The Extended Configurations of ALMA

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A	2007-10-05	All	none	First Issue .

1. Introduction and Philosophy

1.1 Applicable documents

The following documents are included as part of this document to the extent specified herein. If not explicitly stated differently, the latest issue of the document is valid.

Reference	*Document title*	*Date*	*Document ID*
[AD1]	Positions of the inner 151 ALMA antenna stations and their occupation scheme for the inner ALMA configurations	2006-11-06	ALMA-90.02.00.00-006-A-SPE

Table 1

1.2 The Y+ Configuration and the Ring Configuration

The original design for the NRAO Millimeter Array (MMA) called for multiple array configurations with a maximum baseline of 3 km. ESO's Large Southern Array was envisioned to have baselines of up to 10 km. Some early proponents of high resolution sought even longer baselines (Hjellming, 1995). Over the last 20 years, many configuration designers have assumed that a uniform (u,v) coverage was desirable (Cornwell, 1986; Keto, 1997), and designs for ring or Reuleaux triangles proliferated. Uniform coverage results in the highest ratio of average baseline to maximum baseline, or the highest resolution given the size of the array. However, uniform coverage also produces very large near-in side-lobes (15%) that do not average down with earth synthesis (Holdaway, 1996a). Furthermore, uniform-type coverages do not have great imaging properties - and when they do outperform other coverages, it is because of their very short spacing excess coverage! Kogan and coworkers advanced the Donut, or double-ringed arrays, which realized some flexibility in reconfiguring, permitting a new configuration to be made by moving half the antennas. The Donut array was a compromise between the ring and more centrally condensed designs.

In the end, though, it was the logistical simplicity of the self-similar and ever-expanding spiral configuration plan (Conway, 1998, 1999, 2000a, 2000b, 2001, 2002) that swayed people to its clever design. A new configuration can be created in a single day (with luck and short moves, in a single morning before the wind starts to pick up), and the desired resolution could be dialed in with minimum sensitivity loss if tapering was needed to make an exact resolution for multi-frequency comparisons. Of course, the low side-lobe levels, the nearly- Gaussian beams, and the superior imaging quality (Heddle, 2001) all aided in the acceptance of the Conway configuration plan.

Through a compromise with individuals who desired higher resolution, a 27 station Reuleaux triangle of 4.5km diameter was added to the spiral design to achieve higher resolution. If we were somehow constrained to have a maximum baseline of 4.5 km, this would be a reasonable approach. However, a higher resolution array with 14 km baselines was designed to ring the Chascon volcano (Holdaway, 1996b; Conway, 2002, Kogan, 2000). This 14 km configuration shared almost no antenna pads with the 4.5 configuration, hybrid arrays with intermediate resolution were difficult, and the half circumference of the 14 km ring was 22 km, implying something like a 25 km maximum cable run.

In early 2002, Angel Otarola and Mark Holdaway officially proposed an alternative configuration design for the highest resolution array named the Y + configuration (Otarola and Holdaway, 2002). Our configuration design has been named (B!H(BY +(B!I(B because it is a departure from a strict linear Y design such as the VLA, thereby reducing the snapshot sidelobe issues which the VLA suffers from. In order to match the resolution of the 14 km ring, we had to extend the maximum baselines out to 18.5 km. The coverage results in a basically Gaussian (u,v) coverage synthesized beam. This array configuration offered a number of advantages:
* The philosophy of the Y+ arrays is similar to much of the philosophy behind the spiral arrays, and observations with the Y+ will result in similar (u,v) distributions. This means that the processes of making and interpreting images should be very similar for every ALMA configuration longer than the most compact array.
* Hybrid configurations with the entire possible range of resolutions result naturally.
* Just as with the spiral array, the logistics of reconfiguring four antennas per incremental array configuration is very attractive.
* The maximum cable run in the Y+ configuration should be about 15 km, much shorter than the Chascon ring array.
* A substantial savings in the number of pads (and the number of antenna moves) can be achieved, as the 27 station Reuleaux triangle at 4.5 km becomes superfluous. Also, the Y+ array is able to share a few more antenna stations with Conway's configurations.
* Even though the Y+ array has problems with inner side lobes at 7.5%, they are significantly better than the ring array's 15% side lobes. And these inner side lobes do not form a continuous ring, so they do average down somewhat with earth rotation synthesis.

The Y+ array does have its disadvantages. It is sometimes considered a disadvantage that the Y+ doesn't have the same resolution as an 18.5 km ring array. Of course, we can't fit an 18 km ring on the site. Even though the Y+ array has the same resolution as the 14 km ring, the Y+ array has inferior resolving power: the ring array has more long baselines than a Gaussian coverage would have, so its synthesized beam is highly non-Gaussian, dropping to the first null much faster than a Gaussian. This results in an improved ability to resolve close source pairs. While we don't match the 14 km ring array' s abilities, we did improve our Y+ design to be more competitive with the ring array. While we do present a complete design for the Y+ array configuration, this is probably not the last word on the Y+. A number of locations for antenna pads may not be possible because of excessive depth to bedrock or loose bedrock beneath the site. We will continue work on these problems and will make revisions to this document as we are required to do so. Also, issues such as the optimal reconfiguration scheme may change in the future. However, many of the details of the Y+ array and its general shape and maximum baseline length are pretty well set and can be used to design other aspects of ALMA.

1.2 Differences in Approach From the 60 Element Optimization of Holdaway 2003

The design for the Y+ array configuration was initially completed in 2003 when the ALMA array (not including the ACA) was going to have 64 antennas, but four of those were for dedicated total power observations, so configurations were designed for 60 antennas. That design used 16 stations from the Conway configurations and selected locations for 44 stations further out along the three arms. As ALMA has been rebaselined to have 50 antennas in the main array, we have been retasked to design a Y+ configuration for 50 antennas. We use 14 stations from the Conway configurations and have determined locations for 36 other stations farther out along the arms.

2. The Mask of Permitted Antenna Locations

Most configuration optimization algorithms include the possibility of a mask image indicating which locations are acceptable for the placement of antennas. This is absolutely crucial for the Y+ configurations, for which most positions will not permit antenna placement due to steep terrain and accessibility issues. Understanding the details of the mask and how it was generated are key aspects of understanding the Y+ configuration.

2.1 The 10m Resolution Digital Elevation Model

The most fundamental input to the Y+ mask image is the digital elevation model. Formally, a digital elevation model (DEM) is a digital data product provided by the USGS in a proprietary data format. We began using DEM's for South Baldy and Mauna Kea, and converted them into FITS images.

In Chile, no high resolution digital elevation data products were available commercially for the ALMA site. However, overlapping (ie, stereo) diapositives of Chilean Air Force aerial photographs of the region were available, and McClain Aerial in Tucson digitized these images, performed a posteriori ground control using visible features in Chilean topo maps of the region, hence linking the coordinate system of our DEMs to UTM referenced to SAM 1956, the datum of the topo maps which were available at the time of McClain's work (Holdaway et al, 1996). The McClain DEM had a pixel size of 10m, though resolution was variable and accuracy was uncertain and systematic errors were probably due to the a posteriori ground control. Since the first DEM was delivered, the current science preserve concession and the approach from the AOS to the ALMA site were covered in increments and the maps were stitched together. The DEM for the science preserve area is shown in Figure 1. Errors in the stitching of a DEM segment in the ascent from the AOS to the ALMA site resulted in spurious cliffs of about 100 meters elevation in a regional DEM.

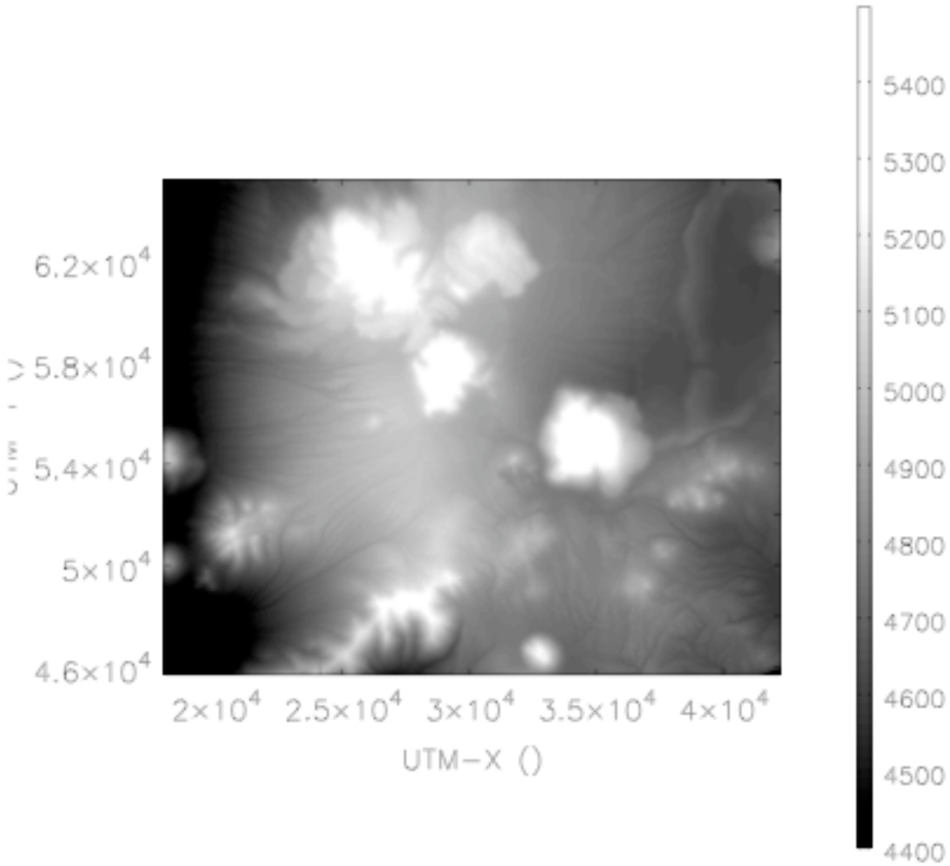

Figure 1 **Digital Elevation model of the Chajnantor site. Note that the coordinates for all FITS files (ie, DEM or MASK) are offset by: UTMX - 600000 m and UTMY - 7400000 m so that software has sufficient precision - about 1 cm - in single precision floats.**

In 2002, the ALMA project paid for new lower altitude (ie, higher resolution) aerial photography and subsequent cartography over the inner 5 x 5 km region and a (500m-wide?) strip covering the route of the access road from the PSF to the high site, but due to an error in the contract, no DEMs were made. Angel Otarola and Mark Holdaway interpolated the AutoCad contours onto a regular 5m grid (ie, a DEM), but it was determined empirically and from conversations with the contractor that the coordinate system was not conventional UTM. The coordinates of the gas pipeline and other monuments which were visible in the aerial photographs permitted us to solve for a mean offset between the newly interpolated DEM and GPS' UTM, which amounted to 29m East, 2m North). The high resolution, high accuracy DEM was required for laying out Conway's spiral configuration, and the 29m offset was significant - if it were not properly acocunted for, antenna station positions could move from flat ground at the edge of arroyos down to the steep sides of arroyos. This offset still comes up as some people unfamilier with the configuration process have not accounted for it in their work.

It was also decided that a new DEM for the Y+ array configuration was too expensive for the ALMA project and the Y+ station locations would be referenced to the old McClain Aerial DEM. Solving for a best-fit offset between the new, accurate, high resolution DEM of the inner 5 x 5 km region and the old DEM covering the same region indicated a position-dependent offset ranging from 0 to 100 m, so we were not entirely confident in the accuracy of the low resolution DEM upon which the Y+ configuration was based. However, in the 2003 Y+ field work, the positions we visited seemed to be consistent with a low offset error of 10-20 m.

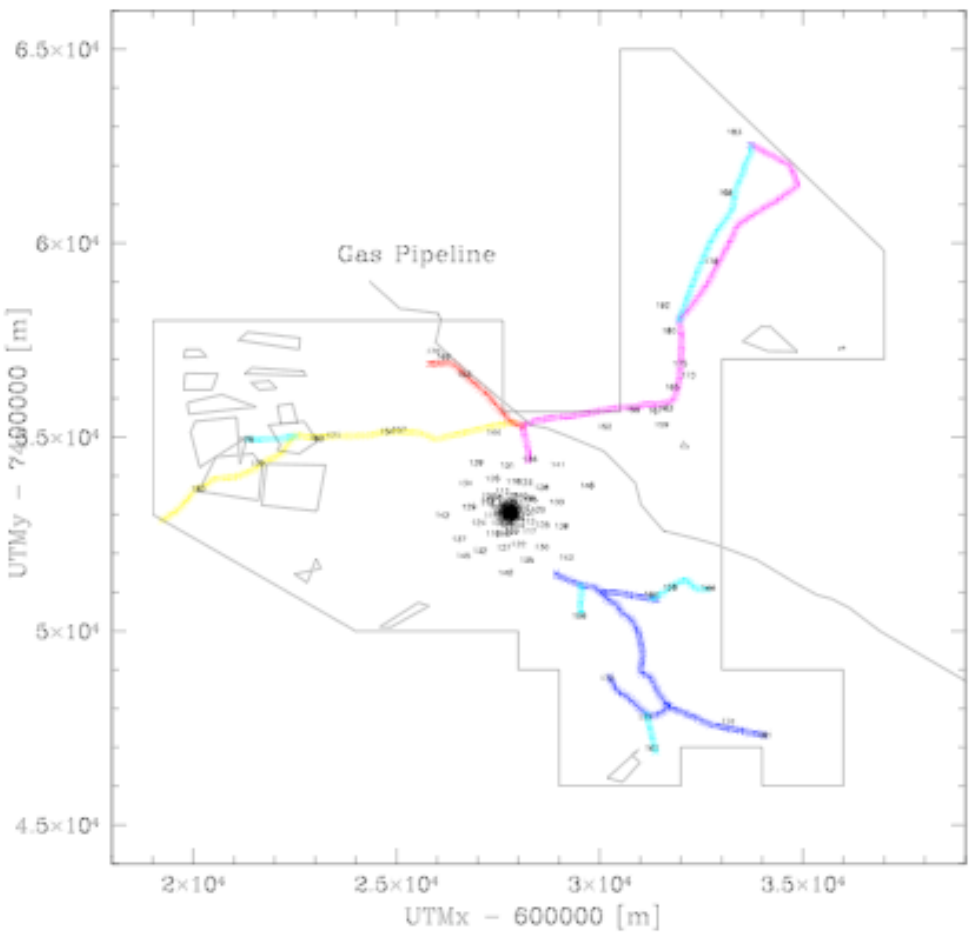

Figure 2 The science preserve outline, designed roads, gas pipeline, and viscacha colonies (little polygons). Note that the coordinates for all FITS files (ie, DEM or MASK) are offse by: UTMX - 600000 m and UTMY - 7400000 m so that software has sufficient precision – about 1 cm - in single precision floats.

2.2 A Road-based Mask

In the 2003 Y+ work, we started with a fairly permissive mask which expanded to fill much of the science preserve. The optimization algorithm took full advantage of this permissive mask, and scattered antennas around, resulting in an array which required prohibitively expensive roads. In the current work however, the mask is based on plausible roads. There were about three iterations of back-and-forth between the road engineers at M3 and the ALMA staff. The plausible roads which formed the basis of the mask are indicated in Figure 2

The terrain surrounding these roads is highly variable. Pampa la Bola to the northeast is very flat and nonrestrictive, so antenna locations could be situated fairly far from the designed road. Arroyos break up much of the western region of the science preserve, and potential antenna locations need to be very close to the roads. Hence, based upon the local topographical restrictions, we formed a mask which extended 80m, 100m, 200m, 300m, or 400m either side of the proposed roads. It was determined that the access road between the OSF and the AOS could be used as the main road for the west arm, and spurs come off of the access road.

2.3 Other Constraints: Science Preserve, Maximum Gradient, Viscacha Colonies, Gas Pipeline, Jama Road, and Shadowing

Several other constraints further reduced the extent of the mask of possible antenna locations. The mask was augmented by the boundaries of the science preserve defined by the land concession from CONICYT. Antenna locations were permitted within 20m of the science preserve boundary. From the DEM, we calculated the maximum gradient at each pixel (Butler, 2001) and locations with a maximum gradient over 14 percent were excluded from the mask. We first tried a 12 percent maximum gradient, but it was found to be too restrictive. Rodents called vizcachas have been found on the ALMA site, and we are not building roads or antennas in the regions biologists have identified as vizcacha colonies. Vizcacha colonies are shown in Figure 2.

We have a 100m safety distance around the gas pipeline and the Jama road. Originally, we had agreed on a 200m safety distance for the gas pipeline, but that has been relaxed. There is one reinforced crossing of the gas pipeline, and other crossings are not permitted. This in conjunction with other topographical constraints makes some patches of apparently accessible land off-limits. In fact, there are thousands of little patches of land which are flat enough to permit an antenna, but are inaccessible (ie, a flat spot at the bottom of an arroyo). These patches are removed from the mask of permitted antenna locations with a mouse-driven AIPS++ image selection tool.

Finally, shadowing was considered with an AIPS++ shadowing tool which read in an antenna configuration and the DEM of the ALMA site. Problem spots were selected (ie, mountain peaks) and the elevation angles at which shadowing occurred were calculated. Shadowing is most important to the north, as shadowed sky to the north cannot be observed at all. Shadowing to the south above 23 degrees (ie, the elevation angle of the south celestial pole) is also a major problem. Shadowing to the east and west is not a major problem as this only reduces the length of the tracks that we can observe a source, and ALMA has been designed as a near-transit instrument, though E-W shadowing will sometimes be an issue when ALMA is engaged in global VLBI. Based on the calculated shadowing elevations and the somewhat subjective interpretation of where shadowing is permitted and where it is not, we added to the mask. Some problem areas include: the northern parts of the Conway configurations, which are shadowed by Chajnantor to the north; the southern part of Pampa la Bola, which is shadowed to the east and west by Chajnantor and Chascon; the black cinder cone at the southern part of the south-eastern arm; and other peaks around the western arm.

The final road-based mask, including gradient, shadowing, viscacha, accessibility, and gas pipeline constraints, superimposed upon the science preserve was used to constrain antenna placement. The road-based Y+ mask is shown in Figure 3. Figure 4 shows the same mask with Conway's mask of the inner 5 x 5 km region inserted.

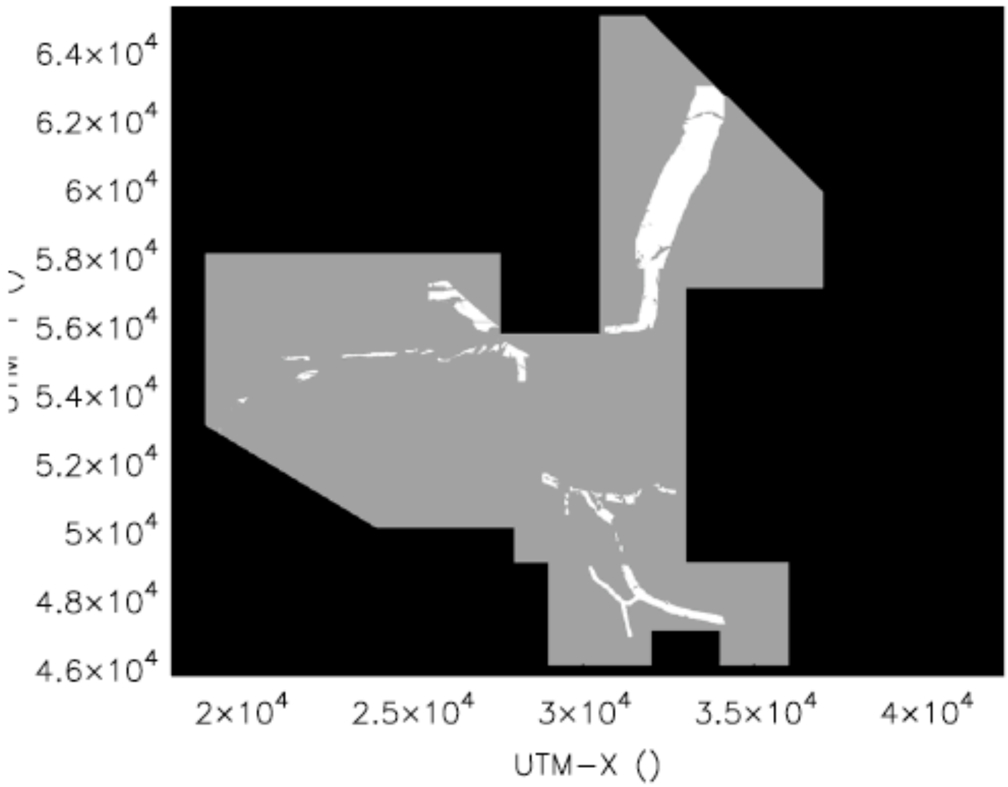

Figure 3 The final road-based Y+ mask, including gradient, shadowing, viscacha, accessibility, and gas pipeline constraints, superimposed upon the science preserve. Note that the coordinates for all FITS files (ie, DEM or MASK) are offset by: UTMX - 600000 m and UTMY - 7400000 m so that software has sufficient precision - about 1 cm - in single precision floats.

3 9 Y+ Configurations

Beyond the most compact array configuration in Conway's 2005 inner array specifications document, subsequent spiral array configurations are made by moving the four innermost antennas to stations on the three spiral arms which are further out than the outermost occupied stations. Moving four antennas to make a new configuration can be achieved if each of the two transporters can move two antennas per day. Even though the spiral array concept cannot expand into the Y+ regime due to topographical constraints, we maintain the reconfiguration style of moving four antennas per new configuration.

However, we are not free to move all the antennas out of the most extended Conway configuration. We require some very short baselines in the array for flux calibration (ie, for observing planets or asteroids). Conways configurations 1-16 all have three pairs of antennas making three baselines of about 27 meters, but starting at configuration 17, those short baselines are lost, but three antennas are moved out to the end of the spiral arms to make three new short baseline pairs. Antennas 114 and 147 make a 79 m baseline, antennas 115 and 148 make an 84 m baseline, and antennas 116 and 149 make an 83 m baseline. These six antennas remain in the same place for Conway's configurations 17, 18, 19, and 20, and also remain fixed for all the Y+ configurations. We somewhat arbitrarily initially chose to keep a total of 14 of the Conway stations occupied through the cycle of Y+ configurations, meaning we must find positions for 36 stations which only participate in Y+ configurations. (Note that in our reconfiguration optimization, these numbers were changed to 18 Conway stations reused in the highest resolution Y+ array and only 32 new stations for the Y+ array.)

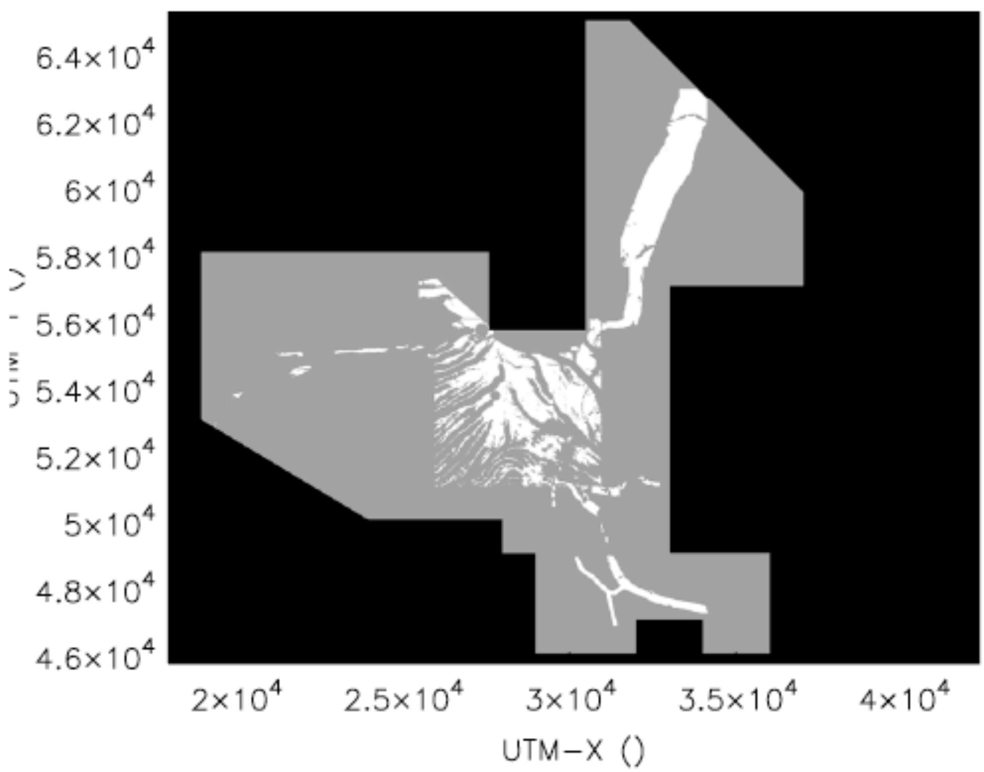

Figure 4 The Y+ mask with Conway's inner 5x5 km mask inserted, superimposed on the science preserve. Note that the coordinates for all FITS files (ie, DEM or MASK) are offset by: UTMX - 600000 m and UTMY - 7400000 m so that software has sufficient precision - about 1 cm - in single precision floats.

So, with 36 new Y+ stations and four antenna moves per configuration in the march outward, this means that we will have 9 Y+ configurations, numbered Y1 through Y9, or numbered 21-29 when appended to Conway's 20 basic inner configurations.

As explained below, we retreated to 8 Y+ configurations, or 32 new and 18 shared antenna stations. The 18 shared antenna stations from Conways configuration number 20 are: 114, 115, 116, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 147, 148, and 149. Figure 5 shows the stations in configuration #20, with the 18 shared stations numbered.

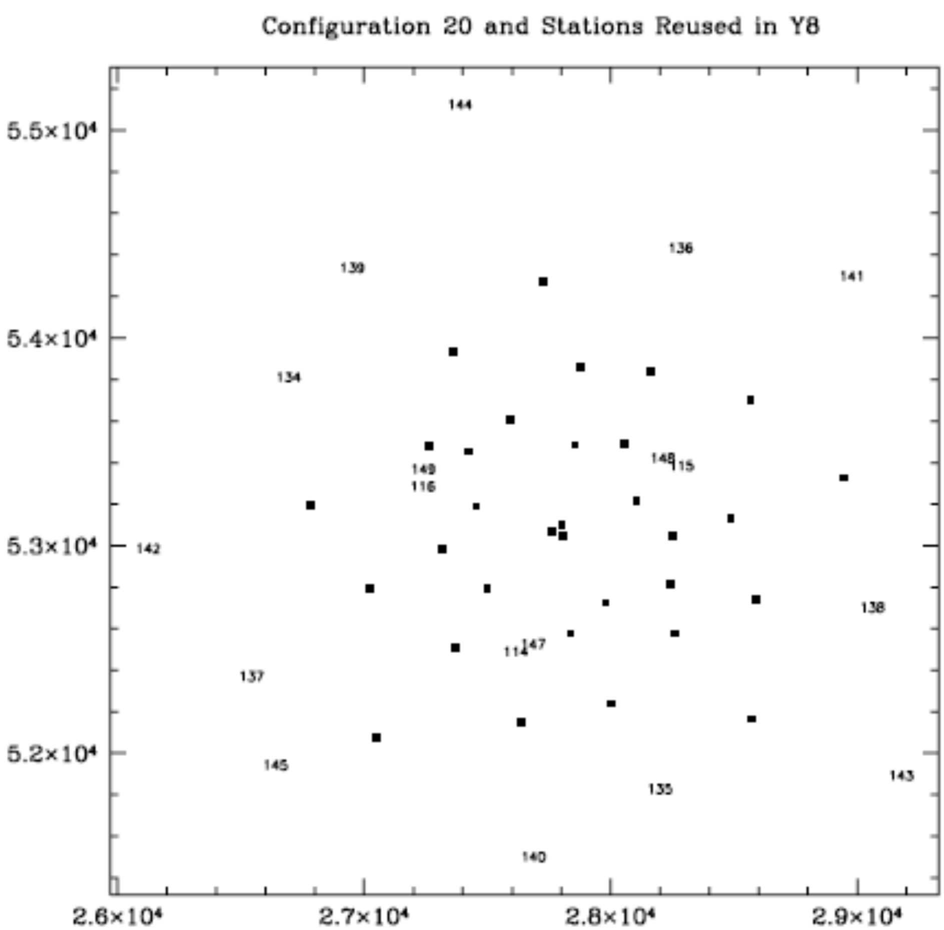

Figure 5 Conway's outermost configuration #20, with the 18 antennas which are also used in the Y8 configuration numbered.

Our desire is for the array configurations' resolution to step smoothly from one configuration to the next. Figure 6 shows the resolution ($\sqrt{(b^2_{maj}+b^2_{min})}$) of the Conway configurations 10 -18 (the inner configurations are not purely spiral) plotted as a function of configuration on a semi-log plot. The mean linear beam size ratio between adjacent configurations is 0.86, which means that the maximum baseline length needs to increase by a factor like 1.16.

It was our intention that each incremental Y+ configuration would have a similar resolution factor to the Conway configurations. However, in addition to the 9 Y+ configurations (a constraint placed upon us by the desire to move only 36 antennas onto Y+ stations and keep the other 14 on Conway pads, there is also a science driver to have as high resolution as we can, hopefully 0.010 - 0.015 arcsec at 300 GHz.

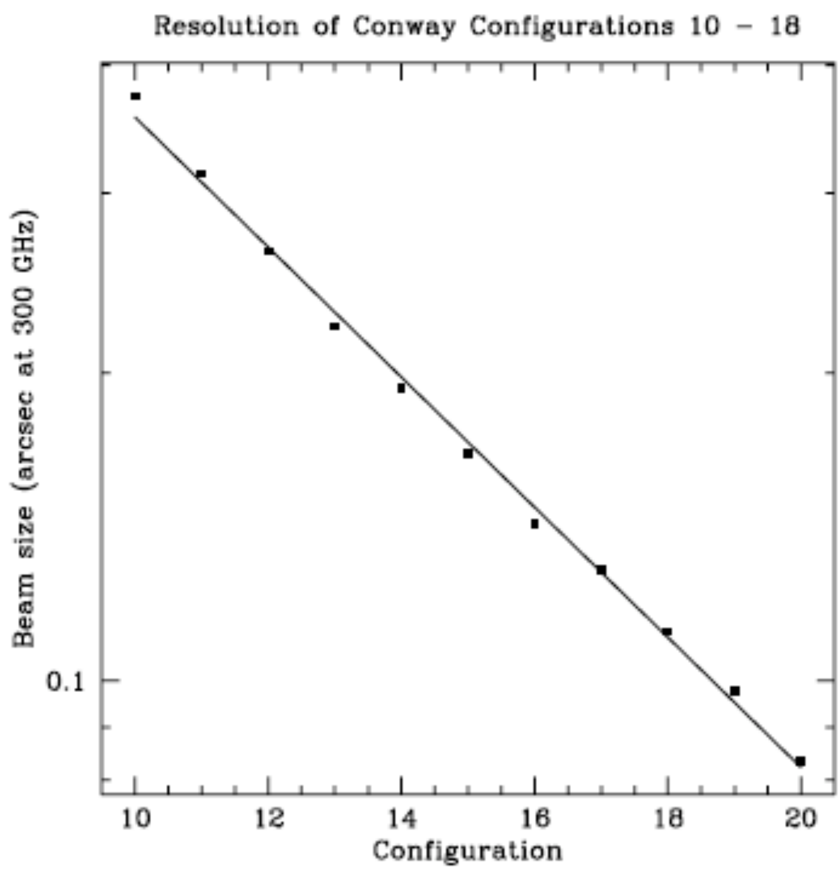

Figure 6 Naturally-weighted Resolution at 300 GHz of Conway configurations 10-18.

The beam of Conway's most extended array configuration #20 is 0.0815 arcsec at 300 GHz. If we desire 9 Y+ configurations with a constant multiplicative resolution factor between each, and with the final Y+ configuration with a 300 GHz resolution of R arcsec, then the resolution step between adjacent configurations will be

$factor = (R/0.0815)^{1/9}$.

If we seek a 300 GHz beam of 0.010 arcsec, then our resolution step factor needs to be 0.79. This is a significantly larger jump in resolution than the Conway spiral configurations' resolution jump of 0.86. In the end, we could not get a configuration with 36 Y+ antennas and 14 antennas in the spiral configuration with 0.010 arcsec resolution and low inner sidelobes. We could get fairly low sidelobes when we relaxed the resolution to 0.017 arcsec naturally weighted. Briggs' weighting gives a resolution at 300 GHz of 0.011 arcsec at a cost of about 10 % in sensitivity. Hence, the desired multiplicative resolution factor between

adjacent configurations is
factor = $(0.017/0.0815)^{1/9}$ = 0.84,
which is close to the resolution step size for the spiral configuration.

As we retreated from 9 to 8 Y+ configurations, the resolution factor between adjacent Y+ configurations ended up being more like
factor = $(0.017/0.0815)^{1/8}$ = 0.82.

4 Optimization

There are several aspects of a good configuration for which we would like to optimize. We would like the (u,v) coverage to be Gaussian, and we would like the point spread function to have low sidelobes. The Y+ configuration has a problem.

Unlike the compact array and the spiral configurations that were optimized for a snapshot, the Y+ configuration needs to be optimized for long tracks. The beam is so small that it is thought that most observations will require long integrations to get sufficient sensitivity. After only an hour or two of earth synthesis rotation, the outer side lobes are greatly diminished, typically by a factor of about 10, as they move among the PSF's pixels. However, the side lobes which are within a few beam widths of the main lobe of the PSF are hardly reduced at all for a one or two hour synthesis, and perhaps by a factor of only 2 after a full six hour synthesis. This indicates that a great deal of attention must be paid to the inner side lobes of the PSF, as they are likely to dominate the image quality of images made from long integrations using

A three armed Y configuration will have snapshot (u,v) coverage resembling a 6-pointed star, or about 60 degrees between adjacent points in the (u,v) coverage on average. Earth rotation aperture synthesis will result in the points of the (u,v) coverage rotating 60 degrees into adjacent points in a time period of 4 hours. Hence, we seek to optimize the beams for a -2h to +2h track. (u,v) points were calculated every 60 s.

We build in a 10% N-S stretch to the baselines (Foster, 1995) by optimizing for a declination of -48 degrees.

As the array site is not flat - the elevation of the antenna stations ranges from 4567 m to 5059 m - we must infer the elevation of each station from the digital elevation model whenever we calculate (u,v) coordinates or beams.

We had several options for how to proceed with the array optimization. We could have sought to optimize all 9 incremental Y+ configurations simultaneously, we could have optimized each incremental configuration (i.e., Y1, Y2, through Y9) one after the other, or we could have optimized the full resolution Y+ array (Y9) and then picked the best intermediate Y configurations subject to those positions. Simultaneously optimizing all 9 incremental configurations was not technically feasible with any of the software packages we tried working with. Baed on our 2004 work, optimizing the incremental Y+ configurations sequentially worked fine out to about Y5, but the inner side lobes got worse and worse for the larger arrays, culminating in a full resolution Y9 configuration with very large near-in sidelobe levels. Apparently, with only four antennas free to move, there are not enough degrees of freedom to fix those side lobes. Optimizing the full resolution array and then finding the best way to make the remaining 8 intermediate Y+ configurations produced arrays which were as good as the individually optimized arrays out to Y5, and superior to the individually optimized arrays between Y6 and Y9. As it is anticipated that the full resolution Y+ array will have more observing time than all the intermediate configurations combined, we chose to do the primary optimization on the full resolution Y9 array and then do a secondary optimization of the intermediate arrays given the positions solved for in the full resolution array.

4.1 Algorithm

We had difficulty with algorithms. Boone's algorithm (Boone, 2002) looked good, and it claimed to handle long tracks as opposed to snapshots, but it only concentrated on the overall shape of the (u,v) coverage and did not deal with sidelobes - in particular the configurations resulting from this algorithm had large near-in sidelobes. The 2004 Y+ configuration work was done using Kogan's CONFI program in Classic AIPS. However, Kogan's algorithm had difficulty in negotiating the very restrictive mask we ended up using, and it also had difficulty in distinguishing between the main lobe of the PSF and the near-in sidelobes. So in the end, we used a homegrown algorithm which wiggled the antenna positions around and sought to a) optimize conformance to a desired fit beam size and shape and b) minimize PSF sidelobes after removal of the best-fit Gaussian main lobe in three regions: near-in (ie, within 1.5 beams of the PSF center), inner (between 1.5 and 10 beams of the PSF center), and outer (between 10 and 64 beams of the PSF center). An L1 norm was used, and relative weights between the beam size and shape "error" as well as weights for the peak sidelobe levels in the three regions were used to guide the algorithm. As gradients with respect to these quantities could not be easily formed, the algorithm was not particularly smart and only improved modestly upon the starting configuration. Hence, a lot of time was spent getting good (u,v) coverage "by hand" - ie, moving antennas around to fill gaps in the (u,v) coverage, and then fine tuning the configuration's beam shape and sidelobes with the optimizer. Some gaps in the (u,v) plane could not be adequately filled given the mask we were working with, and in a couple of cases we got M3 to make additional roads to permit antenna placement which would fill the holes in the (u,v) plane.

The beam was calculated with a 512 x 512 image size, and the cell size was chosen such that there would be four pixels across the PSF main lobe when using natural weighting.

4.2 Different number of antennas on each arm

The algorithm did not constrain the number of antennas on each arm. Solving for the positions of 36 antennas it would seem that we would get 12 antennas on each arm. However, the potential length of the Pampa la Bola arm is the longest, followed by the west arm, and the southern arm is the shortest. The terrain of Pampa la Bola is minimally problematic for antenna placement, the western arm is pretty difficult, and the southern arm is most restrictive in antenna placement. These factors conspire and the algorithm ended up producing a configuration with 9 Y+ stations on the southern arm, 10 Y+ stations on the western arm, and 13 Y+ stations on the northern, or Pampa la Bola, arm.

The initial configurations placed 12 antennas on each arm, and we initially sought to prevent the migration of antennas away from the shorter arms and towards the longer, easier arms. One way to accomplish this was to remove territory from the center of the mask - ie, the inner 5 x 5 km part of the mask which hosts the spiral configuration's stations. In the end, we gave up on preventing antenna migration, as much better (u,v) coverage and lower PSF sidelobes were achieved. However, the arbitrary choice of removing the inner 5 x 5 km region from the mask of acceptable antenna locations has had the result of making the resolution jump to configurations Y1 and Y2 too large, in addition to degrading their (u,v) coverage and PSF properties. We address this concern below in the section "Potential Inner Y+ Configuration Improvements".

4.3 Ground truth and re-optimization

After a design was produced for the highest resolution Y+ configuration, a team went to the site and to work with the local ALMA personnel on determining if these locations were accessible using roads. We made note of station locations with GPS, which we believe is accurate to about 10-20 m in this application. In some cases, we moved the station locations to a particular place because of accessibility or foundation issues - ie, siting the station on a large rock outcropping should reduce the cost of the foundation. Hence, after visiting all Y+ station locations and modifying some, the station locations fell into three categories: a) the position is fine, but it is open to move by tens or even hundreds of meters to improve the configuration, b) the position is fine, but the specifics of this location do not permit movement, or c) a new position must be determined. We then used the flexibility in some of these positions, especially those located on Pampa la Bola, to account for moving some of the other stations into positions which were somewhat detrimental to the (u,v) coverage.

The ground truth process sometimes results in stations locations which are outside of the mask. However, as the mask is an idealized digital version of reality and the ground-truth process presumably gets us closer to reality, we are not concerned with having stations outside of the mask in general. The one place where it becomes an issue is for topographical shadowing.

4.4 Y+ Configuration Properties

Figure 7 shows the (u,v) coverage of the Y8 configuration (as stated below, the difference in beam properties between the Y8 and the Y9 configuration were small enough that we consider the extra 4 antenna stations required for Y9 to be not required). The naturally-weighted PSF, after subtracting off the best fit Gaussian to the main lobe of the PSF, is shown in Figure 8. The larger near-in sidelobes dominate this image.

The large 8% near-in sidelobes are a result of a relative overabundance of intermediate length baselines - at about 3-6 km. This overabundance is due both to correlations among the 18 stations from Conway's outermost configuration and to correlations between these inner antennas and antennas in the inner half of the Y+ array. We could probably get rid of this overabundance of intermediate length baselines if we were able to make a Y+ configuration using nearly all 50 antennas, but we would still have this problem for the intermediate Y+

configurations.

On the other hand, we do have (*u, v*) reweighting schemes that can help us considerably. John Conway has a scheme that reweights the (*u, v*) samples to most nearly reproduce a Gaussian beam. Right now that algorithm only works on snapshot data, but in tests it can typically reduce the near-in sidelobes by about a factor of 2, at a cost of only 5-10 % in sensitivity. Clearly development of such reweighting algorithms will be important in the future.

There is a a bit of a gap in the (*u, v*) coverage in the N-S direction around 6 km. With no N-S arm (rather, the arms go to the northeast and the southeast) it is really difficult to get N-S

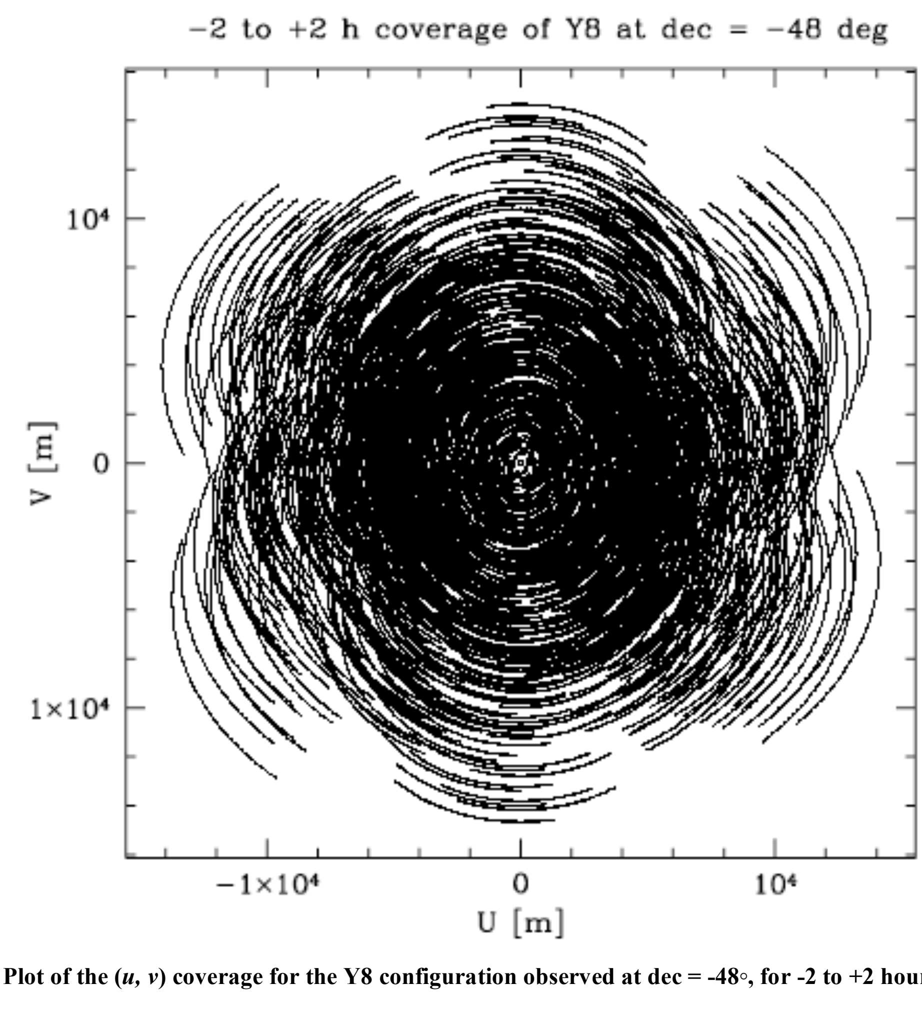

Figure 7 Plot of the (*u, v*) coverage for the Y8 configuration observed at dec = -48◦, for -2 to +2 hour tracks.

baselines. We get a few from earth rotation synthesis, but in order to fill in this part of the (*u, v*) plane as well as we do, we needed to create a spur road going to the east from the northern part of the southern arm. Stations 158, 164, and 166 reside on this spur, and correlations between these stations' antennas and the stations on the inner

Table 1 The sidelobe levels and beam sizes for the naturally weighted and Briggs weighted beams for the Y+ configurations. Y0 is the same as configuration 20 (Conway 2006, [AD1]).

Natural weighting					
	sidelobe levels			beam size [arcsec @ 300 GHz]	
Yconf	near in	inner	outer	bmaj	bmin
0	0.0057	0.0334	0.0295	0.0835	0.0796
1	0.1099	0.0790	0.0302	0.0648	0.0627
2	0.1792	0.1147	0.0434	0.0543	0.0463
3	0.2061	0.1857	0.0365	0.0411	0.0363
4	0.1855	0.1786	0.0349	0.0347	0.0289
5	0.1377	0.1349	0.0353	0.0293	0.0251
6	0.1214	0.1212	0.0334	0.0247	0.0225
7	0.0939	0.0816	0.0366	0.0216	0.0192
8	0.0802	0.0773	0.0392	0.0185	0.0169
9	0.0624	0.0620	0.0292	0.0171	0.0159
Briggs weighting					
	sidelobe levels			beam size [arcsec @ 300 GHz]	
Yconf	near in	inner	outer	bmaj	bmin
0	0.0236	0.0188	0.0206	0.0557	0.0536
1	0.0771	0.0245	0.0231	0.0349	0.0335
2	0.0675	0.0269	0.0232	0.0320	0.0253
3	0.0774	0.0517	0.0213	0.0218	0.0194
4	0.0627	0.0550	0.0221	0.0206	0.0178
5	0.0522	0.0435	0.0213	0.0166	0.0154
6	0.0417	0.0360	0.0218	0.0154	0.0142
7	0.0487	0.0199	0.0195	0.0138	0.0132
8	0.0637	0.0301	0.0197	0.0117	0.0112
9	0.0783	0.0321	0.0218	0.0114	0.0110

part of the north arm help to fill this gap.

4.5 Actual Shadowing

Actual shadowing: The last antenna on the western arm is shadowed at about 13 degrees by several small cinder cones. Chascon shadows 8 antennas in the 10 - 17 degree range. Chajnantor shadows 14 antennas in the 10-17 degree range. Honar shadows 2 antennas at the 15 degree level. And the cinder cone at the end of the southern arm shadows 4 antennas, one of them at 23 degrees.

5 Invent Reconfiguration Scheme

5.1 Algorithm

We sought incremental reconfigurations by moving the innermost four antennas from the spiral configuration out to four Y+ stations such that the new configuration comes closest to having a circular beam, a beam of the correct size, and minimum sidelobes in the three beam regimes. This sub-optimization can be performed by exhaustively searching all possible reconfigurations since the Y+ 36 positions have already been determined. One free parameter is the relative weight to give to offsets from beam circularity, offsets from the desired beam size, and the peak sidelobe levels in the three beam regions. We used the L1 norm and weights of 0.4, 0.6, 0.8, 0.8 and 0.1 for beam circularity, beam size, near in, inner, and outer sidelobes. At times, these weights were adjusted if it seemed the algorithm was paying too much attention to the sidelobes and not enough to the resolution.

5.2 The Configurations

The beam properties for configurations Y0 - Y9 (Y0 is the same as Conway's configuration number 20) are listed in Table 1. Plots of the configurations are shown in Figures 9 through Figures 16, and the antenna positions, elevation, and the array population scheme are listed in Tables 2 through Table 4. The beam size at 300 GHz is shown as a function of Y+ configuration number in Figure 17.

5.3 Dropping Configuration Y9

When we performed the sub-optimization to get the reconfiguration scheme, the improvement in the naturally weighted beam characteristics from Y8 to Y9 was mainly in the sidelobe levels, and the resolution did not change very much, so we removed Y9 from consideration by eliminating the last four Y+ stations. These four stations were not at the ends of the arms, but in the middle of the arms - hence the minimal improvement in the resolution.

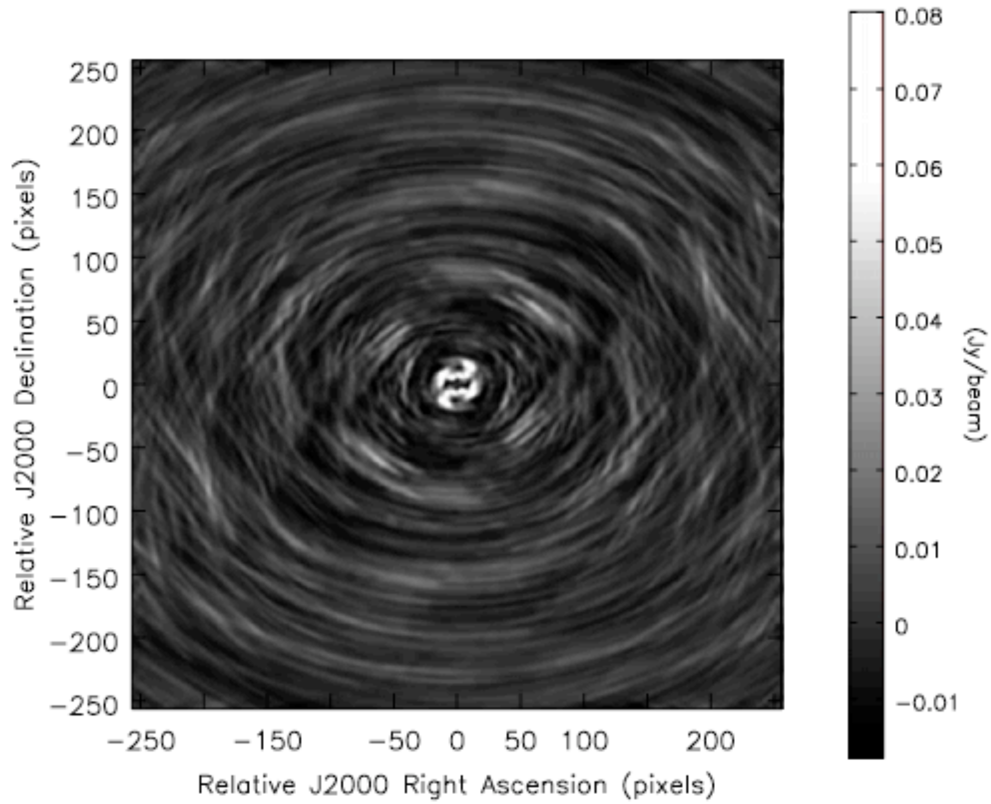

Figure 8 Plot of the naturally weighted PSF, after removing the best-fit main lobe for Y8 configuration observed at dec = -48◦, for -2 to +2 hour tracks.

5.4 Potential Inner Y+ Configuration Improvements

The inner sidelobes are large and the jump in resolution between Conway configuration 20 and configurations Y1 and Y2 is larger than expected. As these configurations were not explicitly considered in the primary optimization, it is not surprising that these configurations don't have great performance. We have explicitly optimized 4 antenna positions for Y1 and four more for Y2 to see if this problem can be easily addressed.

Also, in order to make progress in this direction, we had to use a different mask than we used for the full Y+ configuration work. We added the inner Conway mask to our road-based mask - otherwise we could not get antennas close enough to the spiral configuration to make this work.

The results are shown in Table 5. The beam shapes are nearly circular, the beam sizes are closer to what we want, and the sidelobe levels are consistently low.

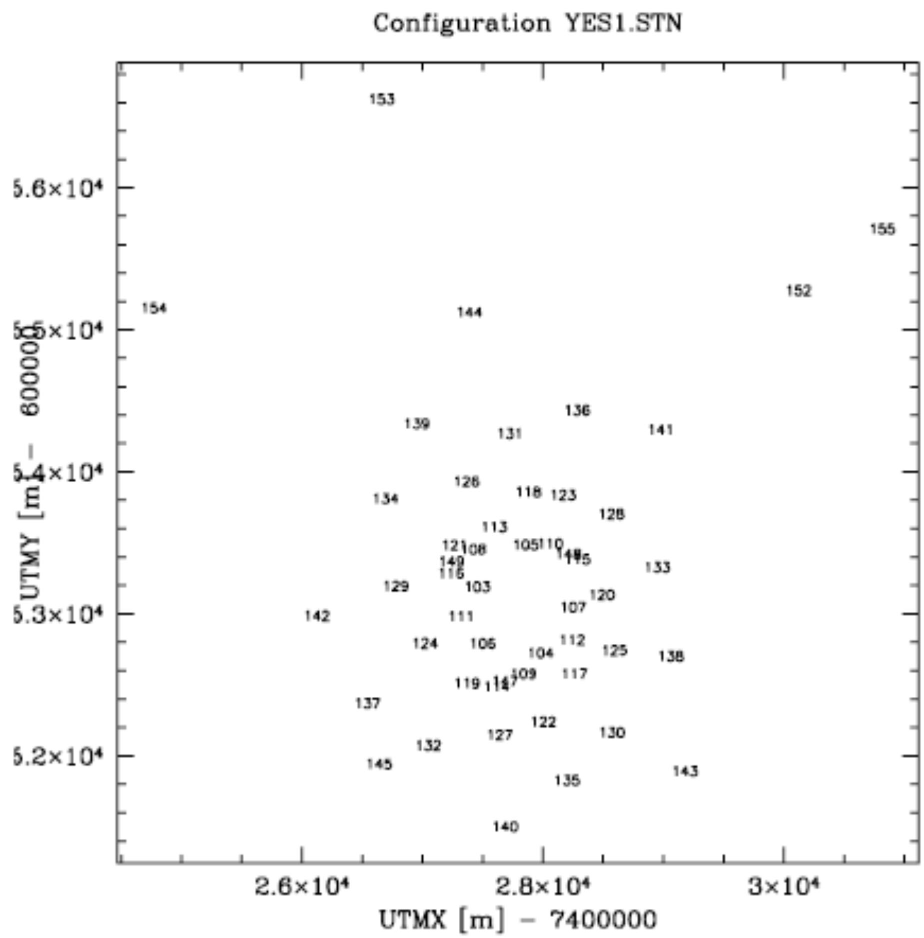

Figure 9 Antenna stations for configuration Y1.

Given these 4 or 8 alternative stations in the inner part of the Y+ configuration, how does that impact the highest resolution Y+ array? To fully answer that question we would have to perform the sub-optimization on the rest of the incremental Y configurations. To get a flavor for the answer, we have just replaced the Y9 configuration's inner 4 Y+ stations with the four new station locations to give us Y9-1a, or replaced the inner 8 Y+ stations to give us Y9-2a. The sidelobe levels and resolution of these configurations are similar to the values when we optimized for the Y9 array, which is encouraging. Rather than simply substituting the inner 4 or 8 stations, we could redetermine the best way of selecting 32 out of the 36 Y+ stations and these additional 4 or 8 stations such that they give us good configurations for Y3 out to Y8.

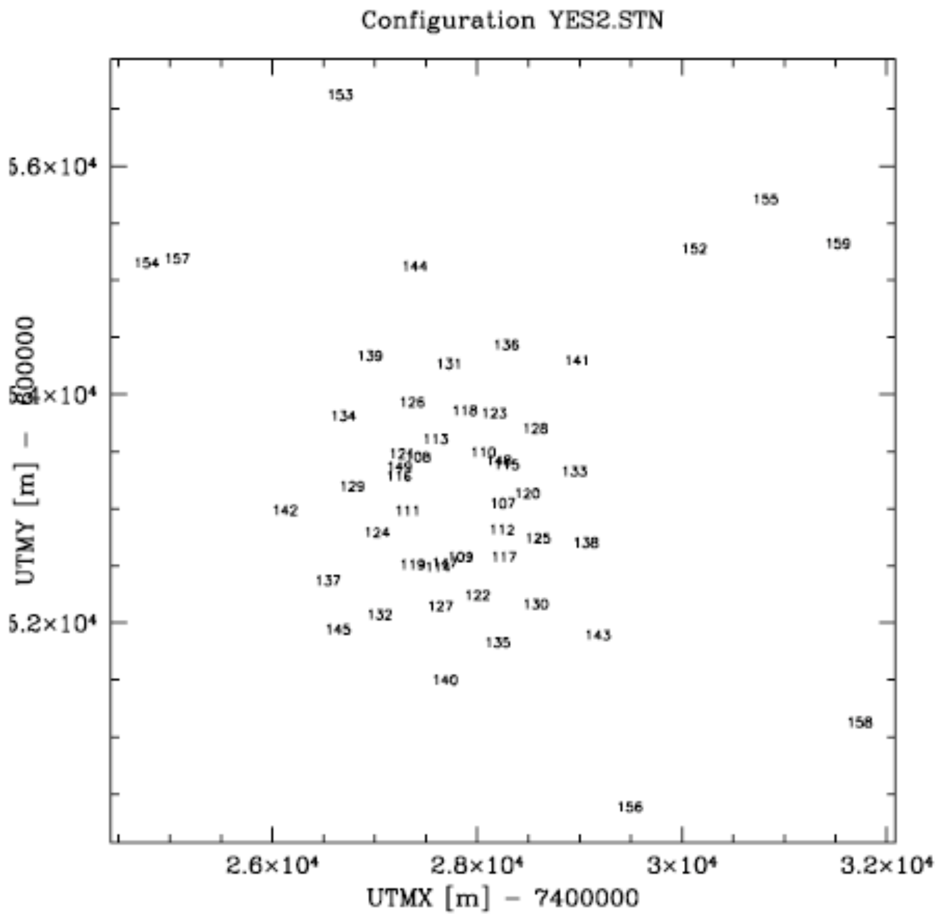

Figure 10 Antenna pad locations for configuration Y2.

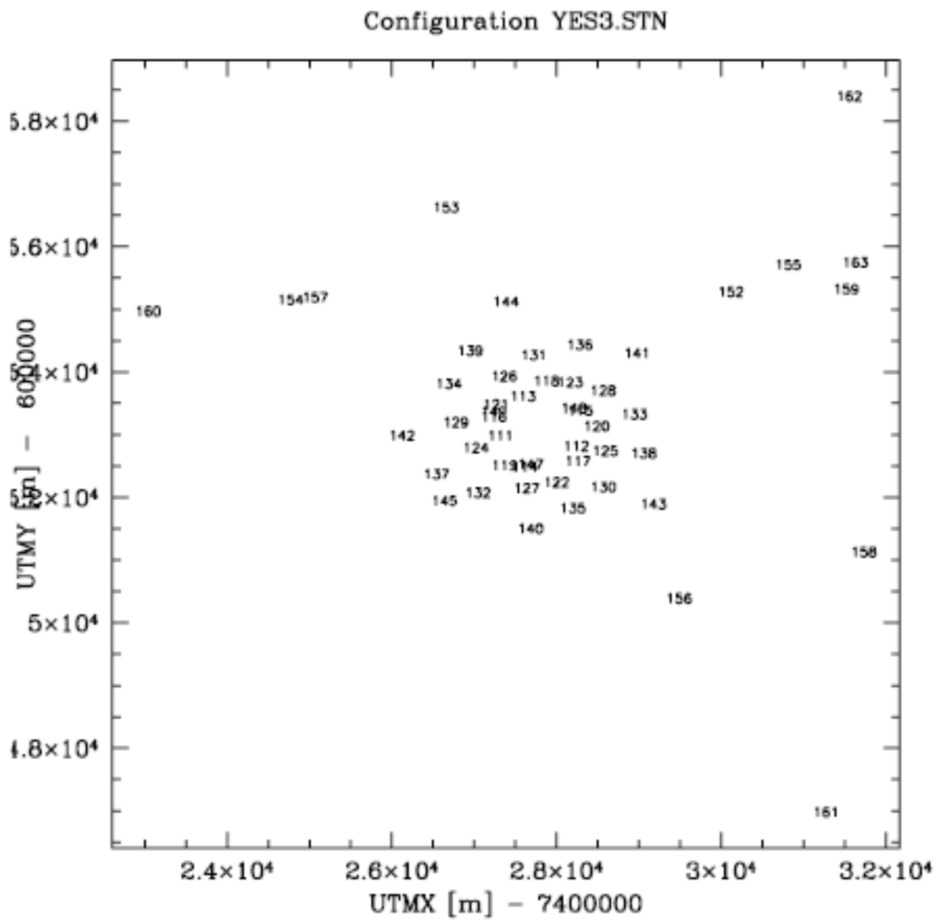

Figure 11 Antenna stations for Configuration Y3.

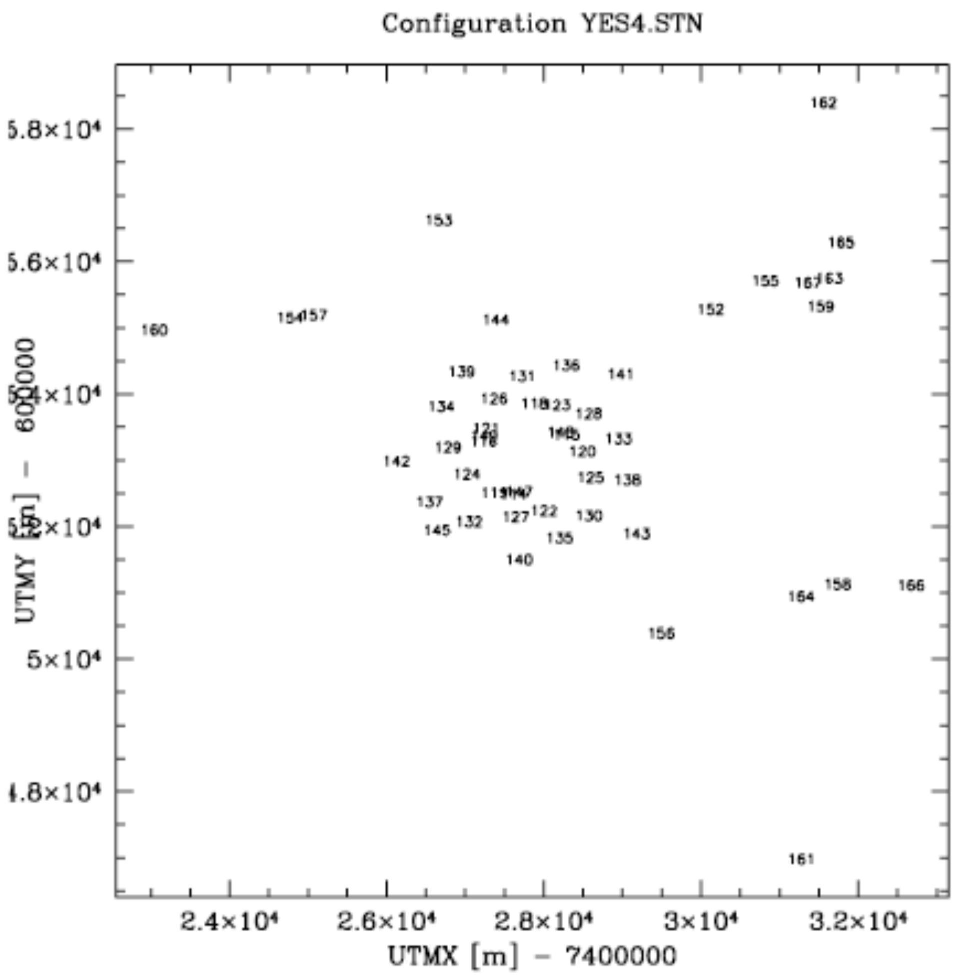

Figure 12 Locations of antenna stations for Configuration Y4

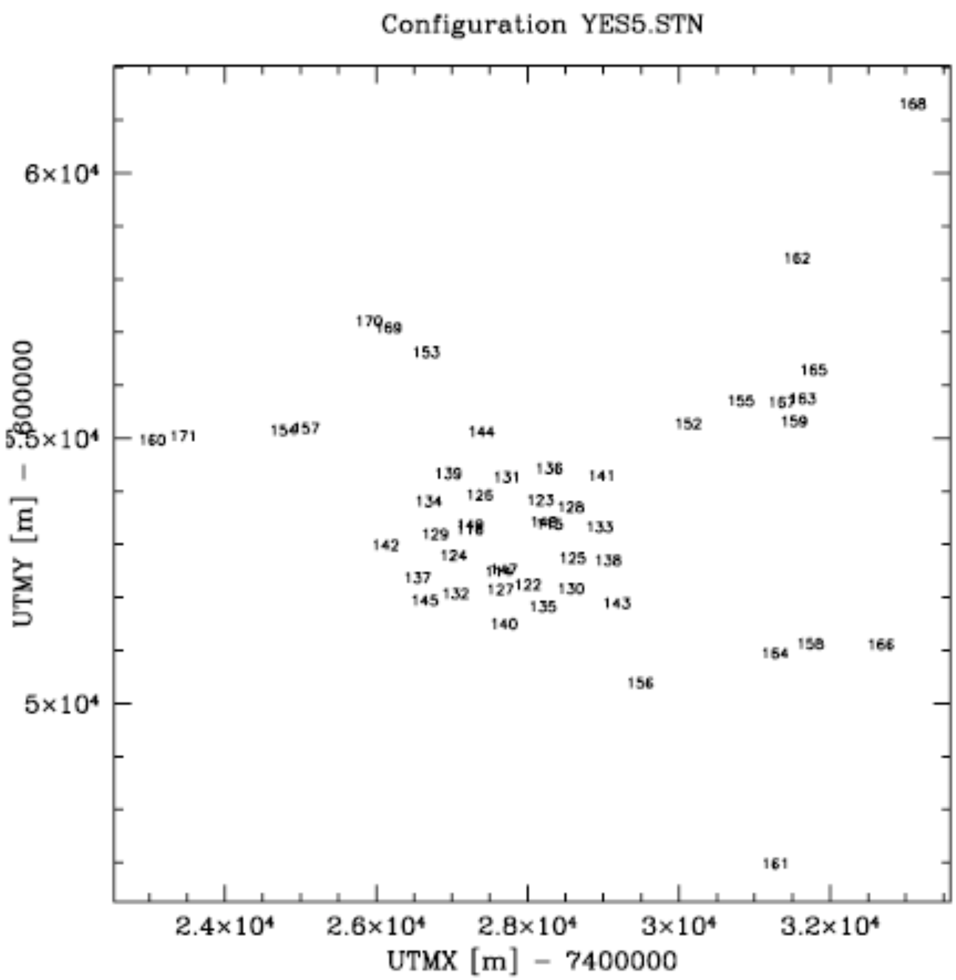

Figure 13 Locations of antenna stations for configuration Y5.

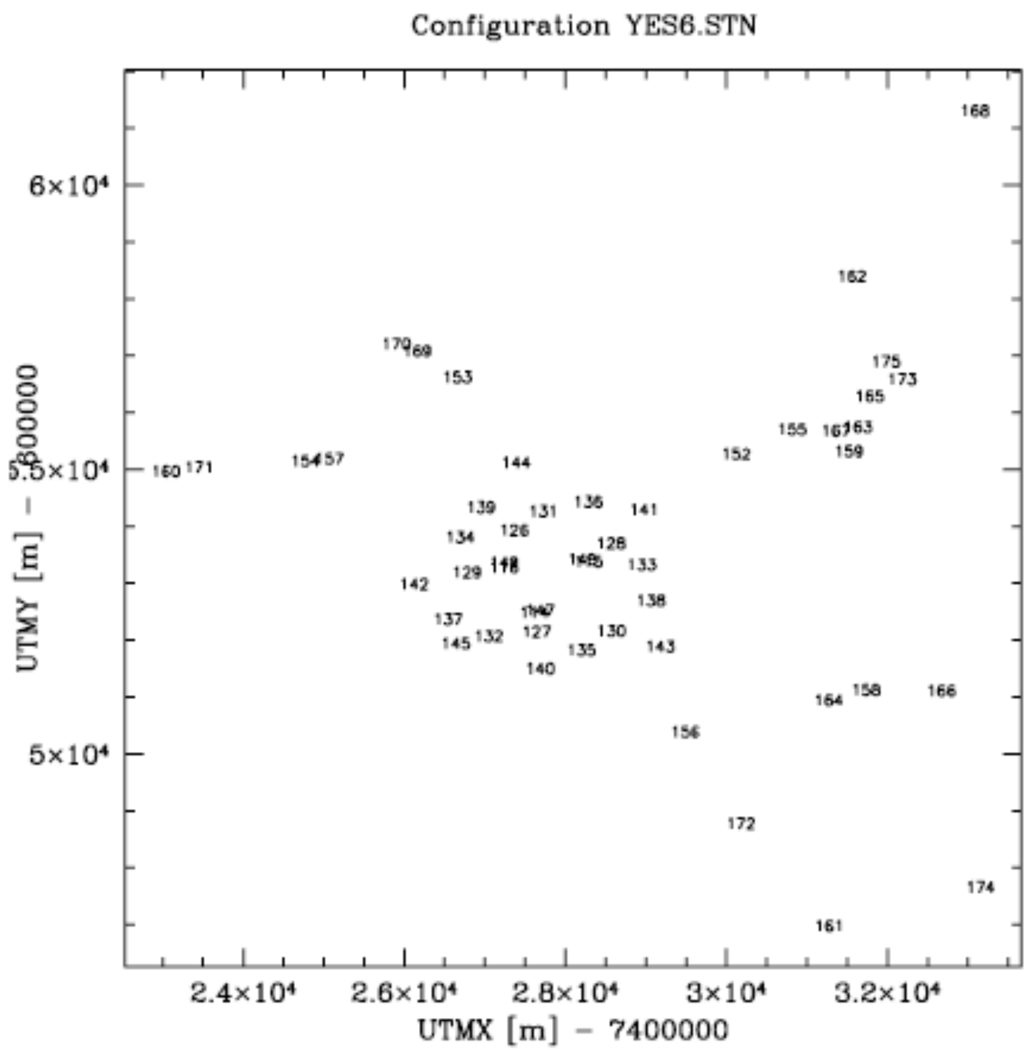

Figure 14 Locations of antenna stations for configuration Y6.

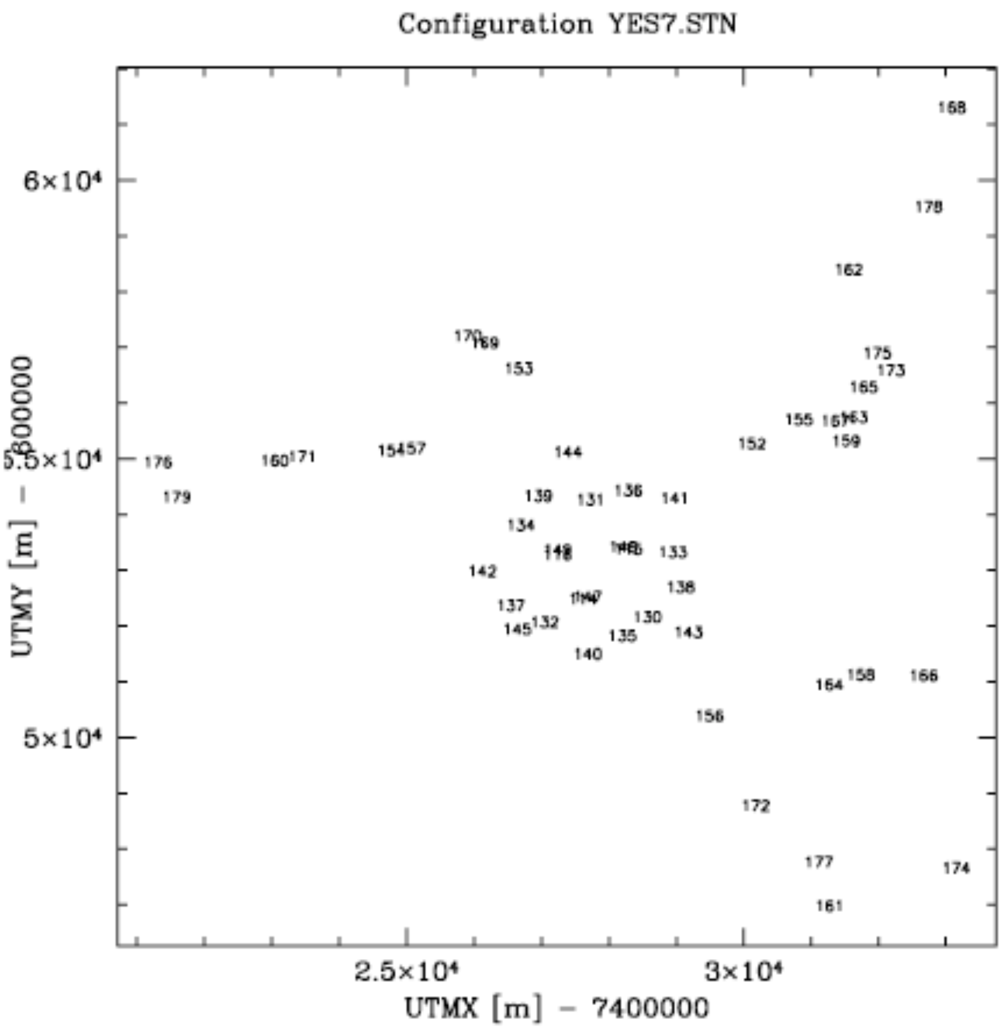

Figure 15 Locations of antenna stations for configuration Y7.

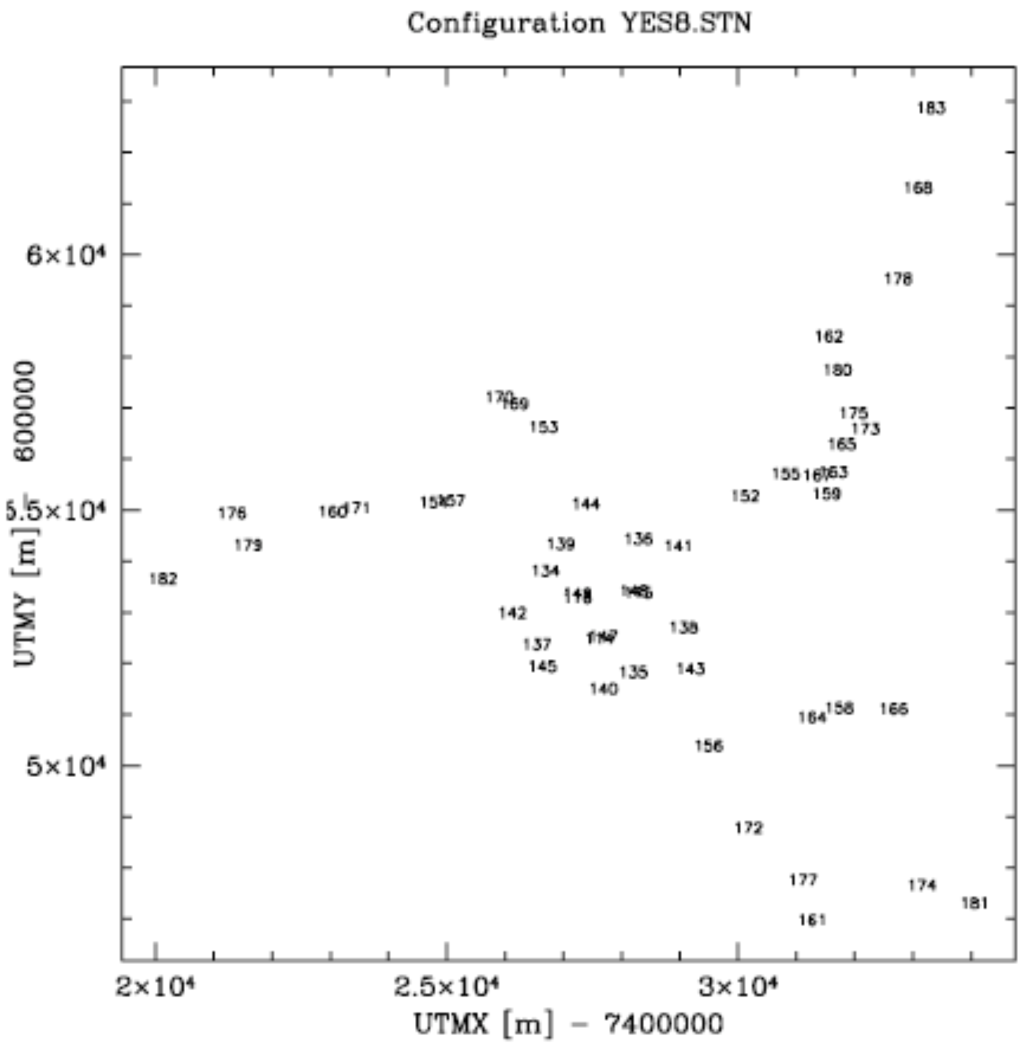

Figure 16 Antenna station locations for Configuration Y8.

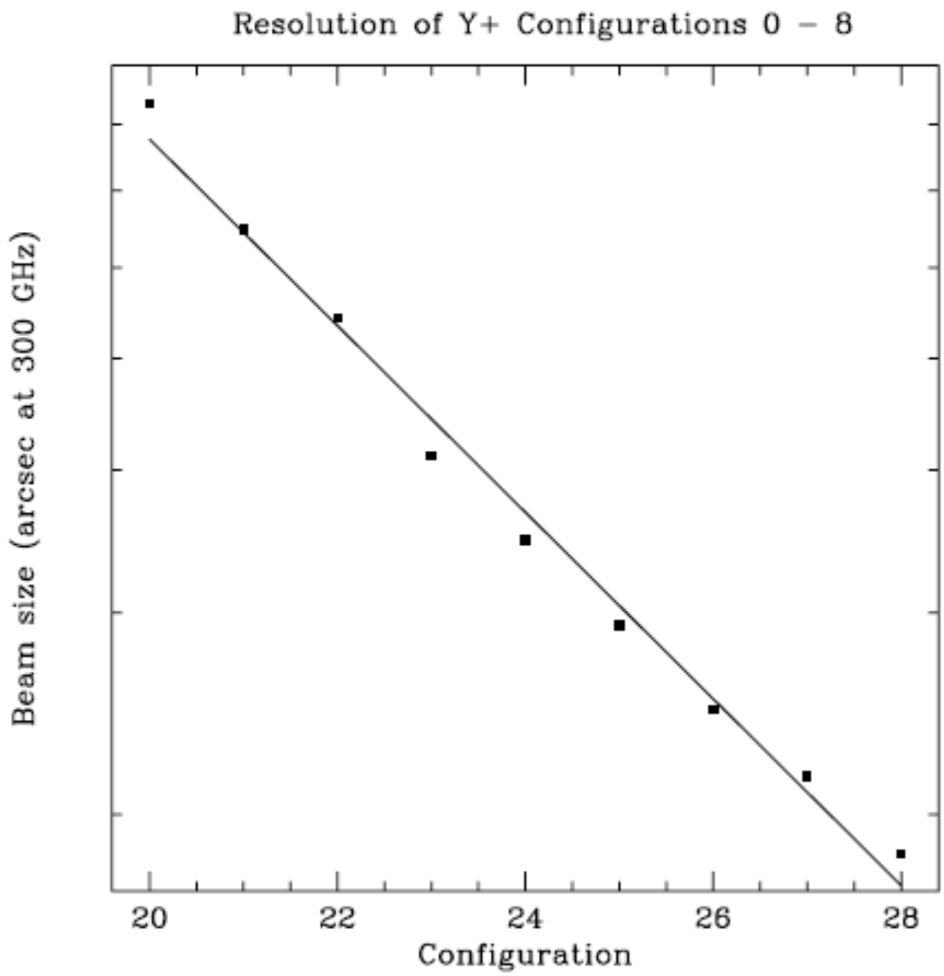

Figure 17 Naturally weighted beam sizes at 300 GHz for configurations Y1-Y8.

Table 2 The population scheme for the eight Y+ configurations, part 1.

Station	UTMx	UTMy	El	Is in this Config?							
	m	[m]	[m]	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8
103	627454.00	7453191.00	5023.4	1	0	0	0	0	0	0	0
104	627980.00	7452724.00	5029.8	1	0	0	0	0	0	0	0
105	627856.00	7453486.00	5026.6	1	0	0	0	0	0	0	0
106	627499.00	7452791.00	5023.5	1	0	0	0	0	0	0	0
107	628250.00	7453047.00	5015.9	1	1	0	0	0	0	0	0
108	627422.00	7453453.00	5029.0	1	1	0	0	0	0	0	0
109	627837.00	7452578.00	5032.9	1	1	0	0	0	0	0	0
110	628059.00	7453493.00	5022.3	1	1	0	0	0	0	0	0
111	627320.00	7452981.00	5025.1	1	1	1	0	0	0	0	0
112	628242.00	7452816.00	5015.9	1	1	1	0	0	0	0	0
113	627593.00	7453611.00	5031.0	1	1	1	0	0	0	0	0
114	627615.00	7452488.00	5028.0	1	1	1	1	1	1	1	1
115	628287.00	7453384.00	5016.4	1	1	1	1	1	1	1	1
116	627237.00	7453285.00	5026.9	1	1	1	1	1	1	1	1
117	628261.00	7452578.00	5019.8	1	1	1	0	0	0	0	0
118	627878.00	7453858.00	5029.4	1	1	1	1	0	0	0	0
119	627369.00	7452511.00	5019.2	1	1	1	1	0	0	0	0
120	628488.00	7453134.00	5007.2	1	1	1	1	0	0	0	0
121	627265.00	7453482.00	5026.1	1	1	1	1	0	0	0	0
122	628003.00	7452241.00	5018.9	1	1	1	1	1	0	0	0
123	628166.00	7453836.00	5022.7	1	1	1	1	1	0	0	0
124	627021.00	7452792.00	5011.4	1	1	1	1	1	0	0	0
125	628593.00	7452742.00	5012.6	1	1	1	1	1	0	0	0
126	627364.00	7453932.00	5025.9	1	1	1	1	1	1	0	0
127	627640.00	7452147.00	5028.4	1	1	1	1	1	1	0	0
128	628567.00	7453703.00	5010.7	1	1	1	1	1	1	0	0

Table 3 The population scheme for the eight Y+ configurations, part 2.

Station	UTMx m	UTMy [m]	El [m]	Is in this Config? Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8
129	626779.00	7453196.00	5013.0	1	1	1	1	1	1	0	0
130	628571.00	7452164.00	5030.1	1	1	1	1	1	1	1	0
131	627725.00	7454268.00	5029.5	1	1	1	1	1	1	1	0
132	627047.00	7452073.00	5015.2	1	1	1	1	1	1	1	0
133	628948.00	7453327.00	4984.2	1	1	1	1	1	1	1	0
134	626693.00	7453811.00	5011.8	1	1	1	1	1	1	1	1
135	628199.00	7451828.00	5035.1	1	1	1	1	1	1	1	1
136	628283.00	7454433.00	5020.5	1	1	1	1	1	1	1	1
137	626543.00	7452370.00	4992.9	1	1	1	1	1	1	1	1
138	629061.00	7452702.00	4998.0	1	1	1	1	1	1	1	1
139	626952.00	7454338.00	5024.2	1	1	1	1	1	1	1	1
140	627686.00	7451501.00	5016.7	1	1	1	1	1	1	1	1
141	628978.00	7454297.00	4990.6	1	1	1	1	1	1	1	1
142	626124.00	7452986.00	4992.9	1	1	1	1	1	1	1	1
143	629178.00	7451892.00	5058.6	1	1	1	1	1	1	1	1
144	627389.00	7455123.00	5032.6	1	1	1	1	1	1	1	1
145	626640.00	7451943.00	4987.6	1	1	1	1	1	1	1	1
147	627685.00	7452525.00	5029.7	1	1	1	1	1	1	1	1
148	628211.00	7453421.00	5019.3	1	1	1	1	1	1	1	1
149	627240.00	7453368.00	5027.1	1	1	1	1	1	1	1	1
152	630121.0	7455276.0	4922.6	1	1	1	1	1	1	1	1
153	626659.1	7456623.9	5031.7	1	1	1	1	1	1	1	1
154	624771.0	7455153.0	4948.1	1	1	1	1	1	1	1	1
155	630815.8	7455710.4	4902.8	1	1	1	1	1	1	1	1
156	629490.2	7450388.2	5009.5	0	1	1	1	1	1	1	1
157	625068.7	7455189.3	4958.9	0	1	1	1	1	1	1	1

Table 4 The population scheme for the eight Y+ configurations, part 3.

Station	UTMx m	UTMy [m]	El [m]	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8
				Is in this Config?							
158	631734.4	7451128.6	4958.6	0	1	1	1	1	1	1	1
159	631521.0	7455321.0	4868.8	0	1	1	1	1	1	1	1
160	623040.0	7454968.0	4845.8	0	0	1	1	1	1	1	1
161	631275.9	7446977.7	4766.8	0	0	1	1	1	1	1	1
162	631556.8	7458399.5	4869.6	0	0	1	1	1	1	1	1
163	631631.2	7455746.8	4877.6	0	0	1	1	1	1	1	1
164	631269.6	7450944.9	4917.4	0	0	0	1	1	1	1	1
165	631778.0	7456289.0	4870.5	0	0	0	1	1	1	1	1
166	632668.2	7451111.2	4970.7	0	0	0	1	1	1	1	1
167	631358.0	7455681.0	4895.3	0	0	0	1	1	1	1	1
168	633085.5	7461307.3	4828.6	0	0	0	0	1	1	1	1
169	626159.9	7457081.8	5010.4	0	0	0	0	1	1	1	1
170	625901.9	7457210.2	5003.5	0	0	0	0	1	1	1	1
171	623451.0	7455040.0	4871.0	0	0	0	0	1	1	1	1
172	630178.0	7448780.1	4835.3	0	0	0	0	0	1	1	1
173	632179.4	7456591.2	4827.9	0	0	0	0	0	1	1	1
174	633155.0	7447659.0	4746.3	0	0	0	0	0	1	1	1
175	631980.1	7456899.0	4851.7	0	0	0	0	0	1	1	1
176	621305.4	7454940.9	4687.9	0	0	0	0	0	0	1	1
177	631114.9	7447761.9	4763.6	0	0	0	0	0	0	1	1
178	632742.0	7459525.3	4815.4	0	0	0	0	0	0	1	1
179	621584.0	7454319.0	4707.3	0	0	0	0	0	0	1	1
180	631703.0	7457742.3	4853.9	0	0	0	0	0	0	0	1
181	634062.0	7447310.0	4728.4	0	0	0	0	0	0	0	1
182	620125.0	7453657.0	4566.7	0	0	0	0	0	0	0	1
183	633309.9	7462869.2	4834.5	0	0	0	0	0	0	0	1

6. References

Boone, F. (2002) ALMA Memo No. 400.

Table 5 The naturally weighted and Briggs weighted beam parameters for specifically optimized configurations Y1a and Y2a, along with the beam parameters of the unoptimized Y9 configuration using the Y1 or Y1 and Y2 station positions for the inner 4 or 8 antennas.

Natural weighting					
	sidelobe levels			beam size [arcsec @ 300 GHz]	
Yconf	near in	inner	outer	bmaj	bmin
1a	0.0233	0.0244	0.0238	0.0694	0.0674
2a	0.0476	0.0355	0.0452	0.0605	0.0578
Y9-1a	0.0808	0.0806	0.0354	0.0174	0.0162
Y9-2a	0.0865	0.0795	0.0377	0.0175	0.0167
Briggs weighting					
	sidelobe levels			beam size [arcsec @ 300 GHz]	
Yconf	near in	inner	outer	bmaj	bmin
1a	0.0201	0.0200	0.0242	0.0453	0.0445
2a	0.0322	0.0233	0.0196	0.0377	0.0373
Y9-1a	0.0773	0.0333	0.0277	0.0114	0.0111
Y9-2a	0.0748	0.0341	0.0257	0.0114	0.0111