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An Analysis of Base Station Location Accuracy within Mobile-Cellular Networks

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***Abstract*—An important feature within a mobile-cellular network is that the location of a cellphone can be determined. As long as the cellphone is powered on, the location of the cellphone can always be traced to at least the cell from which it is receiving, or last received, signal from the cellular network. Such network-based methods of estimating the location of a cellphone is useful in cases where the cellphone user is unable or unwilling to reveal his or her location, and have practical value in digital forensic investigations. This study investigates the accuracy of using mobile-cellular network base station information for estimating the location of cellphones. Through quantitative analysis of mobile-cellular network base station data, large variations between the best and worst accuracy of recorded location information is exposed. Thus, depending on the requirements, base station locations may or may not be accurate enough for a particular application.**

***Index Terms*—Mobile-cellular network, Base station, Cellphone, Location, Information accuracy**

I. Introduction

It is well known that the location of a cellphone, and thus the location of its user, can be determined with a certain degree of accuracy. This information can be used to offer various location-based services and creates the opportunity to build new information services that can be useful to both cellphone users and companies. In addition, location information can be used in other scenarios, such as providing law enforcement agencies with tracking data [1]. One example is that of a murder suspect being found by police after inserting his SIM card into the cellphone of a murder victim [2].

Location information can be used to aid police in tracking movements during investigations and locating suspects. However, it can also be valuable in tracing people for humanitarian reasons, such as search-and-rescue teams defining search areas for locating missing persons. By increasing the accuracy of location information the process of finding the cellphone and its user can be made faster, simpler, and cheaper. In borderline cases it can be the difference between finding someone in need of medical attention in time, or catching a suspect who would have otherwise escaped.

Many of the most feasible methods for estimating the location of a cellphone within a mobile-cellular network depends on using the location of network base stations as known reference points from which to calculate the estimated position of the cellphone. The benefit of such network-based approaches is that no modifications to the handset or network are required. However, by using network, handset, or hybrid approaches the accuracy of location information can be improved [1].

This study investigates the accuracy with which the locations of network base stations are known, as inaccuracy can impair the ability of many of the most feasible methods to provide accurate cellphone location estimates. It starts by providing background information on current techniques for determining the location of a cellphone within a mobile-cellular network. Thereafter the research methodology followed in the investigation is discussed, followed by a report of the data collected. Finally, the findings are presented and the implications are highlighted.

II. Background

Many handset and network techniques for determining location exist. The most widely known, using the internal hardware of the cellphone, is satellite positioning using GPS but WiFi, Bluetooth, and augmented sensor networks can also be employed [3], [4], [5]. The accuracy of these techniques can vary depending on the technology, line-of-sight, and sensor network coverage [6]. An improvement is to use such hardware in combination with mobile-cellular network information, such as in the case of Assisted-GPS (A-GPS) which uses network resources in the case of poor signal reception.

In addition new algorithms have greatly improved the accuracy and efficiency with which a cellphone can calculate its position [7], [8]. However, major obstacles including high energy usage and non-availability of features in older cellphones remain. Thus using location methods based primarily on mobile-cellular network information is widespread.

Global System for Mobile Communications (GSM) networks were not originally designed to calculate locations for the cellphones which access and make use of the network. Many methods have been proposed and developed to be retrofitted to existing networks [9]. There are a range of accuracies and costs associated with the various methods. The following are the most feasible methods, in order of increasing potential accuracy.

- Cell identification (Cell ID) is the simplest location estimation method available, but also the least accurate. The estimated area is at best a wedge shaped area, comprising roughly a third of the cell (for three sectored sites), but can include the entire circular area for sites using omni-directional antennas in low-density single sector cells [10].

- Round Trip Time (RTT) is merely a measure of distance from the base station which is calculated from the time taken by a radio signal to travel from the base station to the cellphone and back. It provides a drastic reduction in the estimated location area compared to the Cell ID method for the same site.
- Cell ID and RTT combines the aforementioned methods to provide an estimated location for the cellphone where these areas overlap [11].
- Observed Time Difference of Arrival (OTDOA) uses hyperbolic arcs from three (or more) base stations to estimate the location of a cellphone. These arcs are determined by the distance that the radio signals travel in the measured time (i.e. the difference) [12].
- Angle of Arrival (AOA) is a seemingly practical solution due to its straightforward method of calculating an estimated location from the intersection of the bearings to the cellphone provided by each base station. In practice this method requires expensive antenna arrays, which limit its feasibility despite its potential for high accuracy [10].

It is important to bear in mind that all of the above methods estimate the location of the cellphone, and thus its user, relative to the location of the base station. Next follows a discussion of factors impacting on accuracy and ways of negating these factors.

A. *Factors that negatively impact accuracy*

There are a number of well recognized challenges to accurately determining the location of cellphones. In addition to degrading accuracy these challenges can also increase the cost of estimating location. These challenges include non-line-of-sight and multi-path propagation of radio waves, the near-far effect in Code Division Multiple Access (CDMA) based third generation networks [12], base station density (or lack thereof) and accuracy of base station locations [13], optimisations for network capacity, and the unsynchronised nature of Universal Mobile Telecommunications System (UMTS) type networks [14].

There are varying levels of accuracy inherent to the methods and combinations thereof, as well as the enhancements which have been implemented for a particular method. In order of increasing accuracy: Cell ID (the whole area of a circular cell), Cell ID and sector (the area of the wedge), Cell ID and RTT (circular band), Cell ID and the intersection of multiple RTT determined hyperbolic arcs and A-GPS (outdoor only and which requires GPS functionality to be available in the cellphone) [15]. Pilot correlation method (PCM) has been left out of the list as it can be made as accurate as the fidelity of the spacing of the measurement sites [16].

Certain base stations with low utilisation, in small towns for example, will not be sectored and there will only be one site. It will be possible to obtain a circular band from RTT calculations, but to achieve a more precise location will require adding another measurement technique such as PCM or probabilistic fingerprinting [17].

B. *Methods of improving accuracy*

To address these challenges there are various solutions and enhancements to methods for estimating location that can be employed. Less accurate measurements can be identified and then discarded, re-weighted or adjusted. It is feasible to use more than the minimum number of required data points, other methods which are not impacted by inaccurate measurements, and improving the precision of data by employing high fidelity measurements and oversampling [15]. It is also possible to employ techniques such as forced soft handover and minimising problems by using methods which are not negatively affected by challenges such as non-line-of-sight or multi-path radio wave propagation.

The methods of estimating location can be organised into two groups. The first group consists of those methods which do not depend on base station location and are thus unaffected by the accuracy with which these locations are known. These methods include A-GPS, PCM [16], probabilistic fingerprinting [17], bulk map-matching, and the centroid algorithm [18].

The second group consists of methods which estimate the location of the cellphone and its user relative to the location of the base station and are therefore dependant on the accuracy with which these network base station locations are known. These include the Cell ID based methods of Cell ID, Cell ID and RTT, enhanced Cell ID and RTT, as well as cell polygons and RTT [15]. The Time of Arrival (TOA), OTDOA, as well its enhancements, such as cumulative virtual blanking, are affected in a similar fashion although this may have more of an impact as these methods are meant to deliver greater accuracy than the Cell ID based methods [14]. While not very widespread in implementation, the methods of AOA and the TOA to the Time Difference of Arrival algorithm are also negatively impacted [12].

There are a range of direct and indirect costs that can be attributed to most methods. The greater the work involved in network configuration, the larger the amount of additional hardware, and the more involved the deployment the higher the cost. Some methods require more human intervention to set up, such as PCM and probabilistic fingerprint matching, whilst others might require additional hardware, such as OTDOA requiring location measurement units. There is also the possibility that certain methods will reduce the network capacity. Thus it is vitally important to the network operator that existing infrastructure information (i.e. network base station locations) is as accurate as possible, to minimise and manage further costs to improve accuracy.

In summary, it can be seen that there are many methods of determining the location of a cellphone within a mobile-cellular network. While some of these are not dependent on base station location, the majority of network-based methods are. The accuracy of such data is thus the main focus of this study.

III. Research Methodology

A quantitative analysis of base station information in a Southern African mobile-cellular network was performed. The population consisted of all active base stations that form part of the network. Any base station that was operational on the network (including those that had recently gone live or are scheduled to be replaced) was included due to the possibility that such a base station could participate in estimating the location of cellphones.

To evaluate the accuracy of base stations locations, they had to be evaluated by comparing their recorded locations to observations of their actual locations. For each base station a GPS location in a valid number format was stored in the network database. The method used to measure the base station's actual observed location in order to be able to compare it to the stored value also served to validate the stored value.

As this is a time consuming process it was not performed for all base station sites. Instead the entire population consisting of all available recorded base station locations was sampled. All sub-populations needed to be represented in the sample in order to be able to compare their results for commonalities or differences. Each of the ten regions which comprise the Southern African network were individually queried to find a list of sites that contain operational base stations. The sampling interval was determined by taking the number of sites and dividing it by the desired minimum sample size of thirty base stations for each region. The sampling interval was then rounded down in order to provide some spare sample base station locations in the event of being unable to locate one or more of the selected base stations and having to select another. A sampling method of a random starting number followed by periodic sampling was employed.

For each sample the latitude and longitude was entered into Google Maps [19] with maximum zoom enabled together with the 'Satellite' and 'Show labels' options selected. The resulting aerial photograph was examined to identify the presence of a base station. If the base station could be identified then its position was measured using a set procedure:

- The map was centred on the base of the sampled base station using the 'Right-Click' and 'Center map here' function.
- The latitude and longitude of the map centred on the base station was copied via the 'Link' function.

For each base station that was found by the above process, the following additional information was captured in a spreadsheet to add to the original recorded base station location:

- The base station's location was categorized as serving either: 1) a population centre (city, town, suburb, village, township, commercial or industrial area), or 2) an area outside of a population centre (mountains, road, farms or mines).
- Categorising information was captured for each base station location: 1) technology generation (second and/or third), and 2) equipment vendor.

Fig. 1. Aerial view of palm tree

Fig. 2. 'Street View' of palm tree

- The GPS coordinates of the recorded and measured locations were then used to calculate the difference in metres between the two using the 'Great Circle' method: 1) employ the law of cosines, 2) convert to radians, and 3) multiply by the radius of Earth.

If a base station could not be identified from the aerial photograph then the Google Maps Street View function was used to assist with identifying the base station location. If the base station still could not be detected then it was discarded and the next base station was selected and the identification and measuring process repeated. Reasons for not being able to identify a base station included unclear satellite photographs, the use of camouflage, and multiple base stations in close proximity to each other. An example of the difficulty in identifying structures is illustrated in Figures 1 and 2, which shows an aerial and 'Street View' of a base station camouflaged as a palm tree.

The first stage of analysis consisted of categorising the collected data into various categories, such as geographic region, technology type, vendor, site owner, and whether or not the base station serves a population centre. This was followed by finding the minimum (best accuracy), maximum (worst accuracy), median, average and standard deviation values for the location accuracy data in each category. Accuracy results for base stations were placed into categories of various intervals of accuracy to better allow for evaluation in terms of desired levels of accuracy of the base station locations for

TABLE I
SUMMARY OF ENTIRE SAMPLE

Interval Spacing	STDV	Worst	Best	AVG	Median	Sample Size
5	152.38	1634	0.52	77.04	25.38	369

varying applications.

The preceding steps allowed for comparisons between different categories to see if there were differences or similarities in terms of accuracy. By identifying the base stations sites for which the recorded location accuracy was far worse and categorising them as outliers, these sites could be revisited in an attempt to find out why they differed so markedly to the rest of the base station locations in the category.

IV. DATA ANALYSIS

Due to the nature of how the network database was constructed the location data was both complete and in a valid number format. Accuracy was examined for the entire sample as well as the various categories of base stations. The best, worst, average (AVG) and median accuracies, together with the standard deviation (STDV) were calculated and is shown in Table I.

By starting with a high level overview of all sampled base station locations it is possible to gain an understanding of the range of accuracies for the overall sample population. The data is represented in Figure 3 as a cumulative percentage of the base stations for a given level of accuracy. For example 66.67 percent of base stations have a recorded location that is accurate to within 50 metres of the measured location while 80 percent of recorded base station locations are accurate to within 100 metres of their measured locations.

In a near ideal situation 100 percent of the base station locations would be accurate to less than two and half metres and rounded down, with zero deviation remaining the ultimate prize. This would result in a vertical line at zero metres from zero to 100 percent (of base stations) after which it would then make a ninety degree turn to the right, indicating that all base station locations are accurate to within the distances given on the X axis.

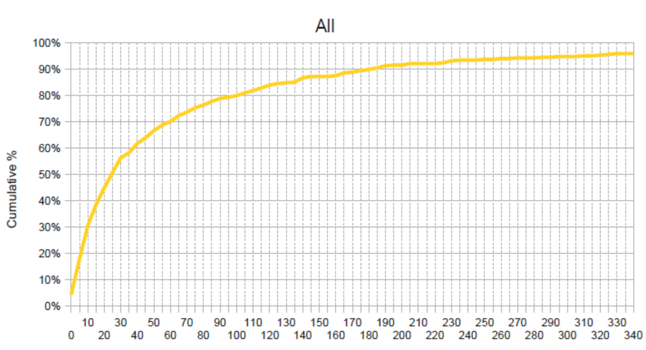

Fig. 3. Entire Sample

Fig. 4. Map of South Africa [20]

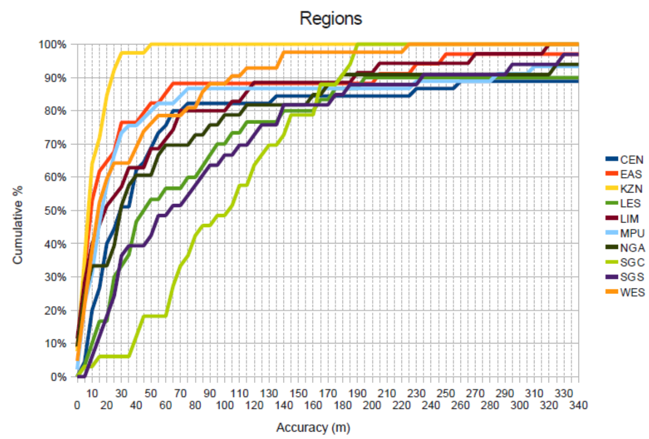

Fig. 5. Distribution per region

A. Regions

The base stations that comprise the sample are situated in ten regions. These regions are Central (CEN), Eastern (EAS), KwaZulu Natal (KZN), Lesotho (LES), Limpopo (LIM), Mpumalanga (MPU), as well as Northern (NGA), Central (SGC) and Southern Gauteng (SGS) and lastly Western (WES). These regions correspond in area to the provinces of South Africa, which are illustrated in Figure 4 for reference. Figure 5 shows the distribution graph for these regions.

The KwaZulu Natal region stands out markedly as having the best average and median accuracy values. It also has the lowest worst accuracy figure, which all told, results in it having the lowest standard deviation.

The Lesotho region has an extremely large worst accuracy figure which results in it having the worst average and the highest standard deviation of all the regions.

The Central Gauteng region stands out for having the highest median value, despite not having a large worst value. The accuracy of the Central Gauteng is lower that of the

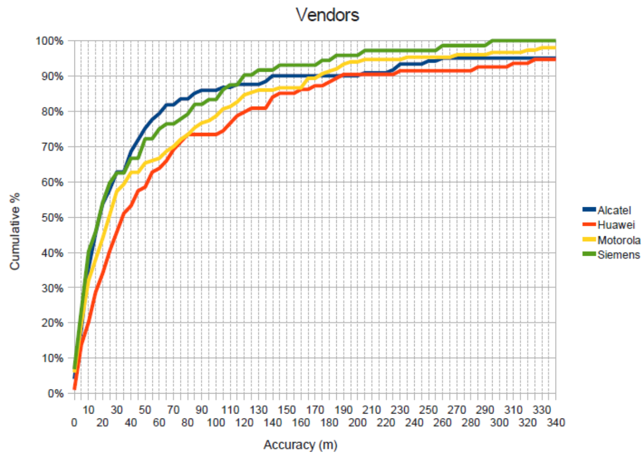

Fig. 6. Vendors

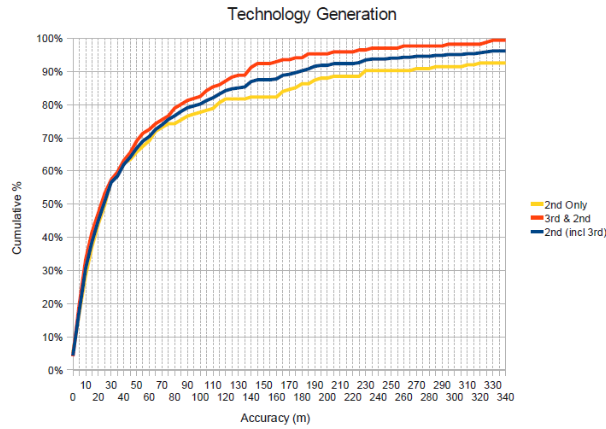

Fig. 7. Technology generation

Lesotho and Southern Gauteng regions for the cumulative most accurate 80 percent of base stations portrayed in Figure 5. It lags the other regions until the 160 metres of accuracy level is reached where it then begins to rapidly surpass the cumulative percentage of the other regions. In addition to the Central Gauteng and Lesotho regions, the Southern Gauteng and Northern Gauteng regions also lag behind the accuracy of the more accurate regions.

B. Vendors

The sampled base stations can also be categorised by the network equipment vendors that supply them. These base station vendors are Alcatel, Huawei, Motorola and Siemens. As before the highest (worst) numbers have been marked in bold and the lowest (best) numbers have been italicised in addition to be marked in bold.

Looking at Table II it is clear that Siemens offers the best overall accuracy of the vendors and Huawei the worst, with Alcatel and Motorola falling in between these two extremes.

However when analysing Figure 6, it is apparent that Alcatel offers the best accuracy for the most accurate cumulative 85 percent of its base stations that were measured (up to 110 metres difference between recorded and measured locations). Only when the last 15 percent of the base stations with accuracies worse than 110 metres are included, is it overtaken by Siemens. The accuracy of the base station location information for Huawei is confirmed as the lowest of the four vendors with Motorola assuming a position between it and the two more accurate vendors.

TABLE II
BASE STATION DATA CATEGORISED BY VENDORS

Vendor	STDV	Worst	Best	AVG	Median	Sample Size
Alcatel	141.77	879.32	***0.52***	68.14	19.98	121
Huawei	133.76	849.44	1.73	**86.8**	**36.59**	94
Motorola	**170.9**	**1634**	1	77.12	25.27	150
Siemens	***62.05***	***296.55***	**1.99**	***47.52***	***19.35***	94

C. Technology generation

When categorising base station locations by technology generation (for example second or third) there are three categories. This is due to co-location of base stations of different generations on the same sites. It is however not a simple 'one for one' correlation but rather a case where a site which has a second generation base station on it may also have a third generation base station on it but the converse is not necessarily true. This results in the three categories of sites:

1) Those with only second generation base stations (2nd Only).
2) Those with both third and second generation base stations (3rd & 2nd).
3) Those with second generation base stations which will possibly, but not necessarily, also include third generation base stations (2nd (incl. 3rd)).

In comparing the sites in Figure 7 it becomes clear that the locations of those sites that contain third (and second) generation base stations are known with better accuracy than those containing only second generation base stations.

Sites that contain second generation base stations, and possibly include third generation base stations, tend to fall in the middle. Unfortunately there is no set of sites that contain only third generation base stations and which would enable the comparison of sites that contain only second generation base stations to those that contain only third generation base stations.

D. Site owner

Base station sites are not necessarily used exclusively by the owner of the sites. This leads to a situation where some base stations are installed on sites that belong to another network operator. The "Own" network sites constitute the vast majority of the sampled base station locations. As such it was necessary to combine the sites from the other vendors into a single category "Other" in order to achieve a meaningful sample size.

According to Table III despite the ”Own” category containing a very large worst accuracy figure and being only slightly worse for best accuracy, it offers better overall accuracy as shown by all other metrics.

When reviewing Figure 8, for any cumulative percentage, the “Own” category has a lower (better) accuracy measure for base stations locations than the “Other” category for at least the first cumulative 95 percent of most accurate recorded locations.

E. Population centres

Base station locations contain base stations that either serve centres of population or the areas in between them. Base stations serving population centres have a higher median value than the those serving the areas between population centres. However, Figure 9 shows that base stations in population centres only have better accuracy once the last (most inaccurate) 15 percent of the base station locations are included.

F. Outliers

Outliers were defined as the ten percent of the total sample with the worst accuracy. Notably this category covers all regions except for the KwaZulu Natal region and with only one base station location for Western region. In Table IV the results for the ten percent least accurate base station locations are presented. Even looking past the ‘Worst’ accuracy figure and instead at the average, median or even the ‘Best’ figures the outlier locations are clearly very inaccurate.

To gain an understanding of why outliers occur and how their accuracies can be so poor, examples of outliers were selected to illustrate the difference in recorded versus measured accuracy.

TABLE III
BASE STATION DATA CATEGORISED BY SITE OWNER

Site owner	STDV	Worst	Best	AVG	Median	Sample Size
Own	151.05	**1634**	**1**	73.07	25.07	318
Other	**161.93**	879.32	0.52	**105.61**	**49.14**	49

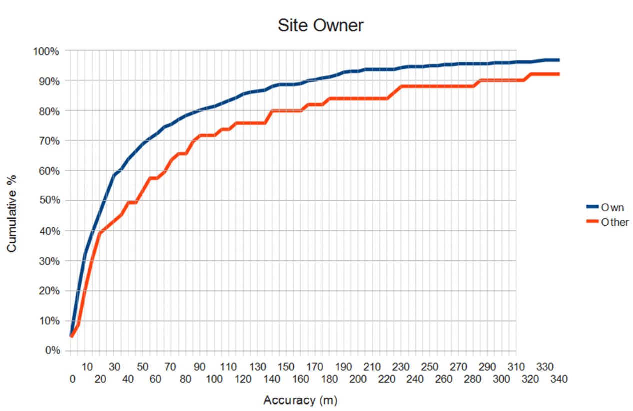

Fig. 8. Site owner

TABLE IV
BASE STATION OUTLIERS

Interval Spacing	STDV	Worst	Best	AVG	Median	Sample Size
25	297.67	1634	178.65	410.15	303.92	38

The location of the access road (marked with a red ‘A’) which is used to reach the base station instead of the location of the base station itself (marked with six red dots) has been recorded in Figure 10. This Northern Gauteng region base station serves a population centre but its location is off by 324 metres.

The Pretoria University building (tagged with Green arrow) in Figure 11 has been recorded instead of the actual location of the base station (indicated by six red dots) on the grounds. This base station serves a population centre in the Northern Gauteng region. It has a difference of 178.5 metres between its recorded and measured locations.

Figure 12 shows that while the recorded location (marked by the red ‘A’) is atop the same mountain in the Central region, it does not follow the track all the way to the base station (circled with red dots). This results in a deviation of 879 metres from the measured location of the base station which serves a

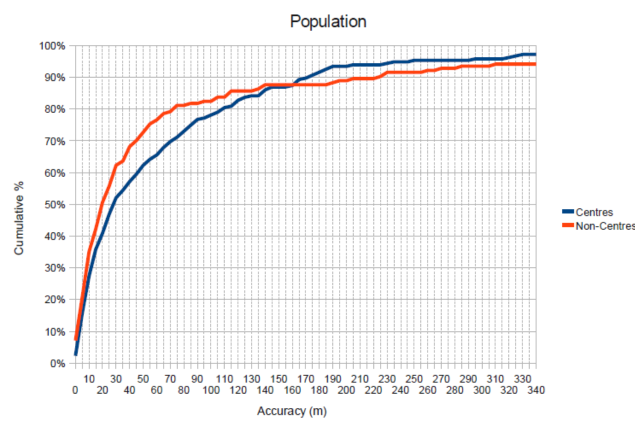

Fig. 9. Population centres

Fig. 10. Watloo Despatch

Fig. 11. Pretoria University

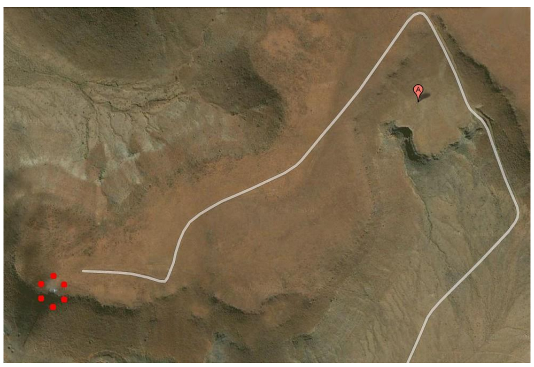

Fig. 12. Carnarvon

population centre at the foot of the mountain.

From the above data several points need to be considered. Firstly, the large outliers and standard deviations for all vendors, technology generations, site owners, and almost all regions. The KwaZulu Natal region was a notable exception to this pattern, proving by example that good accuracy is entirely possible. Secondly, one category could be cumulatively more accurate for the majority of its (more accurate) base station locations but when including its least accurate base stations, these were so inaccurate that its overall accuracy would drop below that of another category. Lastly, the extent of the inaccuracy for the outliers was so great that it warranted further assessment. This revealed the ease with which highly inaccurate locations could be recorded.

V. Conclusions

This paper builds on previous research, emphasising the importance of accurately knowing base station location for cellphone localisation [12], [21]. The nature of this study allows it to be replicated in any country and for any technology type or other category of base station site. The resulting data shows that depending on the requirements, base station locations may or may not be accurate enough for a particular application. This could have serious implications when the data is used for security-related incidents.

Base station accuracies ranged from less than one metre to more that 1600 metres. Fifty percent of base stations were accurate to 25 metres (rounded) and 80 percent are accurate to 100 metres (rounded). However to include 90 percent of base stations it would be necessary to accept base station locations that were off 180 metres (rounded). The deviation of the least accurate ten percent of base station locations ranged from 179 to 1634 metres. The significance of these inaccuracies and their impact would depend on the particular application and its requirement for accuracy. When investigating outliers a discernible pattern emerged, revealing that the given locations were actually the access point, or the access road to the base station was recorded instead of the base station itself.

Network operators can improve the accuracy of the estimated locations that they are able to provide by increasing the accuracy of recorded base station locations. This can be done by analysing and measuring aerial photographs or through taking more accurate measurements when performing routine maintenance, upgrades or equipment swap-outs of base stations.

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