APSYNSIM.
Instructions and exercises

Iván Martí Vidal
Onsala Space Observatory, SE-43992
Chalmers University of Technology (Sweden)

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1 Instructions

1.1 Overwiev

APSYNSIM (*AP*erture *SYN*thesis *SIM*ulator) is a simple interactive tool to help the students visualize and understand the basics of the Aperture Synthesis technique, applied to astronomical interferometers. This simulator is based on Python, and uses the Numpy and Matplotlib (open source) packages. The *APSYNSIM* code is also open (distributed under the GPL version 3).

The students can load many different interferometers and source models (and also create their own), change the observing conditions in real time (e.g., source coordinates, observing wavelength, antenna location, integration time, etc.), and even deconvolve the interferometric images and corrupt the data with gain errors (amplitude and phase).

1.2 Main window. The GUI

The main window of *APSINSYM* is shown in Figure 1. The window can be divided in six parts. From left to right (and from top to bottom):

- **ARRAY CONFIGURATION**. Shows the spatial distribution of the interferometer elements (antennas). The user can pick and drag the antennas, changing the array configuration. All other plots are refreshed in real time. If an antenna is piked and dragged, the user can see the index of the selected antenna, together with its current coordinates, in the upper-left corner of the figure.

- **UV PLANE**. Shows, in gray scale, the amplitude of the Fourier transform of the observed source. It also shows, in red (and blue), the tracks of the projected baselines in the UV plane (i.e., the points in the UV plane where the interferometer has taken measurements of the source's Fourier transform).

In the upper part of the figure, a text showing the current latitude of the observatory (and declination of the source) is shown, together with the hour-angle coverage of the observations. If the user clicks on any point in the UV plane, the program shows the value of the Fourier transform in that point (amplitude and phase). If the click is done over the UV track, the program also shows the baseline (and hour angle) of that particular point.

Last but not least, a view of the Earth, as seen from the observed source, is shown in the upper-right corner of the figure. The motion of the interferometer, due to the Earth rotation, is shown as a yellow line.

- **DIRTY BEAM**. The PSF of the interferometer, which depends on the UV coverage and the visibility-weighting scheme. If the user clicks on any point in the image, the program prints the coordinates (offset with respect to the center) of the point and the intensity (brightness) in Jy/beam.

- **Program controls**. The user can change:

  - The latitude of the observatory.
  - The source declination.
  - The hour-angle coverage (which is always constrained to the time range of the source above the horizon).
  - The observing wavelength.
  - The weighting scheme (based on Briggs), defined from -2 (uniform weighting) to $+2$ (natural weighting).

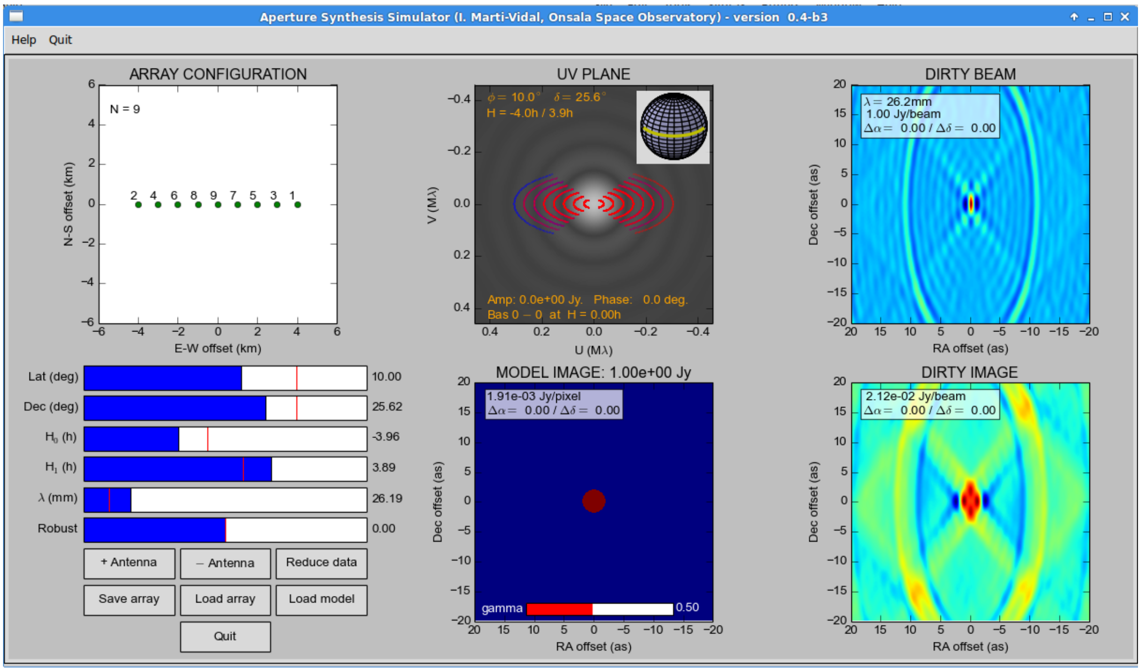
  Other controls are:

  - **+ Antenna**. Will add an antenna to the array. The default position of the antenna is at the array center. The user can drag it to any other position.
  - **− Antenna**. Will remove an antenna from the array (the one with the highest index number). The program remembers the latest position of this antenna (in case the user wants to recover it by pressing **+ Antenna**).
  - **Save array**. Will save the current array configuration into an ASCII file.
  - **Load array**. Will allow the user to load any array configuration from an ASCII file.
  - **Load model**. Will allow the user to load any model source from an ASCII file.

  - **Quit**. Will quit the program. *This is the recommended way of quitting the application!* (together with the *Quit* menu button in the upper part of the window).
  - **Reduce data**. This will open the GUI for the deconvolution (i.e. the CLEAN algorithm) and/or for the data corruption (see next section).

- **MODEL IMAGE**. Shows the source being observed. The units are Jy/pixel (i.e., the source model is not convolved). If the user clicks on the image, the coordinates (RA and Dec offsets) and the brightness of that point are printed (upper-right corner of the image). The gamma correction can also be changed (bar at the lower part of the figure), *just for plotting purposes*. This can be useful if there is high contrast in the source components (e.g., if a point source is observed together with an extended source).

- **DIRTY IMAGE**. Shows the source convolved with the dirty beam (i.e., the PSF of the interferometer). If the user clicks on any point in the image, the program will print the cordinates (RA and Dec offsets) and the brightness (in Jy/beam).



Aperture Synthesis Simulator (I. Marti-Vidal, Onsala Space Observatory) - version 0.4-b3

N = 9

$\phi = 10.0^\circ$ $\delta = 25.6^\circ$
H = -4.0h / 3.9h

Amp: 0.0e+00 Jy. Phase: 0.0 deg.
Bas 0 – 0 at H = 0.00h

$\lambda = 26.2$mm
1.00 Jy/beam
$\Delta\alpha = 0.00$ / $\Delta\delta = 0.00$

MODEL IMAGE: 1.00e+00 Jy
1.91e-03 Jy/pixel
$\Delta\alpha = 0.00$ / $\Delta\delta = 0.00$

2.12e-02 Jy/beam
$\Delta\alpha = 0.00$ / $\Delta\delta = 0.00$

Lat (deg) 10.00
Dec (deg) 25.62
H_0 (h) -3.96
H_1 (h) 3.89
λ (mm) 26.19
Robust 0.00
gamma 0.50

Figure 1: Main window of *APSYNSIM*

Some special keys (which work when the focus is set at the main window) are:

- **Z** (i.e., capital "Z", or Shift+z). Pressing this key will zoom *in* any of the images in the main window, *centered* on the position of the mouse cursor.

- **z** (i.e., small "z"). Pressing this key will zoom *out* any of the images in the main window, *centered* on the position of the mouse cursor.

- **c**. Will change the color palette in the figures (from hue to grayscale and viceversa).

1.3 CLEAN and gain corruption. The GUI

This window shows two figures: The image of the CLEAN residuals (left) and the image of the (convolved) CLEAN model (right).

The user can add CLEAN masks (windows) by clicking and dragging on the *residuals* image with the *left* mouse button. The masks can be removed by clicking and dragging with the right mouse button.

At the left of the window, the user can set the CLEAN parameters (i.e., the loop gain and the number of iterations). Regarding to the buttons at the left of the window:

- **CLEAN**. Will apply the required number of CLEAN iterations, updating the two figures in real time.

- **RESET**. If anything is changed in the *Main Window* (e.g., antenna locations, observing wavelength, visibility weighting, etc.), the user must press this button to update the image of residuals accordingly.

- +/− **Resid**. Will add (or remove) the residuals from the CLEAN image (useful to check the achieved dynamic range in the CLEANing).

- **Show FFT**. Will load another window showing the Fourier transforms of the PSF (i.e., basically, the visibility weighting used in the gridding of visiblities), the residuals (this can be useful to study the effect of corrupting gains in the deconvolution), and the (convolved) CLEAN model (to check the quality of the CLEAN interpolation in the UV plane). An example of this window is shown in Figure 3. Clicking on any point in any of these figures will show (upper-left parts of the figures) the UV coordinates and the intensity values in Fourier space (in Jy).

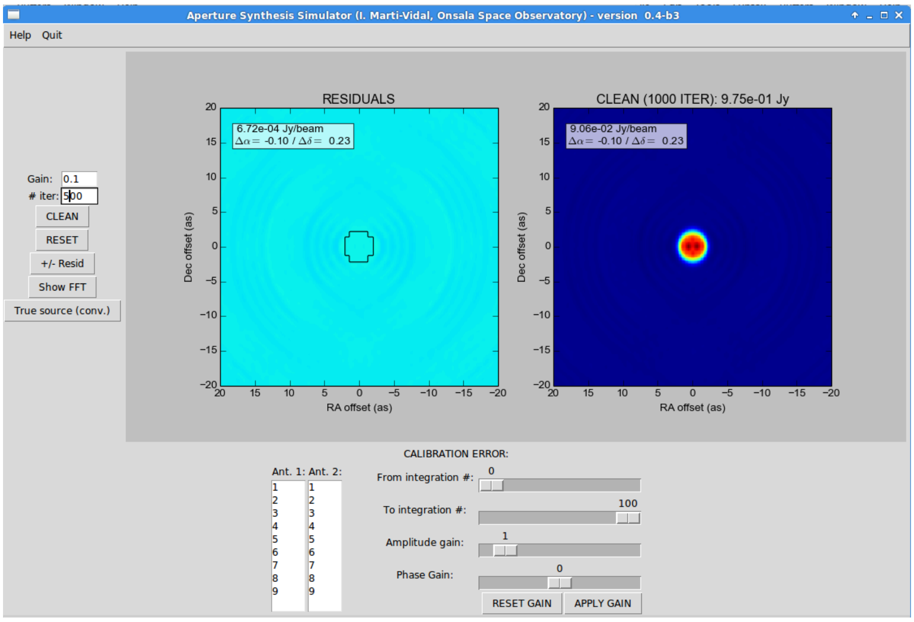
- **True source (conv.)**. Will open a new window showing the source structure (i.e., the *MODEL IMAGE* in the Main Window) convolved with the CLEAN beam (this is useful to check the fidelity of the CLEAN deconvolution). Clicking on any point in this image will show the coordinates (RA and Dec offsets) and the intensity (in Jy/beam).

1.3.1 Corrupting the gains

The lower part of the window shown in Figure 2 has the controls for the data corruption. To apply a given gain to an antenna, just select the antenna index from the "Ant 1" list. If the selection in the "Ant 2" list is equal to that of the "Ant 1" list, then *all* the baselines related to the selected antenna will be modified with the gain. However, if the selections in "Ant 1" and "Ant 2" are not the same, only the selected *baseline* will be modified by the gain.

The simulated observations are homogeneously divided into integration times (100 integrations is the default). The first and final integrations affected by the gain are selected in the sliders named “From integration” and “To integration”, respectively. The amplitude gain (in %) and the phase gain (in degrees) are set with the sliders named “Amplitude gain” and “Phase gains”, respectively.

Pressing **APPLY GAIN** will insert the corrupting gain into the data. Pressing the **RESET GAIN** will undo the data corruption. Notice that if a new array is loaded (and/or if any antenna is added or subtracted from the array) the corrupting gain is reset!



Aperture Synthesis Simulator (I. Marti-Vidal, Onsala Space Observatory) - version 0.4-b3

Gain: 0.1

iter: 500

RESIDUALS: 6.72e-04 Jy/beam, $\Delta\alpha = -0.10$ / $\Delta\delta = 0.23$

CLEAN (1000 ITER): 9.75e-01 Jy — 9.06e-02 Jy/beam, $\Delta\alpha = -0.10$ / $\Delta\delta = 0.23$

CALIBRATION ERROR:

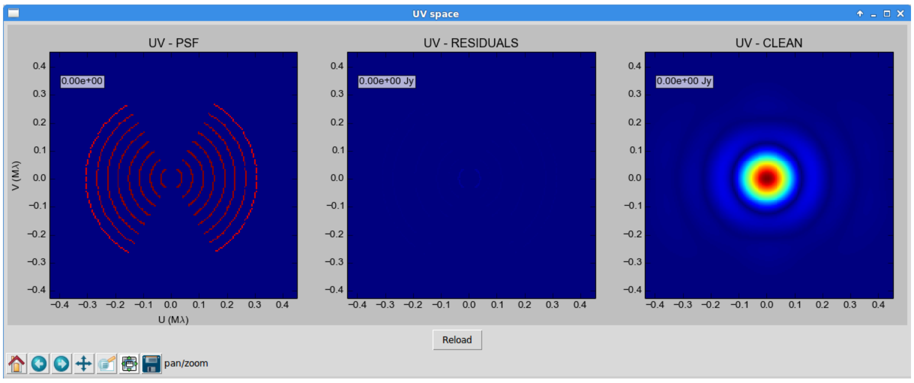
From integration #: 0

To integration #: 100

Amplitude gain: 1

Phase Gain: 0

Figure 2: The CLEAN (and gain-corruption) window



UV space

UV - PSF: 0.00e+00

UV - RESIDUALS: 0.00e+00 Jy

UV - CLEAN: 0.00e+00 Jy

Figure 3: The FFTs of the PSF, residuals, and CLEAN model.

2 Exercises

2.1 Diffraction limit

- Open the *Point-source.model* and the *Two-antennas.array*. Look at the shape of the PSF and the dirty image. Discuss the results.
- Study the width of the PSF fringe as a function of wavelength and baseline length.
- This is a snapshot observation. Now, let the Earth rotate. Increase the observing time (i.e., the hour-angle coverage) from -5h to 5h. What happens to the shape of the PSF? How does the new PSF depend on observing frequency?

2.2 Image deconvolution.

- Observe the *Double-source.model* with the *VLA-C.array* at the default wavelength and time coverage. CLEAN only one of the source components (set a mask around it). Look at the CLEAN model and the residuals (also in UV space). Now, CLEAN the other source too. Add the residuals to the CLEAN model.
- Repeat the above exercise, but now CLEANing the two sources simultaneously. Comment on the results.

2.3 Basic image observables. Flux density vs. surface brightness.

- Observe the *Point-and-Gauss-ALMA.model* with the *Two-antennas.array* (from -5 to 5h time coverage) at a wavelength of 9 mm. Measure, from the dirty image, the peak intensities of the Gaussian and the point source.
- CLEAN the image and measure the peak intensities on the final CLEAN model. Look at the peak amplitude of the CLEAN model in the UV plane. How does it compare to the total CLEANed flux? Comment on the results.
- Now, decrease the wavelength to 5 mm and re-CLEAN. What happens to the peak intensities of the two sources (point and Gaussian) in the image plane? Why?

  Change the wavelength to 2.5 mm and repeat the exercise.
- Take another look at the UV-CLEAN model. Notice how the interpolation of the source FFT has been done!

2.4 Missing flux and dynamic-range limitation.

- Observe the *One-Disc.model* with the *E-W.array*, using an integration time from -4 h to 4 h. CLEAN the image. Compare the surface brightness of the CLEAN image to that of the model (convolved with the CLEAN beam). Compare the total recovered flux desnity to the total flux density of the disc.

- Change the observing wavelength to 26 mm and CLEAN again. Compare the recovered flux density to that in the previous case and discuss the results (a look at the UV PLOT might help understand what is going on). Compare also the dynamic range achieved in the CLEAN images at 26 mm and at the original wavelength.
- Observe the *Nebula.model* with the *Golay_12.array*. CLEAN it and look at the residuals. Compare the CLEAN image with that of the source model convolved with the CLEAN beam. Discuss the results.
- Increase the observing wavelength by, say, a factor 2-3 and re-CLEAN. Discuss the results (look at the residuals in UV space).
- Observe the *Discs.model* with the *Golay_12.array* at 5 mm. CLEAN it and look at the residuals and CLEAN model in UV space. How does it compare to the UV PLANE plot in the main program window? (hint: make a large zoom in by pressing capital ”Z” in the UV PLANE plot). Discuss the results.
- Increase the wavelength to the maximum and re-clean. Discuss what you find.

2.5 Earth Rotation Synthesis.

- Load the *E-W.array* and observe the *Double-source.model* at 50 mm, with a time coverage from -5h to 5h.
- Change the latitude of the observatory and check how that affects the UV sampling of the interferometer. Comment on the results.
- Change the declination of the source and check how that affects the UV sampling of the interferometer. Comment on the results.
- Now move some of the antennas toward North (or South), in order to build a 2D array distribution. Study how this position changes affect the UV coverage when you change source declination and/or latitude of the observatory.

2.6 Visibility weighting.

- Observe the *Discs.model* with the *Golay_12.array*. Change the Robustness parameter and check how it affects the dirty beam and the dirty image. Comment on the results.
- Now, observe with the *WSRT.array*, with a time coverage from -5h to 5h and at a wavelength of 10 mm. Change the Robustness parameter and check how it affects the dirty beam and the dirty image. Compare with the previous case. Comment on the results.

2.7 Calibration-error recognition.

- Observe the *Point-source.model* with the *E-W.array* at 10 mm, with a time coverage from -5h to 5h. CLEAN the source and add the residuals to the CLEAN model.

- Now corrupt antenna #1 with an amplitude gain factor of, say, 7. Apply that gain and re-CLEAN. Add the residuals to the CLEAN model. Take a look at the residuals in UV space. Comment on the results.

- Now apply that corrupting gain to only part of the experiment (e.g., from integration #40 to #60). CLEAN again and look at the residuals in both image plane and UV space. Comment on the results.

- Apply a phase-only gain of 90 degrees to antenna #1 and re-CLEAN. Look at the new residuals. Comment on the results.

- Repeat the previous exercises, but using now the *Five-Gauss.model* source. Comment on the results.

2.8 Array design.

- What do you think are the figures to focus on to design an interferometer with high-fidelity imaging capabilities?

- Study some special array distributions, like Golomb and Golay. Looking at the uv coverage from snapshot observations may help you understand what is special in these distributions. Discuss on the pros and cons of these arrays, in terms of UV coverage and PSF shape.

- Observe a source of your choice with one of the VLA configurations. Start with a snapshot and apply some Earth rotation synthesis afterwards. Discuss on the pros and cons of the VLA antenna distribution.

- Observe a given source with the *ALMA-ACA-Cycle1-Conf5.array.* Use natural weighting (Robust 2.0) and look at the Fourier transform of the PSF. Comment on what you see. As an add-on, you can also compare with uniform weighting (Robust -2.0).

- Design your own array. For instance, create spiral arms (to your taste) or random distributions and check the resulting PSFs.