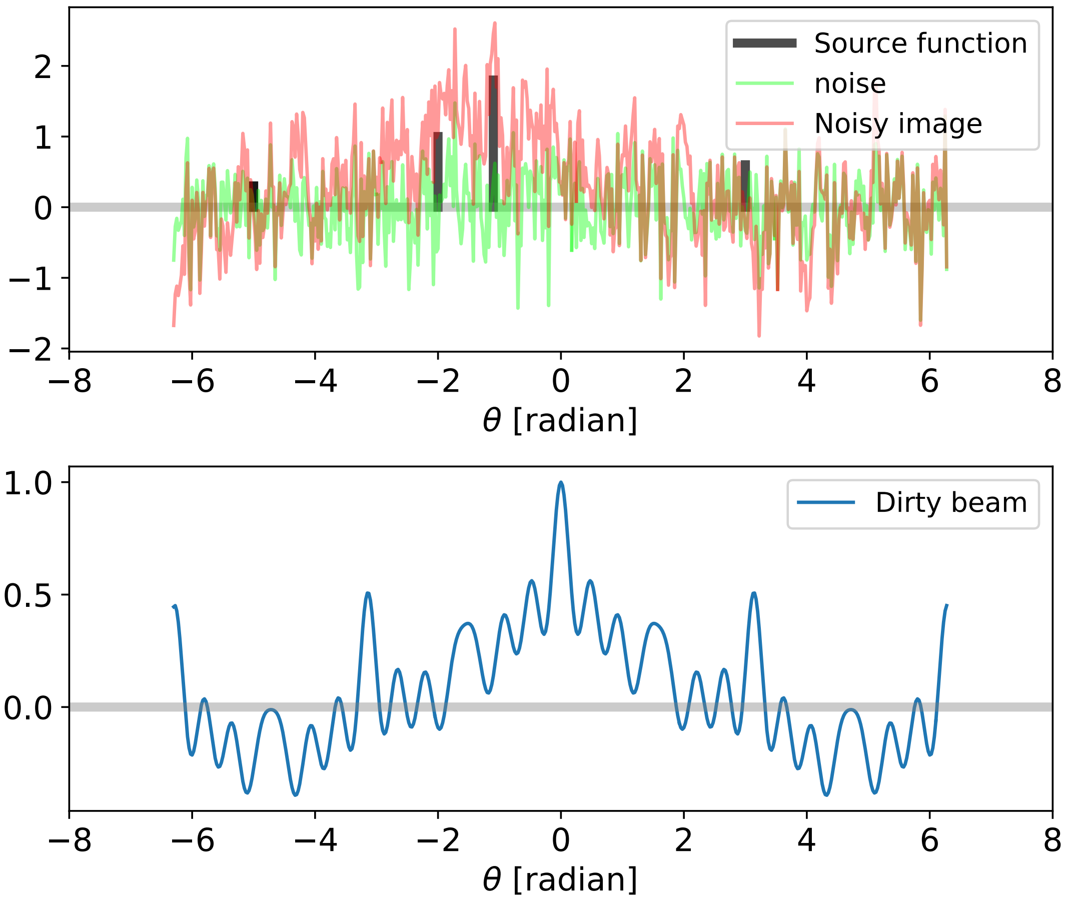
An Introduction to Radio Interferometry

4-5 Clean algorithm and other imaging algorithms

You can find relevant material
on my personal webpage



Naiive inverse fourier transform

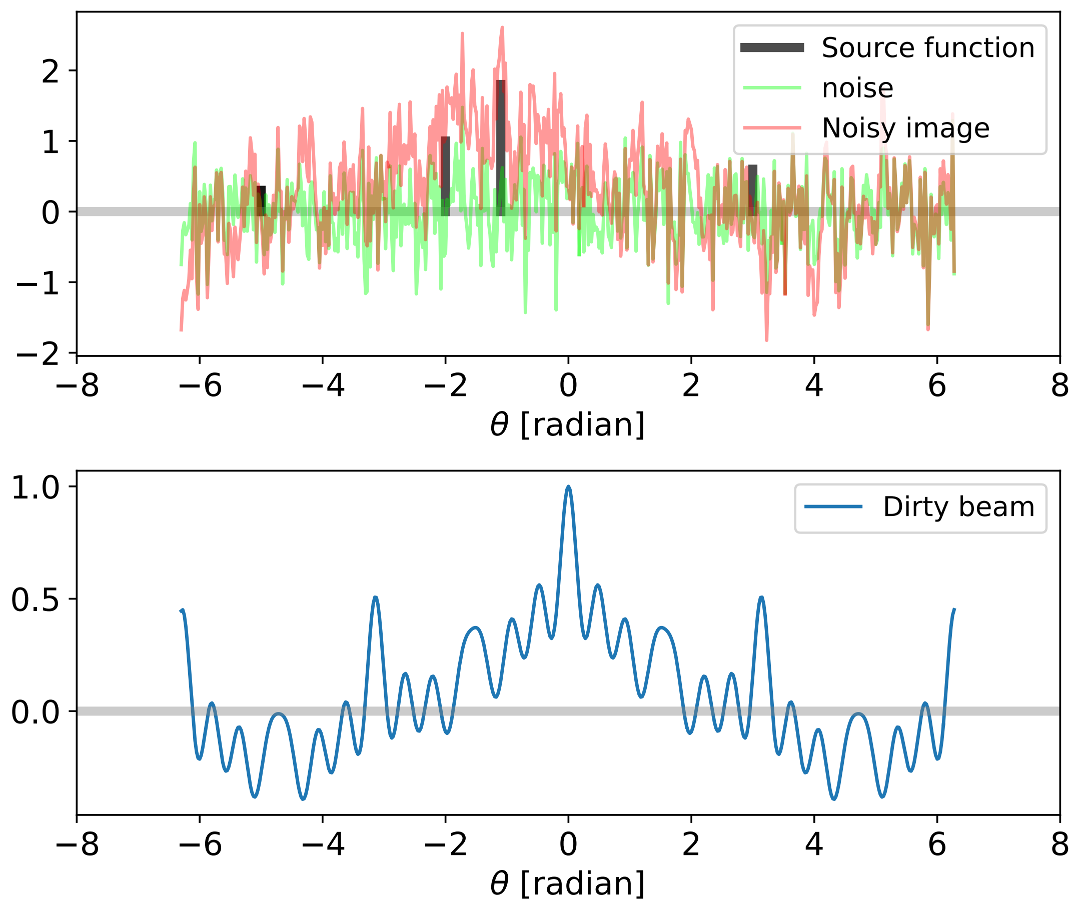
$$\left[A(\theta')\widetilde{P(\theta')}\right]^D \equiv \int S(u)V(u)e^{-i2\pi u\theta'}du$$

$$= \underbrace{\left(\int S(u)e^{-i2\pi u\theta'}du\right)}_{\text{Dirty beam}} * \underbrace{\left(\int V(u)e^{-i2\pi u\theta'}du\right)}_{A(\theta')}$$

$$\Downarrow$$

$$\sum_{k=1}^{M}\int \delta(u-u_k)\cos(2\pi u\theta')\,du = \sum_{k=1}^{M}\cos(2\pi u_k\theta')$$

$$\boxed{\text{Need to deconvolve } \left[A(\theta')\widetilde{P(\theta')}\right]^D}$$



Naiive inverse fourier transform

$$\left[A(\theta')\widetilde{P(\theta')}\right]^D \equiv \int S(u)V(u)e^{-i2\pi u\theta'}du$$

$$= \underbrace{\left(\int S(u)e^{-i2\pi u\theta'}du\right)}_{\text{Dirty beam}} * \underbrace{\left(\int V(u)e^{-i2\pi u\theta'}du\right)}_{A(\theta')}$$

$$\sum_{k=1}^{M} \int \delta(u-u_k)\cos(2\pi u\theta')\,du = \sum_{k=1}^{M} \cos(2\pi u_k\theta')$$

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$

Make a model of the source function, which after convolving with the dirty beam, is consistent with the noisy image.

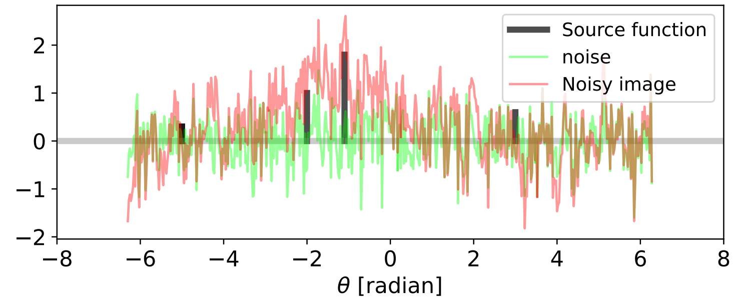
The ordinary CLEAN algorithm (J. Högbom 1974)

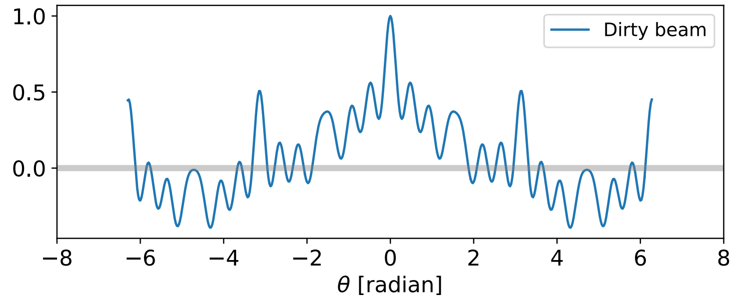
Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$





The ordinary CLEAN algorithm (J. Högbom 1974)

Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

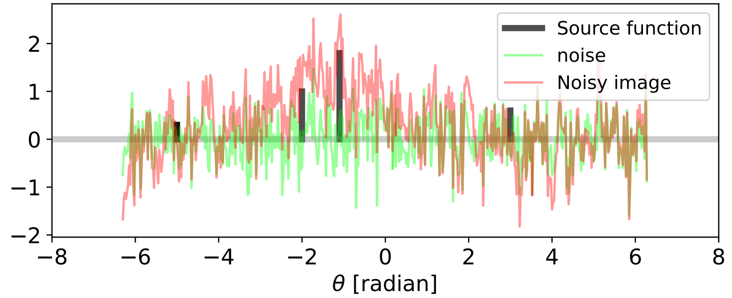
Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$

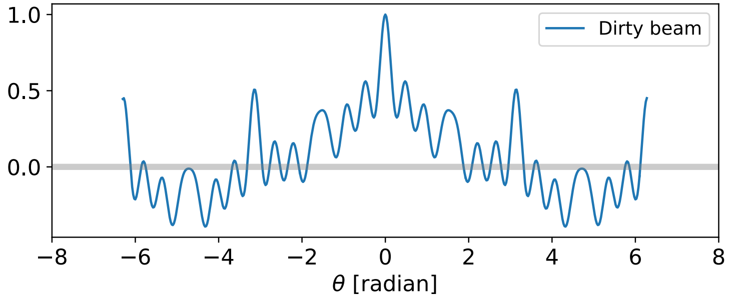
1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

2. Evaluate $(I_m \times g) * B$,
where $I_m \equiv I^{peak}\delta(l,m)$,
g is a loop gain factor usually defaulted to be $0.05 \sim 0.1$,
$\mathrm{B} \equiv \int S(u)e^{-i2\pi u\theta'}du$

Usually, you can change the loop gain from the default value





The ordinary CLEAN algorithm (J. Högbom 1974)

Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

1. Find the intensity peak in (residual) dirty image

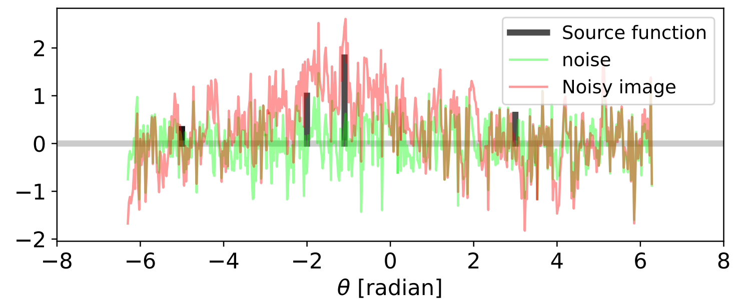
To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

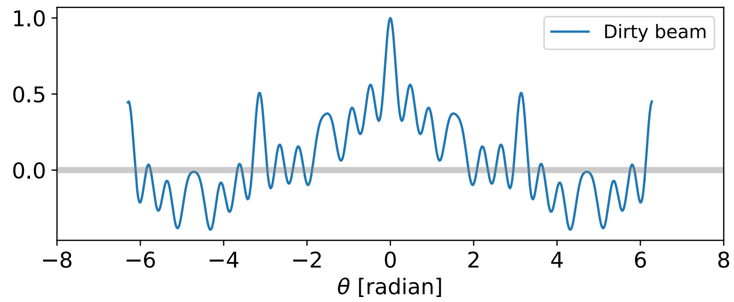
2. Evaluate $(I_m \times g) * B$,
where $I_m \equiv I^{peak} \delta(l, m)$,
g is a loop gain factor usually defaulted to be $0.05 \sim 0.1$,
$\mathrm{B} \equiv \int S(u) e^{-i2\pi u \theta'} du$

Usually, you can change the loop gain from the default value

3. (i) Subtract $(I_m \times g) * B$ from the dirty image (call the dirty image after subtraction the residual image).
(ii) Append the subtracted $(I_m \times g)$ to so called clean model

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$





The ordinary CLEAN algorithm (J. Högbom 1974)

Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

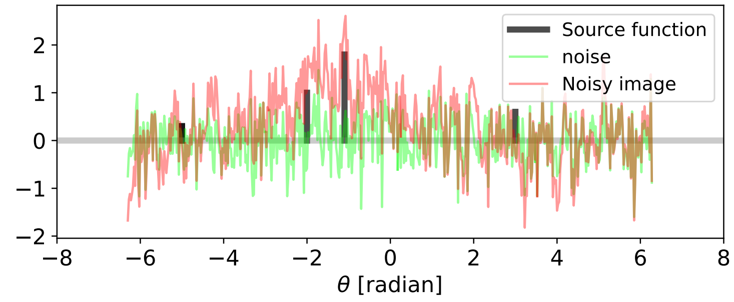
2. Evaluate $(I_m \times g) * B$,
where $I_m \equiv I^{peak}\delta(l, m)$,
g is a loop gain factor usually defaulted to be $0.05 \sim 0.1$,
$\mathrm{B} \equiv \int S(u) e^{-i2\pi u\theta'} du$

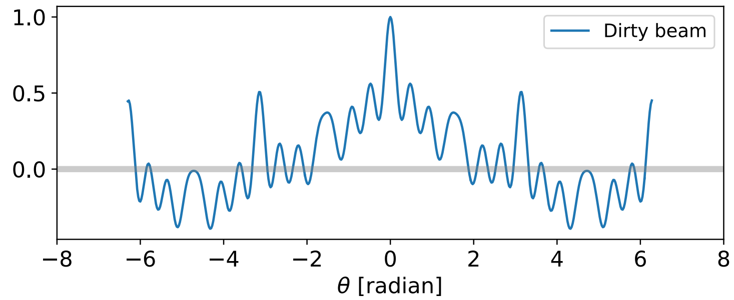
Usually, you can change the loop gain from the default value

3. (i) Subtract $(I_m \times g) * B$ from the dirty image (call the dirty image after subtraction the residual image).
(ii) Append the subtracted $(I_m \times g)$ to so called clean model

4. [Is the intensity peak in the residual image larger than a specified **cutoff**? $1 \sim 2$ times the rms noise, normally.]
&&
[Not yet run more iteration than a specified limit **niter**?]

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$





The ordinary CLEAN algorithm (J. Högbom 1974)

Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

2. Evaluate $(I_m \times g) * B$,
where $I_m \equiv I^{peak}\delta(l, m)$,
g is a loop gain factor usually defaulted to be $0.05 \sim 0.1$,
$B \equiv \int S(u) e^{-i2\pi u\theta'} du$

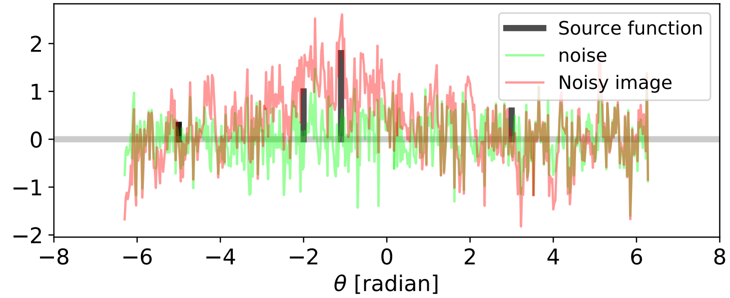
Usually, you can change the loop gain from the default value

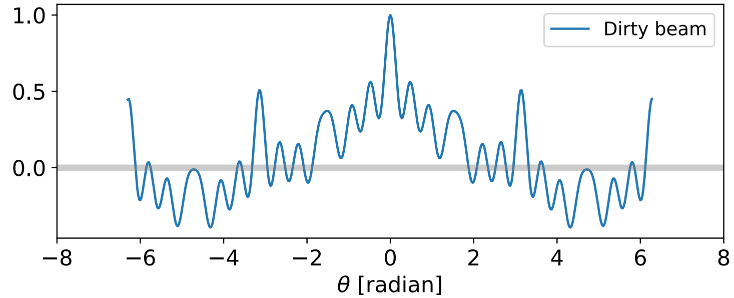
3. (i) Subtract $(I_m \times g) * B$ from the dirty image (call the dirty image after subtraction the residual image).
(ii) Append the subtracted $(I_m \times g)$ to so called clean model

4. [Is the intensity peak in the residual image larger than a specified **cutoff**? $1 \sim 2$ times the rms noise, normally.]
&&
[Not yet run more iteration than a specified limit **niter**?]

True

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$





The ordinary CLEAN algorithm (J. Högbom 1974)

Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$

1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

2. Evaluate $(I_m \times g) * B$,
where $I_m \equiv I^{peak}\delta(l,m)$,
g is a loop gain factor usually defaulted to be $0.05 \sim 0.1$,
$\mathrm{B} \equiv \int S(u) e^{-i2\pi u\theta'} du$

Usually, you can change the loop gain from the default value

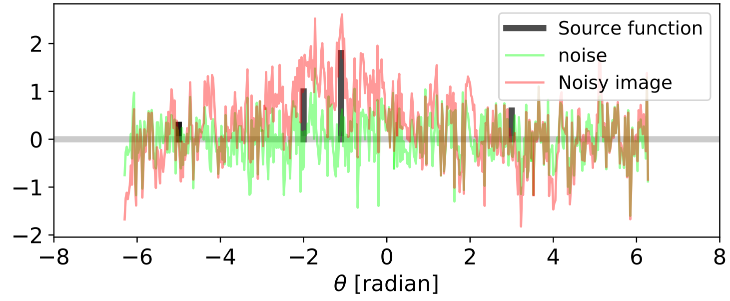
3. (i) Subtract $(I_m \times g) * B$ from the dirty image (call the dirty image after subtraction the residual image).
(ii) Append the subtracted $(I_m \times g)$ to so called clean model

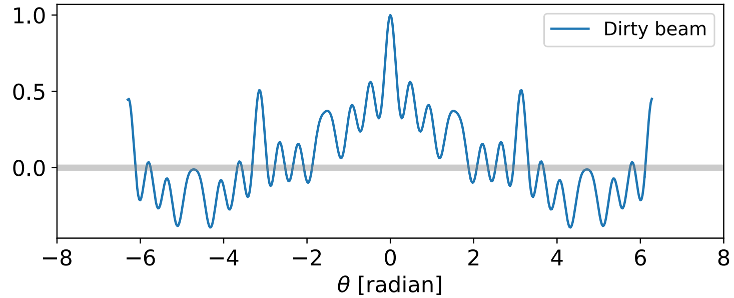
4. [Is the intensity peak in the residual image larger than a specified **cutoff**? 1~2 times the rms noise, normally.]
&&
[Not yet run more iteration than a specified limit **niter**?]

True → 1.

False → 3.

3. (i) Convolve the clean imodel *with the* clean beam, which is the a Gaussian profile obtained from fitting the central lobe of the dirty beam.
(ii) Add the residual image *to* the convolved image.
This is the final product, the clean image.

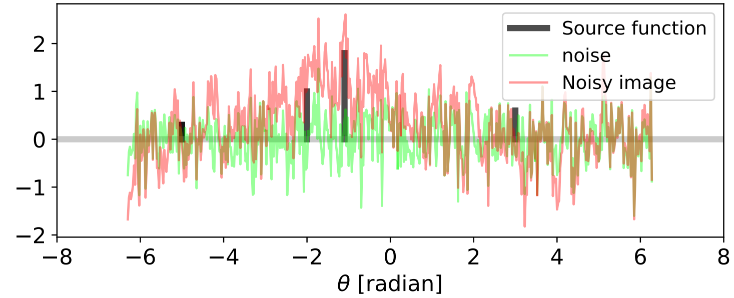


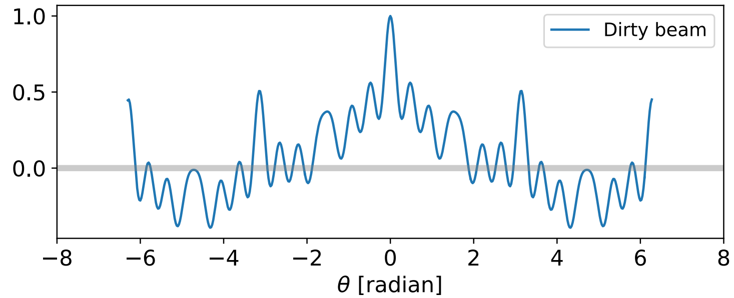


The ordinary CLEAN algorithm (J. Högbom 1974)

Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$





1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

2. Evaluate $(I_m \times g) * B$,
where $I_m \equiv I^{peak}\delta(l, m)$,
g is a loop gain factor usually defaulted to be $0.05 \sim 0.1$,
$\mathrm{B} \equiv \int S(u) e^{-i2\pi u\theta'} du$

Usually, you can change the loop gain from the default value

3. (i) Subtract $(I_m \times g) * B$ from the dirty image (call the dirty image after subtraction the residual image).
(ii) Append the subtracted $(I_m \times g)$ to so called clean model

4. [Is the intensity peak in the residual image larger than a specified **cutoff**? $1 \sim 2$ times the rms noise, normally.]
&&
[Not yet run more iteration than a specified limit **niter**?]

True

False

3. (i) Convolve the clean imodel *with the* clean beam, which is the a Gaussian profile obtained from fitting the central lobe of the dirty beam.
(ii) Add the residual image *to* the convolved image. This is the final product, the clean image.

Clean image is for presentation purposes. It is in fact **inconsistent** with your direct visibility measurement due to this extra convolution!

The Clark CLEAN algorithm (Clark 1980)

Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

2. Evaluate $(I_m \times g) * B$,
where $I_m \equiv I^{peak}\delta(l,m)$,
g is a loop gain factor usually defaulted to be $0.05 \sim 0.1$,
$\mathrm{B} \equiv \int S(u) e^{-i2\pi u\theta'} du$

Usually, you can change the loop gain from the default value

3. (i) Subtract $(I_m \times g) * B$ from the dirty image (call the dirty image after subtraction the residual image).
(ii) Append the subtracted $(I_m \times g)$ to so called clean model

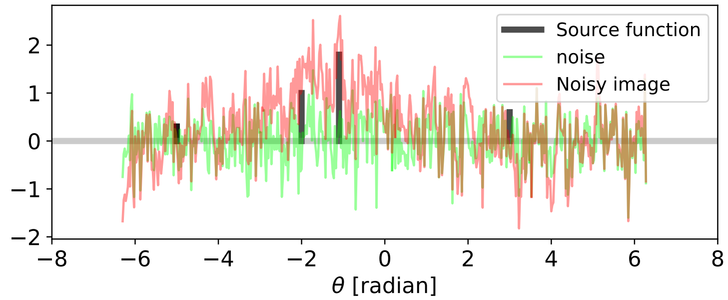
4. [Is the intensity peak in the residual image larger than a specified **cutoff**? $1 \sim 2$ times the rms noise, normally.]
&&
[Not yet run more iteration than a specified limit **niter**?]

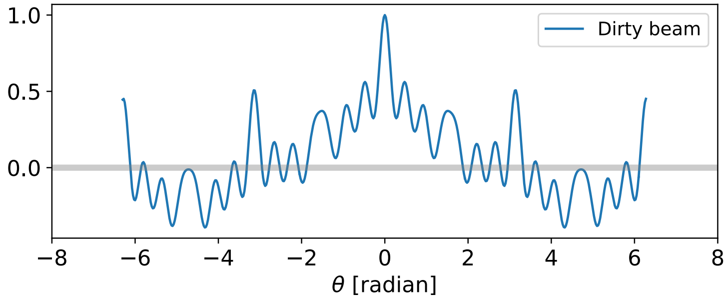
True

False

3. (i) Convolve the clean imodel *with the* clean beam, which is the a Gaussian profile obtained from fitting the central lobe of the dirty beam.
(ii) Add the residual image *to* the convolved image.
This is the final product, the clean image.

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$

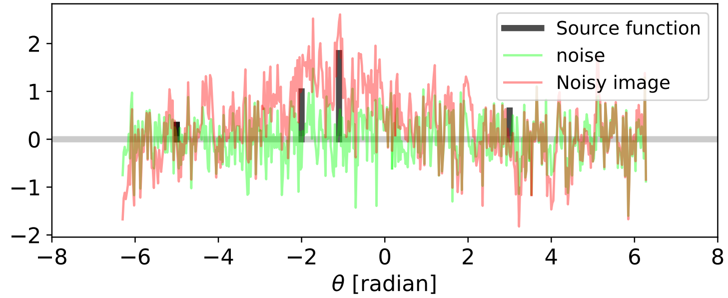


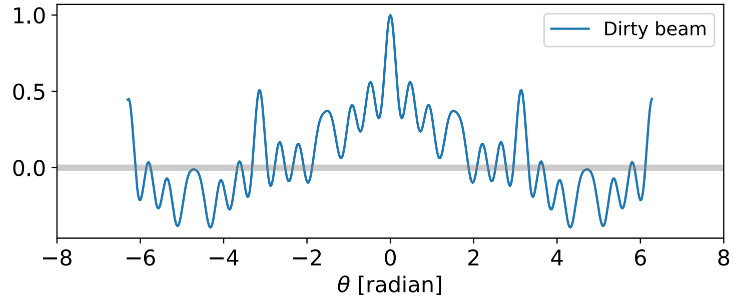


The Clark CLEAN algorithm (Clark 1980)

Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$





1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

2. *Minor cycle*
Use certain conditions to find multiple clean components at a time

Need to set some parameters to control the behavior of minor cycles. Please check

3. (i) Subtract $(I_m \times g) * B$ from the dirty image (call the dirty image after subtraction the residual image).
(ii) Append the subtracted $(I_m \times g)$ to so called clean model

4. [Is the intensity peak in the residual image larger than a specified **cutoff**? 1~2 times the rms noise, normally.]
&&
[Not yet run more iteration than a specified limit **niter**?]

True

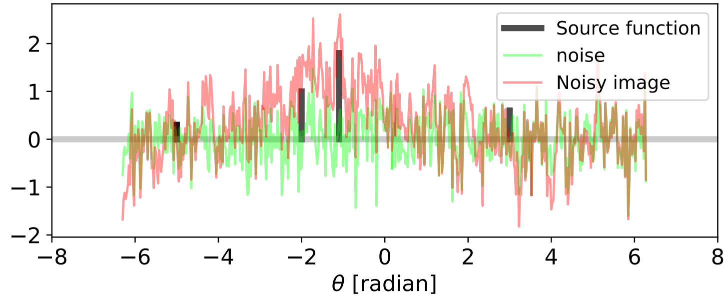
False

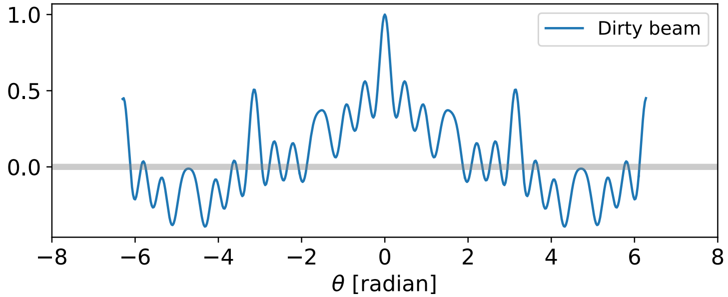
3. (i) Convolve the clean imodel *with the* clean beam, which is the a Gaussian profile obtained from fitting the central lobe of the dirty beam.
(ii) Add the residual image *to* the convolved image. This is the final product, the clean image.

The Cotton-Schwab CLEAN algorithm (Schwab 1984)

Ansatz: intensity distribution of target sources can be approximated by point sources (i.e., a collection of Dirac delta functions).

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$





1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

2. *Minor cycle*
Use certain conditions to find multiple clean components at a time

Need to set some parameters to control the behavior of minor cycles. Please check

3. (i) Subtract $(I_m \times g) * B$ from the ungrided visibility.
(ii) Append the subtracted $(I_m \times g)$ to so called clean model

4. [Is the intensity peak in the residual image larger than a specified **cutoff**? 1~2 times the rms noise, normally.]
&&
[Not yet run more iteration than a specified limit **niter**?]

True

False

3. (i) Convolve the clean imodel *with the* clean beam, which is the a Gaussian profile obtained from fitting the central lobe of the dirty beam.
(ii) Add the residual image *to* the convolved image.
This is the final product, the clean image.

The Multi-Scale CLEAN algorithm (Cornwell 2008)

Ansatz: intensity distribution of target sources can be approximated by point sources and 2D Gaussians with various pre-defined sizes

1. Find the intensity peak in (residual) dirty image

To save time, sometimes specify to search over certain restricted areas, call **clean boxes**.

2. *Minor cycle*
Use certain conditions to find multiple clean components at a time

3. (i) Subtract $(I_m \times g) * B$ from the ungrided visibility.
(ii) Append the subtracted $(I_m \times g)$ to so called clean model

4. [Is the intensity peak in the residual image larger than a specified **cutoff**? 1~2 times the rms noise, normally.]
&&
[Not yet run more iteration than a specified limit **niter**?]

True

False

3. (i) Convolve the clean imodel *with the* clean beam, which is the a Gaussian profile obtained from fitting the central lobe of the dirty beam.
(ii) Add the residual image *to* the convolved image. This is the final product, the clean image.

Need to deconvolve $\left[A(\theta')\widetilde{P(\theta')}\right]^D$

Need to control the point source + Gaussian fittings with some arbitrarily defined weightings, namely the "small scale bias". There is no rule of thumb for how to set the small scale biases. I am almost always very frustrated about this. It easily biases the analyses of multi-wavelength observations. So I never use this variant of clean in my journal publications... There are certainly fans of this algorithm though, for good reasons. It converges very quickly when you are dealing with angularly extended emission. So it is still necessary to know something about it. For more details, check the QR code.

The Maximum Entropy Method (MEM) (e.g., Cornwell & Evans 1985)

Ansatz: intensity distribution is smooth

Iteratively, find an image that satisifies the complex visibility measurements and minimize the entropy:

Intensity at pixel k

$$H = -\sum_{k} I_k ln \frac{I_k}{M_k}$$

Prior intensity at pixel k

The Maximum Entropy Method (MEM) (e.g., Cornwell & Evans 1985)

Ansatz: intensity distribution is smooth

Iteratively, find an image that satisifies the complex visibility measurements and minimize the entropy:

Intensity at pixel k

$$H = -\sum_k I_k ln\frac{I_k}{M_k}$$

Prior intensity at pixel k

Pro: In principle, it will converge rapidly and nicely when you are dealing with angularly extended sources.

The Maximum Entropy Method (MEM) (e.g., Cornwell & Evans 1985)

Ansatz: intensity distribution is smooth

Iteratively, find an image that satisifies the complex visibility measurements and minimize the entropy:

Intensity at pixel k

$$H = -\sum_k I_k ln\frac{I_k}{M_k}$$

Prior intensity at pixel k
(e.g., sometimes a lower resolution image)

Pro: In principle, it will converge rapidly and nicely when you are dealing with angularly extended sources.

Con: It also needs some experience to learn how to make it converge correctly, especially, when there are absorption or Stokes Q and U features in your images that have negative intensity. Angular resolution is not well defined.

1. Imaging: the process to yield an image model that is consistent with the interferometric measurements of complex visibility.
2. Most commonly used algorithms: CLEAN (with variants) and MEM.
3. When performing imaging using the CLEAN algorithm, you usually need to set the weighting scheme, (visibility) griding scheme, pixel sizes, number of pixels, cutoff, number of interations, and some parameters/keywords that are specific to the variant you are using.