# User Manual

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SATRO

Simulation and Analysis Tool for Radio Observations

# Contents

# 1 Introduction

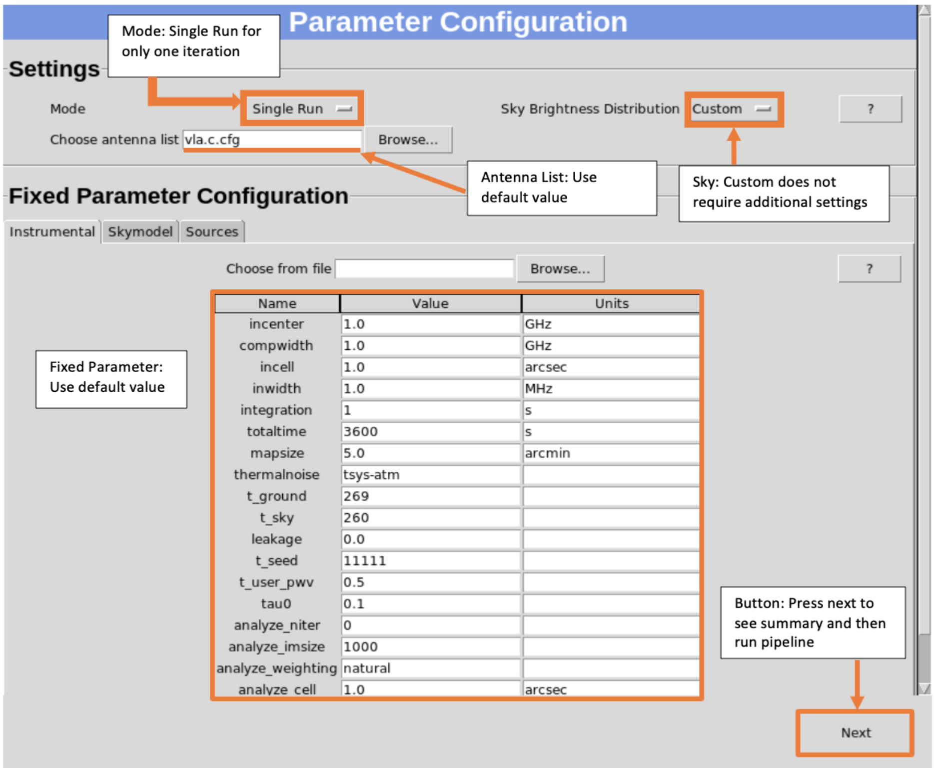
This user manual describes how to run the pipeline for simulating radio observations with a provided graphical user interface using CASA (Common Astronomy Software Application) packages and its parameters settings. The graphical user interface offers parameter selecting and setting for simulations with radio interferometer such as VLA or ALMA.
The pipeline focuses also on the output data which is generated for each iteration. The output data contains important measurements and radio images for further analysis and inspection.

The use of this application requires basic knowledge in CASA and its parameter settings. This guidance helps you to go through every single step in this application to successfully run the pipeline for simulating radio observations.

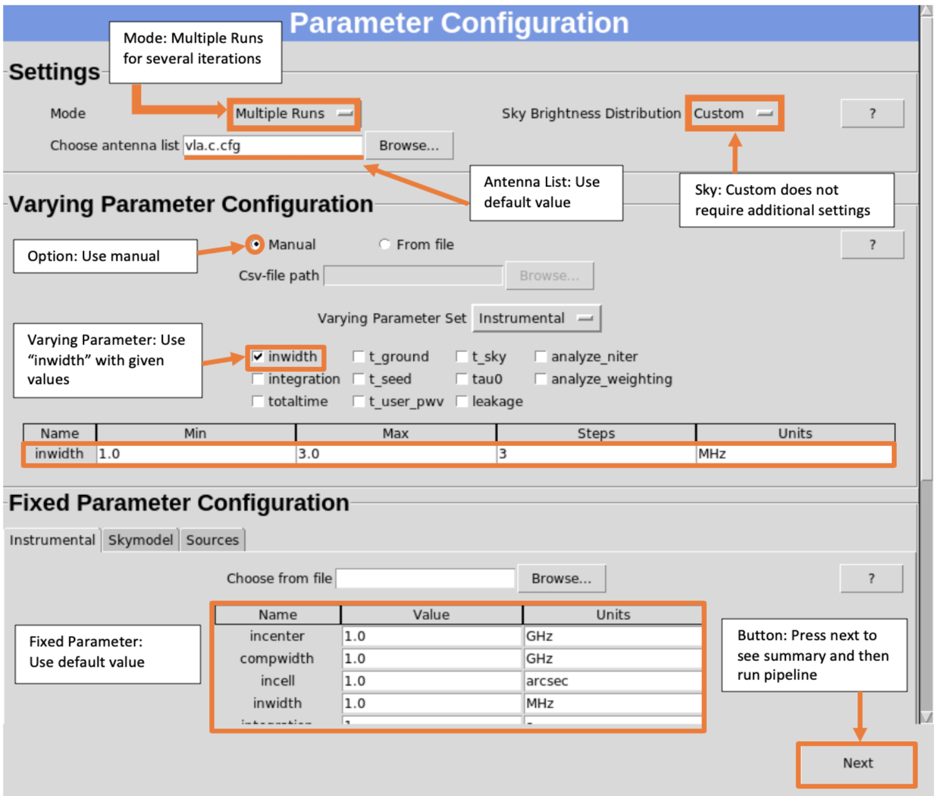
# 2 Quick Start Guide

This quick start guide helps you to simply set the configurations needed to run the pipeline. It shows how to select and set the parameter configurations in order to simulate radio observations.

**Single Run:** The following set-up for a single run:

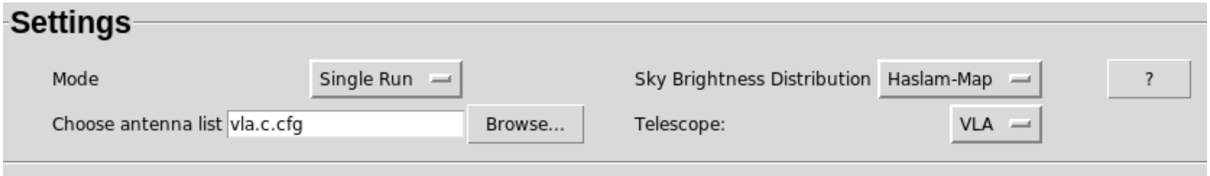



**Multiple Runs:** The following set-up for multiple runs.



# 3 Settings

In this section you can make basic settings for simulating radio observations. The following image shows the user interface for the “Settings” where you can set the desired basic configuration.




### 3.1 Mode

Choose the desired mode for your observation.

*Single Run* -- Single iteration with fixed parameter values. See definition for fixed parameter values in “Fixed Parameter Configuration”.

*Multiple Runs* -- Multiple iterations, that use fixed parameter values and different varying parameter values that change with each iteration. See definition for varying parameter values in “Varying Parameter Configuration”. This mode enables settings for "Varying Parameters Configurations".

### 3.2 Sky Brightness Distribution

Choose desired sky brightness distribution (Sky-model). It shows how the sky appears to the telescope.

*Custom* -- Customized sky brightness distribution with options to change values. When set to custom, the pipeline will create a new sky-model out of provided parameters.

*Haslam* -- Predefined all-sky map. The pipeline will use metadata provided in the fixed sky-model parameters and data from the sky-map of Haslam. See definition Haslam and sky parameters for further information.

*Haslam*

The all-sky 408 MHz map of Haslam is one of the most important total-power radio surveys. It has been widely used to study diffuse synchrotron radiation from our Galaxy and as a template to remove foregrounds in cosmic microwave background data. The map of Haslam is an atlas combining data from four different partial surveys of the sky.

### 3.3 Telescope

Choose the desired telescope when selected “Haslam” as sky brightness distribution. It uses the diameter of the selected telescope for further calculations.

*VLA* -- Telescope configuration of VLA (Very Large Array)

*ALMA* -- Telescope configuration of ALMA (Atacama Large Millimeter Array)

*MWA* -- Telescope configuration of MWA (Murchison Widefield Array)

*Meerkat* -- Telescope configuration of Meerkat

### 3.4 Antenna list

Choose an antenna configuration in your file system for the observation. Default value is vla.c.cfg.

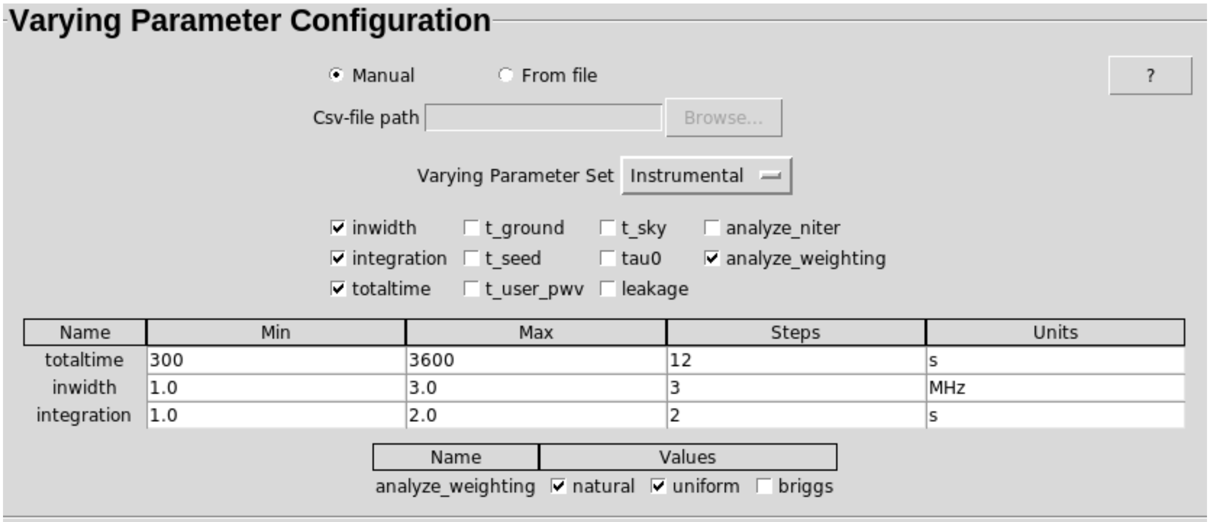
*vla.c.cfg* -- Antenna configuration for Very Large Array (Radio Interferometer)

This configuration file contains information about the antenna list such as coordinates (x,y,z) and dish diameter of each antenna. All antenna configurations of CASA can be found in the "Antennalists" folder.

# 4 Varying Parameter Configuration

In this section you can select desired varying parameters and set their values and units. The following image shows the graphical user interface for the “Varying Parameter Configuration” where you can set the desired values.

*Varying parameter* -- Parameter values are going to be varied in each iteration. Varying parameters are divided in three different sets: Instrumental, Sky-model and Sources. Further description of the parameters can be found in the next section “Fixed Parameter Configuration”.




## 4.1 Manual

Select and set for values/units of varying parameters manually.

## 4.2 From file

Select csv with predefined varying parameter values. Note that the parameters “sm_shape”, “sp_shape” and “weighting” cannot be read from this file and have to be entered manually.

*csv-file path* -- Select csv-file on your file system

## 4.3 Varying Parameter Set

Select desired varying parameter set.

*Instrumental* -- Telescope-based parameters (radio telescope configurations) used by the CASA tasks simobserve and simanalyze.

*Sky-model* -- Sky-based parameters (corresponding to Sky-model values to vary distribution of sources, flux, shapes, etc.) used by CASAs utility tools componentlist, coordinate system, image analysis and quanta.

*Sources* -- Sky-based parameters (additionally adding sources to Sky-model. Corresponding to source values to vary distribution of sources, flux, shapes, etc.) used by the componentlist utility tool from CASA.

*Instrumental & Sky-model* -- Combination of Instrumental and Sky-model parameter sets

*Instrumental & Sources* -- Combination of Instrumental and Sources parameter sets

*Sky-model & Sources* -- Combination of Sky-model and Sources parameter sets

Enter values for the parameters in the chosen varying parameter set.

*Name* -- Name of varying parameter

*Min* -- Minimum value of varying parameter

*Max* -- Maximum value of varying parameter

*Steps* -- Steps between minimum and maximum value of one varying parameter. Number of steps corresponds to number of Iterations.

*Values* -- Values of varying parameter that can be checked or unchecked

**Example:** inwidth

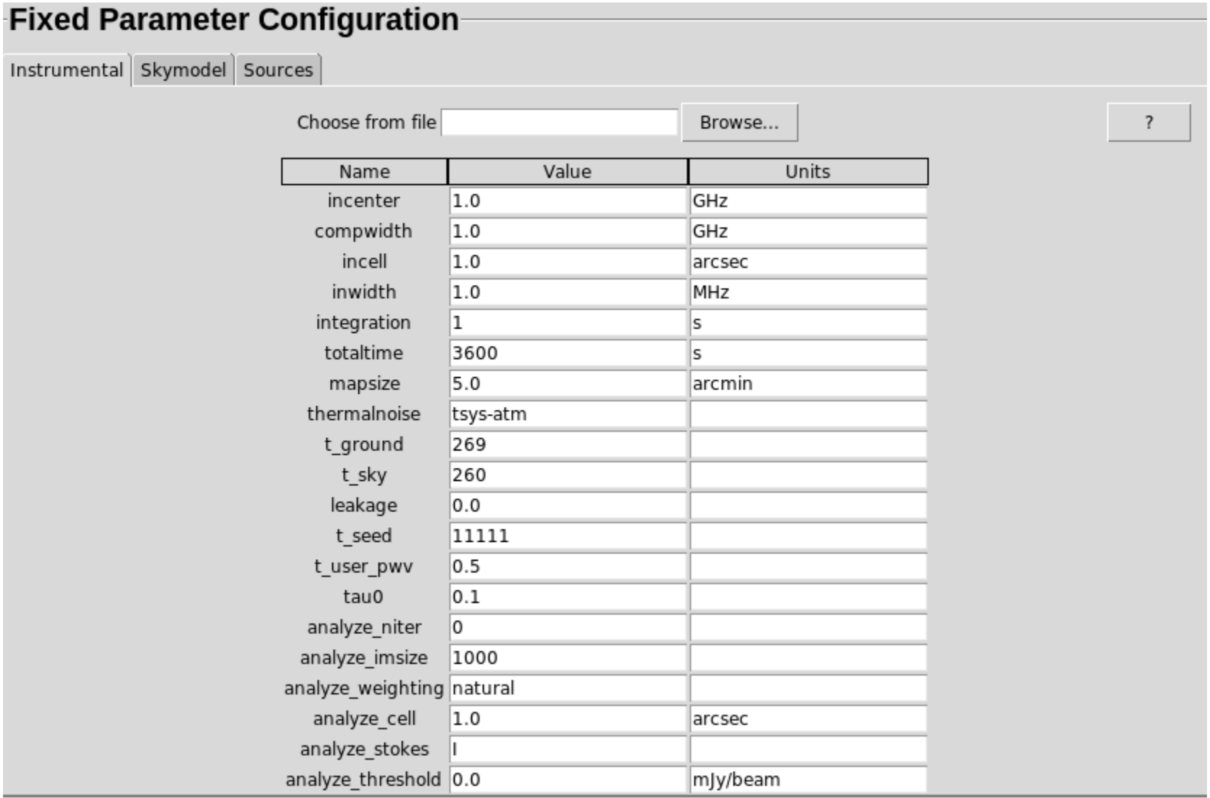
- Minimum value is 1.0
- Maximum value is 2.0
- Steps is 3
- Units “GHz”.

Varying parameter values for the iterations are: 1.0GHz, 1.5GHz, 2.0GHz

# 5 Fixed Parameter Configuration

In this section you can adjust values and units for the fixed parameters. The following image shows the user interface for the “Fixed Parameter Configuration” where you can set the desired values.

> *Fixed parameter* -- Parameter default value that does not change with each iteration while doing multiple runs. Except this parameter is also selected as a varying parameter then the values of the fixed parameters will not be used. Fixed parameters are divided in three different sections: Instrumental, Sky-model and Sources.




| Name | Value | Units |
|---|---|---|
| incenter | 1.0 | GHz |
| compwidth | 1.0 | GHz |
| incell | 1.0 | arcsec |
| inwidth | 1.0 | MHz |
| integration | 1 | s |
| totaltime | 3600 | s |
| mapsize | 5.0 | arcmin |
| thermalnoise | tsys-atm | |
| t_ground | 269 | |
| t_sky | 260 | |
| leakage | 0.0 | |
| t_seed | 11111 | |
| t_user_pwv | 0.5 | |
| tau0 | 0.1 | |
| analyze_niter | 0 | |
| analyze_imsize | 1000 | |
| analyze_weighting | natural | |
| analyze_cell | 1.0 | arcsec |
| analyze_stokes | I | |
| analyze_threshold | 0.0 | mJy/beam |

## 5.1 Choose from file

Select csv with predefined fixed parameter values. It is very important that the csv file has the same structure for each parameter set and that no parameters are omitted.

> *csv-file path* -- Select csv-file on your file system

*5.1.1 Csv-file for Instrumental Parameters:*

Note that this csv-file must contain exactly three column headers (Name, Value, Units) with following instrumental parameter:

| Name | Value | Units |
|---|---|---|
| incenter | 1.0 | GHz |
| compwidth | 1.0 | GHz |
| incell | 1.0 | arcsec |
| inwidth | 1.0 | MHz |
| integration | 1 | s |
| totaltime | 3600 | s |
| mapsize | 5.0 | arcmin |
| thermalnoise | tsys-atm | |
| t_ground | 269 | |
| t_sky | 260 | |
| leakage | 0.0 | |
| t_seed | 11111 | |
| t_user_pwv | 0.5 | |
| tau0 | 0.1 | |
| analyze_niter | 0 | |
| analyze_imsize | 1000 | |
| analyze_weighting | natural | |
| analyze_cell | 1.0 | arcsec |
| analyze_stokes | I | |
| analyze_threshold | 0.0 | mJy/beam |

*5.1.2 Csv-file for Sky-model Parameters:*

Note that this csv-file must contain exactly three column headers (Name, Value, Units) with following Sky-model parameters:

| Name | Value | Units |
|---|---|---|
| sm_flux | 1.0 | |
| sm_fluxunit | Jy | |
| sm_polarization | Stokes | |
| sm_direction_ra | 180.0 | |
| sm_direction_dec | -30.0 | |
| sm_size | 1000 | |
| sm_cellsize | 0.1 | arcsec |
| sm_shape | Gaussian | |
| sm_majoraxis | 0.5 | arcmin |
| sm_minoraxis | 0.5 | arcmin |
| sm_positionangle | 0.0 | deg |
| sm_frequency | 1.0 | GHz |
| component_frequency | 1.0 | GHz |
| frequency_increment | 128 | MHz |
| sm_index | 1.0 | |
| sm_spectrumtype | spectral index | |
| sm_label | | |

### 5.2 Number of Sources

In section “Sources” you can select how many sources you want to add to the Sky Brightness Distribution.

| Parameter | Source1 | Source2 | Source3 |
|---|---|---|---|
| sp_flux | 1.0 | 2.0 | 2.5 |
| sp_fluxunit | Jy | Jy | Jy |
| sp_direction_ra | 180.0 | 180.01 | 180.02 |
| sp_direction_dec | -30.0 | -30.02 | -30.04 |
| sp_shape | point | point | point |
| sp_majoraxis | 0.5arcmin | 0.5arcmin | 0.5arcmin |
| sp_minoraxis | 0.5arcmin | 0.5arcmin | 0.5arcmin |
| sp_positionangle | 0.0deg | 0.0deg | 0.0deg |
| sp_frequency | 1.0 | 1.0 | 1.0 |
| sp_frequency_unit | GHz | GHz | GHz |

### 5.3 Instrumental Parameters

These parameters are used for the CASA-tasks “simobserve” and “simanalyze” and are split into those. Visit the official CASA documentation for further information. Note that the input of parameters is handled differently than in CASA, as their values are concatenated with units.

#### *5.3.1 Simobserve*

| **Name** | **Type** | **Units** | **CASA-equivalence (simobserve)** | **Description** |
|---|---|---|---|---|
| incenter | float | GHz or MHz | incenter | Frequency to use for the center channel (or only channel, if the skymodel is 2D).<br>- Subparameter of skymodel<br>Example: 1.5GHz |
| compwidth | float | GHz or MHz | compwidth | Bandwidth of components.<br>- Subparameter of complist<br>If simulating from components only, this defines the bandwidth of the MS and output images.<br>Example: 1.0GHz |
| incell | float | arcsec | incell | Set new cell/pixel size.<br>- Subparameter of skymodel<br>Example: 1.0arcsec |
| inwidth | float | GHz or MHz | inwidth | Set new channel width.<br>- Subparameter of skymodel<br>Example: 1.0MHz |
| integration | integer | s | integration | Time interval for each integration.<br>Example: 1s |
| totaltime | integer | s | totaltime | The total time of an observation.<br>Example: 900s |
| mapsize | float | arcmin | mapsize | Angular size of of mosaic map to |

| | | | | |
|---|---|---|---|---|
| | | | | simulate.<br>Example: 5.0arcmin |
| thermalnoise | string | - | thermalnoise | add thermal noise.<br>- Options: tsys-atm, tsys-manual, ""<br>See [casadocs](casadocs) for further information.<br>Example: tsys-atm |
| t_ground | float | - | t_ground | Ground/spillover temperature in K.<br>- Subparameter of thermalnoise = 'tsys-atm\|tsys-manual'<br>Example: 269.0 |
| t_sky | float | - | t_sky | Atmospheric temperature in K.<br>- Subparameter of thermalnoise = 'tsys-manual'<br>Example: 260.0 |
| leakage | float | - | leakage | Add cross polarization corruption of this fractional magnitude.<br>Example: 0.0 |
| t_seed | integer | - | seed | Random number seed.<br>- Subparameter of thermalnoise = 'tsys-atm\|tsys-manual'<br>Example: 11111 |
| t_user_pwv | float | - | user_pwv | Precipitable water vapor if constructing an atmospheric model (in mm).<br>- Subparameter of thermalnoise = 'tsys-atm'<br>Example: 0.5 |
| tau0 | float | - | tau0 | Zenith opacity at observing frequency.<br>- Subparameter of thermalnoise = 'tsys-manual'<br>Example: 0.1 |

### *5.3.2 Simanalyze*

| **Name** | **Type** | **Units** | **CASA-equivalence (simanalyze)** | **Description** |
|---|---|---|---|---|
| analyze_niter | integer | - | niter | Maximum number of iterations of clean task (0 for dirty image)<br>Example: 1000 |
| analyze_imsize | integer | - | imsize | Output image size in pixels (x,y) or set to 0 to match model (default)<br>Example: 1000 |
| analyze_weighting | string | - | weighting | This parameter sets the weighting that is to be applied to the visibility data.<br>Options:<br>● natural<br>● uniform<br>● briggs |

| | | | | |
|---|---|---|---|---|
| | | | | See casadocs for further information.<br>Example: natural |
| analyze_cell | float | arcsec | cell | Cell size of the image with units or when unset (default) model cell size will be used.<br>Example: 1.0arcsec |
| analyze_stokes | string | - | stokes | Specifies stokes parameter for resulting images.<br>Example: I |
| analyze_threshold | float | mJy | threshold | Sets the upper threshold for cleaning.<br>Example: 0.0mJy/beam |

### 5.4 Sky Parameters

These parameters are used by the componentlist utility tool from CASA using mainly "addcomponent" to create a sky-model and sources to it. Visit the official CASA documentation for further information. Note that the input of parameters is handled differently that in CASA, as their values are concatenated with units. For the map of Haslam only following Sky-model parameters are used for the simulation:
- sm_direction_ra
- sm_direction_dec
- sm_size
- sm_cellsize
- sm_ frequency

#### *5.4.1 Sky-model*

| **Name** | **Type** | **Units** | **CASA-equivalence (cl.addcomponent)** | **Description** |
|---|---|---|---|---|
| sm_flux | float | - | flux | The flux value.<br>Example: 1.0 |
| sm_fluxunit | string | - | fluxunit | The units of the flux. Any string with the same dimensions as the Jansky.<br>Example: Jy |
| sm_polarization | string | - | polarization | The polarization of the value field. "Stokes", "linear" or "circular".<br>Example: Strokes |
| sm_direction_ra | float | - | dir | The direction measure of the source. it is entered in units of degree, but converted internally in quantities of right ascension. This parameter will be concatenated with sm_direction_dec to represent the full direction value from CASA.<br>Example: 180.0 |
| sm_direction_dec | float | - | dir | The direction measure of the source. it is entered in units of degree, but converted internally in quantities of |

| | | | | |
|---|---|---|---|---|
| | | | | declination. This parameter will be concatenated with sm_direction_ra to represent the full direction value from CASA.<br>Example: -30.0 |
| sm_shape | string | - | shape | The new shape type. A string that is either ’point’, ’Gaussian’, ’disk’, or ’limbdarkeneddisk’.<br>Example: Gaussian |
| sm_majoraxis | float | arcmin | majoraxis | The width (FWHM in the case of a Gaussian) of the larger axis. A quantity with angular units.<br>Example: 0.5arcmin |
| sm_minoraxis | float | arcmin | minoraxis | The width (FWHM in the case of a Gaussian) of the smaller axis. A quantity with angular units.<br>Example: 0.5arcmin |
| sm_positionangle | float | deg | positionangle | The rotation of the axes with respect to the reference frame. A quantity with angular units.<br>Example: 0.0deg |
| component_frequency | float | GHz | freq | The reference frequency of the component. A quantity with units equivalent to the ’Hz’ and frame or a frequency measure, e.g [’TOPO’, ’1.6GHz’], or simply default frame (LSRK) ’1.6GHz’.<br>Example: 1.0GHz |
| sm_spectrumtype | string | - | spectrumtype | The spectrum type, a string that is either ’constant’ or ’spectral index’.<br>Example: spectral index |
| sm_index | float | - | index | The spectral index.<br>Example: 1.0 |
| sm_label | string | - | label | The label for the component. |
| sm_size | integer | - | - | The size of the sky-model image in pixels. The image will be a square with a side length of sm_size pixels.<br>Example: 1000 |
| sm_cellsize | float | arcsec | - | The cell size and units of the sky-model image. A quantity with angular units.<br>Example: 0.1arcsec |
| sm_frequency | float | GHz | - | The channel width in units of Hz.<br>Example: 1.0GHz |

*5.4.2 Sources*

They can be added to Sky Brightness Distribution additionally to simulate the effect of having one or more sources on this image.

| **Name** | **Type** | **Units** | **CASA-equivalence (cl.addcomponent)** | **Description** |
|---|---|---|---|---|
| sp_flux | float | - | flux | The flux value.<br>Example: 1.0 |
| sp_fluxunit | string | - | fluxunit | The units of the flux. Any string with the same dimensions as the Jansky.<br>Example: Jy |
| sp_direction_ra | float | - | dir | The direction measure of the source. it is entered in units of degree, but converted internally in quantities of right ascension. This parameter will be concatenated with sm_direction_dec to represent the full direction value from CASA.<br>Example: 180.0 |
| sp_direction_dec | float | - | dir | The direction measure of the source. it is entered in units of degree, but converted internally in quantities of declination. This parameter will be concatenated with sm_direction_ra to represent the full direction value from CASA.<br>Example: -30.0 |
| sp_shape | string | - | shape | The new shape type. A string that is either ’point’, ’Gaussian’, ’disk’, or ’limbdarkeneddisk’.<br>Example: point |
| sp_frequency | float | - | freq | The reference frequency of the component. A quantity with units equivalent to the ’Hz’ and frame or a frequency measure, e.g [’TOPO’, ’1.6GHz’], or simply default frame (LSRK) ’1.6GHz’.<br>Example: 1.0 |
| sm_frequency_unit | string | - | - | The unit of sp_frequency (‘Hz’)<br>Example: GHz |

# 6 Menu Bar

The application has several features and tools which can be used. These features are listed in the menu bar on the top of the graphical user interface.

### 6.1 Save Configuration

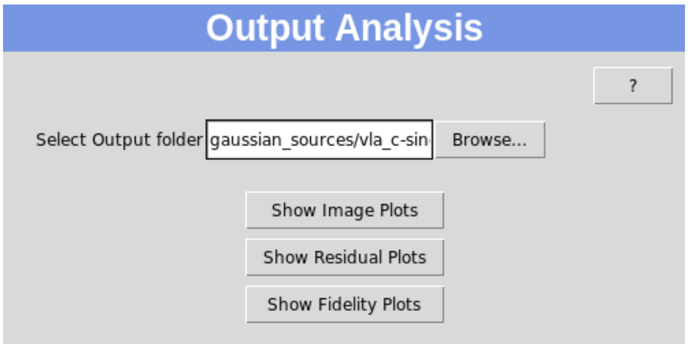
This feature allows you to save the current selected options in the settings and the configurations of the parameter values as pkl-file.

### 6.2 Load Configuration

With this feature you can load a pkl-file with saved configurations into the GUI.

### 6.3 Output Analysis

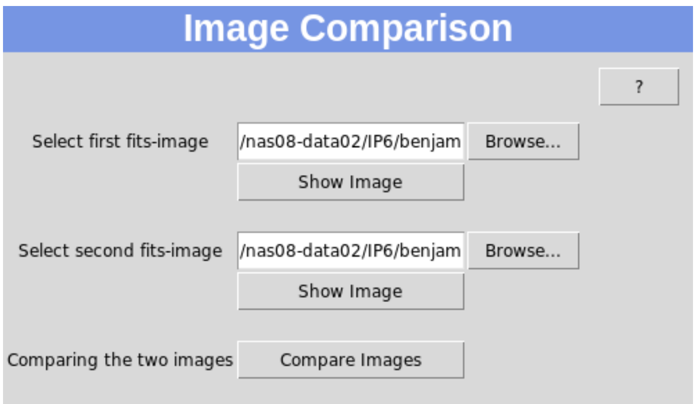
The tool “Output Analysis” allows you to view the generated output data from a simulation. It also shows important metrics that are relevant to quantify the quality of an image. The images are read as FITS-files, hence they are exported as such by the pipeline.




### 6.4 Image Comparison

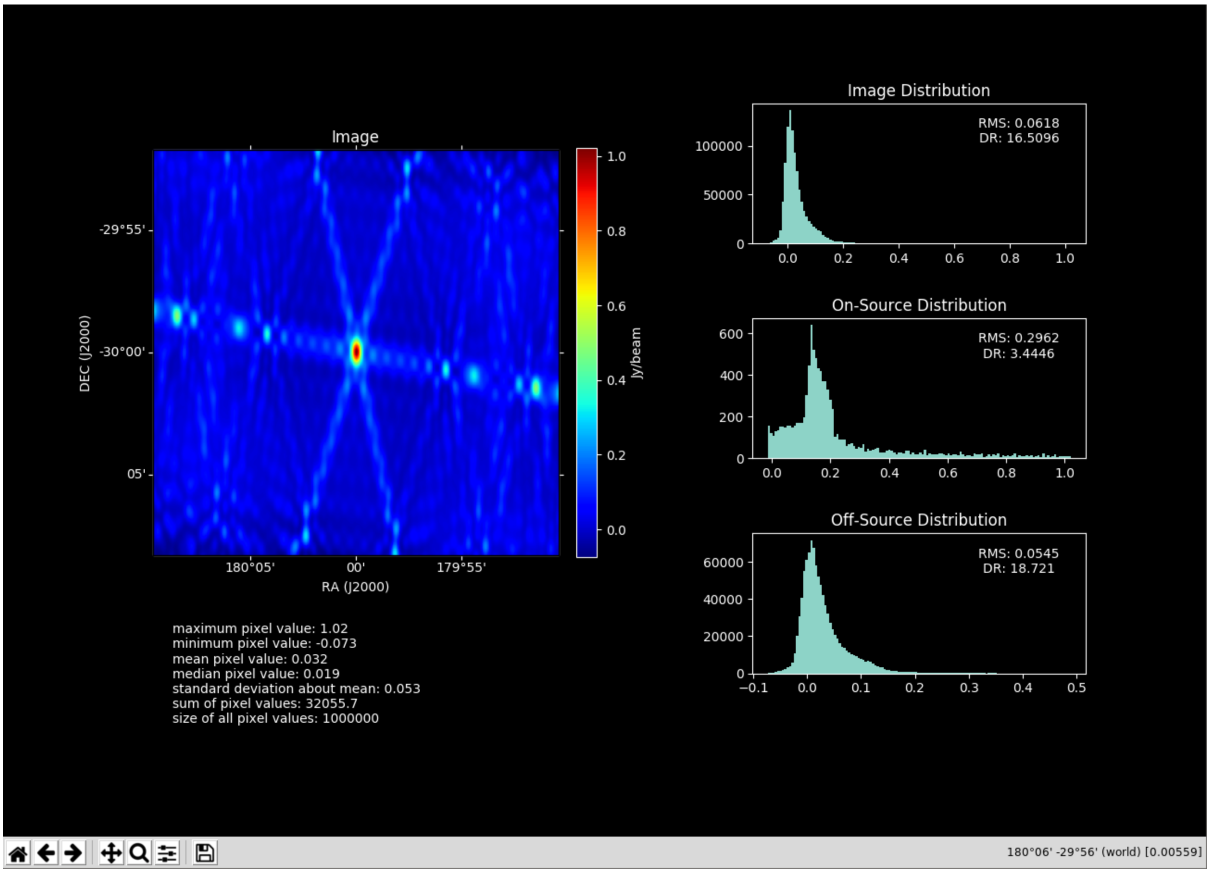
Image comparison allows you to quickly display the difference between two FITS images. The images are required to have the same brightness unit (unit of the pixel values) and shape excluding empty dimensions. The tool shows residual after the subtraction which is defined as:

$I1 - I2$, where $I1$ is the first selected FITS image and $I2$ the second one



## 6.5 Matplotlib Controls

“Output Analysis” and “Image Comparison” display different matplotlib plots. Those plots have some navigation controls that the matplotlib library provides. Visit the official matplotlib documentation for further information.

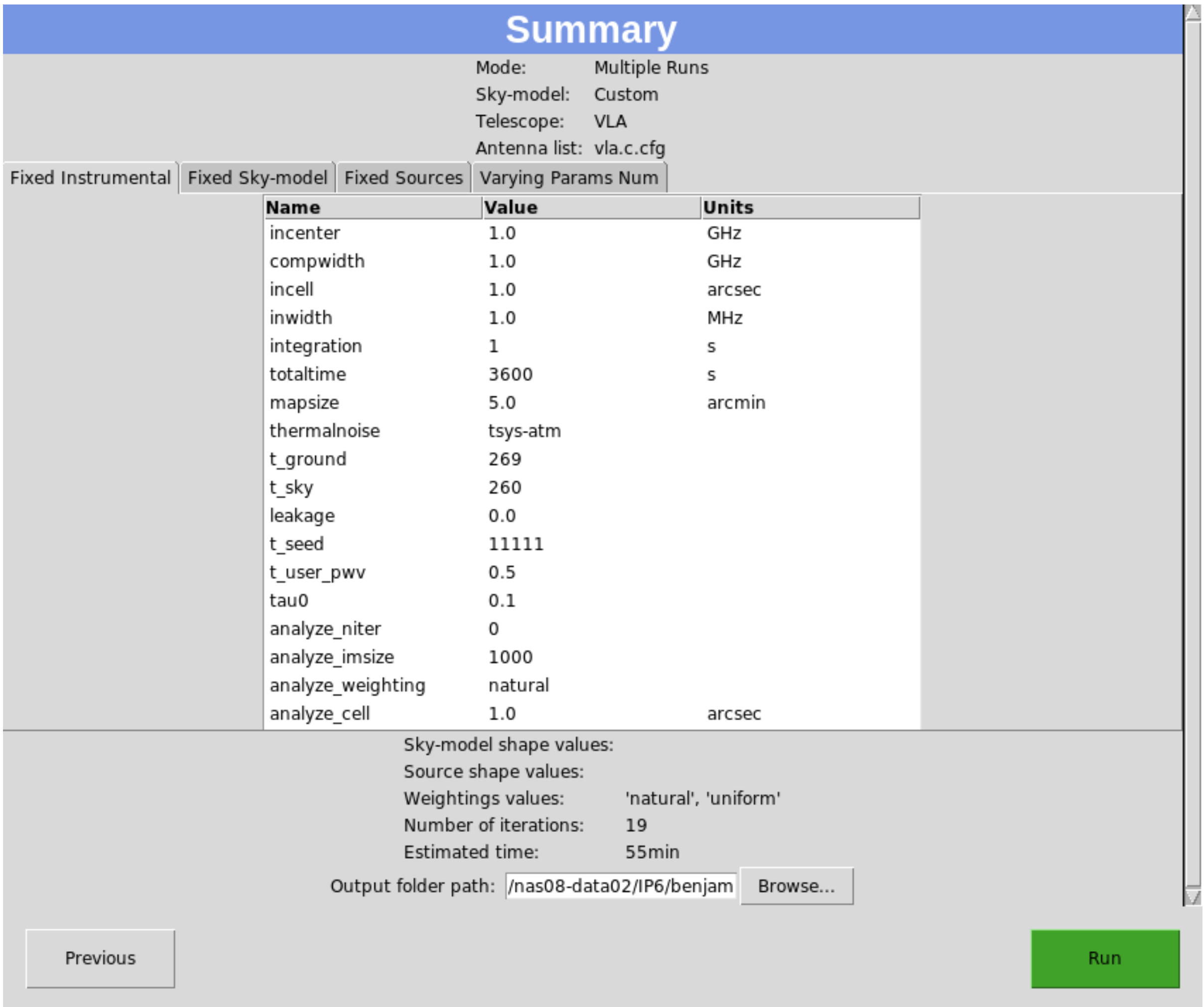



Some basic navigation controls are the following ones:

| | |
|---|---|
| Home/Reset | **h** or **r** or **home** |
| Back | **c** or **left arrow** or **backspace** |
| Forward | **v** or **right arrow** |
| Pan/Zoom | **p** |
| Zoom-to-rect | **o** |
| Save | **ctrl + s** |
| Toggle x axis scale (log/linear) | **L** or **K** when mouse is over an axes |
| Toggle y axis scale (log/linear) | **l** when mouse is over an axes |

# 7 Summary Page

After you have entered the desired settings and parameter value configurations, a summary page appears when clicking the next button in the bottom area of the user interface.
The summary page lists all selected and entered configurations. It also shows the number of iterations for the simulation. Furthermore the page shows you how long the estimated time for a simulation will be. Before running the pipeline by clicking the “Run”-button you can define a desired output folder path. Otherwise it will take a default output folder path.



# 8 Output

In this chapter the output of the pipeline such as naming convention and folder structure will be explained.

### 8.1 Naming Convention

The pipeline creates data for the observation and analysis. This data will be saved in a directory with following naming convention example:

vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0

1 2 3 4 5 6 7 8

1) Antenna list
2) Mode
3) Varying parameter set (if mode is mult)
4) Incenter value and unit
5) Inwidth value and unit
6) Integration value and unit
7) Sky brightness distribution
8) Varying parameter name and iteration (if mode is mult)

### 8.2 Folder Structure

The folder structure of the output will be explained with following example:

FITS_Files
Skymodel
Taskfiles
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.diff
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.fidelity
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.flux
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.image
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.image.flat
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.model
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.ms
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.noisy.ms
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.psf
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.residual
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.skymodel
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.skymodel.flat
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.skymodel.flat.regrid
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.skymodel.flat.regrid.conv
pipeline-20200806-114251.log
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.analysis.png
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.clean.last
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.image.png
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.observe.png
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.ptg.txt
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.simanalyze.last
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.simobserve.last
vla_c-mult-sim-f_1.0GHz-df_1.0MHz-dt_1s-sm_custom-analyze_niter0.skymodel.png

Skymodel: The sky-model image and sky-model fits-file will be stored in this sub-folder. As well as the sources.pkl file.
Taskfiles: The log-files for the CASA-tasks will be stored in this sub-folder. Those files show all used parameters for the tasks “simobserve”, “simanalyze” and “exportfits”.
Log-File: The log-file reports different steps with time measurements during each simulation.
Other folders: The task “simobserve” and “simanalyze” produce measurement-set and different radio images that will be stored directly as different sub-folders.
PNG-Files: The output-images of simobserve and simanalyze will be stored as png-files.

See simobserve and simanalyze for detailed output description.