

CLEAN Algorithm Roadmap

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clean algorithm

1 Introduction

1.1 Related Links

Original Paper: Aperture Synthesis with a Non-Regular Distribution of Interferometer Baselines

NRAO - Radio Imaging and CLEAN

CLEAN Algorithm

NRAO - The 'CLEAN' algorithm

Build a Homebrew Radio Telescope

Fourier Synthesis Imaging

Radio2Space

Deconvolution with CLEAN

Hogbom's CLEAN algorithm. Impact on astronomy and beyond

An analysis of the properties of CLEAN and smoothness Stabilized CLEAN - some warnings

SparseRI: A Compressed Sensing Framework for Aperture Synthesis Imaging in Radio Astronomy

PPT - Deconvolution

Antennas & Receivers in Radio Astronomy

ADAPTIVE REAL TIME IMAGING SYNTHESIS TELESCOPES

Annular synthesis telescopes - A novel class of multiple beam telescopes operating at mm-wavelengths

aperture synthesis

Antennas in Radio Astronomy

Synthesis of Wide Beam Array Patterns Using Quadratic-Phase Excitations

2 Original Paper:

Aperture Synthesis with a Non-Regular Distribution of Interferometer Baselines [[link](#)]

打算翻译本文，翻译的同时理解思考。

2.1 Abstract

In high-resolution radio interferometry it is often impossible for practical reasons to arrange for the measured baselines to be regularly distributed. The standard Fourier inversion methods may then produce maps which are seriously confused by the effects of the prominent and extended sidelobe patterns of the corresponding synthesized beam. Some methods which have been proposed for avoiding these difficulties are discussed. In particular, the procedure CLEAN is described in some detail. This has been successfully applied to measurements taken

with several different radio telescopes and appears to be the best method available at the time of writing.

在高分辨率射电干涉测量的实际过程中，不可能将测量基线布置的均匀。所以标准傅立叶反变换方法生成的 map 可能会被主旁瓣和扩展旁瓣(confused by the effects of the prominent and extended sidelobe patterns of the corresponded synthesized beam)污染(混淆，不知道旁瓣中的结构是真实源的结构还是只是(对应的脏束synthesis beam的)旁瓣)。下文讨论了一些消除这种影响的方法，特别地，详细介绍了在写作本文时效果最好的 CLEAN 算法。

2.2 Introduction

Aperture synthesis measurements are usually made at a set of interferometer spacings and orientations that form a regular pattern in the baseline (u,v) diagram. Such a regular coverage has many practical advantages both in connection with the formal synthesis calculations and the later astronomical interpretation of the synthesis map. However, there are occasions when irregularities in the baseline coverage cannot be avoided. Interference or malfunctioning of some part of the equipment can make it necessary to reject certain portions of the measurements and this will leave gaps in an otherwise regularly covered u,v plane. The gaps give rise to undesirable sidelobes in the synthesized beam, making the synthesis map difficult or impossible to interpret. Similar problems arise when the u,v plane has been covered by a coarse grid of measurements as this will give rise to prominent grating responses in the synthesized beam pattern.

综合孔径测量通常通过一系列在基线(u,v)平面中，位置和方位分布均匀的干涉仪来实现。这种归整(regular)的覆盖在连接以下两方面有不少优势：

1. 早期的合成计算
2. 后期的对脏图(synthesis map)在天文上的解释

然而，基线覆盖不规则无法避免的情况可能会发生。

干涉或设备某些部分无法正常工作使得有必要删除一些测量数据，而这就会使理想的归整的 u, v 覆盖存在缺口 gaps。

这些 gaps 会在合成束(synthesized beam)中产生不想要的旁瓣，使得很难去解读合成图(synthesized map)。

类似的问题会在 u, v 平面被粗糙的测量网格(coarse grid of measurements)时发生，因为这样会在合成束中产生主响应。(give rise to prominent grating responses in the synthesized beam pattern)

Need to know what are synthesized beam and synthesized map:

synthesized beam 就是进行 UV 覆盖采样 Visibility 的可见度采样函数的傅立叶逆变换：即脏束，其实就是 PSF?

synthesized map 就是可见度采样函数与实际天空理论可见度函数相乘得到的实测可见度函数的傅立叶逆变换：即脏图，就是实际观测到的图。

It may, in certain cases, be impossible (or impractical) to arrange for the interferometer measurement to fall on a regular grid in the baseline (u,v) diagram. This is the case for

measurements taken with instruments such as the Caltech and Green Bank interferometers and, in general, for measurements that involve large inter-ferometer spacings. Interferometers can be operated over spacings up to the full diameter of the Earth and from space vehicles and one shall ultimately want to use such measurements in a systematic way to synthesize very high-resolution maps of small diameter sources. Occultations of radio sources by the Moon give rise to similar problems. A few occultations of the same source (or one occultation measured at several observatories) will deliver a number of strip scans at a non-regular set of position angles. These strip scans are equivalent to a u,v coverage along radii at these same position angles.

在特定情况下，不可能（或不切实际）去将干涉阵的测量点落在基线 u, v 平面里的一个归整的网格中。用类似Caltech和Green Bank干涉仪做的测量就是这样，大体上，对于涉及基线很长的干涉阵都如此。干涉仪可以在基线长度跨越整个地球直径甚至空间望远镜下运行，人们总是希望（系统地进行）这样的测量，以合成小直径圆的超高分辨率的图。月球遮挡射电源会导致类似的问题。同一个源的几个不同遮挡（或一次遮挡被几次观测到）将在一系列的方位角中带来一些条带的扫描。这些条带扫描等价于沿着相同方位角下的半径的 u, v 覆盖。

其实标题就体现了这里讨论的问题

3 NARO slide, Radio Imaging and CLEAN

4 CLEAN Algorithm implementation

4.1 Outline

1. UV覆盖

给定台站位置(经纬度)[(Longitude1, Latitude1),(东经, 北纬)], 台站指向[(u_1, v_1, s_1), (u_2, v_2, s_2)]
采样间隔 (秒, 结合地球自转角速度), 观测初始时间 (年月日时分秒), 观测结束时间 (年月日时分秒), 观测频率, 根据地球真实位置, 给出UV覆盖数据点坐标 (以波长为单位, kilolambda (参考Radio Imaging and CLEAN)), 也有用米为单位, 并能实现UV覆盖的绘制 →

Telescope类

telescope.py:

```
class Telescope:
```

```
def __init__(self, poslist, directionlist):
```

```
self.poslist = poslist
```

```
self.directionlist = directionlist
```

```
def uvcoverage(self, dt, t0, t1, freq):
```

```
pass
```

```
return uvcover
```

```
...
```

```
def fake_uvcoverage():
```

```
return uvcover
```

调用：

```
tele1 = Telescope(poslist,directionlist)
uvcover = tele1.uvcoverage(dt,t0,t1,f)
tele1.uvplot()
```

2. Clean 算法：

→

Cleaner 类：

```
cl = Cleaner()
```

属性：

```
cl.dirty_map
cl.residual
cl.model_beam
cl.cleaned_map
cl.brightness (模拟时传入的原始高清图)
cl.uvcover(uv 覆盖)
```

方法：

```
cl.dirty_map_plot(scale="log")
cl.dirty_beam_plot(scale="log") (脏束，为uv采样的傅立叶逆变换)
cl.residual_plot(scale="log")
cl.model_beam_plot(scale="log")
cl.cleaned_map_plot(scale="log")
```

→

把这几个画图的合并到一起：

```
cl.plot(whichimg, scale="log",isuv=False (默认不是画频率的图),save=False (默认不保存图像))
```

还包含的方法：

```
cl.clean(dirty_map,itertime=100,gamma=0.1)
visibility = cl.gen_visibility(self,self.brightness) (模拟时传入高清图得到理论可见度图像)
sampled_visibility = cl.samp_visibility(self,visibility,uvcoverage) (模拟时，用uv覆盖采样理论可见度图像得到实测可见度图像)
dirty_map = cl.gen_dirty_map(self,samp_visibility) (从模拟或实际测量得到的实测可见度函数生成脏图)，然后可与 cl.clean() 函数对接上了
cl.save_visibility()将实测可见度数据保存，要能与当前通用文件格式对上，再写个读取实测可见度的函数，就能与实测数据对接上了。
```

3. 其他

var_config.py → 配置台站，采样间隔，起始时间等参数，直接import 进测试代码主程序

4. 模拟测试

simu_test.py 测试代码主程序

```
from telescope import Telescope
```

```
from cleaner import Cleaner
```

```
import var_config
```

```
tele1 = Telescope(poslist)
```

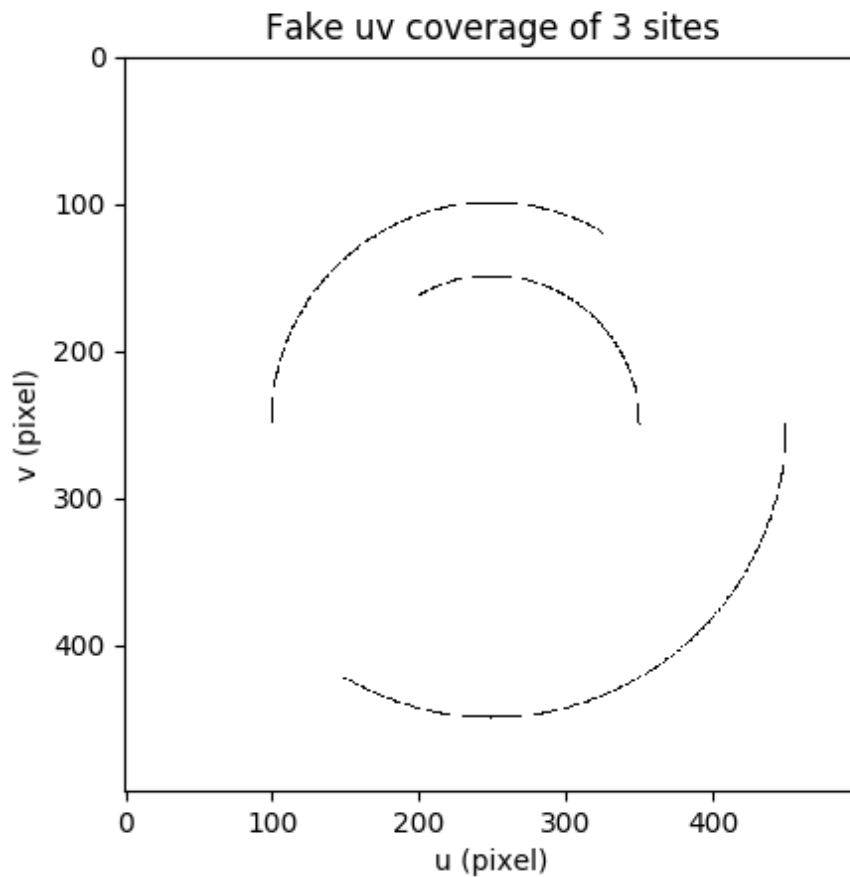
```
uvcover = tele1.uvcoverage(dt,t0,t1,f)
```

```
uvcover.plot()
```

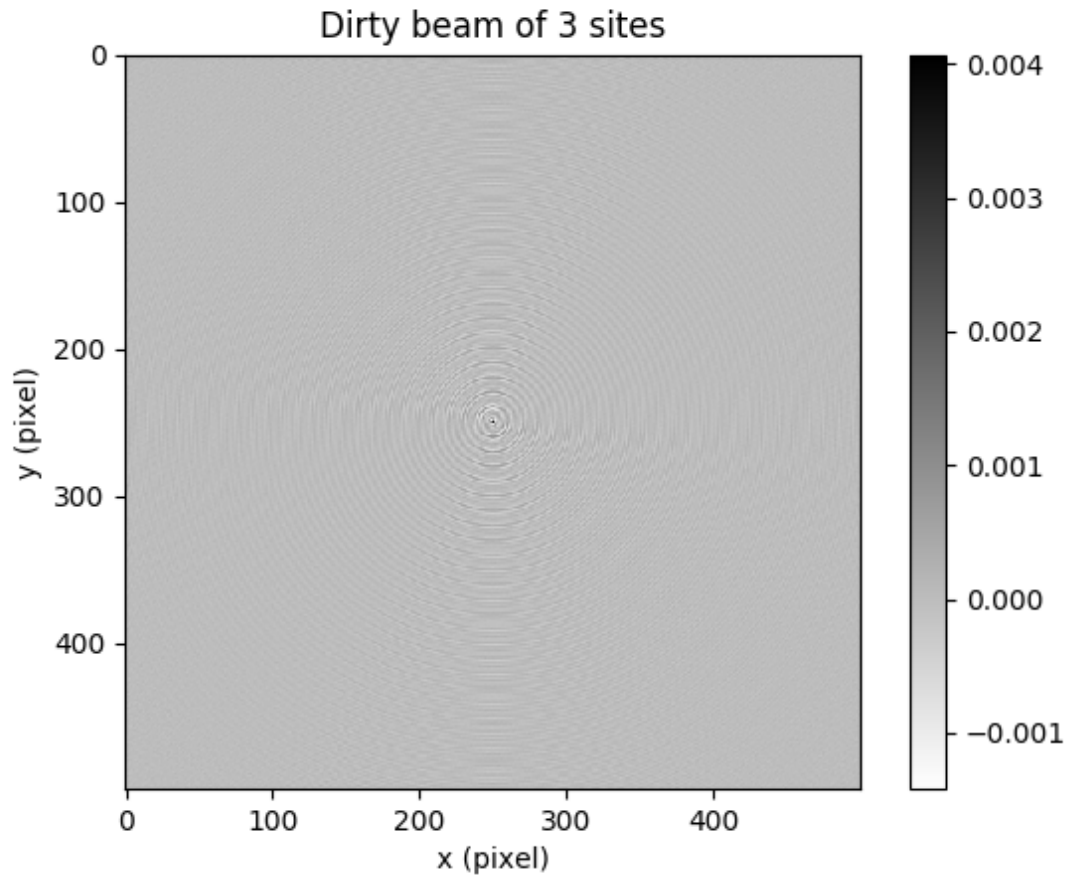
4.2 Codes and Results

1. telescope.py

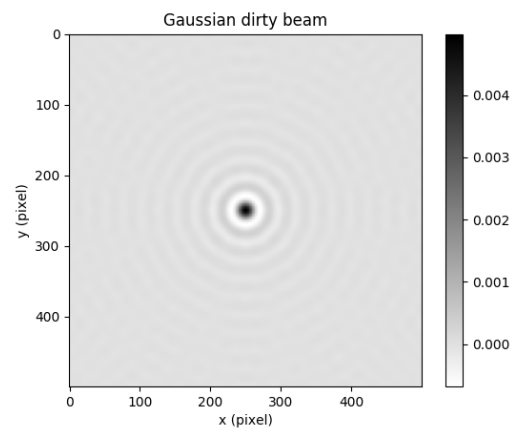
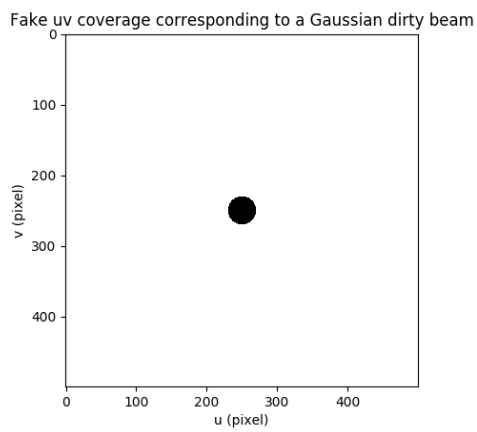
先调用 fake_uvcover()函数产生一个虚假的UV覆盖, 如下图所示:



之后，又添加了画dirty beam的功能



其它UV覆盖的测试：

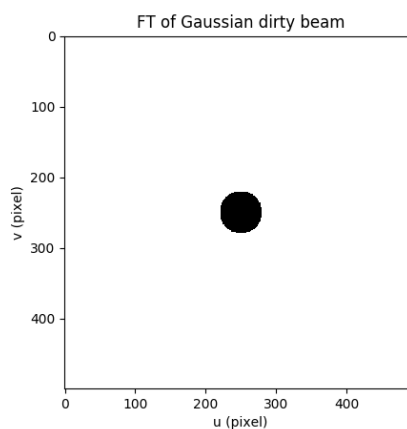
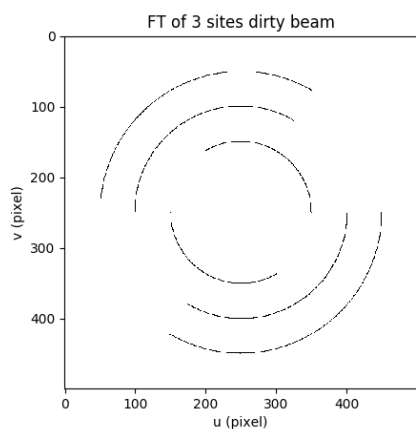


2. utils.py

由于画图函数 plot 重用需求较多，所以将其放入一个单独的文件 utils.py 另外读取原始测试图像（如lenna）的函数也放到 utils.py 里面

另外还将计算图像傅立叶变换的程序放到utils.py 里面：

可以测试前面的 dirty beam的FT是否和初始设置的 UV coverage 一样：



`plt.imshow() → cmap = 'gray'`

现在可以读取lenna图，做傅立叶变换得到理论可见度函数，再用UV覆盖采样得到实测可见度函数，之后进行傅立叶逆变换得到脏图 dirty map：

`RC = (512,512)`

`tele1.fake_uvcover2(RC, 30):`

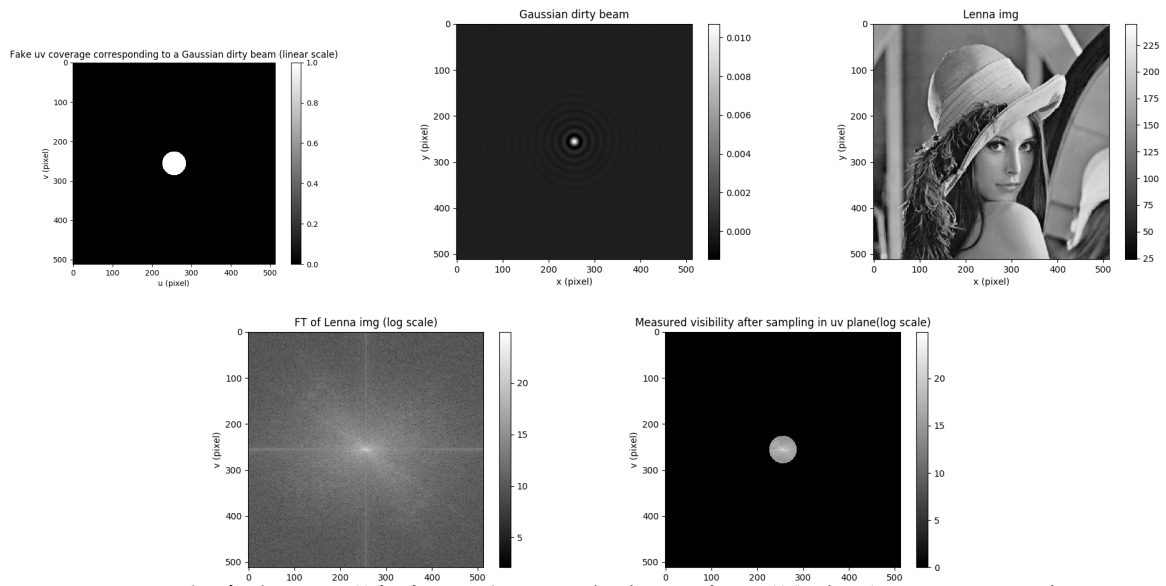
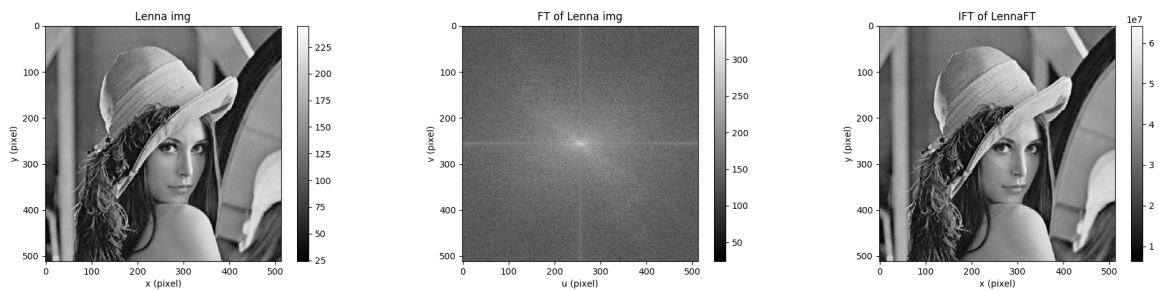


Figure 1: 当UV覆盖中心圆的半径为30个像素时的：UV采样函数、脏束、Lenna原图、理论可见度、实测可见度

前面的代码有问题，从实测可见度逆傅立叶变换得到的脏图不对。
重新验证：



现在可以了：

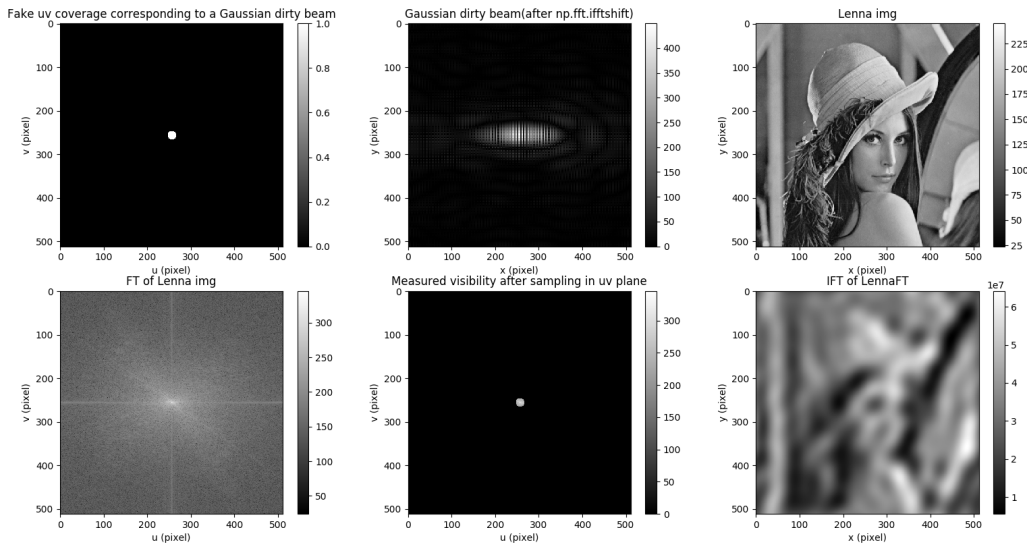


Figure 2: 当UV覆盖中心圆的半径为10个像素时的：UV采样函数、脏束、Lenna原图、理论可见度、实测可见度,脏图

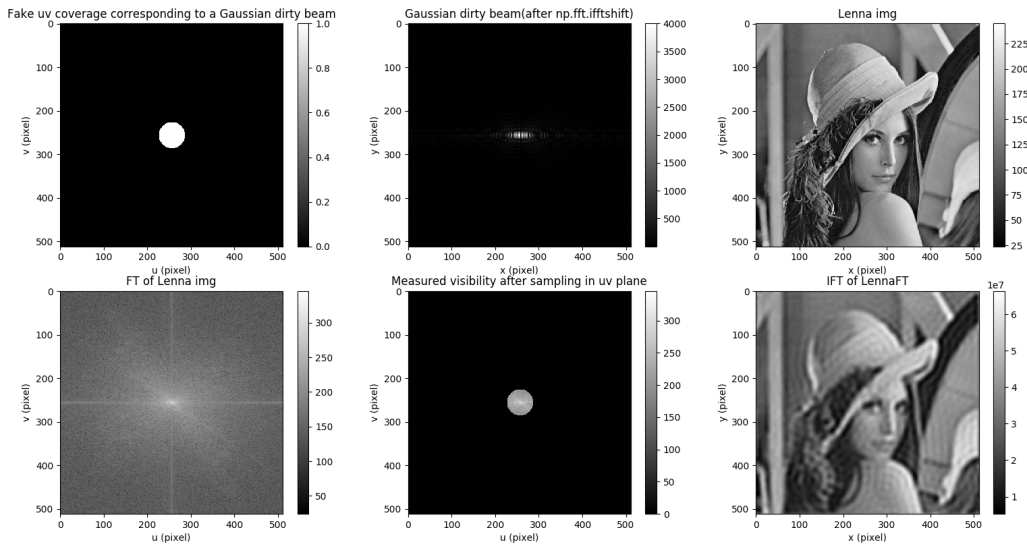


Figure 3: 当UV覆盖中心圆的半径为30个像素时的：UV采样函数、脏束、Lenna原图、理论可见度、实测可见度,脏图

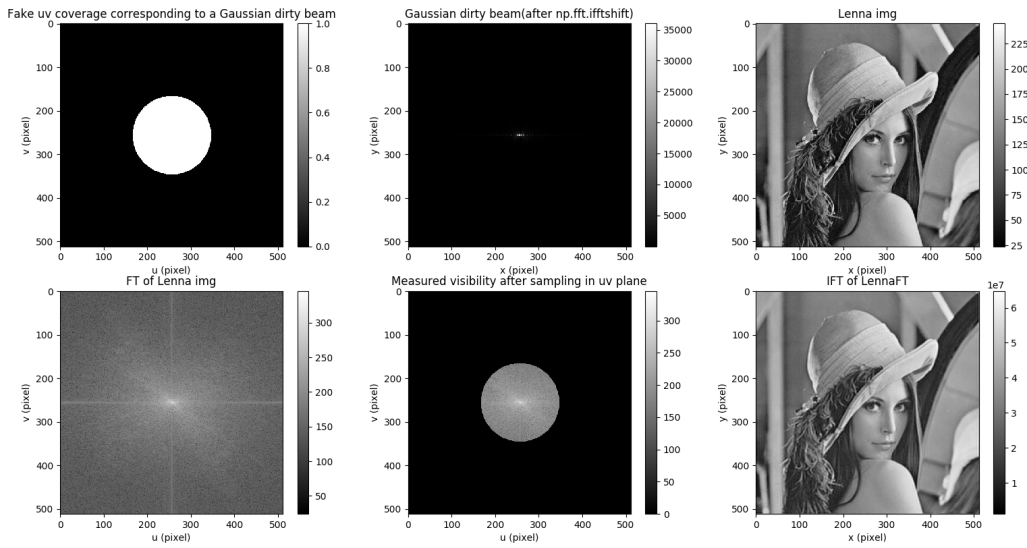


Figure 4: 当UV覆盖中心圆的半径为90个像素时的：UV采样函数、脏束、Lenna原图、理论可见度、实测可见度,脏图

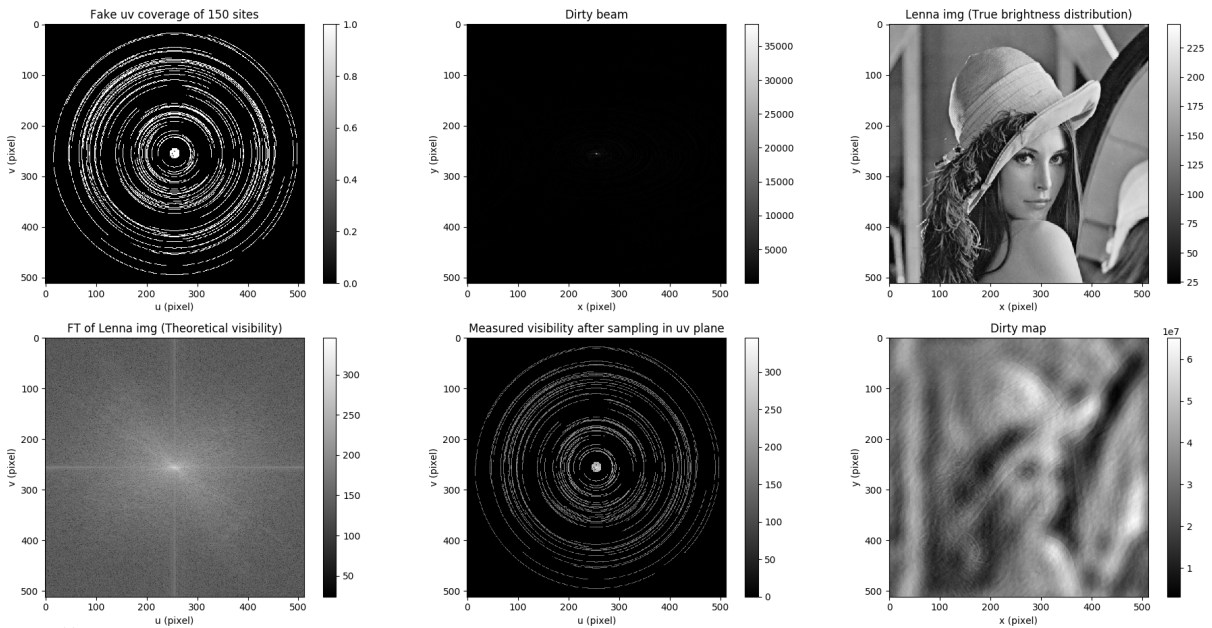
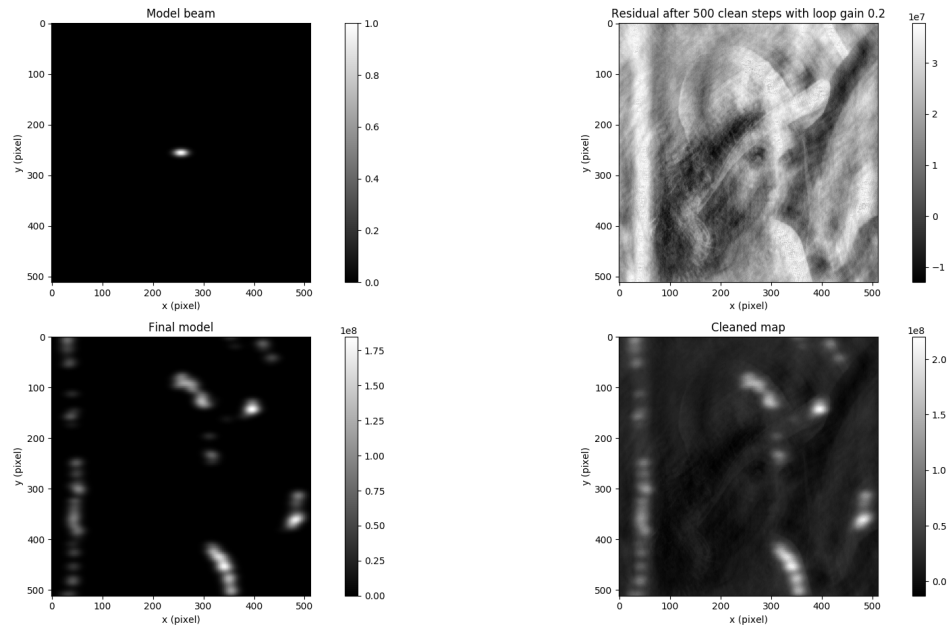


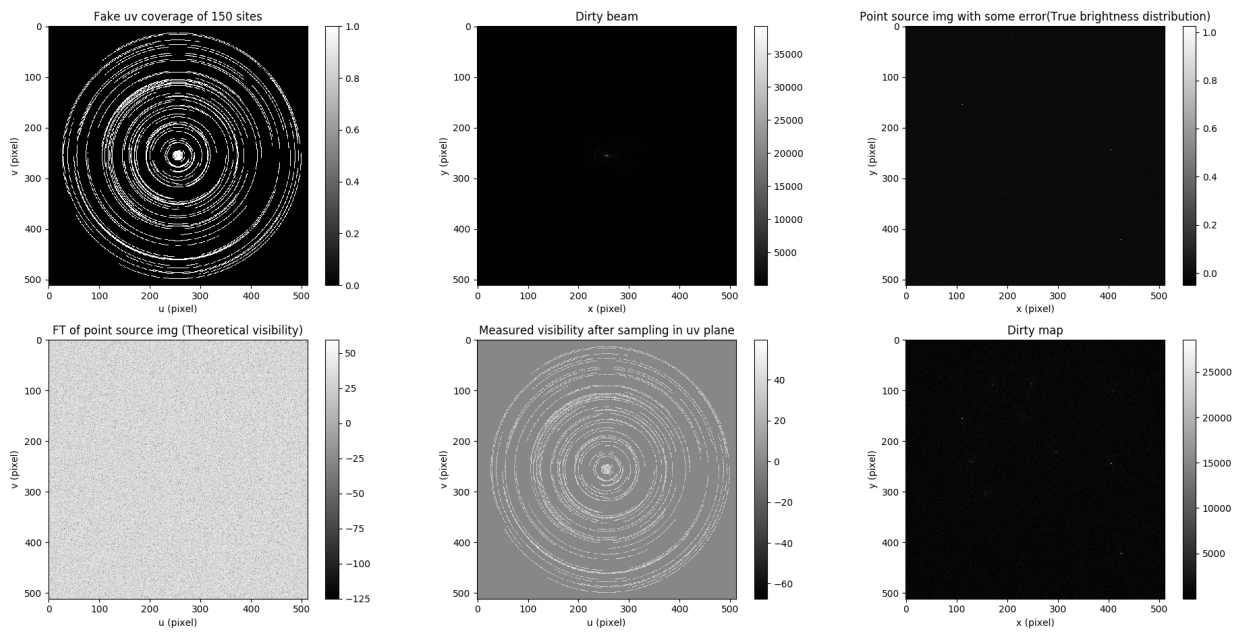
Figure 5: 当UV覆盖来自150个台站时的：UV采样函数、脏束、Lenna原图、理论可见度、实测可见度,脏图

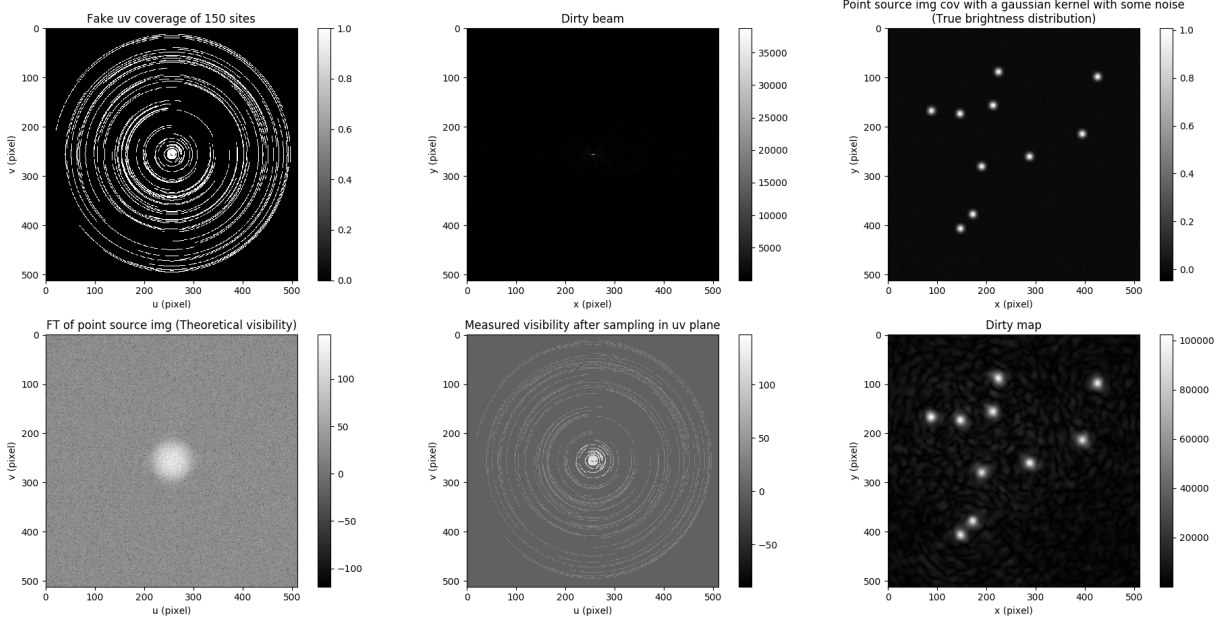
3. cleaner.py:

CLEAN algorithm steps

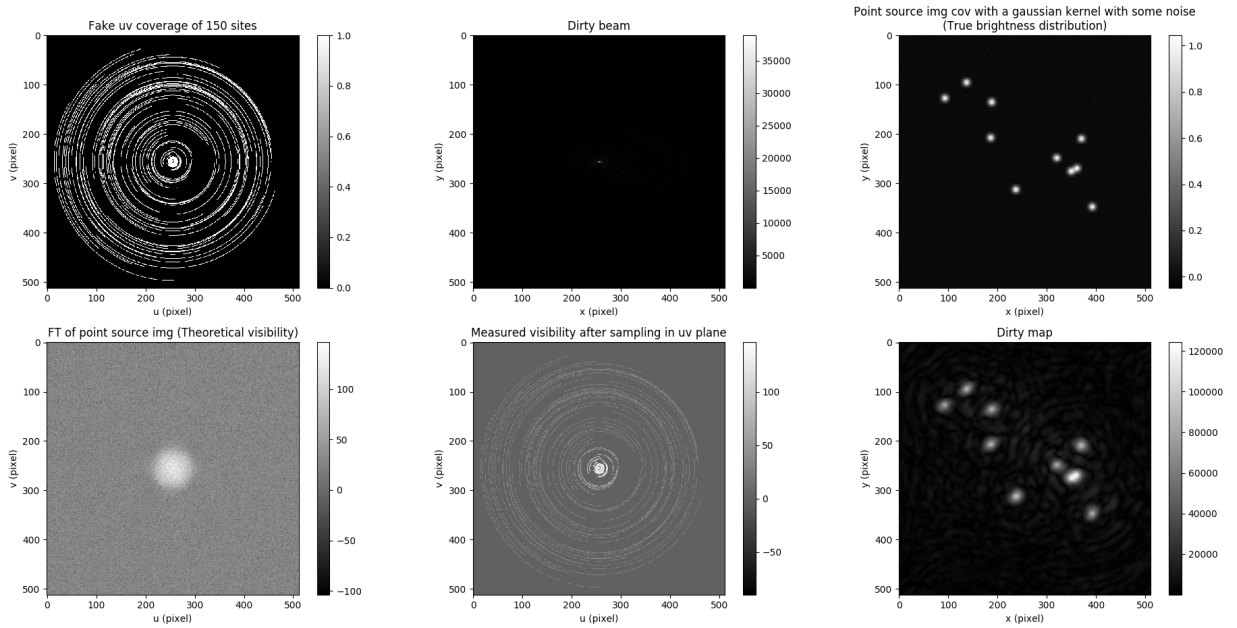


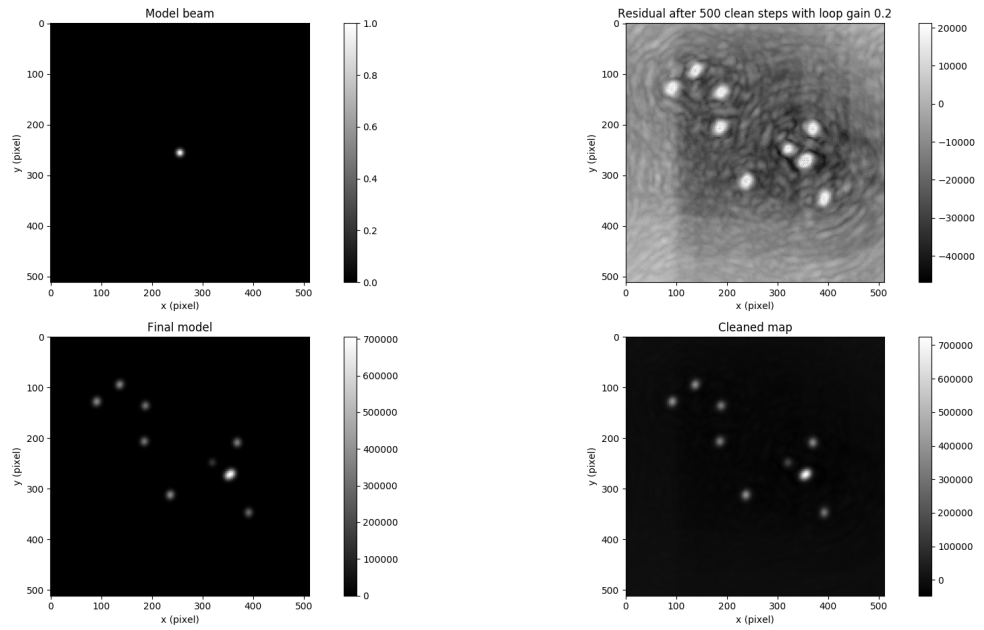
4. 生成点源来测试:



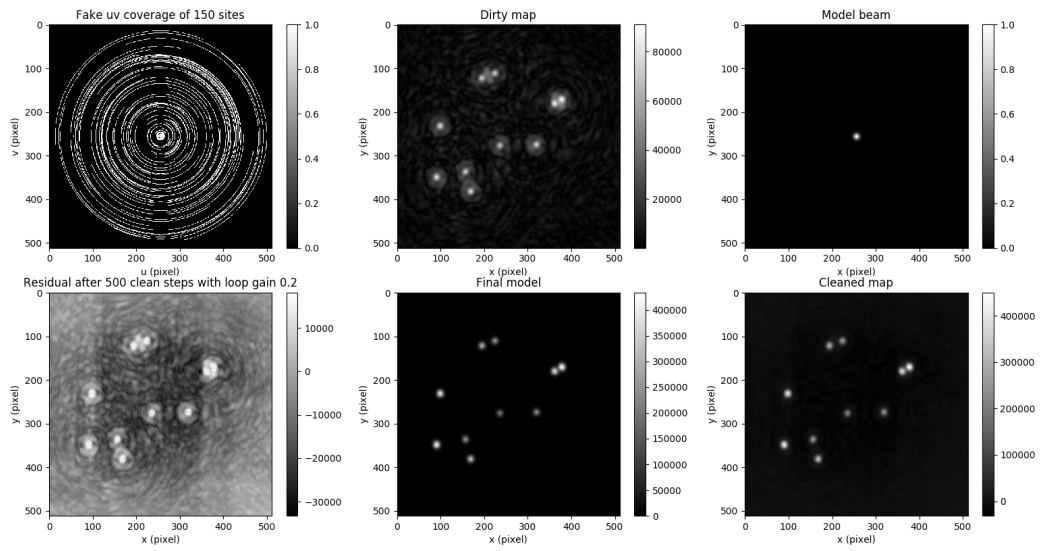


5. 测试CLEAN 算法：

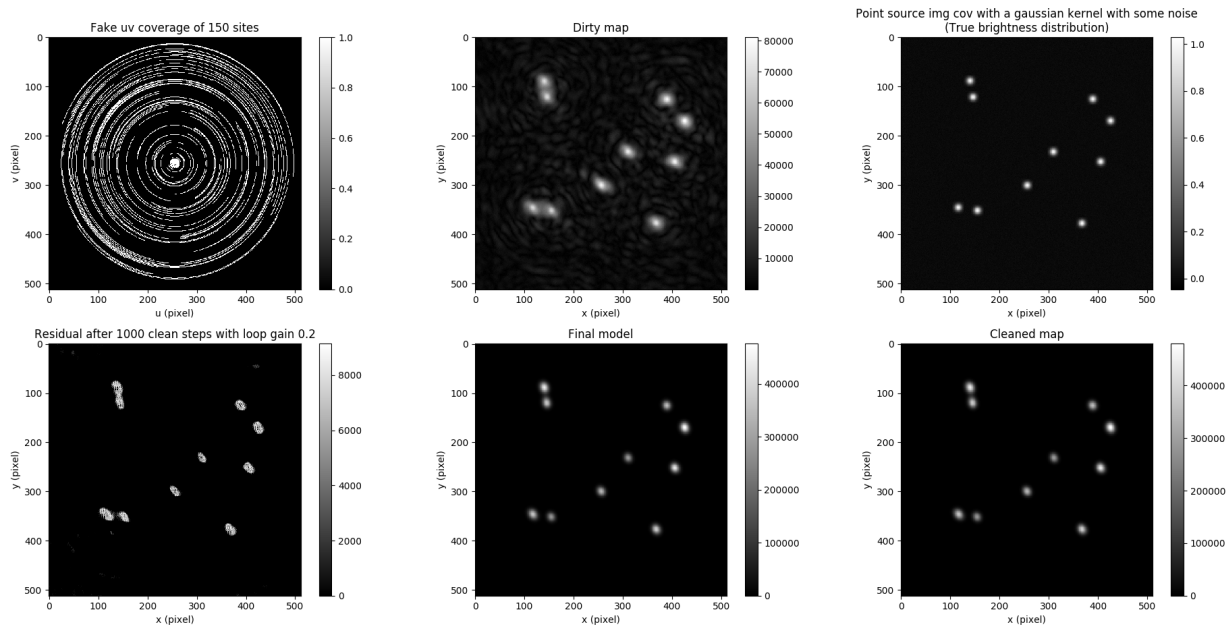




6. 更多测试:



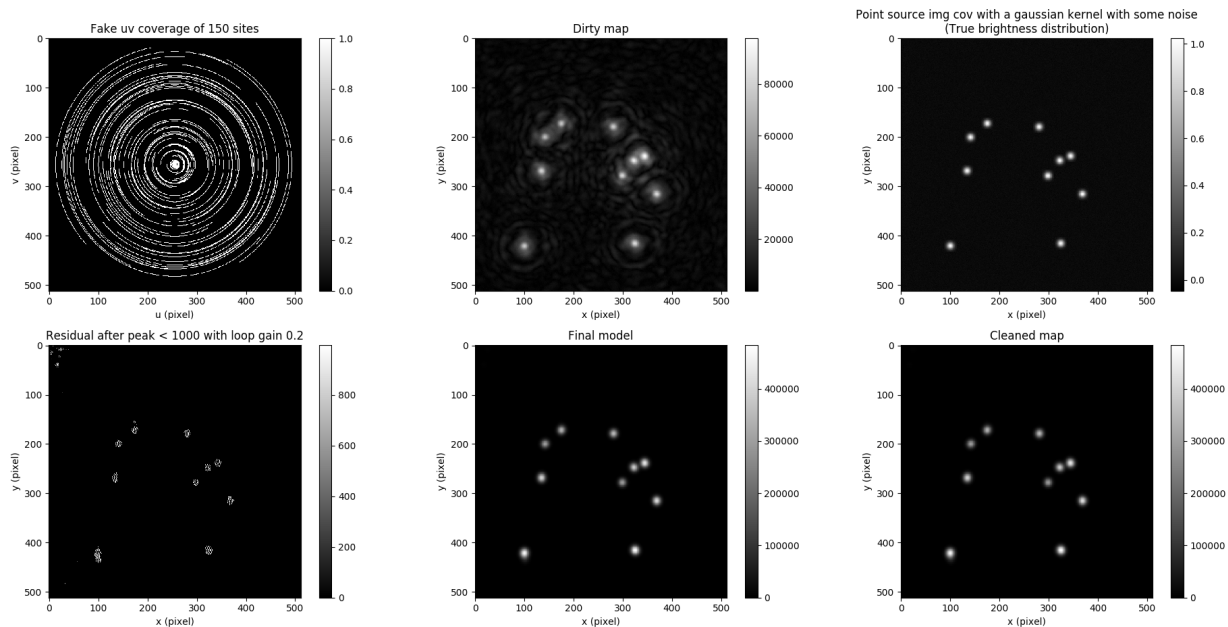
`self.residual[self.residual<0] = 0`



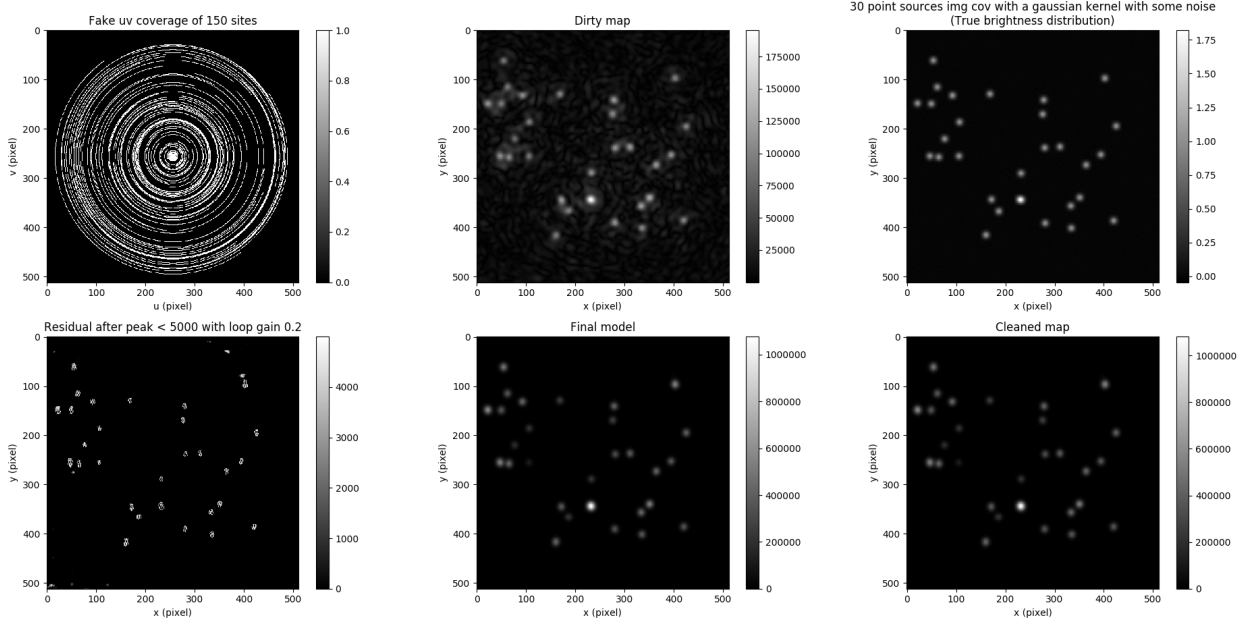
不指定迭代次数，指定：

any remaining peak is below some user-specified level. :

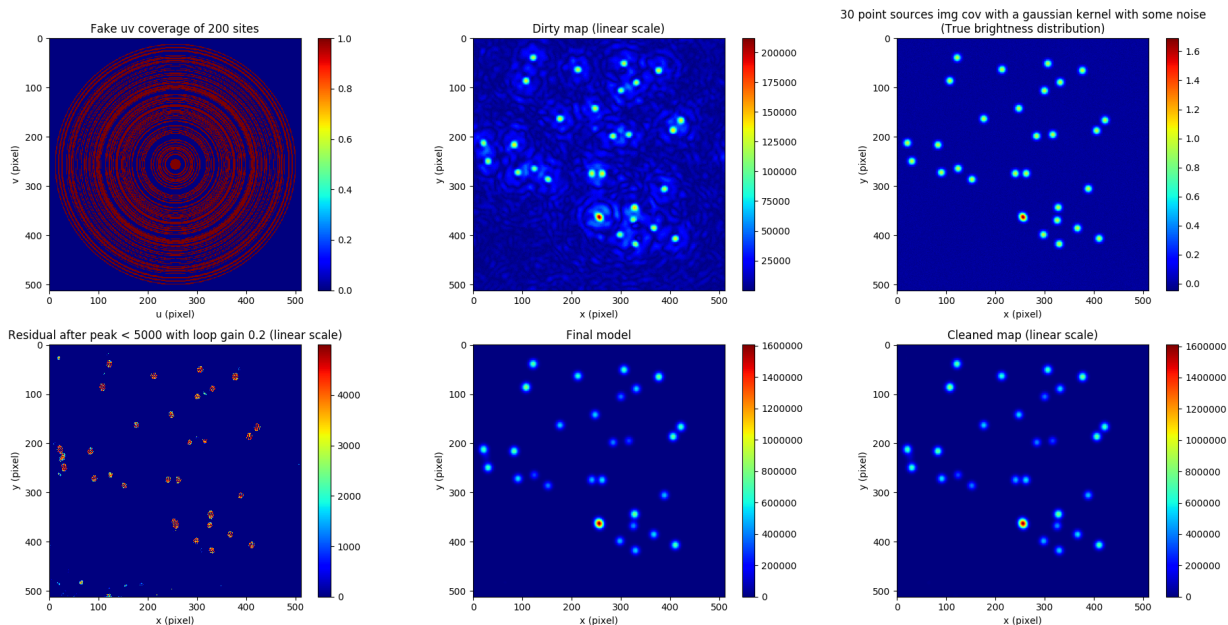
CLEAN algorithm steps



还可以测试当有更多点源时的结果：



彩色: `cmap = plt.cm.jet`



后面还可以测试如果 `model_beam` 和 `known_kernel` (生成 True brightness distribution 时用的卷积核心) 不一样, 会有什么结果。

`model_beam(width 3) known_kernel(width 5)` 没有明显差别

`model_beam(width 100) known_kernel(width 5)`: 更模糊了一些

4.3 polish codes

代码还需进一步修改完善：

1. 真实分布图和dirty map等图像的刻度要改为实际的 arcsec，像素亮度单位要改为实际的 Flux单位 (Jansky...), (参照difmap的输出)，这里还涉及到 dirtymap生成后如何归一化它的亮度

Dirty beam 横坐标为 **赤经 (RIGHT ASCENSION)**，单位mas，纵坐标为 Relative Declination? (单位mas)

图中要标注：Map Center, RA xxx, Dec xxx

Right Ascension, Declination 赤经赤纬

P4

Map peak: xxx Jy/beam

Contours %: 1 2 4 8 16 32 64

Beam FWHM: 2 x 1.9 (max) at ???

colorbar 的单位是 Jy/beam

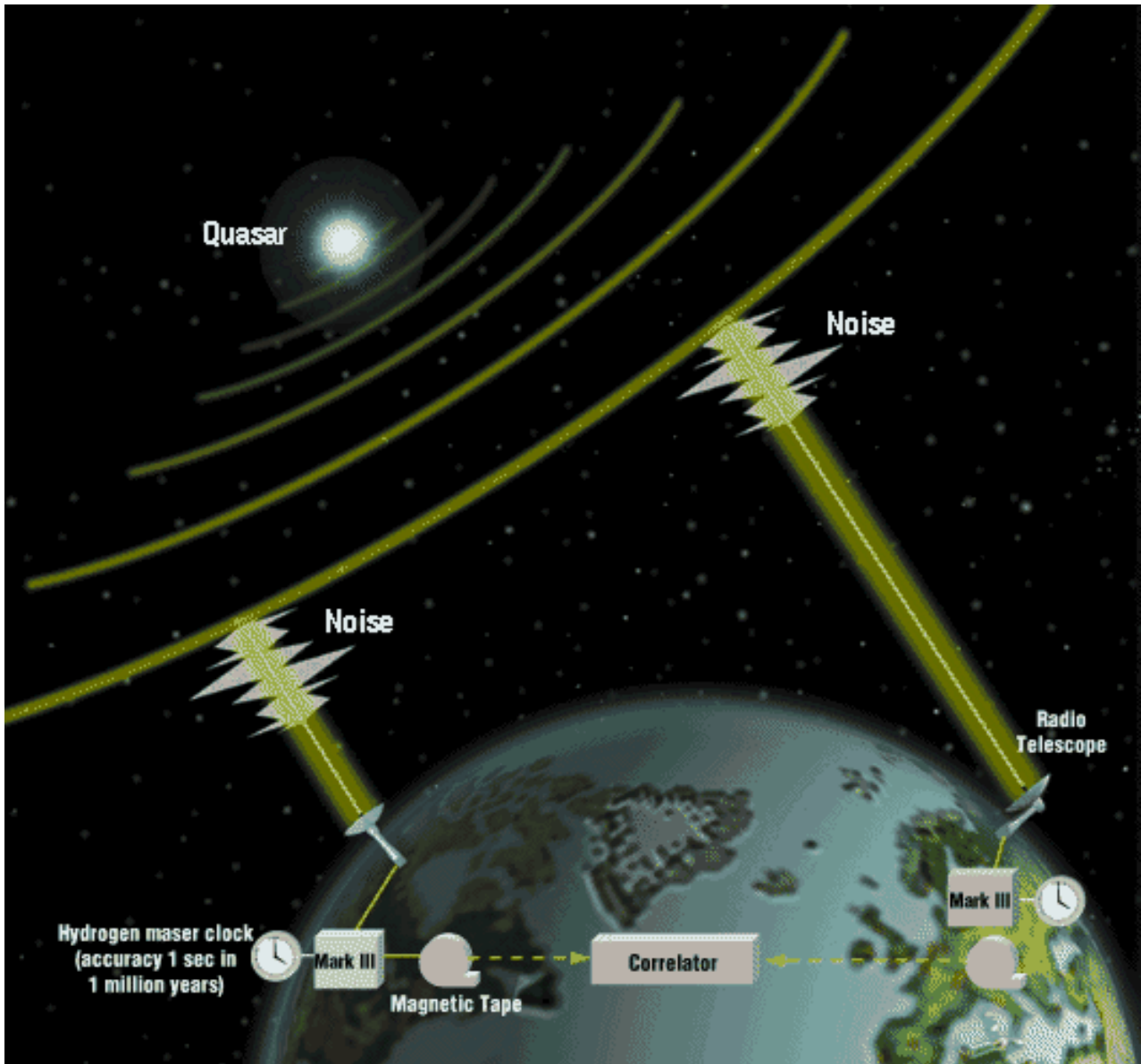
2. 台站生成可见度图像要改为与实际相符
先实现 生成一个台站 在某个经纬度下 在某个天线指向下 给定采样时间间隔 经过一段时间后 对天空的采样的程序
最简单的就是天线指向天顶
所有的台站天线指向都相同，因为要相干
天线指向 \mathbf{s} 用 ??? (一个3维向量) 来表示

$$\mathbf{s} = (\cos \theta \cos \varphi, \cos \theta \sin \varphi, \sin \theta)$$

θ 表示高度角，即 \mathbf{s} 与地面的夹角

φ 表示 \mathbf{s} 在地面的投影向量与东向的夹角

不能这样，要用一个和台站在地球上坐标独立的空间指向，如下图



可以暂时用地球经纬度来表示天线指向。

3. 可见度图像刻度要改为 $kilolambda$

4.3.1 telescope.py

台站经纬度和指向两个方向向量相加，由地球自转带来采样点的变化
 获得所有的采样点，最后成图
 图像以某个台站的天顶为中心
 直接将所有数据减去中心台站的坐标即可
 距离也很好解决，设置好一个像素对应多少角度即可

1. 查找 VLBI 台站的位置坐标

VLBI Techniques

Very Long Baseline Interferometry (VLBI) overview

International VLBI Service for Geodesy and Astrometry - IVS components, IVS list, 点击某个台站可以看到其经纬度(不过大部分看不了)

Very Long Baseline Interferometry

VLBI observations of GNSS-satellites: from scheduling to analysis

查询经纬度



sheshan = (31.0943700000,121.1932500000)

这么找还是不实际，找到一个网站：

Astronomical Observatory Sites by Latitude and Longitude

Non-US Radio Astronomy Observatories

在书中有：《射电天文的干涉测量与合成孔径P130》

模拟程序可以参照 VLBI Reconstruction Dataset - A Dataset Designed to Train and Test Very Long Baseline Interferometry Image Reconstruction Algorithms 里的步骤和

输入参数。

比如对于台站：

主要描述台站的参数有 East Longitude Latitude

X-Position Y-Position Z-Position

Step 3: Specify Telescope Array Add the telescope locations and intrinsic parameters that you would like to use to simulate data

Initialization: Select a pre-loaded telescope

Name: Unique name for each telescope station (up to 12 characters)

East Longitude/Latitude: East longitude and latitude of the array center. For locations less than 180 degrees west of Greenwich a minus sign should precede the longitude entry. (对于在 Greenwich 西边 180度以内的，东经值都为负数)

X/Y/Z Position: Absolute X, Y, Z coordinates of each station (in meters) relative to the center of the Earth

Lower/Upper Elevation: Lower and upper elevation limits of the of the antenna in degrees

SEFD: System equivalent flux density of the antenna

Diameter: Antenna diameter in meters 代码流程，要设置的参数，以及参数的合理值大概为多少，参照：[VLBI imagingchallenge](#)

之后要好好学习 ehtimg的代码

[Coordinate Systems for Astronomy or: How to get your telescope to observe the right object](#)

[Geodetic VLBI with an artificial radio source on the Moon: a simulation study](#)

2. 编写输入台站位置，天线指向，观测频率，采样时间，采样时间间隔，输出 UV 覆盖的程序

最终效果参考：[MIT的UV覆盖结果](#)

Step 4: Specify Date and Time Data is Collected Specify the time of when you would like measurements to be taken, and the time interval between measurements.

Start Time: Specify the time of your first observation in Universal Time (UT). The required format is "YYYY:ddd:hh:mm:ss" where YYYY is the year, ddd is the day number (e.g., December 31 is day 365); hh is the UT hour, mm is the UT minute, and ss is the UT second.

Scan Duration: The length of a continuous scan in seconds

Interval Length: The time in seconds between successive scans Number of Samples: The number of successive scans of this type [Google: how to generate UV coverage](#)

Paper: [OBSERVABILITY AND UV COVERAGE](#)

[Isella_Radio_Interferometry_Basics_Caltech2012](#)

[create_uv_tool](#)

[L1_Jackson_Interferometry](#)

[UV mapping tips](#)

[github uv gen*](#)

V.R.I. - Virtual Radio Interferometer
python-casacore pyrap Documentation
LOFAR synthesis data handling Introduction
casacore developments since 1-May-2009
LOFAR synthesis data handling pyrap

Github: generate uv coverage
SARA-CALIB-time-regularised in Matlab
XRAYVISION - X-RAY VISibility Synthesis ImagiNg
github generate uv coverage - ipynb
ratt-interferometry-course
Fundamentals of Radio Interferometry*****

参考 《Synthesis imaging in Radio Astronomy, Lecture 2》 或 《射电天文的干涉
测量与合成孔径P72-73》 的矩阵变换式，

4 几何关系和偏振测量

本章分析干涉测量的一些实际特性。这些特性包括基线、天线安装和波束形状、偏振辐射响应,所有这些都涉及几何关系和坐标系统。下面集中讨论具备跟踪功能的地基天线阵,阐述涉及的工作原理,尽管相同的原理也被应用于其他系统,如地球轨道的星载单个或多个天线。

4.1 天线间距坐标和 (u, v) 轨迹

各种坐标系均被用于确定天线在天线阵中的相对位置,其中对于地基天线阵比较方便的坐标系如图 4.1 所示。该坐标系是右手定则笛卡儿坐标系统,其中 X 轴和 Y 轴所在的平面平行于地球赤道面, X 轴在子午面内, Y 轴指向东方, Z 轴指向北极。用时角 H 和赤纬 δ 来描述坐标轴, (X, Y, Z) 轴分别为 $(H = 0, \delta = 0^\circ)$ 方向、 $(H = -6^h, \delta = 0^\circ)$ 方向和 $(\delta = 90^\circ)$ 方向。如果在 (X, Y, Z) 坐标系中 D_λ 的分量为 $(X_\lambda, Y_\lambda, Z_\lambda)$, 则 (u, v, w) 分量由下式给出:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} \sin H & \cos H & 0 \\ -\sin\delta\cos H & \sin\delta\sin H & \cos\delta \\ \cos\delta\cos H & -\cos\delta\sin H & \sin\delta \end{bmatrix} \begin{bmatrix} X_\lambda \\ Y_\lambda \\ Z_\lambda \end{bmatrix} \quad (4.1)$$

其中 (H, δ) 通常为时角和参考相位点的赤纬(在 VLBI 观测中,习惯将 X 轴设在格林尼治子午线上, H 的测量是相对子午线而不是相对地方时)。式(4.1)转换矩阵中的元素是 (u, v, w) 轴相对 (X, Y, Z) 轴的方向余弦,从图 4.2 很容易得到它们之间的关系式。另外一种确定基线的方法是根据基线长度 D 以及基线与北半天球交线的时角 (h) 和赤纬 (d) 。天线间距在 (X, Y, Z) 坐标系中的坐标为

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = D \begin{bmatrix} \cos d \cosh \\ -\cos d \sinh \\ \sin d \end{bmatrix} \quad (4.2)$$

从公式(4.1)和公式(4.2)可得出基线在 (u, v, w) 坐标系中的坐标为

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = D_\lambda \begin{bmatrix} \cos d \sin(H-h) \\ \sin d \cos\delta - \cos d \sin\delta \cos(H-h) \\ \sin d \sin\delta + \cos d \cos\delta \cos(H-h) \end{bmatrix} \quad (4.3)$$

(D, h, d) 系统在早期文献中曾广泛使用,特别是对于仅包含两个天线的干涉仪,参见文献(Rowson, 1963)。

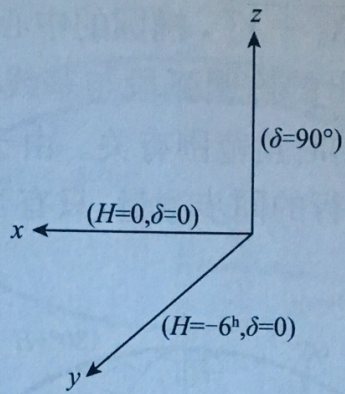


图 4.1 用于确定天线相对位置的 (X, Y, Z) 坐标系
坐标轴方向用时角 H 和赤纬 δ 来确定

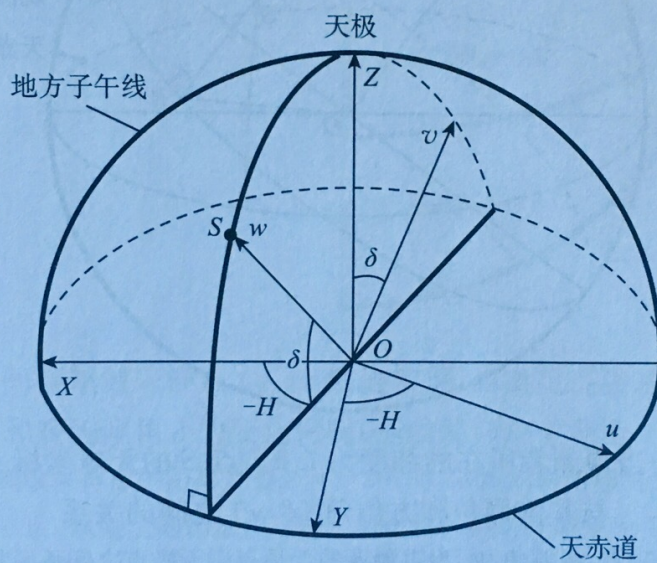


图 4.2 (X, Y, Z) 坐标系和 (u, v, w) 坐标系之间的关系

(u, v, w) 坐标系是以点 S 方向上的观测定义的, 点 S 的时角为 H , 赤纬为 δ 。如图所示, S 在东半球, 因此 H 为负值。式(4.1)转换矩阵中的方向余弦是根据图中的几何关系得出的。如果用 S 代表基线方向, 用基线坐标 (h, d) 替换 (H, δ) , 可得式(4.2)

最终得到的结果如下：

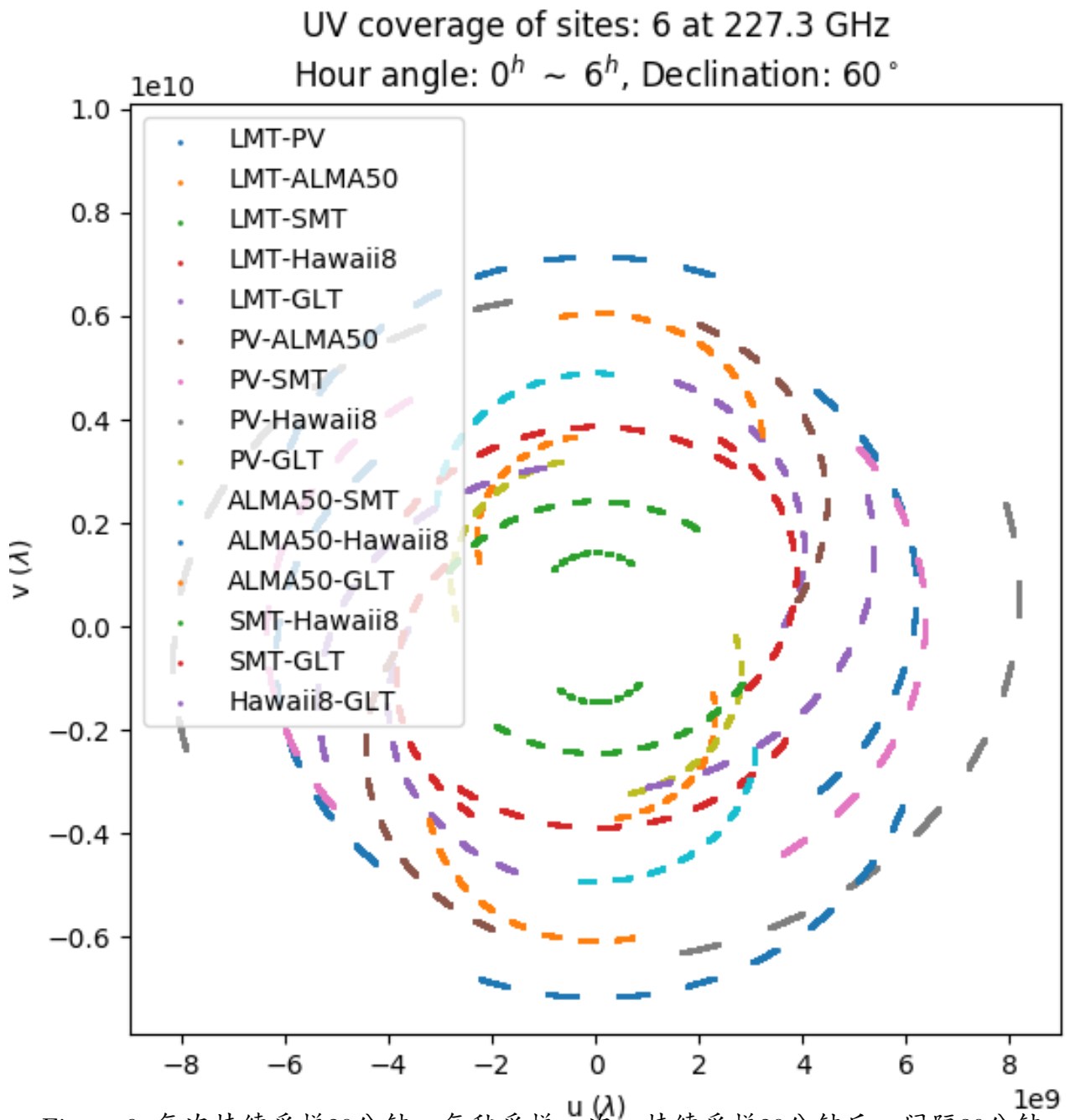


Figure 6: 每次持续采样20分钟，每秒采样一次；持续采样20分钟后，间隔30分钟

clean, calibration (Flux 归一化) 之后：

