In [17]:
```
import ehtim as eh # installed using https://github.com/achael/eht-imaging
# import ehtplot.color # installed using https://github.com/liamedeiros/ehtplot
import numpy as np
import matplotlib.pyplot as plt
```

Input parameters

In [18]:
```
image_filename = 'data/test.fits' # image filename
array_filename = 'arrays/EHT2017.txt'   # telescope array parameters filename

# observation parameters
tstart = 0.0          # start time of observations in hours
tstop = 24.0          # end time of observations in hours
timetype = 'UTC'      # how to interpret tstart and tstop, either 'GMST' or 'UTC'
tint = 60.0           # scan integration time in seconds
tadv = 120.0          # scan advance to new measurement time in seconds (must be lar
mjd = 57850           # Modified Julian Date of observation (night of April 6-7, 201
rf = 230000000000.0   # the observation frequency in Hz
bw = 4000000000.0     # the observation bandwidth in Hz

# measurement noise parameters
add_th_noise=True     # add thermal noise to the measurements. False if you don't wa
ampcal=True           # true if you want the amplitudes to be calibrated, false if n
phasecal=True         # true if you want the phases to be calibrated, false if not (

# computational parameters
ttype = 'direct'      # how to commpute the DTFT measurements. 'direct' formms a DTF
```

Load image

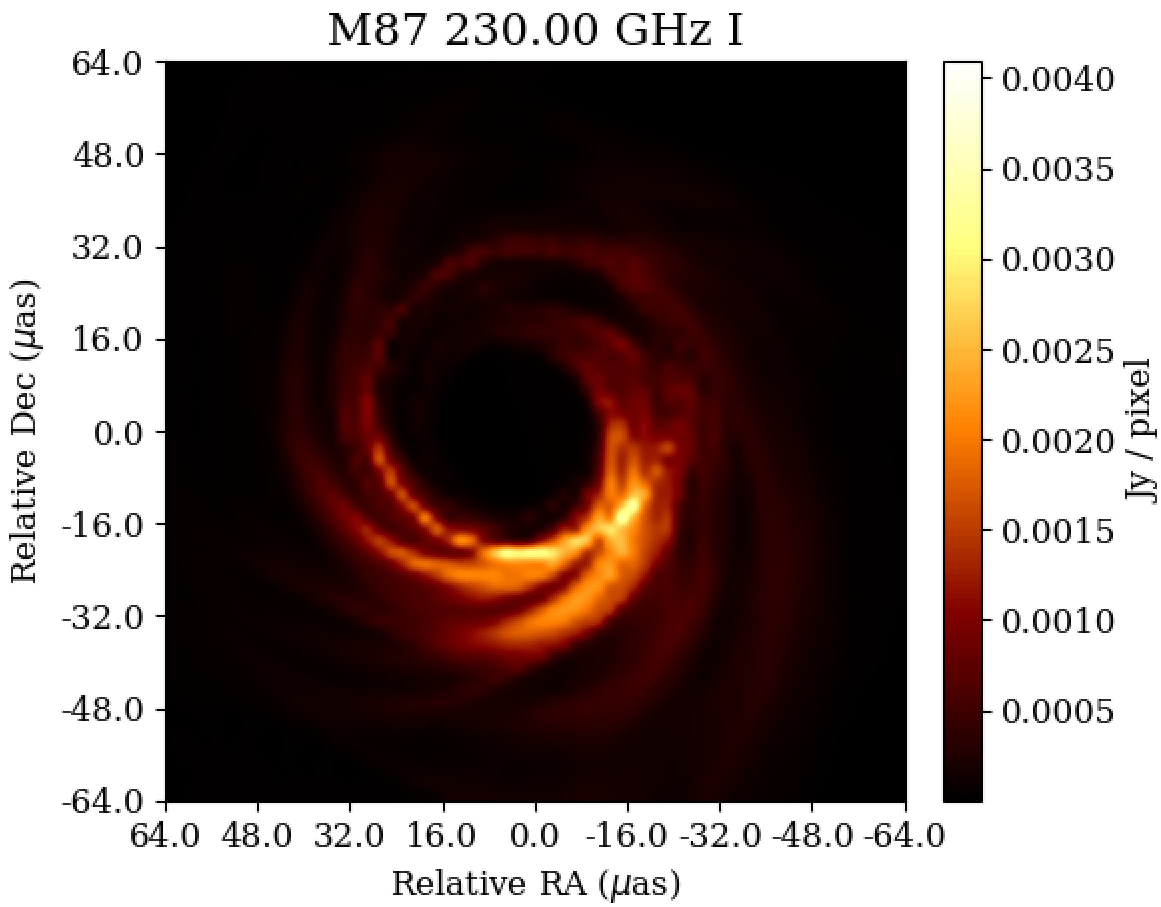
In [19]:
```
im = eh.image.load_fits(image_filename) # loads image in the fits format
```

```
Loading fits image:  data/test.fits
```

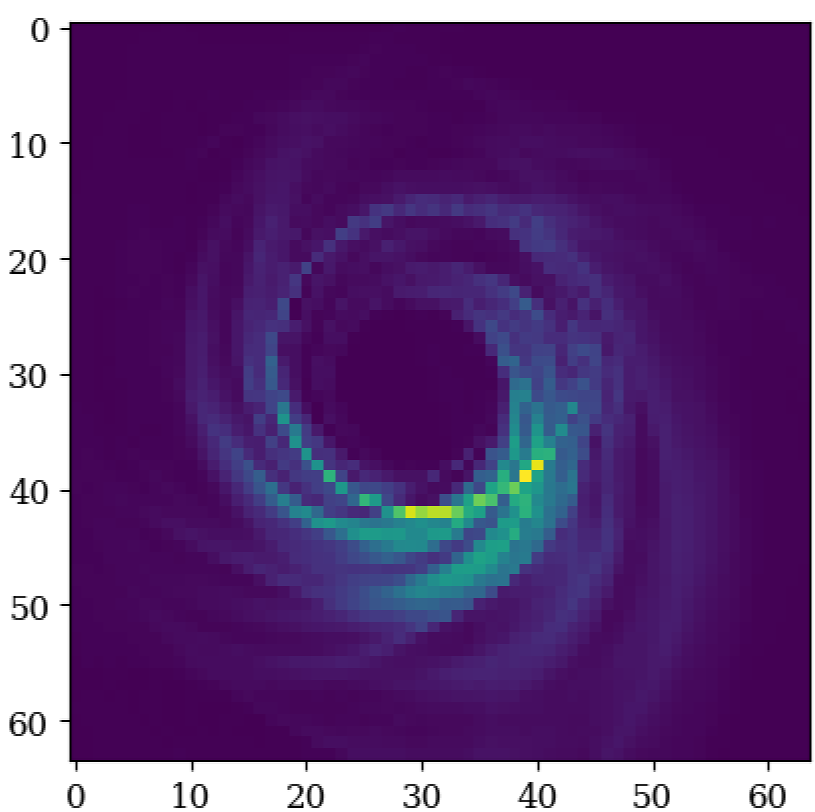
display the image

In [20]:
```
# display the image
im.display() #use the argument cfun="afmhot_10us" to use the same colormap as in th

#display the image by plotting what is in im.imvec. it will appear flipped
plt.imshow(np.reshape(im.imvec, (im.ydim,im.xdim)))
```



Out[20]: <matplotlib.image.AxesImage at 0x22503197400>



Load telescope array file for observing

In [21]:
```
array = eh.array.load_txt(array_filename)
```

array.tarr details of the telescope array:
(name, x position, y position, z position, SEFD, SEFD, followed by parameters of the telescope that affect polarization).

You will likely only care about the telescope names, and the SEFD. the SEFD indicates how much thermal noise is included on measurements made with that telescope (larger SEFD -> more thermal noise)

Note: SPT cannot see the M87 black hole so even if you observe M87 with SPT there will be no data that shows up corresponding to the SPT telescope

In [22]:
```
print(array.tarr)
```

```
[('PV',  5.08896790e+06, -3.01681600e+05,  3825015.8   ,  3600.,  3600., 0.+0.j, 0.+
0.j, 1., -1.,  0.)
 ('SMT', -1.82879620e+06, -5.05440680e+06,  3427865.2   , 14400., 14400., 0.+0.j, 0.
+0.j, 1.,  1.,  0.)
 ('SMA', -5.46452340e+06, -2.49314708e+06,  2150611.75  ,  5600.,  6500., 0.+0.j, 0.
+0.j, 1., -1., 45.)
 ('LMT', -7.68713964e+05, -5.98854180e+06,  2063275.9472,  3600.,  3600., 0.+0.j, 0.
+0.j, 1., -1.,  0.)
 ('ALMA',  2.22506116e+06, -5.44005737e+06, -2481681.15  ,    70.,    70., 0.+0.j,
0.+0.j, 1.,  0.,  0.)
 ('SPT',  1.00000000e-02,  1.00000000e-02, -6359609.7   , 16900., 16900., 0.+0.j, 0.
+0.j, 1.,  0.,  0.)
 ('APEX',  2.22503953e+06, -5.44119763e+06, -2479303.36  ,  4900.,  4900., 0.+0.j,
0.+0.j, 1.,  1.,  0.)
 ('JCMT', -5.46458468e+06, -2.49300117e+06,  2150653.98  , 10000., 10000., 0.+0.j,
0.+0.j, 1.,  0.,  0.)]
```

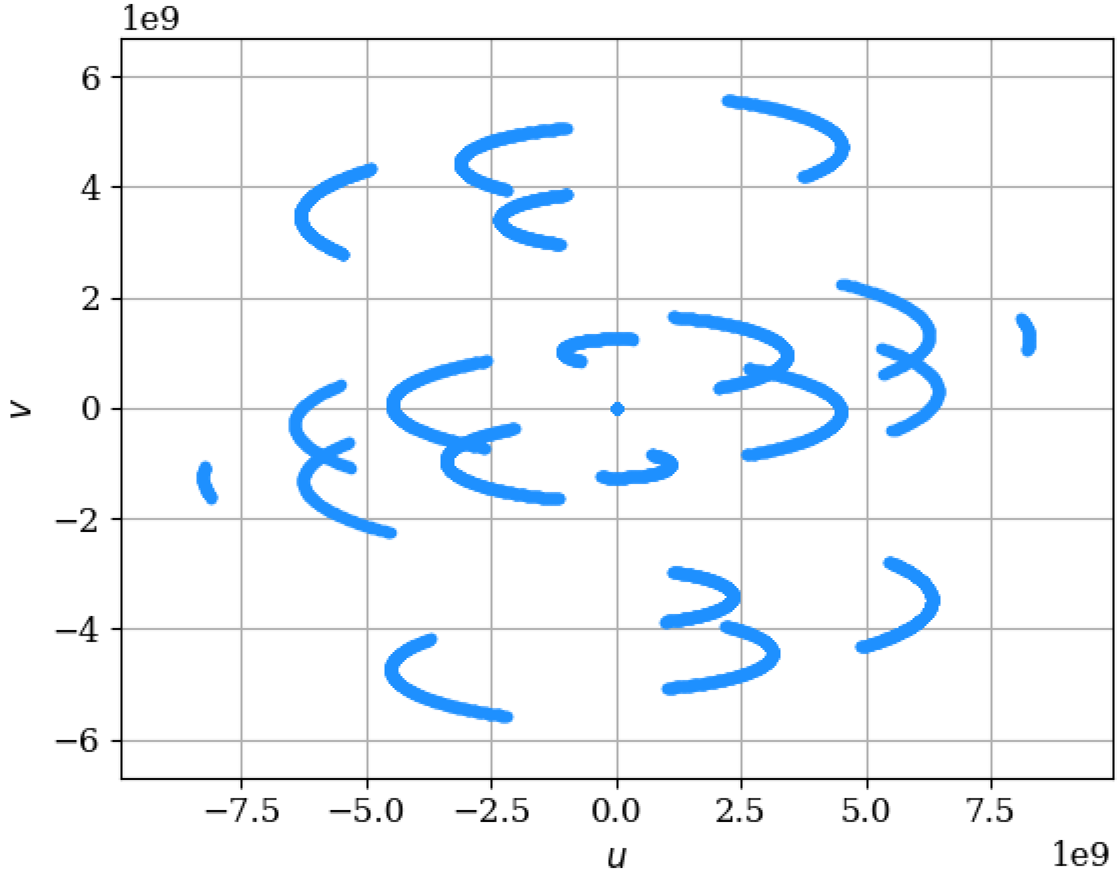
Generate measurements

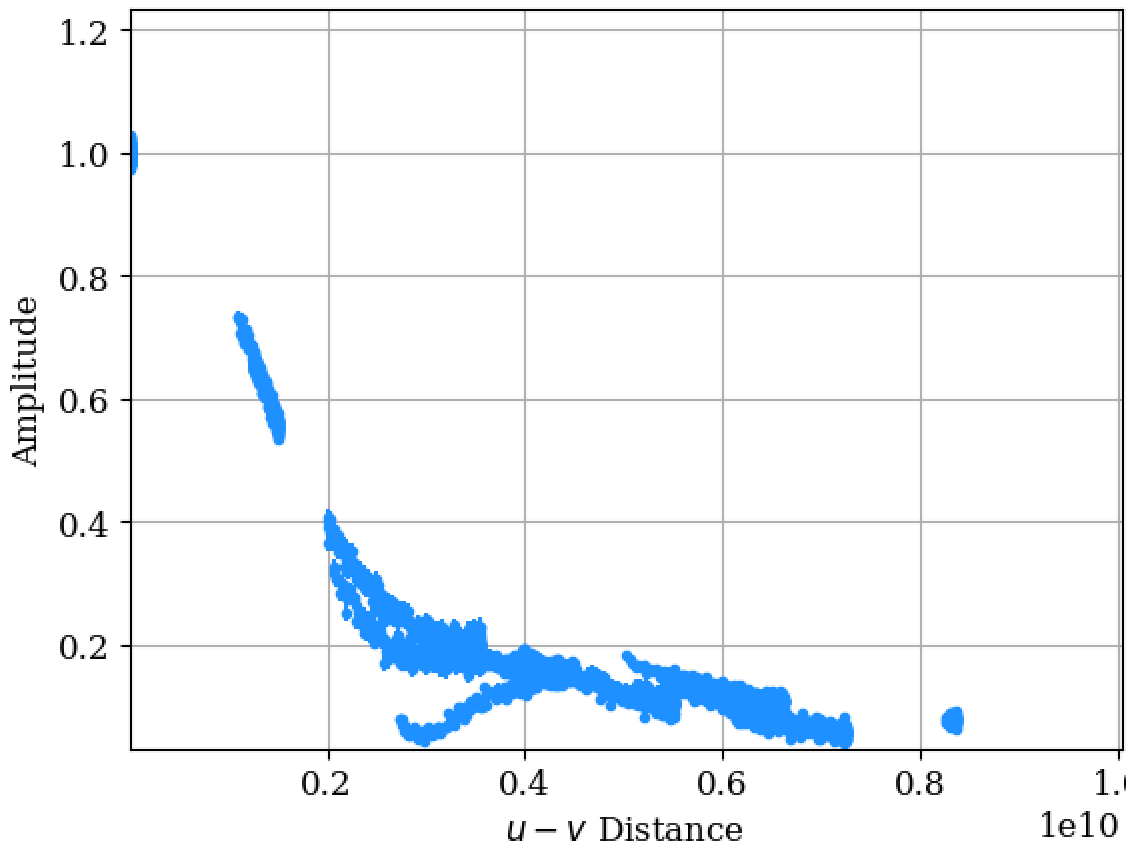
In [23]:
```
# observe the source with the telescope array using the parameters specified above
obs = im.observe(array, ttype=ttype, mjd=mjd, timetype=timetype,
                 tstart=tstart, tstop=tstop, tint=tint, tadv=tadv,
                 bw=bw, add_th_noise=add_th_noise, ampcal=ampcal,
                 phasecal=phasecal)
```

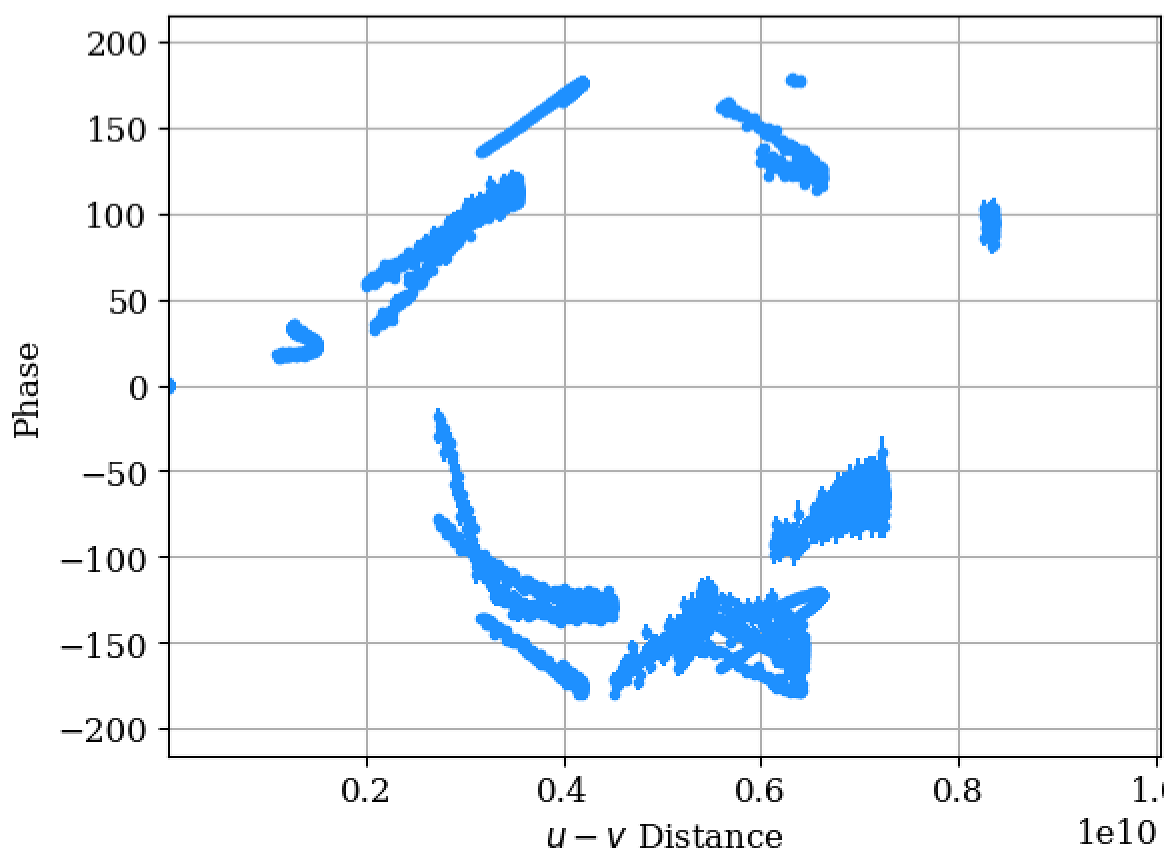
```
Generating empty observation file . . .
Producing clean visibilities from image with direct FT . . .
Adding gain + phase errors to data and applying a priori calibration . . .
Adding thermal noise to data . . .
```

In [24]:
```
# plot out some of the generated data
obs.plotall('u','v', conj=True) # uv-coverage. plot the (u,v) frequencies sampled b
```

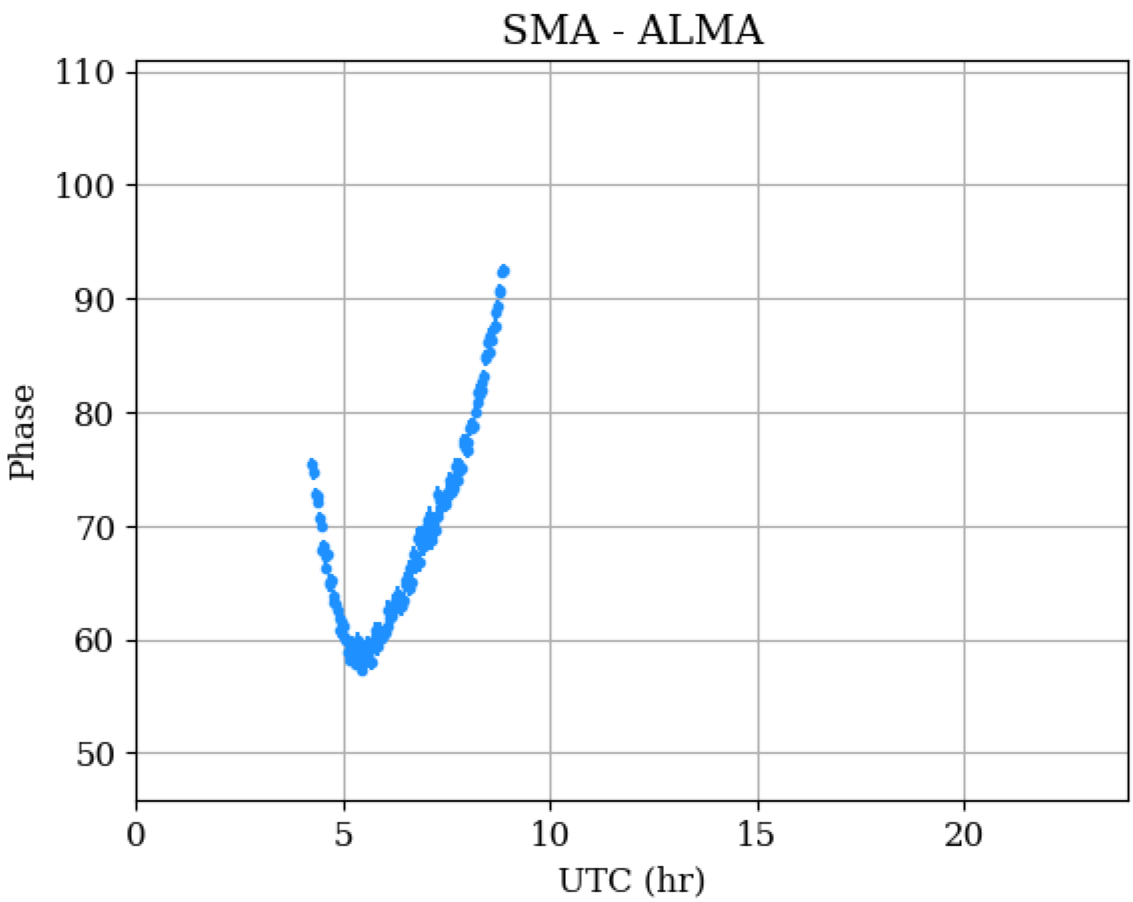
```
obs.plotall('uvdist','amp') # plot the visibility amplitude as a function of baseli
obs.plotall('uvdist','phase') # plot the visibility phyase as a function of baselin
obs.plot_bl('SMA','ALMA','phase') # plot the visibility phase on a baseline (here t
obs.plot_cphase('LMT', 'PV', 'ALMA') # plot the closure phase on a triplet of teles
```

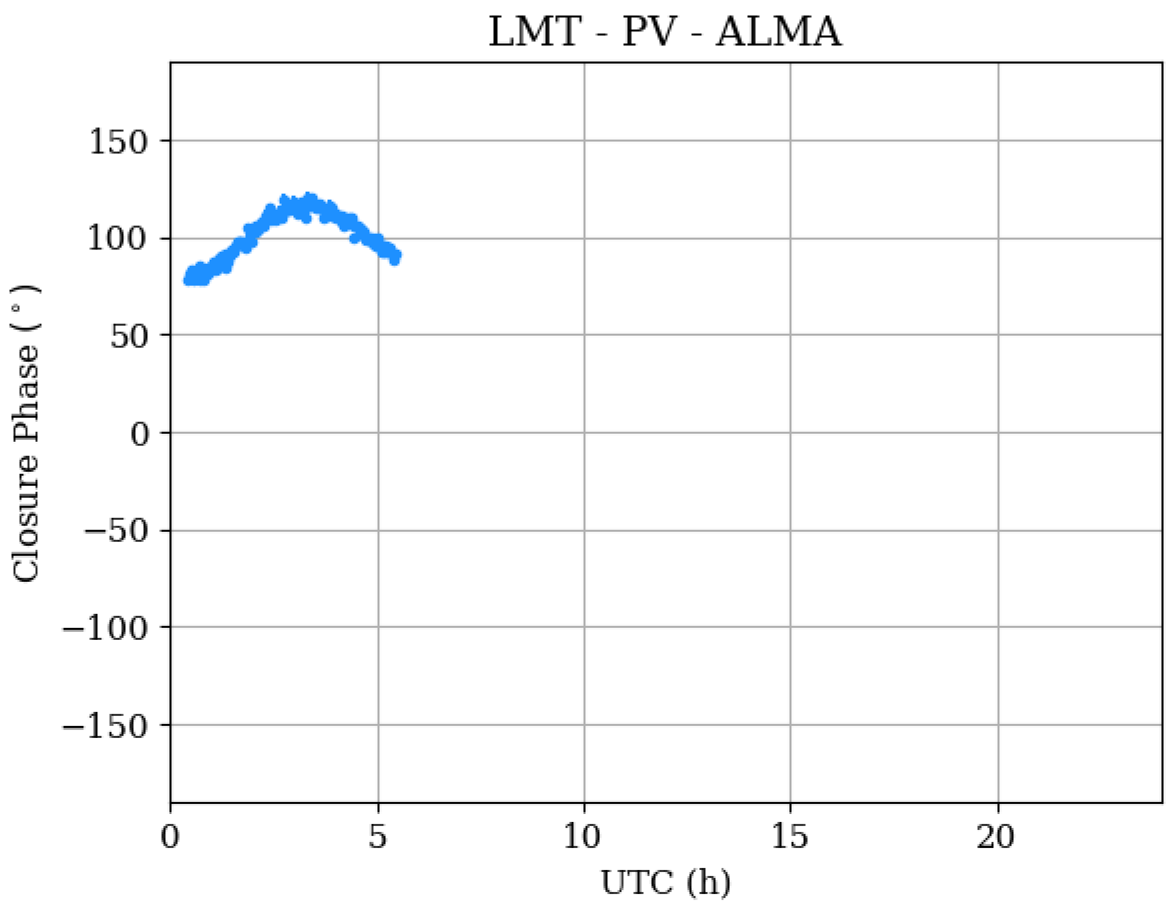



Amplitude
1.2
1.0
0.8
0.6
0.4
0.2
0.2
0.4
0.6
0.8
1.0
1e10
$u-v$ Distance


Phase
200
150
100
50
0
−50
−100
−150
−200
0.2
0.4
0.6
0.8
1.0
1e10
$u-v$ Distance

```
C:\Users\yvett\AppData\Local\Programs\Python\Python39\lib\site-packages\ehtim\obsdat
a.py:509: VisibleDeprecationWarning: Creating an ndarray from ragged nested sequence
s (which is a list-or-tuple of lists-or-tuples-or ndarrays with different lengths or
shapes) is deprecated. If you meant to do this, you must specify 'dtype=object' when
creating the ndarray.
  return np.array(datalist)
```

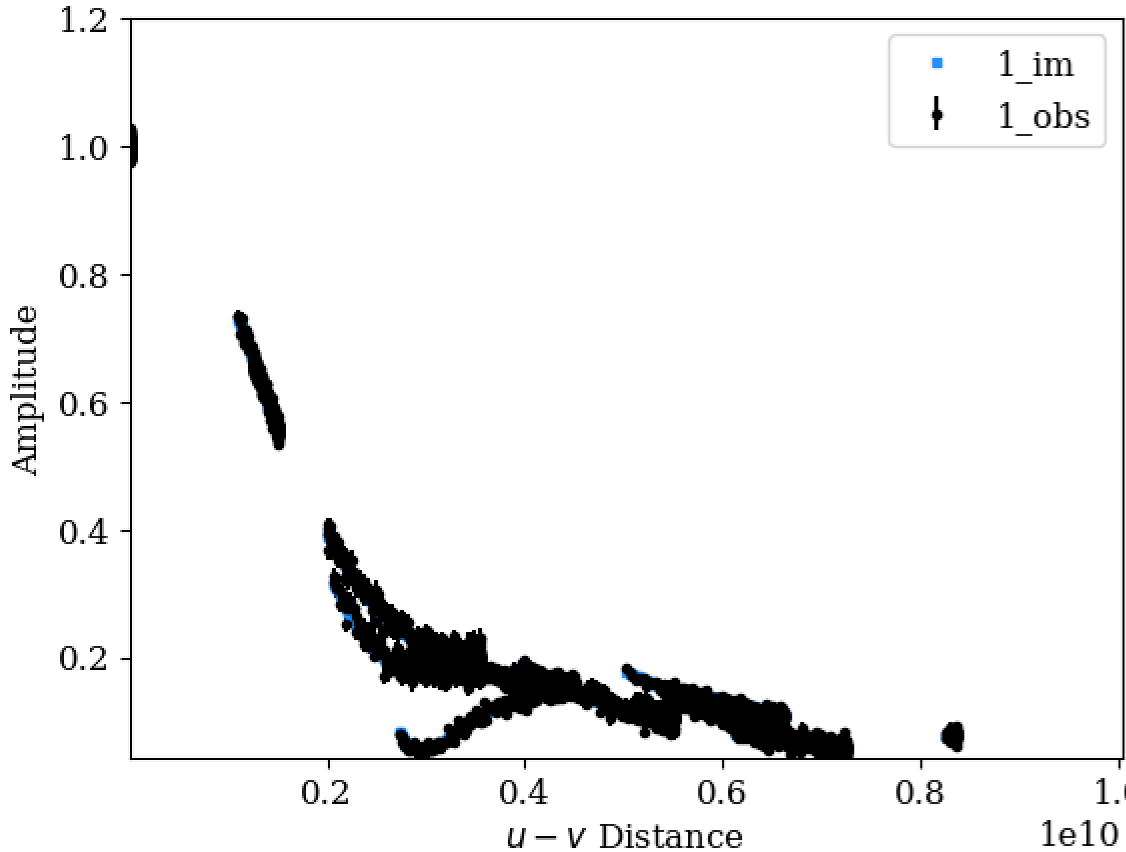




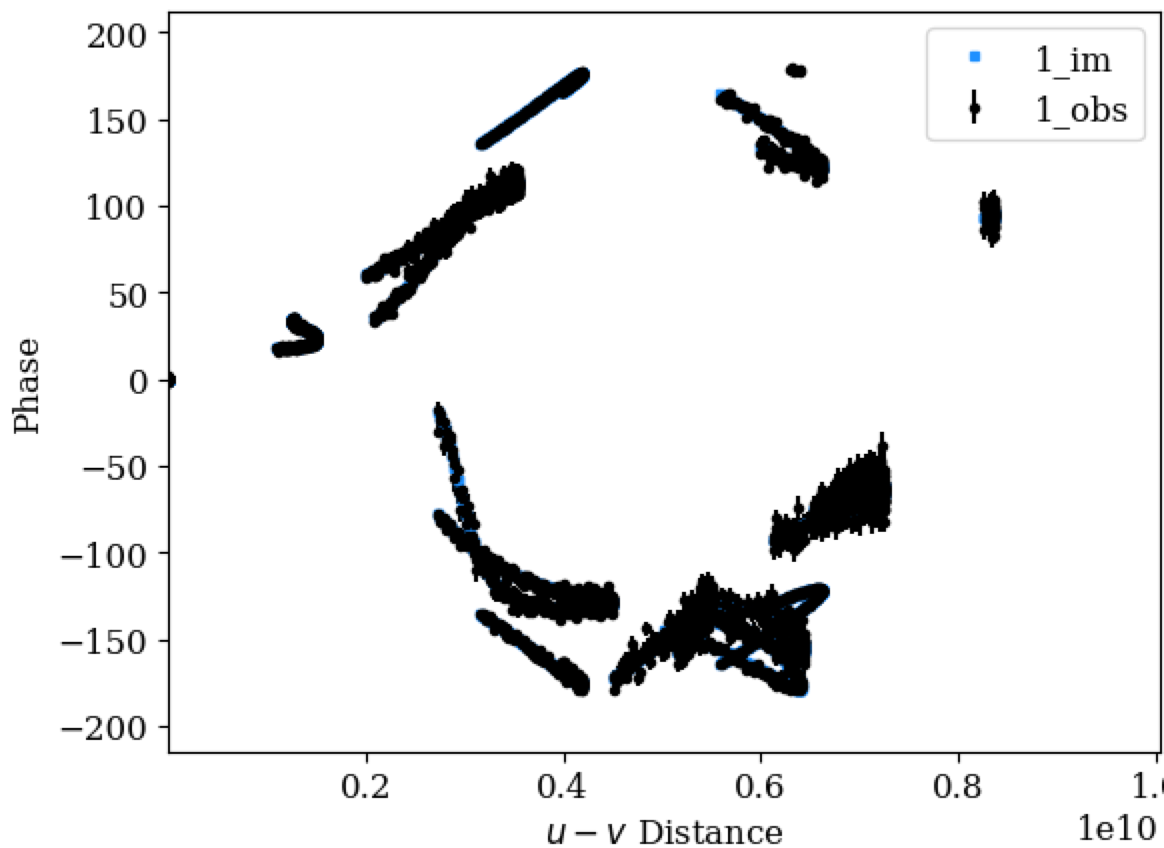
Out[24]: <Axes: title={'center': 'LMT - PV - ALMA'}, xlabel='UTC (h)', ylabel='Closure Phase $(^\\circ)$'>

In [25]:
```
# compare the observed measurements to those that you would get from the image im w
eh.plotall_obs_im_compare(obs, im, "uvdist", "amp", ttype=ttype)
eh.plotall_obs_im_compare(obs, im, "uvdist", "phase", ttype=ttype)
```

```
Producing clean visibilities from image with direct FT . . .
Adding gain + phase errors to data and applying a priori calibration . . .
```




```
Producing clean visibilities from image with direct FT . . .
Adding gain + phase errors to data and applying a priori calibration . . .
```



Out[25]: `<Axes: xlabel='$u-v$ Distance', ylabel='Phase'>`

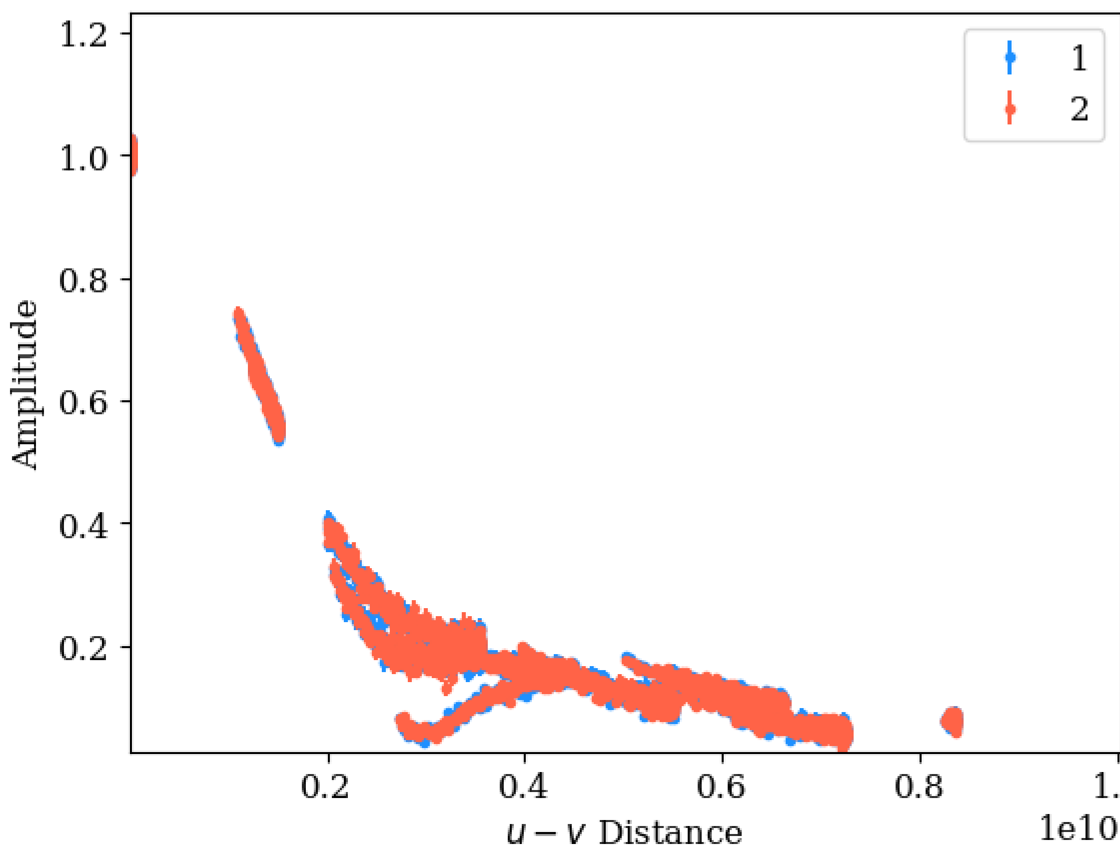
Generate measurements that also experience atmospheric phase error.

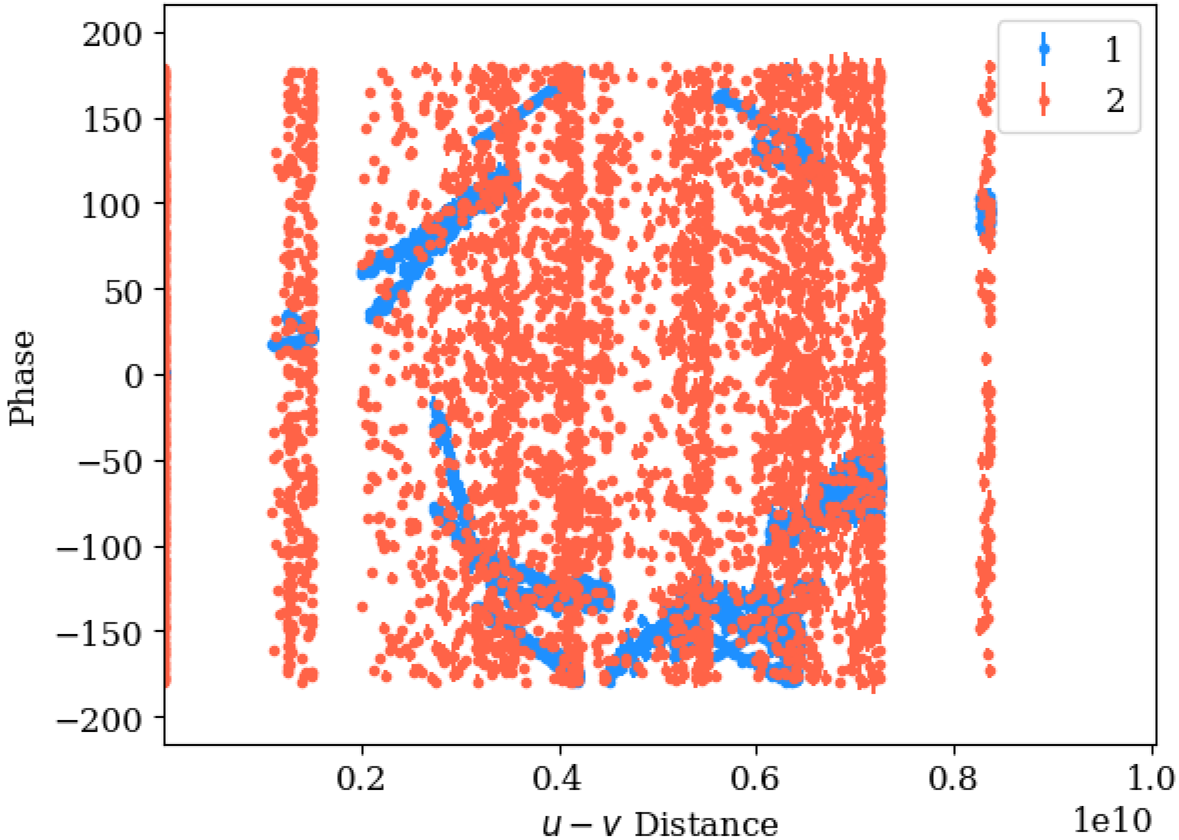
Notice that the amplitudes remain the same (since we have kept ampcal=True), but the phases are randomized. Although the visibility phases now appear randommm, note that the closure phases match the closure phase of the observation with no atmospheric phase error.

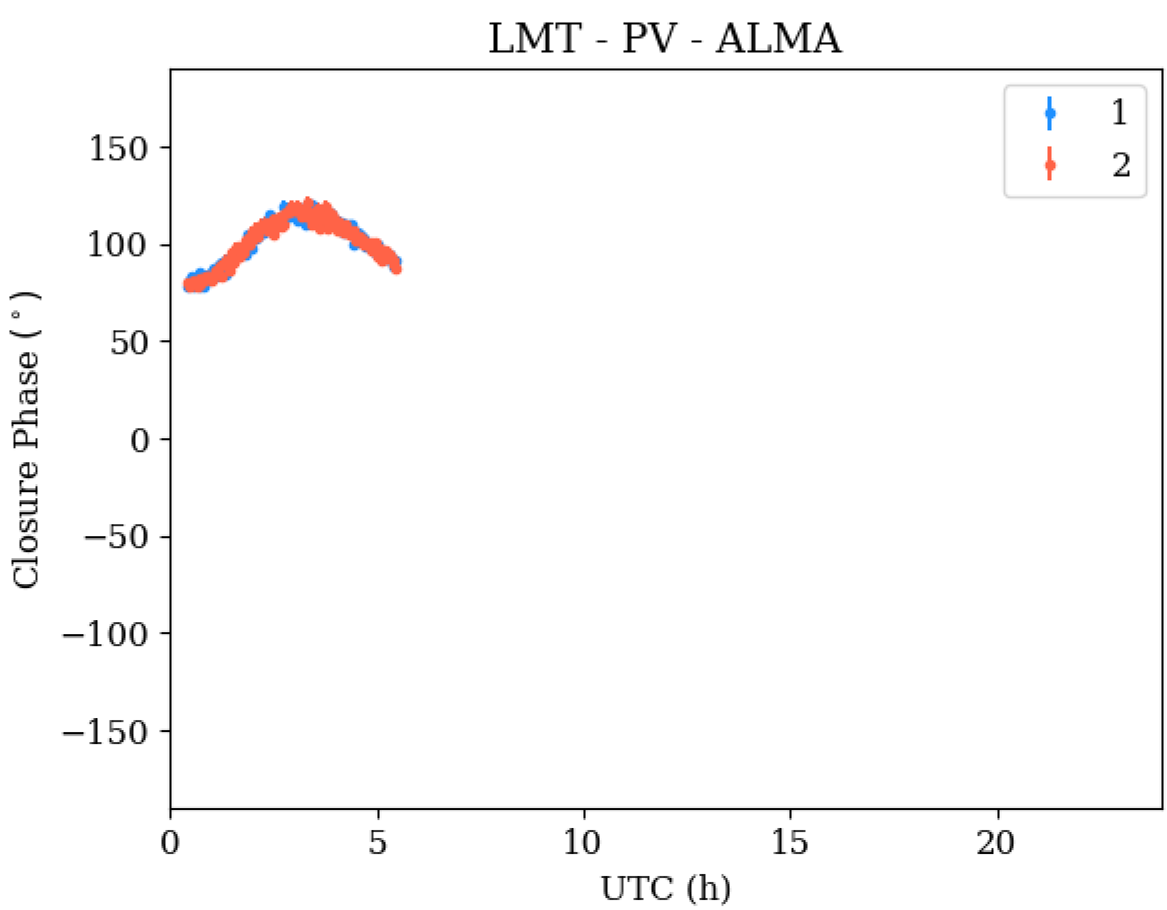
In [26]:
```
phasecal_atmosphere = False
obs_atmosphere = im.observe(array, ttype=ttype, mjd=mjd, timetype=timetype,
                  tstart=tstart, tstop=tstop, tint=tint, tadv=tadv,
                  bw=bw, add_th_noise=add_th_noise, ampcal=ampcal,
                  phasecal=phasecal_atmosphere)

eh.plotall_obs_compare([obs, obs_atmosphere], "uvdist", "amp", ttype=ttype)
eh.plotall_obs_compare([obs, obs_atmosphere], "uvdist", "phase", ttype=ttype)
eh.plot_cphase_obs_compare([obs, obs_atmosphere], 'LMT', 'PV', 'ALMA', ttype=ttype)
```

```
Generating empty observation file . . .
Producing clean visibilities from image with direct FT . . .
Adding gain + phase errors to data and applying a priori calibration . . .
   Applying atmospheric phase corruption: phasecal-->False
Adding thermal noise to data . . .
```







Out[26]: `<Axes: title={'center': 'LMT - PV - ALMA'}, xlabel='UTC (h)', ylabel='Closure Phase $(^\\circ)$'>`

Access Measurement Data

Access visibility measurements

In [27]:
```
u = obs.data['u']          # u coordinate of data points
v = obs.data['v']          # v coordinate of data points
vis = obs.data['vis']      # complex visibilities for associated (u,v) location
sigma = obs.data['sigma'] # standard deviation of thermmal noise on data (if you se
# look at obs.data dictionary to see all data...including telescopes for every meas
```

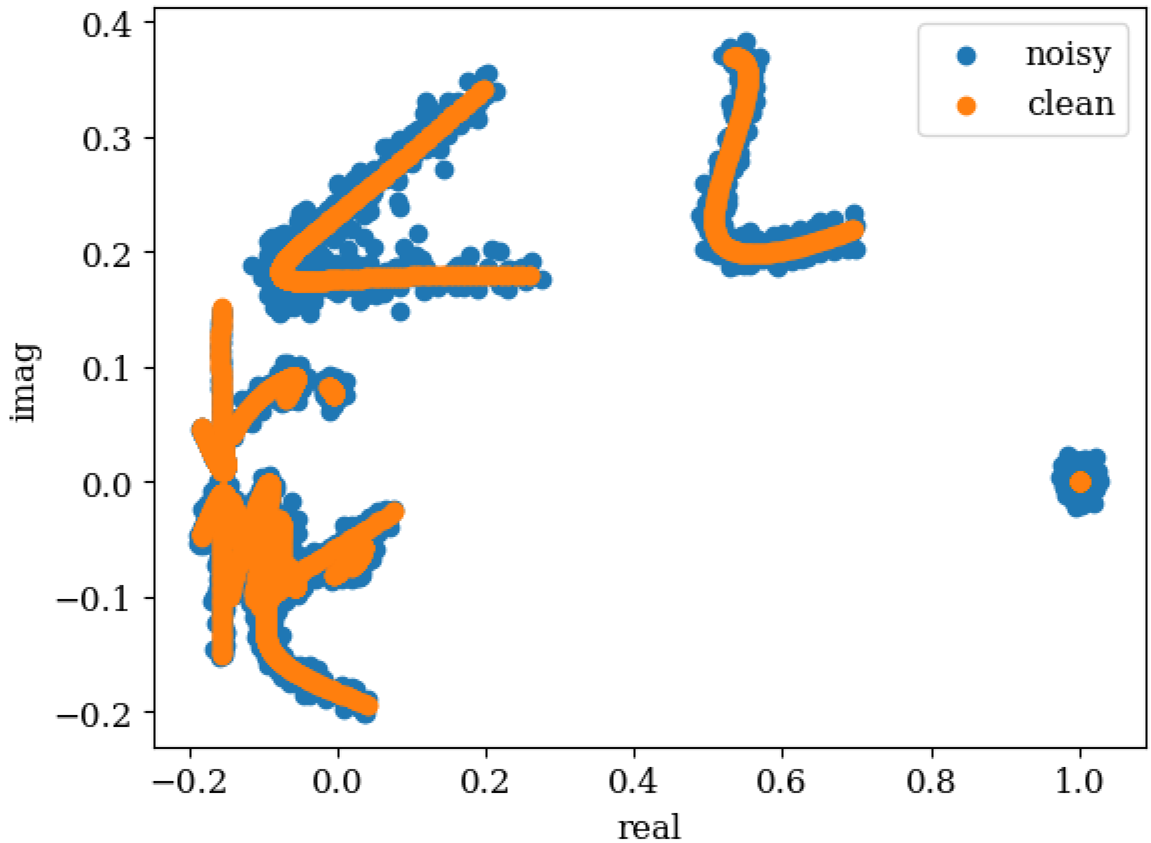
Generate the forward model matrix that can be used to generate clean visibilities

In [28]:
```
# Get the forward model matrix along with the visibilities and standard deviations
# vis: array,
#        List of visibilities for each frame
# sigma_vis: array,
#        List of sigmas for visibilities for each frame
# A_vis: array,
#        List of matrices for visibilities for each frame
vis, sigma_vis, A_vis = eh.imaging.imager_utils.chisqdata_vis(obs, im, mask=[])

#multiplying the image with the forward matrix A gives you the ideal visibilities w
out = np.matmul(A_vis, im.imvec)

# plot to show the overlap in the noisy measured data from obs and the clean visibi
plt.scatter(np.real(vis), np.imag(vis), label="noisy")
plt.scatter(np.real(out), np.imag(out), label="clean")
plt.xlabel("real")
plt.ylabel("imag")
plt.legend()
```

Out[28]:
```
<matplotlib.legend.Legend at 0x2250314a3d0>
```



Access closure phase measurements

In [29]:
```
obs.add_cphase()

# access the closure phases and the associated standard deviations of noise on each
# closure phases are derived from complex visibilities
# closure phase measurements are approximmated as being a sample from a Gaussian di
cphase = obs.cphase['cphase']
sigmacp = obs.cphase['sigmacp']
# obs.cphase parameters: 'time', 't1', 't2,', 't3', 'u1', 'v1', 'u2', 'v2', 'u3', '
```

```
Updated self.cphase: no averaging
updated self.cphase: avg_time 0.000000 s
```

Generate the forward model matricies that can be used to generate clean closure phases

In [30]:
```
# Get the forward model matrix along with the closure phases and standard deviation
# cphase2: array,
#        List of closure phases for each frame
# sigma_vis: array,
#        List of sigmas for closure phases for each frame
# A_cp: array,
#        List of matrices for closure phases for each frame
cphase2, sigmacp2, A_cp = eh.imaging.imager_utils.chisqdata_cphase(obs, im, mask=[]
```

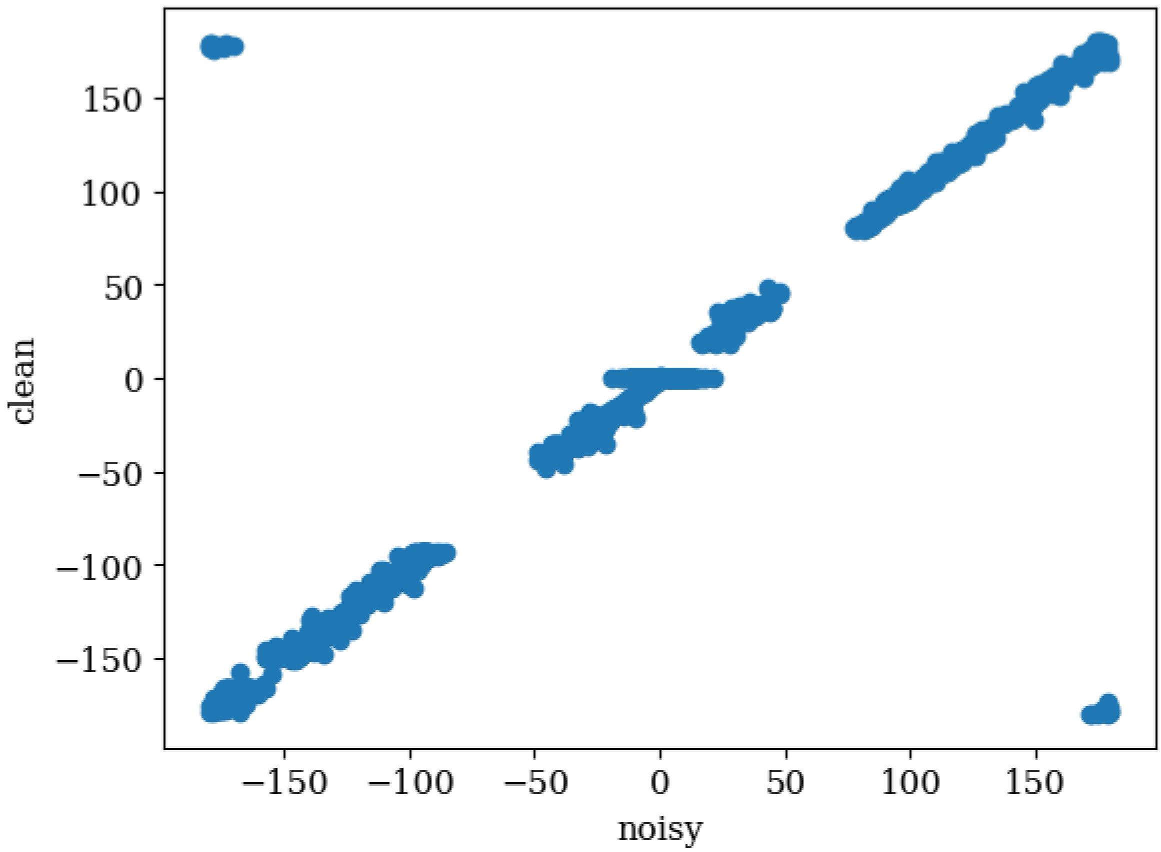
```
# the angle given by the product of each of the forward matrices A0, A1, A2 with th
test_cphase = np.angle(np.matmul(A_cp[0], im.imvec) * np.matmul(A_cp[1], im.imvec)

# plot to show the overlap in the noisy measured data from obs and the clean closur
plt.scatter(cphase2, test_cphase / eh.DEGREE)
plt.xlabel('noisy')
plt.ylabel('clean')
# note that the points on the upper left and bottom right of the plot are due to ph
# note that if add_th_noise is False, then these should be exactly equal (lie on y
```

```
Using pre-computed cphase table in cphase chi^2!
```

Out[30]:

```
Text(0, 0.5, 'clean')
```



Access amplitude measurements

In [31]:

```
obs.add_amp(debias=True) #debiases amplidues when measuremments have low SNR

# access the amplitudes and the associated standard deviations of noise on each amp
# amplitudes are derived from complex visibilities
# amplidude measurements are approximmated as being a sample from a Gaussian distri

amp = obs.amp["amp"]
sigmaamp = obs.amp["sigma"]
# obs.amp parameters: "time", "tint", "t1", "t2", u, v, amp, sigma
```

```
Updated self.amp: no averaging
Updated self.amp: avg_time 0.000000 s
```

Manually compute clean debiased amplitudes

In [32]:
```
amp2 = np.abs(np.matmul(A_vis, im.imvec))  # compute amplitudes as amplitude of vis
amp2 = eh.observing.obs_helpers.amp_debias(amp2, sigma)  # debias amplitudes
plt.scatter(amp, amp2)
plt.xlabel('noisy')
plt.ylabel('clean')
# note that if add_th_noise is False, then these should be exactly equal (lie on y
```

Out[32]:
```
Text(0, 0.5, 'clean')
```