Astronomical Image Reduction and Comet Photometry with AIRTOOLS (v3.2)

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Contents

1 Introduction

The AIRTOOLS software - or **A**stronomical **I**mage **R**eduction **TOOLS**et - has been developed for the purpose of calibrating and analyzing images of astronomical objects captured by CCD or DSLR cameras. The software provides a large number of functions for basic image calibration (e.g. bias-, dark-, flatfield calibration, raw development of bayered images), for automated object recognition, registration and stacking as well as automated astrometric and photometric calibration routines.

Moreover specialized tools have been developed to process comet observations with the goal of obtaining total coma brightness estimates matching closely those of visual observers. The invention of "Large Aperture Photometry" should allow to complement visual observations, extending to fainter magnitude limits (due to deep exposures) with the benefit of added reproducibility.

Recently a graphical user interface has been added to make the software more user friendly. It tries to derive suitable parameters for the underlying functions and programs to hide as much complexity as possible from the average user. Internally a large number of open source software programs for image analysis and visualization is used, e.g. *ImageMagick*, *GraphicsMagick*, *Netpbm* und *Gnuplot*. Powerful and extremely versatile tools well known in the professional area of astronomical image reduction are used as well, e.g.

- SAOImage DS9: Image viewer with extensible tools for analysis and catalog access
- Astromatic Software by E. Bertin: Most notably *sextractor* (Object recognitionand extraction), *scamp* (astrometry), *swarp* (image transformation and stacking), *skymaker* (modelling objects)
- Stilts by M. Taylor: Analysis, filtering and transforming tabular data (e.g. FITS tables)
- WCSTools by J. Mink: Tools to create and manipulate coordinate system information

The AIRTOOLS software is freely available. The project - including source code - is hosted at https://github.com/ewelot/airtools. Pre-compiled binary packages are provided for several Linux distributions.

The AIRTOOLS software has been developed in the hope to proove useful. Its development relies on your feedback, so please do not hesitate to ask any question at t_lehmann@freenet.de. Any suggestion or comment or call for help is welcome.

Good luck and clear skies!

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2 Installation

The AIRTOOLS software must be installed on a Linux operating system, which is not commonly used in the amateur astronomy community. There exist several approaches on how to fullfill this requirement:

- use a dedicated Linux computer or
- configure your computer for dual booting of either Windows (or OS/X) or Linux or
- set up a virtualization software which runs the entire Linux OS in an encapsulated application on your Windows (or OS/X) computer

We will focus on the third approach as it is probably the most convenient way of running Linux on Windows or OS/X hosts. Once the Linux OS is up and running the AIRTOOLS software itself must be installed. The overall installation process therefore can be outlined by the following steps which are described in depth later on:

- install the virtualization software
- setup a virtual machine for the Linux OS
- install the Linux OS on the virtual machine
- install AIRTOOLS on the (virtual) Linux system

The full installation will take about half an hour to complete.

2.1 Installing Oracle VirtualBox

VirtualBox (http://www.virtualbox.org) is a free and powerful virtualization software for enterprise and home users. Get the latest software package (version 6.0.12 at the time of writing) for your host operating system from the Downloads page and install it.

Subsequently you should install the "Oracle VM VirtualBox Extension Pack" for improved performance and additional virtual hardware features. Get it from the appropriate section of the previously mentioned download page. Click on "All supported platforms" and open it using the Oracle VM VirtualBox software. You might be asked to provide credentials to allow installation.

2.2 Setup of a Virtual Machine for Linux OS

Start the Oracle VirtualBox Manager, if not running already. Click on the "New" button and fill in the name of the new VM, e.g. xubuntu-vm. Depending on the name you have choosen you might have to select Type="Linux" and Version="Ubuntu (64-bit)". Continue by pressing "Next".

Set the memory size to >=2 GB (recommended 4 GB or up to 75% of physical RAM) and press "Next".

Create a virtual hard disk of type VDI of fixed size. You can use the proposed file name but it is recommended to create the virtual disk file on a fast physical hard disk drive, e.g. SSD. The file size should be >=50 GB to serve for roughly 10-20 comet observations, based on 10-20 individual exposures each. If you intent to use the AIRTOOLS software regularly to analyze all your comet observations then you should create a much larger virtual hard diskAfter pressing the "Create" button the virtual machine is created.

It is recommended to tweak some additional parameters for improved performance. Click the "Settings" button to access the following tabs:

- Tab System/Processor: increase number of CPU to >=2 (up to number of physical cores minus one)
- Tab Display/Screen: increase Memory to 64 MB

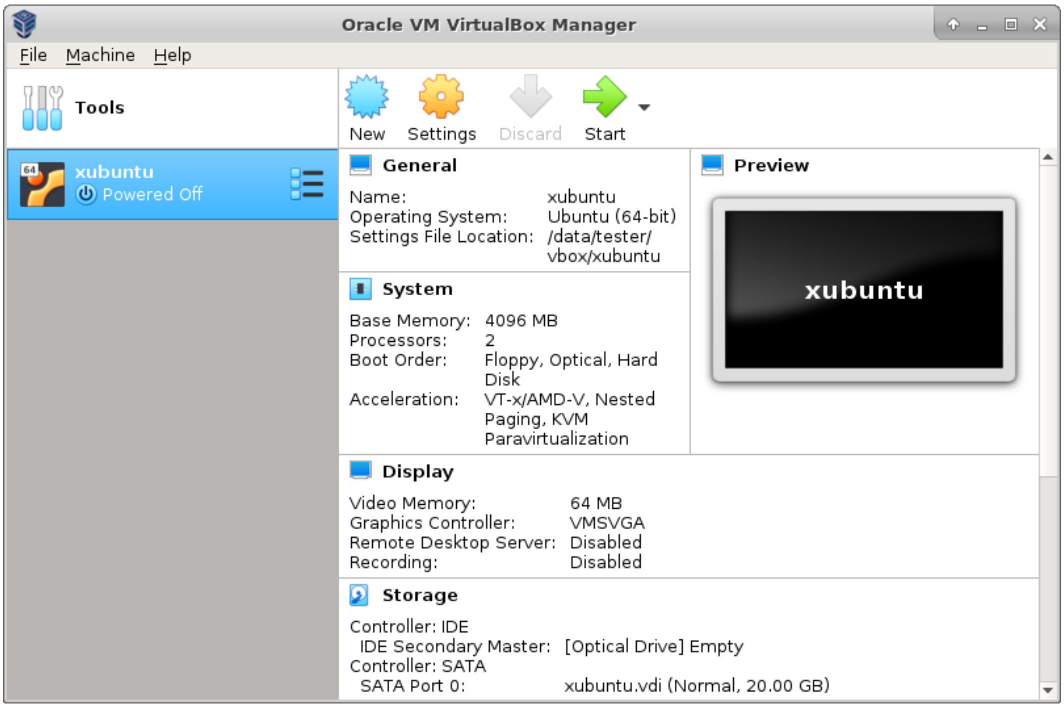


Figure 1: Setup of a virtual machine in the Oracle VirtualBox Manager

- Tab USB: choose USB 3.0 Controller

Finally you should create a desktop icon to directly launch the virtual machine. Locate the name of the virtual machine on the left side of the VirtualBox Manager, press the right mouse and select “Create Shortcut on Desktop”.

2.3 Booting Install Medium of the Xubuntu Linux distribution

Download the ISO image file of the latest Xubuntu LTS release from http://xubuntu.org/. Please note the LTS version label, which indicates a “Long Term Support” release. This Linux OS version is well supported by the AIRTOOLS software. Choose a mirror download close to your location and download the 64-bit desktop image. At the time of this writing it is named `xubuntu-18.04.3-desktop-amd64.iso`.

The ISO image file is used in place of a install medium for the virtual machine. To do so you have to start the VirtualBox software (if not running already) and press the “Settings” button of the selected virtual machine.

Select the “Storage” tab. Within “Storage Devices” click on the CD symbol (labeled “Empty”) and from “Attributes” click the CD symbol near the right border of the window and select the previously downloaded ISO file. Pressing “OK” will save your modified settings and you are ready to start the virtual machine by pressing the green “Start” button.

The following boot process is very similar to a regular boot process of a install CD/DVD on a real computer. In addition, the current virtual machine can be used to start a fully functional Linux live session to evaluate or experiment with the Xubuntu Linux OS (but this is not our goal).

2.4 Installing Xubuntu Linux

Now, the Linux OS has to be installed into the presently empty virtual hard disk of the running virtual machine. Please make sure your host computer has a working internet connection.

From the initial "Welcome" screen you choose your prefered language and click the "Install Xubuntu" button to start the setup program of the installer. You can accept default settings on all the following screens ("Keyboard layout", "Updates and other software", "Installation type"). Please note that the Linux OS is installed on the virtual hard disk only, it does in no way erase data from your host computer's file system. Finally click "Install now" and confirm writing the changes to the (virtual) disk by the "Continue" button.

While the installation process has already started in the background you are asked to provide a few additional informations:

- "Where are you": Select your time zone by clicking close to your geographic location
- "Who are you": Fill in your (full) name, a computer name, username and user password. Note that choosing "xubuntu" for the name of the virtual computer is allowed, despite the given warning message. You might toggle the "Log in automatically" radio button for the sake of convenience.

Continue the installation process which will take a few minutes to complete. Finally you are asked to restart the (virtual) computer. This will take a little time and you might be prompted to remove the installation medium (the ISO file used in the virtual CDROM drive). Press the "Enter" key to continue. There are few combinations of host hardware, VirtualBox version and guest operating system where the virtual machine is not rebooting but showing a black screen for infinite time. In this case you must manually close the virtual machine window and select "Shutdown VM". In the VirtualBox Manager, check that the ISO file is removed from the virtual CDROM drive and start the virtual machine again.

The virtual machine (in virtualbox jargon the "guest" system) will now boot the installed Linux OS from the virtual disk and automatically logs in to the Xubuntu Linux desktop. Please note the different sections of the VirtualBox guest application window: the VirtualBox guest machine's menu bar at the top, a status bar at the bottom and the virtual screen of the Linux Desktop in between.

After booting into the virtual Xubuntu Linux desktop you might be faced by a message window stating "Incomplete Language Support". It is save to skip the update until later as it is not required by the AIRTOOLS software installation.

Similarly the "Software Updater" might pop up at any time with the information about available updates of currently installed packages. Again, those updates are not required right now but should be completed after the AIRTOOLS installation.

2.5 Xubuntu Desktop Basics

On the top of the desktop screen there is a (dark) desktop panel. If you click on the small icon on the left of this panel (it uses the Xubuntu logo which mimics the head of a mouse) the main application menu pops up. From there you can start programs, tweak several desktop settings, log out and shutdown the virtual Linux system. Note the location of the "Log out" icon at bottom-right of the menu, which is also used to shutdown or restart the Linux OS. Get familiar with how to start the web browser and the file manager and how to shutdown the Linux OS.

For additional information please consult the official Xubuntu Documentation or other tutorials on the web. Please keep in mind that you do not have to worry about any hardware specific setups in your Linux system (or for example network connection) because

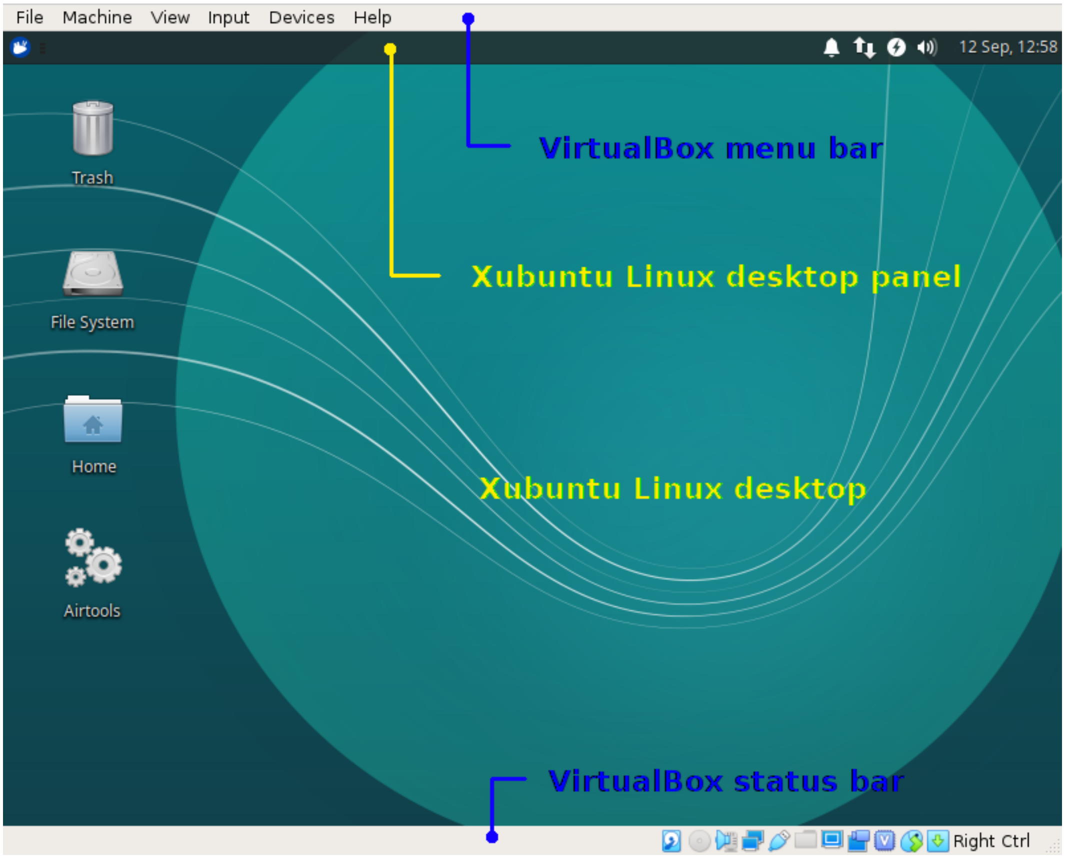


Figure 2: Xubuntu Linux (with AIRTOOLS) running in VirtualBox

all communication to the real devices of the host computer is transparently handled by the VirtualBox drivers.

2.6 Installing VirtualBox Guest Additions

The Guest Additions are designed to be installed inside a virtual machine after the guest operating system has been installed. They consist of device drivers and system applications provided by Oracle VirtualBox that optimize the guest operating system for better performance and usability.

For installation you must

- Boot the guest OS.
- Go to the VirtualBox guest menu item "Devices" and press "Install Guest Additions CD Image". A new CD icon appears on the Linux desktop and a few seconds later the Linux file manager is showing the contents of the Guest Additions virtual CD.
- Open a terminal window using "File" menu of the file manager and select "Open Terminal Here".
- From the command line of the terminal run the following command (you will be asked to provide your password): `sudo apt-get install build-essential`
- Start installation by entering the command: `sudo bash VBoxLinuxAdditions.run`
- If installation has finished close the terminal window and eject the virtual CD by using the eject button (caret-up) next to the CD entry in the file manager.
- Finally you must reboot the Linux guest.

After a restart of the Linux virtual machine you may adjust the guest window size and effectively the screen size of the Linux desktop as needed.

Moreover, you can now configure the virtual machine to use a shared clipboard between host and guest and use drag-and-drop between both systems. Those settings are activated from the "Devices" menu of the VirtualBox guest menu bar on the top of the window.

2.7 Installing the AIRTOOLS software

The AIRTOOLS project is hosted at https://github.com/ewelot/airtools where you can find the latest source code and documentation. Pre-compiled binary packages are build for several Debian based Linux distributions (e.g. Xubuntu) and can easily be installed by running an install script.

The download of the installer requires a few more steps than usual, because you will fetch it from a GitHub source repository:

- From within the Linux virtual machine start the web browser and open the project page at https://github.com/ewelot/airtools.
- Locate the install script `install_deb.sh` within the source tree and click on it.
- On the top-right of the displayed script source locate the button labeled "Raw", click it with right mouse button and select "Save Link As" which will download the installer file.

You run the installer by following the next steps:

- Locate the directory which contains the previously downloaded file `install_deb.sh`. E.g. double-click the "Home" icon on the desktop which starts the file manager and open the "Downloads" folder.
- Open the "File" menu of the file manager and choose "Open Terminal Here". A new terminal window will pop up, ready to enter commands to be executed.
- Enter the following command on a single line: `sudo bash install_deb.sh`

- You must provide your password before the installation is started.

Upon first installation of the AIRTOOLS software the script will download many other required software packages from the official Xubuntu repository. This might take a few minutes depending on the bandwidth of your internet connection. At the end of the installation you will receive some log messages about success (or failure) in the terminal window. A log file is created for later reference and a new icon is showing up on your Linux desktop.

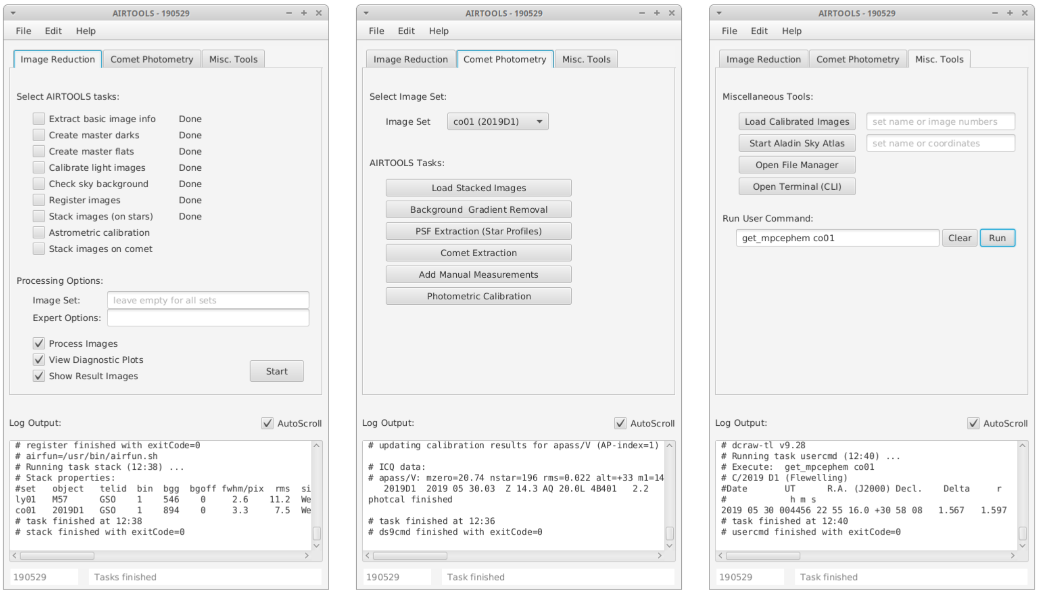
2.8 Updating the AIRTOOLS software

An update of the AIRTOOLS software is issued the same way as the initial installation, that is by downloading and executing the installer `install_deb.sh`. Though, it will complete much faster due to much smaller amount of required downloads.

3 The AIRTOOLS Graphical User Interface

The graphical user interface consists of three tabs. The first tab is used for all basic image reduction steps to process the raw images to finally obtain stacked images of your targets. The second tab is dedicated to the comet extraction and large aperture photometry tasks. Finally, a couple of handy tasks are placed on a third tab.

The lower part of the interface will display text output from any processing steps. There you can watch progress of the running tasks, see some measurement results but also possible error messages. In a few cases during the comet extraction part you will get information about a required user action written to the same log area. Please note that all the textual output is logged to a text file 'airtools.log' as well which comes handy in case of errors are simply for later reference.



4 The first AIRTOOLS Project

4.1 What is a Project?

When observing during a clear night, many different exposures are taken, usually of different targets. It is common practice that an observation of a single target consists of multiple bracketed exposures. Serious observers are capturing calibration frames (darks, flats) as well. It is possible that different instruments (telescopes, filters, cameras) are used. All these images of a single night will be analyzed in a single AIRTOOLS project. Consequently, the project directory itself (and related ones) must have the date of observation used as part of its name. It is good practice to use the date at the beginning of the night.

The following directories are related to a project:

- Project directory:
  It stores all config files of this project, results from image reduction and analysis (images, plots, data tables) and log files. After finishing a project this directory should be saved, e.g. to an external disk drive.
- Raw directory:
  Used for all the individual raw images as created by your image asquisition system, both light frames and calibration images related to the project.
- Temporary directory:
  Used to store individual calibrated images of the project which are used by several different AIRTOOLS analysis tasks as well as temporary files created during those tasks. This directory may be savely deleted when the project is finished.

4.2 Setting up the first Project

Upon first start of the AIRTOOLS software the base directories for the three above mentioned storage places must be defined. Each new project will later create a new subdirectory below these places.

Next, the setup for the first project must be configured. Select the date of observation. This will be used to make initial suggestions for names of the project directory, raw directory and temporary directory. It is allowed to modify those names, e.g. append a letter. E.g. you might want to repeat the image reduction of a given night using other parameters without interfering the original analysis. In that case you could use the same raw directory name but different names for the project and temporary directories.

Further settings are:

Parameter files: Every project will use parameter files for certain configurations. Some of these files are rarely modified and therefore can be copied over from the last project. Modifying this default behaviour is almost never required.

Site: Enter the name of your observatory site as it is used in the parameter file `sites.dat` later on (see below).

TZoff: Enter the time zone offset with respect to UT in hours. Use the value which corresponds to the time of observation written to the header of your raw images. If your data acquisition system stores UT then you need to enter 0 here.

4.3 Parameter Files

The different image acquisition systems used by amateurs do normally write some meta data about telescope, camera etc. to image headers. Those data is required by any image reduction and analysis software. Unfortunately, keyword names and the format of their values is not standardized in any way.

We therefore decided to supply most redundant data by means of parameter files - simple text files, structured in a tabular way. The first line in the file is used to define the columns (name of parameters). Anything that appears after the `#` sign in any other line is considered a comment and will be ignored. Each line describes a separate entry and each parameter value is made by a single word. In some places you are allowed to use the character `-` to indicate an unknown value.

At first the information about your observatory site must be added to the corresponding parameter file `sites.dat`. From the AIRTOOLS application's "Edit" menu select "Edit Site Parameters". This will start a simple text editor (called *mousepad*). The parameter file should have a few entries already, which can be used as reference when adding a new line for your site. The column description is as follows:

ID: This is a unique short identifier for your site (three letters)

location: A unique single word for the name of your observatory location. The previously used entry of the observatory site during project setup must match one of these.

long: Geographic longitude in degrees, negative for a location east of Greenwich meridian.

lat: Geographic latitude in degrees, negative for a locations south of the equator.

alt: Altitude of your observatory in meters.

Save your edits and close the text editor.

The next information you have to provide is those of the instrumentation you have used. Open the parameter file `camera.dat` by selecting "Edit" and "Edit Camera Parameters". Each combination of telescope and camera must have a dedicated entry. Use the existing sample entries as a reference for your newly added lines. The columns used are:

tel: Unique identifier for the telescope and camera, using 3-6 alphanumeric characters.

flen: Focal length of the telescope or camera lens in mm.

aperture: Open aperture of the telescope or camera lens in mm.

fratio: F-ration of the telescope or camera, that is `flen/aperture`.

camera: Camera model, used for your convenience only

camchip: Camera and sensor keys used in final ICQ records of a comet measurement. Refer to the lists of camera keys and sensor keys. Both values have to be provided in a single word, using the character `/` as a delimiter. If you for example have used a Canon 6D DSLR for imaging then the correct entry would be `CDS/CFC`.

flip: Indicate if the image data is flipped top-down (1) or not (0). Essentially this describes the order and interpretation of FITS data: If the FITS file is organized in such a way that the data of the bottom image row comes first and that of the top-most row latest then it is considered unflipped and the other way it is flipped. It seems that MaximDL stores data in a flipped manner.

rot: If the camera is rotated with respect to the sky coordinate system then you should provide a value different from 0. If true north is left on your image then use a value of 90. A rough approximation is sufficient.

rawbits: Original bitdepth or number of bits per pixel in a single color channel. Note that at start of the image reduction the counts (ADU, intensities) are scaled up to the 16-bit range where needed.

satur: Saturation value. Strictly speeking the upper counts (ADU) for which the camera response is linear (proportional to the illumination intensity) must be provided. We need the value after scaling up to the 16-bit range, e.g. if you are using a consumer DSLR where response is linear up to 2/3 of its dynamic range then you should enter a value of 40000 approximately.

gain: Number of electrons per ADU. Use a value of 1 if it is not known.

pixscale: Approximate value of the size of a pixel on the sky in seconds of arc.

magzero: Zeropoint of the non-calibrated instrumental magnitude scale. This is the magnitude of a star which yields a signal of 1 count (ADU) in a 1 second exposure. Initially you can use an arbitrary value but it is useful to refine it to something close to the zeropoint of the calibrated scale (see log output of your first photometric calibration later on)

ttype: Telescope type: L=reflector, R=refractor, A=photo Lens

ctype: Sensor type: CCD=monochrome CCD, DSLR=DSLR raw image (as stored in camera, e.g. files with extension CR2 for a Canon DSLR), use BGGR or RGGB for a one-shot-color CCD or CMOS sensor with a Bayer filter matrix.

Save your edits and close the text editor. Remember that for any subsequent new project you will be able to copy over those parameter files. You only need to add entries to these files if using a new observatory site or a new instrument for the first time.

4.4 Raw Images and Image Set Definition

TODO: - Description of supported RAW formats - Notes about FITS header keywords

Now it is time to copy your raw images to the project's raw directory within the Linux file system. There are different solutions to handle the file transfer between the host operating system and a VirtualBox guest. We suggest using an external USB pen drive or USB disk for this purpose.

Use the file manager of your host OS to copy the raw image files to the USB disk. Wait until all data have been completely written to disk. From the running Linux virtual machine locate the "Devices" menu entry on the VirtualBox VM menu at the top of the window. Select "USB" and you will see a list of USB devices from which you need to identify and select the USB disk. After a few seconds a new USB disk icon will apear on the virtual Linux desktop and little after the file manager window pops up. Use the common copy-and-paste feature to copy your raw images from the USB disk to the appropriate raw directory of the current project. Finally push the eject button on the USB device entry of the file manager and close it.

You are now going to start the first AIRTOOLS task. By pressing the "Extract basic image info" the program reads meta data of all raw image files. At the end an editor window pops up which shows an overview of relevant data for each image. Please note the column which holds a 4-digit image number associated with each image (first column if images are in FITS format, second column if images are RAW files from DSLR). Images are referenced by this number throughout the reduction process.

Now it is time to group the individual images to form "image sets". An image set is a number of images of the same type and target, e.g. a sequence of dark exposures with a given exposure time or a bracketed series of exposures of a comet. All image sets of the project are described in a parameter file called `set.dat` which must be created by yourself. From the AIRTOOLS application's main menu select "Edit" and "Edit Image Set Definitions". Enter lines similar to the following example:

```
# 190329
# Newton 400 mm f=1040 mm
# Canon 5D MkII (CDS), ISO 800, MaximDL

# UT
# h:m set  target type texp n1 n2   nref dark flat tel
20:30 dk01 bias     d   1 0001 0010 -    -    -    N16C
00:03 dk02 dark     d 300 0011 0016 -    -    -    N16C
07:49 sk01 flat     f   1 0017 0022 -    dk01 -    N16C
00:14 co01 2017K2   o 300 0023 0026 0024 dk02 sk01 N16C
```

The syntax is as follows: everything after the character `#` is considered a comment. Each line (uncommented and non-empty) defines an image set using at least 11 fields (words separated by spaces) which are:

h:m: The local time at start of observation (approximation only, not used by the program)

set: The name given to the image set. We do recommend the following scheme: Use the first two letters to denote the image type, where "dk" is for darks (and bias exposures) and "sk" for sky flats, "co" might be used for a comet observation. Any other deep sky target could use two (or three) letters from the constellation it belongs to. After the letters use a two-digit running number, so the image set of the first comet target would be named `co01`, the second `co02` and so on. The set name is used in many places later on, e.g. in the file names of computed stacks and other result files.

target: Short name of the target observed (up to 8 characters).

type: Type of images (1 character): d=dark/bias, f=flat, o=lights, a=addition (continuation) of a previously defined image set. If you for some reason would like to exclude a series of images from the analysis (e.g. a focus sequence) but keep the information about those files for your record then use the character `-` in place of the image type.

texp: Exposure time of a single exposure in seconds.

n1: Number of the first image of the set.

n2: Number of the last image of the set.

nref: Number of the image which is used as a reference image for stacking, typically it should be close to the middle of the bracketed sequence. Not used for darks and flats.

dark: Name of the master dark (image set name) used for calibration.

flat: Name of the master flat used for calibration.

tel: Identifier of the instrument (telescope/camera) used. This must match a valid entry in `camera.dat`.

A note about master calibration images. It is not required and not convenient to capture darks and flats in every night. After you have collected some calibration sets and build some master files by AIRTOOLS it is common practice to reuse them later on. This can be done by simply copying them over from older project directories to the current one using the file manager.

5 Image Reduction

The “Image Reduction” tab is the first tab of the AIRTOOLS graphical user interface. Its main purpose is to provide general tasks for basic reduction of astronomical images that is to process all of the raw image sequences to obtain deep stacked result images of your targets.

The tasks are presented in logical order and may be run one step after the other - which is recommended for first time users - or run completely unattended, including astrometry and blind stacking on a moving comet. Just select the tasks you wish to run in a row. Suitable parameters are determined automatically and will work in most cases. Special cases can be handled by supplying options via the “Expert Options” entry (see Appendix ???).

It is possible to limit the requested tasks to run on a specific image set by providing the set name in the appropriate text entry field.

The final group of checkboxes determines which part of the tasks is executed. Normally, you will want the program to process your images and display any diagnostic plot it creates and show all result images.

Pressing the “Start” button causes the selected tasks to execute. At any time you may interrupt operation by pressing the same button again. Note that interruption is typically defered by a couple of seconds. Running a task for a second time will process any remaining image sets only.

5.1 Master Darks and Flats

The processing of calibration images involves a mixture of median and average operations. For best results it is therefore adviced to capture in multiples of 6 exposures, e.g. 6 individual dark images at any required exposure time (and temperature) and 12 individual flat images for any filter used.

Throughout this manual we refer to the term master dark by meaning of an image which has not been subtracted by a bias image. Within this definition a bias image is just a dark image at zero seconds exposure time. Furthermore a master flat image is a dark-subtracted flat field (where the corresponding master dark was taken at the same exposure time, sometimes called a flat-dark).

If you don’t know your camera/sensor very well then it is a good idea to take more exposures - especially darks. The processing routines include measurements of the dark level in each image. A plot of this measurements is displayed and you can evaluate the stability of the mean intensity level. In addition, the difference of each individual dark exposure with respect to the mean image is computed. A mosaic of the much downsized and contrast enhanced difference images is created and displayed. This is helpful again to judge sensor stability and health. You may measure image intensity withing self defined regions. Note that the mean intensity of difference images has been shifted to 1000 and streched by a factor of 10.

The number of individual flat images has to be choosen to be large enough to provide suitable signal to noise (not degrade the signal to noise of the stacked target image). Also its intensity level should be choosen carefully to provide high signal but fall well within linear range of the sensor response. Creating high quality flat fields is a challenge but crucial for obtaining precise photometry of extended objects like comets.

5.2 Image Calibration

Image calibration involves the subtraction of the master dark image and division by the master flat image. The calibrated images are stored in the temporary directory defined for the project. Their name starts with the image number associated with each individual raw image. Calibrated images are not overwritten by default and kept throughout the project.

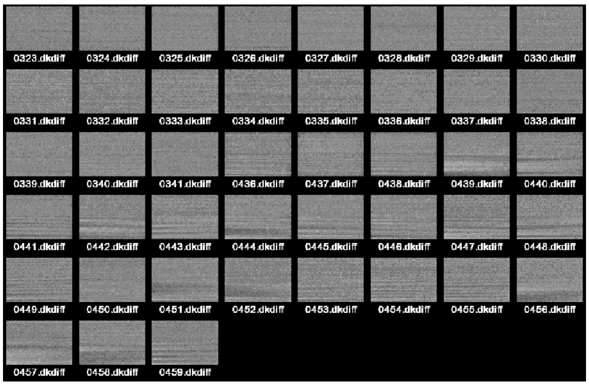


Figure 3: Variation of dark images with respect to master dark (Pentax K-5II DSLR)

There is no plots or result images produced by the caibration task. Though you may display certain calibrated images by using actions from the “Misc. Tools” tab: enter an image set name or specific image numbers and press the button “Load Calibrated Images”.

For DSLR images it is possible to provide a file which contains a list of known hot pixels. Those will be replaced by the interpolation algorithm during the debayering step. The hot pixel file must be named using the telescope/camera identifier as defined in `camera.dat`, e.g. if the identifier is `N16C` then provide a hot pixel file `hotpix.n16c.dat` is the project directory. It is a simple text file containing one line of at least 3 space separated values per pixel. The values are image coordinates in x (starting at left with 0) and y (starting at top with 0) and a third fixed value of 0.

In addition it is possible to manually create masks of bad image regions where necessary (e.g. satellite trails) on calibrated images. Load the calibrated images and use SAOImage regions to surround the affected areas. Save the regions file under the `bgvar` subdirectory using a name containing the given image number, e.g. `0003.bad.reg`. Those image regions will be excluded from the stacking process later on.

5.3 Background evaluation

Often, observations are carried out under non-perfect conditions. If you plan to estimate photometric magnitudes from extended sources, then it is important to carefully check image quality and possibly reject some exposures from stacking of a long sequence of images. Therefore a check of variation in the sky background has been added to the processing pipeline. At first, a downsized background map is created for each image and the average intensity level is plotted.

Then an average background image is created for each image set as reference and difference images are created for each individual exposure. A mosaic of those thumbnail difference images is finally displayed.

5.4 Image Registration

The stacking process involves several steps. At first, sources (stars) are extracted for each calibrated image. Then sources are matched with respect to the reference image of the given set. Some of the brighter, unsaturated stars are used to measure relative brightness between images and an average value of star size (full width at half maximum). Those values are plotted to allow to quantify image quality and sky conditions.

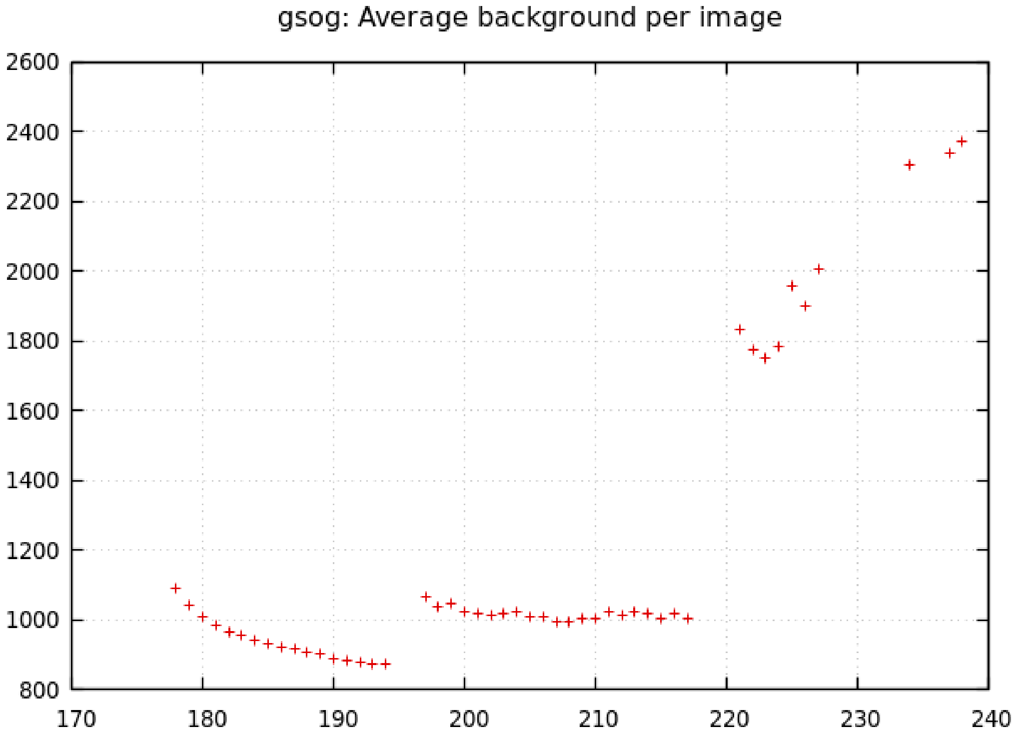


Figure 4: Background intensity (3 image sets)

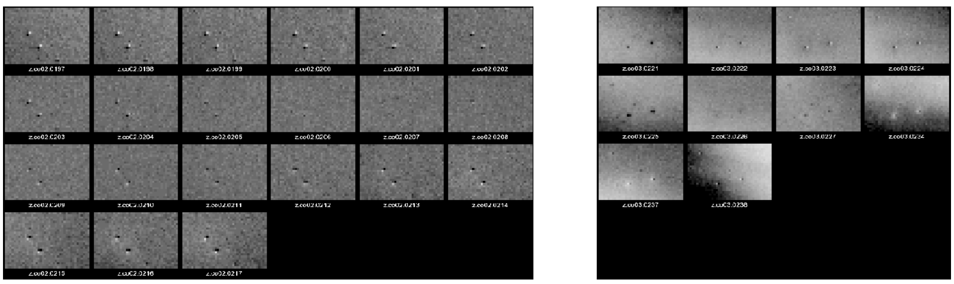


Figure 5: Background variation (2 different image sets)

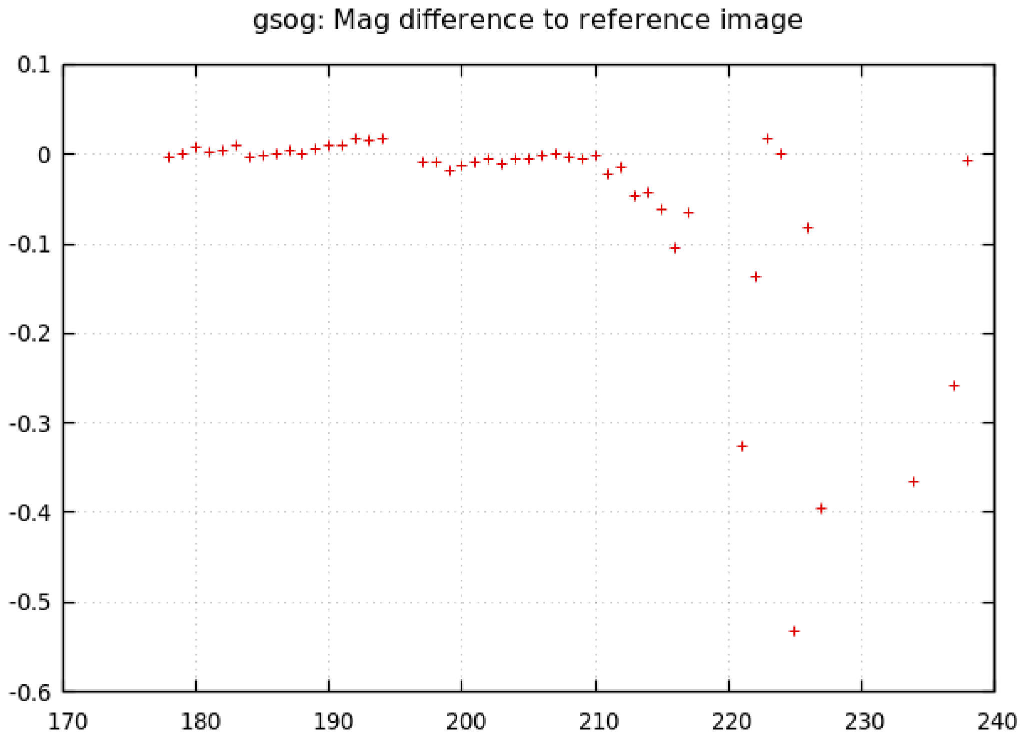


Figure 6: Mag difference

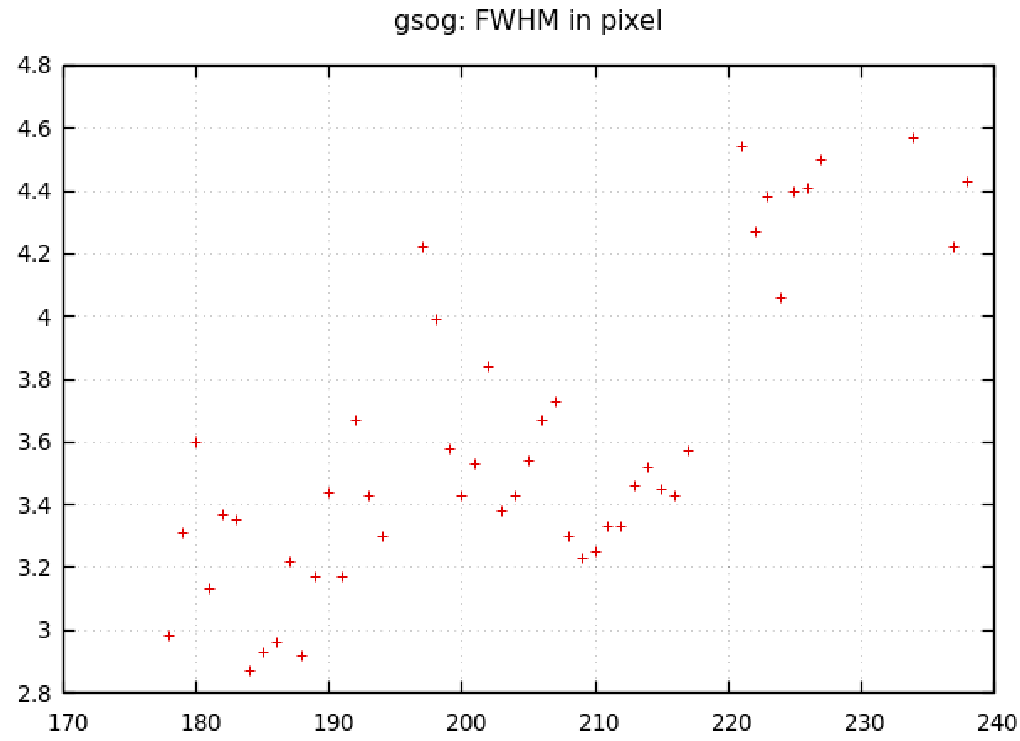


Figure 7: FWHM of stars

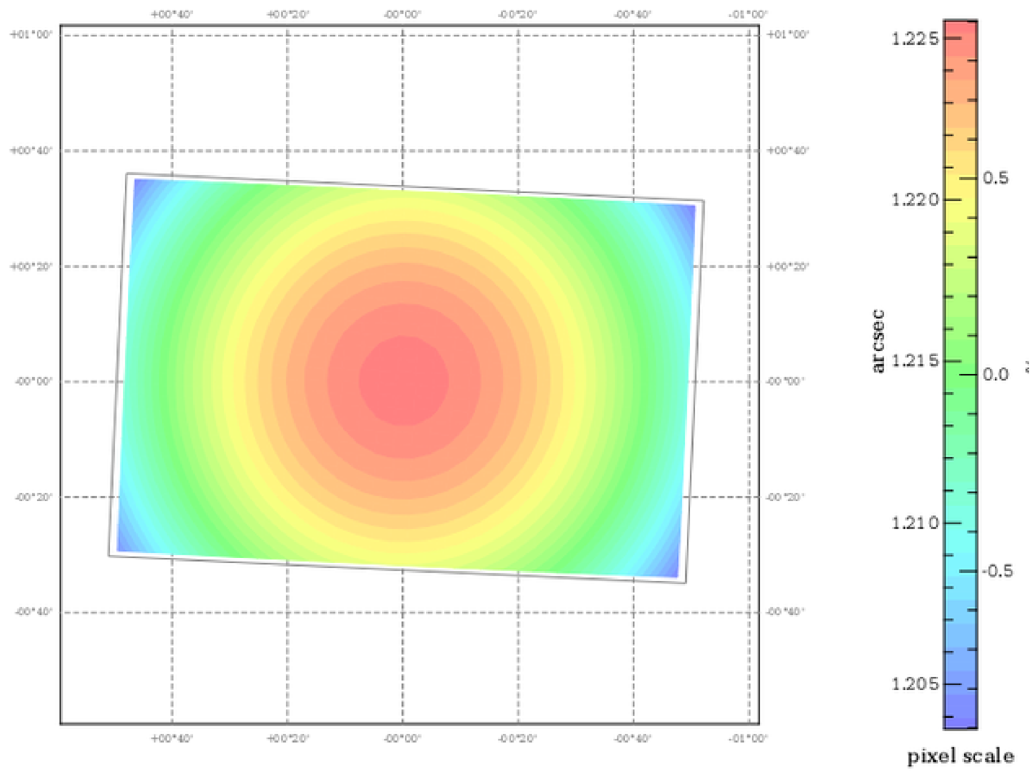


Figure 8: Distortion map (8" Newton f/4, Pentax K-5II)

5.5 Stacking and Astrometry

Finally the images are projected to the reference image arbitrary coordinate system and co-added. The stacked image is used to create an object catalog. Stellar sources of this catalog are matched against a local copy of the Tycho2 catalog to obtain a first astrometric solution (using an offline Astrometry.net solver). In a second step a global model is fitted (using UCAC-4 catalog) over the whole image including to map some degree of distortion. This new WCS model is saved and used later on to identify objects against photometric catalogs. The overall astrometric accuracy is printed to the log output and several diagnostic plots are created to show deviations from catalog position in different axes, a distortion map showing pixel scale variation and a sky chart with detected sources (green).

With the help of the astrometric solution and comet ephemeris data fetched from MPC it is possible to predict the comet motion between individual exposures and use this information to do blind stacking on the comet.

The resulting output images have names starting with the image set name. Stacks centered on the moving comet have a fixed string suffix `_m`. The images contain 16bit integer data and are either in PGM (monochrome, gray image) or PPM (RGB image) format. The choice of these formats over FITS is mainly due to historic reasons - the software originally was written to reduce DSLR images only - and because many of the underlying image reduction software programs simply do not operate on (RGB-) FITS images. image metadata are stored in associated ASCII header files using the file extension `.head`.

6 Large Aperture Comet Photometry

6.1 Comet Observation

6.2 PSF Extraction and Star Removal

6.3 Measuring the Comet

6.4 Photometric Calibration