Assignment_updated

January 4, 2021

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# Thomas Dugdale - Radio Astronomy Assignment - Simulating a Radio␣
 ↪Interferometer
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# Link to binder:
# https://mybinder.org/v2/gh/ThomasNose/Interferometer/HEAD


# References

# http://www-static-2019.jmmc.fr/mirrors/obsvlti/book/Segransan_1.pdf - Used␣
 ↪for uv-plane equations
# https://matplotlib.org/3.1.1/api/ - Where I collected different commands for␣
 ↪matplotlib
# https://online.manchester.ac.uk/webapps/blackboard/execute/content/file?
 ↪cmd=view&content_id=_12102131_1&course_id=_63179_1

import numpy as np                                                          #␣
 ↪Importing packages
import matplotlib.pyplot as plt
%matplotlib inline


def data(config,source): # Data function
    config = np.loadtxt(config)                                            # Loading␣
 ↪in VLA configuration D data
    source = np.loadtxt(source)                                            # Source␣
 ↪1 and 2 data

    return (config,source)
config,source = data("Dconfig.txt","source.txt")

def configuration(config,source):                                          #␣
 ↪Telescope configuration
    XYZ = config[:,0:3]                                                    # Array␣
 ↪with VLA data
```

```
    RAh,RAm,RAs = source[:,0],source[:,1],source[:,2]                #␣
↪Collecting the hours, minutes, seconds of Right Ascension
    DECh,DECm,DECs = source[:,3],source[:,4],source[:,5]             #␣
↪Collecting source declinations
    JySource = source[:,6]

    Y,Z = config[:,1],config[:,2]                                    #␣
↪Telescope coordinates
    plt.scatter(Y,Z)                                                 #␣
↪Plotting the positions of the antennas
    plt.title('VLA D configuration')
    plt.ylabel('y (ns)')
    plt.xlabel('x (ns)')
    plt.show()

    return(Y,Z,JySource)
Y,Z,JySource = configuration(config,source)


def uvcoverage(config,declination,f): # U-V coverage at HA = 0 function
    DATA = []                                                        # Empty␣
↪arrays for modulus baselines, Azimuth and Elevation values
    for i, x_i in enumerate(config):                                 # This␣
↪loop is for calculating all 351 baselines, elevations and azimuth components
        for j, y_i in enumerate(config):
            if i < j:                                                # This␣
↪condition ensures no duplicate values are calculated, ie 2-1 and 1-2, 10-5␣
↪and 5-10 etc.
                DATA.append(x_i-y_i)

    DATA = np.array(DATA)                                            # Loading␣
↪in all the antenna coordinates
    X = DATA[:,0]                                                    #␣
↪Allocating to X,Y,Z
    Y = DATA[:,1]
    Z = DATA[:,2]

    dec = declination

    Lambda = 3e8/f

    U = Lambda*(np.sin(0)*X + np.cos(0)*Y)                           # U-V␣
↪values, again with RA set to 0 hrs
    V = Lambda*(-np.sin(dec)*np.cos(0)*X + np.sin(dec)*np.sin(0)*Y + np.
↪cos(dec)*Z) # Equations taken from Neal Jackson and Segransan
```

```python
    plt.scatter(V/1e3,U/1e3,s=1)                                              # Plotting the UV coverage which is both the positive and negatives values of U and V
    plt.scatter(-V/1e3,-U/1e3,s=1)                                            # Values for U and V are divided by 1,000 to match the units used in the VLA document provided
    plt.xlabel('x (kilo wavelengths)')
    plt.ylabel('y (kilo wavelengths)')
    plt.title('VLA UV coverage HA=0 at dec=45 degrees')
    plt.show()

    return(X,Y,Z,dec)
X,Y,Z,dec = uvcoverage(config,np.pi/4,5e9)                                    # 45 degree declination

def uvcoverageHA(hour,Interval,X,Y,Z,dec,f): # U-V coverage function for HA

    T = (2*np.pi/24) * hour                                                   # Equation which converts the input time (in hours) to radians
    interval = (hour * 3600) // Interval                                      # The interval is every 30 seconds to this says how many data points there should be

    t = np.linspace(-T/2,T/2,interval)                                        # One hour of RA in radians from -0.5 hr to +0.5hr
    u = []                                                                    # Blank u-v arrays for appending
    v = []

    c = 3e8

    for i in range(len(X)):                                                   # Loop for calculating u-v
        u = np.append(u, (f/c)*(np.sin(t)*X[i] + np.cos(t)*Y[i]))             # Equations taken from Segransan + Neal Jackson lectures
        v = np.append(v, (f/c)*(-np.sin(dec)*np.cos(t)*X[i] + np.sin(dec)*np.sin(t)*Y[i] + np.cos(dec)*Z[i]))

    plt.scatter(v/1e3,u/1e3,s=5,c='black')                                    # Plotting the u-v plane
    plt.scatter(-v/1e3,-u/1e3,s=5,c='black')                                  # Negative have to be plotted for other half of u-v plane
    plt.xlabel('x (kilo wavelengths)')
    plt.ylabel('y (kilo wavelengths)')
    plt.title('VLA UV coverage HA=+/-0.5hr at dec=45 degrees')
    plt.show()
```

```
    return(u,v)
u,v = uvcoverageHA(1,30,X,Y,Z,dec,5e9)                                    # 1␣
↪hour (+/- 0.5HA) at 30 second intervals


def truesky(extent_x,extent_y): # Function to be recalled
    TrueSky = np.zeros((extent_x,extent_y))                           # Blank␣
↪array for point sources

    centre_x,centre_y = int(extent_x/2),int(extent_y/2)               # Centre␣
↪value of image

    TrueSky[centre_x,centre_y] = JySource[0]                          # This is␣
↪the first centred image
    TrueSky[20,50] = JySource[1]                                      # This is␣
↪the second source. 3 arc minutes difference in Declination and 10 seconds␣
↪difference in RA.

    plt.imshow(TrueSky,extent=[-centre_x,centre_x,-centre_y,centre_y])# This is␣
↪an image of the two sources
    plt.colorbar()
    plt.title('Observed sources')
    plt.xlabel('RA offset (arcsec, J2000)')
    plt.ylabel('DEC offset (arcsec, J2000)')

    plt.show()
    return(TrueSky)
TrueSky = truesky(400,400)

def visibility(truesky):                                              #␣
↪Function for fourier transforming to get visibilies

    Visibility = np.fft.fft2(TrueSky)                                 # Fourier␣
↪transform of sources
    plt.imshow(np.real(Visibility),extent=[-200,200,-200,200])        # This␣
↪image shows the real fourier space of the two observed sources
    plt.xlabel('RA offset (arcsec, J2000)')
    plt.ylabel('DEC offset (arcsec, J2000)')
    plt.title('Fourier space of two point sources')
    plt.colorbar()
    plt.show()

    return(Visibility)
Visibility = visibility(TrueSky)
```

```
def sampling(extent_x,extent_y,scale):                                    #␣
↪Function for sampling function

    Sampling = np.zeros((extent_x,extent_y))                              # Empty␣
↪array for sampling function
    for i in range(len(u)):
        Sampling[int(u[i]/scale),int(v[i]/scale)] = 1                     # Fills␣
↪in empty image array with a 1 if uv data exists
        Sampling[int(-u[i]/scale),int(-v[i]/scale)] = 1                   # also␣
↪divided by 500 so all u,v data fits within sampling array
    ShiftSampling = np.fft.fftshift(Sampling)                             # Shifts␣
↪the image to the centre of the spectrum

    centre_x,centre_y = int(extent_x/2), int(extent_y/2)                  # Values␣
↪for centering the image

    plt.imshow(np.
↪real(ShiftSampling),extent=[-centre_x,centre_x,-centre_y,centre_y]) #␣
↪Plotting sampling function
    plt.title('U-V sampling function')                                    # sampled␣
↪grid
    plt.xlabel('RA offset (arcsec, J2000)')
    plt.ylabel('DEC offset (arcsec, J2000)')
    plt.colorbar()
    plt.show()

    return(Sampling)
Sampling = sampling(400,400,500)                                          # size␣
↪400x400 with pixels being 500 data points each

def synthesise(extent_x,extent_y,sample_function): # Synthesised beam function

    centre_x,centre_y = int(extent_x/2), int(extent_y/2)                  # Values␣
↪for centering the image

    Synthesised = np.fft.fft2(sample_function)                            # Fourier␣
↪transform of UV image to show synthesised(dirty) beam image
    Synthesised = np.fft.fftshift(Synthesised)                            # This␣
↪command shifts the image to the centre of the plot rather than being at the␣
↪corners
    Synthesised = np.real(Synthesised)
    plt.
↪imshow(Synthesised,vmin=-10,vmax=300,extent=[-centre_x,centre_x,-centre_y,centre_y])␣
↪# Real values plotted
    plt.title('Synthesised beam')                                         # vmin␣
↪and vmax values best show the dirty beam
```

```
    plt.colorbar()                                                      # Shows␣
↪values of the synthesised beam
    plt.xlabel('RA offset (arcsec, J2000)')
    plt.ylabel('DEC offset (arcsec, J2000)')
    plt.show()

    return(Synthesised)
Synthesised = synthesise(400,400,Sampling)                              # Size␣
↪400x400 with sampling function as input

def dirtymap(extent_x,extent_y,sample_function,visibility): # Dirty map function

    centre_x,centre_y = int(extent_x/2), int(extent_y/2)                # Values␣
↪for centering the image

    SampleVis = Sampling * Visibility                                   #␣
↪Multiplying together to get sampled visibilities
    DirtyMap = np.fft.ifft2(SampleVis)                                  # Inverse␣
↪fourier transform to get from sampled visibilities to dirty map
    plt.imshow(np.
↪real(DirtyMap),extent=[-centre_x,centre_x,-centre_y,centre_y]) # Plotting␣
↪and centering dirty map
    plt.xlabel('RA offset (arcsec, J2000)')
    plt.ylabel('DEC offset (arcsec, J2000)')
    plt.title('Dirty map')
    plt.show()

    return(DirtyMap)
DirtyMap = (400,400,Sampling,Visibility)                                # 400x400␣
↪dirty map


def radius(Lambda,D): # Primary beam radius in arcseconds function
    Primary = Lambda / D                                                # Angular␣
↪size of primary beam in radians at 5GHz with 25m apertures
    PrimaryDeg = Primary * (180/np.pi) * 3600                           # Angular␣
↪size of beam in arcseconds
    radius = int(np.round(PrimaryDeg/2))                                # Integer␣
↪and rounded value for radius of primary beam in arcseconds

    return(radius)
radius = radius(3e8/5e9,25)                                             #␣
↪Inputting wavelength calculated by c/f and inputting 25 metre aperture␣
↪diameter
# The above is the radius of the primary beam in arcseconds
```

```
def primarybeam(extent_x,extent_y,Radius): # Primary beam function

    centre_x,centre_y = int(extent_x/2), int(extent_y/2)             # Values␣
 ↪for centering the image

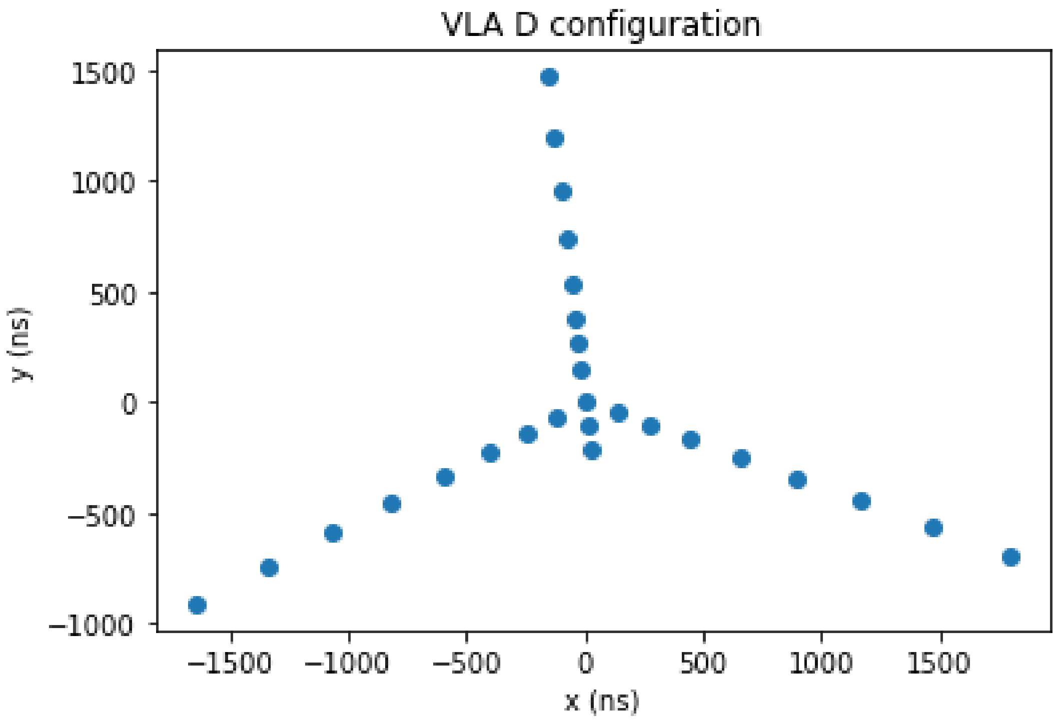
    x = np.linspace(1,extent_x,extent_x)                             #␣
 ↪Creating lists for meshgrid that range over the width of the beam
    y = np.linspace(1,extent_y,extent_y)
    xx, yy = np.meshgrid(x,y)                                        #␣
 ↪Meshgrid for calculating distance to a pixel

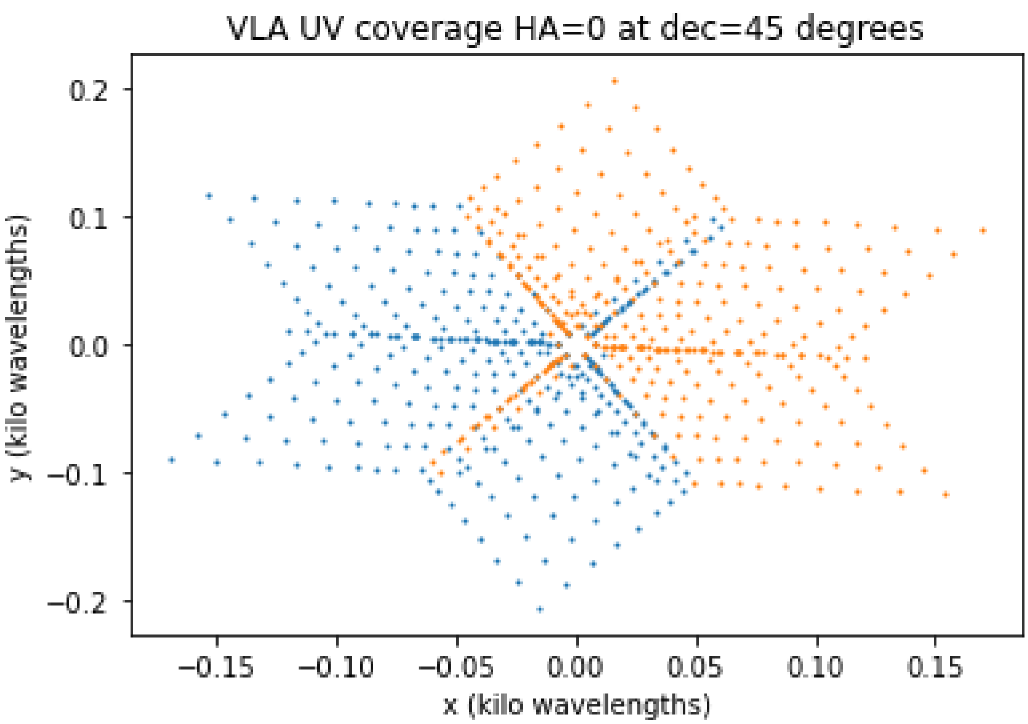
    PrimaryBeam = np.zeros((extent_x,extent_y))                      # Blank␣
 ↪image for primary beam of size width of primary beam
    for i in range(1,2*Radius):                                      # Loop␣
 ↪creating the primary beam
        r = ((xx-x[200])**2 + (yy-y[200])**2)**0.5               # Length from␣
 ↪the centre of the primary beam
        PrimaryBeam += 0.01 * np.exp(-(r/[i]*0.5)**2)                              ␣
 ↪ # 'Temporary' equation for the primary beam

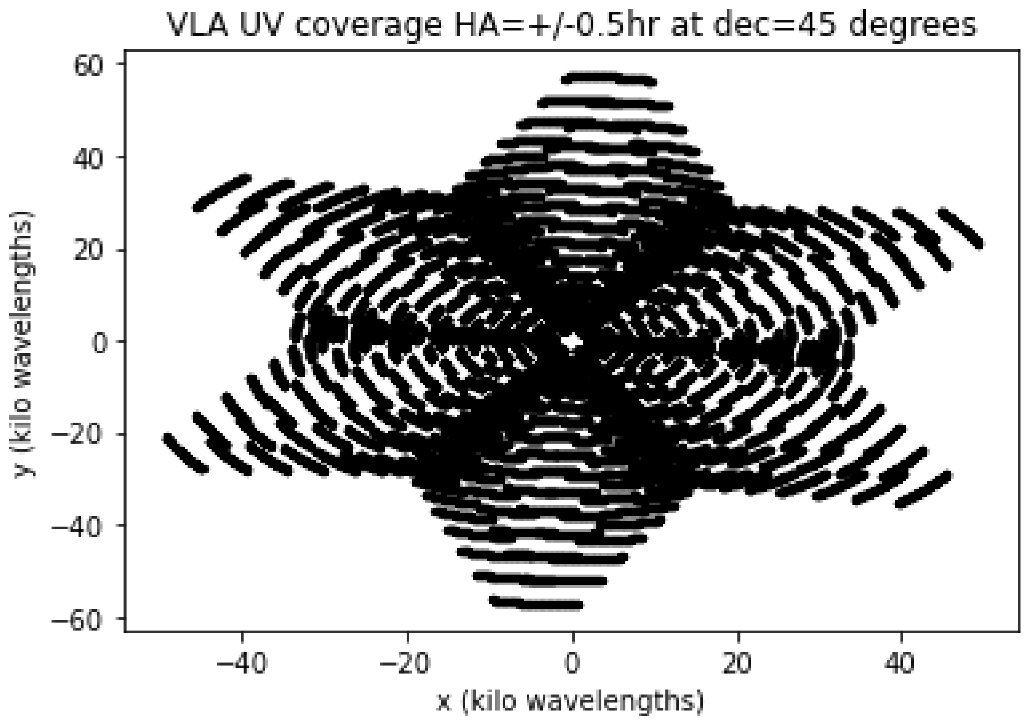
    plt.imshow(PrimaryBeam,extent=[-centre_x,centre_x,-centre_y,centre_y]) #␣
 ↪Primary beam plotted, centre image is [0,0]
    plt.xlabel('arcseconds')
    plt.ylabel('arcseconds')
    plt.title('Primary Beam of VLA')
    plt.colorbar()
    plt.show()

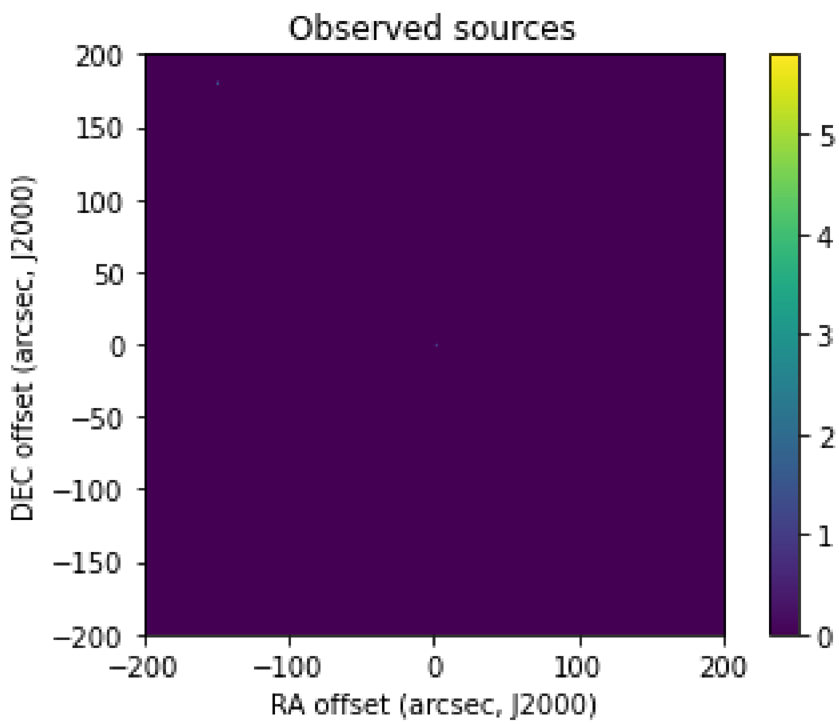
    return(PrimaryBeam)
PrimaryBeam = primarybeam(400,400,radius)                    # Primary beam with␣
 ↪diameter 2*radius

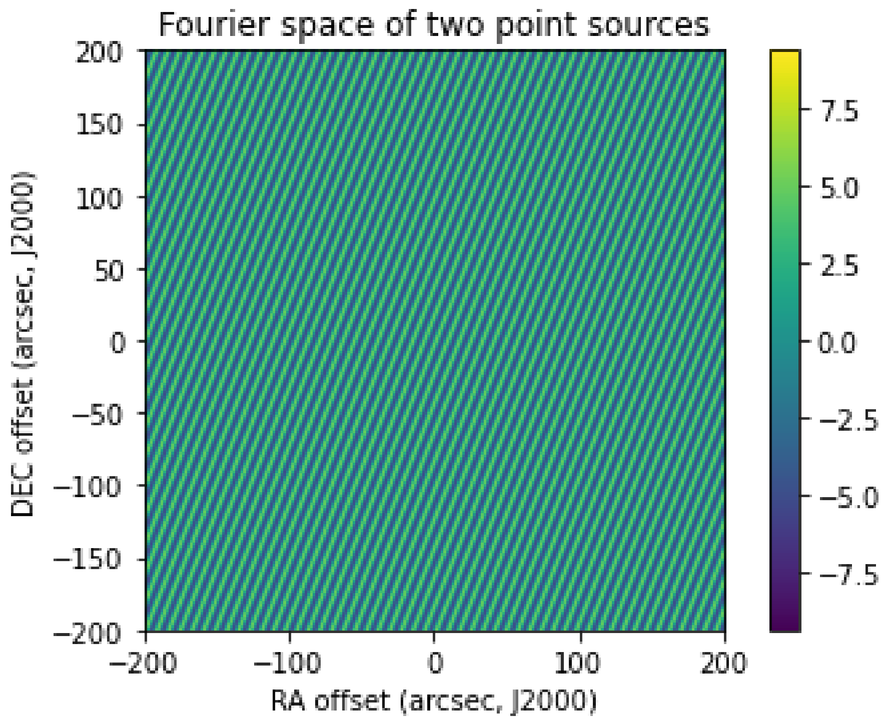

Gauss = np.random.normal(0,0.1,(400,400))
TEST = (Gauss + TrueSky) * PrimaryBeam # True Sky multiplied by Primary Beam␣
 ↪with Gaussian noise
plt.imshow(TEST)
plt.xlabel('arcseconds')
plt.ylabel('arcseconds')
plt.title('True Sky affected by Primary beam')
plt.colorbar()
plt.show()
```

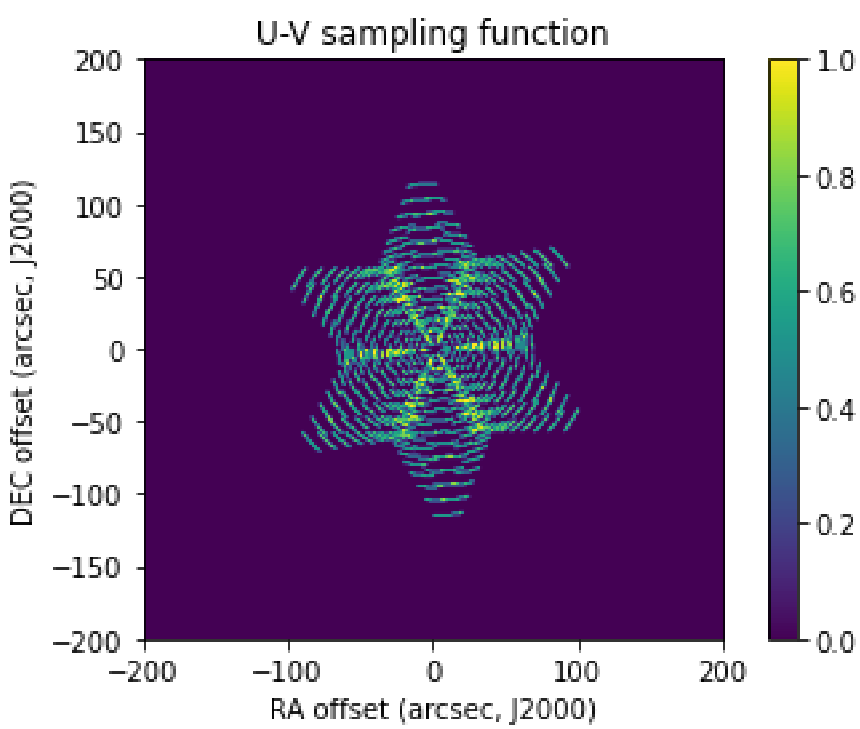

VLA D configuration
y (ns)
x (ns)
1500
1000
500
0
−500
−1000
−1500
−1000
−500
0
500
1000
1500

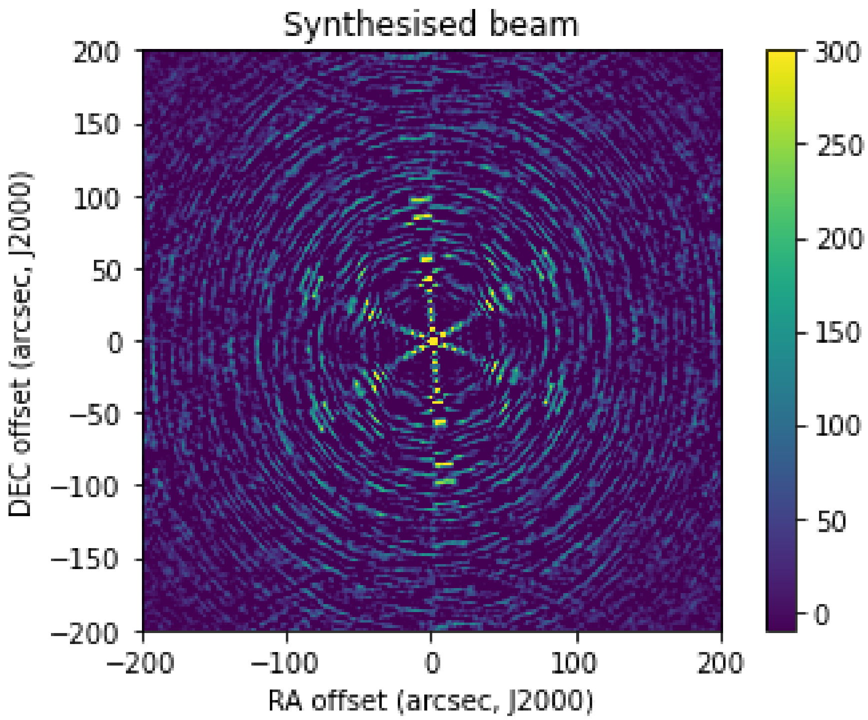

VLA UV coverage HA=0 at dec=45 degrees
y (kilo wavelengths)
x (kilo wavelengths)
0.2
0.1
0.0
−0.1
−0.2
−0.15
−0.10
−0.05
0.00
0.05
0.10
0.15

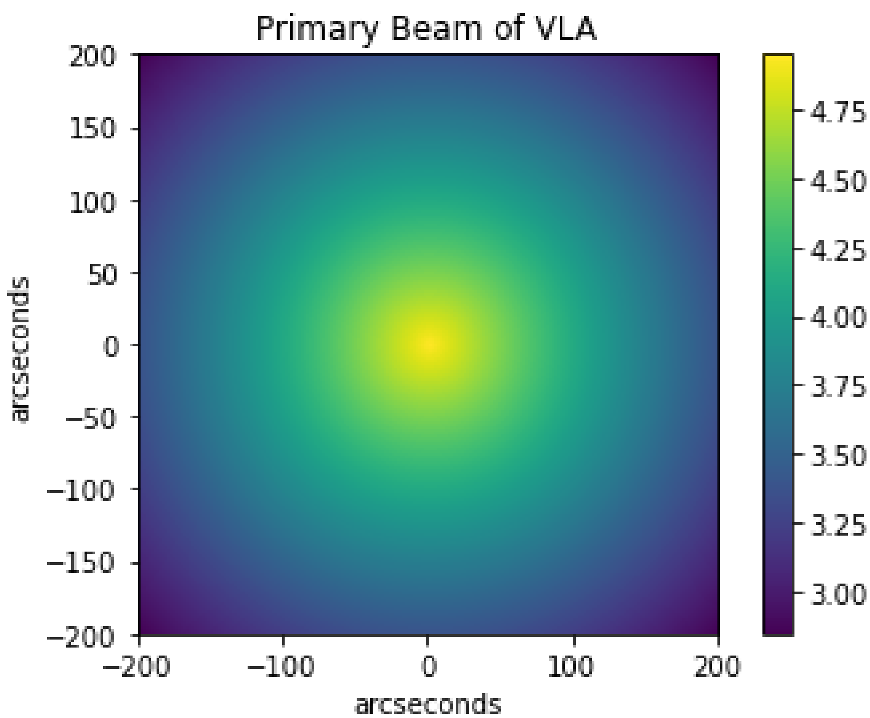

VLA UV coverage HA=+/-0.5hr at dec=45 degrees
y (kilo wavelengths)
x (kilo wavelengths)
60
40
20
0
−20
−40
−60
−40
−20
0
20
40

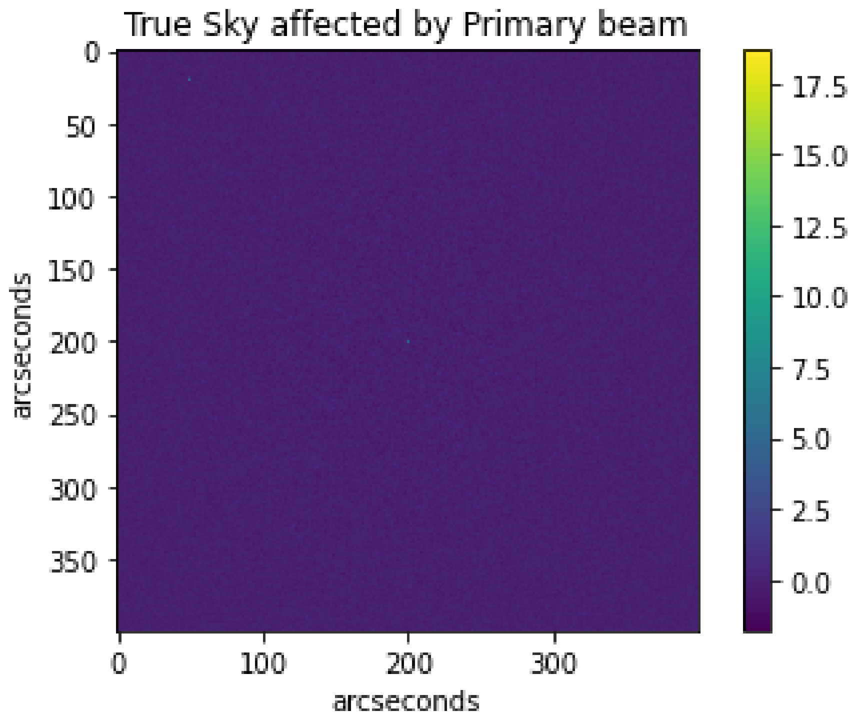

Observed sources
DEC offset (arcsec, J2000)
RA offset (arcsec, J2000)
200
150
100
50
0
−50
−100
−150
−200
−200
−100
0
100
200
5
4
3
2
1
0


Fourier space of two point sources
DEC offset (arcsec, J2000)
RA offset (arcsec, J2000)
200
150
100
50
0
−50
−100
−150
−200
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5


U-V sampling function
DEC offset (arcsec, J2000)
RA offset (arcsec, J2000)
200
150
100
50
0
−50
−100
−150
−200
1.0
0.8
0.6
0.4
0.2
0.0


Synthesised beam
DEC offset (arcsec, J2000)
RA offset (arcsec, J2000)
200
150
100
50
0
−50
−100
−150
−200
−200
−100
0
100
200
300
250
200
150
100
50
0


Primary Beam of VLA
arcseconds
arcseconds
200
150
100
50
0
−50
−100
−150
−200
−200
−100
0
100
200
4.75
4.50
4.25
4.00
3.75
3.50
3.25
3.00


True Sky affected by Primary beam
arcseconds
arcseconds
0
50
100
150
200
250
300
350
0
100
200
300
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0

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[ ]:
```