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Guidelines for the LOFAR Array Configuration

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Abstract

Since LOFAR has to deal with (very) crowded fields, the LOFAR station configuration is required to provide full uv-coverage, preferably in a few hours of observation. In addition, it has to have good brightness sensitivity and a reasonable snap-shot quality. It must be scale-free, to optimise imaging quality at all scales. Its maximum baseline must be long enough to avoid source confusion, and it must be robust w.r.t. loss of uv-coverage through station failure and RFI. This paper defines and quantifies the various requirements. The 'uvbin plot' is introduced as a convenient (and novel) way to appraise a particular configuration at a glance. The tentative conclusion is that a three-armed log-spiral meets the requirements, and that about 100 stations are needed.

Contents

1 Introduction

The LOw Frequency ARray (LOFAR) is a 'next generation' radio telescope proposed by an international consortium consisting of ASTRON, MIT and NRL. It will do astronomical observations in two frequency bands: $10 - 100$ MHz (low) and $110 - 200$ MHz (high). The two bands require different antennas, which can probably be integrated with each other. The telescope consists of an array of about 100 stations, with a maximum separation of 400 km. Each station consists of a phased array of about 100 antennas, which can form multiple beams on the sky. The stations are connected by means of underground fibers to a central processor which forms images of the sky. For more details, see [1].

The purpose of this document is to determine guidelines for the LOFAR station configuration: the number of stations and their distribution.

Ultimately, the most important considerations for the LOFAR station configuration derive from the fact that the observed fields are very crowded with sources. The reason is that, at low frequencies, the station primary beam is relatively large, and radio sources are relatively bright. At the highest LOFAR sensitivity and lowest LOFAR frequencies, a field may contain up to $10^6 - 10^7$ sources brighter than the thermal noise.

2 Background: uv-coverage

The purpose of an interferometer array is to sample the Fourier transform of the observed brightness distribution (visibility function) in the *uv-plane*. The u, v coordinates are the projected baseline length (as seen from the source) measured in wavelengths. The uv-plane sampling function is called the *uv-coverage*. Its Fourier Transform is the point-spread function (PSF) with which the final image is convolved. The optimum sampling density is determined by the size of the uv-plane sampling element, *or uvel*[1]. . In the case of LOFAR this is defined by the station diameter of about 100 m. Obviously, the size of an *uvel* will depend on frequency and elevation if the effective station size does.

$$\Delta u_{uvel} = \Delta v_{uvel} = \frac{2D\sin(EL)}{\lambda} = \frac{2D\sin(EL)}{c} f_{obs} \tag{1}$$

Fig 2 illustrates the uvel concept. With an *uvel* size of 100m and a maximum baseline of 400km, full uv-coverage implies a number of *uvels*:

$$N_{uvel} = \pi \times (400.000/100)^2 \times \alpha \approx 5 \times 10^7 \times \alpha \approx 5 \times 10^7 \tag{2}$$

in which

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[1] the name *uvel* coined here should be compared to *pixel* (picture element) or *resel* (resolution element)

$$\alpha = \frac{\sin(DEC)}{< \sin(EL) >} \approx 1 \qquad (3)$$

The $\sin(DEC)$ term indicates that the uv-area to be covered is smaller (more ellipsoidal) for low declinations, and the $< \sin(EL) >$ term indicates that the average projected station size (and thus the uvel size) gets smaller for lower elevations. The two terms roughly cancel each other, so we will assume $\alpha = 1$ to simplify the present discussion. In any case we are mainly interested at present in the *maximum* number of uvels.

NB: Note that the number of $10^7 - 10^8$ *uvels* is getting dangerously close to the number of sources in the field. This means that at the lowest LOFAR frequencies there will be barely enough information (i.e. independent data points) available to solve for all possible source parameters, in addition to instrumental parameters. One way to deal with this is to provide *a priori* information, e.g. by making general assumptions about the large number of faint sources. This will be discussed in a later paper.

If the sampling is complete, i.e. we have full uv-coverage, the sidelobes of the PSF can be made arbitrarily small by means of suitable (e.g. Kaiser-Bessel) tapering. Significant gaps in the uv-coverage cause higher rms PSF sidelobe levels, which may cause a significant increase in the image noise when observing crowded fields *(sidelobe confusion)*. If we assume that all sources brighter than about 5σ are part of the Sky Model and can thus be subtracted perfectly, we are left with a large number n_{fov} of fainter sources with $S \approx 1\sigma$ in the field-of-view that cannot be subtracted. Their combined PSF sidelobes will increase the thermal noise:

$$S_{noise} = S_{thermal}\sqrt{1 + n_{fov} rms_{psf}^2} \qquad (4)$$

If we require that this factor should be smaller than $\sqrt{2}$, we get the criterion:

$$rms_{psf} < \sqrt{n_{fov}} \qquad (5)$$

which gives $rms_{psf} < 0.001$ $(= 0.1\%)$ for $n_{fov} = 10^6$. See also section 5.

Another reason to require full uv-coverage is the ionosphere, which may cause phase variations of many radians across the primary beam at low frequencies. This can be taken into account when subtracting Sky Model sources (i.e. sources with $S > 5\sigma$) from the uv-data, but that still leaves a large number (crowded fields!) of faint sources in the residual image. Since the latter can only be corrected for *one* point in the sky, the sources away from this point will be increasingly blurred by ionospheric phase errors (NB: this is decorrelation, not scattering!). A solution to this problem is *patch imaging*, i.e. making a mosaic of smaller images over which the ionospheric phase does not vary by more than a radian. The size of a patch may be reduced by averaging (convolving?) over increasingly large areas of the uv-plane, which requires full uv-coverage.

Each interferometer in an array contributes a *uv-track* to the uv-coverage as the Earth rotates. Ideally, the uv-point advances one *uvel* along the track in an integration time. The efficiency of covering the uv-plane with a limited number of tracks can be increased by widening the tracks with *Multi Frequency Synthesis* (MFS), i.e. using the different frequency channels measured with the same interferometer as separate uv-points. After all, the (u,v) coordinates are measured in wavelengths. The price one pays for this is that the fluxes of the sources in the resulting image are the averages over the MFS bandwidth. This is only acceptable if the sources have a flat spectrum or a known spectral index. A commonly used compromise is to use a maximum of 10% relative bandwidth for MFS.

The support (outer envelope) of the uv-coverage determines the width of the central peak of the PSF, and thus the spatial resolution of the image. At the highest LOFAR sensitivity, the density of detectable sources is so large that a resolution in the order of an arcsec [2]is required to avoid *source confusion.* This leads to the requirement that the maximum baseline has to be at least 200-400 km.

3 Summary of requirements and tentative configuration

Apart from the uv-coverage discussed in section 2, there are some other considerations for the LOFAR station configuration. For instance it is desirable that there are relatively many short baselines in order to have good *brightness sensitivity,* i.e. sensitivity for faint extended features. It is also desirable that the instantaneous uv-coverage should be good enough to allow snap-shot observations. And the configuration should be as *scale-free* as possible (i.e. it should be self-similar at all scales) in order to optimise its imaging properties at all scales.

These considerations, combined with practical ones related to cost and availability of sites, can be summarised (in no particular order) as follows:

- If possible, the LOFAR high/low stations, and even the high/low antennas, should be integrated with each other. This automatically implies that the high/low stations are co-located.
- Maximum baseline length: 200 (LOFAR high) - 400 (LOFAR low) km, to avoid source confusion.
- The baselines should be longer in the North-South direction, so as to optimize the uv-coverage when observing low-declination sources.
- Full uv-coverage is required for deep imaging, preferably in 4 hours. NB: Is full uv-coverage required for the longest baselines, for which bandwidth will be more costly?.
- The number of stations (and spiral arms) should be as small as possible, but the configuration should be robust against uv-coverage losses through station failure and RFI.
- Part of the uv-coverage may be obtained by *multi-frequency synthesis* (MFS), i.e. using the different frequency channels measured by an interferometer as different uv-points. No more than 10% relative bandwidth should be used for this.
- The shapshot PSF should have a maximum sidelobe level of 0.5 % (...?).

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[2] This happens to be consistent with the somewhat softer requirement that LOFAR should have a resolution comparable to that of observations in other wavelength areas.

- The density of stations should increase towards the centre of the array (for brightness sensitivity).
- For calibration, about 25% of the stations must be placed in a 'compact core' area with a diameter of 2 km.
- For pulsar observations, 50% of the stations should have full bandwidth (32MHz/beam) connections, and be placed within an area of about 10 km.
- NB: Any special requirements for transient detection...?

Fig 3 shows an example of a configuration that would meet most of the requirements. Note that the stations that would end up in impossible positions (like the North Sea) have been moved to the other side of the array in order to retain their long baselines.

Other configurations are possible, of course, and they can be quickly evaluated using the tools described here. However, it is probably justified to state that an optimal configuration should be *scale-free,* i.e. it should be self-similar at all scales. The log-spiral configuration has this property, and may be close to optimal. Therefore it is used throughout this document to illustrate the various aspects and considerations.

4 Constraints on the LOFAR frequency selection scheme

As fig 1 illustrates, the instantaneous frequency coverage of LOFAR consists of an arbitrary number of sub-bands, of arbitrary width, which can be arbitrarily selected from the *digitised* band (e.g. $B_{dig} = 32MHz$). The sum of all sub-bands is the *processed* bandwidth (e.g.$B_{proc} = 4MHz$). Each sub-band is split into contiguous 1 kHz channels for processing.

A sub-band with bandwidth Δf_{sb} covers a 'footprint' on the uv-plane with a radial size

$$\Delta r_{sb} = \frac{L}{\Delta\lambda} = \frac{L}{c}\Delta f_{sb}$$

in which L is the baseline length and c is the speed of light. The lateral size of a footprint is determined by the integration time, and is not considered here. Fig 2 shows how footprints of wide and narrow sub-bands are mapped onto the uv-plane sampling grid of uvels. As we saw in equ 1, each *uvel* has a size of

$$\Delta u = \Delta v = \frac{D}{\lambda} = \frac{D}{c}f_{obs}$$

in which D is the station diameter. For full uv-coverage, each uvel must be covered by at least one sub-band footprint. In practice, many uvels will be covered by footprints from different interferometers. NB: This 'weak' or 'cross-over' redundancy can be used in calibration.

For full uv-coverage, the gap between adjacent footprints must be smaller than an uvel, but not zero. These gaps can be used to extend the total uv-coverage that can be obtained with a processing bandwidth of 4 MHz. This is necessary, because if the relative bandwidth that is available for MFS is less than 10%, more than 100 stations are needed to achieve full uv-coverage. So, for an observing frequency of 160 MHz, the 4 MHz processing bandwidth has to be distributed over 16 MHz. The condition is that the total (sum) bandwidth of gaps plus the total bandwidth of sub-bands must be equal to the desired relative bandwidth (e.g. $\alpha = 0.1$). Assuming equal-width sub-bands:

$$n_{sb}(\Delta f_{sb} + \Delta f_{gap}) = \alpha f_{obs}$$

Using $n_{sb}\Delta f_{sb} = B_{proc} = 4MHz$ and $\Delta f_{gap} = (D_{station}/L_{max})f_{obs}$ we get the minimum number of sub-bands as a function of f_{obs} :

$$n_{sb} = (\alpha - \frac{B_{proc}}{f_{obs}}) \times \frac{L_{max}}{D_{station}} = (0.1 - \frac{4}{f_{obs}}) \times 4000 = (1 - \frac{40}{f_{obs}}) \times 400 \qquad (6)$$

Equ 6 leads to the following table:

f_{obs}	n_{sb}	Δf_{sb}	
20 MHz	1	2000 kHz	contiguous
40 MHz	1	4000 kHz	contiguous
41 MHz	10	400 kHz	gaps
80 MHz	200	20 kHz	gaps
160 MHz	300	13 kHz	gaps

NB: A drawback of using many non-contiguous sub-bands is that the (computationally very costly) selfcal predict operation can often be limited to predicting for groups contiguous channels. This will now be limited to the small number of channels in a sub-band.

5 PSF sidelobe level estimation

5.1 Rule of thumb

The following simple model helps to get an intuitive understanding of PSF formation. When uv-data are transformed into an image, each *uvel* gives rise to a cosine 'corrugation' in the image plane, with a period and orientation that is determined by its position in the uv-plane. These corrugations add up in phase to produce the peak (=1.0) of the PSF, but get increasingly out of step away from the peak. Without any tapering, each corrugation has the same amplitude $1/N_{uvel}$, and an rms value of $0.7/N_{uvel}$. Far from the peak, where all corrugations may be assumed to be randomly phased, the rms sidelobe level is given by the root of the sum of the squares of N_{uvel} corrigations:

$$rms_{psf} = \sqrt{N_{uvel}} \times (0.7/N_{uvel}) \approx 1/\sqrt{N_{uvel}} \tag{7}$$

This simple formula is valid for all sets of uv-samples, from full uv-coverage to *snap-shot imaging.* In the latter case it should be remembered that each interferometer will usually represent more than one *uvel,* depending on baseline length and relative bandwidth. A typical LOFAR snap-shot will produce $N_{uvel} \approx 10^5$, so it will have an rms sidelobe level of 0.3%.

Equ 2 suggests that the rms sidelobe level is constant out to infinity. In practice, it will decrease with the distance to the PSF peak, especially in cases where the contributing uvels are bunched together (missing uvbin, see below) or if there are many short baselines (long corrugation periods). However, the above approximation is a useful rule of thumb.

5.2 The effect of missing uvels

Assuming that the sidelobes of full uv-coverage are negligible, we may treat the sidelobes of missing uvels as if they are the only uvels measured. The difference is that the amplitude of the contributing corrugations is $1/N_{uvel}^{tot}$ rather than $1/N_{uvel}^{missing}$. The question to be answered is how many uvels may be missing before the PSF becomes unacceptable.

First of all it should be noted that, even if a uvbin in the plot does not contain an interferometer, it will usually be at least partly covered by the uv-tracks of nearby interferometers. Thus, an entirely empty bin will be very rare.

The uvels of a ‘missing’ bin are bunched together, which has an effect on the PSF sidelobe structure. Initial simulations indicate that this causes the PSF sideloble level to decrease inversely proportional (roughly) to the distance to the peak. This means that only the sources in the close vicinity (50 beams or so) of any point in the map determine the sidelobe confusion, so that the size of the primary beam does not matter any more, but only the source density. Intrigingly, this does not change the outcome very much, so that equs 4 and 5 remain valid approximations. *(More about this in later stage).*

The effects of two or more missing bins should increase roughly as the square root of their number.

It will often happen that parts of uvbins are missing, for instance when interference (RFI) or instrument failure renders part(s) of the LOFAR band or certain time-slots useless. Since this will often happen to a significant fraction of the bins, the missing uvels will tend to be distributed over the uv-plane. Therefore, the corresponding PSF sidelobe structure will resemple the shap-shot PSF. *(More about this in later stage).*

6 Configuration appraisal tool

The bottom panels of fig 3 show two views of the instantaneous uv-coverage (at $DEC = 90^o$). Each green cross represents an interferometer, each of which samples a crescent-shaped track on the uv-plane as the Earth rotates, as is shown in the 'conventional' plot on the left. The track length is determined by the observation time (e.g. 3 hr), and its width is determined by the relative bandwidth (e.g. 10%). Both are proportional with baseline length. If we sub-divide the uv-plane into track-shaped *uvbins*, the criterion for full uv-coverage becomes simply that each uvbin should contain at least one interferometer. Red circles indicate empty bins, and blue stars are 'risky' bins that might be empty if a station fails. A uniform distribution of interferometers over the bins is good for the snap-shot quality. Unfortunately, this is not easy to see in the conventional plot.

In the bottom right panel of fig 3, the same uv-coverage is plotted as $\log(ruv)$ vs hour-angle (HA), in which ruv is the effective baseline length, and HA is its orientation angle. This has the advantage that all bins appear to have the same size in the plot (except for baselines comparable to the station size), and can thus be compared by eye. For instance, it is immediately obvious that the log-spiral must be fairly optimal because, if we ignore the inevitable clumpiness, it leads to a rather uniform distribution of interferometers over the bins. This is an indication that the configuration is scale-free. The clumpiness is inevitable in any array with a relatively large number of short spacings, which is an important requirement in its own right.

A simple but effective software tool is available to study the properties and suitability of LOFAR station configurations analytically. Configurations can be either simulated or imported, for instance from a location map of the region. This kind of analytic simulation has the advantage that it is quick to implement, and that it generates a good understanding of the underlying imaging proces. In contrast, the results of brute-force simulations using large data volumes are often hard to interpret. In any case, the analytic tool is available and seems to be sufficient to support initial negotiations with local authorities about LOFAR station sites.

One of the most powerful features of the tool is the *uvbin plot*, a novel and rather useful way to plot the uv-coverage in such a way that a given configuration can be judged at a glance. This is demonstrated in section 7 by means of a series of experiments in which important parameters of the example log-spiral configuration are varied.

Inevitably, there is an increased number of empty and risky bins along the outer rim of the uv-coverage. The best solution is to ignore that part, and only to use the maximum ellipsoid that is fully covered. This limit is indicated in the uvbin plots with a dashed red line, and taken into account when calculating the numbers in the legend.

The uvbin plot is valid for all source declinations and elevations. For $DEC < 90^o$, the distribution of interferometers over bins will be the same, even though the number of uvels per bin will vary slightly with elevation because of the variation in projected size of a LOFAR station. Similarly, the small effect of non-zero w-coordinates of the 2D LOFAR array are neglected because they would complicate the plot without adding essential information.

7 Some experiments with the uvbin plot

7.1 Station position deviations

Fig 4 shows how the uv-coverage is affected if the stations are displaced from their ‘ideal’ positions on the spiral arms. In practice, the ‘ideal’ (algorithmic) positions will often not be available for LOFAR stations. Fortunately, this does not have a serious effect on the uv-coverage. In this experiment, the stations have been randomly displaced from their ‘ideal’ positions on the spiral arms, by a distance that is proportional to their distance to the centre. This assumes that the core area of 2 km will be fully available, and that the inner 10 km will be open country with few placement obstacles (like farms). Outside that area, the freedom of placement rapidly increases, and is at least a km. This should make it easier to find available spots for stations.

7.2 Varying the number of stations

Fig 5 shows the uv-coverage for different numbers of stations. The tentative conclusion is that 80 stations is an absolute minimum for full uv-coverage, but that 160 stations is probably overkill. The optimum in terms of performance and cost might be about 100.

7.3 Varying the number of spiral arms

Fig 6 shows the uv-coverage for different numbers of spiral arms. Only odd numbers are considered, since an array with an even number of arms has much more redundancy and therefore a much less uniform uv-coverage. The distribution seems to be better for smaller numbers of arms, probably because each arm has more stations. Since a single arm gives a rather uneven distribution for long baselines, the optimum in terms of persformance and cost seems to be 3 arms.

8 Some remarks on other radio telescopes

8.1 The uv-coverage of GMRT and VLA

Fig 7 shows the uv-coverage for some existing radio telescopes that are used for low frequency observations. It is clear that they do not have enough antennas for full uv-coverage (unless an unaccepably large relative bandwidth is used).

8.2 Sidelobe confusion and ionosphere effects with the WSRT

(Ger de Bruyn, 300 Mhz): The residual noise seems higher than the PSF sidelobe noise expected on the basis of the available number of uvels (e.g. 40 ifrs, 169 time-slots, 8 freq points, 2 pols). (*More about this later).*

8.3 Does SKA need full uv-coverage?

As we have seen in section **??**, crowded fields are the main driver behind the requirement for full uv-coverage. Thus it might be argued that, at observing frequencies above about 500 MHz, fields will not be crowded enough to require full uv-coverage, even at Square Km Array sensitivities. This would be a welcome conclusion for those SKA concepts that intrinsically have a relatively small number of very large telescopes (i.e. the Canadian and Chinese concepts, and perhaps even the Autralian Luneburg lenses).

Even with un-crowded fields, the question remains whether incomplete uv-coverage is sufficient to subtract the effects of bright sources with the accuracy required for a dynamic range of $1:10^8$. The answer is probably affirmative, because minimization of the uv-data residuals merely requires Selfcal to find one of the possible Sky Models that is consistent with the data. So as long as we are not interested in an accurate model of the bright sources, but merely in removing them, full uv-coverage is not necessary. This conjecture is supported by the experience with existing arrays, especially the WSRT where instrumental errors are modelled most accurately. The remaining question is how incomplete the uv-coverage can be before modelling errors start generating unacceptable secondary effects on the residuals.

9 Conclusions

We now have the tools, especially the ‘uvbin plot’, that can tell us very quickly whether a proposed station configuration is acceptable or not. Experiments with these tools described in this paper have yielded the following general guidelines for the LOFAR configuration:

- The station density should vary logarithmically with the distance to the array centre:
  - Such a configuration has the desirable property of being scale-free.
  - This has the largest station density in the centre, which is good for brigntness sensitivity.
  - It appears to be the cheapest way to get full uv-coverage.
  - It gives a more or less uniform instantaneous distribution of uv-points over uv-bins, which is good for snapshot image quality.
- A log-spiral configuration with an odd nr of arms (probably 3) is probably close to optimal.

- The centre does not have to be the exact geographical centre of the array, as long as all the required baselines are present. Thus, stations in a 'zone of avoidance' (like the North Sea) may be moved to the other side of the array.
- The precise location of the stations may deviate by 10% of their distance to the array centre. This gives considerable freedom in the choice of available sites.
- It is possible to achieve full uv-coverage in 4 hours, using 10% relative bandwidth, with only 80 stations. However, this would minimise robustness against station failure, and also the number of beams probing the ionosphere. Probably the optimum number is about 100 stations.
- In order to 'stretch' an instantaneous processing bandwidth to 10% relative bandwidth, it has to be split into many relatively narrow sub-bands, separated by gaps. See section 4. It should be noted that this can make the selfcal predict operation less efficient.
- NB: If the fields are not crowded, as frequencies > 500 MHz (SKA) incomplete uv-coverage does not affect the capability to subtract bright sources with high accuracy, so it does not limit the dynamic range. See section 8.3.

References

[1] ...

[2] ...

Acknowledgements

The discussion about LOFAR/SKAI station configurations owes much to Colin Lonsdale, who argued the case for many stations. The author is also grateful to Jaap Bregman, Ger de Bruyn, Robert Braun, Johan Hamaker, Arnold van Ardenne, Marco de Vos and Michiel van Haarlem for suggestions and comments.

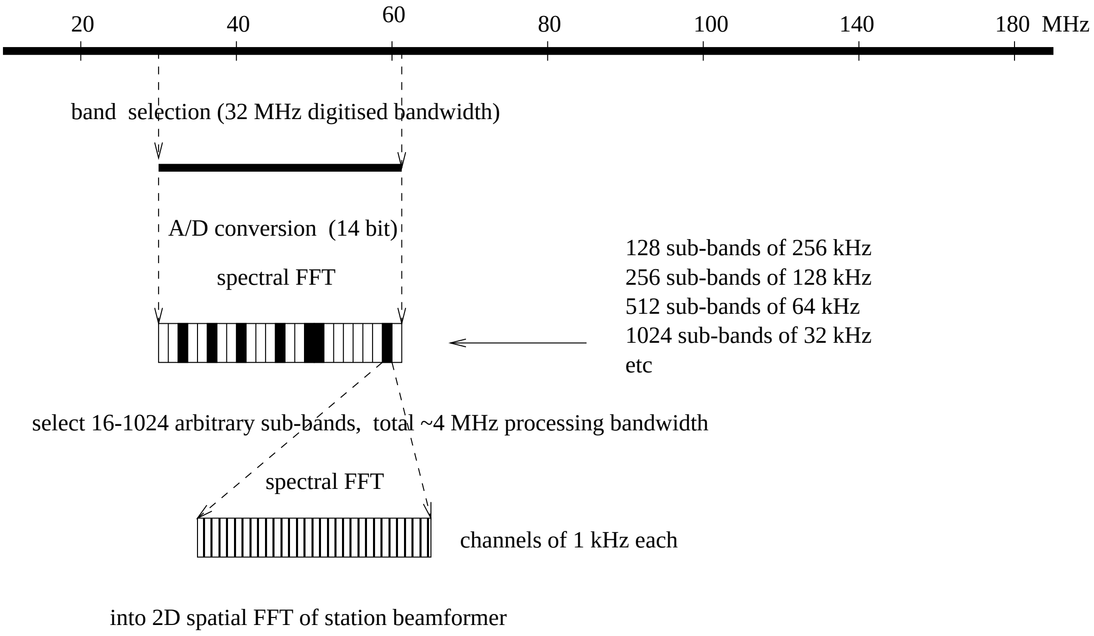

Figure 1: *The instantaneous LOFAR frequency coverage is sub-divided into sub-bands with a total processing bandwidth of 4 MHz. The sub-bands do not have to be contiguous, and can be selected arbitrarily from a digitised band of 32 MHz.*

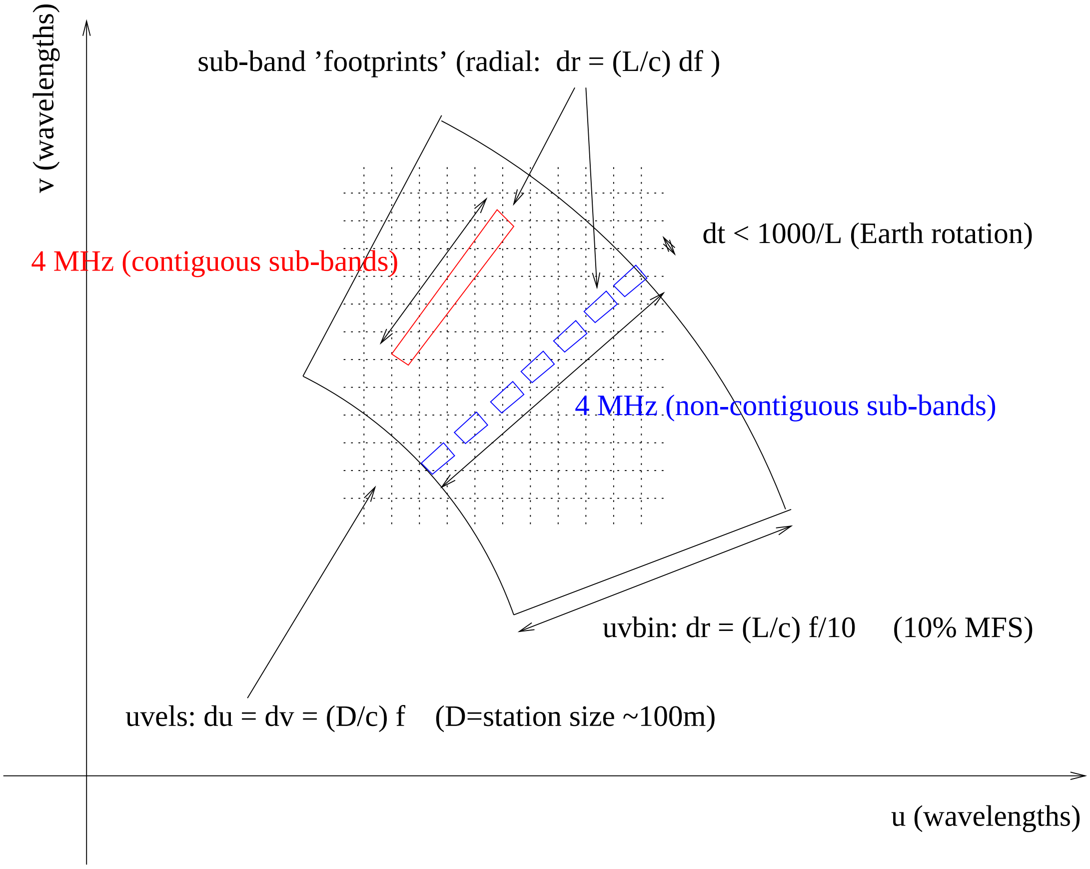

Figure 2: *The uv-plane is sampled in units of an* uvel, *the size of which is determined by the station size. A sub-band maps onto a radial 'footprint' on the uv-plane, with a linear size that is proportional to its bandwidth. For full uv-coverage, the gaps between footprints must be smaller than an uvel. The gaps can be used to extend the total uv-coverage for the limited (4 MHz) processing bandwidth, e.g. to obtain 10% relative bandwidth for Multi Frequency Synthesis (MFS).*

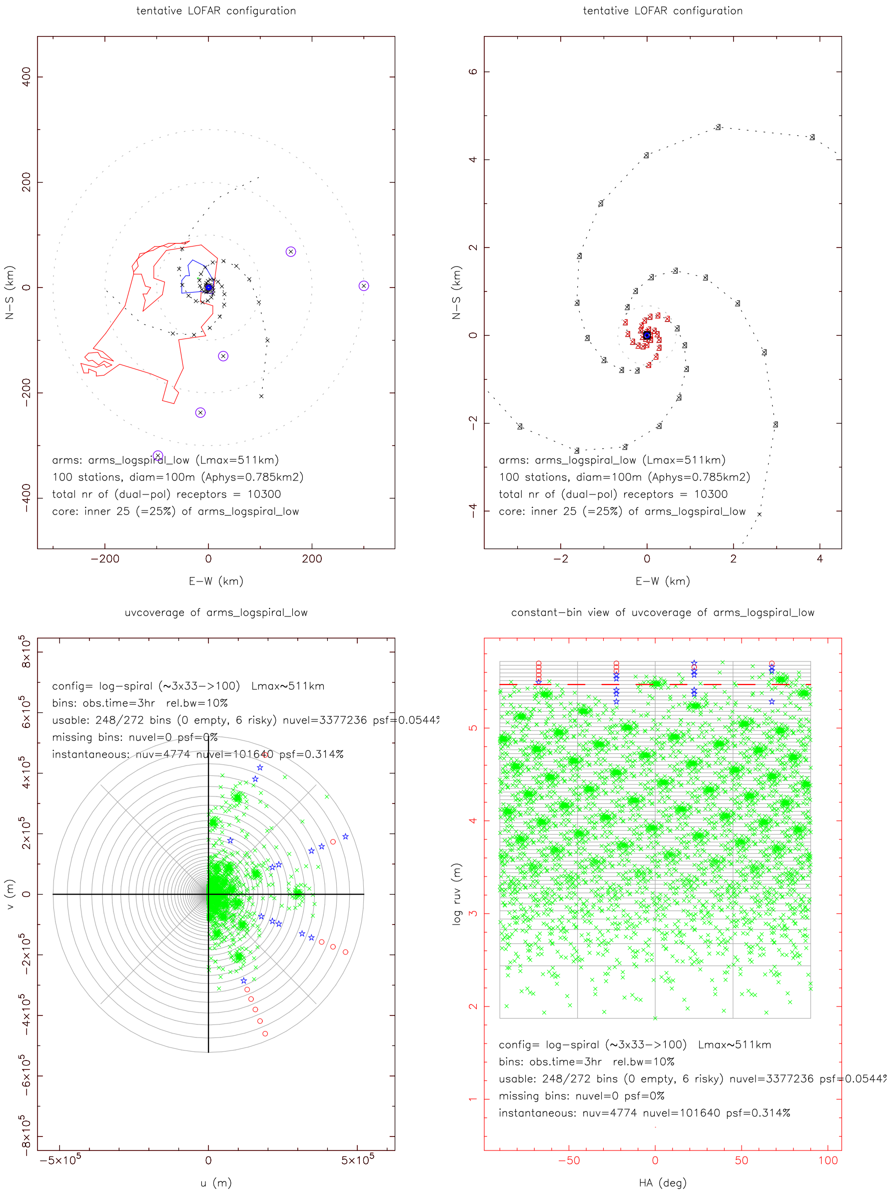

Figure 3: *An example of a three-armed log-spiral configuration that meets the requirements in section ??. Note that the stations that would end up in impossible positions (like the Noth Sea) have been moved to the other side of the array in order to retain their long baselines. The top right panel is an enlargement of the central part of the array, where the density of stations is highest.*
The bottom panels show two views of the instantaneous uv-coverage (at DEC=90). Each green cross represents an interferometer, each of which samples a crescent-shaped track on the uv-plane as shown in the conventional plot on the left. The track length is determined by the observation time (e.g. 3 hr), its width by the relative bandwidth (e.g. 10%), and both are proportional with baseline length. If we sub-divide the uv-plane into track-shaped bins, the criterion for full uv-coverage becomes that each bin should contain at least one interferometer. Red circles indicate empty bins, and blue stars are 'risky' bins that might be empty if a station fails. A uniform distribution if interferometers over the bins is good for the snap-shot quality. The plot on the right is designed to [illegible] at a glance for any given configuration.

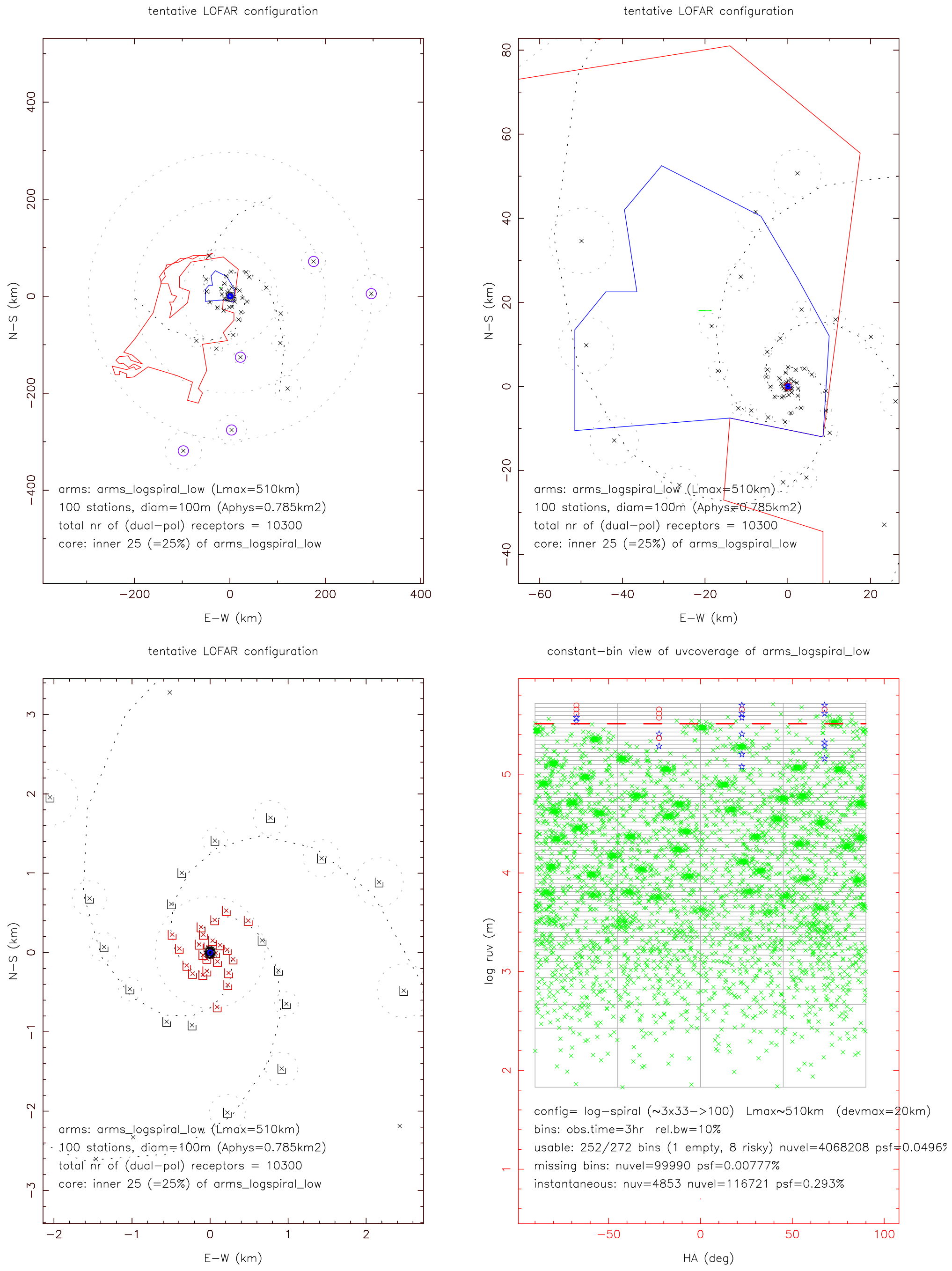

Figure 4: *Experiment: station displacement. In practice, the 'ideal' positions will often not be available for LOFAR stations. Fortunately, this does not have a serious effect on the uv-coverage (compare the bottom-right panel to fig 3). In this example, the stations have been randomly displaced from their positions on the spiral arms, by a distance that is proportional to the distance to the centre. Dotted circles indicate the placement freedom at national, provincial and local scale.*

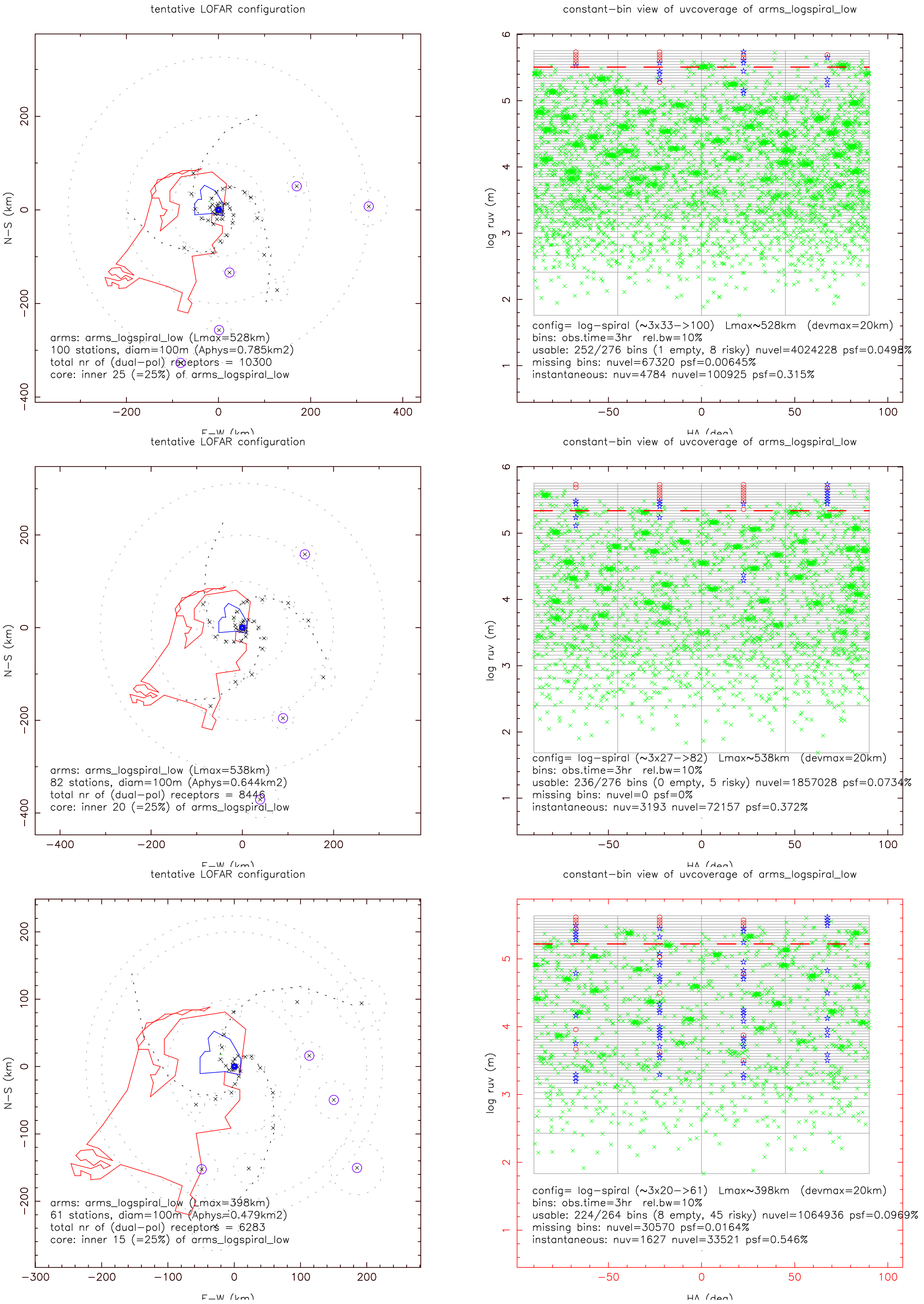

Figure 5: *Experiment: the uvbin plot for 100 (top), 80 (middle) and 60 (bottom) stations. One may draw the tentative conclusion that 80 stations is an absolute minimum.*

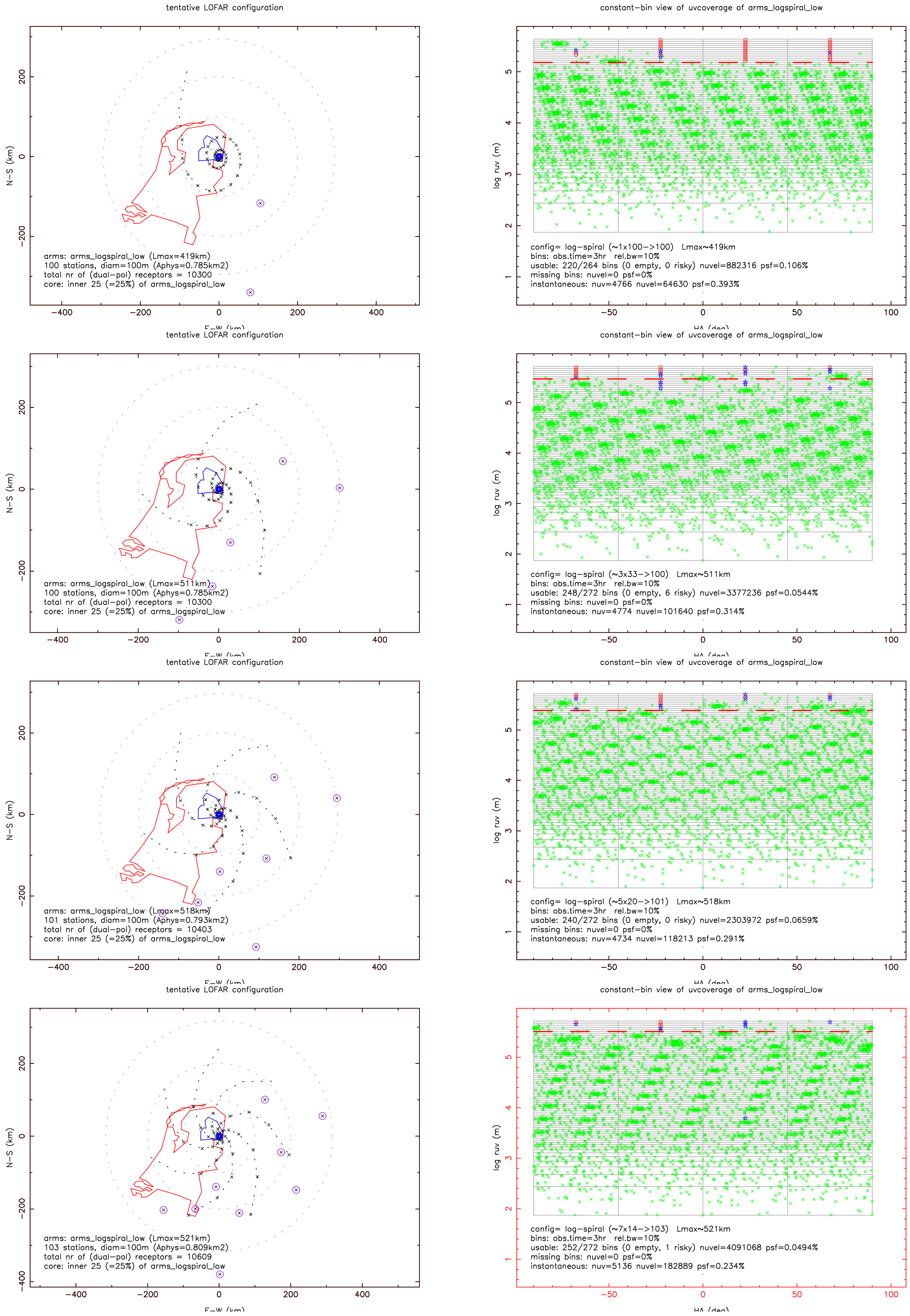

Figure 6: *Experiment: the uvbin plot for different numbers of spiral arms. Assuming that the number of spiral arms should be odd, the optimum seems to be either 3 or 5.*

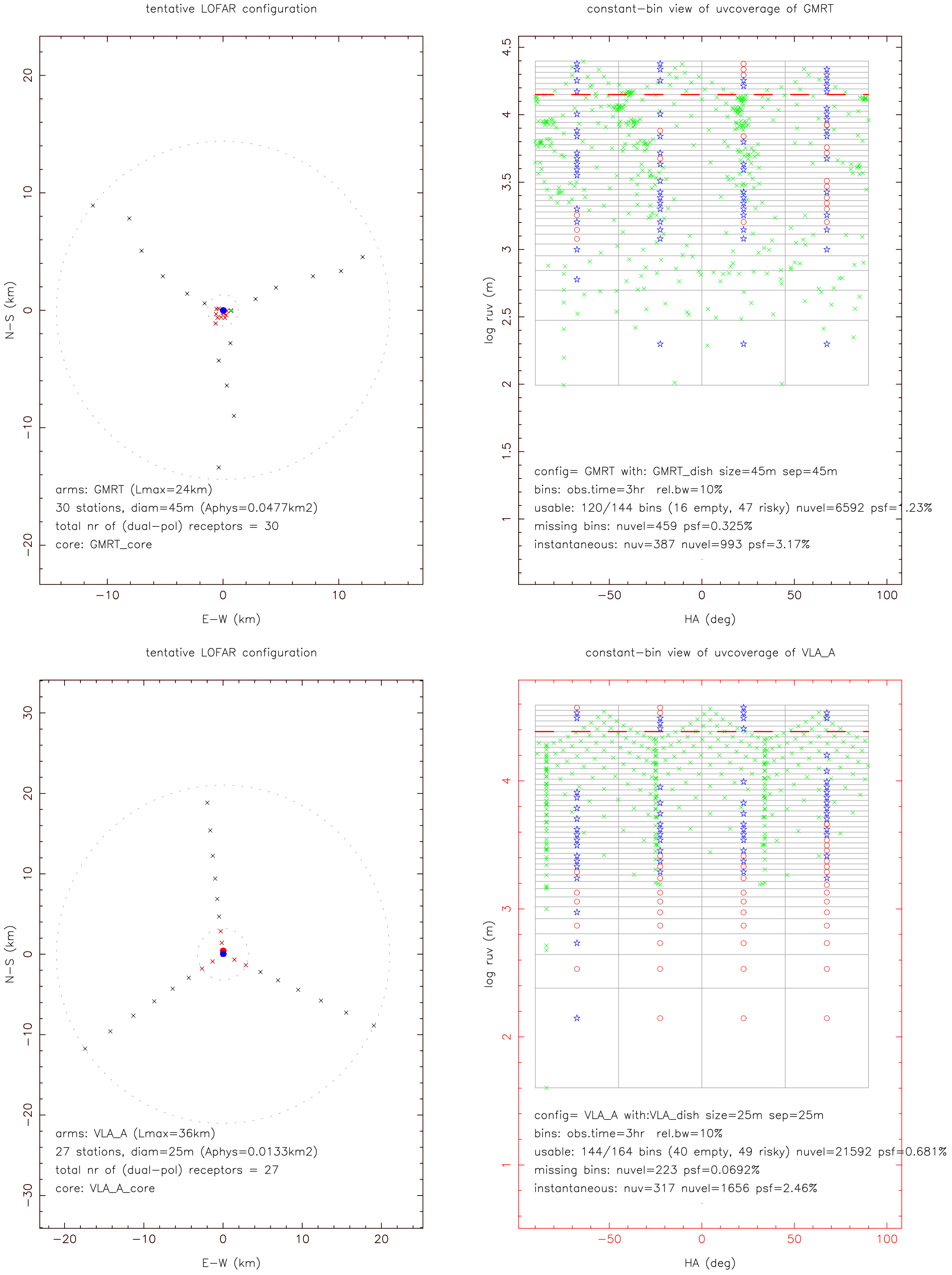

Figure 7: *The uvbin plot for some existing telescopes (GMRT and VLA) that are being used for low frequency observations. It is clear that they do not have enough antennas for full uv-coverage.*