Optimizing the African VLBI Network for Astronomy and Geodesy

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Abstract

The African VLBI Network will be a pan-African network of radio telescopes comprised of converted redundant satellite Earth-station antennas and new purpose-built radio telescopes. The first of these antennas, in Ghana, is currently being converted to a radio telescope and current funding is estimated to permit the conversion of two more antennas in Africa. These antennas will initially be equipped with a 5-GHz and 6.7-GHz receiver and the next receiver likely to be fitted is a 1.4–1.7-GHz receiver. While it would be advantageous for the AVN antennas to be able to participate also in geodetic and astrometric VLBI observations, there is no funding currently for this. In this paper we re-visit the scientific justifications for the AVN in an attempt to optimize the AVN for each science case, both astronomical and geodetic.

Keywords VLBI, geodesy, astrophysics, instrumentation and methods for astrophysics

1 Introduction

The African Very Long Baseline Interferometry Network (henceforth referred to as the AVN), when initially conceived, was to be a modest network of new-built 12-m class radio telescopes in the African Square Kilometre Array (SKA) partner countries. However, it was discovered that, as a result of new optical fiber connectivity into Africa, many large 30-m class telecommunications antennas were redundant and could be converted for astronomy purposes [3].

Currently the SKA, South Africa (SA), and the Hartebeesthoek Radio Astronomy Observatory (HartRAO) are converting the redundant 34-m telecommunications antenna in Ghana to a radio telescope [1]. The Ghanaian radio telescope will be the second element, HartRAO being the first, of what will become the AVN. There are 29 documented 30-m class telecommunications antennas in 19 African countries (though some antennas were destroyed). It is proposed that more of these can be converted and added to the AVN [3]. Each addition will improve the present global VLBI networks; some will have greater impact than others. Currently there are plans, and limited funding, to convert antennas in Kenya, Madagascar, and Zambia. It is presently proposed that each of these new AVN stations will be equipped with the same receivers as Ghana: a 5-GHz and 6.7-GHz receiver and later a 1.4–1.7-GHz receiver [3, 4]. New radio telescopes may also be built. However, no significant evaluation of the optimization of the AVN has been completed. Such an analysis will inform which to convert first, where to build new stations, and what next-generation instruments and receivers they should have.

We discuss our results from analysis of weather data and assessment of the radio frequency interference (RFI) environment for potential AVN sites. Plots of the *u*-*v* coverage for existing VLBI networks together with potential AVN locations are also presented and we show the impact of AVN antennas on geodetic products through simulated VLBI observations. We discuss the potential contributions the AVN can make to current global VLBI experiments, as well as what a stand-alone AVN can do and where co-location of other geodetic instruments can be implemented.

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2 Site Selection and Evaluation

Currently, the only VLBI-capable radio telescopes in Africa are the 26-m and 15-m radio telescopes at HartRAO, SA. An antenna in Ghana is in the process of being converted for radio astronomy. Telecommunications antennas in African SKA partner countries likely to be converted next are in Kenya, Madagascar, and Zambia. There are also plans for a new radio telescope in Mauritius. The above mentioned sites, referred to as Group 1 (see Table 1), were included in all of our analyses as they are most likely to be converted first. All of our analyses and simulations also include the HartRAO site.

The above mentioned sites were assessed to determine viability for both radio astronomy and geodesy purposes. An excellent site is one where there is low precipitable water vapor (PWV), minimal RFI, provide excellent north-south and east-west baselines, and offer exceptional southern skies viewing. The first two criteria speak to the frequency range in which the facility will operate optimally. The latter three provide a measure of how to best improve present science experiments, e.g., VLBI experiments and southern skies accessibility.

Table 1: Potential sites in Africa selected for our analysis. The diameter of the telecommunications antenna at each site as well as the altitude of the site is listed.

Country	Site	Diam (m)	Alt (m)
Group 1			
Ghana	Kuntunse	32	70
Kenya	Longonot	34	1720
Madagascar	Arivonimamo	32	1450
Mauritius	Cassis	new-build	20
Zambia	Mwembeshi	34	1125
Group 2			
Egypt	Cairo	32	40
Ethiopia	Sululta	30	2725
Morocco	Souk el Arba des Sehoul	30	90
Nigeria	Lanlate	32	670
Senegal	Gandoul	30	50

For the purpose of the *u*-*v* coverage plots and the geodetic VLBI simulations we also included some additional telecommunications antennas that can be converted in Morocco, Egypt, Senegal, Nigeria, and Ethiopia. These sites were chosen strategically in terms of their location in order to optimize the network distribution for a stand-alone AVN. These sites will be referred to as Group 2 (see Table 1) throughout this paper.

3 Weather Data

In order to assess atmospheric effects we used the NASA global numerical weather model GEOS-FPIT [5] that assimilates basically all available satellite, radiosonde, and ground meteorological data. The output of this model, at $0.625^\circ \times 0.5^\circ \times 72$ vertical layers $\times 3^h$ resolution, was used to derive the state of the atmosphere at a regular grid. Using the state of the atmosphere, we computed atmosphere air temperature and atmosphere specific opacity at a set of frequencies using the ITU-R (2013) [6] expressions.

In Figure 1 we present, as examples, the atmospheric opacity time series for the Ghanaian and Kenyan sites. We show results for three frequencies (22, 43, and 100 GHz) for the interval from 01 January 2013 to 08 November 2015, using a step size of three hours.

From the weather data, the Ghanaian site is best suited for low- to mid-frequency operations. HartRAO is an excellent site in comparison to the other proposed sites. For experiments requiring high-frequency observations, e.g., 22-GHz observations, the site in Kenya is favored. Though the HartRAO, Malagasy, and Zambian sites have comparable weather patterns the latter two sites have more extreme variations and would only be useful for higher frequency observations during the winter months.

4 Radio Frequency Interference

A number of precautions can be taken to minimize the effect of human generated RFI, e.g., to choose remote locations away from urban centers and industrial zones and implement radio quiet zones. However, most of the AVN stations are existing facilities close to cities and will operate in an already established environment.

A reliable proxy for RFI measurements can be determined from visual inspection of each site using Google Earth maps, where little infrastructure suggests little RFI. Satellite imagery, taken at an altitude of 4.2

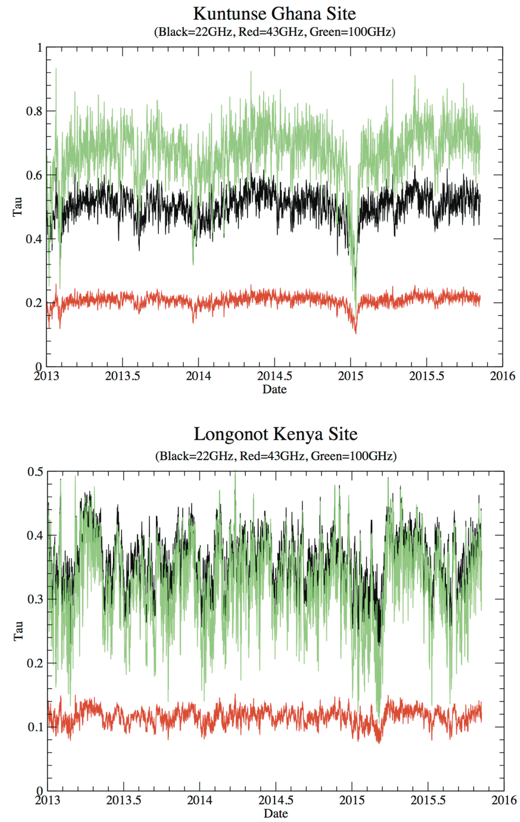


Fig. 1: Time series of atmospheric opacity for the Ghana and Kenya sites at 22, 43, and 100 GHz.

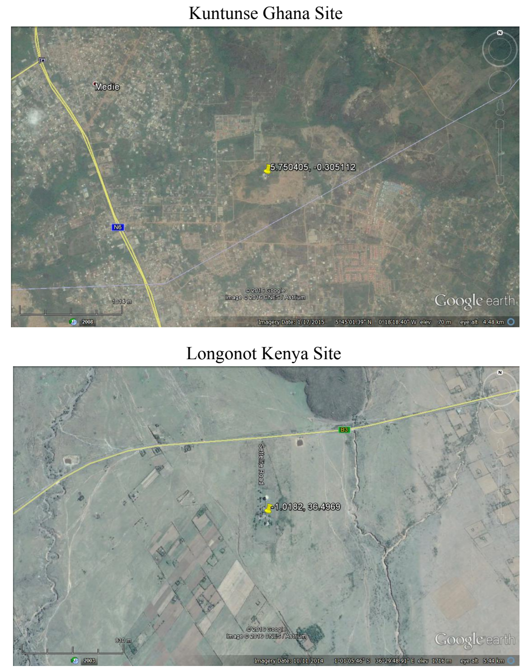


Fig. 2: Satellite imagery for the Ghana and Kenya sites.

km, of the Ghanaian and Kenyan sites are presented in Figure 2 as examples. At 4.2 km the types of dwellings can be identified generally as residential, agricultural, or industrial.

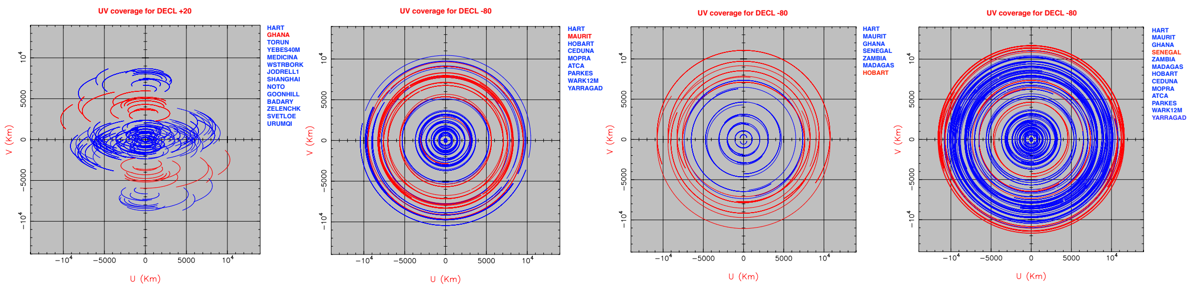
The Kenyan and Zambian sites are in rural settings but each are located in flat areas with no protection, such as the hills surrounding HartRAO. The Ghanaian, Mauritian, and Malagasy sites are in urban areas with significant RFI. All these AVN sites should be characterized for sources of RFI. Since RFI is primarily a problem within the low frequency bands (< 5 GHz), it might be more advantageous for some AVN sites to concentrate on frequency bands at or above 5 GHz.

5 *u-v* Coverage Plots

The HartRAO 26-m radio telescope is valuable in providing long baselines to radio telescope arrays on other continents, e.g., Europe (European VLBI Network, EVN) and Australia (Australia Long Baseline Array, LBA), and thus high angular resolution imaging. However, telescopes that can fill the gap between SA and Europe as well as SA and Australia would substantially increase the image quality.

We generated sample *u-v* coverage plots for existing VLBI networks (EVN and LBA) together with some potential AVN locations, to investigate the possible improvement in the density and the distribution of the *u-v* tracks. The results (see Figure 3 a, b) show that the antennas located roughly half-way between SA and Europe (i.e., Ghana, Kenya, Ethiopia, and Nigeria) provide the biggest improvement, as they fill the gap in *u-v* coverage between the northern EVN antennas and HartRAO. A telescope in Mauritius would be most valuable in filling some of the gaps in the *u-v* coverage between HartRAO and antennas in Australia.

The AVN would greatly facilitate VLBI observations of southern objects. As a stand-alone facility, AVN stations that would make the greatest contributions are in Ghana, Madagascar, Mauritius, Senegal, and Zambia. However, the AVN would still benefit from the long baselines to Australia (e.g., Figure 3 c). An AVN–LBA VLBI network would benefit greatly



(a) EVN + Ghana (b) LBA + Mauritius (c) AVN + Hobart (d) LBA + AVN

Fig. 3: Plots of the *u*-*v* coverage for a source at $+20°$ (a) and $-80°$ (b, c and d) declination, observed over a period of 24 hours. The red tracks show how a telescope in Ghana (a) and a telescope in Mauritius (b) will significantly improve the *u*-*v* coverage in the north and south, respectively. For a stand-alone AVN, an antenna in Australia (e.g., Hobart, c) is still needed for the long-baseline components. A telescope in Senegal (d) will contribute to both the long baselines and filling some of the gap between Australia and Africa.

from another antenna on the West coast of Australia (see Figure 3 d).

6 Simulated Geodetic Observations

In order to assess the influence of the AVN on geodetic products, we scheduled and simulated sessions with different station lists and compared them among themselves and with a state-of-the-art geodetic session (this session was not rescheduled but observations were simulated with the same parametrization). The Vienna VLBI Software (VieVS) [2] was used for scheduling, simulating, and analyzing these sessions.

Figure 4 depicts all the stations which were included in the present analysis. The AVN stations are grouped according to Table 1, the station HartRAO 15 m (Ht) was added and the stations from the session R1675 were used in different setups.

The scheduling parametrization resembles the IVS-R1 sessions as closely as possible. For the simulation of observations the default VieVS parameters (e.g., $C_n = 2.5 \cdot 10^{-7}\ m^{-1/3}$, $H = 2000$ m, $v_e = 8\ m/s$) were used for every station. This does not resemble the true troposphere variability at every site but at the moment there is not enough information about troposphere turbulence at these stations. In order to get statistical information about the estimated parameters, the sessions were simulated 50 times and then analyzed. A standard geodetic analysis was performed with the same models and parameters for every session.

In Table 2 the average formal error and its standard deviation are listed. One can see that adding additional African stations to a typical IVS-R1 session will increase the accuracy of the Earth Orientation Parameters (EOP) by roughly a factor of 2.

Coordinate stability was also examined, but we found no significant differences between the baseline length repeatability of the networks.

Another interesting aspect is the accuracy of source estimates. In the present analysis sources were fixed to their a priori positions but could be estimated session-wise and compared. However, this was not done so far and is subject to future work.

7 Co-location of Geodetic Instruments

There is a scarcity of non-VLBI geodetic instruments in Africa resulting in insufficient data for the International Terrestrial Reference Frame (ITRF). There are only two Satellite Laser Ranging (SLR) systems in Africa: HartRAO and Helwan, Egypt (no longer functional). Global Navigation Satellite Systems (GNSS) stations are the most suitable geodetic technique to densify the ITRF; GNSS stations are low cost, low maintenance, and can operate on solar-powered batteries. It is suggested that each AVN telescope be co-located with at least a geodetic-quality GNSS receiver

Table 2: Average formal EOP errors and their standard deviations.

Network	x_pol (µas)	y_pol (µas)	dut1 (ms)	nutdx (µas)	nutdy (µas)
R1675	41.43 ± 0.95	65.45 ± 1.49	5.12 ± 0.12	26.29 ± 0.60	25.36 ± 0.58
Group 1 + Ht	287.55 ± 6.73	170.87 ± 4.00	16.80 ± 0.39	56.66 ± 1.33	58.53 ± 1.37
Group 1 + 2 + Ht	113.61 ± 1.86	43.80 ± 0.72	7.84 ± 0.13	22.99 ± 0.38	23.64 ± 0.39
Group 1 + R1675	22.54 ± 0.37	30.65 ± 0.51	2.57 ± 0.04	14.69 ± 0.24	15.18 ± 0.25
Group 1 + 2 + R1675	21.78 ± 0.30	22.19 ± 0.31	2.13 ± 0.03	12.50 ± 0.17	12.32 ± 0.17

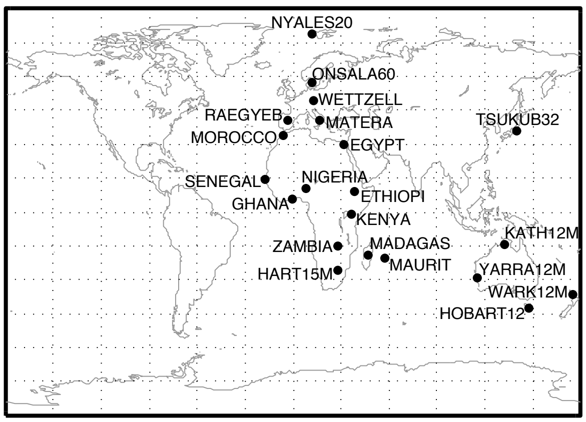


Fig. 4: Map of station positions used in the geodetic simulations. The stations shown in the map are stations from the IVS-R1675 session as well as the AVN antennas from Group 1 and Group 2 listed in Table 1.

and a meteorological station. Suitable stations can also be equipped with a seismometer, accelerometer, and gravimeter.

If funding could be obtained, astronomical VLBI antennas, and specifically new-built VLBI antennas should be considered for geodetic/astrometric work. This would greatly increase the benefit to the hosting nation for several reasons:

- The hosting nation would have a fundamental link to the ICRF, and via the EOP, to the ITRF.
- Such a station would be extremely valuable to the global geodetic community.
- Smaller co-located instruments would be sponsored from global sources at a rapid rate.
- There would be the possibility to eventually become a core (fundamental) site.
- The station would become its country's modern datum defining point, and would allow its realization and contributions to not only the ITRF, but also to the Global Geodetic Reference Frame (GGRF).
- Co-location and geodetic/astrometric VLBI equipped antennas would allow the country to start transforming its (often very dated) geodetic Datum. This would allow for the creation of modern maps, land management, cadastral surveying, and civil engineering, which are all crucial to modern economies.

8 Conclusions

We have investigated the impact on global VLBI networks and found that the AVN will significantly improve each. Antennas in Mauritius and Kenya will greatly improve the EVN and LBA networks, respectively. Co-location of geodetic techniques will best serve the development of the ITRF and African Reference Frame.

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