On the global geodetic observing system: Africa's preparedness and challenges

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ABSTRACT

Space geodetic techniques and satellite missions play a crucial role in the determination and monitoring of geo-kinematics, Earth's rotation and gravity fields. These three pillars of geodesy provide the basis for determining the geodetic reference frames with high accuracy, spatial resolution and temporal stability. Space geodetic techniques have been used for the assessment of geo-hazards, anthropogenic hazards and in the design of early warning systems for hazard and disasters. In general, space geodesy provides products for Earth observation, science and influences many activities (e.g., building and management) in a modern society. In order to further promote the application of space geodetic methods to solving Earth science problems, the Global Geodetic Observing System (GGOS) of the International Association of Geodesy (IAG) was commissioned as an important geodetic infrastructure that integrates different geodetic techniques (such as Global Navigation Satellite Systems, Very Long Baseline Interferometry, Satellite Laser Ranging, Interferometric Synthetic Aperture Radar and Doppler Orbitography and Radio-positioning Integrated by Satellite), models and analysis techniques for the purpose of ensuring long-term, precise monitoring of geodetic observables vital for monitoring Earth system processes. Since its inception, there has been considerable progress made towards setting up the infrastructure necessary for the establishment of the GGOS database. While the challenges that beleaguer the GGOS are acknowledged (at least at global level), the assessment of an attuned GGOS infrastructure in the African context is necessary, yet lacking. In the present contribution, (a) the African preparedness and response to the observing system is assessed, and (b) the specific scientific and technological challenges of establishing a regional GGOS hub for Africa are reviewed. Currently only South Africa has a fundamental geodetic observatory located at Hartebeesthoek, Pretoria. Other countries in Africa have shown interest to participate in global geodetic activities, in particular through interest in the development of a unified African geodetic reference frame (AFREF). In particular interest has been shown in the proposed African VLBI Network (AVN), which will be partially based on existing ex-telecommunication radio antennas. Several countries are investigating their participation in the AVN, including Kenya, Nigeria and Ghana.

1. Introduction

Our knowledge of the complex Earth system affects the way we respond to various phenomena that manifest as natural and human induced disasters. An urgent

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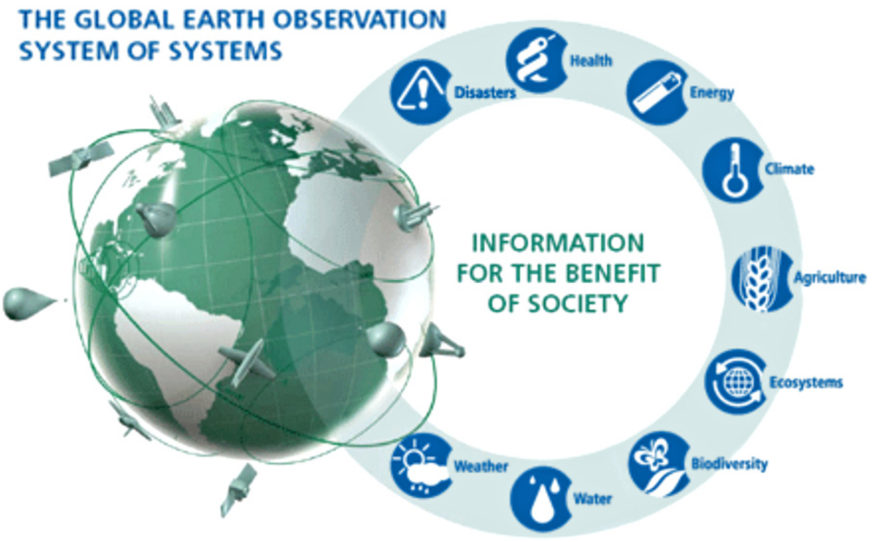

Fig. 1. Scope of the Global Earth Observation System of Systems. Source: 〈http://www.earthobservations.org〉.

challenge in society today is the limited deeper understanding of the processes and nature of the interactions within the Earth system. As a result, there is always need to continuously monitor the system Earth largely by use of stable and robust observational infrastructure, currently known as the Global Earth Observation System of Systems (GEOSS). An artist's impression of GEOSS is depicted in Fig. 1. The Global Earth Observation System of Systems conceptually links together existing and planned observing systems globally and provides technical standards useful for combining different datasets from various instruments. Through the provision of observational datasets, GEOSS contributes towards e.g., understanding of environmental hazards, the society's ability to respond towards climate change and its impacts, as well as contributing towards ecosystem management.

The concept of three pillars of geodesy coined by Bruns in the 19th century still holds today: (a) geometrical geodesy (its origin is in the terrestrial polyhedron; the geometry of the Earth), (b) astronomical geodesy (motion of polyhedron in inertial space, Earth rotation), and (c) gravimetry (gravity field). Modern geodesy plays a significant role towards the understanding of the dynamic system-Earth and now has evolved from just measurements and scientific service to encompass both monitoring and modelling of the system Earth through a number of space geodetic techniques (see Table 1) and has also become a service to society through the Spatial Data Infrastructure (SDI), see for instance Ojwang [1].

In particular, the international geodetic community, through the International Association of Geodesy (IAG) contributes towards the study of system Earth by providing a global picture of surface dynamics of our planet and an assessment of mass anomalies, mass transport and exchange processes (and therefore the global mass balance vital for understanding the global energy balance), see Rummel et al. [6] and Plag and Pearlman [3] for further details. In the context of Earth system research, the IAG established the Global Geodetic Observing System (GGOS); an infrastructure that could integrate the fundamental pillars of geodesy that deal with the determination and evolution of (a) the Earth rotation and orientation, (b) the Earth's gravity field and (c) the Earth's geometry. The main objective of GGOS is Earth observation (at global scales) which generally contributes to global change research through the use of an integrated network of terrestrial, orbital and sub-orbital systems and technologies. As reported in Rummel [7], the specific objectives of GGOS were to, (a) provide a well-defined and reproducible global terrestrial frame, (b) analyse the integral effect on Earth rotation of all angular momentum exchange of the Earth system, (c) establish the spatial–temporal variations of the geometric shape of the Earth's surface, and (d) study the Earth's stationary and time-variable gravity field. The GGOS research concept is schematically presented in the draft GGOS science plan reported by Rummel et al. [6] and is illustrated in Fig. 2.

Table 1
Summary of geodetic techniques to be considered for AGOS. Adopted from Rothacher [5].

Parameter type		VLBI	GPS	SLR	DORIS	LLR
CRS	Quasar positions	x				
	Orbits (Satellites, Moon)		x	x	x	x
EOP	Nutation	x				x
	Nutation rates	x	x	x	x	x
	UT1-UTC	x				
	LOD	x	x	x	x	x
	Polar motion	x	x	x	x	x
TRF	Station positions	x	x	x	x	x
Gravity field	Geocentre		x	x	x	
Atmosphere	Low degree		x	x	x	x
	Troposphere	x	x		x	
	Ionosphere	x	x		x	

Analysis of geodetic data from various observing systems such as Very Long Baseline Inteferometry (VLBI), Global Navigation Satellite Systems (GNSS) such as the

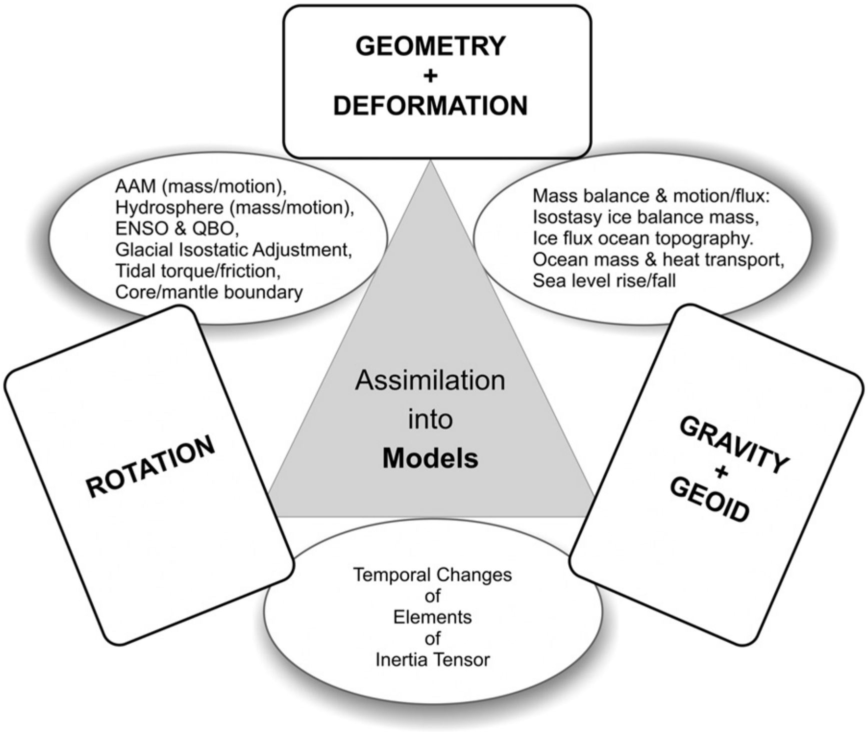

Fig. 2. Global Geodetic Observing System as an infrastructure for observing the system. Source: Ref. [5].

American GPS and the European Galileo system, Satellite Laser Ranging (SLR), Lunar Laser Ranging (LLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Interferometric Synthetic Aperture Radar (InSAR), Satellite Gravimetry (e.g., CHAMP/GRACE/GOCE) and Radio Occultation (RO) and other associated infrastructure (e.g., communication networks for data transfer from the geodetic network instruments to data centres, and analysis centres) is aided by the voluntary contributions of national agencies and institutions and coordinated by the IAG measurement services (see Table 1). The accuracy of geodetic parameters derived from space geodetic observations have greatly improved (e.g., the resolution of the primary geodetic parameters has changed by parts-per-billion order of magnitude) due to; (a) improvement in technology, (b) development of optimal and robust analysis schemes and software (this is partly manifested in the joint co-ordination of GNSS and VLBI analysis software development efforts among the geodetic community), and (c) development of combination of integration schemes during the pre-processing; all these have contributed to, (i) distinguishing genuine geodetic/geophysical systematic signal biases that are technique dependent, and (ii) decomposing inherent geophysical components and processes in the Earth system.

2. Applications of geodetic observations in Africa

As reported in Poutanen et al. [4], a geodetic observing system provides observations and infrastructure that define and maintain a stable and accurate global Terrestrial Reference Frame (TRF). A global TRF is vital for sufficient observations of all parameters of the Earth system. In particular, reference frames and positioning is the cornerstone of all geospatial measurements. The importance of geodetic observations in Africa is directly related to the need for a uniform and reliable coordinate reference frame for projects and services requiring geospatial information. These observations provide a foundation on which all Earth observation systems are built and are fundamental for most societal activities e.g., disaster mitigation, provision of resources (such as water and food), protection of the ecosystem and human health [3].

In addition to the provision of a stable reference frame required for long-term Earth observations, geodetic observations also provide information related to the displacements (see Fig. 3) and strain of the Earth surface associated to the tectonic and seismic processes, man-induced subsidence and motion of man-made infrastructure (e.g., ground water and oil exploration) in the African continent. Tectonic regions such as the East African Rift Valley, the strain induced by the tectonic processes are the dominant contribution to the displacements of the Earth surface. In this regard, IGS products of the GNSS stations which could contribute to the African Geodetic Reference Frame (AFREF) network could be (and have been) used to monitor such motions. In addition, new gravity satellites such as CHAMP, GRACE and GOCE provide gravity field information of Earth, which is then used as proxy parameter for monitoring the dynamics of the Earth system. In particular, observations of gravity fields provide a means of monitoring mass movements such as fluxes in the hydrological cycle including, ground water storage and terrestrial surface flows in Africa. In addition, the GNSS equipment

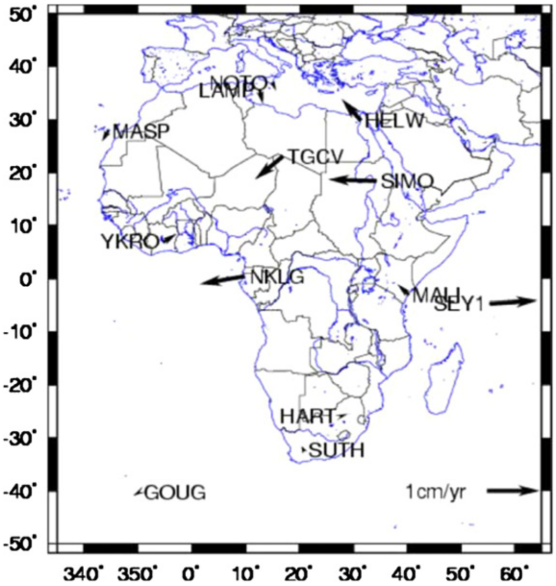

Fig. 3. Residual velocity fields of IGS stations normalised by the velocity of the African plate. Source: Ref. [2].

installed in Africa contributes to global Total Electron Content (TEC) and integrated water vapour content modelling of the ionosphere and lower atmosphere.

In general, current geodetic observations in Africa contribute directly to such areas as surveying and mapping, security, science (atmosphere and Earth observation, hazard assessment, sea level change and crustal dynamics), disaster mitigation (most disasters in Africa are hydro-meteorological: drought and flooding), infrastructure planning and development [9]. The African Geodetic Reference Frame (AFREF) is an African initiative that aims at unifying the geodetic reference frames for Africa through a network of Global Navigation Satellite System (GNSS). It is through AFREF that, regional geodetic activities (which are currently not well developed) would be coordinated and access to high quality positioning infrastructure will be achieved.

3. On the African Geodetic Observing System (AGOS)

3.1. Africa's preparedness

The significance of the African Geodetic Observing System (AGOS) can be evaluated through three main aspects, (a) human capacity development for AGOS so as to enable unlock the hidden potential in AGOS products and services, (b) ensuring that AGOS products and services become part of an information management system satisfying various societal needs, and (c) making available policies, resources and structures that could contribute towards ensuring that information extracted from AGOS products and services are available to decision makers and society when, where and in the form needed.

A number of working groups such as AFREF and Fundamental Datasets, Standards and Capacity Building are currently contributing towards the establishment of an Africa geospatial information infrastructure through government and non-governmental (e.g., African Union and United Nations Economic and Social Council) support. In particular, the AFREF working group has progressed well towards unifying Africa spatially through a common spatial reference frame while the Fundamental Datasets Working Group has to date defined the fundamental geospatial datasets and catalogued the available fundamental datasets [8].

The International GNSS Service (IGS) stations located in Africa contribute data directly to global data centres and therefore contribute towards the establishment and maintenance of the most accurate global frame: ITRF. Notwithstanding this contribution, the geometry of the operational IGS stations (see Fig. 4) is still very poor. Furthermore, Africa has only one fiducial geodetic station located at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) (see Fig. 5), with four instruments of the main geodetic techniques collocated (VLBI, SLR, GNSS, and DORIS). In order to provide a robust reference frame for the long-term observations across Africa, (a) densification of active and operational IGS stations, and (b) establishment of three more GGOS compatible geodetic stations in East Africa (the Regional Centre for Mapping of Resources for Development, RCMRD already exists in Nairobi), West

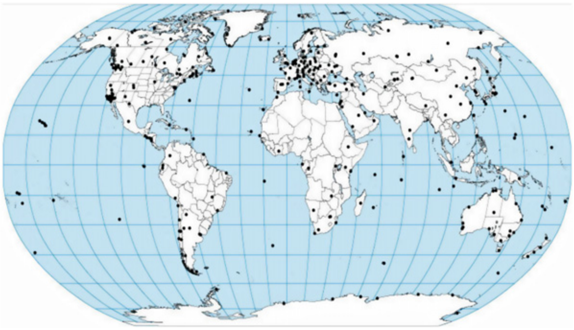

Fig. 4. Uneven distribution of IGS infrastructure (dots).

Fig. 5. Hartebeesthoek Radio Astronomy Observatory. A fiducial geodetic station with four collocated geodetic techniques.

Africa (the Regional Centre for Training in Aerospace Surveys, RECTUS in Nigeria could be modernised) and North Africa is highly recommended. Some of these sites could be collocated with sites identified as probable AVN locations (i.e. where large ex-telecommunications antenna suitable for VLBI exist), as a certain amount of required infrastructure is already in place.

An African Geodetic Observing System (AGOS), linked to and compatible with GGOS, consisting of complementary and/or independent space geodetic techniques is critical for geodetic and geophysical applications. To this end, Africa unfortunately lacks an operational and foreseeable strategy for building, integrating and maintaining a network of instruments and other supporting infrastructure in a sustainable way to support the long term requirements set by GGOS. In part, the design of AGOS ought to consider all of the Earth system research applications e.g., geometric and gravimetric reference frames, Earth Orientation Parameter (EOPs), geophysics, oceanography, etc. Since TRF influences all other AGOS products, due regard must be given to AFREF and thus a full realisation of AFREF is mandatory.

The Hartebeesthoek Radio Astronomy Observatory (member of the GGOS Inter-Agency Committee (GIAC)), recognises that the international space geodesy community faces major instrumental and network changes within the next decade and participate in the realisation of the GGOS concept. Societal relevant issues such as natural hazards, climate change and space engineering requirements call for an increase in performance from the global geodetic networks as encapsulated within the context of GGOS and this is very relevant in Africa. In South Africa the existence of HartRAO and its contribution to international networks of space geodetic equipment has proven invaluable to address many scientific and socially beneficial questions.

Although the contributions of HartRAO are highly rated and valued globally, the continuation of South Africa's role needs to be ensured and its equipment modernised through the development of a new fundamental geodetic observatory strategy, which will support and strengthen the work done at HartRAO (work which must continue) and will provide continuity for the foreseeable future. The different space geodesy techniques needed to meet requirements of GGOS and the science driven geodetic objectives as set out by the NASA Solid Earth Science Working Group Report. All the space geodetic techniques face major challenges; the global networks and its African components need to be re-equipped and its geometric distribution improved. Three phases are proposed to achieve this, which are currently driven in parallel: (1) upgrade of existing infrastructure to full GGOS standards, e.g. addition of a Vertex VLBI2010 antenna at the current HartRAO site, (2) addition of a fundamental site at Klerefontein in the Northern Cape. This new station should be developed in the framework of expectations and synergies embedded in the establishment of the South African National Space Agency (SANSA) and the developments concerning the bid for the Square Kilometre Array (SKA), as realised through the Karoo Array Telescope (MeerKAT), and (3) addition of a fundamental site at Matjiesfontein in the Western Cape, specifically hosting equipment that are not compatible with the radio frequency interference zone of the Northern Cape (SKA/Meerkat criteria).

In the light of GGOS developments, HartRAO has put forward proposals for funding and has actively been promoting the addition of VLBI2010 at HartRAO and the development of two additional sites in South Africa. One site is at Klerefontein (Northern Cape), which is located within the Astronomical Geographical Advantage Programme (AGAP) zone, for which preparations are underway to install a GNSS station, meteorological equipment, and a Russian Federation supported Satellite Laser Ranger. The addition of VLBI2010 at some future point in time will make Klerefontein an additional GGOS compatible site in Africa. Another site under development is located at Matjiesfontein (Western Cape), where a GNSS system has already been installed. This site will be more suitable to house an arsenal of geophysical instrumentation, but it is envisaged that space geodetic equipment (e.g. those that cannot be included at Klerefontein due to radio frequency interference issues) such as DORIS be located there.

In addition HartRAO, in collaboration with the Observatoire de la Cote D'Azur (OCA) and NASA, has commenced with a project to develop a Lunar Laser Ranger (LLR) system based on an ex-OCA 1 m aperture telescope. This LLR should be operational by 2015 and even though it would be dedicated to LLR, should add significantly to the database and strengthen the geometry of the ILRS network in general as it will also be able to track satellites. The AFREF initiative has been supported by HartRAO since its inception, and has been supported by the installation of GNSS equipment in Africa, training of students and other initiatives. The possibility of utilising ex-telecommunications dishes as VLBI antennas has been proposed by HartRAO; several of these exist in Africa and may form the hardware component of an African VLBI Network. These new facilities could be hosting stations for space geodetic instrumentation; planning and discussions concerning the African VLBI Array is considering space geodesy as an integral component at appropriate sites.

3.2. Practical challenges

The core responsibility and distinguishing characteristic of modern geodesy is premised on the maintenance and accessibility of the most accurate reference frames. In order to address the apparent stringent requirements of the geo-scientific mission, modern geodesy has to deal with the challenges of improving technology, infrastructure and services (see for example VLBI2010). In this regard, the technological challenge characteristic of AGOS relates to ensuring accuracy, resolution, reliability and short turn-around time of the geodetic products by an order of magnitude or attains millimetre-geodesy in the same way weather/climate models are.

Funding constraints, human capacity and lack of appreciation of decision makers of the importance of a geodetic observing system (which underpins the global Earth observations, though its fundamental role was inadvertently only acknowledged recently) remain one of the focal constraints of AGOS. In particular, the challenges of designing and building a robust geodetic observing system: AGOS arise from, (a) properly identifying and understanding the societal and scientific problems (specific for Africa) that could be addressed by the geodetic system, and (b) conceptualising a geodetic observing system specifications (and therefore system design) that meet user requirements (both in the African and global context).

Information and Communication Technologies (ICT) such as internet and telecommunication networks play a central role in providing a basic infrastructure (hereafter "a data management") for the implementation of AGOS. The data management infrastructure relates to data acquisition infrastructure, service infrastructure (data storage and processing), data dissemination and end user infrastructure (data utilisation). While some African countries have developed specific national information and communication strategies (e.g., most research institutions in South Africa are all linked to a dedicated broadband gateway: Telnet), most African countries still battle with the high communication costs and low per capita internet access, even though dramatic improvement over the entire continent has taken place with connectivity improving every year.

4. Concluding remarks

We have assessed Africa's preparedness and response to an integrated Earth observing geodetic infrastructure and proposed the setting up of an African Geodetic Observing System (AGOS). Two main overriding issues that the AGOS system ought to address are, (a) the need to articulately identify and understand specific societal and scientific problems that could be addressed by AGOS, (b) ensuring that AGOS system specifications meet the user (local, national, regional and even global) requirements. Furthermore, we have outlined the scientific and technological challenges of establishing such regional geodetic observing system. In particular, since the conceptual framework of AGOS is based on integration of techniques (here a set of geodetic stations, including fundamental stations, are monitored by different techniques) the components of AGOS ought to interact and be compatible with its own structure and routines and techniques must comply with international standards. Additionally, since the Spatial Data Infrastructure (SDIs) in Africa is currently undergoing various developments, the envisioned AGOS products and services ought to be part of the Africa's cooperative geospatial information management process. Integrating AGOS products and services to SDI would certainly be Africa's SDI milestone.

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