Evaluating Various Options for a VLA E Array

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June 10, 1996

Abstract

We investigate three options for high brightness sensitivity observations with the VLA: observing with a tapered D array, observing with a new array with ~9 new stations clustered around the inner D array stations (E1 array), or observing with a close pack array with essentially all new stations (E2 array). Single pointing observations with such arrays will generally be uninteresting because of the small range of measured baselines, so these arrays will mainly be used for mosaicing. Since the arrays still have the 25 m hole in the (u, v) plane, total power measurements are required, which we assume can be measured by the VLA elements as in the MMA's homogeneous array design.

With a maximum spacing of ~500 m, the E1 array would be twice as fast as the tapered D array and would cost about $1.2 Million for new track and stations. With a maximum spacing of ~200 m, the E2 array would be four times as fast as the tapered D array and would cost about $4.3 Million. Contrary to the popular misconception, shadowing is not a serious problem with either E1 or E2 arrays above $\delta = -30°$. A stretched E2 array for observing southern sources could be built for about $1.9 Million. The imaging quality of the E1 array is about 2-3 times better than the imaging quality of the tapered D array, and the imaging quality of the E2 array is 5-10 times better than the imaging quality of the D array.

The E2 array would appreciably enhance the VLA's ability to observe and accurately image low surface brightness and extended sources.

1 Introduction

When the VLA was designed, astronomers were not overly concerned with very high brightness sensitivity, imaging very large fields, or imaging with resolution less than the D array's full resolution; these were all jobs for large single dishes, and the VLA certainly had enough new science to do without such capabilities. However, there is a gap between the capabilities of the large single dishes and the VLA which can best be filled by a very compact interferometric array with total power capabilities. There are scientific problems which require high surface brightness sensitivity and which can best be addressed by an interferometer due to the lower level of systematic errors. There are also objects which would be interesting to be mosaiced at an intermediate resolution.

According to legend, the concept of a VLA E array was first discussed by Arnold Rots in 1979 to address such issues. Rick Perley presented the concept of the E array to the Bahcall

Committee, Radio Panel in 1989. Issues such as surface brightness sensitivity and the minimum spacing problem were well understood, but no quantitative study of the imaging characteristics of the VLA E array had been undertaken. In this memo, I demonstrate that the VLA E array can be used to produce very high quality mosaic images.

2 The Arrays

The D array is familiar to all. The E1 array is adapted from one of three modest modifications to the D array proposed by Jim Ruff in his E-Array Cost Estimates memo of 6/6/94 (see Figure 1). It requires only one major railroad spur and moves the outer three antennas of each arm into the inner array. The E2 array is the commonly held concept of the E array, a close packed configuration of antennas scattered off of five or six parallel railroad spurs (see Figure 2). The E2 array was designed to have essentially Nyquist sampled Fourier coverage, but to have no strong grating response. Hence, the location of the station spurs along the main spurs and the length of the station spurs must be randomized. This E2 array has sidelobes of a few percent. Apart from attempts to reduce the grating response, neither array has been particularly well optimized. Hence, the E1 and E2 arrays presented here should be viewed as a cartoon, demonstrating what surface brightness sensitivity, imaging quality, and shadowing losses will be possible.

In the E1 array, nine new stations and 220 yards of new track are required, bringing the cost of the improvements to about \$1.2 Million. I assume the E2 array requires 27 new stations and about 1400 yards of new track, bringing the cost of the array to about \$4.3 Million. Cost estimates are based on Jim Ruff's internal E-array cost estimate memo (\$101 K per station, \$512 per yard of track, and 20-30% extra for all other materials and work). The E2 array might be able to share four or five stations with the D array, reducing the cost to about \$3.6 Million.

3 Surface Brightness Sensitivity

A common rule of thumb is that the surface brightness sensitivity of an array is proportional to the filling factor of the antenna dishes over the area which the array covers. While this is approximately true for an entire array, arrays with centrally condensed (u, v) coverage, such as the VLA, can achieve higher surface brightness sensitivity by tapering the (u, v) coverage. In principle, the VLA can achieve a factor of 10 increase in surface brightness sensitivity by using only baselines of 100 m or less (see Figure 3.

The resolution of the E2 array at 1.4 GHz is close to $180''$ and the resolution of the E1 array is close to $90''$, so the data sets produced with the E1 and D arrays have been imaged with both $90''$ and $180''$ tapers to provide accurate comparisons. The surface brightness sensitivity for the D, E1, and E2 arrays have been calculated with these tapers and plotted as a function of resolution in Figure 3. The slope of a given array configuration is related to the radial profile of the (u, v) coverage, and since the VLA's (u, v) coverage is so centrally condensed relative to the outermost (u, v) points, its curve falls faster than the E1 and E2 arrays. The E2 array gives an advantage of about 2 in surface brightness sensitivity, or a factor of 4 in time, over the tapered D array. The E1 array gives an advantage of about 1.5 in surface brightness sensitivity, or about 2 in time, over the tapered D array.

The square root of the mean (u, v) density as a function of radial (u, v) distance is plotted for the D, E1, and E2 arrays in Figure 4. This shows the relative sensitivities of the arrays in the (u, v) plane.

4 Image Quality

Since the E2 array has nearly complete instantaneous (u, v) coverage, it is expected that the quality of images produced by the E2 array will greatly exceed that of the tapered E1 and D arrays. To quantify this conjecture, I have simulated 25 pointing homogeneous array mosaics with the D, E1, and E2 arrays. The ratio of the maximum to the minimum measured baseline becomes rather small, so we will assume throughout that *homogeneous array*[1] style mosaicing is in effect, permitting observations of objects much larger than the primary beam. This assumption is probably not inconsistent with the VLA upgrade, though it is inconsistent with the current VLA. Full tracks on each pointing will generally not be possible for mosaicing observations, so simulations have been performed with 1, 2, 4, and 8 snapshots well separated in hour angle but ≤ 4 hours off of transit. To match the surface brightness sensitivity, the D array must observe twice as long as the E1 array and four times as long as the E2 array. If four snapshots of tapered D array results in image quality comparable to a single snapshot of the E2 array, then the speed of the E2 array is its only advantage. Conversely, if single snapshot imaging with the E2 array is significantly better than four snapshot imaging with the tapered D array, then the E2 array offers advantages in both speed and image quality.

We measure the quality of the images with the dynamic range, which gauges off-source errors, and the fidelity index, which gauges on-source errors. The dynamic range for each array-taper combination is plotted as a function of number of snapshots in Figure 5. Figure 6 contains a similar plot for the fidelity index. The dynamic range and fidelity index do not depend strongly on the taper. For each array, both fidelity and dynamic range increase with the number of independent snapshots. The E1 array performs about 2-3 times better than the D array. However, the E2 array outperforms the D array imaging by a factor of 5-10, and the E2 array performs quite well with single pointing mosaicing. Also, the slope of the image quality indicators as a function of snapshots is much steeper for the E2 array than for the D or E1 arrays. The E2 configuration would turn the VLA into a true mosaicing instrument.

5 Shadowing

In order to estimate the sensitivity which is lost to shadowing, I have simulated one hour observations at declinations ranging from $-30°$ to $80°$ and centered on hour angles ranging from -4 to 4. To obtain the relative sensitivity of each one hour simulation, I take the square root of the fraction of the baselines which have not been lost to shadowing for each hour, so a value of 1.00 indicates that no sensitivity has been lost. These relative sensitivity plots are shown for the D, E1, and E2 arrays in Figures 7 through 9. The E1 and E2 arrays only fare significantly worse than the D array where the D array already experiences shadowing, mostly at $\delta \leq -20°$ and at $|HA| \geq 4$. Where shadowing is slight for the D array, it is slight for the E1 and E2 arrays as well.

[1] In the *homogeneous array* mosaicing scheme, total power is measured by the antennas in the interferometric array, rather than by a much larger single dish.

6 The GBT can't fix the VLA D Array

The GBT is nearing completion, and one may ask why NRAO should spend a lot of money upgrading the VLA to do many of the things which can be done by the GBT. In particular, what if we add GBT total power data to VLA D array data? We have performed such simulations, and we find that the resulting images are only slightly better than the VLA D array mosaic images with the VLA dishes measuring total power. The dynamic range and the image fidelity were better by a factor ranging from 1.1 to 1.5, so the VLA D array plus GBT is not even as good as the VLA E1 array. This indicates that the primary limitation in VLA D array homogeneous array mosaicing is the large gaps in the (u, v) coverage beyond $\sim$75 m, rather than gaps in the inner part of the plane. Again, the central 25 m hole is not an issue since we assume the VLA dishes measure total power. The VLA E2 array is an effective way to fill the gaps beyond 75 m.

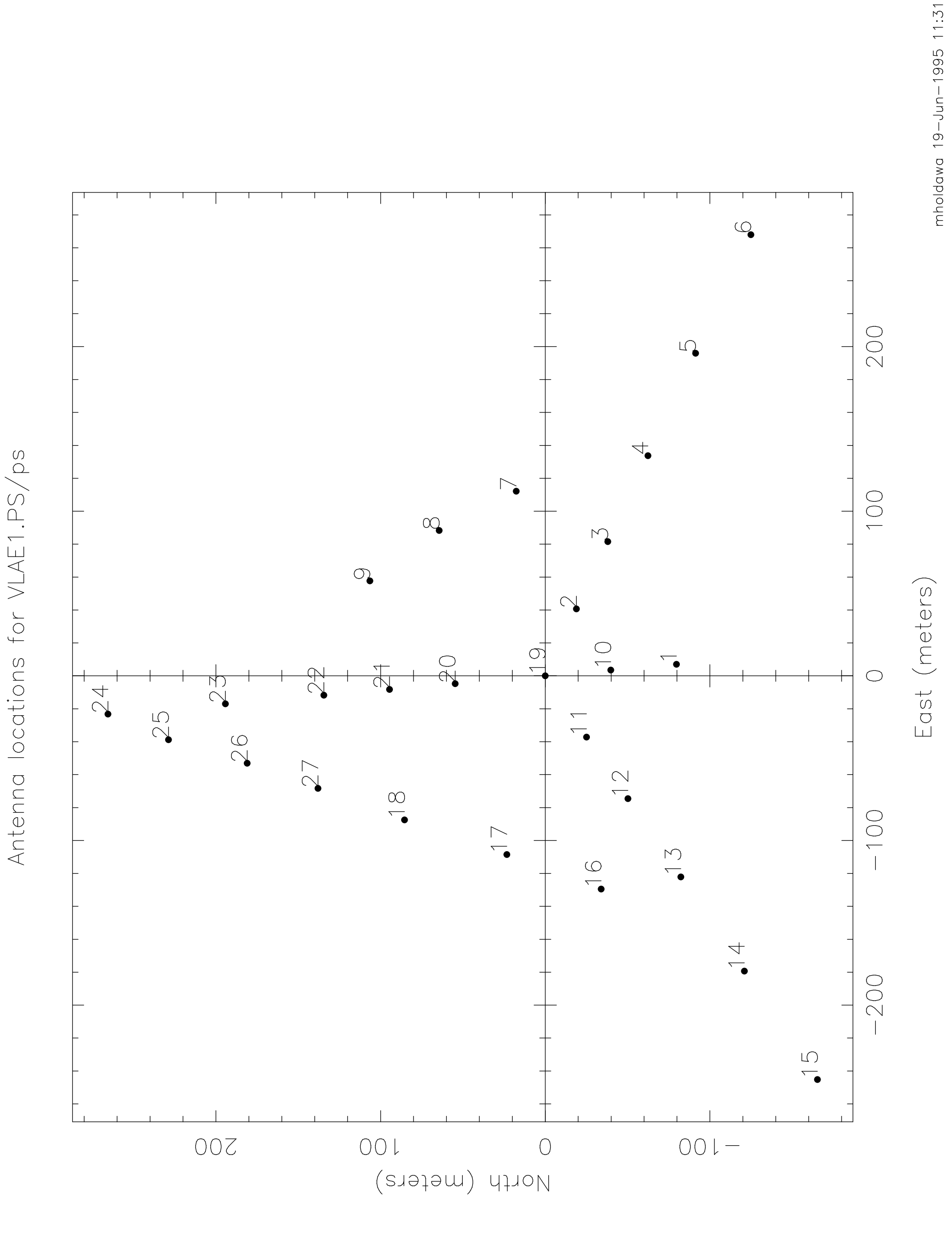

Figure 1: E1 Array.

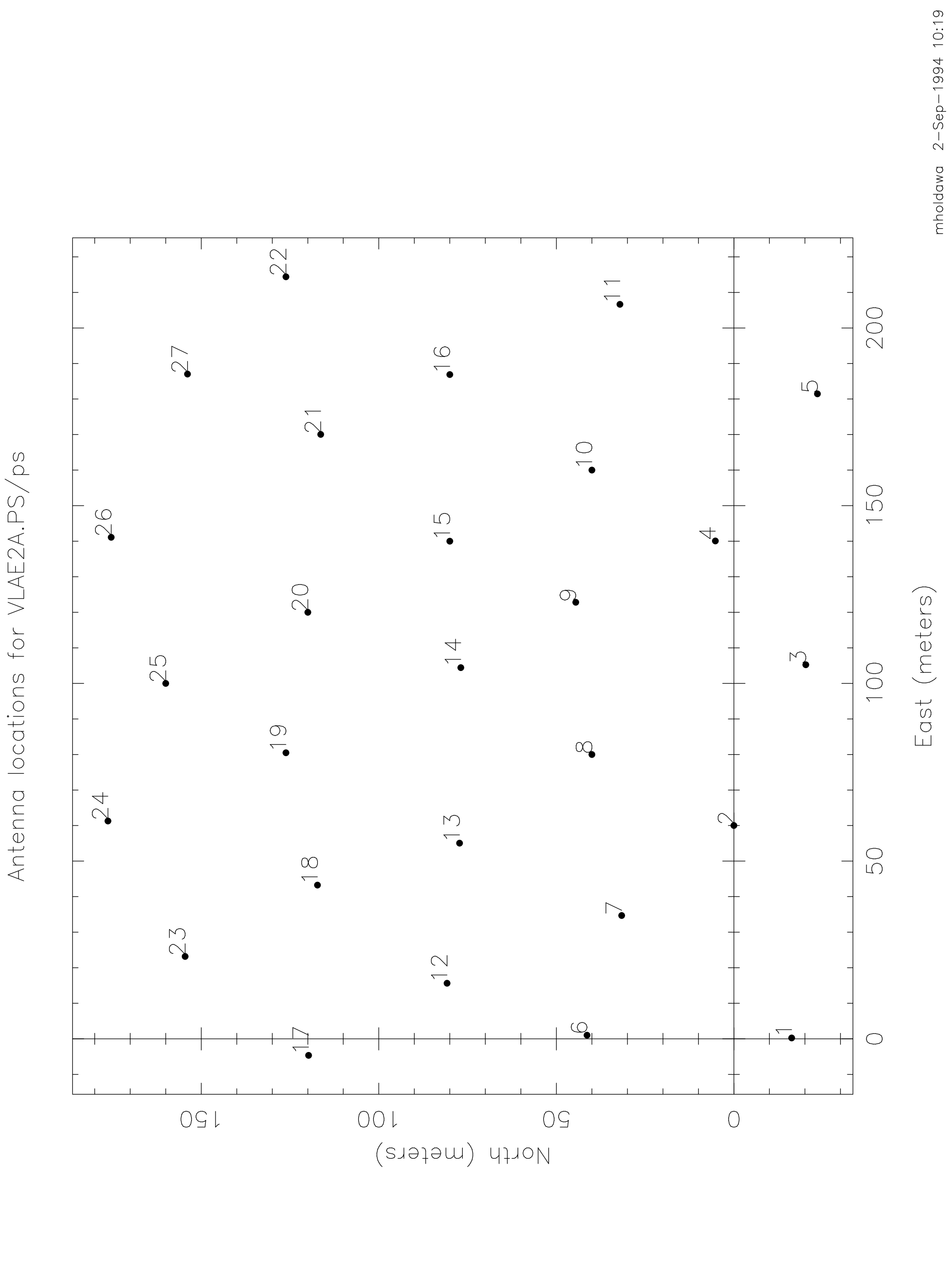

Figure 2: E2 Array.

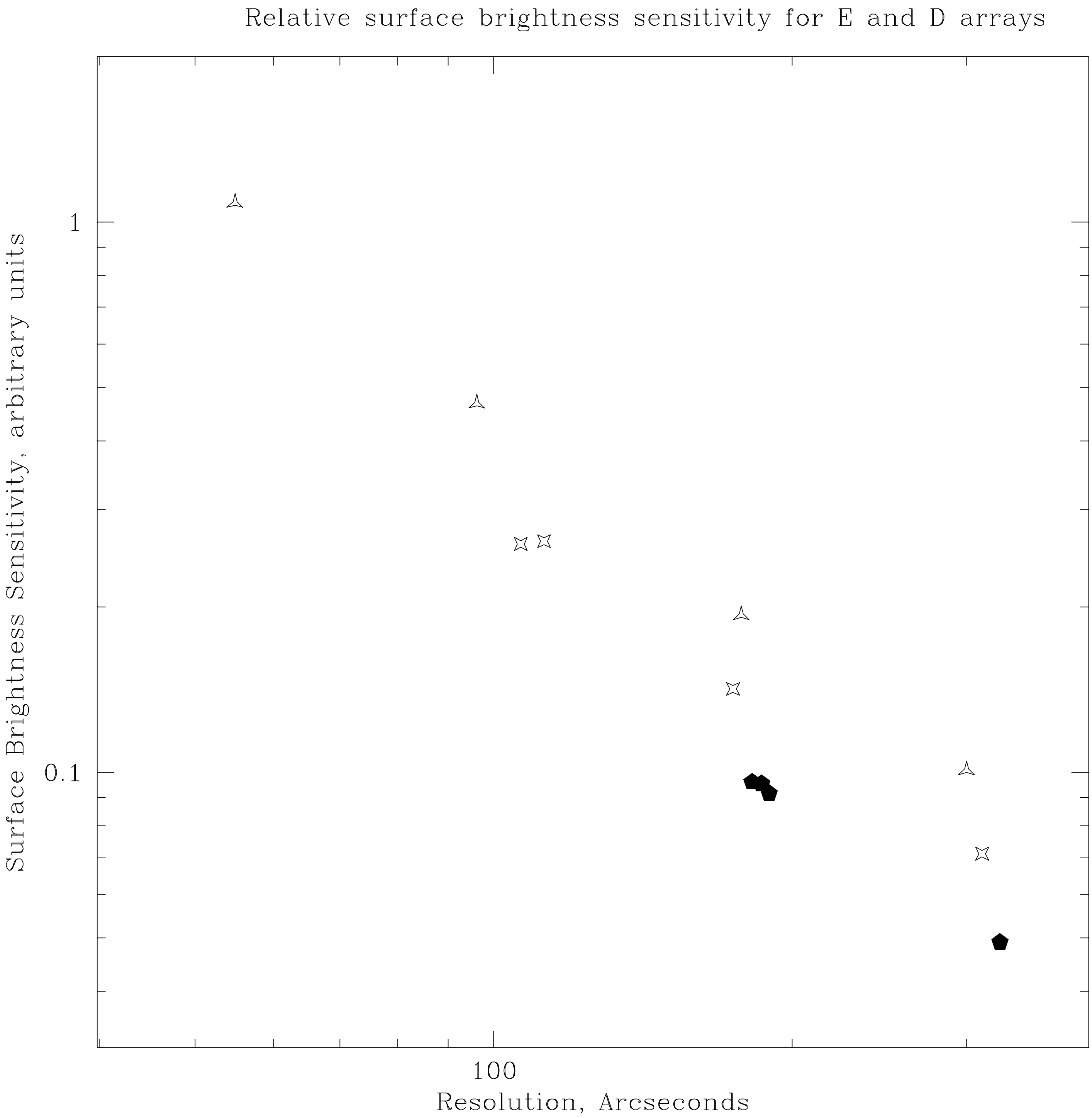

Figure 3: Surface brightness sensitivity as a function of resolution for the VLA D, E1, and E2 arrays.

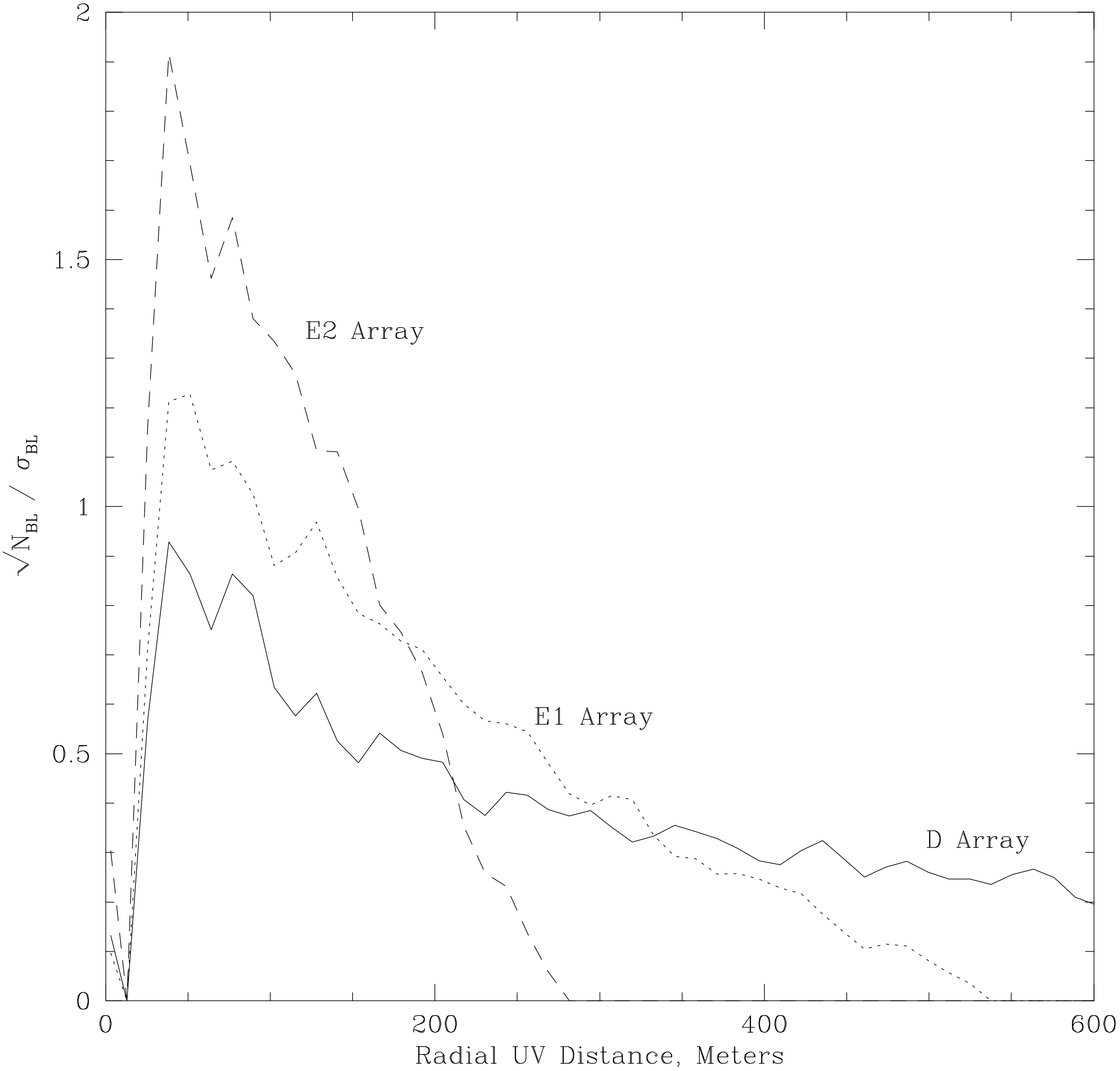

Figure 4: Density of (u, v) samples as a function of radius for the D, E1, and E2 arrays.

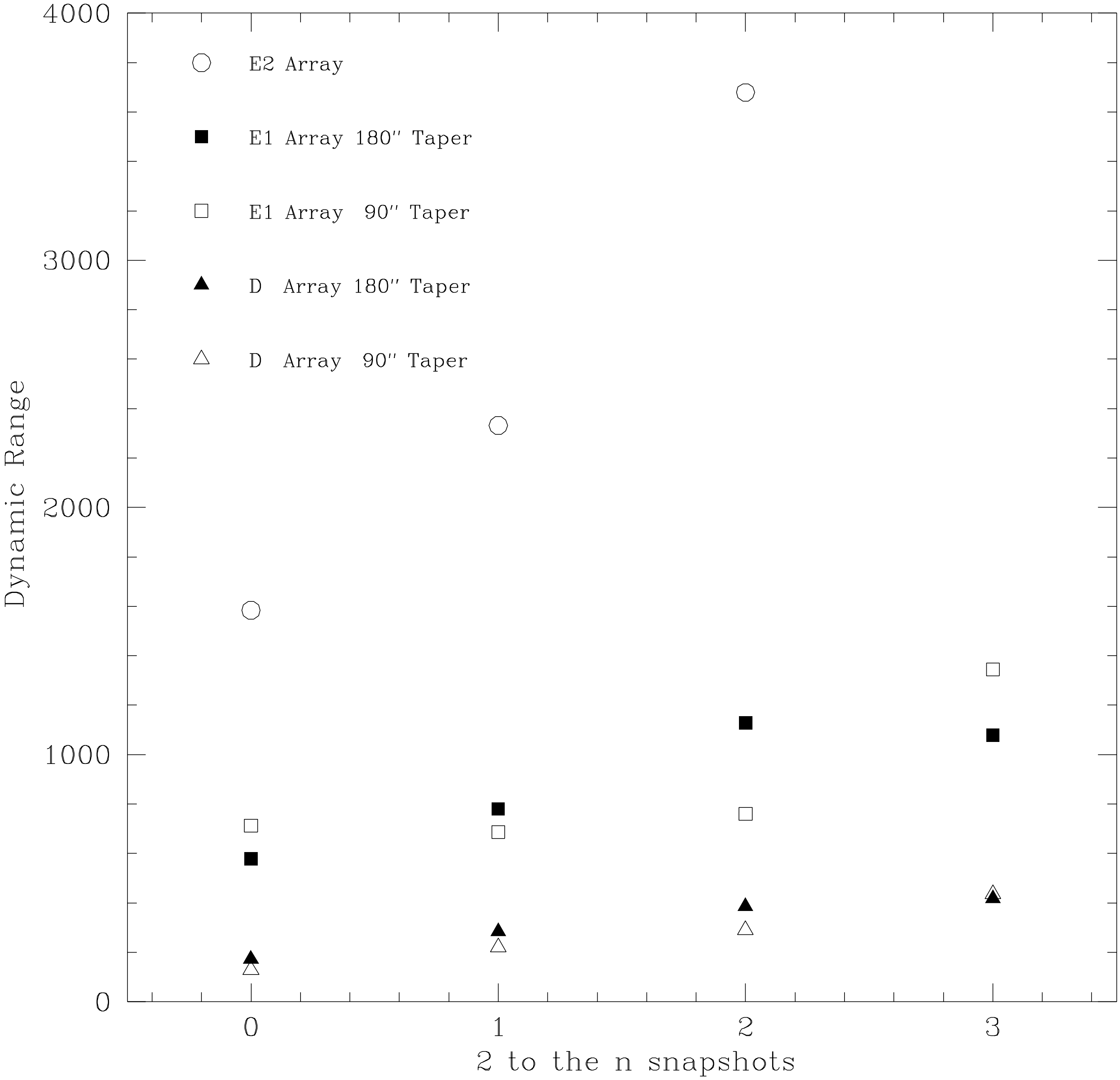

Figure 5: Dynamic range as a function of snapshots for a mosaic made with the D, E1, and E2 arrays.

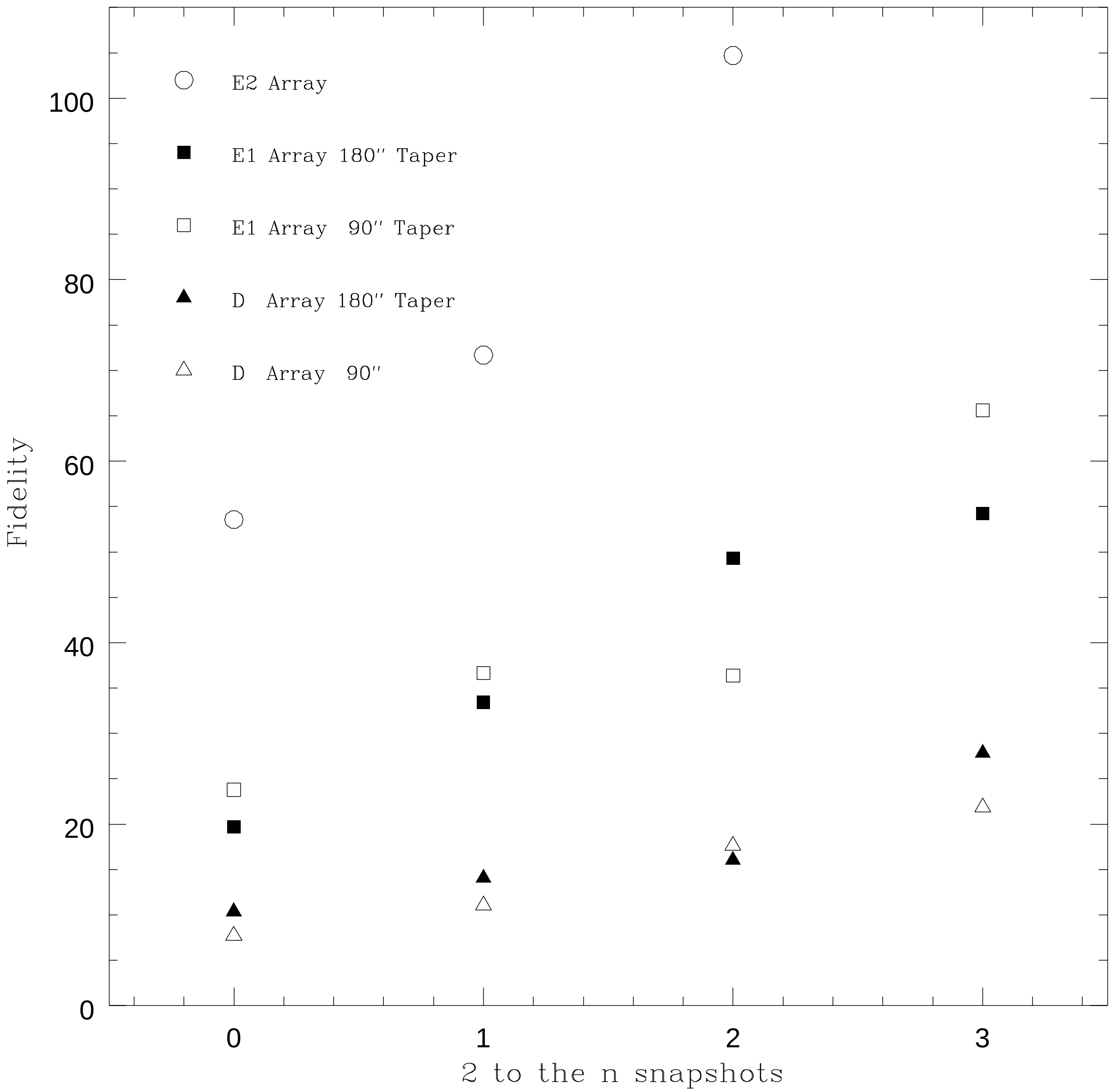

Figure 6: Fidelity as a function of snapshots for a mosaic made with the D, E1, and E2 arrays.

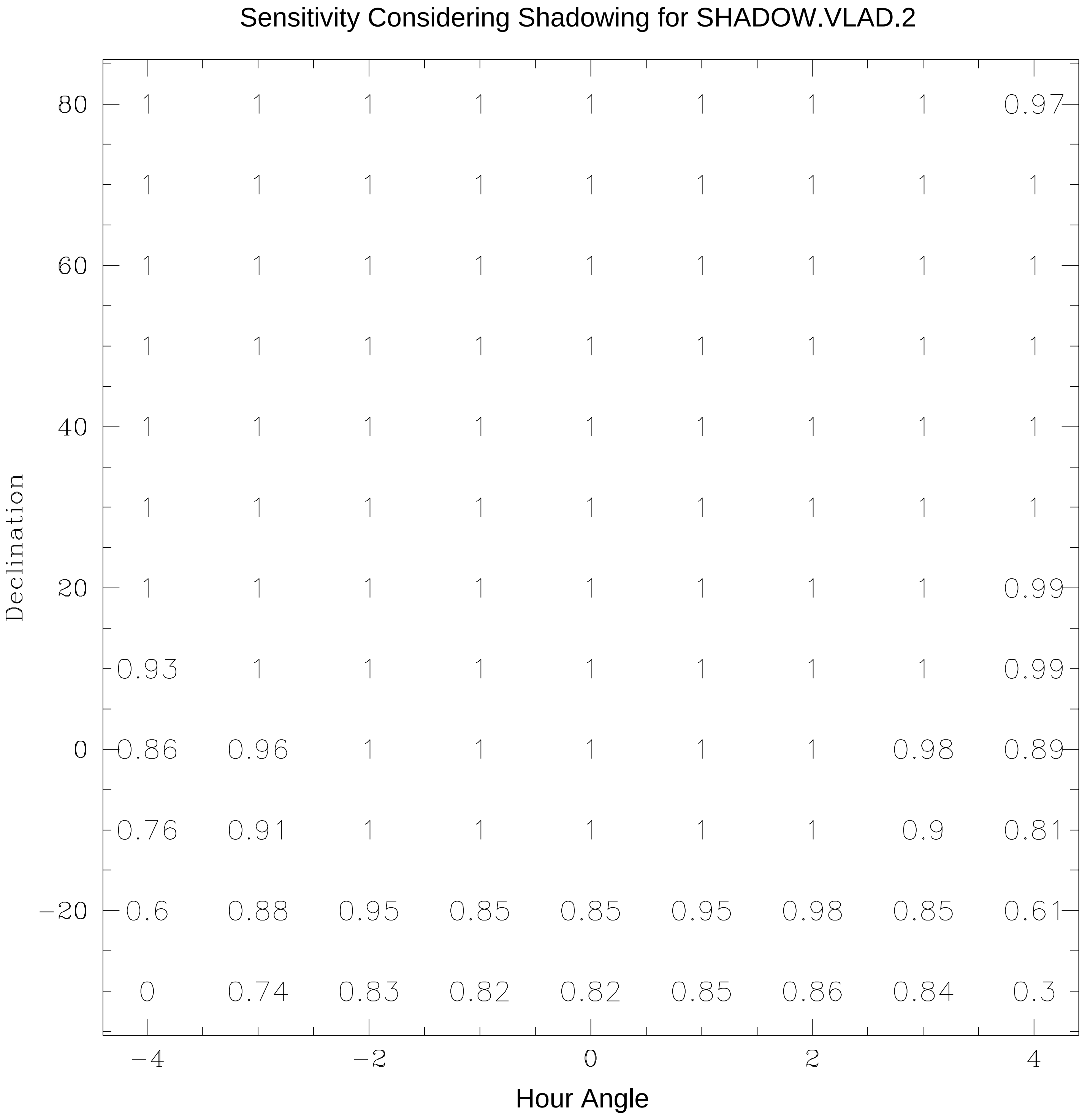

Figure 7: Shadowing in the VLA D array. The array's normalized sensitivity in one hour observations is posted as a function of hour angle and declination.

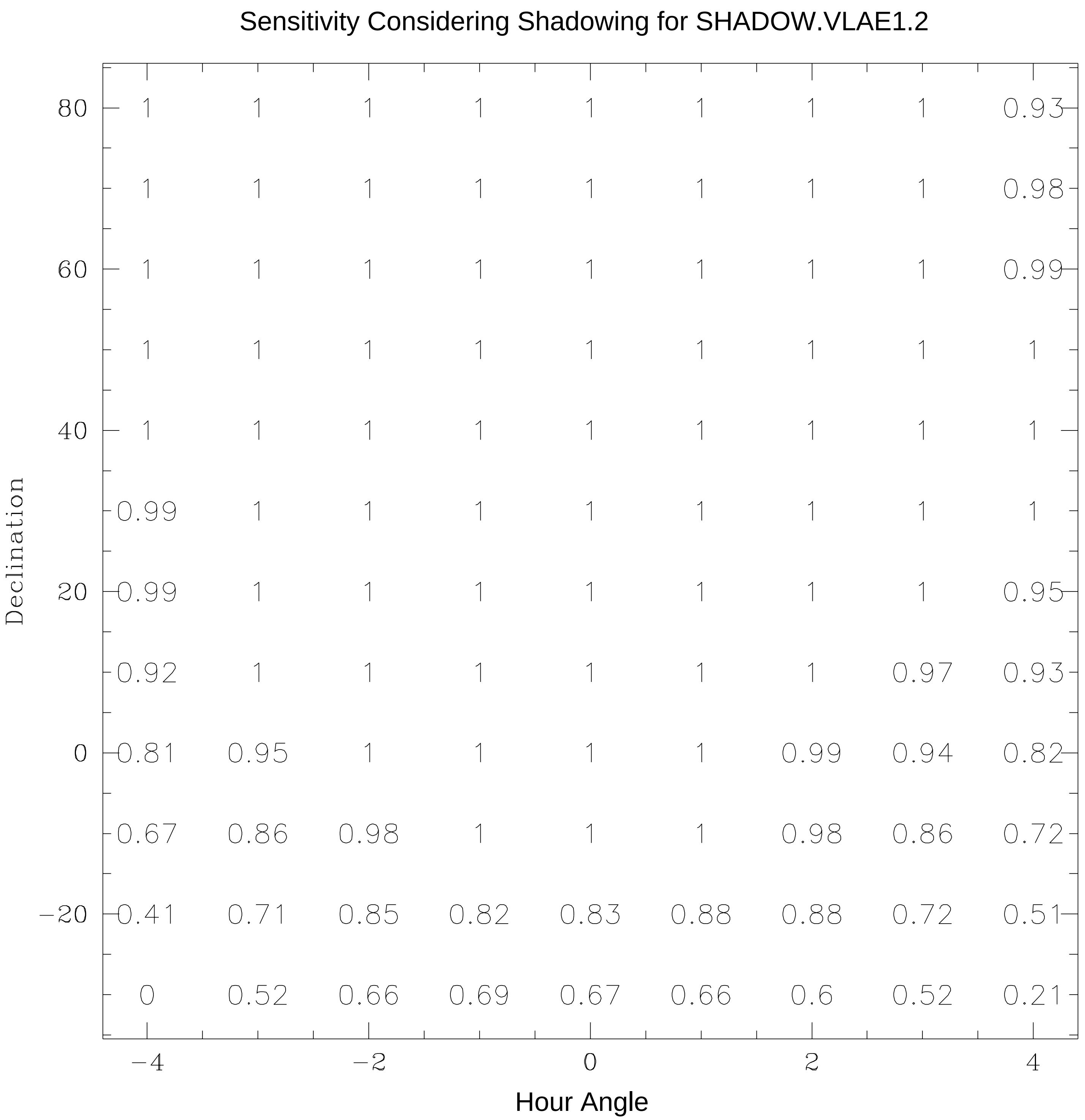

Figure 8: Shadowing in the VLA E1 array. The array's normalized sensitivity in one hour observations is posted as a function of hour angle and declination.

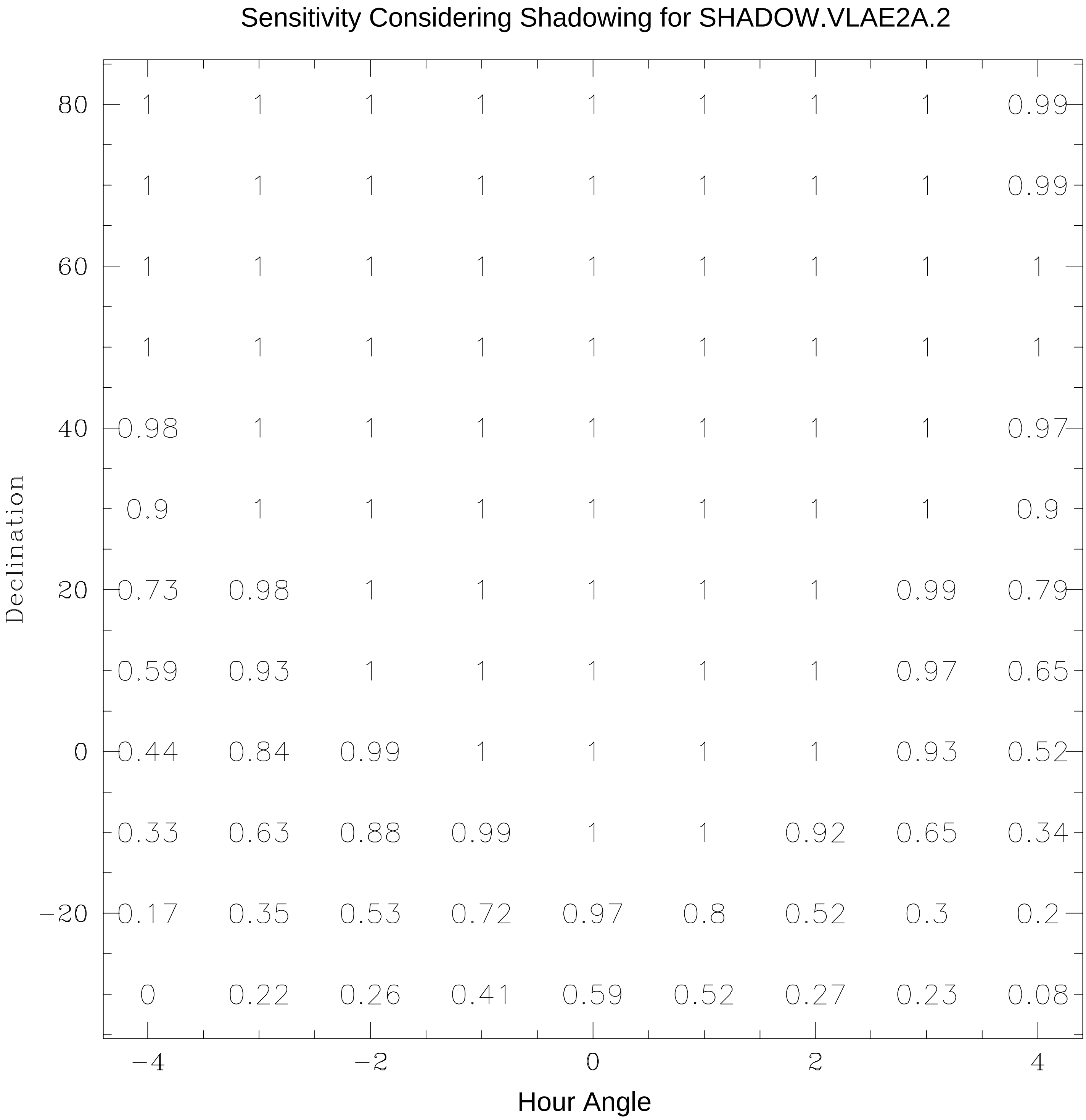

Figure 9: Shadowing in the VLA E2 array. The array's normalized sensitivity in one hour observations is posted as a function of hour angle and declination.