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A New Method for Optimizing the Configuration of the Chinese Square Kilometer Array

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Abstract KARST, the Chinese SKA concept, consists of some 30 individual FAST-type elements to be set up in a karst region of Guizhou Province. A crucial question is how to select 30 optimized sites from hundreds of candidates. Here we introduce a uniform weight method, which can pick out suitable sites on the basis of uniformity and completeness of the u-v coverage. In order to meet some special scientific goals, such as imaging extended sources, a modification of this method is also discussed. Although the method is specially designed for the KARST array, it could be useful for more general types of arrays.

Key words: techniques: interferometric — instrumentation: interferometers

1 INTRODUCTION

SKA (Square Kilometer Array) is a major next generation, multi-element radio telescope with an effective collecting area of one square kilometer. A key challenge in the design is to determine a suitable array configuration. For two dimensional arrays, there is no exact solution, and it is even difficult to specify an optimization criterion (Bunton 1999). Thus, a careful consideration takes on a particular importance. Currently, numerous groups in different countries are involved in simulation investigations involving the number of stations, the layout at various scales, and geographic and cost constraints. A set of various sample configurations has been presented and analyzed, for example, asymmetric array, several-armed spiral forms for SKA (Bunton 2000), a doughnut shape and maximally filled arrays for the Allen Telescope Array (ATA) (Borck 2000), and a new method to minimize side-lobes in a region by specific array element shift, which has some restrictions in general use (Kogan 1997).

KARST (Kilometer-square Area Radio Synthesis Telescope), the Chinese contribution to the international SKA cooperation (Peng & Nan 1997), consists of tens of FAST (Five-hundred-meter Aperture Spherical Telescope) type telescopes. It will be constructed and installed in a karst region. Several hundreds of karst depressions in the southern part of Guizhou Province have been detected and studied (Nan et al. 1995), and it is natural and necessary for KARST to select an optimized set of sites from the original set of candidate depressions. In the following section, a new uniform weight method is described to realize this selection. In order to fulfil some special array design requirements, a modification of this method will be introduced in the same section. The application of the two methods are illustrated in Sect. 3. During the array optimization, it is assumed that KARST will have 30 antennas, each roughly 200 m in diameter, except FAST which has a 300 m effective diameter, to be located at around 25° latitude (Tian et al. 1995).

2 APPROACH TO THE PROBLEM

2.1 Uniform Weight Method

The optimum array configuration depends on the science goals. Most of the array performance factors have been discussed by Perley et al. (1989). Here we introduce a new method aiming at a uniform and complete *u*-*v* coverage in the absence of any prior information about the goals of observation. It is well known that, in the *u*-*v* coverage of an instantaneous snapshot observation, those *u*-*v* points located in a dense area of the *u*-*v* plane, have a low uniformity weight. They represent redundant information in the later image processing. If we must drop some *u*-*v* points, then such low-weight *u*-*v* points should be the first ones to be discarded. To define the weights of *u*-*v* points as well as antennas, we usually start with a gridded *u*-*v* plane. The points in a gridded area have the same uniform weights, which are inversely proportional to the number of the points. In this case, many *u*-*v* points may be given the same weight. Thus, it is difficult to precisely compare their *u*-*v* coverage quality. To overcome this, we define here the uniform weight of a *u*-*v* point to be the distance between the point and its nearest neighboring *u*-*v* point, and the uniform weight of an antenna as the sum of the weights of its relevant *u*-*v* points.

To explain further, we take an example of an array with five antennas. A cartoon of a snapshot *u*-*v* coverage of this array is displayed in Fig. 1. First, for a *u*-*v* point, we find its nearest neighboring *u*-*v* point. For example, the *u*-*v* point nearest to the point (2, 5) is (2, 4). Therefore, the uniform weight $w(2,5)$ of the *u*-*v* point (2, 5) is the distance between (2, 5) and (2, 4), i.e.,

$$w(2,5) = \sqrt{(u_{(2,5)} - u_{(2,4)})^2 + (v_{(2,5)} - v_{(2,4)})^2}, \tag{1}$$

Secondly, we calculate the uniform weights of all the relevant *u*-*v* points of the antenna, and add them together. The sum is the weight of this antenna. For example, the weight of antenna 5 is the total distance of all the dash lines shown in the figure.

Let us suppose there are N candidate sites. To obtain an optimized array with M ($M < N$) sites, we take following steps:

1) Calculate the uniform weight $w(m,n)$ of each *u*-*v* point, where m and n denote any two candidate sites. Calculate the uniform weights $W(m)$ ($m = 1, 2, ..., N$) of all the candidates, where

$$W(m) = \sum_{n=1}^{N} w(m,n). \qquad (n \neq m) \tag{2}$$

2) For all the candidate sites, find the one with the least uniform weight W. Now remove this site, and $N-1$ candidates are left. Then return to the step 1), discard another site, and so on, until only M sites are left.

When applying the above algorithm of weighting each u-v point and each telescope, care should be taken of the overall density in the u-v plane. Then the snapshot u-v coverage of the selected M elements array will be close to a uniform and complete distribution.

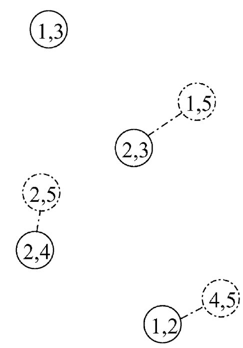

Fig. 1 u-v coverage of a snapshot observation of a 5-element array. Each u-v point is represented by a small circle, with two numbers representing the antennas of a baseline. Dashed lines connect the u-v points of the five antennas and their nearest u-v points.

2.2 Modified Uniform Weight Method

The optimum array configuration depends quite strongly on the source structure. Normally, uniformly distributed u-v coverage has a high angular resolution. This kind of u-v coverage is suitable for observations of compact objects. For extended sources, however, their structure information mainly resides in the visibilities in the central part of the u-v plane, while the visibilities in the outer region contribute little to the source structure. In order to obtain better images of extended sources, then, the snapshot u-v coverage of an array should be denser in the central region and sparser in the outer region.

Under this requirement the solution is to deliberately lower the weight of the u-v points in the outer region. Quantitatively, the above defined uniform weight of a u-v point, $w(m,n)$, is multiplied by a selection function, for example a Gaussian taper function. Thus, the modified weight of the u-v point is

$$w'(m,n) = w(m,n) \times \exp\left(-r^2/D^2\right), \tag{3}$$

where r is the distance of this u-v point from the origin of the u-v plane, and D is a free parameter which controls the concentration of the u-v coverage.

3 RESULTS

Octave is an open source numerical computing environment in Linux. It is Matlab compatible, and has good connection with C/C++. We have written several tasks in Octave which can do array optimization using the uniform weight method or the modified uniform weight method. So we wrote the key subroutines in C++, which greatly improved the speed of calculation.

Before applying the optimization, we took arbitrarily a source with $\alpha = 60°$ and $\delta = 60°$. The observing wavelength was set at 18 cm. Calculations were made for a total of 288 original candidate sites. These sites are archived karst depressions which are suitable to construct

FAST-type radio telescopes. The positions and qualities of these karst sites have been tested. Figure 2 shows the locations of the 288 sites and the corresponding snapshot u-v coverage. A total of 30 sites were selected using the uniform weight method (see the left panel of Fig. 3). The corresponding snapshot u-v coverage and beam pattern are shown in the right panel in Fig. 3 and the left panel of Fig. 5, respectively. We also chose another 30 sites by using the modified uniform weight method, where the parameter D is taken as 0.3×10^6 wavelengths. Their locations, snapshot u-v coverage, and beam pattern are shown in Fig. 4 and the right panel of Fig. 5, respectively. For comparison we randomly picked 30 sites. Their snapshot u-v coverage and beam pattern are displayed in Fig. 6.

From these figures, it is obvious that the u-v coverage of the 30 sites selected by the uniform weight method, being approximately uniform, gave almost the same result as do the 288 original sites. In contrast, the u-v coverage of the 30 randomly selected sites is not uniform and has a smaller u-v area. Its beam pattern is much worse (see the right panel of Fig. 6) from the point of view of resolution and side-lobes. The u-v coverage of modified uniform weight selected sites, as we expected, is denser than that of uniform weight selected sites, and its beam is a bit wider (see Fig. 5).

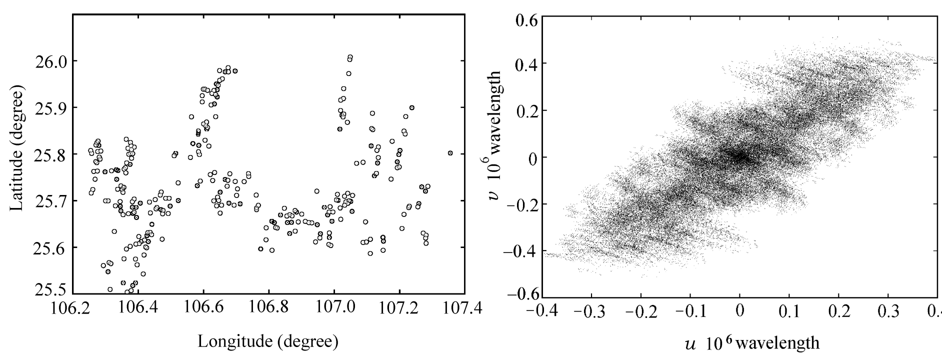

Fig. 2 Distribution of 288 candidate sites in Pingtang county (left) and the corresponding snapshot u-v coverage (right).

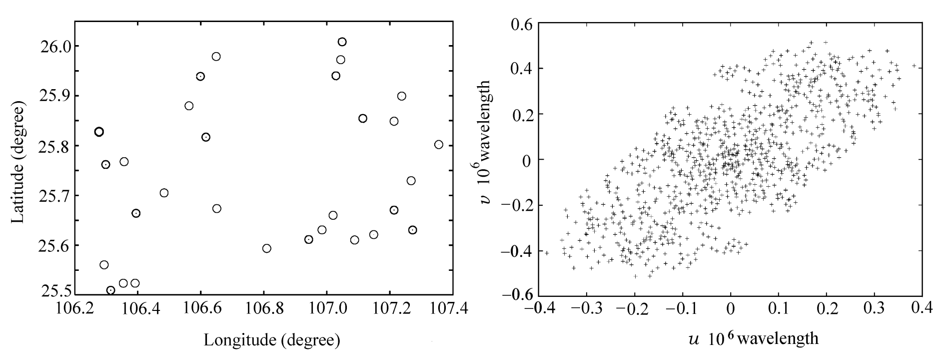

Fig. 3 Distribution of 30 sites picked by the uniform weight method (left) and its corresponding snapshot u-v coverage (right).

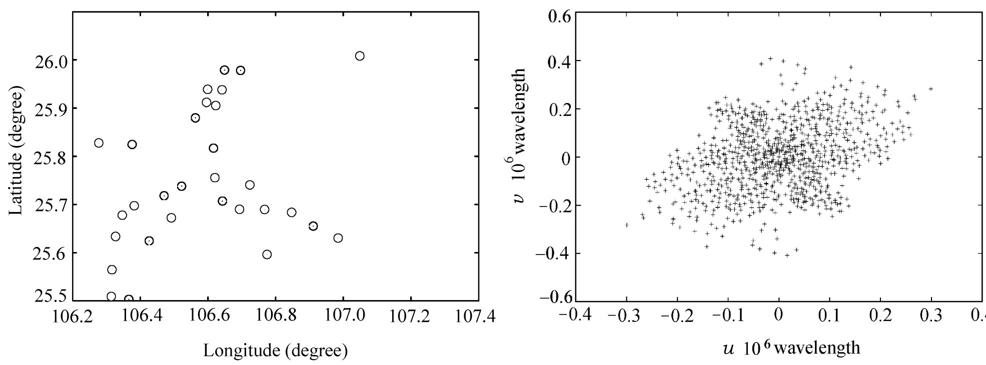

Fig. 4 Distribution of 30 sites picked by the modified uniform weight method (left) and its corresponding snapshot u-v coverage (right).

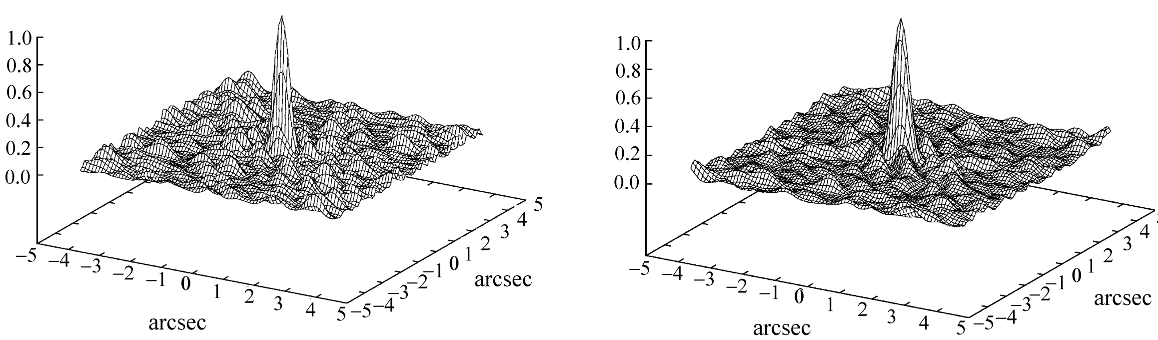

Fig. 5 Beam patterns of the 30 sites by the uniform weight method (left) and the 30 sites by the modified uniform weight method (right).

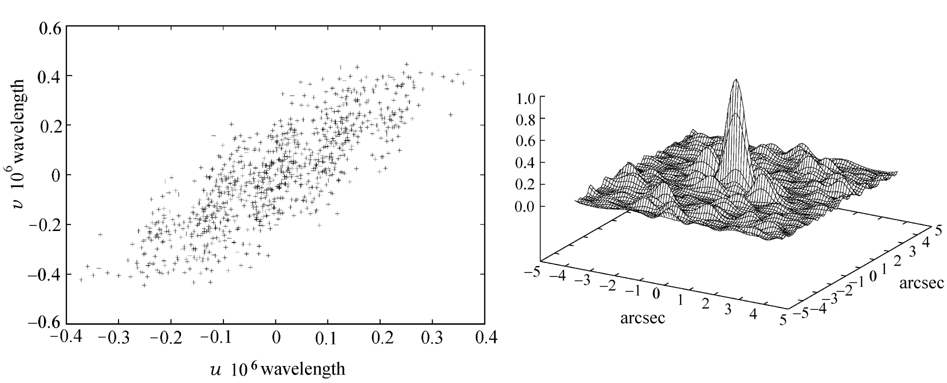

Fig. 6 Snapshot u-v coverage of 30 randomly selected sites (left) and their beam pattern (right).

For further comparison, we select another set of 30 sites for a source of declination $\delta = 40°$, using the uniform weight method. Compared to the former set of 30 sites selected with a source of $\delta = 60°$ by the different method, 14 of them are the same, 16 are different (see the left panel of Fig. 7). The 14 coincident sites tend to be located in the outer region. In observing the same source, the two sets of sites will generate quite similar *u*-*v* coverage (see the right panels of Fig. 3 and Fig. 7). Therefore, in order to finally decide which set is the best, we may add other selection criteria, such as the quality of the depression and the transportation cost, etc.

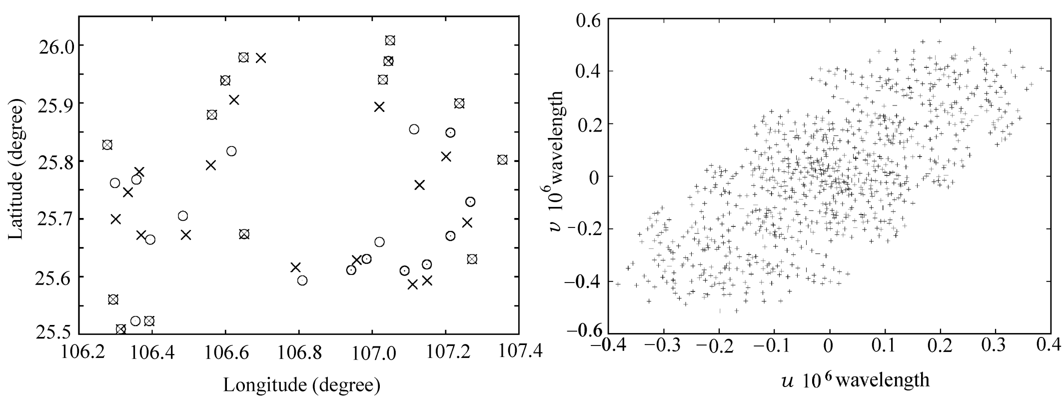

Fig. 7 Left: two sets of sites selected using different sources (circles: source declination $\delta = 60°$; crosses: $\delta = 40°$). Right: snapshot *u*-*v* coverage of the 30 sites, marked with crosses in the left panel.

4 REMARKS

Obviously, since the 288 original sites mainly lie in the east-west direction, their snapshot *u*-*v* coverage is not so good in the north-south direction. It should be noted that this is not the final configuration for KARST because these sites are confined to only a single county that has been investigated sufficiently. Site surveys and studies are being carried out in other counties which possess a large number of karst depressions. If they are included, the *u*-*v* coverage will be expected also good in the north-south direction.

Here we have developed a new criterion of weighting every *u*-*v* point and a given telescope. Although the study in this paper mainly aims at the KARST array, it could also be applied to other array configuration designs. It should also be noted that the algorithm of the uniform weighting could be applied without any limitation on the number of telescopes. For example, if we plan to construct a 200-element VLBI array somewhere, we may regularly or randomly set thousands of virtual candidate sites in the area, and select suitable sites by taking the algorithm listed above. For some sites where radio telescopes have already been constructed or will definitely be constructed, we can add these and deliberately increase their uniform weights. Thus these sites would not be dropped during the optimization. For increasing the precision of optimization, more and denser virtual sites can be loaded, which will take up more computing time.

This method can be applied with much flexibility. It is very likely the SKA will have a compact component of 1–3 km diameter containing almost half of the collecting area (Bunton

2000). For such a case, the compact component could be the first in the consideration and application of the uniform weighting algorithm. Then, take the compact component as a single element, add more candidate sites around it and obtain the final array configuration by applying uniform weighting algorithm again. It is important to note that if a very small space between u-v points are required in the package program, it can be achieved by changing the boundary conditions.

Because of the uniformity and completeness of the u-v coverage, the modified uniform weight method with an appropriate taper function with its flexible u-v coverage can be used to observe different objects.

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