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TECHNICAL GUIDE ON GEODETIC REFERENCE FRAMEWORKS

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LIST OF ACRONYMS

AFREF	African Geodetic Reference Frame
AU	African Union
BIH	Bureau International de l'Heure
BM	Benchmark
CORS	Continuously Operating Reference Station
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
EUREF	European Reference Frame
EPN	European Permanent Network
ETRS89	European Terrestrial Reference System 1989
FAO	Food and Agriculture Organization of the United Nations
FIG	International Federation of Surveyors

GDOP	Geometric Dilution of Precision
GGOS	Global Geodetic Observing System
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GRFs	Geodetic Reference Frameworks
GRS80	Geodetic Reference System of 1980
IAG	International Association of Geodesy
ICPAC	IGAD Climate Prediction and Application Centre
IERS	International Earth Rotation Service
IGAD	Intergovernmental Authority on Development
IGN Fi	IGN France International
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
KENREF	Kenya Geodetic Reference Frame
KTH	Royal Institute of Technology in Stockholm
LIS	Land Information System
LLR	Lunar Laser Ranging
MSL	Mean Sea Level
NAD83	North American Datum 1983
NAVD88	North American Vertical Datum 1988
NMAs	National Mapping Agencies
RCMRD	Regional Centre for Mapping of Resources for Development
RINEX	Receiver Independent Exchange Format
SDGs	Sustainable Development Goals
SIRGAS	Sistema de Referencia Geocéntrico para las Américas
SMD	Survey and Mapping Department
SLR	Satellite Laser Ranging
TRF	Terrestrial Reference Frame
TRS	Terrestrial Reference System
UGRF	Uganda Geodetic Reference Frame
UNAVCO	University NAVSTAR Consortium
UTM	Universal Transverse Mercator
VLBI	Very Long Baseline Interferometry
WGS84	World Geodetic System of 1984

FOREWORD

IGAD with support from the Swedish Embassy in Addis Ababa, has developed this technical guide on the establishment and modernization of geodetic reference frameworks that can be used by IGAD member states who are desirous to design, develop and modernize their geodetic networks in order to leverage and enjoy the enormous benefits of modern geodetic reference frameworks. The best practice examples from Uganda, Ethiopia and Kenya should serve as an encouragement to all IGAD member states who may not be sure where to start. Additionally, the regional GRFs for Europe and America can serve as examples for the IGAD region towards the goal of establishing a regional GRF covering all IGAD member states.

The work was coordinated by the IGAD Land Governance Unit and the guide was developed by a team of experts from Technology Consults Ltd, discussed and validated by land professionals from all the IGAD member states. Although the authors strove for accuracy, please let us know if you find any errors and we will amend the text accordingly in future versions.

We hope that this guide will be able to help all IGAD member states irrespective of the current state of their geodetic networks to chart a roadmap towards the establishment of a modern geodetic reference frame.

EXECUTIVE SUMMARY

Land governance across borders or transnational land governance looks at rule making, standard setting and institution building. In the IGAD Region, national organization as a structuring principle of societal and political action can no longer serve as the orienting reference point. This creates the need for increased cooperation among nations. With the support of the Swedish Embassy, IGAD seeks to improve the performance of the land administration function in the IGAD region moving closer to convergence and enabling the implementation of cross border initiatives that have a bearing on land. In this regard, this technical guide on the establishment and modernization of the geodetic reference frameworks seeks to provide an understanding of geodetic reference frameworks and to provide practical steps and approaches for the establishment of geodetic reference frameworks within the IGAD region.

The working draft of the guide was initially developed by a team of experts from Technology Consults Ltd. This draft was shared with the IGAD Land Governance Unit which provided useful suggestions and comments that were incorporated into an improved draft that was rigorously discussed in a 5-days hackathon by a team of land professionals from the IGAD member states. Based on the proposals and comments from the hackathon, a final draft of the technical guide was validated by a team of experts from the IGAD member states.

The guide recognizes that there has been a challenge in maintaining and modernizing geodetic reference frameworks in the IGAD region, with all member states depending on geodetic networks that were established in the colonial times for which many of the old stations are either destroyed or lost. However, the guide is cognizant of the efforts of some member states including Ethiopia, Kenya, and Uganda, who have been working independently to upgrade and modernize their geodetic reference frameworks using Global Navigation Satellite Systems (GNSS). The guide hopes that the efforts of these member states will encourage other member states to follow suit in establishing and modernizing their geodetic reference frameworks to ensure that the region is able to enjoy the enormous benefits of modern geodetic networks.

To provide a clear pathway for IGAD member states that are desirous to establish and modernize their geodetic reference frameworks, the guide proposes eleven practical steps that the member states can follow. These are

i) Formulation of policy and/or legal framework
ii) Setting up and/or reviewing the institutional arrangements
iii) Assessment of the human resource capacity

iv) Inventory of existing network

v) Datum definition

vi) Network design

vii) Monumentation

viii) Equipment

ix) Observations

x) Publication

xi) Maintenance and monitoring

The guide however makes it clear that the practical steps are neither prescriptive nor must be followed in the order in which they are presented. Member states can use the guide to assess the status of their geodetic network and identify what needs to be done to establish a modern geodetic reference framework that can leverage the benefits of new and improved positioning technologies including GNSS. Thus, the guide provides checklists of minimum requirements for various components of the geodetic network that the member states can use in their planning.

1.0 BACKGROUND

1.1 Land Governance

The concept of land governance was introduced in the early 2000s by the World Bank and Food and Agriculture Organization of the United Nations (FAO) as an extension of the concept of land management. It includes aspects of governance and the political economy of land, which are highly relevant in addressing the complex challenges that the world is facing including poverty, land degradation, climate change and the call for sustainable development (Enemark, 2022).

Land Governance concerns the rules, processes and structures through which decisions are made about access to land and its use, the way the decisions are implemented and enforced, and how competing interests are managed (FAO, 2009). Within the IGAD region, transnational land governance looks at rule making, standard setting and institution building across borders. Thus, national organization as a structuring principle of societal and political action can no longer serve as the orienting reference point. This creates the need for increased cooperation among nations. The IGAD region finds itself in a time where economic, social, and political developments in one country are increasingly affected by developments in others; and where opportunities and threats to people are no longer exclusively the responsibility of individual governments; The transnational sphere of land governance in the IGAD region is built neither upon nor beyond national institutional frameworks (full integration). Rather, the transnational sphere of land governance in the IGAD region transcends national borders while at the same time being entangled in historically contingent institutions and shaped by actors rooted in locally and nationally diverse contexts (Convergence). In dealing with cross border contexts in land governance, it is important to understand how transnational rules are implemented on the ground, how they are monitored by civil and public actors, and whether there is any learning from local experiences.

There has been a challenge in densification, maintaining and modernizing geodetic reference frameworks (GRFs), which form the foundation for creation of geospatial information and associated systems in the IGAD region. The GRFs which were established during colonial times were heavily affected by the loss of too many old stations. There have been efforts by member states such as Ethiopia, Kenya and Uganda, working independently to upgrade and modernize their GRFs using Global Navigation Satellite System (GNSS) techniques. These efforts are hampered by several challenges that have made the realization of modern geodetic reference frames an unfulfilled dream.

1.2 Global Geodetic Reference Frame (GGRF) as a precursor for modern GRFs

The role and importance of geodetic reference frameworks has been recognized by the global community culminating into the adoption of the UN General Assembly Resolution on a Global Geodetic Reference Frame for Sustainable Development – recognizing the importance of a globally-coordinated approach to geodesy. In furtherance of the resolution, the International Association of Geodesy (IAG) established the Global Geodetic Observing System (GGOS) in 2016 to be the component that integrates the various geodetic contributions to ensure the quantification of the planet's changes in space and time with the highest accuracy and reliability. This is undertaken primarily through activities such as the maintenance, and continuous improvement of the geodetic instrumentation networks and space geodetic missions, and the combined analysis of geometric and gravimetric observations made by these networks using a variety of space and terrestrial geodetic techniques. In such a framework, the GGRF plays a key role in facilitating the integration of the different geometric and gravimetric observations, with the goal of providing reliable, high quality geodetic products.

The GGRF is intended to support the increasing demand for positioning, navigation, timing, mapping, and geoscience applications. The GGRF is essential for a reliable determination of changes in the Earth system, natural disaster management, monitoring sea-level rise and climate change, and to provide accurate information for decision-makers. Furthermore, due to globalization and interoperability requirements, there is a growing demand for spatial data infrastructure. Precise spatial information is needed in many areas of benefit to society, including transportation, construction, infrastructure, process control, surveying and mapping, and Earth sciences, and is especially important for monitoring progress towards the UN's Sustainable Development Goals.

With the resolution on a Global Geodetic Reference Frame for Sustainable Development and the establishment of the GGOS, the UN Member States are requested to:

i. Encourage, together with relevant international organizations, global cooperation in providing technical assistance, especially for capacity development in geodesy for developing countries;
ii. Openly share geodetic data, standards, and conventions, through relevant national mechanisms and intergovernmental cooperation, and in coordination with the IAG;
iii. Maintain, and improve their national geodetic infrastructures;
iv. Engage in multilateral cooperation that addresses infrastructure gaps and duplications; and

v. Assist in the development of outreach programs that make the GGRF more visible and understandable to society.

1.3 Challenges to the Establishment and Modernization of GRFS in the IGAD region

Within the region, there were apparent challenges in maintaining those geodetic reference frameworks. The advent of modern GNSS techniques has opened opportunities for the upgrade and modernization of the geodetic reference frameworks at both national and regional levels. However, member states may differ a little in terms of their level of adoption and implementation of modern techniques in upgrade and modernization of geodetic reference frameworks and need for the associated expertise. The major challenges facing countries member states as regards establishment and modernization of GRFs can be summarized as:

i) Inadequate funding to the land governance sector in general and the modernization of geodetic infrastructure (limited resources)

ii) Limited human capacity regarding the expertise required for the establishment and modernization of GRFs

iii) Failure to appraise any new projects/programs related to modernization of land administration systems within the IGAD region leading to poorly managed projects that do not address the challenges in land governance

iv) The accuracy standards of GRFs are usually necessarily high and cannot be compromised. This requires enormous investment in terms of the cost to realize a modern GRF based on modern techniques like GNSS.

v) Absence of political will to support specific programs for establishment, maintenance, and monitoring of GRFs within the IGAD member states

vi) Members states within the IGAD region use different geodetic datums

Addressing the above challenges is key to the establishment, maintenance, and modernization of GRFs in the region.

1.4 Application areas of Geodetic Reference Frameworks

GRFs that were established in colonial times had limited but important applications restricted to provision of the necessary survey and mapping infrastructure, their densification, and the associated limited high-cost surveying activities. The advent of new GNSS positioning techniques has revolutionized the implementation of geospatial applications including those in land administration and management. There are enormous opportunities which have been made available by modernization of GRFs, with the potential to reduce the cost of geospatial products including surveying, mapping, land administration and management activities. The application areas of modern GRFs include:

1. Cadastral Surveying. The adjudication and demarcation of the land rights of the citizens of the IGAD member states is important for the sustainable development of the region. Well documented land rights are a precursor to the achievement of the SDGs including SDGs 1, 5 and 15. Cadastral surveys form the foundation for the documentation of land rights. However, proper cadastral surveys require that the GRF in the country is well established and maintained to reduce the cost of the surveys leading to reduction in the overall cost involved in land registration.
2. Agriculture. The backbone of the majority of the IGAD member states economies is in agriculture. This sector contributes greatly to sustaining the economies through exports in coffee, tea, cereals, etcetera. The application of modern GRFs especially Continuously Operating Reference Stations (CORS) in smart agriculture is becoming handy in most countries.
3. Scientific applications. The practical scientific applications of the GRF including seismic studies, landslide prediction and monitoring, land degradation analysis, etc. require regional cooperation in the establishment and modernization of GRFs. This is very important as the IGAD Region is astride the East African Rift Valley, which is prone to seismic activity and sometimes volcanic eruptions, with far-reaching implications for the population of the member states.
4. Infrastructure. There are various infrastructure projects in the individual IGAD member states and increasingly a growing portfolio of trans-national infrastructure projects. These projects include road and railway construction projects, hydropower projects, airports and seaports, industrial parks, urban and regional planning, and free zones, etc. All these require geospatial information that is based on a proper well-functioning GRF not only in the member states but also at the regional level.
5. Mining, oil, and gas sector. Most of the IGAD member states have invested a lot of capital in this sector. The day-to-day functionality of this sector is dependent on accurate and timely spatial information that is used for analysis and management of the activities. However, the

region is challenged by inadequate coverage of CORS which has contributed to delayed project implementation and the accompanying high costs.

6. Tourism, forestry, and wildlife conservation. The IGAD member states have invested heavily in the tourism sector to attract foreign exchange. The application of accurate and timely spatial information in these sectors has been found to be very vital. The cost of acquiring this spatial information can considerably be reduced through modernized GRFs in the region.
7. Weather Forecasting. IGAD through the IGAD Climate Prediction and Application Centre (ICPAC) provides timely early warnings and preparedness for disasters. Additionally, it provides medium and long-range forecasting, numerical weather prediction and training to meteorological departments of member states. Modern GRFs based on GNSS provide the data necessary for ICPAC to carry out its mandate.
8. Contribution to AFREF. The modernization of GRFs in the IGAD region will contribute to the AFREF project which aims at unification of the very many GRFs of African countries using data from a network of permanent GNSS stations contributing to the geospatial information requirements for continental wide infrastructural projects.
9. Navigation on air, land, and water. The IGAD region lies astride the Indian ocean and is home to several inland lakes and rivers. This makes navigation on water key to the transport system within the region. The GRFs are the basis for the geospatial information of navigation routes on water and land. Additionally, GRFs have important applications in the areas of security, defense, and the fight against terrorism within the region.
10. Climate change monitoring. Climate change is the gravest challenge humanity faces, endangering peace and prosperity, food security, and the full enjoyment of human rights for every person on earth. Climate change devastates communities, degrades ecosystems, destroys livelihoods, and deepens existing gender and social inequalities. There is now consensus among development practitioners on the need to combat climate change and its associated challenges such as poverty, hunger, drought, etc. and champion the rights of women and other vulnerable groups through securing their rights. GRFs provide the foundation for representing the geospatial information on maps, charts and plans which offer a powerful visual representation that is useful in ensuring climate justice, resilient environments, and gender equity.
11. Demarcation of cross-border transhumance corridors. The IGAD member states lie astride the cattle corridor in which its cattle grazing communities are involved in moving across the

countries in search for grazing land and water among others for the animals. The seasonal movement requires monitoring for sustainable management including reducing conflicts among the herders and farmers. The GRFs provide the required geospatial information for monitoring and sharing spatial information on the seasonal movement of the communities.

12. Demarcation of international boundaries. The IGAD member states as part of the African Union (AU) are mandated to implement the resolution of the AU on realization of re-affirmed international boundaries. A modern and, specifically a unified regional GRF is essential in achieving this resolution.

1.5 The Need to Mainstream Gender in the Establishment and Modernization of GRFs

Most of the IGAD member states subscribe to global and regional frameworks like the UN 2030 Agenda for Sustainable Development. One of the key global issues addressed by SDG 5 is gender inequality. SDG 5 aims to achieve gender equality and empower all women and girls. Equality between men and women is an integral part of human rights and a fundamental criterion for democracy. Other relevant frameworks and policies include the AU Agenda 2063, AU Gender Policy 2009, and Action Plan. There are other Policies, Legal and Planning Frameworks in the IGAD Member States that provide for Gender Mainstreaming in Land Administration.

In line with the legal and policy frameworks and general principles of natural justice, IGAD member states are required to uphold and promote the rights of women and girls, to mainstream a gender perspective in all policies and operations, and to work towards the empowerment of women and the elimination of all forms of inequality in land access, ownership, land rights and use.

GRFs form the spatial foundation for the creation of any Land-Information System (LIS). They provide not only an accurate and efficient means for positioning data, but they also provide a uniform, effective language for interpreting and disseminating land information, which contribute to implementation of efficient and effective land administration systems. It is therefore important to mainstream gender in the establishment and modernization of GRFs within the region to ensure that women equally benefit from them. This can be carried out by ensuring that gender-sensitive language is used in all GRF related training and capacity building, women and men are equally involved in decision making related to the establishment and modernization of GRFs e.g., by intentionally recruiting women surveyors, using gender-sensitive illustrations and images when preparing public relations materials and giving women an equal opportunity to participate in any GRF related projects.

1.6 Purpose and Scope of the Guide

The main goal of the technical guide is to provide an understanding of GRFs and to provide practical steps and approaches for the establishment of Geodetic Reference Frameworks within the IGAD region. While some IGAD member states such as Ethiopia, Kenya, and Uganda, have worked independently to upgrade and modernize their Geodetic Reference Frameworks using GNSS techniques, the rest of the member states are still facing a challenge. The guide therefore provides an overview of good practices that exist in the IGAD Region and also propose some practical guides on the establishment and maintenance of GRFs. This should facilitate a more informed approach to the design, development, implementation, maintenance, and monitoring of Geodetic Reference Frameworks for member states.

The guide does not provide detailed discussions of GRFs and does not prescribe specific procedures for the establishment and modernization of GRFs within the IGAD region but focusses on generic requirements for the establishment, maintenance, and monitoring of GRFs. Users of the guide are therefore expected to interpret the guide in context of the needs of the specific countries and the current state of their GRFs.

1.7 Format and Organization of the Guide

The guide is organized under 5 chapters all with sections and subsections. Chapter one provides the background to land governance within the IGAD region and presents an overview of the application areas of GRFs while discussing the challenges that have hindered the establishment and modernization of GRFs in the region. This is followed by Chapter 2 which presents the theoretical foundation of GRFs with a detailed discussion of both international and national terrestrial reference frames and systems. Chapter 3 then discusses both horizontal and vertical control networks and provides the practical steps followed for the realization of geodetic datums. Chapter 4 presents the status of GRFs in the IGAD member states while highlighting the progress made towards establishing modern GRFs in each of the member states. Finally, Chapter 5 provides guidance on practical steps that any IGAD member state can follow in order to design, develop and modernize its GRFs. Checklists for various components of the GRF are provided in the Appendices to act as a guide for any member state on what is required as a minimum.

2.0 THEORETICAL OVERVIEW OF GEODETIC REFERENCE FRAMEWORKS

A geodetic reference framework forms the spatial foundation for the creation of any Land-Information System (LIS). Consisting of monumented points whose locations have been accurately determined with respect to a mathematical framework, this system permits the spatial referencing of all land data to identifiable positions on the Earth's surface. A geodetic reference framework provides not only an accurate and efficient means for positioning data, but it also provides a uniform, effective language for interpreting and disseminating land information (National Research Council, 2010).

2.1 Geodetic Datums

Two main reference surfaces (or Earth figures) are used to approximate the shape of the Earth. One is called the ellipsoid; the other is the Geoid. The **ellipsoid** provides a relatively simple mathematical figure of the Earth. It is used to measure locations, the latitude (ϕ) and longitude (λ), of points of interest. These locations on the ellipsoid are then projected onto a mapping plane. An ellipsoid is defined by its semi-major axis ***a*** and semi-minor axis ***b*** as shown in Figure 1. For maps at small scales, we can use the mathematically simpler sphere.

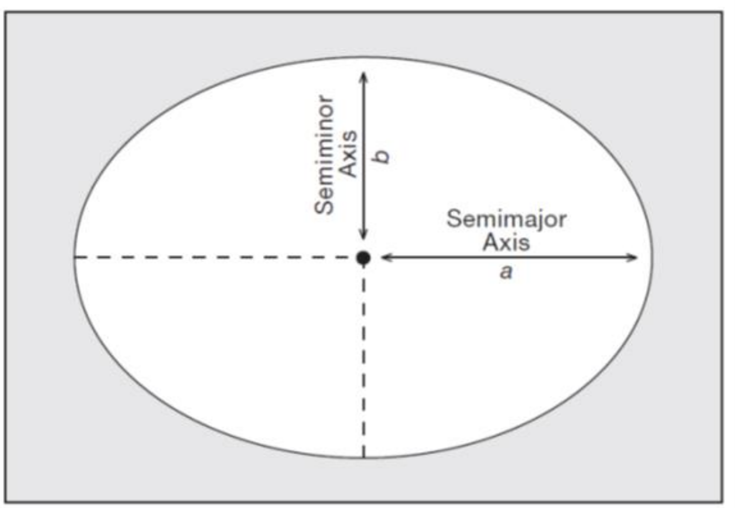


Figure 1: Cross-section of the Reference Ellipsoid

To measure locations accurately, the selected ellipsoid should fit the area of interest. Therefore, a horizontal datum (also called geodetic datum) is established, which is an ellipsoid but positioned and oriented in such a way that it best fits to the area or country of interest. There are a few hundred of these local horizontal datums defined in the world. Recent years have seen that globalization is leading to the definition of global (or geocentric) datums, such as the International Terrestrial

Reference Frame (ITRF) or WGS84. Table 1 shows the geodetic datums for the IGAD member states, with the Adindan and Arc1960 datums most dominate within the region.

2.2 Legacy horizontal datums in the IGAD region

Within the IGAD region, the most well-known national horizontal datums are

i) Arc1950 datum

ii) Arc1960 datum

iii) Adindan datum

2.2.1 Arc1950 Datum

Arc 1950 is a geodetic datum first defined in 1950 and is suitable for use in Botswana, Lesotho, Malawi, Swaziland, Zambia, Democratic Republic of Congo, and Zimbabwe. It references the Clarke 1880 (Arc) ellipsoid and the Greenwich prime meridian with the origin at Fundamental point: Buffelsfontein. Latitude: 33°59'32.000"S, longitude: 25°30'44.622"E (of Greenwich).

2.2.2 Arc1960 Datum

Arc 1960 is a geodetic datum first defined in 1960 and is suitable for use in Kenya, Tanzania and Uganda. It references the Clarke 1880 (RGS) ellipsoid and the Greenwich prime meridian with the origin at Fundamental point: Buffelsfontein. Latitude: 33°59'32.000"S, longitude: 25°30'44.622"E (of Greenwich).

2.2.3 Adindan Datum

Adindan is a geodetic datum first defined in and is suitable for use in Eritrea; Ethiopia; South Sudan and Sudan. It references the Clarke 1880 Modified ellipsoid and the Greenwich prime meridian with the origin at Fundamental point: Station 15; Adindan. Latitude: 22°10'07.110"N, longitude: 31°29'21.608"E (of Greenwich). It includes the 12th parallel traverse of 1966-70 (Point 58 datum, code 6620), which is connected to the Adindan network in western Sudan.

Table 1 : Geodetic datums and ellipsoids for IGAD member states

No.	Country	Datum	Reference Ellipsoid	Semi–Major Axis	Flattening

1.	Djibouti	Ayabelle Lighthouse	Clarke 1880 Modified	a = 6378249.145 m	298.465
2.	Ethiopia	Adindan	Clarke 1880 Modified	a = 6378249.145	298.465
3.	Kenya	Arc1960	Clarke 1880 (RGS)	a = 6378249.145 m	298.465
4.	Somalia	Adindan	Clarke 1880 Modified	a = 6378249.145 m	298.465
5.	South Sudan	Adindan	Clarke 1880 Modified	a = 6378249.145 m	298.465
6.	Sudan	Adindan	Clarke 1880 Modified	a = 6378249.145 m	298.465
7.	Uganda	Arc1960	Clarke 1880 (RGS)	a = 6378249.145 m	298.465

2.3 Coordinate System on the Ellipsoid

Describing a point on the Earth's surface requires that a location's latitude and longitude be known with respect to an origin (Slocum, et al., 2014). The latitude is defined with respect to the equator and the longitude with respect to the reference meridian, which is usually the prime meridian. To complete the ellipsoidal coordinates, height ***h*** is defined as the distance between a point on the physical surface of the earth and the ellipsoid measured along the normal of the ellipsoid passing through the point.

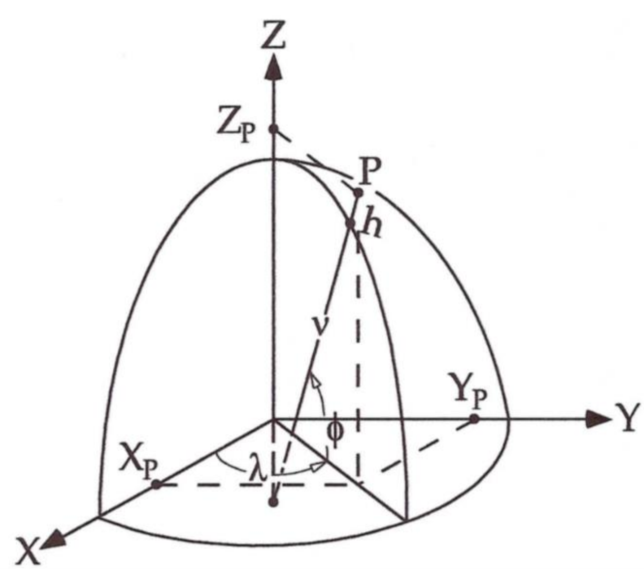


Figure 2 : Relationship between geodetic and cartesian coordinates

The Cartesian coordinate system is the simplest coordinate system in which coordinate axes are mutually perpendicular and equally scaled. In this system, coordinates of a point are defined by the length of segments on the coordinate axes denoted by (*x*, *y*, *z*). For the Earth, the cartesian axes (XYZ) form a right-handed orthogonal geocentric (earth-centred) system with the origin corresponding to the earth's centre of mass, the Z-axis passing through the minor axis of the ellipsoid, the X-axis in the equatorial plane and aligned with the prime meridian and the Y-axis completing a right-handed system.

2.4 Projected/Grid Coordinate System

The projected coordinate system represents locations on the Earth's surface using cartesian coordinates (x,y) on a planar surface created by a particular map projection. Each projected coordinate system, such as Universal Transverse Mercator (UTM) is defined by a choice of map projection (with specific parameters), a choice of GRF to bind the coordinate system to real locations on the earth, an origin point, and a choice of unit of measure.

The UTM system shown in Figure 3 is a special map projection system which divides the Earth into 60 zones, each 6° of longitude in width. Zone 1 covers longitude 180° to 174° W with the zone numbering increasing eastward to zone 60, which covers longitude 174°E to 180°. Each of the 60 zones uses a transverse Mercator projection that can map a region of large north-south extent with low distortion (Slocum, et al., 2014).

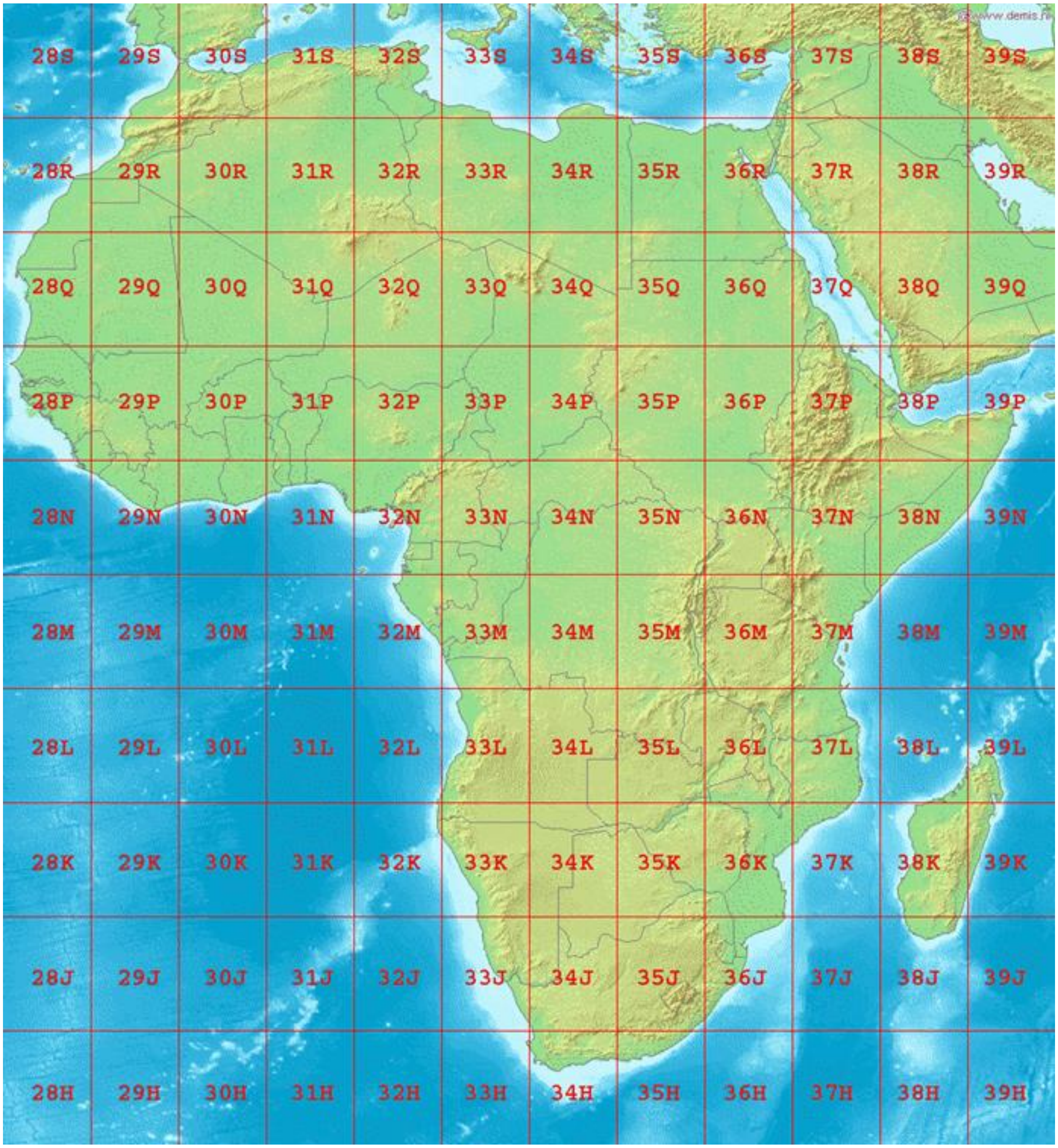


Figure 3 : UTM zones for African Countries

2.5 The Geoid and Height Datums

The **Geoid** is the equipotential surface at mean sea level and is used for measuring heights represented on maps. The starting point for measuring these heights are mean sea level points established at coastal places. These points represent an approximation to the Geoid. There are several realizations of local mean sea levels in the world. These are called ***local vertical datums*** or height datums. A height datum is the practical realization of a height system.

2.5.1 Orthometric heights

Heights with respect to the geoid are known as orthometric heights (H). The orthometric height for a point on the Earth's surface is the positive upward distance from the geoid to the point measured along the plumbline (the instantaneous direction of gravity). By adding the orthometric correction, spirit-levelled height differences can be converted into orthometric height differences thus precise levelling is the traditional method of determining orthometric heights. With the advent of GNSS, orthometric heights can be determined provided the geoid undulation (geoid height) from a gravimetric geoid model is available for the same point.

$$H = h - N \tag{2.1}$$

Where, H is the orthometric height, h is the ellipsoidal height from GNSS and N is the geoid height from a gravimetric geoid model.

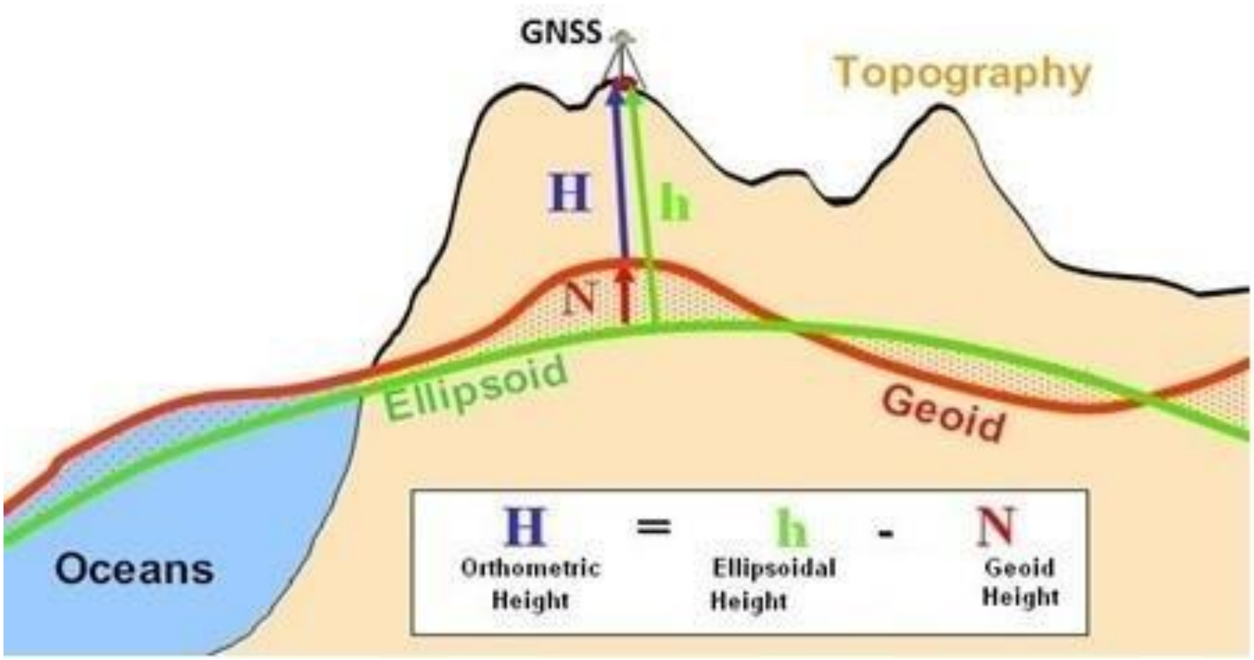


Figure 4: The geoid and orthometric height

The procedure for the computation of national gravimetric geoid models is a complex mathematical endeavor that requires optimal combination of terrestrial and satellite gravity anomalies (from global geopotential models) using several techniques including KTH method (Ssengendo, 2015) and Remove-compute-restore (Valty, et al., 2012). An interim geoid model can be obtained by fitting either a local geoid model or a global geopotential model (e.g., EGM2008) to the levelling benchmarks using parameter-fitting techniques.

2.5.2 Quasigeoid, Normal Heights and Normal-Orthometric Heights

The quasigeoid is a non-equipotential surface of the Earth's gravity closely aligned with the geoid. It was introduced by Molodensky (1945) as an alternative theoretical surface to the geoid. Its determination does not require knowledge of the topographic density of the Earth with all the computations performed on the telluroid, which is a theoretical surface where the normal gravitational potential is equal to the gravitational potential of the Earth's surface (Brown, et al., 2022). Heights with respect to the quasigeoid are known as normal heights.

The normal height $\left(H^N\right)$ of a point on the Earth's surface is the vertical distance measured along the normal gravity plumbline from the reference ellipsoid to the telluroid. Like orthometric heights, normal heights can be determined using GNSS provided the quasigeoid height $\left(\zeta\right)$ i.e., distance measured along the ellipsoidal normal between the reference ellipsoid and the quasigeoid, can be obtained from an appropriate gravimetric quasigeoid model.

$$H^N = h - \zeta \tag{2.2}$$

where, H^N is the normal height, h is the ellipsoidal height from GNSS and ζ is the quasigeoid height from a gravimetric quasigeoid model.

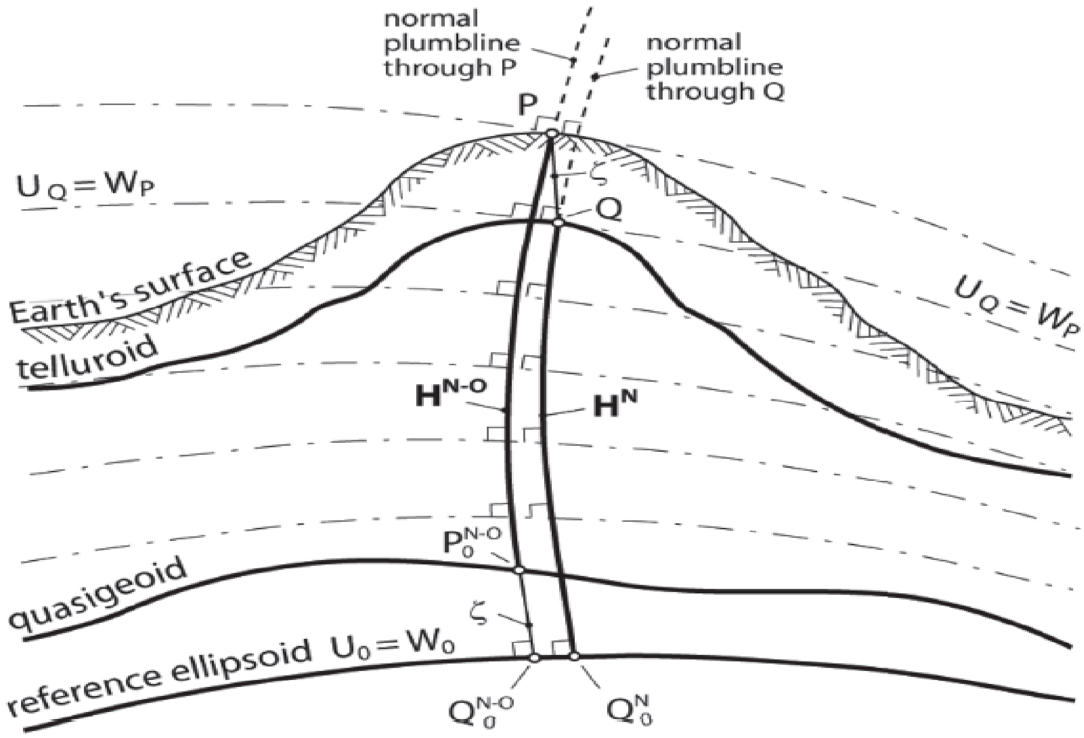


Figure 5 : The normal height, normal-orthometric height and their relationships to the telluroid and quasigeoid (Source: Featherstone and Kuhn, 2006)

For some of the IGAD member states, neither pure orthometric nor normal heights were defined due to the absence of actual gravity observations along the levelling routes (Ssengendo, 2015; Loxton, 1952; Dyus, 1965). In this case normal-orthometric heights were adopted. Normal-orthometric heights use only the normal gravity field to approximate the Earth's gravity field hence avoiding the need for gravity observations along the levelling route (Ssengendo, 2015). Like orthometric and normal heights, normal-orthometric height differences can be computed by adding normal-orthometric corrections (e.g., Rapp, 1961; Amos, 2010); Price, 1932; Bomford, 1971) to the spirit-levelled height differences.

The normal-orthometric heights can also be determined from GNSS using the formula below

$$H^{N-O} \approx h - \zeta \tag{2.5}$$

Where, H^{N-O} is the normal-orthometric height, h is the ellipsoidal height from GNSS and ζ is the quasigeoid height from a gravimetric quasigeoid model.

2.6 Global and Regional datums

2.6.1 International Terrestrial Reference System & Frame

The International Terrestrial Reference System (ITRS) is a world spatial reference system co-rotating with the Earth in its diurnal motion in space. Its realization is the International Terrestrial Reference Frame (ITRF), which is produced by the International Earth Rotation Service (IERS) based on a combination of individual TRF solutions computed by IERS analysis centers using the observations of Space Geodesy techniques (GPS, VLBI, SLR, LLR and DORIS) of stations located on sites covering the whole Earth (IERS Conventions, 2010).

The ITRF is a dynamic global reference designed to support all geodetic and earth science applications. It underpins national geodetic datums, supports satellite navigation, and enables the monitoring of tectonic plate motion. Since it is not fixed to any specific tectonic plate, ITRF station coordinates will change over time. Therefore, ITRF coordinates are valid for specific dates (called epochs) and are accompanied by velocity estimates that reflect station motion and are useful to propagate coordinates over time. Individual realizations of ITRF are denoted by ITRFyy, where yy represents the last year for which data was included in a particular solution. Since 1990, ITRF realizations have been the most accurate and stable terrestrial reference frames available. ITRF2020 is the most recent realization of the ITRS. Details regarding ITRF realizations, including datum definition and transformation parameters, can be found on the ITRF website (ITRF, 2022). The ITRF solutions do not directly use an ellipsoid. ITRF solutions are specified by cartesian ECEF (Earth-Centered, Earth-Fixed) coordinates X, Y, and Z. If needed they can be transformed to geodetic coordinates (Longitude, Latitude and Height) referred to an ellipsoid of choice. Usually, the Geodetic Reference System 1980 ellipsoid denoted as GRS80 with semi-major axis a=6378137.0 m, and flattening (1/f) =1/298.257222101 is used. This ellipsoid was adopted at the XVII General Assembly of the International Union of Geodesy and Geophysics (IUGG).

2.6.2 World Geodetic System (WGS84)

WGS84 is a three-dimensional ECEF reference system that was originally developed to serve as the official GPS reference system. Unlike ITRF, the WGS84 definition includes the parameters of a reference ellipsoid supporting both cartesian and ellipsoidal coordinate representations. WGS84 ellipsoidal parameters (*a=6378137.0 m* and flattening *(1/f) = 1/298.257223563*) are identical (up to a very small difference in flattening) to GRS80. The origin of WGS84 is defined at the center of mass of the whole Earth, including its oceans and atmosphere. Its *Z*-axis corresponds to the direction of the BIH Conventional Terrestrial Pole (CTP) at epoch 1984.0. The *X*-axis of the system is at the intersection of the IERS Reference Meridian (IRM) and the plane passing through the origin and normal to the *Z*-axis. The most recent realization is WGS84 (G1762) epoch 2005.0 introduced on 16th October, 2013, which is coincident with ITRF at centimeter level, yielding conventional 0-transformation parameters.

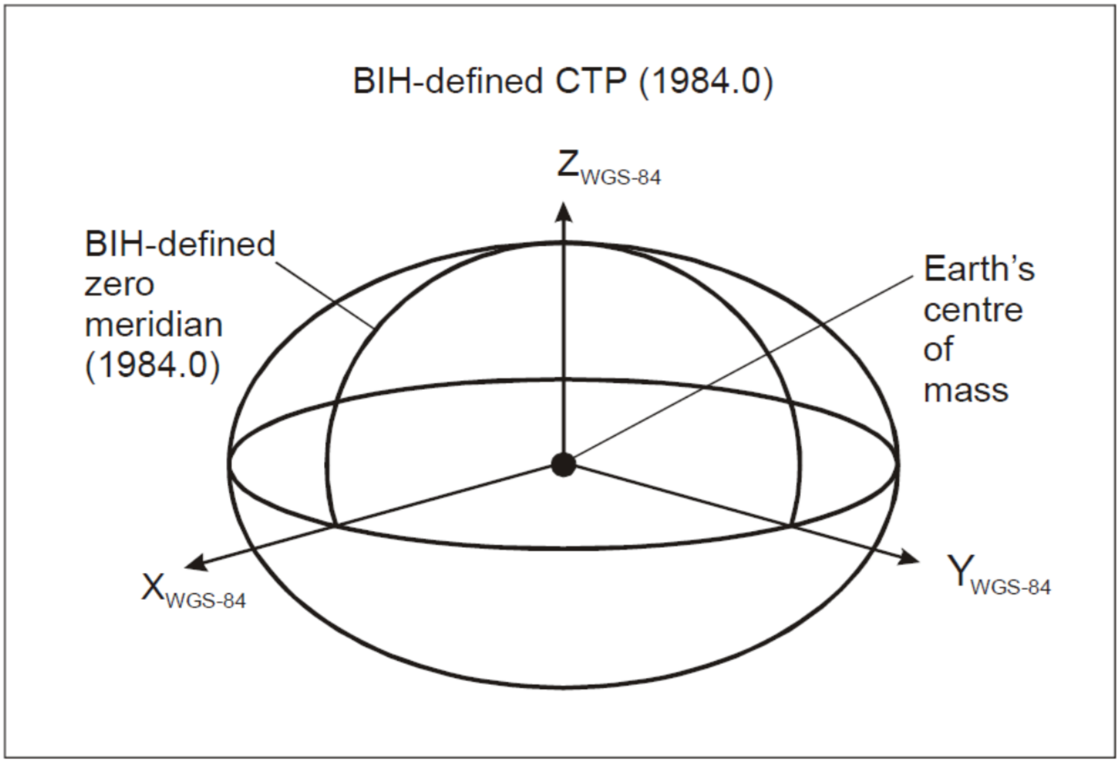


Figure 6 : WGS84

2.6.3 African Geodetic Reference Frame (AFREF)

The African Geodetic Reference Frame (AFREF) is a project designed to unify the very many geodetic reference frames of Africa using data from a network of permanent GNSS stations as the primary data source for the realization of such a uniform reference frame. For each of the primary stations, suitable geodetic grade GNSS receivers are installed and managed by National Mapping Agencies (NMAs) and Universities in Africa, International agencies, and organizations (http://afrefdata.org/).

The following objectives of AFREF were defined by the AFREF Working Group at a pre-conference meeting of the African Association of Remote Sensing of the Environment (AARSE) in August, 2004 in Nairobi

i) Define the continental reference frame of Africa

ii) Realize a unified vertical datum

iii) Establish continuous, permanent GPS stations such that each nation or each user has free access to, and is at most 1000km from, such stations

iv) Provide a sustainable development environment for technology transfer

v) Assist in establishing in-country expertise for implementation, operations, processing, and analyses of modern geodetic techniques, primarily GPS and

vi) Determine the relationship between the existing national reference frames and the ITRF

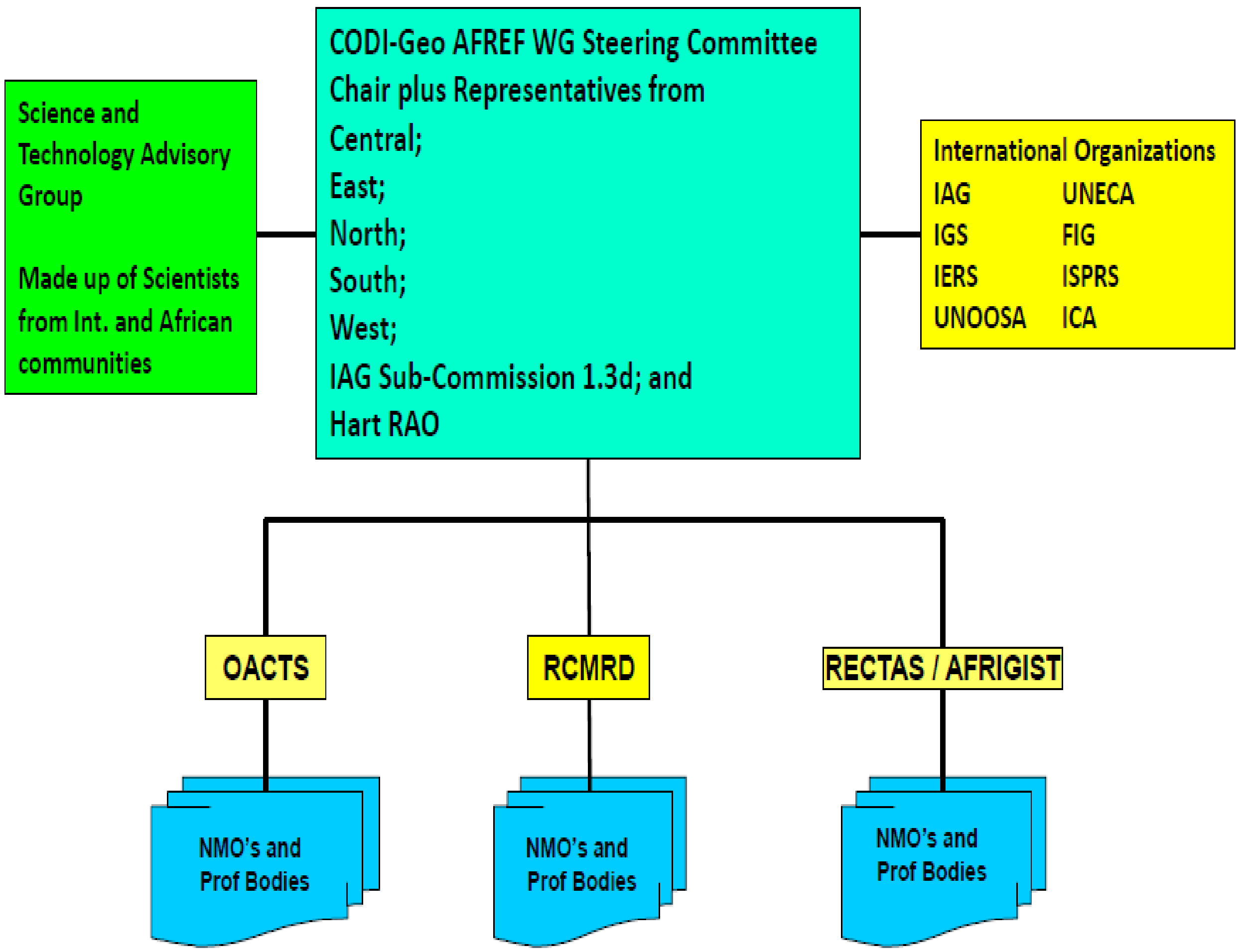


Figure 7 : Structure of AFREF (RCMRD, 2022)

The above objectives and structure of AFREF (Figure 7) were approved by the NMAs in August 2008. The AFREF Operational Data Centre was set-up in 2009 and is currently managed by the National

Geospatial Information (NGI) of South Africa. As of November 2017, approximately 112 stations were noted on the ODC website. However, only about 40 stations were providing daily data up to November 2017. In December 2012, ITRF 2008 coordinates of 50 AFREF stations were computed by the four computing centers in South Africa, Tanzania, and Portugal (RCMRD, 2022).

2.7 Types of geodetic datums

2.7.1 Static Geodetic Datums

These are geodetic datums that are aligned with a fixed epoch of an ITRF realization. The new geodetic datum for Uganda ITRF2005 is a static geodetic datum with an epoch of 2010. Static geodetic datums have the following practical limitations if GNSS positioning techniques are used (FIG, 2014):

i. GNSS point positioning uses orbit models defined in ITRF or WGS84 reference frames. Consequently, the precise location within these frames will change as a function of time due to tectonic processes and other deformation sources such as subsidence, soil creep and post glacial uplift.
ii. Unless precise GNSS positions are localized (e.g., via a local CORS or site transformation at a geodetic reference mark), users will notice positions of 'fixed' (in a local reference frame) objects changing every few months.
iii. Rigid tectonic plates rotate slowly over the Earth's mantle however the rotation is rapid enough to introduce errors in static GNSS baseline processing and RTK over long baselines if the rotation rate is high and there is large interval between the measurement and reference epochs.

2.7.2 Semi-Dynamic Geodetic Datums

These are geodetic datums in which a deformation model forms an integral part of the datum definition. GNSS point positions determination and geodetic data analysis is undertaken in the kinematic ITRF reference frame, using the latest realization of ITRF. Resulting coordinates are then propagated back to the fixed reference epoch of the semi-kinematic datum, so that spatial data can be integrated seamlessly over long periods of time. The utility of the semi-kinematic datum approach is that precision data analysis is not degraded because of un-modelled deformation, however to the end user, the geodetic datum appears to be static at a fixed reference epoch (FIG, 2014).

2.7.3 Fully Dynamic Geodetic Datum

A fully kinematic datum overcomes a lot of the limitations of unmodelled deformation in positioning, however the major limitation (currently) is that it is very difficult to integrate spatial data acquired over a longer period, unless a precise deformation model is embedded in the data or somehow explicitly referenced (FIG, 2014).

3.0 GEODETIC CONTROL NETWORKS

3.1 Horizontal and Vertical Control Networks

Geodetic control networks consist of monumented points that provide the reference for positioning. The classical horizontal and vertical datums were realized separately by the application of classical geodetic methods. The horizontal networks determine the latitude and longitude of points on the terrestrial surface and were mainly observed by triangulation, trilateration, and traversing or a combination (Ghilani & Wolf, 2012). The two-dimensional results were referred to the reference ellipsoid. The vertical network also referred to as the leveling network, determines the vertical datum for obtaining the heights of points on the earth's surface. Leveling networks (usually called benchmarks) are established by leveling as the primary method and supplemented by trigonometric leveling. The benchmark values are computed with respect to the vertical datum which consists of a zero-elevation surface and permanent leveling origin. The Mean Sea Level (MSL) is adopted as zero point and is computed by taking tide gauge readings for a period of 18.61 years.

3.2 Passive and Active Control Networks

3.2.1 Passive Control Networks

Passive control points are ground markers or pillars on which users install their survey instruments to connect to the reference frame and integrate their surveys. Geodetic passive control points with stable monuments can be re-observed periodically to estimate displacements caused by crustal dynamics, used to access the datum, used for transformations and control for different projects.

3.2.2 Active Control Networks

Active control stations (commonly known as CORs) are reference points on which GNSS receivers are permanently deployed to continuously track all navigation satellites in view. They are usually connected to a communication network providing remote access to the observation data. CORs may also stream satellite range measurements in real-time, enabling precise differential positioning and navigation.

Figure 8 : Active control station

3.3 Classification of Control Networks

The control networks can be made of either a single order or different orders. Single order networks are applicable in small territories for mapping purposes to ensure homogeneous accuracy in the network. For wide territories, they have different networks with different orders varying from higher to lower orders. The traditional control networks have had three distinct orders of accuracy that governed them: First order, Second order and Third order.

For horizontal networks, the first order is termed as the primary and these are made up of trigonometric (triangulation) points with a station separation of 30 to 100 km and are usually of the highest accuracy levels. The second order at a station separation of 10 to 30 km and 1 to 2km for lower orders. The second order and third order have two accuracy classes: class I and class II.

Vertical networks are classified according to the precision of the levelling, which is expressed by the standard error per unit distance that is $\sigma\sqrt{K}$ where σ is the standard deviation in mm and K is the distance between benchmarks in kilometers (Vanicek and Krakiwsky, 1982). Table 3.1 gives maximum relative elevation errors allowable between two benchmarks based on the 1984 Federal Geodetic Control Subcommittee (FGCS) of the USA (Ghilani and Wolf, 2012).

Table 2 : 1984 FGCS Vertical Control Survey Accuracy Standards

Order and Class	**Relative Accuracy Required Between Benchmarks**
First Order	
Class I	$0.5\ mm\ x\ \sqrt{K}$
Class II	$0.7\ mm\ x\ \sqrt{K}$
Second Order	
Class I	$1.0\ mm\ x\ \sqrt{K}$
Class II	$1.3\ mm\ x\ \sqrt{K}$
Third Order	$2.0\ mm\ x\ \sqrt{K}$

3.4 Design of Control Networks

The establishment of geodetic networks usually starts with network design. The design stage involves consideration of the configuration of the network, the types of the observations to be carried out and their precision, the location and distribution of the points to be coordinated. In addition, it is necessary to consider the cost involved in order to arrive at an optimal network design, i.e., a network that minimizes cost but maximizes the precision and reliability of observations (Kuang, 1996, p.195). In general, the quality of a network is evaluated based on three general criteria, i.e., precision, reliability and economy. A network should therefore be designed such that (Schmitt, 1985, p.7)

- The postulated precision of the network elements, and of arbitrary estimable quantities, can be realized;

- It is as sensitive as possible against statistical testing procedures, which allow for example the detection of outliers in the measurements and the detection of movements in deformation networks, and
- The marking of the points and the performance of the measurements are satisfying some cost criteria.

To carry out network optimization to achieve an optimal network, the problem of network design is divided into four different orders (Grafarend, 1974):

i. Zero-order design (ZOD), which involves the choosing of the optimum datum and coordinate system, i.e., reference system;
ii. First-order design (FOD) where the best locations of the points are selected and an optimum observation plan is selected provided the a priori precision of the observations is known;
iii. Second-order design (SOD) which involves choosing which observations to make and assigning suitable weights to the observations, i.e., choosing the precision with which to make the observations;
iv. Third-order design (THOD) which is about the optimal extension of an existing network.

3.5 Monumentation

Generally, standards require that all Zero, First and Second order stations be monumented, described, and imbedded in stable places. The monumentation involves the station mark, an underground mark, and two or more reference marks. The station marks can be either metallic disks set on rocks or concrete monuments with subsurface marks. For each monument set, the following information should be available.

i) Geodetic datum and coordinate system
ii) Monument name
iii) Monument location
iv) Year of establishment
v) Order of accuracy
vi) Measurement units (feet or meters)

The locations of the monuments in the classical networks favored higher grounds (like hills and mountains) due to optical intervisibility requirements. For the GNSS networks, stations are located where needed without the influence of the terrain. Special attention must be given to the environmental factors like physical objects obstructing the GNSS signals and multipath.

For active control networks, the monuments can be ground-based pillars, braced or roof-based. The ground-based pillars should have the following specifications:

i) Approximately 1.5m above the ground surface where there are no obstructions
ii) Deep concrete foundation of at least 4m. The top of the pillar should be narrower than the widest part of the antenna.

For roof-based pillars, special attention must be given to the type of building materials used in constructing the building. Solid brick or reinforced concrete buildings are recommended and the building should be at least 5 years in existence without cracks on the outside or inside walls. To avoid the effects of thermal expansion and multipath, the following are not allowed.

a) buildings taller than two stories,
b) buildings constructed of wood,
c) metal frame buildings with metal walls or roof.

Generally, active control monumentation demands that more factors are investigated like the continuous power supply and site security.

For passive control networks, the pillars should be 1.5m above the earth's surface with a deep foundation of about 2m. The ground marks should have a deep foundation of about 1.5m.

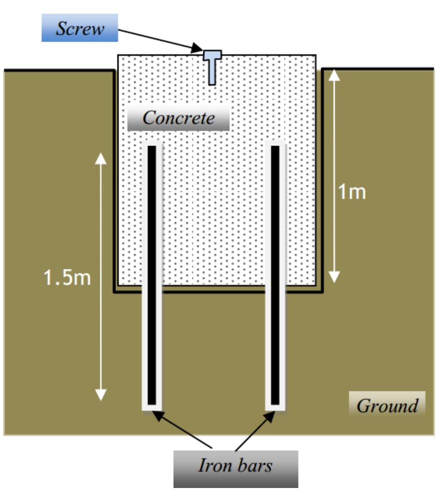


Figure 9 : Monumentation of a passive control station

3.6 GNSS Observations

The taking of observations is influenced by factors like the level of accuracy needed, the number of available equipment, the number of skilled field staff available, error sources in GNSS and the processing software. The design of the observational network can be looked at in two parts: -

i) An existing network- This refers to the old points whose geometry and distribution is known and cannot be changed. One must consider the density of the network on either to create more points or not.

i) New network- This involves selecting control sites and adhering to some survey standards set. The spatial distribution of the selected site is key on the network design.

After the network design step, the next is the GNSS data capture step where the following procedures are to be considered (Ghilani & Wolf, 2015): -

ii) For each session, the GNSS receivers should be more than 4.

iii) The session interval is dependent on the length of the baselines in the network and the accuracy levels required

iv) The sample rate of observations being 15s

v) The GDOP value being less than 6

vi) At least two points are observed commonly between two successive sessions.

vii) The redundant occupations should be done at least 30% of the points.

3.7 Processing and Analysis

The first activity under processing is the transfer of observation data to a central storage center e.g., a high-end computer, and the selection of the different GNSS software to be used. For control networks, scientific GNSS software like **Bernese** GNSS software (Bernese GNSS Software (unibe.ch)) is recommended as they provide the ability to carry out complex analysis of the observations and computations. Once the data is downloaded, then pre-processing of the observations should be carried out using software like **teqc** which solve many pre-processing problems with GNSS observations and can be used in translating, editing and quality checking the observations (TEQC | Software | UNAVCO). There are a number of other scientific and commercial GNSS Data Processing software that can be used to process, analyze and resolve ambiguities in GNSS data processing. The analysis involves two levels i.e., pre-analysis and post-analysis of measurements (Ghilani & Wolf, 2015):

- Pre-analysis of measurements involves accuracy analysis of observations, observation data pre-processing and pre-adjustment data screening.
- Post-analysis of measurements looks at least squares network adjustment, post-adjustment data screening, quality analysis of the results and reporting network results and their quality.

3.8 Publication

Once the coordinates of the control points have been precisely determined then they must be published and made available to users. Usually, a description card is prepared for each of the stations giving key information including the name, location, survey method used, geographic and grid coordinates, parameters of the ellipsoid, the projection parameters, photograph, etc.

3.9 Coordinate Conversions and Transformations

A geodetic datum can have different types of coordinates. Coordinate conversion is about changing coordinates from one type to another within the same datum whereas coordinate transformation is the process of moving coordinates from one geodetic datum to another using transformation parameters.

3.9.1 Geodetic – Grid Coordinates Conversion

The coordinate conversion from geodetic coordinates to grid coordinates is termed as a projection. Grid coordinates are coordinates on a projected plane and are commonly referred to as Eastings and Northings. The focus is given to the coordinates on a Universal Transverse Mercator projection and to obtain them, an appropriate false easting and false northing must be involved. The conversion can be carried out by several methods including the Krueger n-series equations and Krueger λ-series equations (see Krueger, 1912 in Brown, et al., 2022).

3.9.2 Cartesian – Geodetic Conversion

The forward conversion of geodetic coordinates (ϕ, λ, h) to cartesian coordinates *(X, Y, Z)* can be accomplished using the formulae below

$$X = (V + h)\cos\phi\cos\lambda$$
$$Y = (V + h)\sin\phi\cos\lambda$$
$$Z = \left(\left(V(1 - e^2\right) + h\right)\sin\phi$$

Where, *e* is the first eccentricity and *V* is the radius of curvature in the prime vertical defined as:

$$V = \frac{a}{\sqrt{1 - e^2 \sin^{-2} \phi}}$$

The reverse conversion i.e., cartesian to geodetic is iterative for the latitude and ellipsoidal height based on the formulae below

$$\lambda = \arctan \frac{Y}{X}$$

$$\tan \phi = \frac{Z}{(V + h)\cos \phi} \left(1 - e^2 \frac{V}{V + h}\right)^{-1}$$

$$h = \left(\frac{\sqrt{X^2 + Y^2}}{\cos \phi} \right) - N$$

3.9.3 Coordinate Transformations

The geodetic datum whose coordinates need to be converted is the source datum and the one where they will be is the target datum. Coordinates of Point (P) on datum1 (blue) and datum2 (red) are different, so moving P from datum2 to datum1 is coordinate transformation.

Transformation parameters are quantities that determine how position coordinates in the source datum are changed to position coordinates in the target datum. The transformation parameters commonly applied are:

i) Scale (to create equal dimensions in the coordinate systems);
ii) Rotations (to make the reference axes of the systems parallel); and
iii) Translations (to create a common origin for the systems)

At a national level, a transformational model should satisfy the following: -

i) Simplicity- to facilitate understanding and adoption by users
ii) Efficiency- to minimize time and computational demands
iii) Uniqueness- to ensure only one solution exists
iv) Rigor - to provide the best possible transformation result

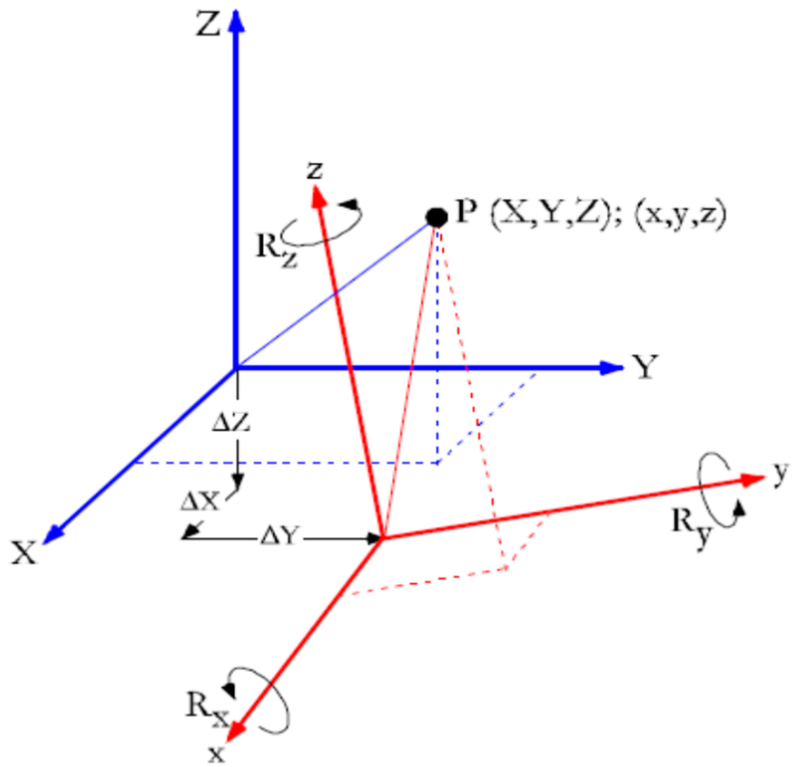


Figure 10 : Coordinate Transformation

The 7-parameter similarity transformation is the most common method of coordinate transformation. It is based on the 7-parameter Helmert transformation, which consists of three rotations (R_X, R_Y, R_Z), three translations ($\Delta X, \Delta Y, \Delta Z$) and a scale factor (μ) (Ghilani & Wolf, 2015).

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{datum1} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{datum2} + \underbrace{\begin{bmatrix} \mu & +R_Z & -R_Y \\ -R_Z & \mu & +R_X \\ +R_Y & -R_X & \mu \end{bmatrix}}_{\text{Rotation angles and scale factor}} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}_{datum2} + \underbrace{\begin{bmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{bmatrix}}_{\text{shift of origin}}$$

Note that the rotation matrix is only valid for small rotation angles ($<10''$), otherwise a full rotation matrix shown in the equation below should be used.

$$R = \begin{bmatrix} \cos R_Z & \sin R_Z & 0 \\ -\sin R_Z & \cos R_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos R_Y & 0 & -\sin R_Y \\ 0 & 1 & 0 \\ \sin R_Y & 0 & \cos R_Y \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos R_X & \sin R_X \\ 0 & -\sin R_X & \cos R_X \end{bmatrix}$$

4.0 THE STATUS OF NATIONAL GRFs FOR IGAD MEMBER STATES

4.1 Djibouti

4.1.1 The Old Geodetic Reference Frame

Djibouti's national legacy network was established in the late 1880s by triangulation method. The network was established on the Ayabelle Lighthouse datum using Clarke 1880 ellipsoid (NIMA

TR8350.2). There is little information about the status of the network and it is not clear on how many control points and benchmarks still exist.

4.1.2 Modernization of the GRF

As part of the modernization process, the country has established regional independent geodetic points based on the UTM projection for the capital city (Djibouti) and five (5) other regions. In addition, there is one (1) CORS station located at Observatoire Geophysique d' Arta established by the Centre National d'Etudes Spatiales (CNES) as part of the International GNSS Service (IGS) network.

4.2 Ethiopia

4.2.1 The Old Geodetic Reference Frame

The horizontal datum in Ethiopia was established through a triangulation network extended from Gedarif of Sudan to the west part of Ethiopia that covers the Nile basin. All position computations were made on the Adindan datum using Clarke 1880 ellipsoid. The horizontal network is made up of 365 Geodetic points established by Triangulation method. The vertical network comprises of 905 Bench Marks established by leveling from Gedarif (Sudan) and referred to MSL Alexandria.

4.2.2 Modernization of the GRF

After the introduction of GPS technology, the country was able to establish 28 First-order geodetic points in 2004, which were complemented with 30 Zero order control points in 2017 with the support of the Finland government. In terms of the CORS, the first CORS was established in 2007 by the Institute of Geophysics, Space Science, and Astronomy (IGSSA) at Addis Ababa University's Arat Kilo Campus as part of the international GNSS service (IGS) stations. In 2015, the TANA IGS station was built by the Institute of Land Administration (ILA) at Bahir Dar University. An additional four CORS at Gondar, Jimma, Dire Dawa, and Addis Ababa were established by the Ethiopian Geospatial Information Institute (GII). Currently 4 CORS shown in the Map below are operational in the country.

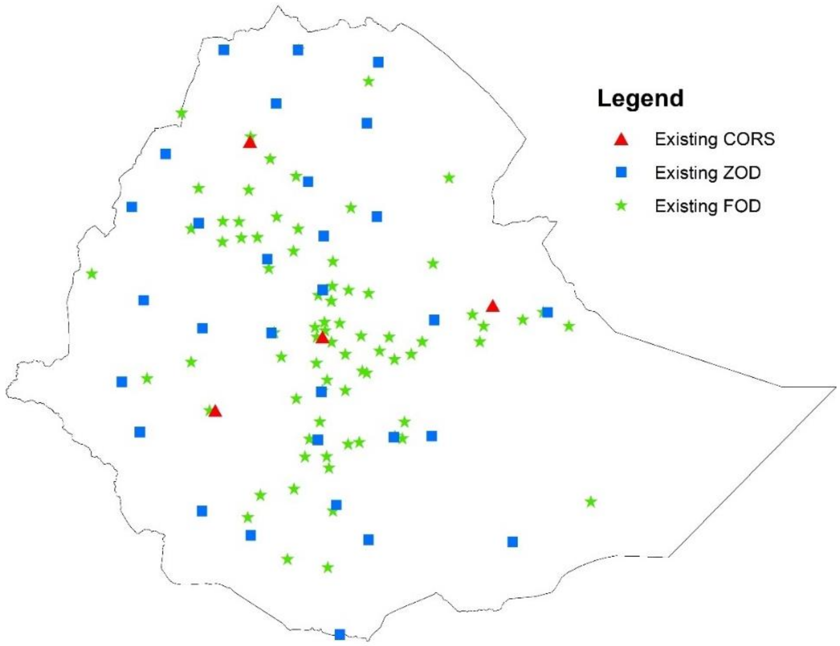


Figure 11 : Distribution of the existing CORS, Zero and First-order geodetic network distribution in Ethiopia

As part of modernization of the national GRF, Ethiopia has developed a ten-year implementation plan for modernizing geodetic services through the establishment of a CORS network, development and validation of a geoid model, and densification of geodetic control stations. It is planned to establish 50 CORS, 450 zero-order, 1000 first-order, and 1435 first-order level BMs across the country. Out of 1435 level BMs, 400 BMs will be implemented to validate the geoid model in Ethiopia that will be collocated points that have both GNSS and levelling data. Additional about 90,000 airborne gravity data was collected from 2006 to 2008 and used as the basis for the development of a geoid model for Ethiopia.

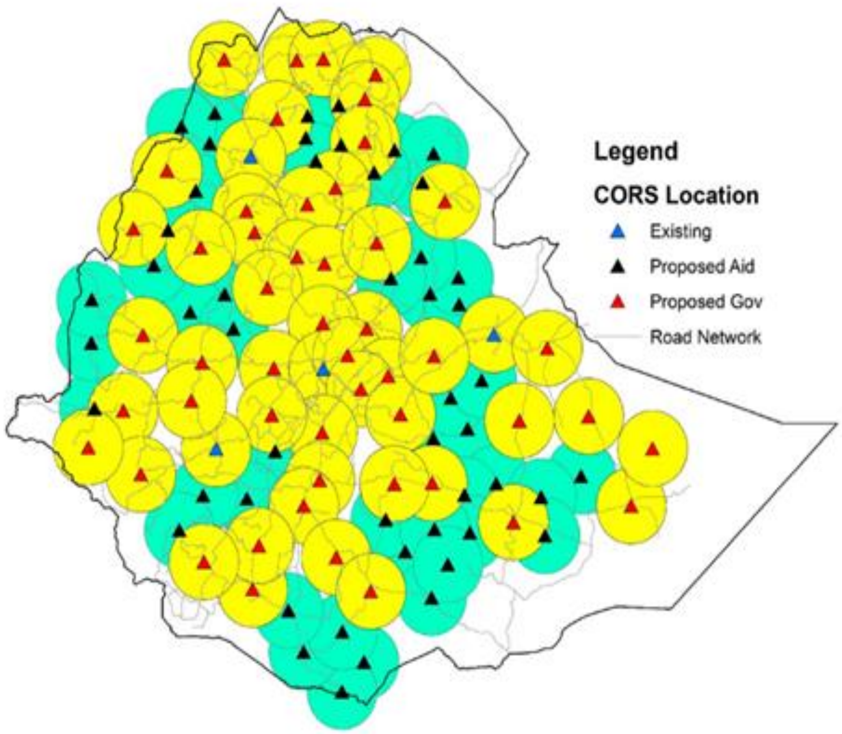


Figure 12 : Existing and proposed CORS network in Ethiopia

4.3 Sudan

4.3.1 The Old Geodetic Reference Frame

The old GRF for Sudan was established between 1898 to 1945. The network was established on the Adindan datum using Clarke 1880 ellipsoid. Coordinates of the pillars and benchmarks were listed in both geographic coordinates (latitude, longitude, ellipsoidal heights) as well as the UTM projection. It is not clear how many of the geodetic control points still exist today.

4.3.2 Modernization of the GRF

The Republic of Sudan is in the process of establishing a new national geodetic network that shall be composed of 600 First-order geodetic control points by the National Government and the establishment of the second order control points. It is envisaged that CORS will be established by the Federal States and the private Sector. The planned GRF shall be based on the WGS84 Reference Ellipsoid, ITRF 2008 as Datum and the Vertical Datum from Port Sudan with UTM as its Projection. All linear measurements will be in meters.

4.4 South Sudan

4.4.1 The Old Geodetic Reference Frame

The legacy GRF for South Sudan was established by the then Sudan between 1898 to 1945. The network was established on the Adindan datum using Clarke 1880 ellipsoid. Coordinates of the pillars and benchmarks were listed in both geographic coordinates (latitude, longitude, ellipsoidal heights) as well as the UTM projection. However, most of the legacy geodetic control points have been destroyed.

4.4.2 Modernization of the GRF

The Republic of South Sudan is in the process of modernizing the GRF. However, the private sector and other agencies such as RCMRD have established a few passive geodetic control points in major towns. The planned activities for the modernization are still at the infancy.

4.5 Kenya

4.5.1 The Old Geodetic Reference Frame

The first triangulation network to be observed by the Anglo-German Boundary Commission (AGBC) in East Africa was between Kenya and Tanganyika (current Tanzania) between 1892 and 1893. The second triangulation network was done by the Anglo German Boundary Commission of 1902-1906. The current Geodetic network in Kenya is based on the 1960 Arc Datum using the Clarke 1880 ellipsoid with coordinates in UTM.

4.5.2 Modernization of the GRF

The modernized Kenya Geodetic Reference Frame (KENREF) which is tied to AFREF was designed to include a Zero Order Geodetic Network consisting of 25 reference stations approximately 200 km apart and a First-order network consisting of 75 reference stations approximately 70 km apart. Based on the two networks, a CORS Network was to be gradually set up with its control center based in Nairobi. Development of KENREF started in 2010 with the construction of 18 Zero order network station pillars. The Survey of Kenya (SoK) has installed a total of 20 Roof Top - Tier 3 CORS. The KENREF system has not been officially launched for use by the public. The CORS is based on Arc Datum 1960 and Clarke 1880 ellipsoid. In addition, there are about 60 CORS services operational by the Private Sector.

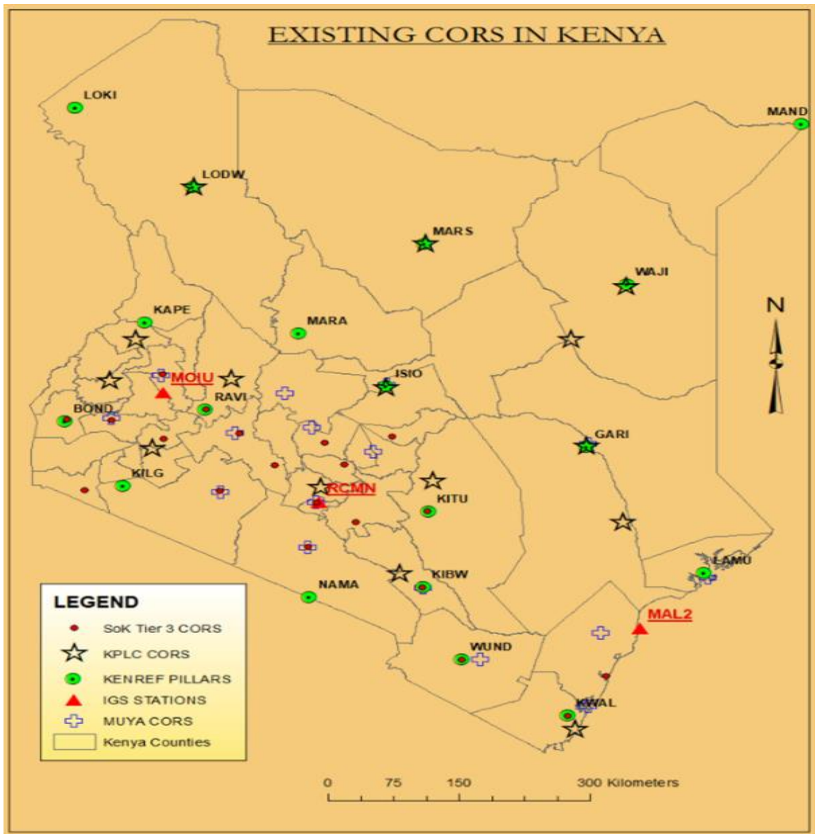


Figure 13 : Existing CORS Network in Kenya

4.6 Uganda

4.6.1 The Old Geodetic Reference Frame

The horizontal geodetic control network comprising of 1,730 geodetic control points was based on the triangulation method and referenced to the Arc1960 datum and the Clarke 1880 ellipsoid. It was completed in the 1960s. The vertical control network consisting of 3,033 benchmarks all referenced to the New Khartoum vertical datum was completed in 1972 (Okia and Kitaka, 2003). Most of these control points were either lost or destroyed with a few existing points which were crosscuts on rocks.

4.6.2 Modernization of the GRF

Uganda has modernized her national geodetic control points with the establishment of 9 passive Zero Order control points and 12 CORS. In addition to the Zero Order points, the country established 129 First-order and 297 Second Order geodetic points covering the entire territory of Uganda (Home (ugrf.go.ug)). The modernized GRF for Uganda is based on the ITRF 2005 (Epoch 2010.0) as datum and UTM projection. The reference ellipsoid is GRS80 with linear measurements being in meters. The private sector has contributed to the national CORS network with the establishment of about 40 points Zero Order network with establishment of about 40 CORS (www.eaglecors.com and www.survnet.ug).

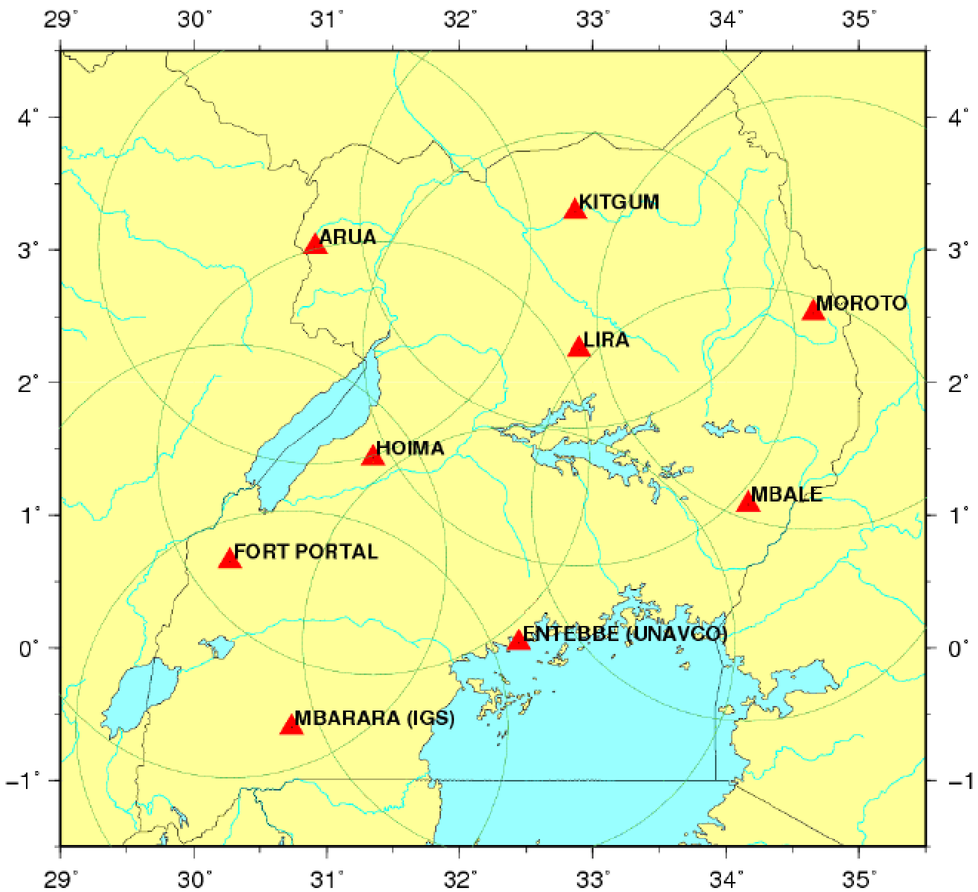


Figure 14: Zero Order Network

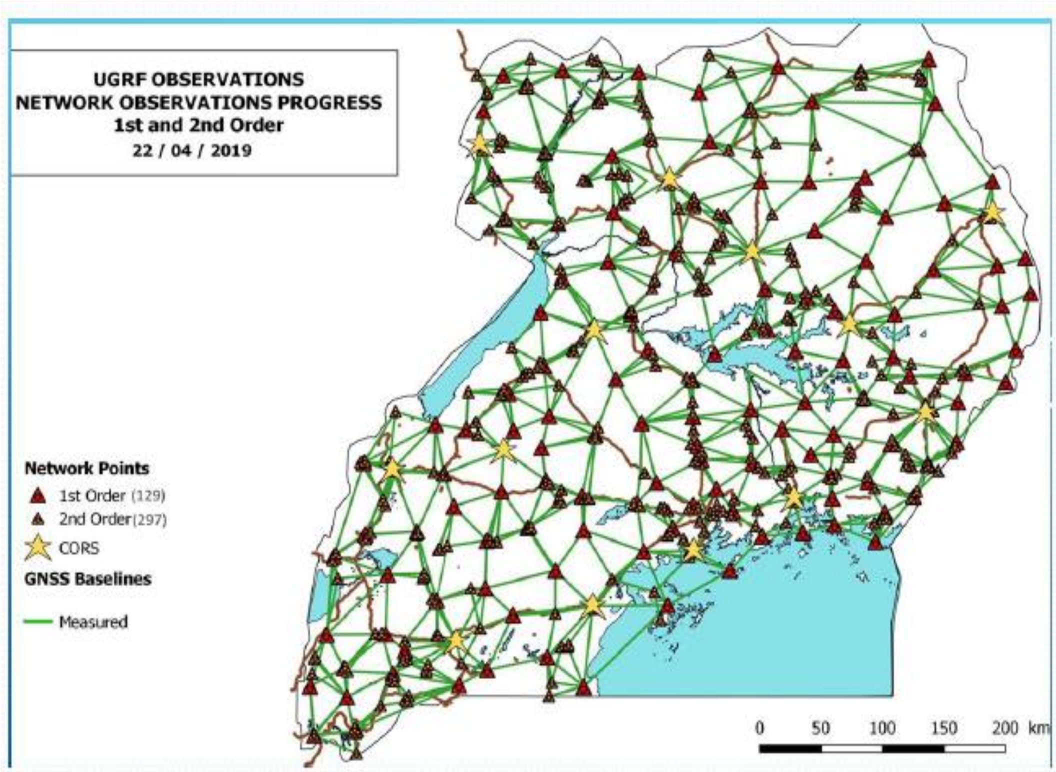


Figure 15 : Overview of Uganda's geodetic network

4.7 Learning Lessons from other Regions in Modern GRF Sustainability

4.7.1 The European Reference Frame (EUREF)

The European Geodetic Reference Frame was developed from 1987 as a precise continent-wide modern reference near to the WGS84 and usable for multinational Digital Cartographic Datasets. Its main objective is to unify national reference systems for surveying, mapping, GIS and navigation in Europe. In 1990, EUREF designed the European Reference System 89 (ETRS89) in such a way that it would be based on the ITRS except that it is tied to the stable part of Europe, so that the relations between European stations are kept fixed. Coordinates in ETRS89 are expressed as either three dimensional (X, Y, Z) Cartesian coordinates or as 3D ellipsoidal coordinates based on the GRS80 ellipsoid (www.euref.eu). The solutions of ETRS89 correspond to the ITRS solutions. For each ITRS solution, a matching ETRS89 solution is made. ETRS89 is realized by EUREF through the maintenance of the EUREF Permanent Network (EPN) and continuous processing of the EPN data in a few processing centres. Users have access to ETRS89 via EPN data products and real-time streams of differential corrections from a set of public providers based on the EPN stations (EUREF Permanent GNSS Network (oma.be)).

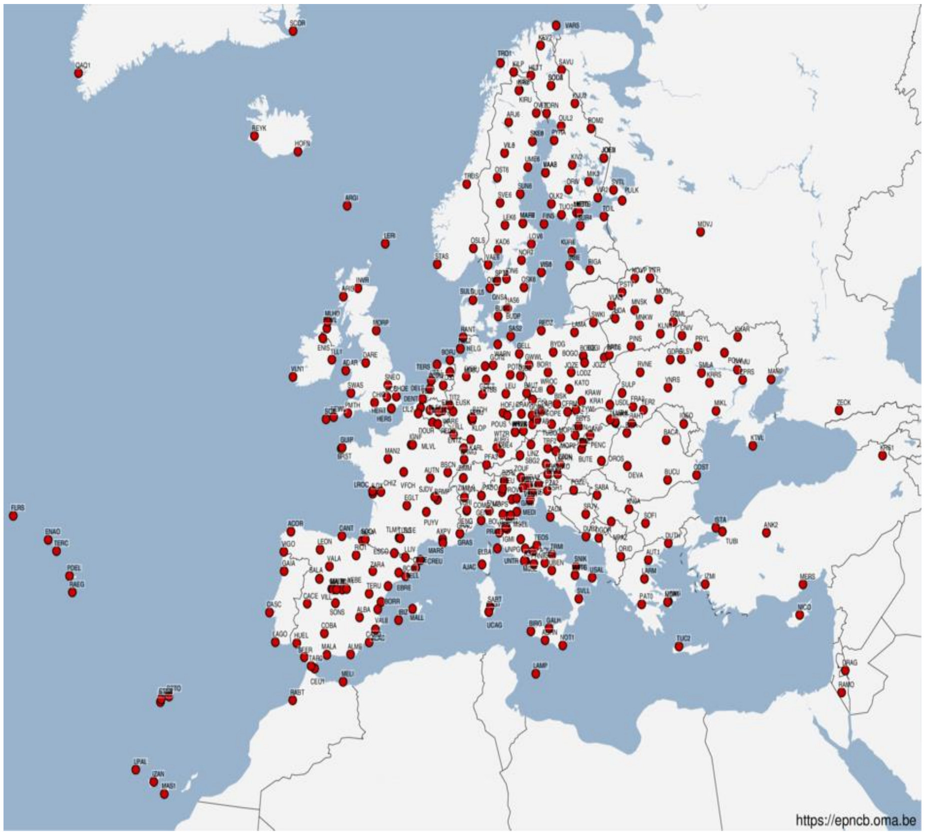


Figure 16 : EUREF Permanent Network

4.7.2 The North American Datum of 1983 (NAD 83)

NAD 83 is the horizontal and geometric control datum for the United States, Canada, Mexico, and Central America. NAD 83 was released in 1986 and re-adjusted in 2007 and 2011 with the incorporation of GPS measurements (https://geodesy.noaa.gov/). NAD83 coordinates are defined based on the GRS80 ellipsoid.

As part of the GRF for the United States, Canada and Mexico, the North American Vertical Datum of 1988 (NAVD 88) was established in 1991 as the vertical control datum. It held fixed the height of the primary tidal bench mark, referenced to the new International Great Lakes Datum of 1985 local mean sea level height value, at Father Point/Rimouski, Quebec, Canada. Additional tidal bench mark elevations were not used due to the demonstrated variations in sea surface topography. NAVD 88 consists of a leveling network on the North American Continent, ranging from Alaska, through Canada, across the United States, affixed to a single origin point on the continent (https://geodesy.noaa.gov/).

As part the modernization of the GRF, the USA will replace both NAD83 and NAVD88 with four new terrestrial reference frames and a geopotential datum, which will rely primarily on GNSS and a gravimetric geoid model (https://geodesy.noaa.gov/).

4.7.3 Geodetic Reference System for the Americas (SIRGAS)

SIRGAS is the Geodetic Reference System for the Americas. Its definition corresponds to the ITRS and it is realized by a regional densification of the ITRF in the Americas. Besides the geometrical reference system, SIRGAS includes the definition and realization of a vertical reference system, based on ellipsoidal heights as geometrical component and geopotential numbers (https://sirgas.ipgh.org).

The first realization of SIRGAS (SIRGAS95) refers to ITRF94, epoch 1995.4. It is given by a high-precision GPS network of 58 points distributed over South America. In 2000, this network was re-measured and extended to the Caribbean, Central and North American countries and includes 184 GPS stations and refers to ITRF2000, epoch 2000.4. The third and present realization of SIRGAS is given by a network of continuously operating GNSS stations distributed over the Americas and the Caribean called SIRGAS-CON (SIRGAS Continuously Operating Network). SIRGAS-CON is processed on a weekly basis to generate instantaneous weekly station positions aligned to the ITRF and multi-year (cumulative) reference frame solutions(https://sirgas.ipgh.org).

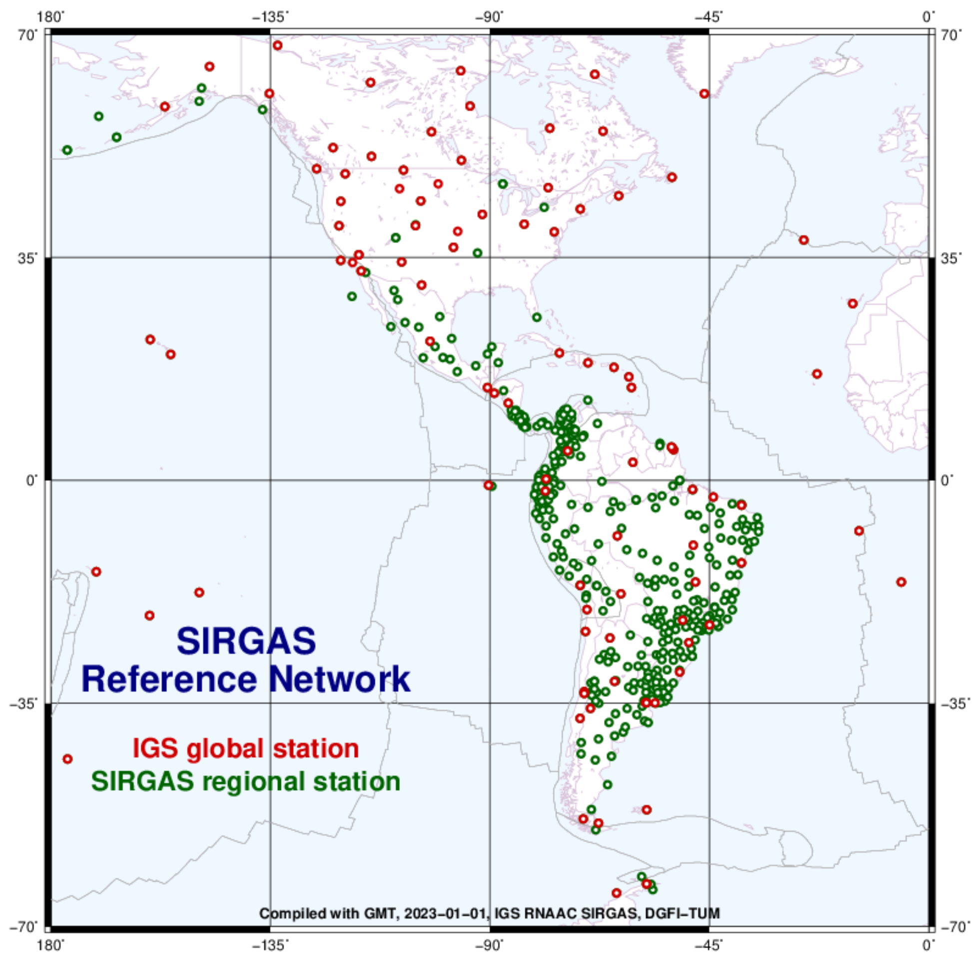


Figure 17: SIRGAS Reference Network

5.0 GUIDING PRINCIPLES FOR THE ESTABLISHMENT AND MODERNISATION OF GRFs IN THE IGAD REGION

The main goal of this Technical Guide is to provide practical steps and approaches for the establishment and modernization of GRFs within the IGAD region. Member states can use the guide to assess the status of their geodetic network and identify what needs to be done to establish a modern GRF that can leverage the benefits of new and improved positioning technologies including GNSS. The practical steps discussed in this chapter are therefore not prescriptive but can be used as a guide depending on the status of the GRF in the member states. The following are the proposed steps that a member state may follow to establish and modernize its GRF:

i) Formulation of policy and/or legal framework
ii) Setting up and/or reviewing the institutional arrangements
iii) Assessment of the human resource capacity
iv) Inventory of existing network
v) Datum definition
vi) Network design
vii) Monumentation
viii) Equipment
ix) Observations
x) Publication
xi) Maintenance and monitoring

5.1 Formulation of policy and/or legal framework

The first step towards the establishment of a reliable GRF in any country would be the development of a national policy to guide the practice of land surveying, geodesy, and geospatial activities. The aim of the policy is to harmonize, consolidate and improve on any existing policies and legislations on land surveying, geodesy, and geospatial mapping discipline in line with the existing legal framework of the country. The policy should also define the vision, mission, and strategies for implementation of land surveying, geodesy, and geospatial activities in the member state.

Once the policy is developed, the next step is to formulate and/or review the legal framework to support the implementation of the land surveying, geodesy, and geospatial functions. The law should provide for the organization, management, financing, and fulfilment of the activities in the fields of land surveying, geodesy, and geospatial information.

With an enabling policy and legal framework, the next step is to develop a strategy for establishment and modernization of GRFs. The strategy should address the following issues: -

i) Governance arrangements necessary for an optimal GRF
ii) The resources required for the establishment and modernization of the GRF
iii) The timeline for setting up of the GRF
iv) The capacity building requirements and knowledge transfer
v) The standards of the GRF
vi) Consideration of the sustainability of the GRF

5.2 Setting Up and/or Review of the Institutional Arrangements

The key to the establishment and modernization of GRFs depends a lot on the institutional arrangements in the country. Within the IGAD region, there are different institutional arrangements that have been adopted e.g., in Ethiopia, the Ethiopian Geospatial Information Institute is an autonomous agency that oversees all spatial information in the country; in Uganda, the Surveys & Mapping Department in the Ministry of Lands, Housing and Urban Development is the responsible agency while in Djibouti, it is the Land department in the Ministry of Budget. After an assessment and a review of the different institutional arrangements within the region, member states can adopt an appropriate institutional arrangement that will ensure that the vision and mission of the land surveying, geodesy and geospatial information sector are achieved.

5.3 Assessment of the Human Resource Capacity

The Assessment of the Human Resource Capacity will take a snapshot look at the numbers of personnel and types of skills needed at the regional, national, and local level government structures to implement the GRF, as well as human resource management practices such as communication, coordination, planning, supervision, monitoring and evaluation. The assessment should result in the development of Strategic Plans addressing salient issues like recruitment, gender mainstreaming, capacity building, communication, evaluation among others.

5.4 Inventory of the Existing Network

For most of the member states, many of the geodetic control points from the existing networks have disappeared over time and there are poor records of which ones still exist because of poor maintenance. It is therefore important to review maps, charts, reports, and description cards of the existing network to assess the control points that may still be in existence. Field trips can then be organized to identify the points that exist and their condition.

5.5 Datum Definition

Currently each of the member states has a datum which was established based on the traditional surveying techniques. The advent of modern GNSS techniques has opened opportunities for the upgrade and modernization of the GRFs at both National and Regional levels. This requires that each member state defines the appropriate modern datum that can leverage modern positioning techniques while providing a linkage to the legacy network. Importantly the datum selected should consider regional and transborder projects that may involve mapping across international boundaries. For IGAD as a region, the proposed datum is the ITRF since it is a time dependent reference frame that is closely aligned with WGS84, which is the reference frame for GPS. However, depending on the needs of each member state, the following must be agreed upon as part of datum definition: -

i) The ITRF realization to adopt
ii) The epoch of the datum
iii) Whether to implement a static, semi-dynamic or fully dynamic datum
iv) The vertical datum (height system) to adopt i.e., geoid/quasigeoid only, levelling only, combined, interim based on a global geopotential model.

5.6 Network Design

Network design requires consideration of precision, reliability, and cost to achieve an optimal network. Experience within the IGAD region has shown that the initial investment in the modernisation of the GRF is huge forexample, the establishment of the Uganda Geodetic Reference Frame cost approximately 3.49 million Euros (MLHUD, 2020). Therefore, care must be taken to ensure that establishment of modern GRFs is cost effective and will be sustainable by ensuring good maintenance programs are put in place backed up by capacity building programs. The network design should address the following key issues: -

i) The purpose of the network and its implementation phases

ii) Whether to establish a purely passive network, fully active network, or a combination of the two i.e., establishing several passive control points with some active stations

iii) The number of control points for each of the orders of the network

iv) Whether the private sector can be allowed to provide some of the services as the case is in Uganda and Kenya where there are private service providers for CORS

v) The minimum technical requirements for the network

vi) Cost effectiveness of the design

vii) The internet coverage for the network to operate

viii) Accessibility of the points

ix) Security of the points

5.7 Site selection and Monumentation

Prior to monumentation, reconnaissance must be carried out to identify the possible locations of the control points. For the passive network, emphasis should be taken to select locations that are free from possible obstructions to GNSS signals and the protection of the points once monumented.

For CORS, the location should be an open area with minimal obstructions and minimum likelihood of change in the environment surrounding the monument, e.g., avoid sites with future tree or shrub growth, building additions, rooftop additions, new antenna masts, satellite dishes, parking lots, chain link fences, etc. Additionally, the possible sites should be free from obstructions (at least 10 degrees above the horizon) and away from possible radio frequency interference (e.g., TV, microwave, FM radio stations, cellular telephones, VHF and UHF repeaters, RADAR, high voltage power lines) as these can cause additional noise, intermittent or partial loss of lock or even render sites inoperable.

At the stage of monumentation for the passive network, each of the points should be monumented with a concrete block and strengthened by iron bars for enhanced stability (a sample monumentation process is shown in Figure 18). For the CORS monuments, the International GNSS Service (IGS) monument standards should be embraced for uniformity (https://www.igs.org/).

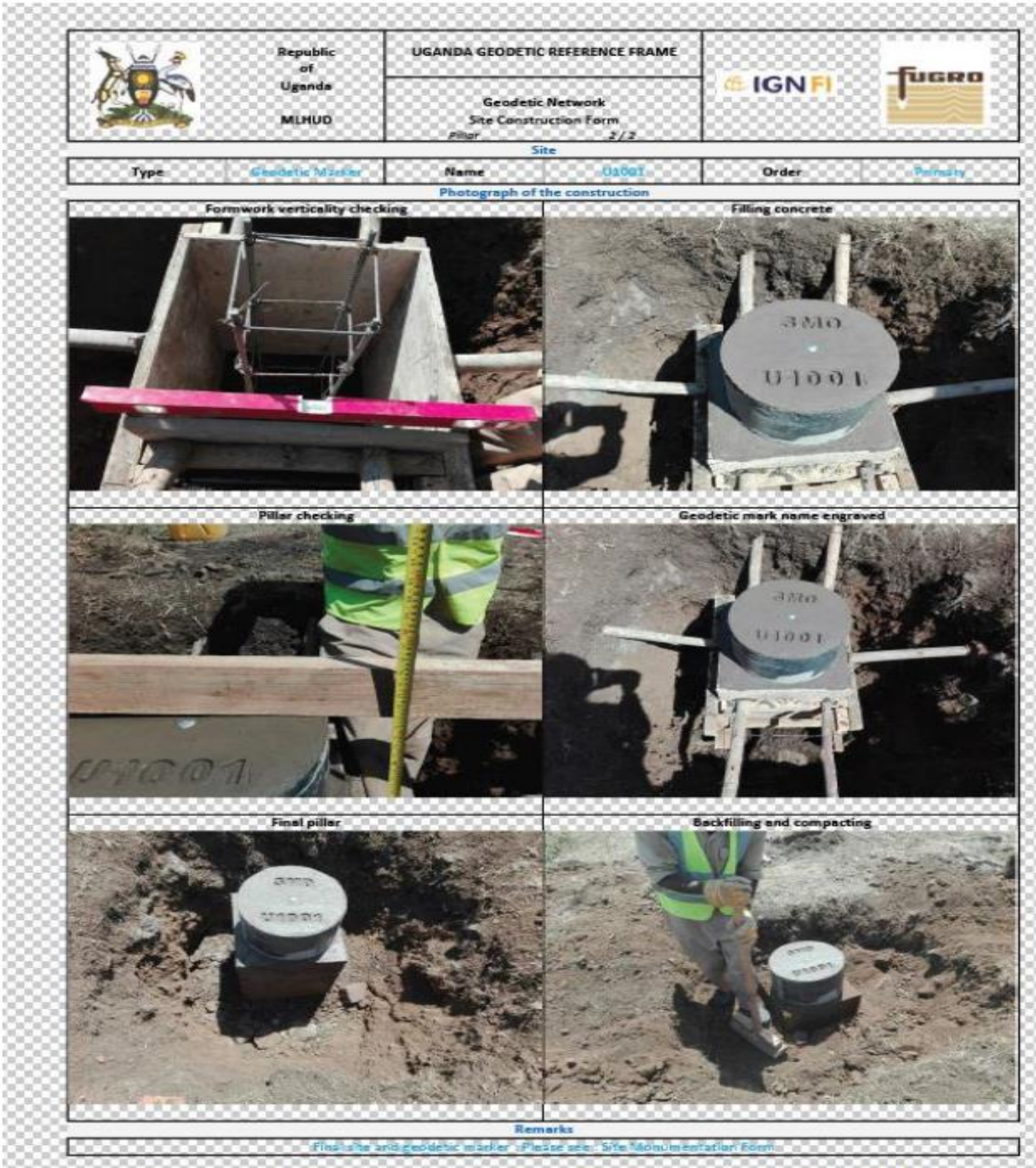


Figure 18 : Sample monumentation for the passive network (Source: MLHUD, 2020)

Figure 19 : Sample monumentation of CORS in Australia (Source: ICSM, 2020)

5.8 Equipment

For both the passive and active networks, selection of the appropriate equipment is important considering the need to balance technology, cost, efficiency, and demand. The key equipment includes GNSS receivers and antennas, antenna cables, meteorological sensors (temperature, pressure, humidity, etc.) and communication accessories for connection to internet network. For all detailed specifications for GNSS Antennas and Receivers, the links below can be used: https://kb.unavco.org/article/unavco-resources-gnss-antennas-458.html and https://kb.unavco.org/article/unavco-resources-gnss-receivers-434.html.

5.9 Observations

Once the equipment has been installed, GNSS observations should then be carried out based on the network design. It is important to maintain a site log which contains all the historical information about a site including the details of the equipment and monument used, the type of observations made, the sampling rate, the time when the observations started and when stopped (if required) and any problems that might have been encountered during the observations. It is advisable that the site log follows the format specified by the International GNSS Service (https://files.igs.org/pub/station/general/blank.log). In addition, the observation times will depend on the length of the baselines.

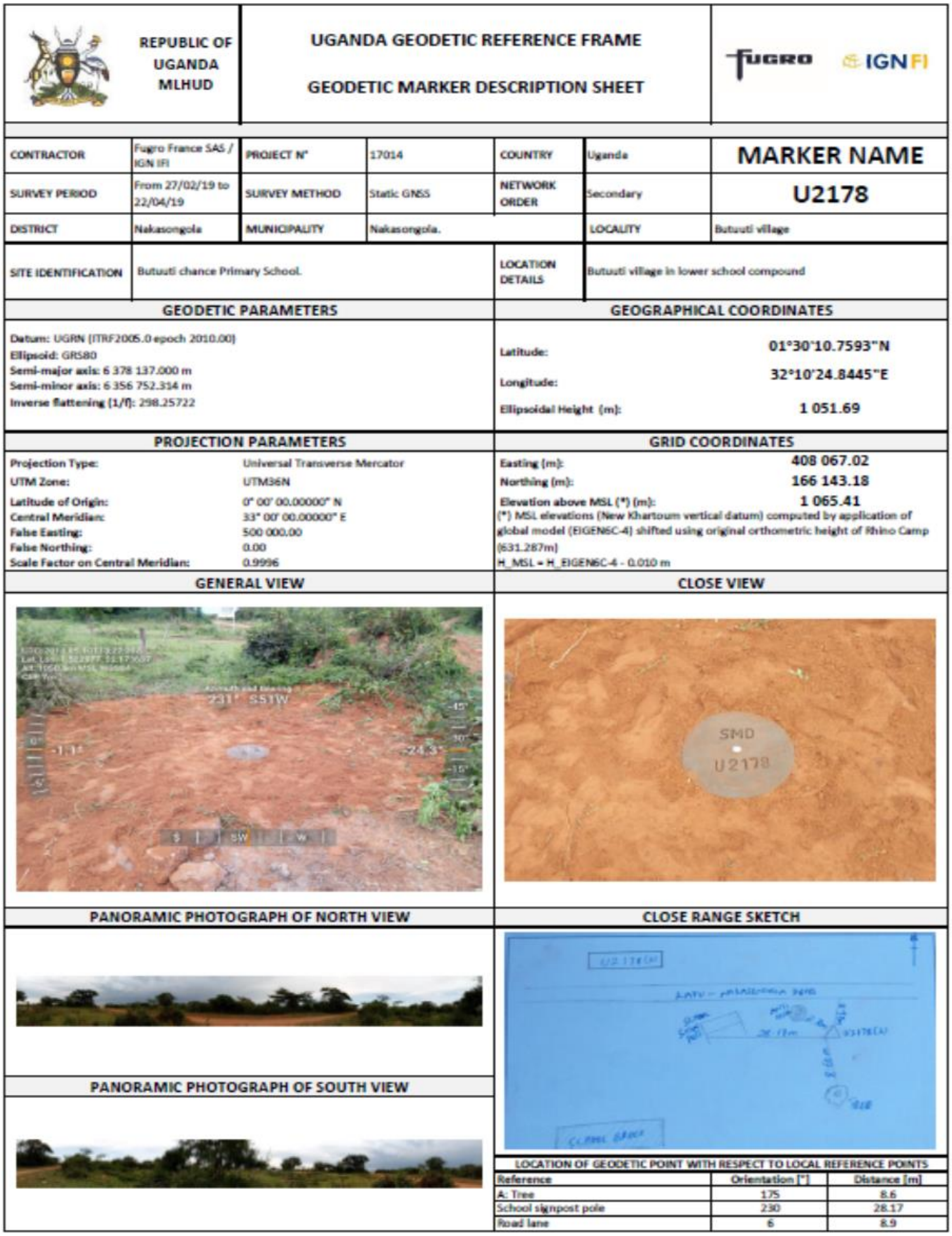
5.10 Processing of the observations

The raw GNSS data should be downloaded and archived in secure servers. Sufficiently comprehensive processing software and tools with the capability to achieve reliable estimates for GNSS baselines and baseline uncertainties should be used to determine the final coordinates (e.g., Bernese GNSS Software (unibe.ch)). It is important to pay attention to gathering sufficient information and the models required to minimize the relevant biases, and care should be exercised when configuring the processing parameters.

5.11 Publication

A description card should be prepared for each of the control stations. Figure 20 is an example of a description card as used in Uganda. The card provides some relevant information about the control station that is helpful to surveyors and other users of the products and services of the GRF.

It is also advisable to set up a website and a geodetic network mobile App through which the general surveying community can have easy access to the coordinates and other relevant information about the geodetic control network. As an example, Uganda setup a dedicated website Home (ugrf.go.ug), which provides access to the UGRF network.



REPUBLIC OF UGANDA MLHUD	UGANDA GEODETIC REFERENCE FRAME GEODETIC MARKER DESCRIPTION SHEET					FUGRO IGNFI
CONTRACTOR	Fugro France SAS / IGN FI	PROJECT N°	17014	COUNTRY	Uganda	MARKER NAME
SURVEY PERIOD	From 27/02/19 to 22/04/19	SURVEY METHOD	Static GNSS	NETWORK ORDER	Secondary	U2178
DISTRICT	Nakasongola	MUNICIPALITY	Nakasongola.		LOCALITY	Butuuti village
SITE IDENTIFICATION	Butuuti chance Primary School.			LOCATION DETAILS	Butuuti village in lower school compound	

GEODETIC PARAMETERS

Datum: UGRN (ITRF2005.0 epoch 2010.00)
Ellipsoid: GRS80
Semi-major axis: 6 378 137.000 m
Semi-minor axis: 6 356 752.314 m
Inverse flattening (1/f): 298.25722

GEOGRAPHICAL COORDINATES

Latitude:	01°30'10.7593"N
Longitude:	32°10'24.8445"E
Ellipsoidal Height (m):	1 051.69

PROJECTION PARAMETERS

Projection Type:	Universal Transverse Mercator
UTM Zone:	UTM36N
Latitude of Origin:	0° 00' 00.00000" N
Central Meridian:	33° 00' 00.00000" E
False Easting:	500 000.00
False Northing:	0.00
Scale Factor on Central Meridian:	0.9996

GRID COORDINATES

Easting (m):	408 067.02
Northing (m):	166 143.18
Elevation above MSL (*) (m):	1 065.41

(*) MSL elevations (New Khartoum vertical datum) computed by application of global model (EIGEN6C-4) shifted using original orthometric height of Rhino Camp (631.287m)
H_MSL = H_EIGEN6C-4 - 0.010 m

GENERAL VIEW

CLOSE VIEW

PANORAMIC PHOTOGRAPH OF NORTH VIEW

PANORAMIC PHOTOGRAPH OF SOUTH VIEW

CLOSE RANGE SKETCH

LOCATION OF GEODETIC POINT WITH RESPECT TO LOCAL REFERENCE POINTS

Reference	Orientation [°]	Distance [m]
A: Tree	175	8.6
School signpost pole	230	28.17
Road lane	6	8.9

Figure 20 : Example of a description card (Source: MLHUD, 2020)

5.12 Maintenance, monitoring and sustainability

Experience within the IGAD region has shown that the state of the GRFs deteriorated due to the absence of proper maintenance and monitoring. To ensure that the modern GRFs are well maintained the following recommendations are proposed: -

1) A dedicated department/section/unit should be revitalized and/or established under the National Mapping Agency to oversee the maintenance/improvement/monitoring of the geodetic network;
2) If a CORS network is established as part of the geodetic network, then a National Control Centre should be setup to oversee the storage of the GNSS observation data, transfer of the data from the CORS stations, provision of reliable communications between the CORS stations and the management of connectivity for users;
3) Guidelines/standards/technical instructions on the use of GNSS should be developed and shared with the surveying community. This may be carried out jointly with the professional associations for surveyors;
4) The established GRF should be adopted as the new GRF for the respective IGAD member states. The adoption of the new GRF should be officially published for users and be able to submit GNSS Observation data to the regional and international GNSS host sites such as the AFREF and IGS;
5) There should be a dedicated program to continuously improve the transformation parameters as this provides a linkage to the legacy network and associated data (maps, charts, cadastral deed plans, etc.);
6) Plans to develop a more accurate geoid/quasigeoid model should be drafted with a clear implementation plan since for most of the member states it is likely that an interim geoid model will initially be used;
7) There should be continuous capacity building and training of the personnel overseeing the management, operation, maintenance, and monitoring of the geodetic network;
8) The NMA should continuously train the users of the network on the most efficient way of using the network especially as regards the CORS network;
9) A sustainability plan that will comprehensively address several issues including maintenance, communication, improvements, monitoring, capacity building, collaboration with the private

sector and academic institutions should be developed, promoted, and implemented to ensure that the GRF meets its intended purpose;

10) Public awareness and sensitization programs should be designed to ensure continuous stakeholder engagement aimed at providing the need and protecting the established GRF.

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GLOSSARY OF WORDS

Terms	**Definitions**
Coordinate conversion	The process of changing coordinates on one geodetic datum from one type to another.
Coordinate transformation	The process of moving coordinates from one geodetic datum to another using transformation parameters.

Geodetic Datum	Reference frame for precisely representing the position of locations on Earth
Geodetic height	The distance of a point from the earth's surface measured along the normal to the reference ellipsoid. It is not associated to gravity.
Geodetic Latitude	The angle that the normal to the ellipsoid at a point makes with the equatorial plane of the ellipsoid. Its negative south of the equator.
Geodetic Longitude	The angle between the plane of the local geodetic meridian and the prime meridian. Its positive while measured eastwards from the prime meridian.
Geoid	A surface of a constant gravity potential and coincides with the mean sea level after removing the effect of sea surface topography over the oceans. It's a reference surface for orthometric heights.
GNSS	This is a collection of satellite positioning systems operating or planned to operate in the future.
Height	The metric distance of a point on the terrain surface vertically positioned above a reference surface.
Horizontal datum	This is a surface for determining the horizontal coordinates of a point.
Map Projection	The transformation from geodetic 3D to 2D (planar coordinates).
Normal height	The distance from the point to the quasi-geoid along the normal plumb line.
Orthometric height	A linear distance measured along the gravity vector from a point on the surface to the equipotential surface (geoid).
Quasi-geoid	This is a reference surface for normal heights, it's not an equipotential surface.
Reference Ellipsoid	This is a mathematical figure that closely approximates the actual geoid and a surface for geodetic heights. It is defined by the semi-major axis *(a)* and flattening *(f).*
Vertical datum	This is any reference surface for elevations of points.

APPENDICES

The following checklists are included as a guide.

Minimum Recommended Standards for CORS		
Item	**Type**	**Recommended minimum Standards**
1	**GRF General Checklist of Items**	
		- Resource mobilization (human, capital, etc.) - GRF Legal Framework Realization Plan - Implementation Strategy or Plan - Mobilization and Sensitization Plan - Environmental and Social Safeguards Plan - Public Information and Awareness Campaign Plan/Communication Strategy - Choice of the tie to be used for CORS and Order of the Passive Geodetic Control Points to establish - Desktop Design of the modernized GRF - Reconnaissance of the legacy network and new sites for modernization of the GRF - Active (CORS) and Passive (Geodetic Control Points) establishment - Reliable GNSS Equipment for CORS and for observation of GRF Sites - Computation and Publishing of the results - Capacity building and training for technical personnel and managers - Remittance of GNSS observations data to IGS for CORS
2	**Passive Geodetic Control Point Requirements**	
	Location and Site Selection	- Make arrangements in case of emergency and periodic access to the site - Establish contact personnel, required for notifications and special local arrangements

		- Design a Field Application Form for collecting Site Information - Select sites according to the following: - Strong likelihood that the site remains undisturbed in the future (site located at minimum distance from existing roads, tracks, crossroads, planned construction etc.) - Unquestionable ground stability (sites far enough from marshlands, swamps, dry riverbeds and other lowlands liable to flooding, slopes liable to erosion, clayey areas liable to swelling, backfilled terrains liable to settlement, groundwater pumping areas liable to subsidence, etc.) - Sites clear of any underground structures (pipes, cables etc.). - Location at or near inhabited areas (towns, villages), excluding remote areas - Clear sky view on 360° - Absence of any structure liable to induce GNSS signal reflection or multipath - Feasibility of monumentation (access with a FWD pickup and a truck) - Use of robust rocky outcrop and other massive concrete piers wherever possible - Prioritization to the lands located in the public domain - If possible, in the built-up areas, direct visibility with higher order point or selection of a dedicated Reference Orientation point (RO) - Permanent access to all potential users

	Security	- Site security should guarantee for protecting the GCP site and equipment from vandalism, weather, lightning, animals and securing long-term tenure
	Design	- Design the Passive GRF network according to the requirements for the Orders in this Guide
	Monumentation	- Provide for safety equipment and wares - Monument using the appropriate ratios of sand, cement and concreate - Use iron bar reinforcements to frame the Station Marker - Write the official inscriptions (SMD and Site name), engraved in concrete before the concrete dries
	Observation	- Make an observation plan according to the required accuracy depending on the Order of the Station(s) - Apply appropriate Surveys and GNSS Observation requirements (e.g., clear weather, minimal obstruction, etc) - Implement observation time (period) to attain the required accuracy according to the Order of the Station(s) - Record the starting and ending time of the observation - Observations should be carried out by relative GNSS positioning from each GCP
	Computation	- Coordinates should be determined by relative GNSS positioning from known GCP(s) - GNSS baselines observed between Geodetic markers should be processed with appropriate GNSS Data Processing Software

	Connection to CORS and Legacy Network	- A number of datum control surveys between the CORS, the new Geodetic Markers and Legacy Survey control marks are recommended to ensure suitable connection to datum - It is highly recommended that advice on Legacy survey control markers selection is sought from the organization responsible for datum and survey control in the relevant jurisdiction
3	**GNSS Receiver**	
	Software	- Should be provided by the equipment manufacturer as per CORS system configuration and should ensure un-interruptible performance of the equipment and system
	Logging	- On-board continuous logging of raw unsmoothed data - On-board logging of data stored as 1 Hz hourly and 30 second daily RINEX files simultaneously - On-board logging of input sensor data
	Internet Communications	- Dedicated Network (Ethernet) Port - Serial/USB port - Static IP address - HTTP/S interface ftp over Transfer Control Protocol (TCP) • IP Configurable LAN/WAN connectivity
	Radio Communications	- Radio output port capability (Tier 3 only) where required - 4,800 – 115,200 baud rate
	Signal Tracking	- 12 channels per frequency per system tracked - Records all available carrier phase, pseudo-range, Doppler, and Signal-to-Noise Ratio (SNR) per tracked frequency - Ideally simultaneous GPS L2C and P2 tracking

		- Pseudo-range measurements should not be smoothed for RINEX - GPS and GLONASS tracking - Capability to observe future signals when available is an advantage - Receivers capable of tracking space-based augmentation services should have this function turned off
	Power	- Nominal 12 V DC input - Extended operational range between 10.5 and 28 V DC - Dual power inputs
	Inputs	- External Frequency (Zero Order and First Order) - Meteorological Sensor (Zero Order and First Order)
	Output	- Current RTCM SC-104 at 1 Hz on multiple ports - NMEA-0183 - Proprietary raw data streaming - Capable of streaming data to multiple locations - 1 Pulse Per Second (PPS) output (for timing applications)
	Internal Memory	- Capability to store at least 60 days (Zero Order and First Order) or 30 days (Tier 3) of raw and RINEX data on-board per the logging specification - Internal file memory management - USB storage devices may be used to extend the receivers logging capability
	Remote Control Settings	- Full control of receiver functions via web-based GUI including: - Data protocols and logging rates - Data transfers - Quality settings - Power cycling

		- General system management - Client access authentication - Firmware upgrades
	Environment	- Operating Temperature of -40° C to +65° C - Dustproof/waterproof to IP67 - Humidity MIL-STD 810F - Shock resistant to 1 m drop on hard surface
4	**GNSS Antenna**	
	Software	- Should be provided by the equipment manufacturer as per CORS system configuration and should ensure un-interruptible performance of the equipment and system
	Antenna type	- Tier 1 and 2 sites shall have choke ring antennas, preferably with Dorne-Margolin elements. Dorne-Margolin elements are required at AuScope and ARGN sites - Tier 3 CORS may use a choke ring or ground plane antenna - Antenna satellite signal tracking capabilities should be matched with or exceed the capability of the GNSS receiver
	Antenna Phase Centre (APC) Calibration	- All Tier 1 and 2 CORS antennas shall have a valid IGS absolute antenna calibration (IGS, 2013a) or undergo individual antenna calibration. - An IGS antenna calibration is preferred for Tier 3 sites. NGS (2013) antenna calibration may be used at Tier 3 CORS with caution - The source of the antenna calibration shall be noted in the station site log and metadata.

	Antenna Reference Point (ARP)	- All antenna-offset measurements shall refer to the ARP
	Radome	- The use of antenna radomes is strongly discouraged - If conditions require a radome, use a hemispherical radome/antenna combination with a valid absolute antenna calibration - Do not remove radomes from existing sites unless antennas are replaced due to failure - Conical radomes should not be used.
	Antenna Orientation	- The antenna should be oriented to ±5° of True North - If deflection from True North is greater than ±5° the actual alignment must be measured and recorded on the station site log and metadata.
	Environmental	- Weatherproof and corrosion resistant
5	**Antenna Cable**	
	Cable Type	- Use an antenna cable type sufficient for the length of the intended cable run between antenna and receiver. The selected cables and components should have a total signal loss of less than 9 dB over the length of the cable run
	Cable Protection	- Protect antenna cables from weather, pest and fire using suitable conduit - Seal antenna cable connectors with self-amalgamating ultra-violet stable tape for protection against water infiltration and ultra-violet radiation
	Cable Tension	- Avoid tension in the antenna cable, particularly at the receiver and antenna interfaces
	In-line Amplifiers	- Avoid in-line amplifiers where possible - If an in-line amplifier is used it should be noted in the station site log and metadata

	Cable Splitters	- Only use antenna splitters where a secondary receiver is connected or planned - DC block the splitter to the secondary receiver - Record splitters in the station site log and metadata
	Lighting Protection and Earthing	- Include a grounded lightning protector in the antenna cable, especially in lightning prone areas - In lightning prone areas, reduce the horizontal cable-run length to minimize the risk of signal induction from nearby lightning strikes - If this is not possible, fit the lightning arrestor toward the receiver end of the cable.
6	**Meteorological and other Sensors**	
	General requirements	- Pressure measurement accuracy better than ± 0.5 hPa - Temperature measurement accuracy better than ± 1° C - Relative Humidity measurements better than ± 2% - The height difference between the pressure measurement reference mark of the meteorological sensor and the CORS reference point should be determined to better than 10 millimetres
7	**National Control Centre (NCC)**	
	Software	- License for Internet Security, Virus and Malware Protection software (preferable enterprise solution) - Servers virtualisation and network management software to ensure functionality - Adequate storage array software as might be required to manage GNSS data storage - NCC specialised software to enable monitoring and management of the configuration of network, online data computation services, NRTK services and other functionality as per requirements, including the

		licence to manage possible number of CORS sites and provide positional services to concurrent Users - Use of recommended GNSS Software and license (e.g., Bernesse) for the GNSS Data Processing, long vectors computation etc. - Reliable "IT oriented" software to make the system running, being safe and secure and organizing communications either towards the station or from/to Internet (e.g., Servers and Synology Bays) - Reliable "GNSS oriented" software to fulfill all the required GNSS and geodetic technical specifications for CORS - Reliable software for accessing the NCC VPN through the Firewall - GNSS data acquisition and receiver remote management software such as Leica GNSS Spider Suite(https://leica-geosystems.com/products/gnss-reference-networks/software/leica-gnss-spider), Trimble GNSS Software (https://realtimenetworks.trimble.com/Real-Time-Networks-Software), Topcon GNSS software (https://topconcare.com/en/software/network-applications/), Hi-Target GNSS software (https://en.hi-target.com.cn/products/cors-precise-positioning/), etc.
	Hardware and Equipment	- Design a reliable architecture for the hardware and equipment installation and arrangement - Dedicated server virtualization hardware components - Synology storage servers - Keyboard Mouse Monitor - Router - Firewall

		- Ethernet network switch - Uninterruptible Power Supply - APN Router provided by a reliable telecom company - Internet Router by a reliable telecom company - Scree for monitoring (Display and Visualization) of CORS sites
	Installation	- Considerably a secure Server Room within the host building
	Security	- Site security should guarantee for protecting the NCC site and equipment from theft, vandalism, weather, lightning, animals, insects and securing long-term tenure.
8	**CORS Network Design**	
	Key Parameters	- Distance between the CORS - Connection to the reference frame and / or national geodetic datum - Effect of a station outage on service delivery.
	Inter-section Distances	- Tier 1 CORS: 500 to 1,500 Km - Tier 2 CORS: 80 to 500 Km - Tier 3 CORS: 20 to 80 Km
9	**CORS Establishment**	
	General Principles	- Permission to build the monument - Site access and Site security (identification and contact information) - Site stability (monument foundation, antenna monument and antenna mounts) - Antenna Reference Point (ARP) stability - Signal quality and data completeness - A continuous and reliable power supply - A reliable communications system with minimum latency

		- Infrastructure that resists the ambient environmental and security conditions
	Reconnaissance requirements	- Significant signal obstructions - Potential multipath and Radio Frequency Interference (RFI) sources - Access restrictions - Access to available power and communications - Cable length requirements - Human, pest and environmental site security issues - Tenure and land ownership of the property - Potential changes to sky visibility from tree growth and development at adjacent sites - Site foundation suitability
	Antenna Monument Requirements	- Short, medium, and long-term stability - Minimal multipath - Sufficient height to minimize obstructions - True verticality within 1 mm (Tiers 1 and 2) or 5 mm (Tier 3) - Simple design for ease of manufacture, installation and maintenance - Low maintenance - Corrosion, erosion, and subsidence resistant - Capable of bearing the mass of antenna - Tamper-proof design

GRF Public Information and Awareness Campaign (PIAC)

Public Information and Awareness Campaign minimum requirements	
1	**General**

		- Develop a PIAC Plan to provide information support to the implementation of the GRF project or activities - The PIAC design should use all communication channels available (local authorities, opinion leaders, landlords, radio, social media, newspaper, etc) to transmit valuable information about the GRF project activities
2	**Objectives of the PIAC**	
		- Increase the public awareness regarding advantages of using the modern GNSS technology and accurate positioning services for the economy, and facilitate the communication with landlords regarding the Geodetic Control Point Sites and CORS sites reconnaissance and installation - Inform the user community and the public about the advantages of the GRF for land administration and encourage users of GNSS technology to embrace modern techniques for data capture and data processing - Inform the user community and the public about the importance of the GRF infrastructure including the CORS stations and associated installations and monuments for the Passive network points with a view to encourage them to protect the physical infrastructure and eliminate possibilities for destruction of the infrastructure and ensure ownership of the GRF by the citizens - Get feedback of the user community acceptance and evaluation of the GRF services provided - Inform the project stakeholders such as government agencies and private sector about the project progress, achievement and benefits for the stakeholders
3	**Activities of the PIAC**	

		- Preparation and dissemination of flyers and leaflets with information about the Geodetic Reference Framework benefits and roles of stakeholders - Preparation of posters and information to the public explaining CORS and passive network accessibility procedures for display in local government premises (as appropriate) - Publications of articles in the local newspapers - GRF awareness training programs and seminars for stakeholders such as Surveyors, Engineers, etc - GRF awareness meetings with the local communities and leaders from the local administrative units to village level as appropriate - Regular internal information sharing and exchange for the Host Agency Administration (such as NMA)