# MK+ building sequence

Hans-Rainer Klöckner[1]

[1]Max-Planck-Institut für Radioastronomie, Bonn, Germany

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The MeerKAT extension will be accomplished by building additional SKA-MID antennas for the existing array in the upcoming years. The optimal distribution of these antennas has been evaluated in a two-stage simulation that has lead to the final MeerKAT+ array configuration (LAY8). The details of the evaluation process is summarised in the MK+ configuration report in 2020.

In the meantime the Max-Plack-Society (MPG) and the MPIfR, in collaboration with the South African Radio Astronomy Observatory (SARAO), have installed the SKA-MPG pathfinder antenna (SKA-MPG-PA) at the Karroo area, which is located within the MeerKAT layout. In order to understand the impact of utilising the SKA-MPG antenna within the MeerKAT extension the pre-selection simulation used in configuration report has been applied. In these simulations the MK+ is populated with different number of antennas either including or excluding the SKA-MPG-PA position. Simulations, with increasing number of antennas, are used to investigate if there is a preferred building sequence of the MeerKAT extension. For a total of up to 13 antennas the simulations favour MK+ antenna positions exclusively, whereas for a larger number of antennas the simulations favour the SKA-MPG-PA position to be included. Comparing the differently populated MK+ configurations, it shows that the extension can be build in a continuous sequence by adding SKA034, SKA116, SKA060, SKA026, SKA114, SKA020, SKA023 respectively as a basic configuration of 13 antennas. Whereas when including the SKA-MPG-PA position there is only a continuous sequence of up to 17 positions possible, adding SKA-MPG, SKA116, SKA034, SKA114 to the basic configuration.

Including the SKA-MPG-PA antenna into the extended MeerKAT configuration therefore would favour a 3-stage building sequence in order to reduce the risk compared to the continuous building sequence of the MK+ array without the antenna. In the first phase up to 13 antennas could be built, whereas in the second stage only 2 antennas should be added (SKA116, SKA034), and finally the MK+ array could be completed by building the remaining 5 antennas.

## 1 MeerKAT and the SKA-MPG pathfinder antenna

In the upcoming years the MeerKAT observatory will see a substantial upgrade of its key-components including a physical extension of its configuration by adding a substantial number of SKA-MID antennas to the array. The layout of the MeerKAT extension (MK+) is based on the SKA-MID antenna positions (Heystek L. et al. 2015) and has been determined using a two-stage simulation process, including a pre-selection process and detailed `AIPS` and `CASA/stimela` imaging simulations (Klöckner H.-R. et al. 2020). The MK+ array layout (LAY8), shown in Figure 1, will be composed of the MeerKAT array as a central core, including a few SKA-MID antennas up to 10 km away from the central MeerKAT position (-30:42:49, +21:26:38). The MK+ configuration will have 3 arms with a maximum separation between the individual antennas of the order of 16.3 km.

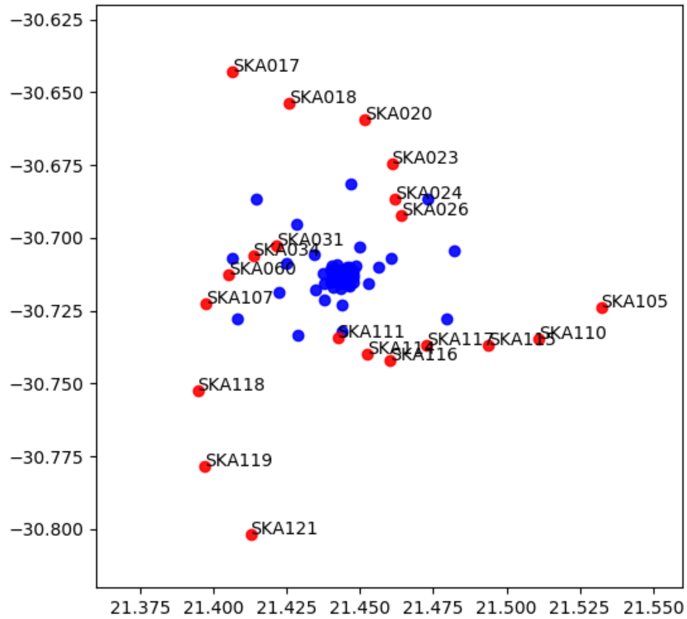


Figure 1: MeerKAT+ configuration in longitude and latitude, the blue dots indicate the MeerKAT configuration whereas the red dots show the SKA-MID antenna positions and the labelling is based on the SKA document (Heystek L. et al. 2015).

In a collaboration with the South African Radio Astronomy Observatory (SARAO) the Max Planck Institute for Radioastronomy (MPIfR) of the Max-Plack-Society (MPG) have built the SKA-MPG pathfinder antenna (SKA-MPG-PA; longitude -30.718 deg, latitude 21.413 deg) in the outer region of the MeerKAT array. The SKA-MPG-PA position is not an official SKA position, however due to the central location the antenna may provide crucial baselines for the MK+ array. In order to investigate the impact of potentially using the SKA-MPG-PA for MeerKAT+ observations the pre-selection simulations, used in the configuration report, has been applied. This process evaluates antenna configurations based on their UV distributions and the properties of their synthesised dirty beams. The used evaluation criterion is based on the side-lobe contribution of the synthesised power-beam, which is the same criterion as the one applied in the configuration report. A full description of the pre-selection method can be found in the configuration report (Klöckner H.-R. et al. 2020).
In order to investigate the building sequence of the MK+ array, the array configuration has been populated with an increasing number of antennas (12 to 19). The pre-selection process was executed twice, either including or excluding the SKA-MPG-PA position. The results of the 16 simulations are listed in Table 1. The evaluation criterion of *minimised side-lobe level contributions* favours a lower value to be better, such that the ranking of 1.054 of the full MK+ configuration is the best value possible. In this light, the simulations show a linear relation of the total number of antennas used and the rank of the differently populated MK+ configurations. The ranking of using 12 or 13 antennas does not differ if the SKA-MPG-PA position is taken into account or not. Whereas, if more than 13 antennas are used the ranking prefers configurations including the SKA-MPG-PA position.

The different populated configurations are shown in the Figure 2 to 9 in the Appendix. The blue dots in the figures indicate the MeerKAT antenna positions whereas the red dots show the highest ranked positions of that particular simulation run, respectively.

The results for 12 and 13 possible antenna positions are shown in Figures 2 and 3, respectively. The

| Layout | No antenna | rank |
|---|---|---|
| LAY8 | 20 | 1.05386 |
| | | |
| SIM19-MPG | 19 | 1.08058 |
| SIM19 | 19 | 1.08242 |
| SIM18-MPG | 18 | 1.11187 |
| SIM18 | 18 | 1.11356 |
| SIM17-MPG | 17 | 1.14553 |
| SIM17 | 17 | 1.14659 |
| SIM16-MPG | 16 | 1.18131 |
| SIM16 | 16 | 1.18255 |
| SIM15-MPG | 15 | 1.22053 |
| SIM15 | 15 | 1.22125 |
| SIM14-MPG | 14 | 1.26452 |
| SIM14 | 14 | 1.26518 |
| SIM13-MPG | 13 | 1.31408 |
| SIM13 | 13 | 1.31408 |
| SIM12-MPG | 12 | 1.36719 |
| SIM12 | 12 | 1.36719 |

Table 1: Ranking of the MeerKAT+ configurations populated with increasing number of antennas. Note that the ranking for 12 and 13 antenna positions are the same, because the simulations do not favour the SKA-MPG-PA position to be included.

preferred positions of 12 antennas are: SKA017, SKA018, SKA023, SKA024, SKA105, SKA110, SKA115, SKA117, SKA119, SKA118, SKA107, and SKA031. In case of 13 possible antennas the SKA121 position can be added, for the upcoming discussion this will make up the base configuration.

Increasing the number of antennas in the simulations, based on the MK+ antenna positions only, shows a clear preferred sequence in building up the MK+ array from 14 to 20 antennas by adding the SKA034, SKA116, SKA060, SKA026, SKA114, SKA020, and SKA111 positions, respectively. On the other hand the simulations using the MK+ and the SKA-MPG-PA positions do not show a preferred sequence to the full array. Here only a continuous sequence of building 14 to 17 antennas is possible, by adding SKA-MPG, SKA116, SKA034, and SKA114 to the base configuration of 13 antennas. Increasing the number of antennas further to 18 or 19 would indicate a change of the above sequence, starting from 17 antennas. Therefore the configuration with 18 antennas would be made out of the base configuration adding SKA-MPG, SKA116, SKA034, positions as before, and finally adding the SKA026 and SKA060. The configuration with 19 antennas would be built by adding the SKA114 position to the end of the sequence.

## 2 Results

The impact of including the SKA-MPG antenna in the building sequence of the MK+ array has been investigated. The ranking of the individual configurations show a clear relation of the number of antennas and the ranking parameter — higher number of antennas indicate a better ranking. Comparing the individual ranking of configurations with a fixed number of antennas shows that including the position of the SKA-MPG antenna provides a better ranking. Apart from the ranking parameter, the distributions of the antenna positions of the individually populated MK+ configurations show differences between using the MK+ positions alone and including the SKA-MPG-PA position. Taking these findings into account a staged sequence is proposed to build the MeerKAT+ extension.

The base configurations, for which the SKA-MPG-PA has not been selected, are the configurations of 12 or 13 antennas, using the SKA017, SKA018, SKA023, SKA024, SKA105, SKA110, SKA115, SKA117, SKA119, SKA118, SKA107, SKA031, and SKA121, respectively and would made up the first building stage. Comparing the build sequences of the simulations runs with and without the SKA-MPG-PA to the next 3 antennas, with SKA034, SKA116, SKA060 or SKA-MPG, SKA116, SKA034, respectively, indicates the second building stage of including the antenna positions of SKA034 and SKA116. In a final step one would fully populate the MK+ array configuration by building SKA060, SKA026, SKA114, SKA020, SKA111.

## References


[1] Heystek L. et al. *SKA1-MID PHYSICAL CONFIGURATION COORDINATES*. SKAO. May 4, 2015. URL: https://astronomers.skatelescope.org/wp-content/uploads/2016/09/SKA-TEL-INSA-0000537-SKA1_Mid_Physical_Configuration_Coordinates_Rev_2-signed.pdf.

[2] Klöckner H.-R., Makhathini S., Mao S.A., Dean R., and Smirnov O. *MeerKAT+ Configuration Simulation Report*. SARAO. 2020.

# A Appendix: Preselection results

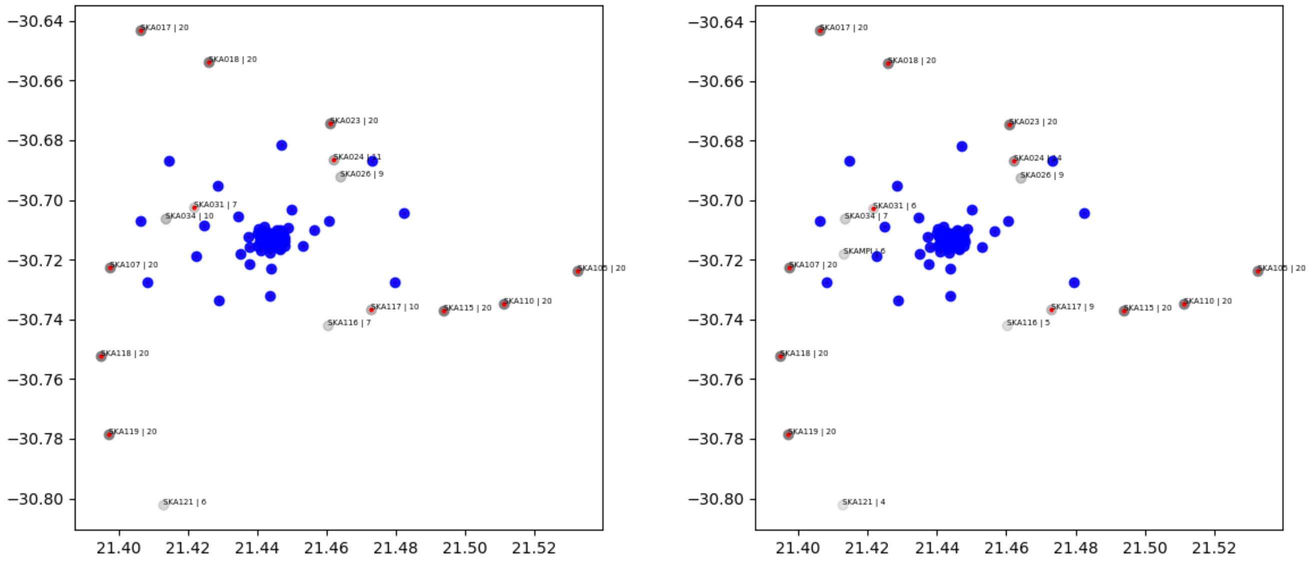


Figure 2: Simulations extracting 12 potential antenna position. The red dots are the position of the highest ranked configuration. Left: Selection is based on MK+ positions; right: Selection is based on MK+ and the SKA-MPG telescope position.

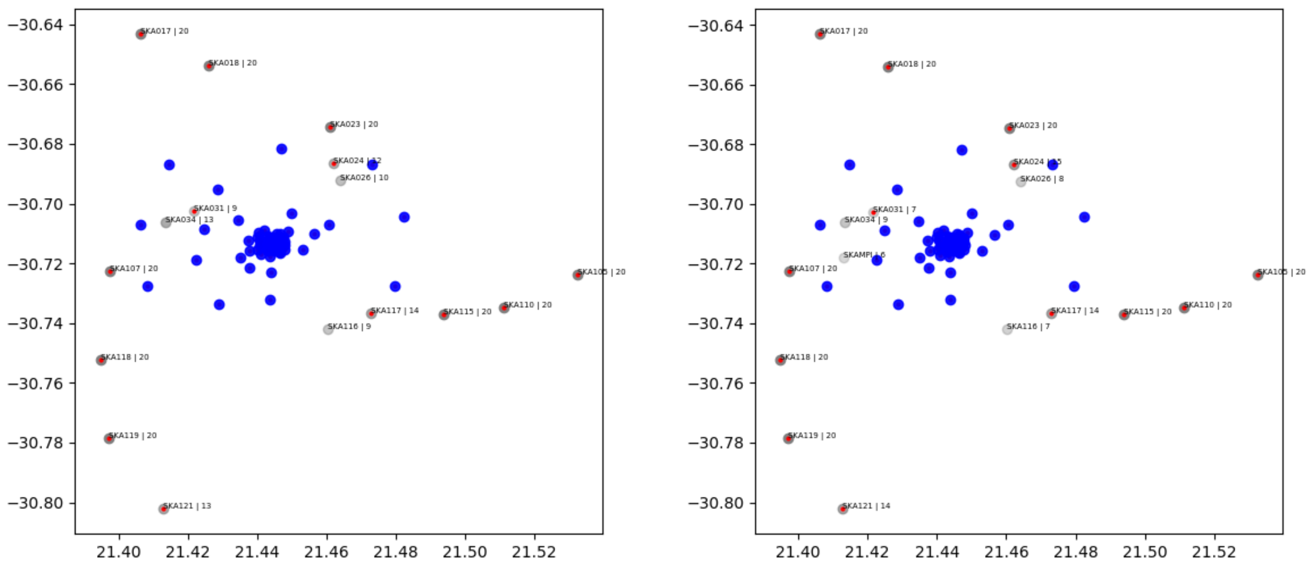


Figure 3: Simulations extracting 13 potential antenna position.

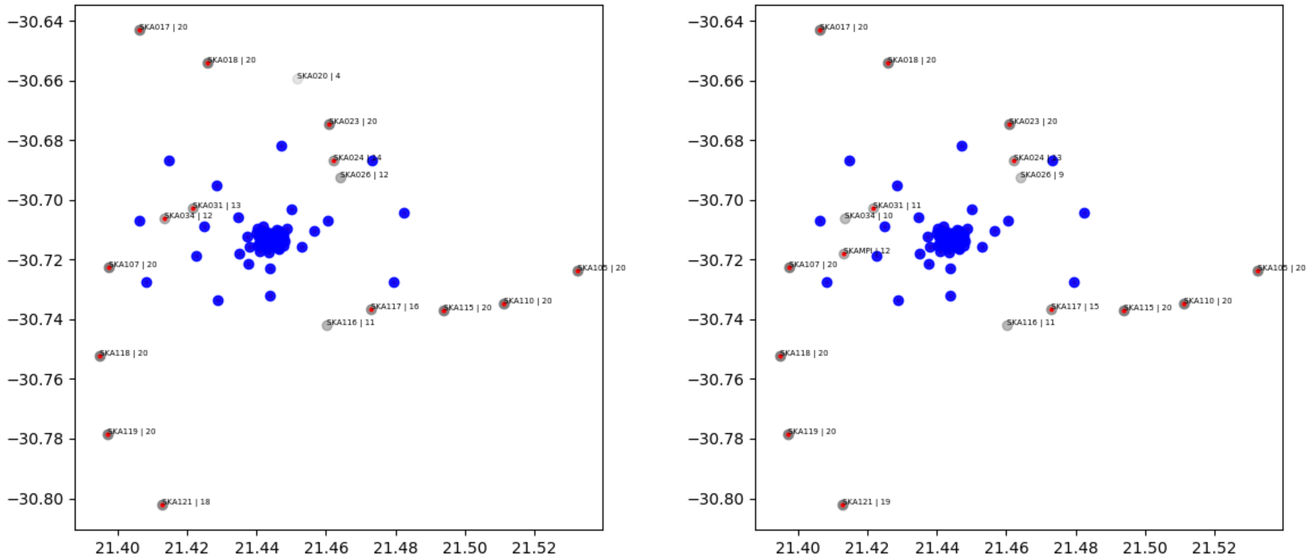


Figure 4: Simulations extracting 14 potential antenna position.

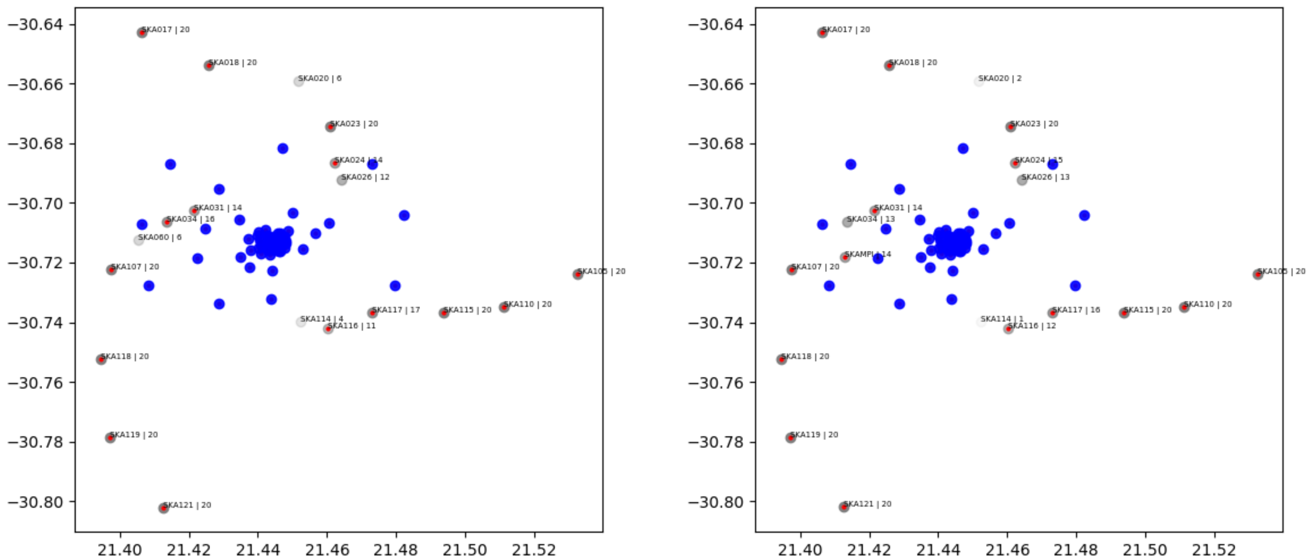


Figure 5: Simulations extracting 15 potential antenna position.

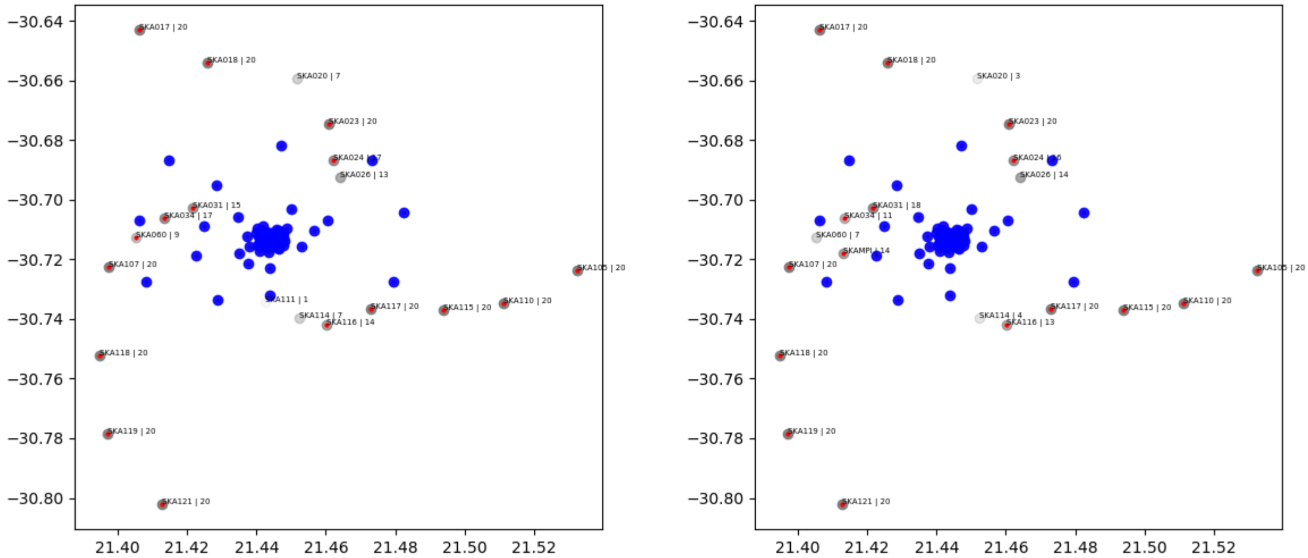


Figure 6: Simulations extracting 16 potential antenna position.

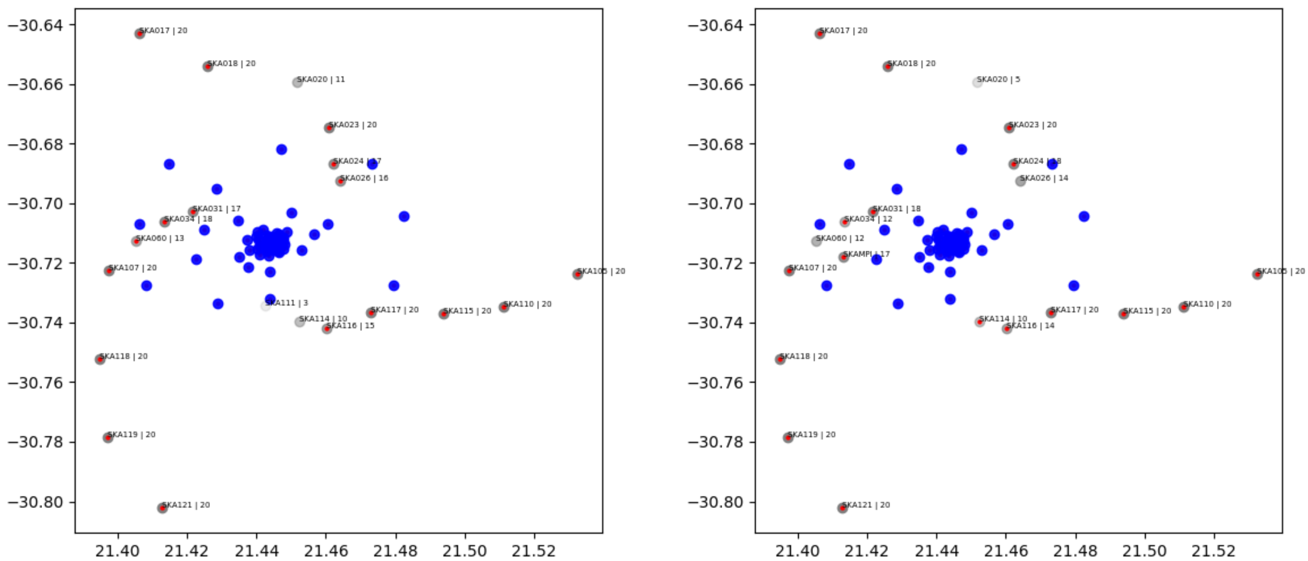


Figure 7: Simulations extracting 17 potential antenna position.

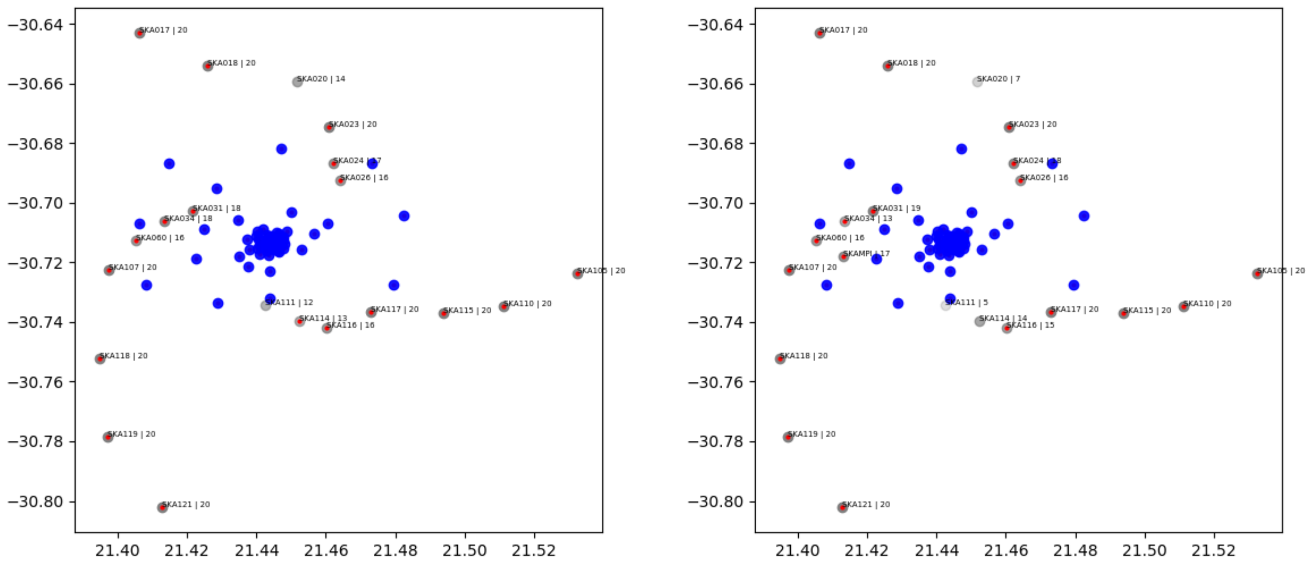


Figure 8: Simulations extracting 18 potential antenna position.

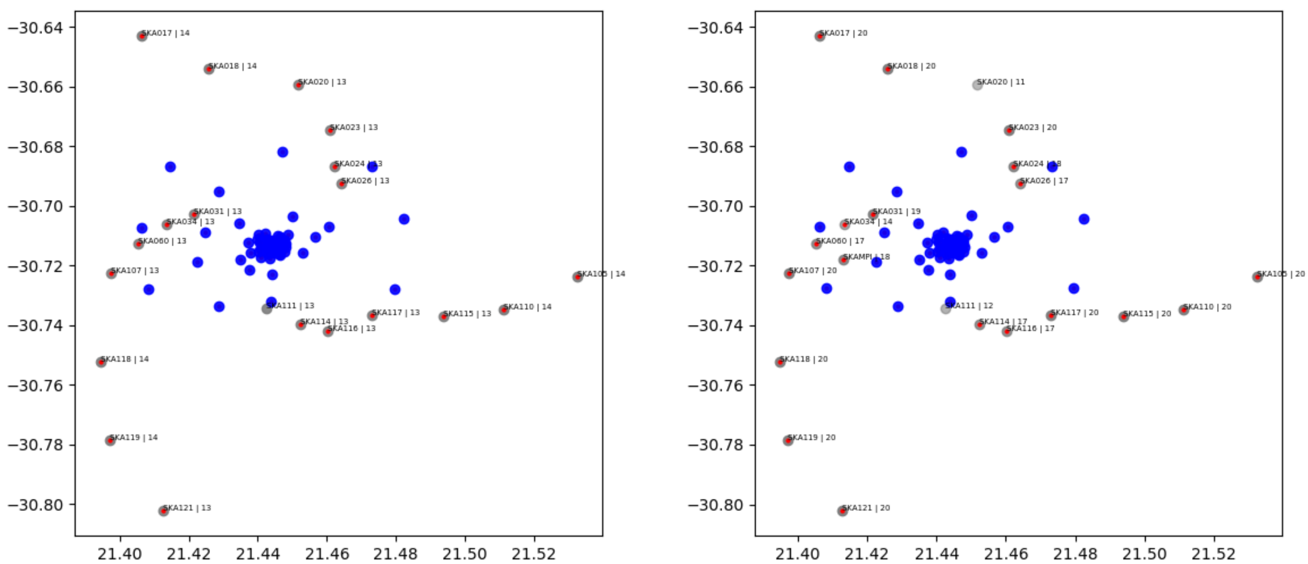


Figure 9: Simulations extracting 19 potential antenna position.