	[in_spec] [out_fram] [xboxmn,xboxmx] [yboxmn,yboxmx] [clip] [losig,hisig]
	make sky illumination correction frame(s)
SKYFLAT/CCD	[in_spec] [out_fram] [xboxmn,xboxmx] [yboxmn,yboxmx] [clip] [losig,hisig]
	apply sky observation to flat field
ALIGN/MOSAIC	in_frm in_tab out_frm method,data [xref,yref] [xoff,yoff] [x_size,y_size]
	align the elements of the mosaiced frame
CREATE/MOSAIC	in_cat out_frm out_tab nx_sub,ny_sub
	mosaic a set of (infrared) ccd frames
FIT/MOSAIC	in_frm in_msk in_tab out_frm [match] [nxrsub,nyrsub] [xref,yref] [x_size,y_size]
	align and match the elements of the mosaiced frame
MATCH/MOSAIC	in_frm in_tab out_frm method,data [match] [xref,yref] [xoff,yoff] [x_size,y_size]
	aign and match the elements of the mosaiced frame
SHIFT/MOSAIC	out_tab [curs_opt] [csx,csy] [clear_opt]
	get x and y shifts of subrasters in the mosaiced frame

Table 3.12: CCD command continued