Filling the \textit{uv}-gaps of the current VLBI network in Africa

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\textbf{ABSTRACT}
In the African continent, South Africa has world-class astronomical facilities for advanced radio astronomy research. With the advent of the Square Kilometre Array project in South Africa (SA SKA), six countries in Africa (SA SKA partner countries) have joined South Africa to contribute towards the African Very Long Baseline Interferometry (VLBI) Networks (AVN). Each of the AVN countries will soon have a single dish radio telescope that will be part of the AVN, the European VLBI Network, and the global VLBI network. The SKA and the AVN will enable very high sensitivity VLBI in the southern hemisphere. In the current AVN network, there is a gap in coverage in the central African region. This work analyses the scientific impact if new antennas were to be built or old telecommunication facilities were to be converted to radio telescopes in each of the six countries in central Africa i.e. Cameroon, Gabon, Congo, Equatorial Guinea, Chad, Central African Republic. The work also discusses some economical and skills transfer impacts of having a radio interferometer in this area of Africa.

\textbf{KEYWORDS}
Square Kilometre Array; Very Long Baseline Interferometry; AVN; EVN.

\section{1. Introduction}

The spatial resolution of a particular telescope determines how well one can see details of cosmic objects. This resolution depends on the size of the telescope and the wavelength of the astronomical sources. Thus to have a better resolution, one solution would be to build a telescope with a large diameter. However, there is a practical limitation on the size of a telescope and this led to the development of interferometry. That is, instead of having one large telescope, one can cross-correlate signals from individual antennas and the resolution of the combined array of antennas (so-called interferometer) is determined by the largest separation (baseline) between the individual antennas. The combined array is therefore equivalent to a huge single-dish telescope with a diameter
equal to the longest baseline. Many radio telescopes were built after the development of interferometry technique. However, by the mid-1960s (Clark 2003), it was realised that some radio sources could not be resolved even with radio telescopes of a few hundred km baselines. The quest for higher resolution led to the development of the Very Long Baseline Interferometry (VLBI) (Kellermann 2001). The VLBI is a technique of cross-correlating signals recorded by different antennas (and/or array of antennas) separated by a large distance of up to the diameter of the earth. With this technique, detailed images of astronomical objects at milliarcsecond resolution have been obtained. In addition, high-precision astrometry has also been achieved.

The SKA (TWild 2017) will be split in a mid-frequency (350 MHz-14GHz) part build in South Africa, which will incorporate MeerKAT (Booth 2012), and a low frequency (50-350MHz) part in Australia. To enable high resolution interferometry through VLBI, the SKA South Africa currently leads an effort to convert existing unused telecommunications dishes in partner countries (Botswana, Ghana, Kenya, Madagascar, Mauritius, Mozambique, Namibia and Zambia) to radio telescopes. The converted antennas will then become part of a network of antennas distributed throughout Africa to form the African VLBI Network (AVN). Ghana has already successfully converted its old telecommunication dish to a working radio telescope. Efforts to do the same in other African partner countries are underway. The AVN will significantly improve the science capabilities of the global VLBI community. The AVN combined with the existing international VLBI facilities will produce huge quantities of data, presenting new challenges in data processing and storage (Atemkeng 2018). New techniques to manage the data must be developed, this includes: storage systems and data compression techniques, machine learning methods, software design techniques, control and monitoring systems that parallel the internet of things, data flow architecture and systems dealing with massive scale computing. All of these challenges will strengthen the scientific collaborations between South Africa and its partner countries. In addition, Africa will become an international science and technology focus.

The central African states are currently not part of the AVN. This paper investigates the technical impact of this in terms of the AVN image quality and science capabilities. We will demonstrate by means of simulations how the AVN image quality improves if antennas were added in these countries. This paper also highlights the economical and technological benifits for these countries should they join the AVN project.

2. Motivations

The Central African States (ECCAS) have not yet joined the AVN. However, a number of opportunities will open up for these countries should they become part of the AVN. In addition, as we will demonstrate in the next section, the existing AVN community will also benefit a lot from the participation of these countries to the project. Below we highlights potential benefits of joining the AVN.

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1Economic and Community of Central African States
2.1. Education and Research impacts

Joining the AVN will boost international cooperation in the field of Astronomy and engineering and enable participation in international scientific research. Running a radio telescope requires skilled engineers, scientists and technicians who will manage and run the facility. These personnels need to be trained in various disciplines, from radio astronomy and astrophysics to computer science and engineering. The decision to join the AVN network will trigger the development of critical skills and institutional capacity necessary to optimize ECCAS participation in the SKA. High-end technologies and high performance computing facilities needed to operate and maintain the telescopes are being developed in South Africa. The Centre for High Performance Computing (CHPC) is already in place and running.

As mentioned before, Ghana has already successfully converted its old telecommunications dish into a functioning radio telescope. This is a demonstration that Africa can participate in high-level scientific research. The skills and experience from the development of these facilities will be transferred to the ECCAS states if they join the AVN project. In addition, the project will bring new scientific opportunities to the ECCAS countries on a relatively short timescale. Currently, students in the AVN partner countries are benefiting from a number of scholarships to pursue further studies, trained and acquired more skills. Some of those scholarships includes but are not limited to: the SKA scholarship; the Development for Africa with Radio Astronomy (DARA) project in the United Kingdom; a number of South African Research Chairs Initiative (SARChI) of the Department of Science and Technology and the National Research Foundation. Further benefit of joining the project includes the training of African scientists, engineers and technicians, with a view to ensure that partner countries benefit from the second phase of the SKA.

2.2. Economic Impacts

The AVN will trigger foreign investment and expenditure (including local contracts and suppliers). The skills development that will be promoted by the project should enhance ECCAS engineering and scientific capabilities, promoting science and engineering breakthroughs for other sectors such as medicine, remote sensing and telecommunications, thereby enhancing innovation and competitiveness among industries. The construction or conversion of the telescopes will pave the way for a major boost to the local businesses e.g., tourism industries, construction industries, hospitality industries, thus creating new job opportunities and enhancing local revenues.

2.3. Scientific Impacts

The $uv$-coverage of the current AVN combined with the European VLBI Network (EVN) have large unsampled $uv$-gaps (“holes”) due to the absence of medium-length baselines. The combined VLBI networks comprises two types of baselines: the long baselines that link the EVN with the AVN antennas in South Africa and the short baselines from each of them. The possible medium-length baselines from this combined instrument are from the single antenna in Ghana. We need more medium-length baselines in between the longer and the shorter baselines to fill the “holes” in the $uv$-coverage. These medium-length baselines can only come from linking the AVN and the EVN to antennas from the central Africa or ECCAS countries.
3. Radio interferometer, VLBI and \(uv\)-coverage

The maximum resolution attainable by a single dish telescope with a diameter \(D\), observing at a wavelength \(\lambda\) is approximately:

\[
\theta \sim \frac{\lambda}{D}.
\]  

(1)

Therefore, to achieve high-resolution observations, the diameter of the antenna must be large or the observing wavelengths must be short. However, different scientific goals require observations at different wavelengths. Thus, to resolve a radio source at a resolution comparable with an optical telescope, astronomers use interferometry and aperture synthesis techniques.

In an interferometer the signals received by every antenna in the array are cross-correlated with each other, either in real-time or off-line, these cross-correlation products are accumulated during a set period which is called the integration time. If the number of antennas is \(N\) then the instantaneous number of correlation during the integration time is \(N(N-1)/2\). Note that the image quality depends on the number of cross-correlated signals. Because the relative orientation of the array and the sources change as the Earth rotates, one can take advantage of the Earth rotation to measure more samples (Fomalont, 1973; Thompson, 1999). This is called aperture synthesis, traditionally known as the Earth rotation synthesis. The use of aperture synthesis techniques give a resolution comparable to that of a single dish telescope with a diameter equal to the longest separation, \(B_{\text{max}}\), between two antennas. Therefore, the \(D\) in Eq. (1) can now be replaced by \(B_{\text{max}}\). In order to achieve a milliarcsecond resolution the network of antennas requires baselines longer than \(10^4\) km. Achieving such a high-resolution observation requires a VLBI technique.

Eq (2) shows the differential of the spatial frequencies measured in wavelength as a function of the baseline vector with components \(L_x, L_y, L_z\) along the axes of the ITRF coordinate system (Bridle, 1999). The baseline is tracking a source at declination \(\delta\) and hour angle \(h\):

\[
\frac{\partial u}{\partial t} = \frac{\omega_e}{\lambda} (L_x \cos h - L_y \sin h)
\]

\[
\frac{\partial v}{\partial t} = \frac{\omega_e}{\lambda} (L_x \sin \delta \sin h + L_y \sin \delta \cos h)
\]

\[
\frac{\partial w}{\partial t} = \frac{-\omega_e}{\lambda} (L_z \cos \delta \sin h + L_y \cos \delta \cos h),
\]

where \(\omega_e = 7.2925\times10^{-5} \text{ rad.s}^{-1}\) is the angular velocity of the Earth. The \(uv\)-coverage is the set of all the projected baseline vectors, \((u, v, w)\) in the Fourier plane or \(uv\)-plane. In other words, the \(uv\)-coverage describes the Fourier transform of the interferometer response toward a source at the phase centre of the observer. An efficient way to fill the \(uv\)-coverage is to add many antenna telescopes together, while making use of the Earth’s rotation, the frequency coverage and antennas layout of the interferometer. The more complete the \(uv\)-coverage, the better the response of the instrument.
Figure 1. Blue points: Locations of the Kuntunse antenna in Ghana, the MeerKAT stations in South Africa and the EVN. Red points: Locations of abandoned old telecommunication satellite facilities in the ECCAS area and/or possible sites to build new radio telescopes.

3.1. Why the missing samples in the EVN + Kuntunse + MeerKAT uv-coverage?

In this section, we discuss the performances in uv-coverage density of the combined Kuntunse antenna in Ghana with the MeerKAT telescope in South Africa, correlated to the full EVN. The full EVN consists of 12 stations across the globe i.e. Badary, Effelsberg, Hartebeesthoek, Jodrell Bank, Medicina, Noto, Onsala, Shanghai, Svetloe, Torun, Westerbork and Zelenchukskaya. Figure 1 shows an African map where the blue points are the Kuntunse antenna, the MeerKAT in South Africa and the EVN. There are some stations of the EVN that do not appear on the map (e.g. Shanghai), these are stations that are in the other side of the globe. The 64 antennas of the MeerKAT do not appear all on the map, this is because the antennas are very close to each other making it difficult to visualise in a bigger scale. The points in red are locations of abandoned old telecommunications satellites in the ECCAS countries or locations suitable to build new radio antennas.

Figure 2 shows the uv-coverage of Kuntunse combined with the MeerKAT and both correlated to the EVN. This uv-coverage is obtained by simulation at a frequency of 16 GHz, during a total period of 10 hours with 1 s integration time and 256 MHz bandwidth divided into channels of 100 kHz each. This uv-coverage is tracking a source at a declination of +45 deg. We made sure that all the antennas are able to see the source at this position. It is clearly seen from this uv-coverage that there are missing samples in the middle area i.e. the area in between the core and the outer core of the uv-coverage. The samples from the core are from shorter baselines; these shorter baselines are the internal baselines of the MeerKAT telescope and the EVN. The samples at the outer core are from the longer baselines; these relate the AVN antennas in the upper hemisphere to MeerKAT and Hartebeesthoek in the southern hemisphere. There are few medium-length baselines coming from the correlation between the antennas in the
upper hemisphere or southern hemisphere to the Kuntunse antenna in Ghana. To fill these missing samples, we need more medium-length baselines. These medium-length baselines can only be obtained if some of the antennas are placed around the equatorial line in Africa. Most of the countries in Africa around the equator are the French-speaking countries or the ECCAS countries. Using simulations we show in this work that if one were to build radio telescopes and/or convert old abandoned telecommunication satellite antennas to radio telescopes in the ECCAS countries no matter where these antennas are to be located in each of these countries, this should improve the current AVN uv-coverage significantly.

4. Existing abandoned telecommunication facilities

The potential for converting obsolete large antennas for radio astronomy has been recognized World-wide. The opportunity exists for African countries to re-use these initially expensive assets that have become redundant with the advent of the optical fiber. Such thrusts in infrastructure revamp could lead to the development of fertile paths for local research in radio astronomy and space science as well as promote science development on the continent, at a relatively low cost. The SKA Africa partner countries that currently host such redundant large antennas are South Africa (3 antennas), Ghana, Kenya, Madagascar and Zambia. Similar large antennas have been located in Algeria (2), Benin, Cameroon (2), Congo Peoples Republic, Egypt (2), Ethiopia, Malawi, Morocco, Niger, Nigeria (3), Senegal, Tunisia, Uganda, Gabon and Zimbabwe. The antenna in Mozambique was dismantled and probably also the one in Togo. Gabon is a country in the ECCAS community currently hosting such idling ground station. We use it here as a benchmark for describing the typical fate of other existing dishes in the ECCAS region. The satellite telecommunication antenna in Gabon was commissioned in early 1973 as a node of access into the global network of Intelsat Satellite Earth Stations. The latter was part of a thrust initiated in the 1960’s when communication via satellites orbiting the Earth was introduced to carry voice, data and TV signals, to supplement undersea cables. The radio bands allocated for these satellite communications were 5.925 – 6.425
GHz for uplink and 3.700 – 4.200 GHz for downlink. These are within the frequency range commonly referred to as “C-band”. Initially a Standard A antenna had to be at least 30 meters in diameter, and the antennas built in Africa from 1970 to 1985 are this size (Gaylard 2014). Exactly as the one in Gabon visible in Figure 5 of Appendix A.

5. Simulations and results

Two simulations are performed using antennas as showed in Figure 1. Firstly, we simulate the uv-coverage using only the 6 antennas of the ECCAS countries i.e. antennas with position marked in red in Figure 1 by evaluating the performance of this single interferometer if this were to be used to observe the sky individually. Secondly, we correlate the 6 ECCAS antennas with the AVN and the EVN. The latter demonstrates the scientific advantages of adding these 6 antennas to the current VLBI network.

5.1. Performance assessment of the uv-coverage of the ECCAS antennas

Figure 3 shows the uv-coverage of the 6 antennas in the ECCAS countries at two declinations. This uv-coverage was simulated during 10 hr total time with 1 s integration time and total bandwidth of 256 MHz divided into channels of width 100 kHz. The positions of the antennas are shown in Figure 1 red points. As expected, the uv-coverage is very poor as the 6 antennas are spread over a large distance. Each of these antennas can function as a single dish radio telescope and can do high level science e.g., observing pulsars, masers, hot gas from the Milky Way or distant galaxies. They will thus significantly broaden the science area of the local Universities. The radio telescope in Ghana has already demonstrated its ability to do real science by observing methanol masers and pulsars. These telescopes can also be used to train local students and also serve as outreach facilities to motivate students and local residents to be interested in science. Finally, the telescopes can join the geodesy, geodynamics and astrometry research with the VLBI network, thereby broadening its scientific research capabilities.
5.2. Filled uv-coverage for ECCAS + MeerKAT + EVN + Kuntunse

This section describes the main results of this paper. The simulation presented in section 3.1 is repeated. This time the MeerKAT telescope, EVN and Kuntunse are correlated to the ECCAS antennas. The full antennas used in the simulation are shown in Figure 1. Figure 4 shows the principal result achieved in this work. The blue points in Figure 4 are data from the EVN, MeerKAT and Kuntunse antenna, while the red points are data coming from the ECCAS antennas and their correlation to the EVN, MeerKAT and Kuntunse. We note that while the 6 ECCAS antennas on their own give poor uv-coverage as presented in Figure 3, they significantly improve the current uv-coverage of the full VLBI network.

6. Conclusion

We conclude that the uv-coverage for a full VLBI observation will improve if few antennas were to be added in the ECCAS region. The resulting Fourier transform of the uv-coverage compactness will only lead to low confusion noise limit which is suitable for high signal-to-noise or dynamic range images requirement. Building or converting old abandoned satellites telecommunication facilities in the ECCAS region is a guarantee that the science results from these antennas will expand the universities international visibility. As part of the VLBI, the scientific community of the ECCAS region will fully be prepared in a strong scientific involvement with the SKA.
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Appendix A: Decommissioned 32 meter large Satellite Earth Station antennas in Gabon

Today, while remaining the property of the state, the idling dish above is part of the infrastructure currently leased to a private operator in the mobile telephony sector. It is located in an area known as Nkoltang, in the Northern part of Libreville. The dish is adjacent to the telemetry ground station used by the French CNES to perform follow up of ARIANE launch from French Guyana. If refurbished, idling satellite Earth station antennas such as the one in Gabon will operate from existing facilities relatively close to cities in relatively populated neighborhood. The issue of relatively high level of pre-existing Radio Frequency Interference (RFI) will therefore need to be dealt with appropriately. Standard procedures currently in place in Kuntunse easily serve as a template. Kuntunse, in Ghana is currently the site hosting the first ever idling ground station in Africa that has been successfully refurbished to become an opera-
tional radio-telescope. In the absence of dedicated protocols, the dominant approach there consists in performing standard flagging during the data analysis with standard packages. Such approach has the advantage to provide further opportunities for building capacity in standard procedures using standard resources often very well supported by the community. Coupled with the advent of MOOC\(^2\) the initial demand on expert human capital as trainers is therefore minimized.

\(^2\)Massive open online course