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Continuously Operating Reference Stations (CORS): Transformation between KPLC CORS System and the Kenya National Geodetic System

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Declaration

I, Thiong'o Peter Njuguna, do hereby declare that this project is my original work. To the best of my knowledge, the work presented here has not been presented for an award of a degree in any other institution of higher learning.

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This project has been submitted for examination with our approval as University Supervisors.

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Mr. Sammy Mwangi Matara	…………………..	….……………….

ABSTRACT

Advances in GNSS technology such as multiple constellation, receiver capability, improved software as well as new measurement techniques have increased the applications of GNSS in positioning. The need to continuously observe and measure using GNSS technology has led to the installation of Continuously Operating Reference Stations (CORS) around the world that provide real-time and accurate positioning for geodetic and other applications. In Kenya, several organizations have installed CORS for improved location accuracy in support of their operations. Kenya Power and Lighting Company (KPLC) is one such organization, currently with 15 CORS stations installed at various sites across the country. KPLC uses its CORS primarily to improve the accuracy of data in support of geospatial data management for its utilities. The KPLC CORS has the potential to support surveying within the company and beyond and thus can potentially generate more revenue to the company. To achieve this, it is necessary to establish the transformation parameters between the KPLC CORS Coordinate system (ITRF 2008) and the Kenya national geodetic system (UTM Arc 1960 datum) which is the official datum for surveying and mapping purposes. In addition, knowledge of transformation parameters between the two systems will make it possible for datasets in the two systems to be used on a common GIS environment through appropriate transformations. Six sets of coordinates of common points in the two systems were used to compute the transformation parameters using the Bursa-Wolf transformation. Coordinates data for the common points in the Kenyan geodetic system were acquired from the Survey of Kenya, while the coordinates in the KPLC CORS system were observed using geodetic quality receivers, post-processed and adjusted using KPLC CORS. The transformation parameters between the two systems comprising of three translations parameters, three rotation parameters and a scale factor were then determined. The translations in X, Y and Z axes were found to be -198.084m, -6.207 m and -10.275 m respectively, rotations about X, Y and Z axes are 1.21 arc seconds, 7.24 arc seconds and -6.16 arc seconds respectively, and the scale factor is 2.985 ppm. It was established that the differences in post-processing and adjustment results using a single CORS station and multiple CORS stations were small, averaging 0 ° 0' 0.0014 arc seconds in latitude, 0 ° 0' 0.0003 arc seconds in longitude and 0.025 m in height. The transformation parameters so determined needs to be tested for validity using test data, which was not available at the conclusion of the project. Further research involving more common points and a wider geographic extent is recommended.

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TABLE OF CONTENTS

List of Tables

List of Figures

ACRONYMS

AC - Analysis Centre

AFREF - African Geodetic Reference Frame

CIGNET - Cooperative International GPS Network

CORS - Continuously Operating Reference Stations

DC - Data Centre

DORIS - Doppler Orbitography and Radio positioning Integrated by Satellite

ESA - European Space Agency

FDB – Facilities Database

GIS – Geographic Information System

GGOS - Global Geodetic Observing System

GNSS - Global Navigation Satellite System

GPS - Global Positioning System

GRS – Geodetic Reference System

IAG – International Association of Geodesy

IERS – International Earth Rotation and Reference System Service

IGS - International GNSS Service

IPCU – Iron Pin in Concrete Underground

ITRF - International Terrestrial Reference Frame

KPLC – Kenya Power and Lighting Company Limited

MEO-Medium Earth Orbit

NGS - National Geodetic Survey

NOAA - National Oceanic and Atmospheric Administration

NRTK – Network RTK

NSRS - National Spatial Reference System

NTRIP - Network Transport of RTCM by Internet Protocol

OCS- Operational Control Segment

OPUS - Online Positioning User Service

PIVOT – Progressive infrastructure Via Overlaid Technology

PPM – Parts Per Million

PPP – Precise Point Positioning

RCMRD- Regional Centre for Mapping of Resources for Development

RINEX – Receiver Independent Exchange Format

RTAC – Real-Time Analysis Centre

RTCM - Radio Technical Commission for Maritime Services

RTCM-SSR - RTCM-State Space Representation

RTK-Real Time Kinematic

RTS – Real Time Service

SLR - Satellite Laser Ranging

SoK – Survey of Kenya

TPP – Trimble Pivot Platform

UFCORS – User Friendly CORS

USACE – U.S. Army Corps of Engineers

USCG – U.S. Coast Guard

USGS – United States Geological Survey

VLBI - Very Long Baseline Interferometry

WAAS- Wide Area Augmentation System

WADGPS – Wide Area Differential GPS

CHAPTER 1

INTRODUCTION

1.1 Background

Most applications of Global Navigation Satellite Systems (GNSS) technology in surveying, mapping, engineering and related disciplines have accuracy requirements that require the use of relative positioning techniques. GNSS reference stations provide GNSS observational data required for relative positioning as well as generation of satellite ephemerides and clock correction data, earth and atmospheric studies and monitoring of crustal motions. In order to simplify the process of relative GNSS positioning, many international organizations, academic institutions and national mapping agencies have established Continuously Operating Reference Stations (CORS) that are configured to continuously collect and record GNSS data. One such organization is the U. S. National Geodetic Survey (NGS). NGS manages the development and operation of a network of continuously operating reference stations (CORS) owned and operated by different organizations to establish precise geodetic control and for the definition and realization of the National Spatial Reference System (NSRS).

The International GNSS Service (IGS) uses a network of GNSS tracking stations to achieve its mandate. The mission of IGS is to "provide the highest-quality GNSS data and products in support of the terrestrial reference frame, Earth rotation, Earth observation and research, positioning, navigation and timing and other applications that benefit society" (https://kb.igs.org/hc/en-us/articles/201950526-IGS-Terms-of-Reference) [accessed on 16 January 2019]. IGS achieves its mission using a worldwide network of tracking stations that provide continuous tracking using high accuracy receivers. IGS collects, archives and distributes GNSS observational data sets that are of sufficient accuracy to support a wide range of scientific objectives and needs such as realization and improvement of a global International Terrestrial Reference Frame (ITRF), climate studies and research, satellite orbit determination and earth rotation monitoring. Currently, IGS has 3 CORS stations in Kenya, namely RCMN in Nairobi, MOIU in Eldoret and MAL2 in Malindi. Figure 1.1 shows the IGS stations in Kenya.

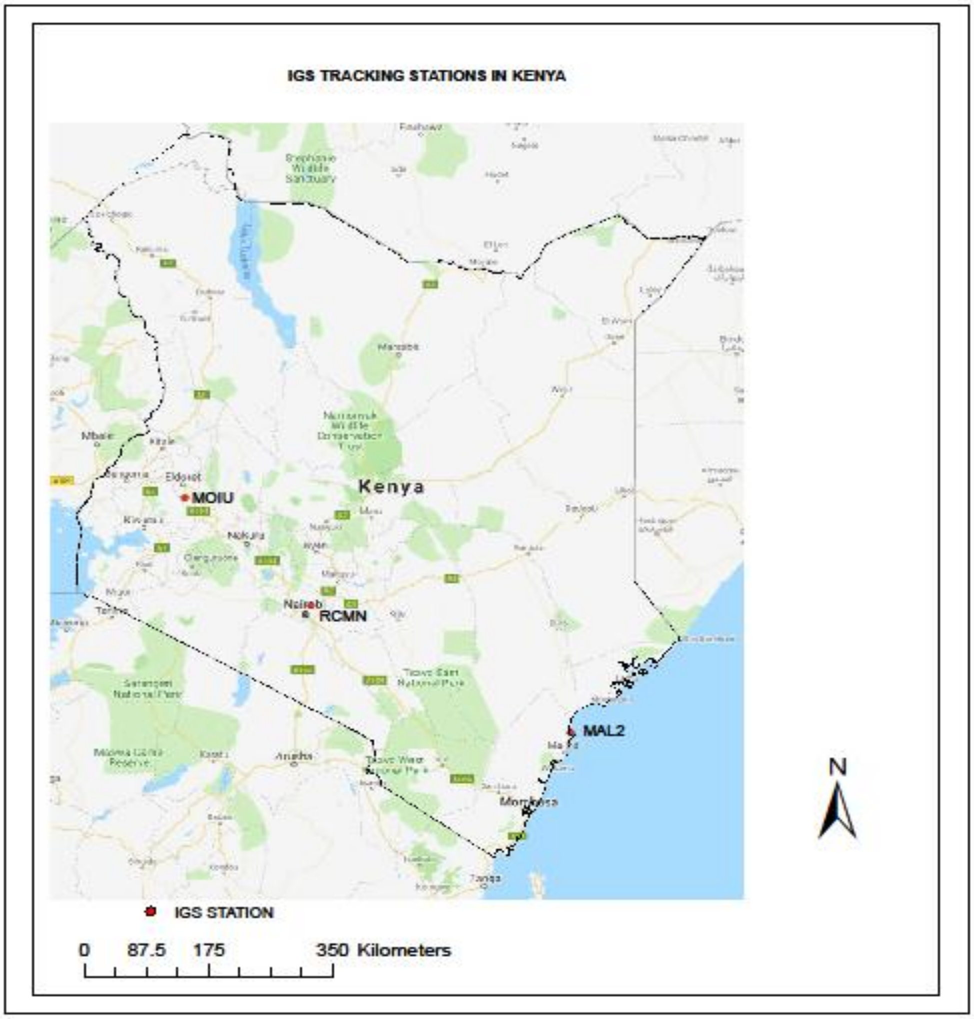

Figure 1.1: IGS CORS Stations in Kenya (IGS)

CORS provide Global Navigation Satellite System (GNSS) data consisting of carrier phase and code range measurements. This data is used in a wide range of areas such as three-dimensional positioning, meteorology, surveying, engineering, utility industry and scientific research. Surveyors, engineers, scientists, GIS experts and the public that collect GNSS data can use CORS data to improve the precision of their positions.

All GNSS-based positioning techniques operate under a set of constraints (Rizos, 2002) such as baseline length, geometrical strength, achievable accuracy, availability of satellite signals, time for a solution fix, instrumentation, assured reliability, modes of operation among others. Single base RTK systems provide high performance in terms of achievable accuracy, time to get a solution, generation of real-time solutions and are cost-effective. Due to these capabilities, the use of RTK systems in positioning is widespread. However, the 10-15km baseline constraint necessitates the development of an infrastructure of base stations to support users to overcome this baseline restriction. However, it is not realistic to deploy reference receivers throughout a country or region dense enough so that all users are within 10-15km of a reference receiver. To overcome this, Network RTK techniques, which are the basis of the CORS concept, are deployed. Network RTK technique allows base station separations of several tens of kilometres, which reduces the number of reference stations required.

The development of Network RTK has been influenced by three technological developments: The first of these developments is the evolution of advanced GNSS Surveying techniques that preserve single-base RTK performance for larger inter-receiver distances. The shift from single reference to multi-reference station approach has allowed for the empirical modelling of distance-dependent measurement biases. Secondly, GNSS Geodesy has evolved to become a powerful, ultra-precise positioning technique in support of a wide range of applications that includes: definition of geodetic framework, tectonic motion measurement, and scientific research among others. GNSS Geodesy uses a multiple receiver data processing technique where all measurement biases are accounted for through double-differencing of carrier phase observables.

Finally, WADGPS and WAAS techniques employ sparse networks of reference base stations as the basis of their operations (Lachapelle et al., 2002). Data from these sparse reference station networks are streamed to a central control centre that generates empirical models of the distance-dependent biases in the form of ‘corrections’. The corrections are then transmitted to users over a wide geographic area through communication and data links. However, since these Augmented GNSS techniques make use of pseudo-range data and large inter-station distances ranging from hundreds to several thousands of kilometres, the attainable positioning accuracy is of sub-decimetre level. Thus in order to achieve a significant improvement in accuracy, Network RTK is desired as well as the densification of reference stations.

In Kenya, various organizations and agencies have established CORS stations and networks in fulfilling their needs for improved positioning. One such organization is KPLC, which currently operates a network of 15 CORS stations distributed throughout the country. These reference stations comprises of Trimble NetR9 GNSS receivers and Trimble Zephyr 3 geodetic antenna, and are managed using the Trimble Pivot Platform (TPP) software. The KPLC CORS network is tied to ITRF 2008 Reference Frame and Somalia tectonic plate. Currently, the CORS network is being used to enhance the accuracy of data collected for the utility company's electricity network in support of its business objectives. There is real possibility of extending the use of the KPLC CORS network to support surveying and mapping in the Kenyan geodetic system (UTM Arc 1960). In order for this to happen, it is necessary to investigate the relationship between the CORS system and the national geodetic system so that the transformation between the two systems can be realized. In order to achieve this, it is necessary to obtain the coordinates of control points established in the Kenyan geodetic system using the KPLC CORS and establish the transformation parameters between the two systems. Once the transformation parameters between the two systems has been determined, KPLC CORS can be used to do surveying in the Kenyan geodetic system by offering correction services to users at a premium, which can increase the revenue of the company and at the same time benefit many users. The surveying community can also benefit from the CORS infrastructure as they would only need to invest in GNSS rovers only without the need to invest in base stations. In addition, the knowledge of the transformation parameters between the two systems will enable the use of the two datasets on a common system by enabling transformation from one system to another in a geographic information system (GIS) environment. Through a CORS network approach and integrated use of communication systems within them, precise and accurate positioning solutions in real time and post-processing is achievable. Figure 1.2 shows the KPLC CORS stations.

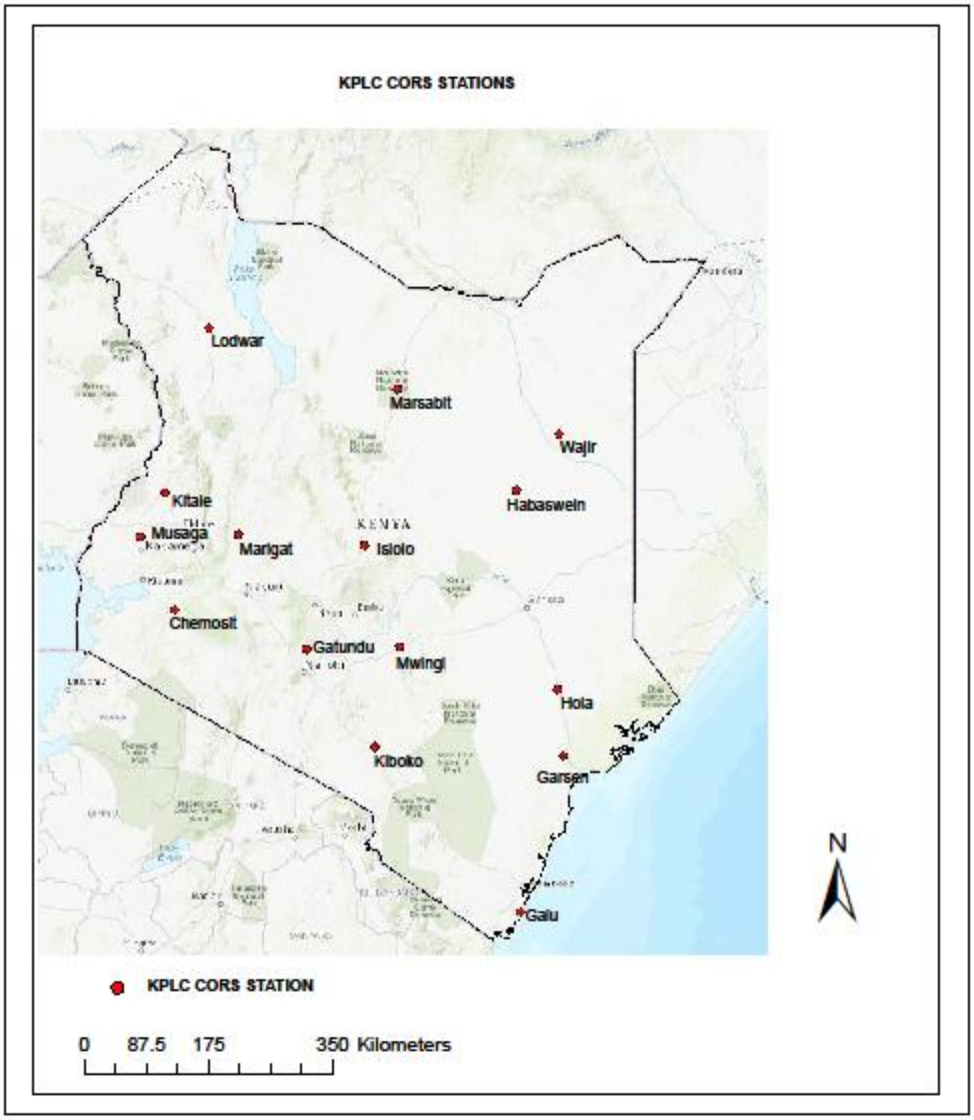

Figure 1.2: KPLC CORS

1.2 Problem Statement

Continuously Operating Reference Stations (CORS) offers an important enhancement to a wide range of GNSS applications. There is growing interest in the installation and use of CORS by various organizations and agencies in Kenya to improve the accuracy and precision of spatial data. KPLC is one such organization that operates CORS primarily to improve the accuracy of its data products for better utility management in its GIS platform called Facilities Database (FDB). In order to leverage on the existing CORS infrastructure, there is need to explore the application of CORS in surveying and mapping by determining the transformation parameters between the KPLC CORS system and the Kenya national geodetic system which is the official coordinate system for surveying and mapping in Kenya. This research proposal seeks to establish the transformation parameters between the KPLC CORS system and the Kenya national geodetic control system.

1.3 Objectives

1.3.1 Main Objective

To compute the transformation parameters between KPLC CORS Coordinate system (ITRF2008) and the Kenya National Geodetic Control System (UTM ARC 1960)

1.3.2 Specific Objectives

1. Establish the transformation parameters between the KPLC CORS system and the Kenya national geodetic system
2. Compare post-processed observations by use of a single reference station (Gatundu) and multiple reference stations

1.4 Justification for the Study

Advances in GNSS technology have led to the emergence of new technologies in support of the ever increasing applications of GNSS across many fields such as surveying, agriculture, utility industry, mapping, engineering applications, transportation, neotectonics and navigation. One such technology is the Continuously Operating Reference Stations (CORS). CORS improve the efficiency and accuracy of the data products it supports and extends the GNSS applications through a host of derived data products. It offers many advantages over other positioning methods such as provision of wide coverage, eliminates the need for setting up a base station, provides users with a stable and consistent coordinates reference frame and enhances the performance and quality of field data. In Kenya, there are several CORS stations that have been established by various organizations and agencies. One such organization is KPLC, which operates a network of 15 CORS stations that are being used primarily to improve the accuracy of geospatial data in the GIS platform. However, the CORS network has the potential to support other applications such as surveying and mapping in the Kenyan geodetic system, the official coordinate system for surveying and mapping in Kenya. This has the possibility of generating more revenue for the company and optimizing its return on investment to the company while benefitting the surveying community. In order to apply KPLC CORS in surveying in the Kenya geodetic system, it is necessary to establish the transformation parameters between the KPLC CORS system and the Kenya geodetic system. Furthermore, knowledge of the transformation parameters will enable the use of data sets in the two systems on a common GIS platform through the application of appropriate transformations.

1.5 Scope of work

The project scope involved establishment of common points in the Kenyan geodetic system and the KPLC CORS system within Nairobi, Machakos and Kiambu counties. The control points were limited to a radius of 100km from Gatundu base station. However, the control points identified on site are within a radius of 50 km from Gatundu CORS. The control points identified were observed using GNSS geodetic rovers and the resulting observations adjusted and post-processed using KPLC CORS, first by using Gatundu CORS alone and then using all the 5 CORS available during the period of observation. The coordinates obtained using multiple CORS reference stations were used to compute the transformation parameters between the KPLC CORS systems and the Kenyan Geodetic system using Bursa-Wolf 7-parameter transformation.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 GNSS Overview

2.1.1 GNSS Systems

The Global Navigation Satellite System (GNSS) refers to all constellations of satellites that provide signals from space that transmit positioning and timing data to GNSS receivers. Operational GNSS constellations include Galileo, Global Positioning System (GPS), GLONASS and BeiDou.

2.1.2 Global Positioning System

The Global Positioning System (GPS) is owned by the United States government and is operated by the U.S. Air Force. It provides continuous, accurate, three-dimensional position, navigation and time information to user receivers worldwide. GPS comprises of the space segment, the control segment and the user segment. Figure 2.1 illustrates a GPS Constellation.

Figure 2.1: GPS Constellation

2.1.3 GLONASS

GLONASS is a space-based navigation satellite system that provides users with reliable positioning, navigation, and timing services on a continuous basis worldwide. It is based on 24 satellites using 12 frequencies. GLONASS signals have the same polarization and comparable signal strength as GPS signals. The GLONASS constellation provides visibility to a variable number of satellites depending on the user's location. A minimum of four satellites in view allows a GLONASS receiver to compute its position in the GLONASS Reference System in three dimensions using satellite technology based on triangulation principles, and to synchronize with the system time. It is an alternative and complementary to other GNSS systems constellations.

2.2 Relative Positioning

The use of two or more GNSS receivers makes relative positioning possible. Use of several GNSS receivers stationed separately to observe from the same satellites simultaneously yields extensive correlations between the observations. This results in better accuracy than using point positioning. Two receivers operating simultaneously and receiving signals from the same satellites records similar errors since the distance between the two receivers is shorter compared with the altitude of the satellites.

2.3 Some GPS Surveying Techniques

Several GPS surveying methods are in use today.

2.3.1 Real Time Kinematic (RTK) Positioning

This is a relative positioning technique that uses two or more GNSS receivers tracking the same satellites simultaneously. This technique is appropriate for providing the location of unknown points within a radius of 15-20 km of a known point in real time. The base receiver remains stationary over the known point. The base receiver measurements, coordinates and antennae height are transmitted to the rover receiver through a radio link. The rover combines and processes the GPS measurements collected at the base and rover receivers using the built-in software to obtain the rover coordinates in real-time. The expected accuracy in positioning is of the order of 10 mm + 1 ppm (rms) for the horizontal component and 20 mm + 1 ppm (rms) for the vertical component. Figure 2.2 illustrates RTK positioning technique.

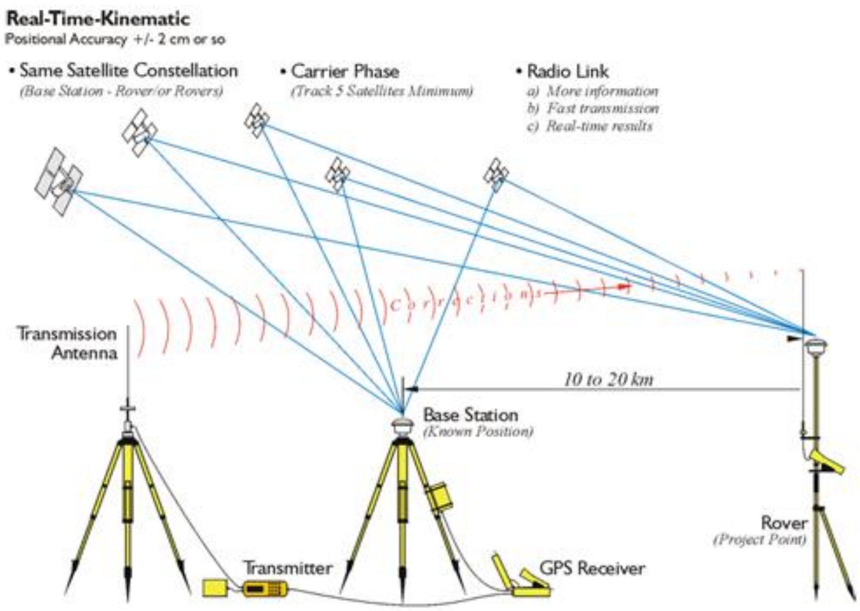

Figure 2.2: RTK Positioning (Van Sickle, J., 2008)

2.3.2 Network-Based RTK

The limitation of single-base RTK positioning is that the distance between the base station and a rover receiver is limited to10- 20 kilometres (Rizos 2003), for reliable and adequate resolution of carrier phase ambiguities. When this distance limit is exceeded, the errors at the base station and the rover receiver become less correlated and will not be properly resolved through double differencing. However, these errors can be modelled accurately by use of several GNSS reference stations to observe simultaneously. This enables RTK positioning to be extended from a single base to a multiple base technique. NRTK increases the baseline among reference stations from 15-20km up to 70km or even longer. In doing so, NRTK reduces the number of reference stations required, which results in significant cost reduction to the operators and service providers (Wanninger 2006).

2.3.3 Static Surveying

This technique involves several stationary GNSS receivers simultaneously collecting data from the same satellites. At least four satellites are required and the observation durations range from

30 minutes to 2 hours. This technique yields accuracies in the range of 1 ppm – 0.1ppm over tens of kilometers. It is the primary GPS surveying technique in use today.

2.4 Continuously Operating Reference Stations (CORS)

2.4.1 CORS History and Evolution

This section provides a history in the development and use of CORS technology by leading organizations and the current developments in the application of CORS.

2.4.1.1 NGS and CORS

Continuously Operating Reference Stations (CORS) system history can be traced to the National Geodetic Survey (NGS) of the U. S. Department of Commerce’s National Oceanic and Atmospheric Administration (NOAA). NGS defines and manages the National Spatial Reference System (NSRS), the official geographic coordinate system for the United States. The NSRS defines latitude, longitude, height as well as other geodetic parameters that support a broad range of three-dimensional positioning applications. For about two centuries, realization and access to NSRS system has been through monumented ground control stations. The horizontal and height coordinates of these control points have historically been determined through mechanical and optical surveying methods, and geodetic computations. Over the last few years, the realization and access to the NSRS has been through modern applications of GNSS.

During the early stages of GPS development, NGS recognized that the Global Positioning System (GPS) had the potential to contribute towards the realization and enhancement of the National Spatial Reference System. Upon this discovery, NGS began to deploy GPS equipment and field techniques that would improve the NSRS in the late 1980s. The traditional surveying techniques that applied line-of-sight equipments were replaced with three-dimensional GPS techniques. From 1987, NGS in collaboration with other organizations, state and federal agencies established a high accuracy reference network (HARN) in each of the 50 states. These state-wide HARNs were incorporated into a more accurate and sparse network spanning across the nation, whose coordinates were also determined using GPS techniques, first in the year 1987 and again in the year 1990 (Soler et al. 1992).

In order to carry out accurate HARN surveys, the Cooperative International GPS Network (CIGNET) was introduced by NGS in 1986 (Chin et al. 1987), which is the precursor of the

CORS network. Each station of the CIGNET network was equipped with a high quality dual-frequency GNSS receiver capable of continuously recording signals from GNSS satellites. The CIGNET network was gradually augmented by NGS, resulting in the first public global GNSS network that has evolved into the current IGS network that falls under the auspices of the International Association of Geodesy (IAG). The concept to have a network of CORS stations covering the entire United States was first postulated by Strange (1994). Around the year 1995, several federal agencies such as the US Coast Guard (USCG), the Federal Aviation Administration (FAA) and the U.S. Army Corps of Engineers (USACE) started to establish networks of continuously operating reference stations. The U.S. Geological Survey (USGS) and NASA's Jet Propulsion Laboratory (JPL) and were also using CORS technology in crustal motion studies and in the determination of satellite orbits.

Eventually, CORS stations that were originally part of CIGNET were incorporated into the CORS network. Data from these reference stations were made available to users via the Internet. Selected U.S. permanent GPS base stations were continually added to the NGS CORS network. By December 1997, NGS CORS network had expanded to 108 stations. The NGS CORS network continued to grow, surpassing the 200-site milestone in the year 2000. In 2001, NGS developed a Web-based utility service known as Online Positioning User Service (OPUS) as a way to enhance the functionality and value of the CORS network. This utility enables users to determine their positions relative to the CORS network in an automated manner. A user only needs to observe GNSS data at a given location of interest, and then upload the observations to the utility. UFCORS is another Web-based utility that supports download of CORS data. NGS has provided guidelines for establishing CORS stations (NGS 2006) and carried out an upgrade on its GPS analysis software (PAGES). The NGS National CORS system has become the preferred method for providing accurate three-dimensional positioning in the United States and other foreign countries. As of August 2015, the NGS CORS network comprised of almost 2,000 stations, contributed by over 200 different organizations, and the network continues to grow.

Figure 2.3 is a map showing the NGS CORS network map as at January, 2019. [Source NGS: https://geodesy.noaa.gov/CORS_Map/]

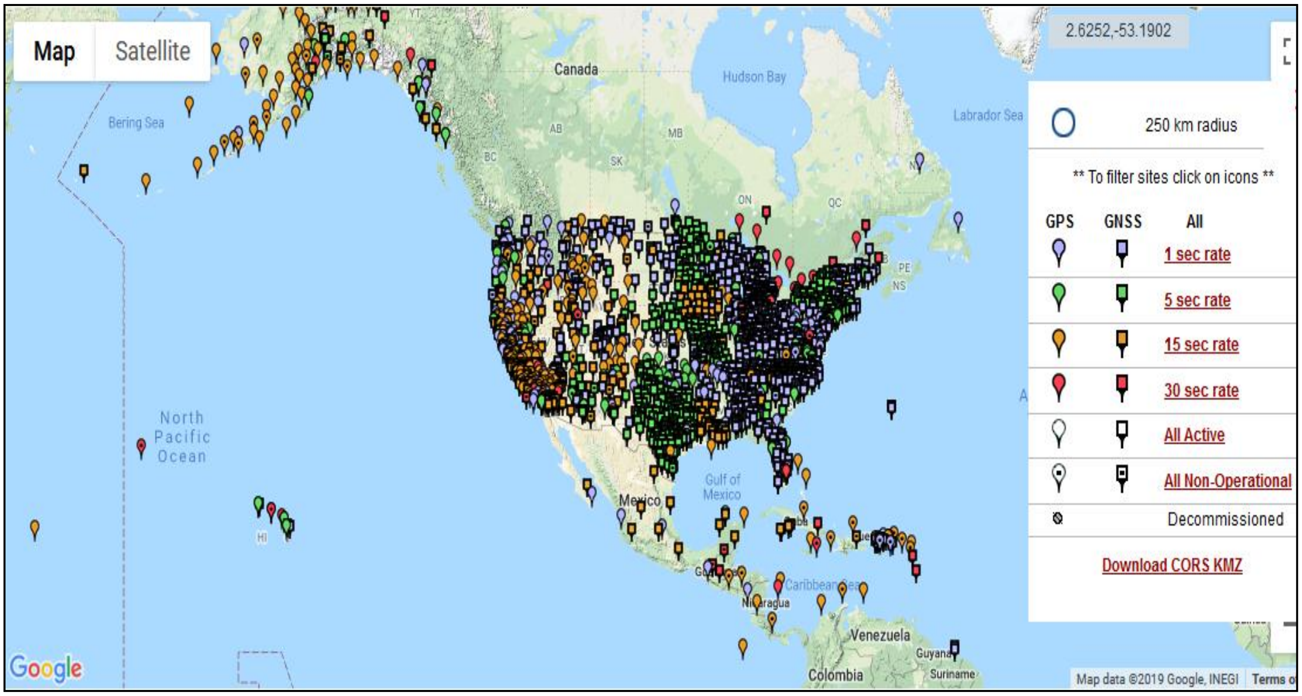

Fig. 2.3: NGS CORS Map

2.4.1.2 IGS and CORS

The International GNSS Service (IGS) is a voluntary federation comprising of over 200 agencies, research institutions and universities all over the world. It was established in 1992 and was formally launched on 1st January 1994. IGS "collects, archives, and freely distributes Global Navigation Satellite System (GNSS) observation data sets from a cooperatively operated global network of ground tracking stations" (http://www.igs.org/network/information) [Accessed on 16 January 2019].

The IGS stations "provide continuous tracking using high accuracy receivers and have data transmission facilities allowing for rapid (minimally: daily) data transmission to the data centers" (http://www.igs.org/network/information) [Accessed 16 January 2019].

IGS promotes expertise sharing culture that encourages global best-practices for developing and delivering GNSS data and products worldwide. IGS develops and releases to the public a set of standards, guidelines and conventions that guides the collection and use of GNSS data and products as a way of supporting best-practices amongst the user community globally. The benefits of being a contributing member of IGS includes enhanced accuracy of the reference frame in the member's region of interest, enhanced accuracy of GNSS products, and a more accurate determination of transformation parameters between the realization of ITRF and the respective national datum.

IGS is a key member of the Global Geodetic Observing System (GGOS) and performs three important roles: The first role is to provide a linkage between the other techniques that comprise the global geodetic observing network i.e. Satellite Laser Ranging (SLR) systems, Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS) ground beacons, and Very Long Baseline Interferometry (VLBI) telescopes. These linkages are fundamental to the realization of the International Terrestrial Reference Frame (ITRF). The establishment and maintenance of VLBI and SLR equipment requires huge investment costs, and direct co-location of VLBI, DORIS, and SLR is not always viable. As a result, IGS provides a cost effective means of linking these techniques geometrically. The second role of IGS is to densify and improve the geometry of distribution of the global geodetic network (ITRF) to allow accurate modelling of satellite orbits and clocks, monitoring atmospheric behaviour and other earth processes such as neo-tectonics.

ITRF provides an accurate and consistent datum that facilitates the referencing of positions at different times and in different locations all over the world. The realization of ITRF through IGS extends the number of stations significantly and thus makes the reference frame easily accessible. The third role of IGS is to enable the user segment to access the ITRF. This is especially important due to continued improvement in accuracy of publicly accessible GNSS products, as well as the need to establish the relationship between ITRF and national datums. The stations in the IGS network must meet the minimum set of physical and operational standards as defined by the "Current IGS Site Guidelines" on (https://kb.igs.org/hc/en-us/articles/202011433) in order to guarantee continuous tracking of GNSS data for high accuracy. Figure 2.4 shows station locations of IGS global tracking network. (Source: The International GNSS Service, pg. 4).

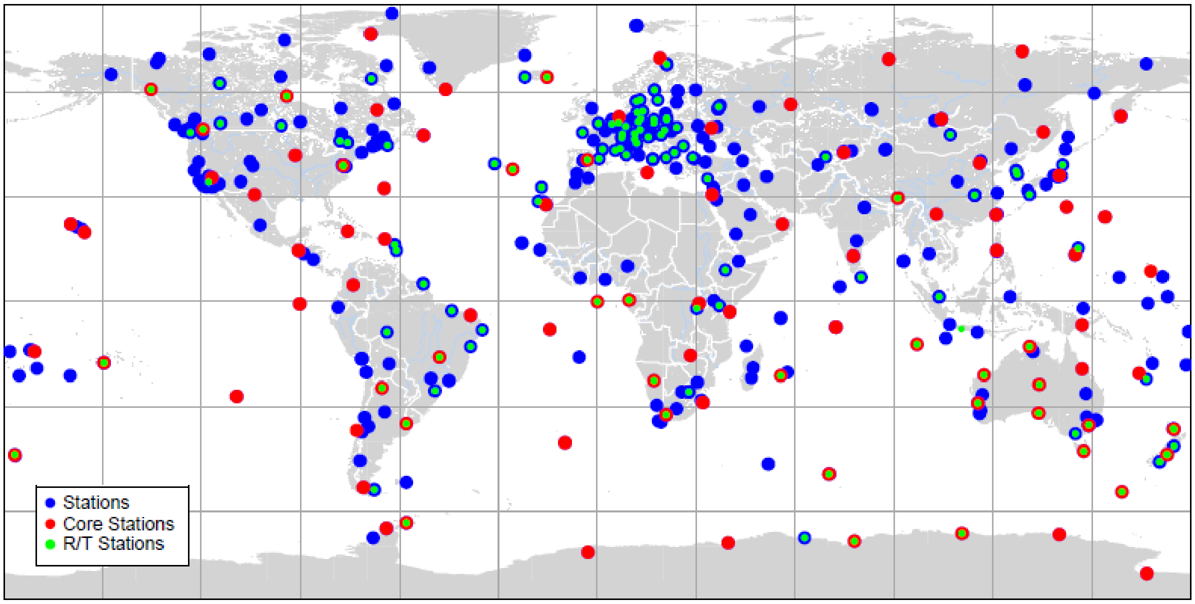

Figure 2.4: IGS Global Tracking Stations (International GNSS Service)

The IGS network in Fig. 2.4 comprises of a well-distributed subset referred to as “reference frame stations” symbolized in red. This subset is called the IGb08 core network and is recommended for alignment of global solutions to the IGb08 reference frame so as to mitigate the aliasing of station non-linear motions into transformation parameters.

IGS reference frame stations provide the highest GNSS quality in the world (IGS). This quality has a direct impact on the accuracy levels that are achievable by using the ITRF. Currently, IGS network comprises a global network of over 450 permanent and continuously operating stations of geodetic quality. These stations track signals from GPS, GLONASS, Galileo, BeiDou, QZSS as well as Space-Based Augmentation Systems (SBAS). Figure 2.5 shows the IGS tracking stations as at January 2019 (Source:http://www.igs.org/network) [Accessed on 16 January2019]

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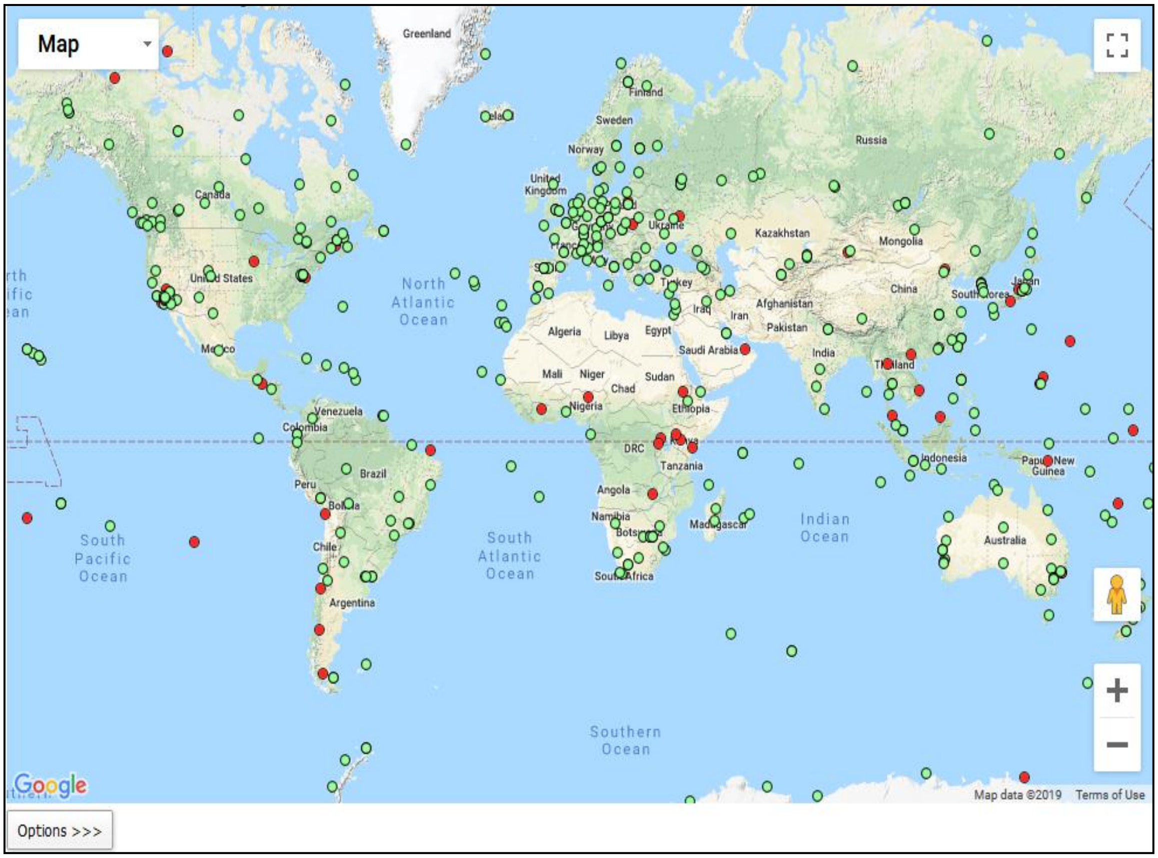

Figure 2.5: IGS tracking stations

Throughout its history, IGS continues to undertake projects that support emerging GNSS developments, as well as generation of new GNSS products. The IGS Real-Time Working Group (RTWG) provides support in the development and integration of appropriate infrastructure, technologies and standards that result in production of high accuracy real-time IGS products. The working group operates the IGS Real Time Service (RTS), launched in April 2013 to support real-time Precise Point Positioning (PPP) at global scale. The RTS is openly available to users and the subscription is free. This supports scientific, educational and commercial applications such as weather forecasting, at worldwide scales, time synchronization and early warning systems. RTS is comprised of a network of GNSS tracking stations, Data Centres (DCs) and Real-Time Analysis Centres (RTACs).

It is necessary to have a network that provides redundancy, and globally distributed stations so as to provide global coverage and ensure a reliable streaming of real-time data. Figure 2.6 illustrates real-time data being streamed to multiple DCs and ACs, a arrangement that guarantees redundancy into the RTS (Source NGS).

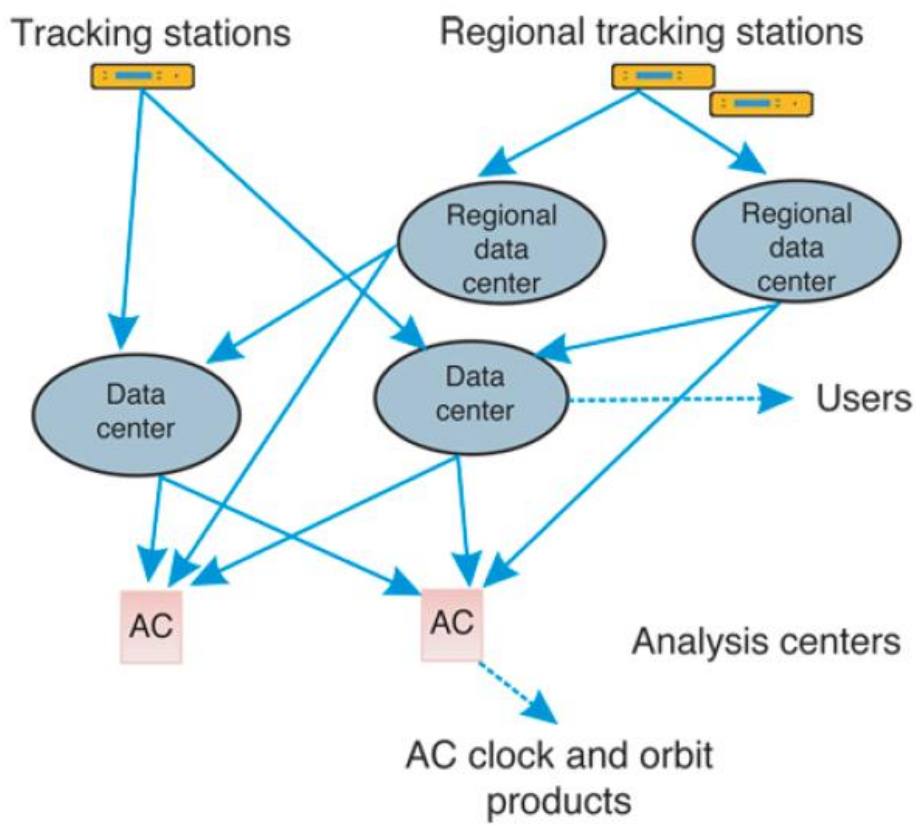

Figure 2.6: Redundancy in RTS

Upon receipt of real-time data from every data center, individual correction products are generated within each RTAC. The final products delivered from the RTS are thus a combination of individual RTAC correction products, resulting in the generation of a more stable and reliable set of products as compared to using any single RTAC product. Figure 2.7 illustrates RTS architecture combination.

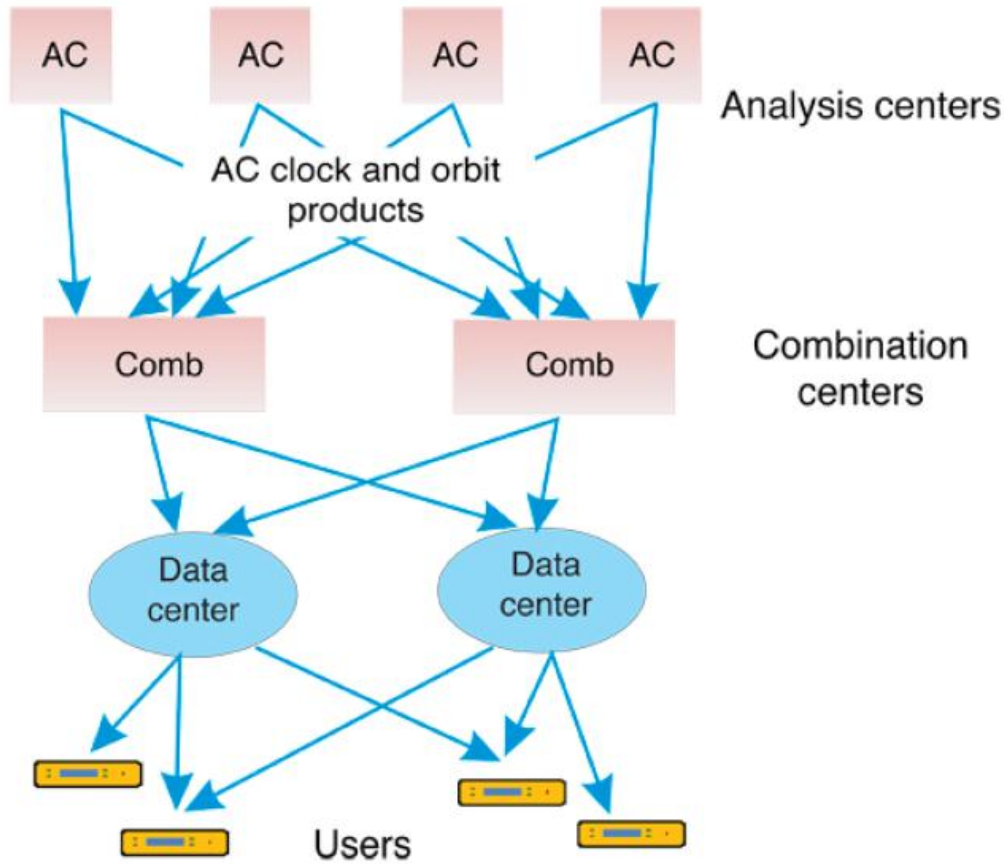

Fig. 2.7 RTS Architecture Combination

2.4.1.3 AFREF and CORS

AFREF was conceived to establish and maintain a unified geodetic reference frame for Africa. The aim of this unified reference frame is to serve as the fundamental basis for the national and regional three-dimensional reference networks that are fully consistent and homogeneous with the International Terrestrial Reference Frame (ITRF). AFREF uses a network of permanent GNSS reference stations and Continuously Operating Reference Stations (CORS) as the primary source of data for the realization of a uniform reference frame. Various international agencies, organizations, national mapping agencies and universities have installed geodetic grade GNSS receivers in different locations throughout Africa. RCMN is one such GNSS reference station hosted by RCMRD in Nairobi. AFREF, through the Open Data Centre (ODC) collects the data on a daily basis from these databases and uses the data to realize the reference frame. Figure 2.9 shows the current CORS network that contributes towards the realization of AFREF.

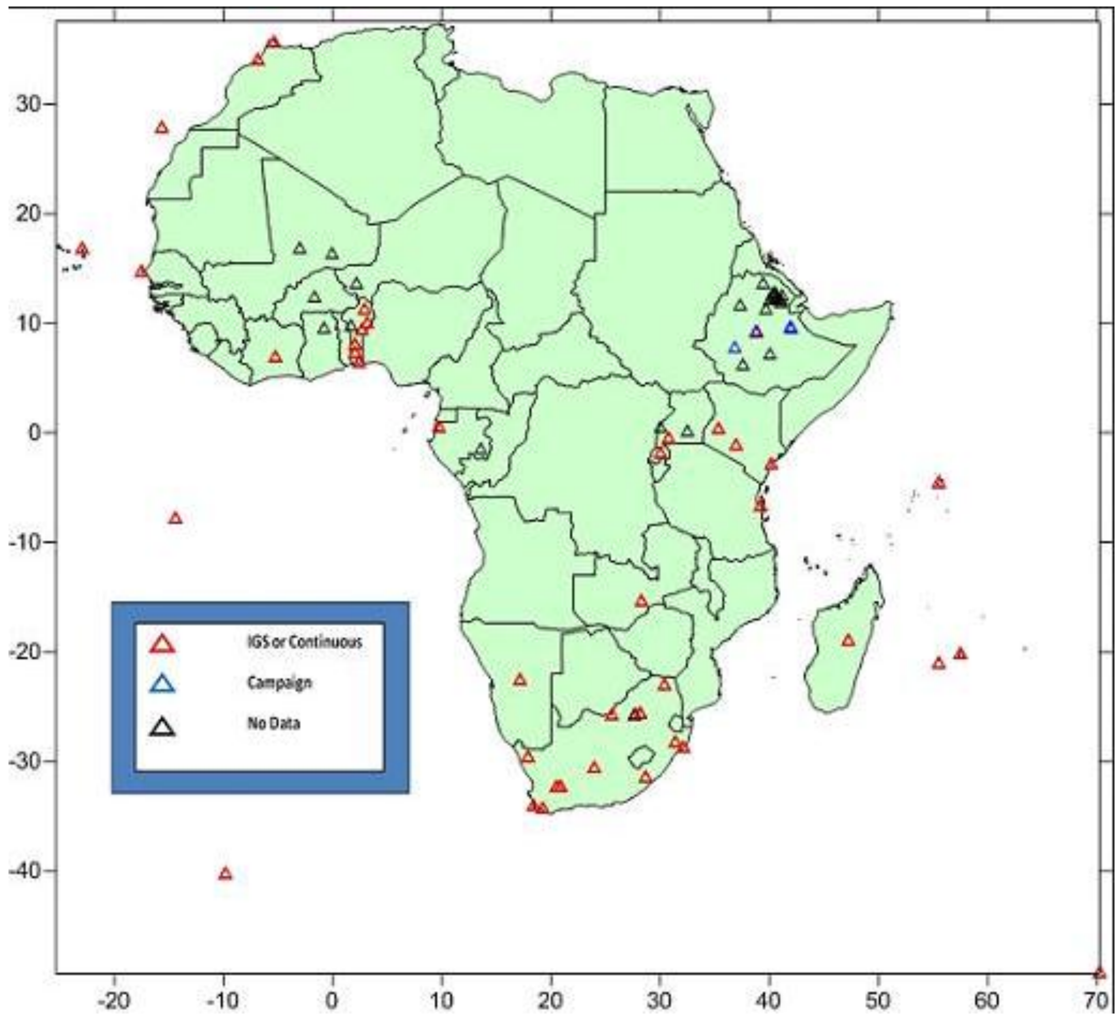

Figure 2.8: AFREF Network Stations (http://afrefdata.org/).

Other examples of operational CORS networks include:

SWEPOS - This is the national CORS network for Sweden and is operated and managed by Sweden national mapping authority. The system comprises more than 170 stations with about 30 stations being of higher quality i.e. bedrock-mounted while the rest are mounted on buildings. Correction data is provided in the RTCM format, version 3.0.

SAPOS – This is operated by the German state surveys and uses GSM, internet and radio transmission for communication to provide both real-time and post-processing products. Positioning accuracy ranges from 1-2 cm (HEPS service) up to 0.5m -3m (EPS service) using VRS, RTK concepts.

GSI - The Japanese's Geographical Survey Institute (GSI) operates and manages approximately 1,200 GPS-based control stations distributed throughout the country to enable monitoring of the movement of the land of Japan on a daily basis by GPS Earth Observation Network System (GEONET).

Trignet – This is the CORS network for South Africa. It comprises of over 55 reference stations (AFREF Newsletter, 2018) distributed throughout the country at inter-station distance of 80km-300 km. Each CORS station continuously streams observed GNSS data to the Trignet control centre. The Trignet control centre processes the data and publishes post-processing data files on the web. In addition, it streams real-time corrections to users.

RwandaGeonet – This is the CORS network for Rwanda comprising of 8 CORS stations distributed across the country. It provides raw GNSS data files in RINEX format as well as correction streams to users in Rwanda upon registration.

2.4.2 CORS Hierarchy

Rizos (2008) proposed a hierarchy for CORS, based on the primary purpose for which the CORS station has been established and the stability of the monument.

2.4.2.1 Tier 1 CORS

Tier 1 CORS are mounted on highly stable (bedrock) monuments and are used to support geo-scientific research activities and in the definition and realization of the global reference frame. These reference stations are established primarily to support IGS global geodetic and scientific applications. Figure 2.9 shows a sample Tier 1 monument.

Figure 2.9 Tier 1 CORS (Source: ICSM)

2.4.2.2 Tier 2 CORS

Tier 2 CORS are mounted on high stable monuments and are typically established by national geodetic agencies in support of the definition and realization of national geodetic reference frames. Tier 1 CORS reference stations are usually a subset of Tier 2 reference stations and enable the transformation between national geodetic datum and ITRF. Figure 2.10 is a typical Tier 2 CORS.

Figure 2.10 Tier 2 CORS (ICSM)

2.4.2.3 Tier 3 CORS

These are mounted on stable monuments such as walls of buildings, and are usually established by national, state and commercial agencies in support of densification of the national CORS network, and in the provision of real-time products and services. Tier 3 CORS stations enable access to the national datum but are not used in the datum definition. Figure 2.11 shows a Tier 3 CORS station on a wall mounted bracket, and Figure 2.12 is a wall mounted antenna.

Figure 2.11: Tier 3 CORS Station

Figure 2.12: Tier 3 CORS Antenna

2.4.3 CORS Components

CORS is comprised of four components namely:

Reference Station System – This comprises the GNSS receivers, power supply, antennae, and modem for communication with the control centre. This system collects records and transmits GNSS observables to the data control and management centers.

Data Processing system – This is the CORS centre control comprising of the control centre server and software. It includes computational models for computation of differential correction data and systems for transmission, recording, management and distribution of correction data streams to users as well as effective user management (Lei Wang nd Wu-Sheng Hu, 2013)

Communication System – This is the communication infrastructure that enables communication between the reference stations, the data centre and the rovers (users). It comprises of the internet, data transfer protocols and communication technologies and accessories. It is the most important component of a CORS system.

User Application System – This is comprised of the GNSS receiving antennae, data receiver and the communication module. The user receiver can send data to the data control centre and receive correction streams from the control centre.

2.4.4 The Working Principle of CORS

CORS comprises of one or more GNSS reference stations equipped with a GNSS receiver of geodetic quality that continuously track GNSS satellites. The data observed at the reference stations is transmitted to the data centre via the internet for processing. Users with rovers of adequate GNSS quality then send raw data of their positions to the data centre via the internet/ 3G GPRS where the corrections are computed and the correction data sent back to the rover. The rover software uses the corrections to compute its precise location in real-time or near-real time and the accuracy of the resulting position can reach cm, sometimes mm level (Lei Wang, Wu-Sheng Hu, 2013). As such, only a single GNSS receiver is required for field operations. Figure 2.13 illustrates the working principle of CORS.

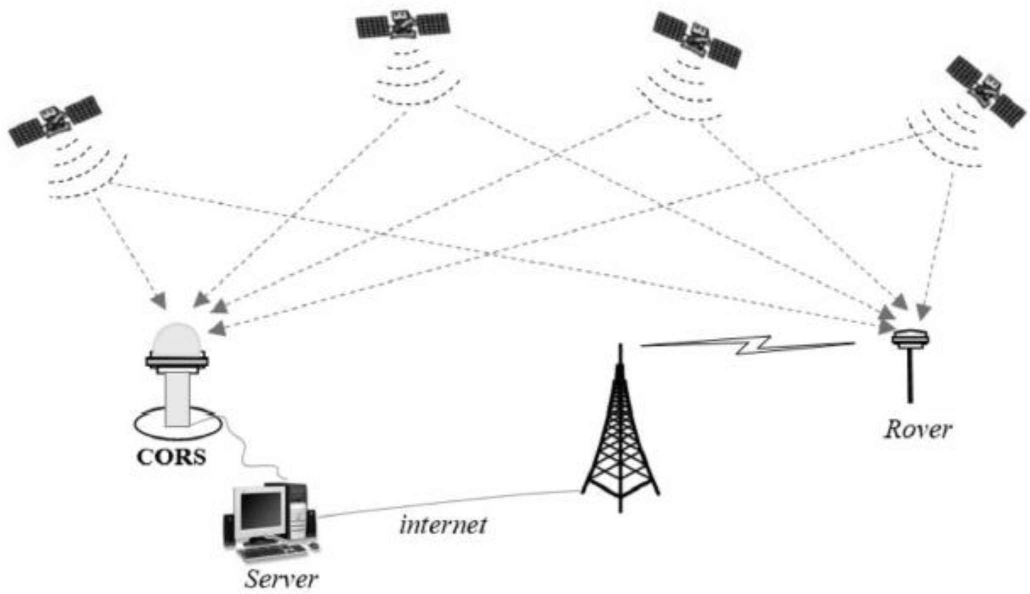

Figure 2.13: Working Principle of CORS (Source: ICAMT, 2016)

2.4.5 Positioning Solutions of CORS

There are various positioning solutions of CORS technology based on the correction method used.

Virtual Reference Station (VRS)

This solution is based on a network of CORS stations that are connected via data links to a control centre. A new, invisible, unoccupied station called a Virtual Reference Station is created, situated only a few meters from a rover location. The GNSS rover sends its approximate position to the control center through a mobile phone data link, such as GSM, to send a standard NMEA position string called GGA. The rover interprets and uses the data just as if it were coming from a real reference station. This greatly improves the performance of RTK. The control centre accepts the position and responds by sending correction data in RTCM format to the rover. Upon receipt of the correction stream from the control centre, the rover computes a DGPS position solution of high quality and updates its position coordinates. The rover then communicates its new position to the control center. The control centre then compute new RTCM corrections for this new position and transmits the corrections to the rover over the internet. The DGPS solution ensures that both ephemeris and atmospheric distortions are modeled for the entire network of reference stations and are correctly applied in order to yield an accuracy of +/-1 meter.

This technique greatly improves RTK positioning within the entire station network. The rover should not move over considerable distances during the same session (i.e. before disconnecting and reconnecting) to prevent inappropriate corrections for new rover location (Landau et al., 2003). Figure 2.14 illustrates the VRS technique.

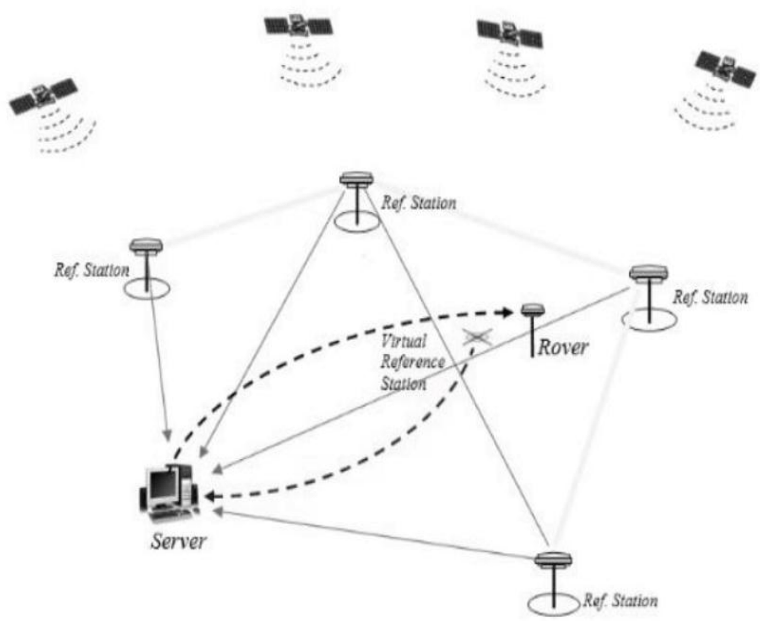

Figure 2.14: VRS Technique (Nguyien Viet Ngiah, 2016)

FKP (Korrektur-Parameter-Flanchen)

This is a regional correction parameter system that uses information from the reference station to obtain parameters that linearly describe the errors due to the influence of the orbit and the atmosphere. These parameters are passed to the data processing centres to interpolate the errors for each region. The technique also applies where the rover station receives the coordinates of the reference stations from the central processing system and the rover chooses the most suitable station.

Master-Auxilliary Corrections (MAC)

In this positioning technique, the data processing centre transmits measured coordinates of the master station and at the same time broadcasts auxiliary parameter station and the coordinate differences of the auxiliary and master stations through connection protocols (RTCM3.1). Once the rover receives the signal, it calculates the correction of its location and applies the corrections to obtain its location.

CHAPTER 3

3.0 RESEARCH METHODOLOGY

Determination of transformation parameters between two datums requires availability of common points whose coordinates in both datums are known. The coordinates of control points in the Kenya geodetic system are known and were obtained from the Survey of Kenya. As the coordinates of the same points in the KPLC CORS datum are not known, they were observed using GNSS techniques in order to facilitate computation of transformation parameters between the two systems. This research project uses a 7-parameter similarity transformation, also known as the 7-parameter Helmert transformation or the Bursa-Wolf transformation. This transformation preserves the shape but lengths and positions are subject to change. It involves three translations along each of the three axes X, Y, and Z, three rotations about each of the axes and a scale factor.

3.1 Area of Study

The area of study was within Nairobi, Machakos and Kiambu Counties, covering a radius of 50 km from Gatundu CORS station.

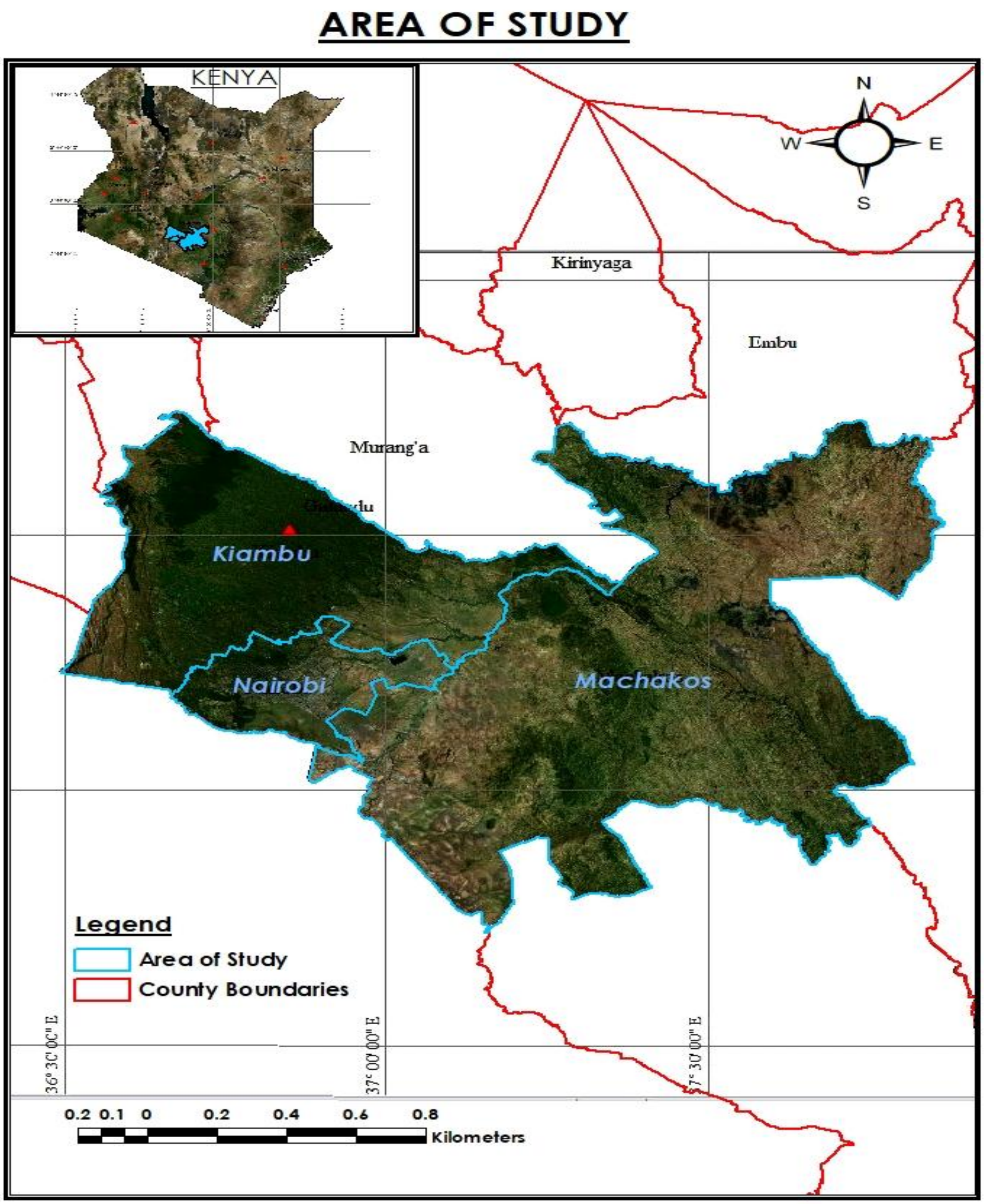

Figure 3.1: Area of study

3.2 Equipment and Resources

The equipment and resources used in this research project included a PC, Global Mapper software V.18, ArcGIS V 10.3, Topcon-GR3 GNSS receivers, Trimble Pivot platform software, KPLC CORS, Matlab R2019a, Topcon Tools software, Trimble GeoXT GNSS receiver, Teqc, Runpkr00 and RTKLIB.

3.3 Datum Transformations

This research study uses the Bursa-Wolf 7-parameter transformation to compute the transformation parameters between KPLC CORS (ITRF2008) and the Kenya national geodetic datum (Arc 1960). The choice of this method is informed by the fact that it can be implemented easily into a computer program and is adequate for relating two coordinate systems that are homogenous, i.e. without local distortion in scale or orientation.

Mathematically, this transformation is expressed as below:

$$\begin{bmatrix} X_C \\ Y_C \\ Z_C \end{bmatrix} = \begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix} + (1 + \delta s) \begin{bmatrix} 1 & \gamma & -\beta \\ -\gamma & 1 & \alpha \\ \beta & -\alpha & 1 \end{bmatrix} \begin{bmatrix} X_A \\ Y_A \\ Z_A \end{bmatrix} \qquad \text{Equation 1}$$

Where:

(X_C, Y_C, Z_C) and (X_A, Y_A, Z_A) are the coordinates of a point in KPLC CORS datum and Arc 1960 datum respectively.

$(\Delta X, \Delta Y, \Delta Z)$ are the coordinates of the origin of KPLC CORS datum in the Arc 1960 datum.

α, γ, β are small differential rotations around the X, Y, Z axis of Arc 1960 datum

δs is the differential scale change between the two datums.

A minimum of three common points is required to sufficiently determine the 7 transformation parameters. More common points are recommended for redundancy and to minimize the effects of errors in the coordinates through a least squares solution. In this research, six common points were used in the determination of the transformation parameters.

Equation 1 was rewritten and rearranged for ease of computations in Matlab as follows:

$$A=\begin{bmatrix}1\ 0\ 0\ XA\ 0-ZA\ YA\\ 0\ 1\ 0\ YA\ ZA\ 0-XA\\ 0\ 0\ 1\ ZA-YA\ XA\ 0\end{bmatrix};\ X=\begin{bmatrix}\Delta X\\ \Delta Y\\ \Delta Z\\ \delta s\\ Rx\\ Ry\\ Rz\end{bmatrix};\ L=\begin{bmatrix}Xc-XA\\ Yc-YA\\ Zc-ZA\end{bmatrix} \qquad \text{equation 2}$$

Curvilinear coordinates were converted into geocentric Cartesian coordinates using equation 3 (Vanicek and Krakiwsky, 1986):

$$\begin{bmatrix}X\\ Y\\ Z\end{bmatrix}=\begin{bmatrix}(\upsilon\ +h)\cos\varphi\cos\lambda\\ (\upsilon+h)\cos\varphi\sin\lambda\\ (\upsilon(1-e^2\,)+h)\sin\varphi\end{bmatrix} \qquad \text{Equation 3}$$

Where:

υ is the radius of curvature in the prime vertical and is given by:

$$\upsilon=\frac{a}{\sqrt{1-e^2 Sin\ ^2\varphi}} \qquad \text{Equation 4}$$

Where:

α is the semi-major axis

e^2 is the squared first eccentricity of the ellipsoid, given by:

$$e^2 = 2f - f2 \qquad \text{Equation 5}$$

f is the flattening factor, which is given by:

$$f = {}^{(\alpha - b)}\!/_{a} \qquad \text{Equation 6}$$

3.4 Desktop Study

This involved a review of relevant information regarding the research topic. During the study, the parameters for the reference ellipsoids were obtained. KPLC CORS system is based on ITRF2008 datum. ITRF2008 datum does not have a reference ellipsoid, but the International Earth Rotation Service (IERS) recommends the use of GRS80 ellipsoid in geodetic computations involving ITRF2008 datum. ITRF coordinates are coincident with WGS84 coordinates at 10cm level (ftp://itrf.ensg.ign.fr/pub/itrf/WGS84.TXT) [Accessed 15 May 2019]. Arc 1960 datum uses the Clarke 1880 ellipsoid. The coordinates of control points in the Kenya Geodetic system are grid coordinates i.e. Northings and Eastings, and height is Orthometric height. For purposes of this research, the coordinates were converted to curvilinear latitude and longitude using Global mapper software for subsequent conversion to geocentric Cartesian coordinates.

Table 1: Reference ellipsoid parameters

Datum	**Reference Ellipsoid**	**Semi-major Axis (m)**	**Inverse flatting**
Arc 1960	Clarke 1880	6378249.145	293.45
KPLC CORS (ITRF2008)	GRS80	6378137.0	298.257222101

Computation of ellipsoidal heights in the Kenyan geodetic datum was not possible due to unavailability of geoidal heights and a geoid model for Arc 1960 datum. As a result, ellipsoidal heights in Arc 1960 datum for this research study were observed during reconnaissance visits.

3.5 Data Acquisition

Control data in form of trig index cards and T.C & S.T charts (1256 & 1202 A) within the area of study was acquired from the Survey of Kenya, which is the custodian of official control data for surveying and mapping. Trig cards obtained are 148.S.2, 148.S.3, 148 UT 172, 148 UT 179, 148 UT 180, SKP.411, SKP.208 I, SKP. 209, 149. S 3C, SKP. 217, SKP. 219, 162 ST 2, 162 ST 6 and 162 ST 14.

3.6 Reconnaissance

Field visits to the various control points were carried out with the aid of navigational tools including Trimble GeoXT, Google Earth and Garmin Car Navigation in order to establish their existence and condition. Unfortunately, many primary and secondary geodetic control points were found to have been destroyed and vandalized and could not be used for observations. Six points were found to be okay and sufficiently distributed and thus suitable for observations. These points and their coordinates are as shown in Table 2. The ellipsoidal heights for the six points were observed during reconnaissance, since they were not available and no sufficient information to obtain them from computations.

Table 2: Common Points Coordinates in Arc 1960 datum

Station Name	**Northing (m)**	**Easting (m)**	**Orthometric Height (m)**	**Ellipsoidal height (m)**	**Class of Control Point**
149.S.3	9837592.787	284419.100	1837.96	1833.652	IPCU
149.S.2	9878315.02	289949.59	1500.01	1496.07	IPCU
KISM 7X	9872069.74	264174.21	1590.49	1588.83	Brass plug in Concrete
VA/9	9863310.11	241146.86	1996.13	1993.14	Brass plug in Concrete
V/6	9856148.25	257722.89	1661.84	1659.93	Brass plug in Concrete
KJ21	9847119.74	270063.27	1615.52	1614.18	Brass plug in Concrete

3.7 Field Observations

The identified control points were observed on the 18th of April 2019 by setting up two geodetic receivers Topcon GR-3 at stations 149.S.3 (Lukenya) and VA/9 (Kikuyu) as base stations during the observation period, and using the third receiver as a rover to observe the other points for a period of 2 hours each. Station field notes including observation start and end time, reciver height and station names were recorded. The weather was sunny throughout the day, with little to no cloud cover. During the observation period, the KPLC CORS stations were continuously observing and streaming GNSS data to the KPLC CORS server.

3.8 Processing and Network Adjustment

The observation files were downloaded from the GNSS receivers into the computer using Topcon tools software. KPLC CORS data for five stations (Gatundu, Chemosit, Kitale, Musaga and Marsabit) which were continuously tracking satellites and streaming to the KPLC CORS server during the observation period was obtained in form of raw data files in .T02 format. To ensure overlap in the observed data, the time period for the KPLC CORS was specified for 13 hours, an hour earlier than the commencement of the first observations and one hour after the last observation. The raw data files in .T02 format were first combined into a single data file for each CORS, since they were stored as individual files for every hour, and then converted to .Dat format using the runpkr00 software. Teqc software was used to convert the resulting .Dat files into Rinex 2.11, a format compatible with most proprietary post-processing software.

The observations for the common points were post-processed and adjusted using Topcon tools software, first by using Gatundu CORS as the base, and then using all the five CORS. Adjustment report with adjusted coordinates and baselines was generated for both cases.

3.9 Computation of Transformation Parameters

As is the case with most geodetic computations, determination of datum transformations parameters require use of a computer program due to the rigorous nature of computations involved. In this research study, a program for the determination of the transformation parameters was written in Matlab. The software was preferred due to its robustness in handling matrices which are an integral part of the computations. During the computations, all observations were assumed to carry equal weights.

CHAPTER 4

4.0 RESULTS AND DISCUSSIONS

The results of the various computational procedures and processes are presented and discussed in this chapter.

4.1 Post-processing and Adjustment Results

During the period of observation, five KPLC CORS stations namely Gatundu, Chemosit, Musaga, Kitale and Marsabit were continuously observing and streaming GNSS observations to the KPLC CORS server. Using the KPLC CORS data for the five stations, GNSS observations of the common points were post-processed and adjusted using Topcon tools software. The first approach was to post-process and adjust using the nearest CORS, in this case Gatundu, as the base station as illustrated in Figure 4.1. The results obtained are as in table 3.

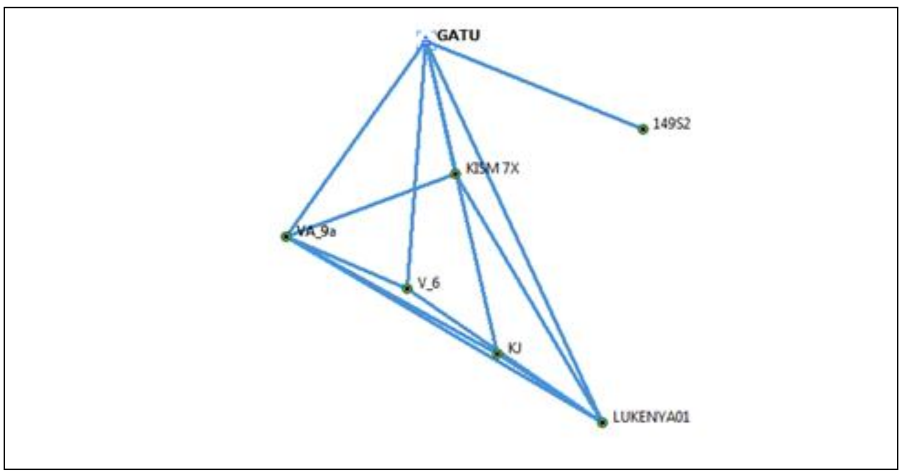

Figure 4.1: Network of Observations with Gatundu CORS

Table 3: Coordinates in KPLC CORS system (Gatundu CORS)

Name	WGS84 Latitude	WGS84 Longitude	WGS84 Ell.Height (m)
149S2	1°06'11.12246"S	37°06'47.36912"E	1496.133
GATUNDU	0°59'33.55567"S	36°50'45.22093"E	1799.971
KISM 7X	1°09'33.55815"S	36°52'53.85757"E	1575.231
KJ21	1°23'05.80528"S	36°56'03.64135"E	1602.032
149S3	1°28'16.31981"S	37°03'47.66655"E	1821.58
VA/9	1°14'18.03617"S	36°40'29.04685"E	1981.275
V/6	1°18'11.58887"S	36°49'24.81976"E	1646.269

The second approach was to post-process and adjust the observations using all the 5 CORS as base stations as illustrated in Figure 4.2. The result is as shown in Table 4.

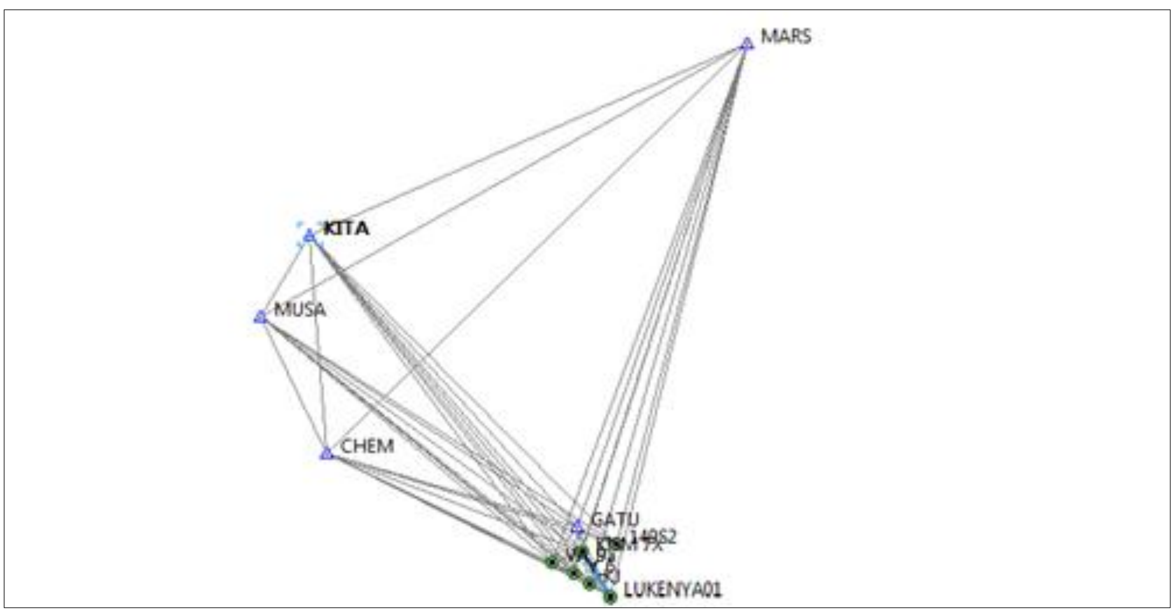

Figure 4.2: Network of Observations with 5 CORS

Table 4: Coordinates using 5 CORS

Name	WGS84 Latitude	WGS84 Longitude	WGS84 Ell. Height (m)
149S2	1°06'10.85913"S	37°06'47.55518"E	1484.596
CHEM	0°29'20.02798"S	35°09'55.60785"E	1778.347
GATUNDU	0°59'33.55657"S	36°50'45.22093"E	1799.971
KISM 7X	1°09'33.56054"S	36°52'53.85701"E	1575.271
KITALE	1°00'35.90000"N	35°03'12.66000"E	1828.575
KJ21	1°23'05.80624"S	36°56'03.64153"E	1602.048
149S3	1°28'16.32090"S	37°03'47.66667"E	1821.585
MARSABIT	2°19'56.28000"N	37°59'12.36000"E	1349.581
MUSAGA	0°27'05.32000"N	34°43'50.20000"E	1499.749
VA/9	1°14'18.03794"S	36°40'29.04651"E	1981.294
V/6	1°18'11.58965"S	36°49'24.81995"E	1646.312

The differences in coordinates between the two sets of coordinates were obtained by subtracting the coordinates obtained using Gatundu CORS from those obtained using all the five CORS stations. The differences are as shown in Table 5.

Table 5: Coordinate differences using 1 CORS and 5 CORS

Station Name	Δlat	Δlong	Δh (m)
149S2	0° 0' 0.2333"	0° 0' 0.18606"	-11.537
GATUNDU	0° 0' 0.0"	0° 0' 0.0"	0
KISM 7X	0 ° 0' 0.00239"	-0 ° 0' 0.00056"	0.04
KJ21	0 ° 0' 0.00096"	0 ° 0' 0.00018"	0.016
149S3	0 ° 0' 0.00109"	0 ° 0' 0.00012"	0.005
VA/9	0 ° 0' 0.00177"	0 ° 0' 0.00034"	0.019
V/6	0 ° 0' 0.00078"	0 ° 0' 0.00019"	0.043
Mean	0 ° 0' 0.00139"	0 ° 0' 0.000278"	0.0246

From the results in Table 5, the differences in the two coordinates are small, yielding a mean of 0° 0' 0.000139 arc seconds in latitude, 0 ° 0' 0.000278 arc seconds in longitude and 0.024 m in height. The large differences for station 149S2 are noted, and can be attributed to the lack of sufficient overlap in the observations for this particular station for post-processing and adjustment using one CORS. Being the last station to observe, the two fixed receivers stopped observing soon after the station was occupied due to exhaustion of batteries. As a result, the station lacked sufficient overlap to post-process when using only one CORS and was not used in the computation of the mean differences in table 5. However, this was compensated for while using all the 5 CORS to post-process and adjust the observations as the station overlapped with the other CORS station observations, to form triangles and result in better adjustment. In addition, multiple CORS stations results in more redundancy and insurance in case one or more CORS fail to stream data to the server during the observation period for whatever reason. As a result, the coordinates obtained by using multiple CORS stations were used in the computation of transformation parameters between KPLC CORS and the Kenya national geodetic datum.

4.2 Transformation Parameters

The transformation parameters were computed using the Bursa-Wolf 7-parameter transformation. Computation of the 7 unknown parameters requires a minimum of three common points in the two datums for the problem to be determined. Six common points were used in this research, resulting in over determined solution to the problem. A least squares approach was used to ensure the best fit to the solution. A Matlab script was written and executed to generate the transformation parameters, as well as the statistical measures of the parameters. The computed transformation parameters and their standard deviations are presented in Table 6.

Table 6: Transformation Parameters

Parameter	**Value**	**Standard deviation**
ΔX(m)	-198.084318	0.251349471331932
ΔY(m)	-6.206632014	0.251349471331932
ΔZ(m)	-10.27467938	0.251349471331932
Rx(rad)	0.0000058563048	0.000000039396864
Ry(rad)	0.0000351072905	0.000000065564953
Rz(rad)	-0.0000298654707	0.000000049267942
Δs (ppm)	2.9847292	0. 039406569ppm
Overall Standard Deviation	0.615677951881543	

4.3 Result Testing

Due to unavailability of common points in the two datums for testing the transformation parameters, the suitability of the transformation parameters was limited to the statistical values of the parameters, i.e. the overall standard deviation, the standard deviation of the individual parameters and the residuals for the common points. The standard deviation for the individual parameters is small, indicating a better approximation of the parameters. In addition, the residuals for the common points are relatively small and randomly distributed as illustrated in Figure 4.3.

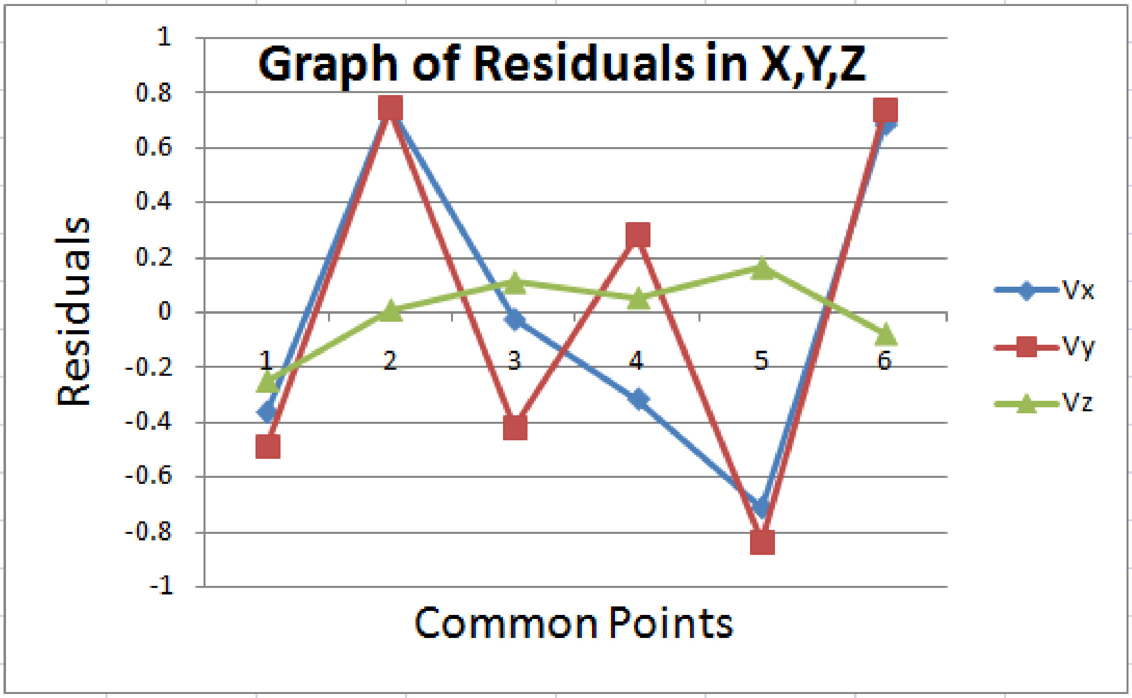

Figure 4.3: Graph of Residuals of Common Points

CHAPTER 5

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Interest in the use of CORS for precise positioning has gained momentum in Kenya in recent years due to the many benefits it offers over conventional RTK methods. KPLC is one of the various entities that have embraced CORS technology to enhance the accuracy of geospatial data in support of its utility management. KPLC CORS is based on ITRF2008 datum. On the other hand, the Kenya national geodetic datum, UTM Arc 1960, is the official geodetic system for surveying and mapping. Knowledge of the transformation parameters between the two systems is necessary in order to enable transformation of coordinates between the two systems. In addition, the transformation parameters will enable smooth handling of datasets in the two systems on a common GIS platform through appropriate transformations.

The determination of transformation parameters requires the knowledge of a minimum set of common points in the two systems. The coordinates of identified control points in Arc 1960 datum were available from the Survey of Kenya. The corresponding coordinates in KPLC CORS were determined from GNSS field observations, post-processing and adjustment using Topcon tools software. The coordinates obtained using one CORS for post-processing and adjustment were compared with the corresponding coordinates obtained using 5 CORS stations. The differences in the two results were found to be small, in the region of fractions of seconds for latitude and longitude, and a few centimetres for heights. Use of more than one CORS for post-processing and adjustment was found to be more reliable, due to the redundancy it offers, as well as compensating for insufficient overlap for stations with challenges in GNSS observations.

The Bursa-Wolf 7-parameter transformation, involving three translations, three rotations about each of the X, Y, and Z axes, and a scale factor was used in this research project. In order to obtain the 7 unknown parameters, a minimum of three common points is required. Six common points were used to compute the transformation parameters through a least squares solution. Matlab software was used for writing a script to compute the transformation parameters. Matlab was preferred due to its robustness in handling matrices, rigorous computations and an interactive environment for developing algorithms. The transformation parameters were determined to be three translations -198.084318m, -6.206632014m, and -10.27467938m about X, Y and Z axes respectively, three rotations of 1.20794955 arc seconds, 7.24139847 arc seconds and -6.16019553 arc seconds about X, Y and Z axes, and a scale factor of 2.9847292 ppm.

5.2 Recommendations

Following this research, it is recommended that:

1. The transformation parameters need to be tested for validity using test data which is currently not available.
2. Further research be conducted covering a wider geographic extent and more common points.
3. A geoid model for Arc 1960 datum be developed to facilitate computation of geoidal heights.
4. Densification of control points in the Kenya geodetic system to more accessible and secure locations as most of the primary and secondary control points are located on hill-tops and have been destroyed.

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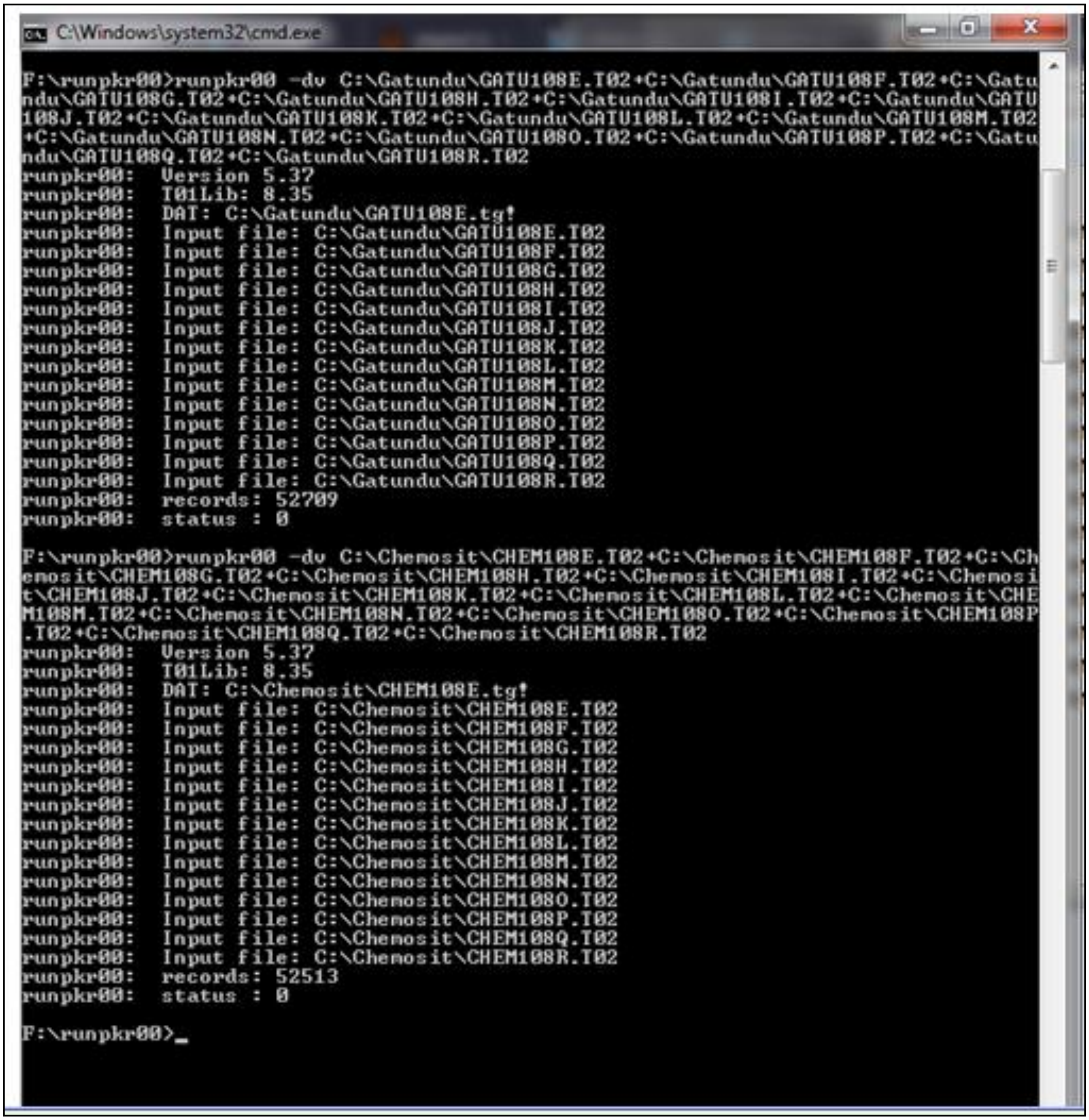
APPENDICES

APPENDIX A. CURVILINEAR COORDINATES (ARC 1960)

Station	Latitude	Longitude
149.S.3	1° 28' 7.0887" S	37° 03' 44.6476" E
149.S.2	1° 06' 1.5156" S	37° 06' 44.4996" E
KISM 7X	1° 09' 24.2406" S	36° 52' 50.8356" E
VA/9	1° 14' 8.7458" S	36° 40' 26.0351" E
V6	1° 18' 2.3183" S	36° 49' 21.8101" E
KJ21	1° 22' 56.5506" S	36° 56' 0.6224" E

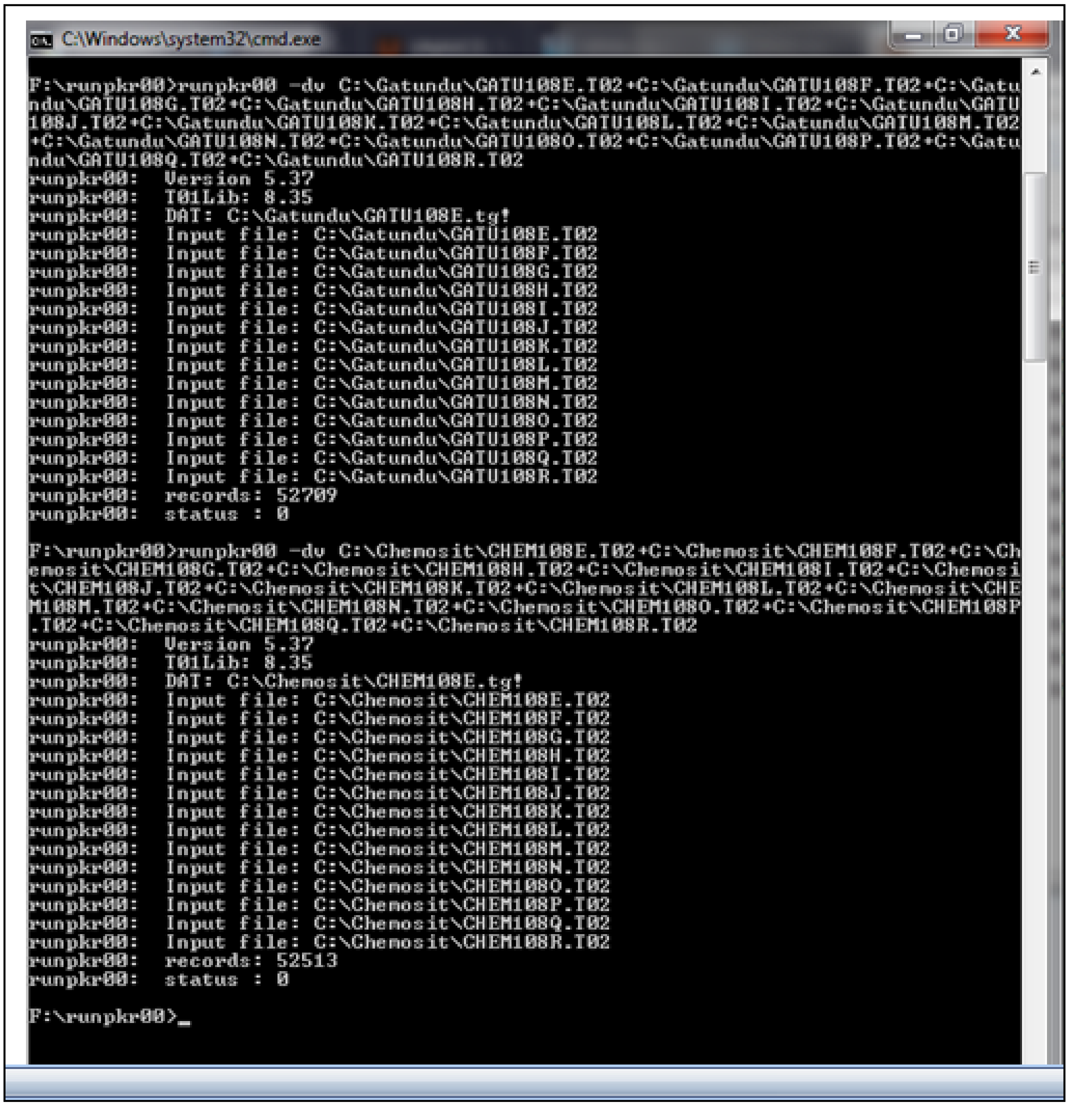
APPENDIX B: CONVERSION OF RAW GNSS DATA FILES FROM KPLC CORS

B. 1 Conversion from .T02 format to .Dat format using runpkr00 software

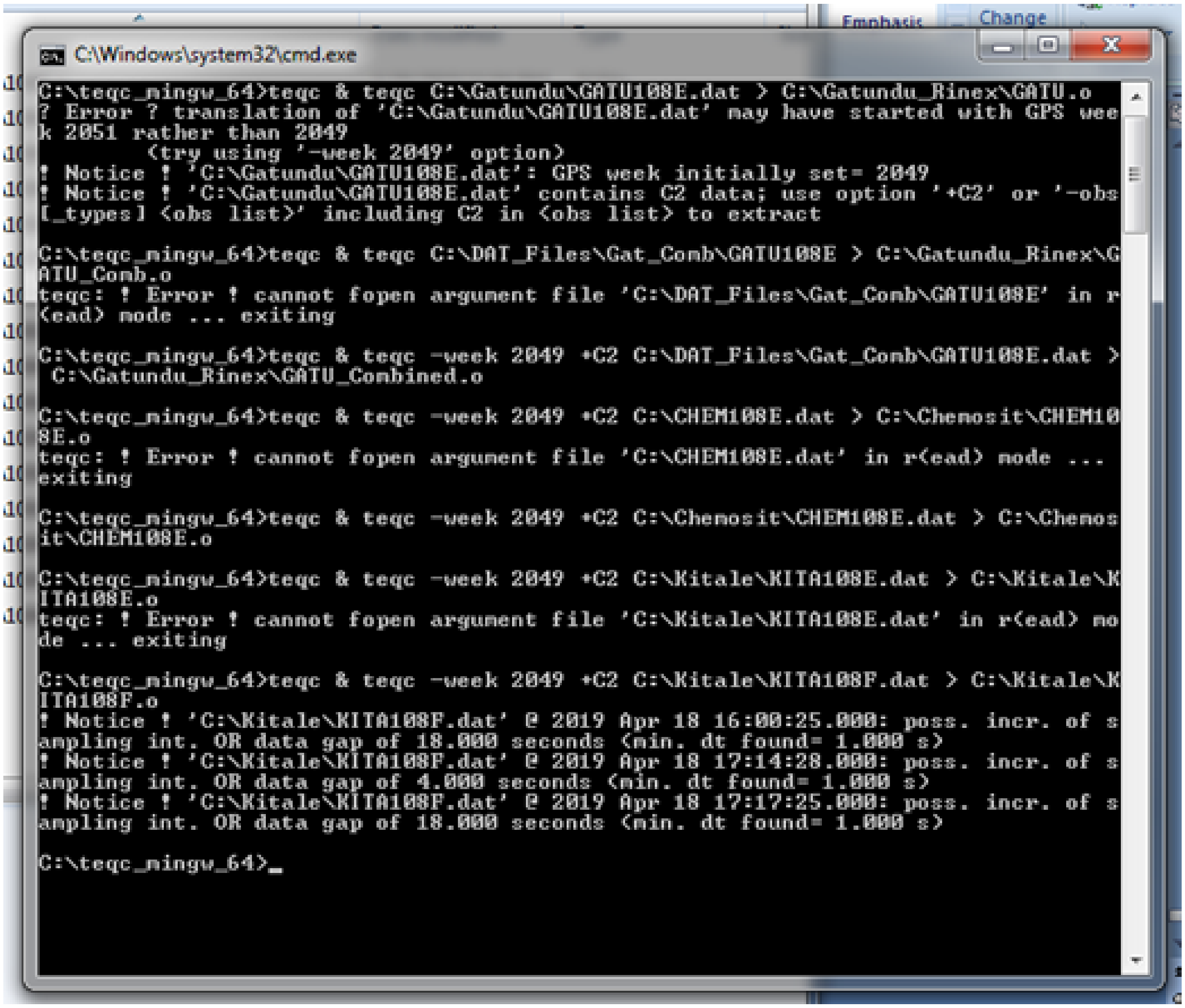


```
C:\Windows\system32\cmd.exe

F:\runpkr00>runpkr00 -dv C:\Gatundu\GATU108E.T02+C:\Gatundu\GATU108F.T02+C:\Gatu
ndu\GATU108G.T02+C:\Gatundu\GATU108H.T02+C:\Gatundu\GATU108I.T02+C:\Gatundu\GATU
108J.T02+C:\Gatundu\GATU108K.T02+C:\Gatundu\GATU108L.T02+C:\Gatundu\GATU108M.T02
+C:\Gatundu\GATU108N.T02+C:\Gatundu\GATU108O.T02+C:\Gatundu\GATU108P.T02+C:\Gatu
ndu\GATU108Q.T02+C:\Gatundu\GATU108R.T02
runpkr00:  Version 5.37
runpkr00:  T01Lib: 8.35
runpkr00:  DAT: C:\Gatundu\GATU108E.tg!
runpkr00:  Input file: C:\Gatundu\GATU108E.T02
runpkr00:  Input file: C:\Gatundu\GATU108F.T02
runpkr00:  Input file: C:\Gatundu\GATU108G.T02
runpkr00:  Input file: C:\Gatundu\GATU108H.T02
runpkr00:  Input file: C:\Gatundu\GATU108I.T02
runpkr00:  Input file: C:\Gatundu\GATU108J.T02
runpkr00:  Input file: C:\Gatundu\GATU108K.T02
runpkr00:  Input file: C:\Gatundu\GATU108L.T02
runpkr00:  Input file: C:\Gatundu\GATU108M.T02
runpkr00:  Input file: C:\Gatundu\GATU108N.T02
runpkr00:  Input file: C:\Gatundu\GATU108O.T02
runpkr00:  Input file: C:\Gatundu\GATU108P.T02
runpkr00:  Input file: C:\Gatundu\GATU108Q.T02
runpkr00:  Input file: C:\Gatundu\GATU108R.T02
runpkr00:  records: 52709
runpkr00:  status : 0

F:\runpkr00>runpkr00 -dv C:\Chemosit\CHEM108E.T02+C:\Chemosit\CHEM108F.T02+C:\Ch
emosit\CHEM108G.T02+C:\Chemosit\CHEM108H.T02+C:\Chemosit\CHEM108I.T02+C:\Chemosi
t\CHEM108J.T02+C:\Chemosit\CHEM108K.T02+C:\Chemosit\CHEM108L.T02+C:\Chemosit\CHE
M108M.T02+C:\Chemosit\CHEM108N.T02+C:\Chemosit\CHEM108O.T02+C:\Chemosit\CHEM108P
.T02+C:\Chemosit\CHEM108Q.T02+C:\Chemosit\CHEM108R.T02
runpkr00:  Version 5.37
runpkr00:  T01Lib: 8.35
runpkr00:  DAT: C:\Chemosit\CHEM108E.tg!
runpkr00:  Input file: C:\Chemosit\CHEM108E.T02
runpkr00:  Input file: C:\Chemosit\CHEM108F.T02
runpkr00:  Input file: C:\Chemosit\CHEM108G.T02
runpkr00:  Input file: C:\Chemosit\CHEM108H.T02
runpkr00:  Input file: C:\Chemosit\CHEM108I.T02
runpkr00:  Input file: C:\Chemosit\CHEM108J.T02
runpkr00:  Input file: C:\Chemosit\CHEM108K.T02
runpkr00:  Input file: C:\Chemosit\CHEM108L.T02
runpkr00:  Input file: C:\Chemosit\CHEM108M.T02
runpkr00:  Input file: C:\Chemosit\CHEM108N.T02
runpkr00:  Input file: C:\Chemosit\CHEM108O.T02
runpkr00:  Input file: C:\Chemosit\CHEM108P.T02
runpkr00:  Input file: C:\Chemosit\CHEM108Q.T02
runpkr00:  Input file: C:\Chemosit\CHEM108R.T02
runpkr00:  records: 52513
runpkr00:  status : 0

F:\runpkr00>_
```

B. 2 Combining individual .T02 into a single file using runpkr00 software



B.3 Converting from .Dat format to Rinex 2.11 using teqc software



B4. Sample Rinex file

GATU_Combined.o - Notepad

File Edit Format View Help

```
     2.11           OBSERVATION DATA    G (GPS)             RINEX VERSION / TYPE
teqc  2019Feb25                         20190429 18:43:09UTCPGM / RUN BY / DATE
Linux2.6.32-573.12.1.el6.x86_64|x86_64|gcc|Win64-MinGW64|=+ COMMENT
-00.992654603 (latitude)                                    COMMENT
+036.84589470 (longitude)                                   COMMENT
+1799.97      (elevation)                                   COMMENT
+.000000      (antenna height)                              COMMENT
BIT 2 OF LLI FLAGS DATA COLLECTED UNDER A/S CONDITION       COMMENT
GATU                                                        MARKER NAME
1                                                           MARKER NUMBER
-Unknown-           -Unknown-                               OBSERVER / AGENCY
5543R50295          TRIMBLE NETR9       0.00                REC # / TYPE / VERS
14411004            TRM55971.00     NONE                    ANT # / TYPE
        0.0000        0.0000        0.0000                  APPROX POSITION XYZ
        0.0000        0.0000        0.0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     8    L1    L2    C1    P1    C2    P2    S1    S2      # / TYPES OF OBSERV
    18                                                      LEAP SECONDS
 SNR is mapped to RINEX snr flag value [0-9]                COMMENT
  L1 & L2: min(max(int(snr_dBHz/6), 0), 9)                  COMMENT
  2019     4    18     4     0    0.0000000     GPS         TIME OF FIRST OBS
                                                            END OF HEADER
 19  4 18  4  0  0.0000000  0 12G01G03G06G07G08G09G11G17G22G23G28G30
 128309543.122 6  99981486.773 6  24416494.070                           24416500.637
                        41.400          41.000
 113993648.105 7  88826246.421 7  21692270.414                           21692276.949
                        47.700          47.200
 121810376.883 7  94917199.379 7  23179744.539                           23179750.453
                        44.700          43.800
 118685811.533 7  92482485.905 7  22585167.070                           22585171.129
                        47.400          43.800
 128463484.989 6 100101444.392 6  24445790.305                           24445798.465
                        40.900          38.200
 120990382.507 7  94278239.643 7  23023702.445                           23023708.191
                        44.600          43.500
 131640242.54946 102576834.92543  25050303.9454
  25050307.8984         37.8004         21.7004
 127463775.203 6  99322408.768 6  24255545.352                           24255549.348
                        39.900          36.000
 122733368.38647  95636407.84144  23355384.1644
  23355385.4804         42.6004         29.0004
 122380783.71347  95361656.79544  23288290.9774
  23288293.5634         43.6004         27.6004
 110778396.72548  86320796.67845  21080416.0554
  21080418.5434         48.0004         34.3004
 115520538.850 8  90015989.265 7  21982819.563                           21982826.164
                        49.300          46.000
 19  4 18  4  0  1.0000000  0 12G01G03G06G07G08G09G11G17G22G23G28G30
 128311902.882 6  99983325.551 6  24416943.469                           24416949.164
```

APPENDIX C: POST-PROCESSING AND ADJUSTMENT REPORTS

C1. Post-processing and Adjustment using 1 (Gatundu) CORS

Project Report

Project name: Processing3.05.2019.ttp
Project folder: C:\Users\catherine\TopconTools\Jobs
Creation time: 4/19/2019 5:46:25 PM
Created by:
Comment:
Linear unit: Meters
Angular unit: DMS
Projection: UTMSouth-Zone_37 : 36E to 42E
Datum: WGS84
Geoid:

Point Summary Report

Name	WGS84 Latitude	WGS84 Longitude	WGS84 Ell.Height (m)	Code
149S2	1°06'11.12246S	37°06'47.36912E	1496.133	146S2
GATU	0°59'33.55567S	36°50'45.22093E	1799.971	
KISM 7X	1°09'33.55815S	36°52'53.85757E	1575.231	KISM
KJ	1°23'05.80528S	36°56'03.64135E	1602.032	MLO
LUKENYA01	1°28'16.31981S	37°03'47.66655E	1821.58	PLR
VA_9	1°14'18.03617S	36°40'29.04685E	1981.275	
VA_9a	1°14'18.03631S	36°40'29.04683E	1981.279	
V_6	1°18'11.58887S	36°49'24.81976E	1646.269	NYAYO

Identical Points Report

Point 1	Point 2	Distance (m)
VA_9	VA_9a	0.0045

GPS Obs Report

Name	dN (m)	dE (m)	dHt (m)	Horizontal Precision (m)	Vertical Precision (m)
149S2−GATU					
GATU−KISM 7X					
GATU−KJ	-43382.25	9879.958	-197.931	0.08	0.071
GATU−LUKENYA01	-52909.354	24235.569	21.602	0.017	0.033
GATU−VA_9	-27191.549	-19036.092	181.308	0.01	0.02
GATU−VA_9a	-27191.553	-19036.095	181.318	0.01	0.02
GATU−V_6	-34353.452	-2460.341	-153.737	0.054	0.036

KISM 7X–LUKENYA01	-34477.545	20244.478	246.587	0.102	0.097
KISM 7X–VA_9	-8759.629	-23027.208	406.044	0.009	0.02
KJ–LUKENYA01	-9527.082	14355.563	219.565	0.013	0.025
KJ–VA_9	16190.745	-28915.977	379.155	0.063	0.059
LUKENYA01–VA_9	25717.805	-43271.664	159.709	0.016	0.031
LUKENYA01–VA_9a	25717.801	-43271.662	159.699	0.017	0.032
LUKENYA01–V_6	18555.916	-26695.979	-175.306	0.05	0.037
VA_9a–V_6	-7161.882	16575.656	-335.004	0.007	0.015

Adjustment Report

Adjustment type: Plane + Height, Minimal constraint

Confidence level: 95 %

Number of adjusted points: 7

Number of plane control points: 1

Number of used GPS vectors: 13

Number of rejected GPS vectors by plane: 3

A posteriori plane UWE: 0.4480203 , Bounds: (0.5220153 , 1.480287)

Number of height control points: 1

Number of rejected GPS vectors by height: 1

A posteriori height UWE: 0.8540064 , Bounds: (0.4546061 , 1.551881)

C.2 Post-processing and Adjustment Report using 5 CORS

Point Summary Report

Name	WGS84 Latitude	WGS84 Longitude	WGS84 Ell.Height (m)	Code
149S2	1°06'10.85913S	37°06'47.55518E	1484.596	146S2
CHEM	0°29'20.02798S	35°09'55.60785E	1778.347	
GATU	0°59'33.55657S	36°50'45.22093E	1799.971	
KISM 7X	1°09'33.56054S	36°52'53.85701E	1575.271	KISM
KITA	1°00'35.90000N	35°03'12.66000E	1828.575	
KJ	1°23'05.80624S	36°56'03.64153E	1602.048	MLO
LUKENYA01	1°28'16.32090S	37°03'47.66667E	1821.585	PLR
MARS	2°19'56.28000N	37°59'12.36000E	1349.581	
MUSA	0°27'05.32000N	34°43'50.20000E	1499.749	
VA_9	1°14'18.03794S	36°40'29.04651E	1981.294	
VA_9a	1°14'18.03708S	36°40'29.04706E	1981.31	
V_6	1°18'11.58965S	36°49'24.81995E	1646.312	NYAYO

Adjustment Report

Adjustment type: Plane + Height, Constraint
Confidence level: 95 %
Number of adjusted points: 12
Number of plane control points: 5
Number of used GPS vectors: 49
Number of rejected GPS vectors by plane: 29
A posteriori UWE: 1.430442 , Bounds: (0.7786205 , 1.220797)
Number of height control points: 5

GPS Obs Report

Name	dN (m)	dE (m)	dHt (m)	Horizontal Precision (m)	Vertical Precision (m)
149S2−CHEM	67823.708	-217042.71	299.829	0.163	0.072
149S2−GATU					
149S2−KITA	233882.589	-229473.649	358.062	0.159	0.062
149S2−MARS	379813.095	97291.77	-118.167	0.157	0.058
149S2−MUSA	172025.081	-265551.51	26.878	0.168	0.071
CHEM−GATU	-55636.871	187275.776	16.481	0.032	0.058
CHEM−KISM 7X	-74068.74	191266.846	-209.222	0.028	0.063
CHEM−KITA	166058.856	-12430.769	58.239	0.03	0.054
CHEM−KJ	-99019.07	197155.675	-183.565	0.073	0.064
CHEM−LUKENYA01	-108546.173	211511.226	35.295	0.032	0.066
CHEM−MARS	311989.369	314334.433	-417.916	0.076	0.065

CHEM−MUSA	104201.385	-48508.721	-273	0.023	0.045
CHEM−VA_9	-82828.344	168239.682	196.768	0.031	0.057
CHEM−VA_9a	-82828.35	168239.669	196.902	0.031	0.057
CHEM−V_6	-89990.224	184815.367	-138.671	0.068	0.048
GATU−KISM 7X	-18431.941	3991.052	-225.578	0.008	0.015
GATU−KITA	221695.726	-199706.553	41.763	0.053	0.062
GATU−KJ	-43382.194	9879.86	-200.017	0.075	0.066
GATU−LUKENYA01	-52909.303	24235.447	18.866	0.017	0.032
GATU−MARS					
GATU−MUSA	159838.255	-235784.501	-289.46	0.037	0.071
GATU−VA_9	-27191.475	-19036.106	180.335	0.01	0.02
GATU−VA_9a	-27191.477	-19036.104	180.342	0.011	0.02
GATU−V_6	-34353.369	-2460.393	-155.242	0.04	0.025
KISM 7X−KITA	240127.594	-203697.603	267.416	0.068	0.057
KISM 7X−LUKENYA01	-34477.452	20244.39	244.494	0.046	0.036
KISM 7X−MARS	386058.248	123067.326	-208.82	0.134	0.097
KISM 7X−MUSA	178270.084	-239775.768	-63.807	0.101	0.072
KISM 7X−VA_9	-8759.593	-23027.179	405.965	0.008	0.02
KITA−KJ	-265077.925	209586.387	-241.77	0.086	0.069
KITA−LUKENYA01	-274605.024	223942.013	-22.905	0.066	0.061
KITA−MARS					
KITA−MUSA	-61857.474	-36077.945	-331.24	0.019	0.035
KITA−VA_9	-248887.19	180670.434	138.562	0.044	0.071
KITA−VA_9a	-248887.197	180670.395	138.628	0.071	0.044
KITA−V_6	-256049.078	197246.128	-196.94	0.075	0.053
KJ−LUKENYA01	-9527.107	14355.53	218.903	0.012	0.023
KJ−MARS	411008.614	117178.824	-234.402	0.189	0.175
KJ−MUSA	203220.443	-245664.475	-89.394	0.108	0.091
KJ−VA_9	16190.746	-28915.924	380.308	0.063	0.06
LUKENYA01−MARS	420535.6	102823.27	-453.203	0.085	0.058
LUKENYA01−MUSA	212747.566	-260019.983	-308.326	0.065	0.06
LUKENYA01−VA_9	25717.829	-43271.555	161.47	0.016	0.031
LUKENYA01−VA_9a	25717.866	-43271.524	161.526	0.064	0.049
LUKENYA01−V_6	18555.938	-26695.909	-174.09	0.05	0.037
MARS−MUSA					
MARS−VA_9	-394817.783	-146094.747	614.651	0.048	0.086
MARS−VA_9a	-394817.731	-146094.89	614.714	0.089	0.042
MARS−V_6	-401979.718	-129519.312	278.954	0.114	0.069
MUSA−VA_9	-187029.739	216748.424	469.724	0.049	0.065
MUSA−VA_9a	-187029.722	216748.403	469.903	0.038	0.071
MUSA−V_6	-194191.633	233324.059	134.356	0.063	0.059
VA_9a−V_6	-7161.884	16575.612	-335.562	0.007	0.015

APPENDIX D: MATLAB CODE FOR COMPUTING THE TRANSFORMATION PARAMETERS BETWEEN KPLC CORS AND ARC 1960 DATUM

```
>> clear all

>> %Reading coordinate files

>> CORS=textread('CORS.txt');

>> Arc=textread('Arc.txt');

>> lat_CORS=CORS(:,1); %latitude of CORS observations

>> long_CORS=CORS(:,2); %longitude of CORS observations

>> hC=CORS(:,3); %height of CORS observations

>> %Arc 1960 Datum values

>> lat_Arc=Arc(:,1); % latitude in Arc 1960

>> long_Arc=Arc(:,2); % longitude in Arc 1960

>> hA=Arc(:,3); % ellipsoidal height

>> %Ellipsoidal parameters for CORS(GRS80 ellipsoid)

>> aC=6378137.0; % semimajor axis

>> invC=298.257222101; % inverse flattening

>> %Ellipsoidal parameters for Clarke 1880 ellipsoid

>> aA=6378249.145; % semimajor axis

>> invA=293.465; % inverse flattening

>> %

>> % Computations starts
```

```
>> format long
>> %
>> % Converting degrees to radians
>> latC=deg2rad(lat_CORS);
>> longC=deg2rad(long_CORS);
>> latA=deg2rad(lat_Arc);
>> longA=deg2rad(long_Arc);
>> %
>> fC=1/invC;
>> fA=1/invA;
>> e2C=(2*fC)-fC^2; % first eccentricity for GRS80 ellipsoid
>> e2A=(2*fA)-fA^2; % first eccentricity for Clarke 1880 ellipsoid
>> %
>> sinlatC=sin(latC);
>> sinlatA=sin(latA);
>> % radius of curvature in the prime vertical for GRS80 ellipsoid
>> VC=aC./sqrt(1-(e2C.*sinlatC.*sinlatC));
>> % radius of curvature in Clarke 1880 ellipsoid
>> VA=aA./sqrt(1-(e2A.*sinlatA.*sinlatA));
>> da=aC-aA;
>> df=fC-fA;
```

```
>> %
>> %Formulation of the matrix for inputs
>> % Computation of Geocentric cartesian coordinates X, Y, Z in CORS system
>> cosphiC=cos(latC);
>> coslambdaC=cos(longC);
>> sinphiC=sin(latC);
>> sinlambdaC=sin(longC);
>> %
>> %Computation of Cartesian Geocentric coordinates for CORS observations
>> format long
>> XC=(VC+hC).*cosphiC.*coslambdaC;
>> YC=(VC+hC).*cosphiC.*sinlambdaC;
>> ZC=(VC-e2C*VC+hC).*sinphiC;
>> % Geocentric cartesian coordinates in Arc 1960 datum
>> cosphiA=cos(latA);
>> coslambdaA=cos(longA);
>> sinphiA=sin(latA);
>> sinlambdaA=sin(longA);
>> %
>> XA=(VA+hA).*cosphiA.*coslambdaA;
>> YA=(VA+hA).*cosphiA.*sinlambdaA;
```

```
>> ZA=(VA-e2A*VA+hA).*sinphiA;

>> %

>> % The L matrix of inputs

>> % Computing the difference between the 2 sets of Cartesian coordinates

>> xd=XC-XA;

>> yd=YC-YA;

>> zd=ZC-ZA;

>> %

>> m=6; % number of common points

>> % Equations for the design and absolute matrix

>> for i=1:m

A((3*i-2):3*i,1:7)=[1,0,0,XA(i),0,-ZA(i),YA(i);0,1,0,YA(i),ZA(i),0,-XA(i);0,0,1,ZA(i),-
YA(i),XA(i),0];

%

format long

L((3*i-2):3*i,1)=[xd(i);yd(i);zd(i)];

end

>> format long

>> X=A\L;

>> %

>> % Computation of residuals
```

```
>> Residuals=((A*X)-L);

>> u=7; % number of unknown transformation parameters

>> % Variance computation

>> variance=(Residuals'*Residuals)/(3*m-u);

>> sd=sqrt(variance) % standard deviation

sd =

   0.615677951881543

>> % Compute standard deviation for individual parameters

>> sdX=sd*sqrt(diag(A'*A).^-1)

sdX =

>> % Compute standard error

>> se=sd/sqrt(m);
```

APPENDIX E: RESIDUALS FROM DERIVED PARAMETERS

Vx(m)	Vy(m)	Vz(m)
-0.36654	-0.49168	-0.25157
0.745598	0.742198	0.008145
-0.02894	-0.42185	0.108764
-0.31863	0.278706	0.051477
-0.7153	-0.83886	0.163016
0.683808	0.731484	-0.07984

APPENDIX F: GEOGRAPHIC COORDINATES OF COMMON POINTS

	KPLC CORS (ITRF2008) Datum			Arc 1960 Datum		
Station Name	**Latitude**	**Longitude**	**Ell. Height (m)**	**Latitude**	**Longitude**	**Ell. Height (m)**
149S2	1°06'10.85913"S	37°06'47.55518"E	1484.596	1°06'1.5156"S	37°06'44.4996"E	1496.07
KISM 7X	1°09'33.56054"S	36°52'53.85701"E	1575.271	1°09'24.2406"S	36°52'50.8356"E	1588.83
KJ21	1°23'05.80624"S	36°56'03.64153"E	1602.048	1°22'56.5506"S	36°56'0.6224"E	1614.18
149S3	1°28'16.32090"S	37°03'47.66667"E	1821.585	1°28'7.0887"S	37°03'44.6476"E	1833.652
VA/9	1°14'18.03794"S	36°40'29.04651"E	1981.294	1°14'8.7458"S	36°40'26.0351"E	1993.14
V/6	1°18'11.58965"S	36°49'24.81995"E	1646.312	1°18'2.3183"S	36°49'21.8101"E	1659.93

APPENDIX G: COORDINATES OF KPLC CORS

	Geocentric Cartesian Coordinates			Geographic Coordinates		
Station Name	X(m)	Y(m)	Z(m)	Latitude(dd)	Longitude(dd)	Height(m)
CHEMOSIT	5215344	3674312	-54073.9	-0.488896661	35.16544663	1778.347
MARSABIT	5023874	3923212	257877.5	2.332299869	37.98676753	1349.581
MUSAGA	5242878	3634486	49933.1	0.451477433	34.73061171	1499.749
GATUNDU	5104792	3825253	-109788	-0.992654603	36.8458947	1799.971
KITALE	5221936	3663712	111703.5	1.009971786	35.05351726	1828.575

APPENDIX H: GNSS OBSERVATIONS AT STATION 149S3 (LUKENYA)