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Review

The Status of Space Weather Infrastructure and Research in Africa

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Citation: Baki, P.; Rabiu, B.; Amory-Mazaudier, C.; Fleury, R.; Cilliers, P.J.; Adechinan, J.; Emran, A.; Bounhir, A.; Cesaroni, C.; Dinga, J.B.; et al. The Status of Space Weather Infrastructure and Research in Africa. *Atmosphere* **2023**, *14*, 1791. https://doi.org/10.3390/atmos14121791

Academic Editor: Luca Mortarini

Received: 2 November 2023
Revised: 22 November 2023
Accepted: 27 November 2023
Published: 5 December 2023

Abstract: Space weather science has been a growing field in Africa since 2007. This growth in infrastructure and human capital development has been accompanied by the deployment of ground-based observing infrastructure, most of which was donated by foreign institutions or installed and operated by foreign establishments. However, some of this equipment is no longer operational due to several factors, which are examined in this paper. It was observed that there are considerable gaps in ground-based space-weather-observing infrastructure in many African countries, a situation that hampers the data acquisition necessary for space weather research, hence limiting possible development of space weather products and services that could help address socio-economic challenges. This paper presents the current status of space weather science in Africa from the point of view of some key leaders in this field, focusing on infrastructure, situation, human capital development, and the research landscape.

Keywords: space weather infrastructure; space weather capacity building in Africa

1. Introduction

1.1. What Is Space Weather?

Space weather refers to the highly variable conditions in the geospace environment, including those on the sun, the interplanetary medium, and the magnetosphere-ionosphere-thermosphere system.

Space weather can have serious adverse effects on the advanced technology that our society depends on, such as satellite communications, Global Navigation Satellite Systems (GNSS) positioning, navigation and timing (PNT) services, and power grids, among others. The primary sources of space weather are solar flares and coronal mass ejections (CMEs), both initiated by the Sun. Solar flares produce sudden bursts of radiation, while CMEs are associated with bursts of plasma, embedded with magnetic field structures, that travel in the solar wind before interacting with the Earth's magnetosphere [1]. Energy and radiation from these events can harm astronauts, damage electronics on spacecraft, and impact GNSS precision, tracking, and acquisition. The geospace response to these changes includes impacts on the radiation belts, multiple large-scale and small-scale changes in the ionosphere, and the production of intense geomagnetically induced currents. To better mitigate space weather impacts on humanity and technological systems, there is a recognized need for improved forecasts, better environmental specifications, and more durable infrastructure. Improved monitoring and modelling of space weather has been identified as critical for the better protection of infrastructure and national economies during periods of large space weather events.

Understanding space weather is of great importance for awareness and avoidance of the consequences attached to space weather events either by system design or by efficient warning and prediction systems. Providing timely and accurate *space weather* information, nowcasts and forecasts are possible only if sufficient *observation* data are continuously available. Based on a thorough analysis of current conditions, comparing these conditions to past situations, and using numerical models similar to terrestrial weather models, forecasters can predict space weather on time scales of hours to weeks.

1.2. The African Context

The African Union (AU) has identified space science and technology as a key enabler of Africa's Agenda 2063 and created an African Space Agency (AfSA). The long-term goal of the agency is to enable Africa to leverage technologies developed in the space sector to address societal challenges, in addition to opening up new frontiers of space applications that could be a basis for the establishment of industries that would provide job opportunities for the many unemployed youths in Africa.

Space weather science, in particular, is one of the areas under active consideration by the AU partly due to growing interest in the acquisition and deployment of satellites in space and also the requirement by the International Civil Aviation Organization (ICAO) for the provision of space weather services to the aviation industry across the world [2]. Space weather science has been a growing field in Africa since 2007, the year of the International Heliophysical Year (IHY 2007), during which time deployment in Africa of most ground-based observing infrastructure commenced. The deployment of ground-based observing infrastructure was rolled out through collaborations between African universities and their counterparts, mostly American institutions (such as Boston College, United States Airforce Research Laboratories (AFRL), Stanford University), and Kyushu University (Japan), among others. The deployments have often been accompanied by workshops aimed at African university lecturers and their students, with a focus on data acquisition, data processing, and interpretation. The training workshops, which continue to be held at least once a year, are run jointly through partnerships of the Abdus Salam International Centre for Theoretical Physics (ICTP) and Boston College. Supplementing these efforts is the training provided by the Scientific Committee on Solar-Terrestrial Physics (SCOSTEP).

However, despite these efforts, there are still considerable gaps in ground-based space-weather-observing infrastructure in African regions/countries. This hampers the data acquisition necessary for space weather research, hence limiting the provision of products and services that could help address socio-economic challenges. Due to the growing investment in space activities in Africa, including the building of nano-satellites/cubesats and the purchase and deployment of off-the-shelf satellites, there is a growing need for Africa to develop a critical mass of expertise to help mitigate space weather effects on critical space-based and ground-based technological infrastructure. Space weather effects could be felt in the aviation industry, power grid, land/sea and air navigation, and high-frequency communications, among other technological systems. Evidence of space weather's impact in Africa includes South Africa's space-weather-induced loss of its homemade SumbandilaSat satellite in September 2011 and of several high-voltage power transformers following the impacts of the Halloween storm of October 2003 on power systems through geomagnetically induced currents [3]. These events created awareness in Africa about the realities of space weather's impact on investments in the space sector and power sector, and they also brought to the fore the need for thorough space weather modelling and forecasting to prepare Africa to mitigate the consequences of space weather impacts on technologies.

Space weather preparedness is important not only for Africa but indeed the rest of the world. Space weather preparedness is underpinned by three elements: designing mitigation into infrastructure where possible; developing the ability to provide alerts and warnings of space weather and its potential impacts; and having in place plans to respond to severe events. This kind of preparedness calls for high-level research and national and international coordination.

This paper provides information on space weather infrastructure, human capital development, research achievements, ongoing and upcoming projects, international collaborations, funding sources, gaps in infrastructure, and human resources, as well as suggestions on what needs to be done going into the future.

This paper is organized as follows: In Section 2, we present the distribution of space weather infrastructure in Africa and discuss data accessibility and reliability; Section 3 deals with human capital development (HCD), completed and on-going postgraduate research, and various HCD initiatives; Section 4 gives insight into gaps in infrastructure and current and planned space weather projects; and in Section 5, we give the conclusion and way forward.

2. Distribution of Space Weather Infrastructure in Africa

The information captured in this paper was obtained using desktop research; information from individual and institutional equipment hosts in various countries who also participated in authoring this paper; internet sources; reports; and other publications that are publicly available.

2.1. Space Weather Monitoring

In monitoring space weather, ground-based instruments and satellites are used to monitor the Sun for any changes and issue warnings and alerts for hazardous space weather events.

Solar activities, such as solar flares, coronal mass ejection, and moon shadow of an eclipse, induce the rapid change of ionosphere morphology, so-called ionospheric weather, which significantly impacts radio communication and navigation systems. Ground-based GNSS receivers can measure the ionospheric total electron content (TEC) and the ionospheric electron density (through ionospheric tomography). This tool allows continuous monitoring of ionospheric weather and modelling of ionospheric climate. Magnetometers make it possible to follow the regular variations of electric currents in the ionosphere and magnetosphere caused by solar wind dynamics. During magnetic storms, the magnetic variations are affected by the disturbance of ionospheric and magnetospheric currents generated by solar events. Thus, GNSS receivers and magnetometers are very useful in monitoring the impact of solar disturbances on the Earth's environment and in the development of space weather science in Africa.

Many other instruments are used for space weather monitoring, including very-high-frequency (VHF) and very-low-frequency (VLF) receivers, ionosondes, incoherent scatter radar, all-sky cameras, and Fabret–Perot interferometers, among others. Some of these are discussed below.

2.1.1. Global Navigation Satellite Systems Receivers

GNSS has been used in all forms of transportation: space stations, aviation, maritime, rail, road, and mass transit. PNT plays a critical role in telecommunications, land surveying, law enforcement, emergency response, precision agriculture, mining, finance, scientific research, and so on. Space weather is one of the major limiting factors for the precision and reliability of PNT services from GNSS. Geomagnetic storms and substorms, solar flares, and ionospheric irregularities can result in PNT deterioration.

Since the ionosphere is a very dynamic medium and due to its dispersive nature, dual-frequency GNSS measurements may effectively be used to derive robust and accurate information about the ionospheric state under quiet and perturbed space weather conditions. Ground-based measurements enable mapping of the total ionization of the ionosphere (i.e., TEC). The hosts of most of the equipment installed for space weather research have a free data policy for research purposes, so the accessibility of data via the internet is not a challenge.

(a) GNSS Receivers for Ionospheric Scintillation Monitoring

Most of the dedicated high-rate GNSS receivers required for GNSS ionospheric scintillation and TEC monitoring (GISTM) were donated by US Air Force Research Laboratories (AFRL) and Boston College [4]. The deployments took place mostly between the years 2007 and 2014.

These instruments are primarily used for L-band monitoring of scintillations on GNSS signals traversing through the ionosphere. Figure 1 and Table 1 below show the distribution of GNSS ionospheric scintillation receivers across the continent. The map in Figure 1 shows a limited number of GISTMs in North and Southern Africa, which are mid-latitude regions with a low incidence of ionospheric scintillation. East Africa stands out as the area with the largest number of instruments for GISTM, followed by West Africa [5–14]. The line running from the geographic longitude 10° to the east in Figure 1, Figure 3, Figure 4 and Figure 5, is the geomagnetic meridian.

The USA equipment donors (SCINDA) and their collaborators deployed most of the instruments in Central Africa, which is the region with the highest incidence of ionospheric scintillation. Due to problems with maintenance, power, security, and internet access, there is a considerable gap in the currently operating ionospheric scintillation monitoring infrastructure in large parts of Africa. The GISTM stations and their host countries are listed in Table 1.

Other than the above-listed stations, the South African National Space Agency (SANSA) also operates Novatel GSV4004B scintillation receivers at several other locations in South Africa and on nearby islands, namely at Louisvale (28.49° S, 21.23° E), Grahamstown (33.32° S, 26.5° E), Gough Island, (40.34° S, 9.88° W), and Marion Island (46.87° S, 37.85° E). Since 2017, SANSA has installed Novatel GPStation6 and Septentrio PolaRx5S multi-constellation GNSS scintillation receivers for real-time data streaming from each of the following locations in Africa: Kilifi (Kenya, 3.62° S, 39.84° E) [15], Kabwe (Zambia, 28.46° N, 14.44° E), Lagos (Nigeria, 6.52° N, 3.38° E), and Busitema (Uganda 0.75° N, 34.04° E). SANSA is currently working on the deployment of a few more such receivers in Central and East Africa (Gaborone in Botswana, Tororo in Uganda, and Bahir Dar in Ethiopia) to provide essential real-time data to the Regional Space Weather Warning Centre of the International Space Environment Service (ISES) at the South African National Space Agency in Hermanus.

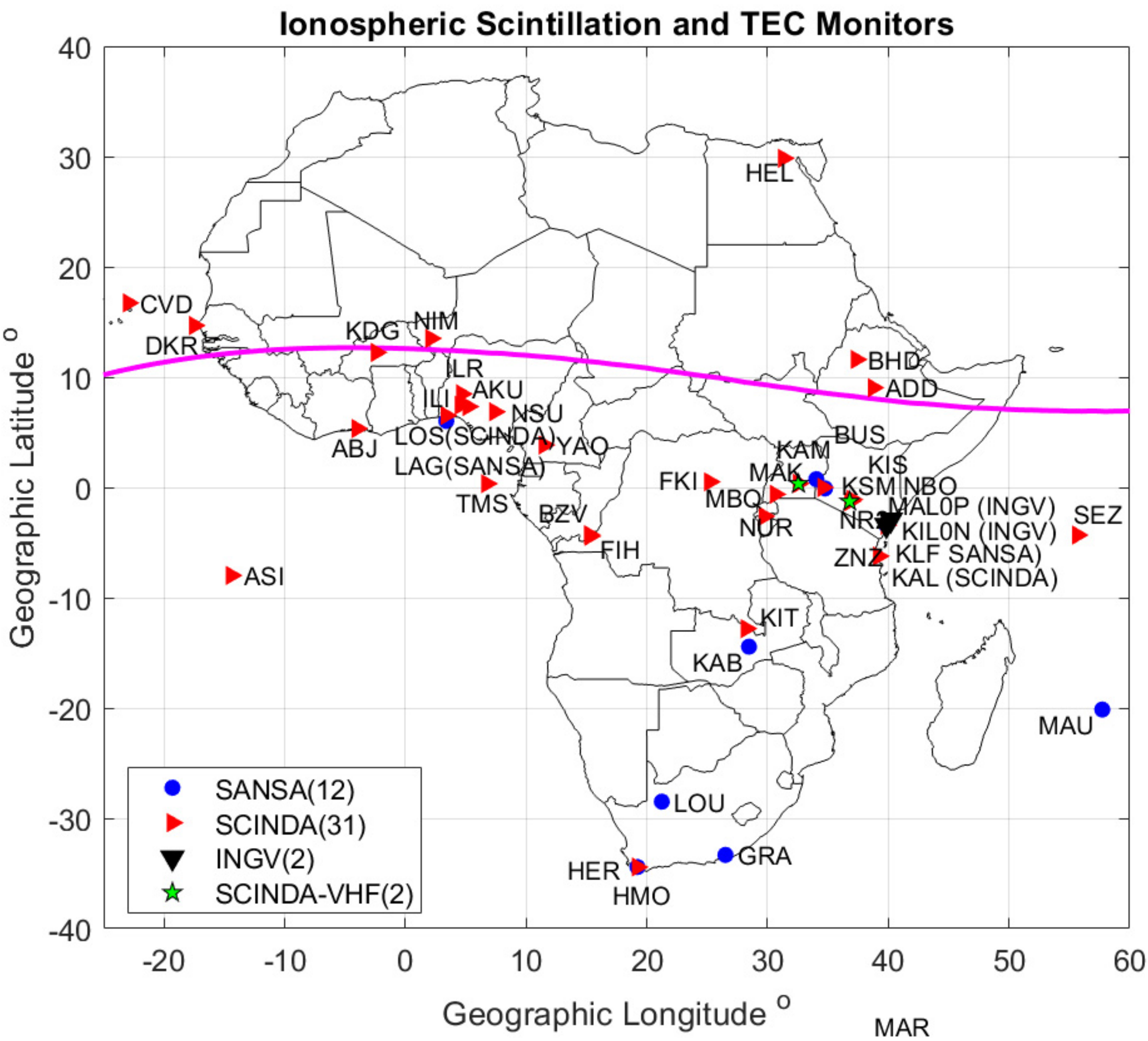

Figure 1. Distribution of GPS ionospheric scintillation and TEC monitors (GISTM) deployed by Boston College (USA) and US Air Force Research Laboratories in Africa (SCINDA 2007–2014) and by the South African National Space Agency (SANSA). The line running from the geographic longitude 10° is the geomagnetic meridian.

Table 1. GPS ionospheric scintillation and TEC monitors in Africa.

Locations	Host Nation	Station Code	Network	Latitude	Longitude
Abidjan	Ivory Coast	ABJ	SCINDA	5.34	5.36
Addis Abeba	Ethiopia	ADD	SCINDA	9.33	38.75
Ascension Island	Atlantic Ocean	ASI	SCINDA	−7.98	−14.41
Bahir-Dar	Ethiopia	BHD	SCINDA	11.57	37.39
Brazzaville	Congo	BZV	SCINDA	−4.28	15.25
Busitema	Uganda	BUS	SANSA	0.75	34.04
Butare	Rwanda	NUR	SCINDA	−2.61	29.74
Cape Verde	Atlantic Ocean	CVD	SCINDA	16.73	−22.94
Dakar	Senegal	DKR	SCINDA	14.68	−17.46
Helwan	Egypt	HEL	SCINDA	29.87	31.32
Hermanus	South Africa	HMO	SCINDA	−34.42	19.22
Ilorin	Nigeria	ILR	SCINDA	8.48	4.67
Kabwe	Zambia	KAB	SANSA	−14.44	28.46
Kampala	Uganda	KAM	SCINDA	0.37	32.56
Kampala	Uganda	KMP	SCINDA-VHF	0.37	32.56
Kilifi	Kenya	KIL0N	INGV	−3.62	39.84
Kilifi	Kenya	KAL	SANSA	−3.62	39.84
Kinshasa	Congo	FIH	SCINDA	−4.42	15.31
Kisangani	Congo	FKI	SCINDA	0.51	25.21
Kitwe	Zambia	KIT	SCINDA	−12.80	28.24
Koudougou	Burkina Faso	KDG	SCINDA	12.24	−2.40
Lagos	Nigeria	LOS	SCINDA	6.52	3.39
Lagos	Nigeria	LAG	SANSA	6.52	3.39
Malindi	Kenya	MAL0P	INGV	−2.93	40.21
Maseno	Kenya	KIS	SCINDA	0	34.6
Mbarara	Uganda	MBQ	SCINDA	−0.62	30.65
Nairobi (J K U)	Kenya	NBO	SCINDA	−1.09	37.02
Nairobi (U of Nairobi)	Kenya	NR2	SCINDA	−1.27	36.81
Nairobi (U of Nairobi)	Kenya	NAI	SCINDA-VHF	−1.27	36.81
Niamey	Niger	NIM	SCINDA	13.50	2.10
Nsukka	Nigeria	NSU	SCINDA	6.86	7.41
Sao Tome and Principe	Atlantic Ocean	TMS	SCINDA	0.34	6.74
Seychelles	Indian Ocean	SEZ	SCINDA	−4.32	55.69
Yaounde	Cameroon	YAO	SCINDA	3.90	11.50
Zanzibar	Tanzania	ZNZ	SCINDA	−6.23	39.21

In 2019, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) started the installation of new GNSS receivers for scintillation monitoring covering both East and West Africa. At present, three receivers in Kilifi (Kenya, 3.62° S, 39.84° E), Malindi (Kenya, 2.93° S, 40.21° E), and Abuja (9.07° N, 7.49° E) are operational, making their data available in real-time.

Almost 50% of installed SCINDA GISTMs in Africa are non-operational. This state of affairs is not suitable for space weather research in Africa. The reasons for this are damage, intermittent electricity supply, and poor internet connectivity, thus prohibiting data transfer to the central server in Boston College; missing equipment parts; equipment reaching the end of its useful operational lifetime; and system configuration problems (see Figure 2). This means mitigating space weather effects is not possible in large swathes of Africa due to the infrastructure gaps and the non-operational status of most receivers. Consequently, space weather advisories to various sectors would only be possible in certain parts of Africa but not in others. This is particularly bad for the aviation industry since the International Civil Aviation Organization (ICAO) now requires all airports to integrate space weather information in their aeronautical information services [16]. This state of the GISTMs in Africa hampers space weather research in the continent and jeopardizes networking and collaborations. In addition, it highlights the lack of goodwill by the hosts to avail funds to replace damaged equipment or even add more to the network to enable research work to continue.

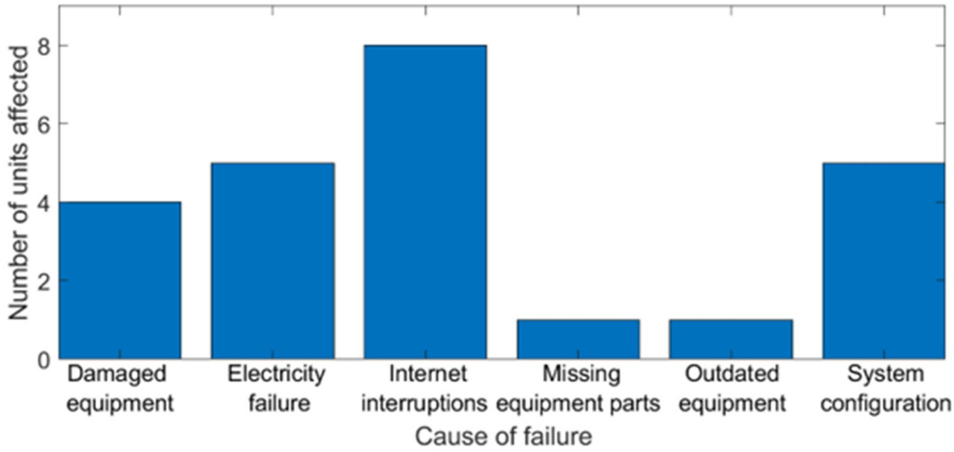

Figure 2. The causes of the non-operational status of SCINDA GISTM stations and the number of stations affected by each of these causes.

Figure 2 clearly shows that most of the GPS receiver stations are unable to transmit data to external collaborators because of poor internet connectivity, followed by unreliable electricity supply, and lack of technical expertise to configure the receiver systems properly. These equipment hosts often need thorough training to be able to run and maintain the equipment, but usually, this is at the cost of the external collaborator. For operational stations, not all operate optimally (i.e., some GPS receiver stations operate intermittently, a few are fully operational, and the vast majority are non-operational).

(b) Geodetic GNSS Receivers and GNSS reference receivers for surveying and mapping.

GNSS receivers have been deployed by several external parties (NASA, NOAA, ESA, BKG, and others) for geodetic studies of the African continent. Besides the GNSS receivers deployed by external parties, national mapping agencies in many African countries have installed GNSS reference receivers to support mapping and surveying work. Figure 3 shows the distribution of GNSS geodetic and reference receivers in and around Africa.

(b1) International Global Navigation Satellite Systems Service (IGS).

The IGS is a voluntary federation of many worldwide agencies (350) that pool resources and data from permanent GNSS stations (512 in 2023) to generate precise GNSS products. The International GNSS Service provides, on an openly available basis, the highest-quality GNSS data, products, and services in support of the terrestrial reference frame; Earth observation and research; PNT; and other applications that benefit science and society [17].

Out of a total of 118 countries around the world, only 22 countries in Africa participate in this network. The list of the 30 operational stations in 2023 is given in Table 2.

Table 2. IGS GNSS stations operating in 2023.

Marker	Country	Latitude	Longitude
ABPO	Madagascar	−19.018	47.229
ACRG	Ghana	5.641	−0.207
ADIS	Ethiopia	9.035	38.766
ASCG	Ascension Is.	−7.916	−14.333
CPVG	Cape Verde	−16.732	−22.935
DJIG	Djibouti	11.526	42.847
FUNC	Portugal	32.648	−16.908
HARB	South Africa	−25.887	27.707
HNUS	South Africa	−34.425	19.223

Table 2. *Cont.*

Marker	Country	Latitude	Longitude
JCTW	South Africa	−33.951	18.469
LLAG	Canary Is.	28.482	−16.321
LPAL	Canary Is.	28.764	−17.894
MAL2	Kenya	−2.996	40.194
MAS1	Canary Is.	27.764	−15.633
MAYG	Mayotte	−12.782	45.258
MBAR	Uganda	−0.601	30.738
MELI	Spain	35.281	−2.952
MFKG	South Africa	−25.805	25.540
NKLG	Gabon	0.354	9.672
PRE3	South Africa	−25.746	28.224
RABT	Morocco	33.998	−6.854
REUN	La Reunion	−21.208	55.572
SEYG	Seychelles Is.	−4.679	55.531
STHL	Sainte Helene	−15.943	−5.667
SUTH	South Africa	−32.380	20.810
TDOU	South Africa	−23.080	30.384
ULDI	South Africa	−28.293	31.421
VACS	Mauritius	−20.297	57.497
VOIM	Madagascar	−21.906	46.793
WIND	Namibia	−22.575	17.089
YKRO	Ivory Coast	6.871	−5.240
ZAMB	Zambia	−15.426	28.311

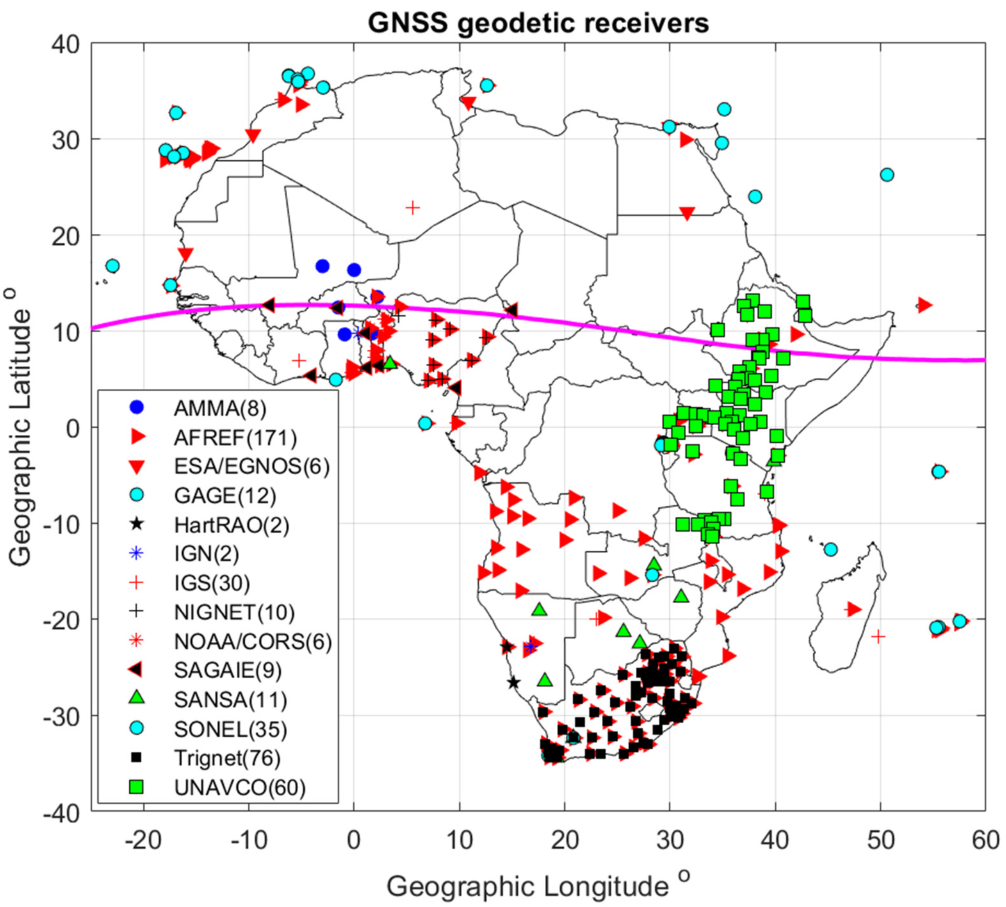

Figure 3. GNSS geodetic and reference receiver distribution. The purple line shows the location of the geomagnetic equator.

The measurements from 1994 are available on two websites in the United States, NASA's CDDIS and SOPAC [2,18], and on regional sites (IGN in France [19] and BKG in Germany [20]).

(c) GAGE/UNAVCO Network

The Geodetic Facility for the Advancement of Geoscience (GAGE, formerly UNAVCO, ***University NAVSTAR Consortium***) is a non-profit university-governed consortium funded by the National Science Foundation (NSF) and The National Aeronautics and Space Administration (NASA). It provides technical support to scientists for geodesy, tectonic, and geophysical events and education. It is responsible for archiving and disseminating measurements in RINEX format. The main projects are for North America and the poles. However, for more than 20 years, UNAVCO has supported a project covering the African continent ('AfricaArray'), with the installation of many GNSS receivers mainly around the East African Rift for a few months up to several years, which can be used for space weather research (Figure 4). The files are available on their site via ftp or web GUI [21].

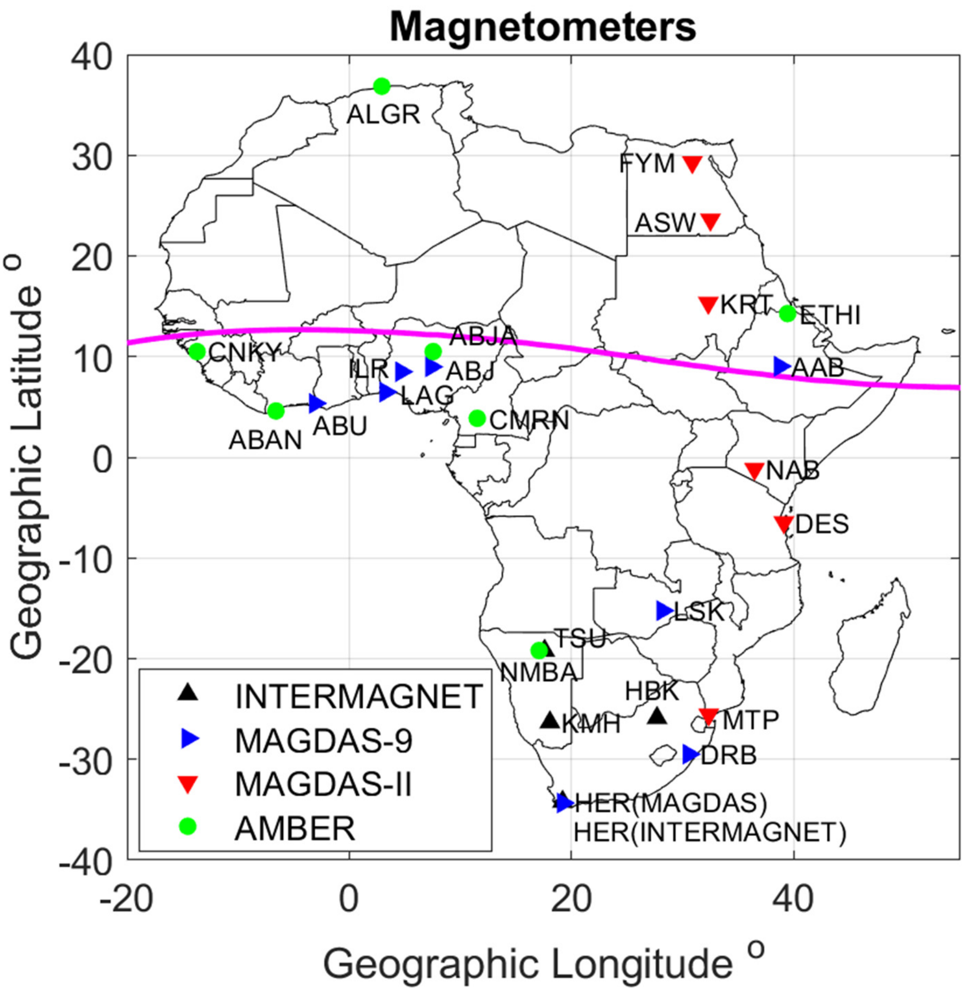

Figure 4. Locations of magnetometers of various networks in Africa. The purple line shows the location of the geomagnetic equator.

(d) The African Geodetic Reference Frame (AFREF)

The African Geodetic Reference Frame (AFREF) was conceived as a unified geodetic reference frame for Africa and as the fundamental basis for national and regional three-dimensional reference networks that are entirely consistent and homogeneous with the International Terrestrial Reference Frame (ITRF). Continuously Operating Reference Stations (CORS) or GNSS base stations were established to achieve this. The AFREF operational data center collects data daily. The data from all the stations of the IGS and GAGE networks are freely available on this website [22].

(e) The TRIGNET Network

The geodetic GNSS reference receivers of the TRIGNET network in South Africa are deployed and maintained by the South African Chief Directorate: National Geospatial Information (CD:NGI). This network of more than 60 GNSS receivers has provided South Africa with better GNSS infrastructure than the rest of the African countries. Data from the TRIGNET network is available via the web link of the Chief Directorate: National Geospatial Information (CD:NGI) [23].

SANSA (South African National Space Agency) recently deployed multi-constellation geodetic GNSS receivers for real-time ionospheric monitoring in South Africa (SUTG, 32.37° S, 20.81° E), in Southern Botswana (PALP, 22.60° S, 27.13° E; and LETL, 21.42° S, 25.57° E), in Zimbabwe (HARG, 17.78° S, 31.05° E), in Namibia (KMHG, 26.53° S, 18.1° E) and in Lagos, Nigeria (TSUG, 19.20° S,17.58° E).

(f) African Monsoon Multidisciplinary Analysis (AMMA) GPS Network [24]

The AMMA GNSS receivers were installed in Djougou (Benin), Niamey (Niger), Gao (Mali), Tamale (Ghana), Ouagadougou (Burkina-Faso), and Tombouctou (Mali) during the period 2006–2009. Although the data can be used across disciplines, these GNSS stations were established for meteorological applications, but the data can also be used for space weather studies and can be downloaded from the AFREF website.

(g) The CNES/SAGAIE network

CNES (France) began the implementation of the SAGAIE (Stations ASECNA GNSS pour l'Analyse de la Ionosphère Equatoriale) network in 2013 for the real-time correction of an extension of SBAS/EGNOS to Africa. The current network includes nine stations (Table 3), all installed at major airports, often with one geodesy receiver and one scintillator receiver at each station. Operational monitoring is carried out by ASECNA (**Agence pour la Sécurité de la Navigation aérienne en Afrique et à Madagascar**). Unfortunately, these data are not yet freely accessible [25].

Table 3. CNES/SAGAIE stations operating in 2023.

Marker	Country	Latitude	Longitude
ABI1	Ivory Coast	5.32	−4.03
CTO1	Benin	6.37	2.39
DAK2	Senegal	14.76	−17.38
NIA1	Togo	9.74	1.12
LOM2	Togo	6.14	1.24
NDJA	Chad	12.12	15.06
OUAG	Burkina Faso	12.36	−1.53
DOUA	Cameroon	4.05	9.71
BAM1	Mali	12.65	−8.00

(h) The SONEL network

SONEL (Système d'observation du Niveau des eaux Littorales) produces accurate sea level measurements from tide gauges and geodetic receivers. There are more than 1000 GNSS stations near the coasts around the world, but only a few dozen around the African continent. The measurements are available on their website [26].

(i) CORS and Private Networks

There are many CORS networks in several African countries. Unfortunately, their advertising is limited, so it is very difficult to establish a list of operational stations in each. Those responsible do not offer web links, and the measurements taken are unfortunately inaccessible. Two exceptions can be cited:

The NOAA/CORS network in Benin included 7 stations (BJKA, BJNA, BJNI, BJPA, BJSA, BJAB, BJCO). The network was shut down in January 2020.

The NIGNET network (Nigerian GNSS Reference Network) in Nigeria. It included up to 14 stations distributed in each region (BKFP, HUKP, MDGR, RECT, FPNO, ABUZ, CGGT, FUTY, OSGF, ULAG, UNEC, RUST, CLBR, GEMB). The measurements were used for geodesy, troposphere, and ionosphere. The network was shut down in 2017. The data of these two networks are available on the AFREF website.

(j) OMNISTAR Differential GNSS

OmniSTAR provides GNSS receivers for their space-based GNSS correction services that can improve the accuracy of precise positioning applications. The OMNISTAR (Trimble Private Network) GPS receivers are mainly deployed along the African coast to improve the accuracy of GPS positioning for ocean navigation, but they are still useful for space weather studies. OMNISTAR is a private commercial network of satellite-based augmentation services. The data from this network are not freely available [27].

2.1.2. Magnetometers in Africa

Magnetometers are ground-based infrastructure used in space weather monitoring for monitoring the impact of geomagnetic storms. Figure 4 and Tables 4–7 provide the locations and other details of the magnetometers in Africa.

Table 4. AMBER magnetometer stations in Africa.

Station and Host Country	Code	Geo Lat/ Geo Lon	Mag Lat/ Mag Lon	L-Shell Value
Medea Station Algeria	ALGR	36.85 2.93	27.98 77.67	1.30
Yaounde Station Cameroon	CMRN	3.87 11.52	−5.30 83.12	1.00
Abidjan Station Côte d'Ivoire	ABAN	4.60 −6.60	−6.00 65.80	1.00
Adigrat Station Ethiopia	ETHI	14.28 39.46	5.90 111.06	1.00
Conakry Station Guinea	CNKY	10.50 −13.70	−0.50 60.40	1.00
Windhoek Station Namibia	NMBA	−19.20 17.09	−33.15 84.65	1.40
Abuja Station Nigeria	ABJA	10.50 7.55	0.55 79.63	1.00

Table 5. AMBER network host institutions and contact persons.

Name	Organization	Email Address
Fatma Anad	Centre de Recherche en Astronomie Astrophysique et Géophysique (CRAAG), Algeria	f_anad@yahoo.fr
Cesar Biouele PhD.	University of Yaounde I, Cameroon	cesar.mbane@yahoo.fr
Amoré Nel, PhD	South African National Space Agency (SANSA), Hermanus, South Africa	anel@sansa.org.za
Alem Mebrahtu PhD.	Adigrat University, Ethiopia	alemmeb@yahoo.com
Rabiu Babatunde, PhD.	Centre for Atmospheric Science, National Space Research and Development, Nigeria	tunderabiu@yahoo.com

Table 6. Magnetometers installed in Africa by Kyushu University, Japan. The geomagnetic dipole coordinates are determined using model calculations provided by the British Geological Survey—Geomagnetism (https://www.bgs.ac.uk/?s=coordinate+calculator, accessed on 26 November 2023) The geomagnetic coordinates and the dip latitude were calculated using the BGS online IGRF model (https://geomag.bgs.ac.uk/data_service/models_compass/igrf_calc.html, accessed on 26 November 2023).

Abbrev.	Station Name	Nation	GG Lat.	GG Lon.	GM Lat.	GM Lon.	L-Shell	Dip Lat.	Installed	Type
FYM	Fayum	Egypt	29.30	30.88	26.76	103.64	1.15	43.68	08/01/14	MAGDAS-II
ASW	Aswan	Egypt	23.59	32.51	20.88	108.75	1.07	33.98	08/12/23	MAGDAS-II
KRT	Khartoum	Sudan	15.33	32.32	12.76	107.18	1.01	16.30	08/09/23	MAGDAS-II
AAB	Addis Ababa	Ethiopia	9.04	38.77	5.56	112.51	1.00	3.39	06/08/19	MAGDAS-9
ILR	Ilorin	Nigeria	8.50	4.68	10.42	78.83	1.00	−8.44	06/08/24	MAGDAS-9
ABU	Abuja	Nigeria	8.99	7.39	10.48	81.60	1.00	−6.75	10/08/15	MAGDAS-9
LAG	Lagos	Nigeria	6.48	3.27	8.65	77.11	1.00	−13.91	08/09/04	MAGDAS-9
ABJ	Abidjan	Ivory Coast	5.35	−3.08	8.52	70.62	1.00	−17.41	06/09/01	MAGDAS−9
NAB	Nairobi	Kenya	−1.16	36.48	−4.18	108.73	1.09	−22.36	08/09/16	MAGDAS-II
DES	Dar Es Salaam	Tanzania	−6.47	39.12	−9.83	110.54	1.09	−33.10	08/09/10	MAGDAS-II
LSK	Lusaka	Zambia	−15.23	28.20	−16.78	98.25	1.24	−52.48	08/09/25	MAGDAS-9
MPT	Maputo	Mozambique	−25.57	32.36	−27.63	100.52	1.53	−60.40	08/09/15	MAGDAS-II
DRB	Durban	South Africa	−29.49	30.56	−31.20	97.92	1.67	−62.05	08/09/08	MAGDAS-9
HER	Hermanus	South Africa	−34.34	19.24	−34.14	85.64	1.83	−64.74	07/09/14	MAGDAS-9

Table 7. MAGDAS magnetometer station host countries and their universities.

Station Code	Station Name	Country	Institution
ABJ	Abidjan	Ivory Coast	University of Cocody
LAG	Lagos	Nigeria	Redeemer's University
ILR	Ilorin	Nigeria	University of Ilorin
ABU	Abuja	Nigeria	National Space Research and Development Agency
AAB	Addis Ababa	Ethiopia	Addis Ababa University
HER	Hermanus	South Africa	SANSA Space Science
DRB	Durban	South Africa	University of KwaZulu Natal
MTP	Maputo	Mozambique	Eduardo Mondlane University
LSK	Lusaka	Zambia	University of Zambia
DES	Dar es Salaam	Tanzania	University of Dar es Salaam
NAB	Nairobi	Kenya	University of Nairobi
KRT	Khartoum	Sudan	University of Khartoum
ASW	Aswan	Egypt	Helwan University
FYM	Fayum	Egypt	Helwan University

(a) AMBER Magnetometers [28–31]

The African Meridian B-field Education and Research (AMBER) magnetometer network is operated by Boston College and funded by NASA and the Air Force Office of Scientific Research (AFOSR). The principal investigators are Endawoke Yizengaw, PhD. (Ethiopia), Boston College, USA and Mark Moldwin, PhD, University of Michigan, USA (http://magnetometers.bc.edu/index.php/amber2, accessed on 26 November 2023). The

AMBER stations in Africa are Adigrat (Ethiopia), Medea (Algeria), Yaounde (Cameroon), Tsumeb (Namibia), Abuja (Nigeria), Conakry (Guinea), and Abidjan (Ivory Coast).

(b) Magnetic Data Acquisition System (MAGDAS) stations in Africa [32–38]

The principal investigator (PI) of the project which installed these magnetometers was Prof. Kiyohumi Yumoto (deceased) of the International Center for Space Weather Science and Education (ICSWSE), Kyushu University, Japan. ICSWSE, Kyushu University, is one of the few research institutes/universities conducting research and education in space weather in the world. The MAGDAS network has over seventy fluxgate magnetometers distributed across the world, with 14 of them installed in Africa. The MADGAS data have been used by several researchers in Africa for space weather research, but quite a number of these magnetometers are no longer operational.

The African countries and their respective universities hosting the magnetometers are listed in Table 7.

Most of these facilities are hosted by departments of physics and a few by the electrical engineering departments in the respective universities. Ensuring the continuity of operations of the magnetometers has been a challenge since the funding stream from Japan dried up after the demise of the PI.

(c) INTERMAGNET

INTERMAGNET is a global network of observatories dedicated to monitoring geomagnetic field variations across the world. There are INTERMAGNET magnetometers in five countries in Africa, namely Ethiopia, Madagascar, South Africa, Algeria, and Senegal. Details of the four INTERMAGNET observatories and other magnetometers in Southern Africa can be found in [16,39–42]. At each of the four INTERMAGNET observatories in Southern Africa, there are several types of magnetometers, including Overhauser Scalar Magnetometer GSM-90, 3-axis Fluxgate Magnetometers DMI FGE, and 3-axis Fluxgate Magnetometers LEMI025.

2.1.3. Other Ground-Based Facilities

Several other ground-based facilities that can be used for space weather monitoring have been deployed in Africa. Figure 5 depicts the distribution of most of the other space weather equipment in Africa.

(a) Incoherent Scatter Radars

The incoherent scatter radar (ISR) is one of the most powerful sounding methods developed to estimate certain properties of the ionosphere. This radar system determines the plasma parameters by sending powerful electromagnetic pulses to the ionosphere and analyzing the received backscatter. This analysis provides information about parameters such as electron and ion temperatures, electron densities, ion composition, and ion drift velocities. Nevertheless, in some cases, ISR analysis has ambiguities in the determination of plasma characteristics. They are in Ethiopia and Nigeria. There is also one under construction in Kenya.

(b) Ionosondes

The ionosondes are used to generate ionograms and assist in determining the state of the ionosphere and selecting the optimum frequencies for HF radio communication.

The ionosondes are installed in South Africa (four), Kenya (one), Ethiopia (one), and Nigeria (one). The stations in Kenya, Ethiopia, and Nigeria are non-operational. In the Ethiopian case, the electric power supply is unreliable and unstable, and in the Kenyan case, there are issues with system configuration as well as storage of data. Only two of the ionosondes in South Africa are currently operational (HR, GR), while the two others are being refurbished after vandalism and theft.

A new ionosonde was installed in July 2023 in Malindi, Kenya, at the Broglio Space Center (BSC) managed by the Italian Space Agency and it is the only one operational, at present, outside South Africa.

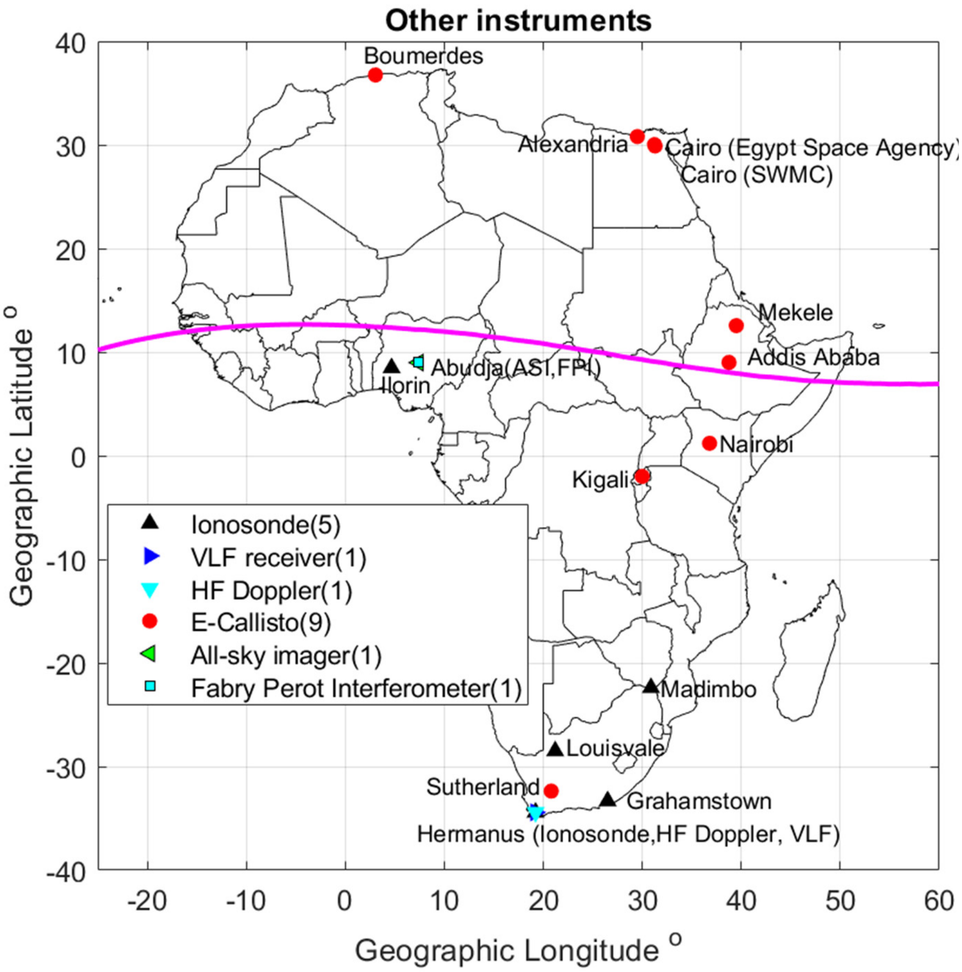

Figure 5. Distribution of other infrastructure dedicated to space weather monitoring in Africa.

(c) Very-Low-Frequency (VLF) and Very-High-Frequency (VHF) receivers

Several VLF devices have been distributed by Stanford University (USA) and installed in several African countries (See Table 8) to monitor the lower layer of the ionosphere (D layer). They are divided into two groups: those related to the AWESOME (Atmospheric Weather Education System for Observation and Modeling of Effects) network and those related to the SID (Sudden Ionospheric Disturbance Monitor) and super-SID receivers. Besides these, there is also the Compact Astronomical Low-Cost Low-Frequency Instrument for Spectroscopy and Transportable Observatory (*CALLISTO*) *spectrometer* [43,44], which operates between 45 to 870 MHz. The monitors are installed in Kenya, Ethiopia, Uganda, Egypt, Algeria, and South Africa. The principal investigator of CALLISTO is Christian Monstein of the Radio Astronomy Group (RAG) at ETH Zurich, Switzerland. SANSA operates an e-Callisto Solar Radio Spectrometer (http://e-callisto.org/) at Sutherland in South Africa (Lat 32:38° S, Lon 20:81° E). Table 8 gives some details of the VLF and VHF receivers installed in Africa.

Some VHF monitors [11] were installed across the continent by AFRL. The host countries are Congo (Brazzaville), Egypt, Ethiopia, Kenya, Nigeria, South Africa, and Uganda.

Most of North Africa and parts of Central Africa have substantial infrastructure gaps. Several countries in these regions are politically unstable, thus making the installation of ground-based space weather equipment rather difficult. These gaps will need to be filled so that there will be sufficient data to enable adequate coverage of Africa in terms of space weather research.

Table 8. The number of VLF and VHF receivers installed.

Countries	AWESOME	VHF	SID
Algeria	1	0	2
Burkina Faso	0	0	1
Congo Brazzaville	0	0	6
Ivory Coast	0	2	2
Egypt	1	2	14
Ethiopia	1	2	14
Kenya	0	2	3
Libya	2	0	1
Morocco	1	0	0
Namibia	0	0	1
Nigeria	0	2	38
Senegal	0	0	1
South Africa	0	2	13
Tunisia	1	0	9
Uganda	0	2	4
Zambia	0	0	2

2.2. Data Access and Reliability

Most of the data generated by the observing equipment have a free access policy, except for those owned by national mapping agencies in various countries. However, different data providers have imposed conditions to be met before granting access to the data. In most cases, if the data is purely for research, and not for commercial use, then free access is always granted, but some acknowledgement of the data source is required whenever a publication is produced with them. The SANDIMS data portal at SANSA [45] provides free access, via a data request for research applications, to all geomagnetic, ionospheric, and magnetospheric data gathered from SANSA Space Science's instrumentation network. The eSWua web portal of Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Italy [46] provides free access to visualization and downloads of the data from instruments managed by INGV. The users can access data from a GUI or a service from which massive data downloading can be performed automatically.

This open data policy has enabled many African researchers to benefit from space weather data generated by equipment hosted in the continent and beyond. In effect, this has contributed immensely to human capital development in space weather science in many countries in Africa. However, a major setback is the non-operational status of most of the equipment due to several factors such as non-stable electric power supply, poor internet connectivity, poor system configuration, poor maintenance, and equipment operating beyond its useful lifetime. Replacement of ageing equipment and maintenance issues are made worse by the fact that some African equipment hosts do not actually use the data for any training or research and hence have no interest in maintaining or replacing the equipment. Although some of the factors limiting successful equipment functioning could be addressed by the hosts (e.g., unreliable electric power by investing in solar power), most of the equipment hosts do not have funding for this, and most of the host institutions do not provide support towards that end.

The lack of a good network of space weather monitors in Africa is limiting the modelling of the African sector of the near-earth space environment and thus the development of space weather products and services. For example, it is known that scintillation threatens the performances of GNSS-reliant services requiring high-precision positioning, but forecasting scintillation is still a challenge. The development of ionospheric climatology over various geographic regions of Africa would be a useful step in providing space weather information. Climatology is only possible with a proper network of space weather monitors that continuously provide data over an extended period.

2.3. Space Weather Products and Services

There is a need to develop thresholds of space weather threats on a variety of technological systems in Africa. This includes the aviation industry since ICAO now recommends the provision of space weather alerts as part of regulations and standards for enhanced safety in civil aviation. Except for SANSA Space Science in South Africa, the rest of Africa has not developed space weather products and services for the aviation industry and other industrial sectors. Commercialization of space weather research findings will help mitigate economic losses brought about by space weather events, and it could also possibly provide funding streams to support space weather research. At the moment, there is a huge disconnect between industry and academia in Africa.

3. Human Capital Development

The training and research in space weather in various African countries are at different levels. We provide a detailed summary of the human resource situation in selected countries below.

3.1. Capacity Building

Activities geared towards human capital development are given in Table 9. These include training workshops and doctoral studies in some countries in Africa as of the end of 2022. Table 9 also gives a list of the universities involved.

Efforts by the United Nations Basic Space Science Initiative (UNBSSI) since the year 1991 have led to an increase in space weather capacity building. For example, there were 10 PhD theses defended during the first decade (1991–2001), while 84 PhD theses were defended during the period 2001–2023. Presently, there are 68 PhD theses in progress.

3.2. International Achievements [47,48]

Since 2014, many African space weather researchers have obtained international awards for exemplary research in space weather (Table 10).

Thus, capacity building in this field is growing, and the quality of African space weather researchers is comparable to the rest of the world. This is exemplified by the number of recipients of international awards coming from Africa, and also by the sheer number of those graduating with PhDs or with PhDs in progress.

3.3. Initiatives by Professional Societies/International Organizations

Some selected initiatives in support of space weather research in Africa are mentioned here.

(a) African Geophysical Society

The African Geophysical Society (AGS) is a dynamic, innovative, and interdisciplinary scientific association committed to the pursuit of understanding Earth and space for the benefit of mankind. The objectives of the AGS are to expand and strengthen the study in the African continent of the Earth and other planets, including their environments. The main goals are to facilitate cooperation among scientists; create national, regional, and international scientific organizations involved in geophysical and other related research and intiating new research and training programs; and popularize various geophysical research and training programs via scientific conferences, publications, and training in both the short and long terms.

The AGS has brought together African researchers and created platforms for collaborative research, co-supervision of students, and external examination of theses/dissertations. This has greatly improved the space weather research landscape in Africa.

Table 9. Capacity building by African scientists.

Country	School/Workshop	PhD	Universities/Institutions
Algeria	ISWI Maghreb Algerian (ISWI Maghreb) School organized in 2013 at Algiers University—6–16 May 2013	PhDs defended: 4; in progress: 3	USTHB, CTC Arzew, CRAAG
Benin	No school but the participation of students in l ISWI school, Maghreb, West Africa	PhDs defended: 1; in progress:1	University of Abomey-Calavi
Burkina Faso	No schools/workshops but the participation of students in the ISWI School, Maghreb West Africa	PhDs defended: 16; in progress: 16	University Nobert ZONGO University Joseph Ki-ZERBO University Nazi BONI (Bobo Dioulasso) IRSAT/National Center for Scientific Research and Technology
Cameroon	No school, but the participation of students in the ISWI, school, Maghreb, West Africa	PhD defended: 1	Higher Technical Teacher Training College/Department of Geomatics, University of Ebolowa, Cameroon
Ivory Coast	International school in Abidjan (15–25 October 1995), Ivory Coast 3rd edition of the ISWI-Magreb-West Africa Space Weather School (IMAO), UFHB, Bingerville (16–28 October 2017), Ivory Coast	PhDs defended: 15; in progress: 4	University Félix Houphouët Boigny, Cocody, Abidjan University of Man University Pelefero gon Coulibaly, Korhogo
Democratic Republic of Congo	School ISWI in Kinshasa, 11–24 September 2011	PhDs defended: 5; in progress: 1	University of Kinshasa
Egypt	International Space Weather Initiative (ISWI) UN/NASA/JAXA Workshop 6–10 November 2010 Helwan, Egypt International Workshop on Space Weather and Space Navigation, 3–4 October 2017, Beni-Suef University, Egypt African Geophysical Society Conference on Space Weather, 25–28 March 2019, Cairo, Egypt	PhDs defended: 5; in progress: 3	Space Environment Research Lab at Egypt, Japan University of Science Technology (E-JUST) Space Weather Monitoring Center at Helwan University Faculty of Navigation Science and Space Technology-Beni Suef University Department of Astronomy and Meteorology, Faculty of Sciences, Cairo University National Research Institute of Astronomy and Geophysics (NRIAG) National Authority for Remote Sensing & Space Sciences Egyptian Space Agency
Ethiopia	IHY—Africa Space Weather Science and Education workshop, 12–16 November 2007, Addis Ababa, Ethiopia AGU-Chapman conference, Addis Ababa, 12–16 November 2012 First ISWI Space Science School in Bahir Dar University, November 2010 in Ethiopia. 14th International Symposium on Equatorial Aeronomy, 19–23 October 2015, Bahir Dar, Ethiopia	PhD defended: 10 in progress: 6	Physics Department Science College, Bahir Dar University, Washera Geospace and Radar Science Research Laboratory at Bahir Dar University Department of Physics, Addis Ababa University Institute of Geophysics, Space Science and Astronomy (IGSSA), Addis Ababa University, Entoto Observatory and Research Center, Ethiopia
Guinea	No school, but participation of students in the ISWI Maghreb West Africa school	PhD defended: 1	
Kenya	African Geophysical Society Conference on Space Weather, Nairobi, 21–25 September 2015 The Eastern Africa GNSS and Space Weather Capacity Building Workshop, 13–17 May 2019 The second edition of the Eastern Africa GNSS and Space Weather Capacity Building Workshop, 21–25 June 2021 East, Central, and Southern Africa GNSS and Space Weather Workshop, 9–23 July 2010, Nairobi, Kenya. ISWI/SCOSTEP Space Science School, October 21– 1 November 2013, Kenya Institute of Education, Nairobi, Kenya	PhDs defended: 3; in progress: 1	Pwani University Technical University of Kenya Maseno University Jomo Kenyatta University of Science and Technology University of Nairobi Masinde Muliro University of Science and Technology
Morocco	Workshop on Space Weather and Instruments with the Illinois Space Weather team, the Moroccan team, and master's and PhD students for the installation of the RENOIR (Remote Equatorial Night-time Observatory of Ionospheric Regions), 4–11 November 2013 ISWI school (Space Weather) organized in 2014 at Cady Ayyad University, 5–10 May 2014	PhDs defended: 3; in progress: 3	University Cady Ayyad at Marrakech

Table 9. *Cont.*

Country	School/Workshop	PhD	Universities/Institutions
Morocco	ISWI School of Space Weather and GNSS, 16–21 February 2015 African Workshop on GNSS and Space Weather, 5–6 October 2020 ICTP activity co-organized by CRASTE-LF UNOOSA–ICG and Boston College scheduled in Rabat and held online because of COVID-19		African Regional Centre for Space Science and Technology Education in French Language (CRASTE-LF)
Nigeria	Third United Nations/European Space Agency Workshop on Basic Space Science, 18–22 October 1993, Lagos First Annual National Workshop of the International Heliophysical Year (IHY), Nigeria, 27 October 2005, Federal University of Technology, Akure, Nigeria African Regional International Heliophysical Year School (AFRIS), 9–22 November 2008, Enugu, Nigeria Nigerian National Meeting on GNSS Science and Application: National Augmentation System For GPS (application to geodesy, air, ground and water navigation systems), 16–19 November 2009, Virtual Library Hall, National Universities Commission (NUC), Abuja, Nigeria 2009 African Regional Conference of the International Academy of Astronautics; 24–26 November 2009, Abuja, Nigeria ISWI/MAGDAS School on Litho-Space Weather, 15–21 August 2011, Redeemer's University, Mowe, Nigeria UN/Nigeria Workshop on International Space Weather Initiative ISWI, 17–21 October 2011, Abuja, Nigeria 2nd African Regional Centre for Space Science Technology Education—English (ARCSSTEE) regional conference, 22–24 August 2012, Obafemi Awolowo University, Ile-Ife, Nigeria National Conference on Space Weather and Space-Based Technologies, 2–9 February 2013, Bells University of Technology, Ota, Nigeria 2nd Cyril Onwumechili School on Physics of Upper Atmosphere, 23–27 June 2013, Centre for Atmospheric Research, Anyigba, Nigeria International Space Weather School, 20–25 January 2014, Bells University of Technology, Ota, Nigeria Centre for Satellite Technology Development (CSTD) Space Week 2014, 3–5 June 2014, Abuja, Nigeria. African Geophysical Society Conference 2–6 June 2014, Abuja, Nigeria 2nd Annual Nigerian Geophysical Society Conference, 17–20 March 2015, Covenant University, Canaanland, Ota, Nigeria International School on Equatorial and Low-Latitude Ionosphere (ISELLI), 14–18 September 2015 Centre for Atmospheric Research, National Space Research and Development Agency (NASRDA), Abuja, Nigeria Radicella 80th Birthday Symposium, University of Lagos, Akoka, Nigeria, UNILAG, 8th May 2017 Nigerian Geophysical Society 4th International Conference, Bayero University, Kano, Nigeria, 9–12 May 2017 5th Nigerian Geophysical Society Annual International Conference, Federal University, Dutse, Jigawa, Nigeria, 19th and 22nd June 2018. Superdarn radar workshop, Bowen University, Iwo, Nigeria, June 3–7 June 2019 International Colloquium on Equatorial and Low-Latitude Ionosphere (ICELLI, UNILAG), 9–13 September 2019 2nd International Colloquium on Equatorial and Low-Latitude Ionosphere (ICELLI), online, 15–17 September 2020 International Colloquium on Equatorial and Low-Latitude Ionosphere (ICELLI), Bowen University, Iwo, Nigeria, September 13–18, 2021,	PhDs defended: 20; in progress: 15	More than 20 Nigerian Universities are offering graduate programs in space-weather-related fields Centre for Atmospheric Research, National Space Research and Development Agency, Anyigba, Nigeria African Regional Centre for Space Science and Technology Education in English Language (ARCSSTE-E)

Table 9. *Cont.*

Country	School/Workshop	PhD	Universities/Institutions
Rwanda	School for describing and analyzing solar data for a better prediction of space weather: postponed in July-August 2022	PhDs in progress: 2	University of Rwanda—College of Science and Technology University of Rwanda—College of Education
Republic of Congo	School IHY in RC, 2–9 December 2009	PhD defended: 1; in progress: 2	University Marien Ngouabi
Senegal	ISWI, Maghreb, West Africa school organized in 2019 at Thiès University—15 to 25 October 2019	PhDs defended: 2; in progress: 3	University Iba Der Thiam of Thiès
South Africa	International Reference Ionosphere Workshop hosted by SANSA: 10–14 October 2011 African Workshop on Space Science Research held at SANSA, Hermanus, South Africa: 04–08 May 2015 South African National Space Agency (SANSA) and European Space Agency (ESA) The Path to South Africa—European Space Innovation Partnerships Workshop Program, Hermanus, 31 January 2019–2 February 2019 Joint IAPSO-IAMAS-IAGA Assembly, Cape Town, South Africa, 26 Aug–01 Sept, 2017 The 17th European Incoherent Scatter Scientific Association (EISCAT) Symposium and 42nd Annual European Meeting on Atmospheric Studies by Optical Methods (42AM), Hosted by SANSA during 14–18 September 2015 SANSA also participates in the International Space Weather Camp (ISWC), which brings together students from South Africa, the USA, and Germany to learn about space physics topics, including space weather. This is an annual event, with the three countries alternating in hosting.	At least 15 students supervised by SANSA staff (in various universities) have graduated with MSc and PhD degrees in the past 4–5 years	South African National Space Agency, Hermanus, South Africa
Tunisia	The First IHY International Workshop on Advancing VLF Science Through the Global AWESOME Network, 30 May–01 June 2009, Tunis	PhD defended: 1	Faculty of Sciences of Tunis
Uganda	No international school or conference has been organized in Uganda. The plan to host ISWI in Uganda in 2020 failed due to the COVID-19 pandemic	PhDs defended: 2; in progress: 3	Physics Department, Muni University, Arua City, Uganda Physics department, Mbarara University of Science and Technology, Mbararara City Physics Department, Busitema University
Zambia	No space-weather-related international school or conference has been organized in Zambia. Zambia is strengthening its collaboration with South Africa. A workshop to sensitize government officials in space science is planned for June 2022. This has been organized specifically because the government is developing a space policy and strategy, and a need has arisen to educate the decision makers on the key benefits of space science	1 PhD in progress	Department of Physics of Natural Sciences, University of Zambia, Lusaka Department of Physical Sciences, School of Natural Sciences, Kwame Nkrumah University

Table 10. Awards.

Name	Country	Year of Award	Award
John Bosco Habarulema	Uganda	2014	Basu Early Career Award in Sun-Earth System Science.
John Bosco Habarulema	Uganda	2016	AGU Africa Award for Research Excellence in Space Science
Joseph Olwendo	Kenya	2016	Basu Early Career Award in Sun-Earth System Science.
Melessew Nigusie	Ethiopia	2017	AGU Africa Award for Research Excellence in Space Science
Frédéric Ouattara	Burkina Faso	2018	AGU Africa Award for Research Excellence in Space Science
Zama T. Katamzi-Joseph	South Africa	2018	Basu Early Career Award in Sun-Earth System Science.
Andrew Akala	Nigeria	2019	AGU Africa Award for Research Excellence in Space Science
Olawale S. Bolaji	Nigeria	2020	AGU Africa Award for Research Excellence in Space Science

(b) URSI Commission G Working group: "Capacity building and training"

During the International Radio Science Union (URSI) General Assembly 2021, held in Rome from 28 August to 4 September, a new working group (WG) in the framework of Commission G (Ionospheric Radio and Propagation) has been established. This WG, named "Capacity Building and Training," is chaired by C. Cesaroni (INGV, Italy) and co-chaired by J. Olwendo (PU, Kenya), B. Nava (ICTP, Italy), and P. Doherty (now deceased; BC, USA). The "Capacity Building and Training" working group deals with activities related to the training of students and young scientists mainly from developing countries. The main objectives of the working group are: to rganize international workshops, especially for young scientists from developing countries; to facilitate visits/exchanges for young scientists by putting in place actions for fundraising; and to organize periodical webinars for sharing new research among the commission G community members. This group is championing the aspirations of the African space weather research community.

(c) Scientific Committee on Solar-Terrestrial Physics (SCOSTEP)

Many African master's and doctoral researchers have benefited from the SCOSTEP visiting scholar program, whereby a scholar is sponsored to undertake his/her study in another institute to access facilities and expertise that are not available at their home institute. This has provided excellent opportunities for networking and co-authorship of research articles.

(d) The Abdus Salam International Centre for Theoretical Physics/Boston College/INGV

Every year since 2009, the ICTP and Boston College have been organizing training workshops on GNSS and space weather for developing countries. Recently, INGV has been contributing by organizing additional workshops in collaboration with the aforementioned institutions. Many African lecturers and students have been trained in space weather monitoring equipment installation and maintenance and data acquisition, reduction, and interpretation. Some of these works have been organized in Africa and have greatly impacted space weather research capacity in Africa.

(e) Groupe de Recherche en Géophysique Europe Afrique (GIRGEA) network [49–53]

In the framework of the UNBSSI program, the GIRGEA network organized has schools on space weather since 1995. Since 2013, the GIRGEA scientific network has been organizing regional schools every two years.

3.4. International Collaborations

Space weather training in Africa has been built on two models, namely:

(a) Training of trainers and their students: The first cohort of African lecturers who were converted from their fields of research to space weather research were made hosts of space weather equipment. The equipment hosts were then trained to archive and use the data produced for research. The pioneering students who used the data for their postgraduate research were jointly supervised by their home-based academic staff and equipment donors. This model has enabled Africans to do research at their home institutions where they were/are registered as students while also building international networks and collaborations. The model forestalled potential brain drain.

(b) Intra-Africa co-supervision of postgraduate research: Many African students are given research topics by their African senior researchers who co-supervise them and also host them for research visits whenever possible.

The weak link in these two models is the lack of investment by the researchers' home institutions in space weather infrastructure development.

3.5. Funding Sources

Space weather research in Africa has been supported through a variety of funding streams. These include:

(a) External financing: Most of the space weather capacity building has been supported through external funding, especially for the acquisition and installation of research equipment, but local African universities have often provided their students with the necessary facilitation to enable them to undertake their research work. More often than not, the facilitation has been in terms of tuition fee waivers and in-kind support.
(b) Government: Some national space agencies and research councils/agencies are now funding space weather research and training workshops to build a critical mass of expertise within the shortest time possible.
(c) Industry: A few industry stakeholders, like the aviation industry and electric power distribution companies, in some few African countries have also come on board to support space weather research, although their involvement is still at a very low level. The challenge here has been that the industry players are not aware of the relevance of space weather research to their businesses. This calls for more awareness campaigns to enlighten the industry, and thus possibly attract more funding from the sector.

4. Gaps in Infrastructure and Human Resources

Gaps

There are many countries in Africa where space weather research is non-existent or infrastructure for space weather monitoring is lacking. In some cases, institutions in some African countries may be hosting facilities whose data they do not use at all, and hence they take little interest in ensuring the functionality of the facilities. This situation is equivalent to cases where there are no facilities installed at all because the result is the same, namely, there is no data to facilitate research.

Gaps in infrastructure are evident in regions like Chad, Central African Republic, Somalia, Eritrea, and South Sudan. Incidentally, these countries lie on or very close to the geomagnetic equator, where ionospheric conditions are very dynamic and have potentially adverse consequences for the technological systems in use. This lack of ground-based observing facilities makes the understanding of space weather dynamics over Africa difficult. Non-deployment of space weather monitors may have been occasioned by political instability in those countries. In some other countries, the infrastructure exists but is not operating optimally due to erratic electric power supply, low internet bandwidths, poor maintenance, or lack of funds to replace ageing or obsolete monitors. Another aspect of the gaps observed is the non-uniform spread of different types of monitors across the continent. The reason for this is partly because collaborators would normally deploy their facilities where they already have points of contact or in a region of interest depending on the relevant space weather campaign at that time. This aspect informs the observed trends in the distribution of equipment across Africa.

The gaps in infrastructure also go hand in hand with the lack of or inadequate human resources in many countries. Many countries do not have well-established departments of physics where space weather research could thrive. This badly limits postgraduate research in space weather. However, despite the gaps in the deployment of monitors, some current and upcoming projects will help improve the situation (see Table 11). This table may not be exhaustive, but it indicates that more facilities are coming to Africa.

Table 11. Completed, current, and upcoming projects in space science/space weather in Africa.

Country	Projects	Contacts
Algeria	- March 2022: installation of the Algerian GNSS network across the national territory with 109 stations by the INCT (National Institute of Cartography and Teledetection)	Naima ZAOURAR USTHB naimaboulasba@gmail.com
Benin	- Organization of a conference on the importance of space weather in the development of countries	Adébiyi Joseph ADECHINAN Physics Department University of Abomey-Calavi adechinanjoseph@yahoo.fr
Burkina Faso	- Developing SIG and drones for expert surveyor training - Burkina Sat1 project of nanosatellite launching (for agriculture, land management, Earth atmosphere study, and so on) - Acquisition of scintillator (Septentrio) for ionospheric investigation - Planetarium for presenting educational shows about astronomy -Meteorological station - Understanding the effect of geomagnetic activity on ionospheric dynamics	Jean-Louis ZERBO University Nazi BONI (Bobo Dioulasso) JeanLouis.zerbo@gmail.com
Cameroon	- African Meridian B-field Education and Research (AMBER) magnetometer Array Project since 2008 - SCINDA-GPS installation in 2009	Honoré MESSANGA Higher Technical Teacher Training College/Department of Geomatics, University of Ebolowa, Cameroon messanga.honore@gmail.com
Ivory Coast	- Organization of IMAO5 (ISWI Maghreb West Africa, School) 2022 in Abidjan, 17–28 October - Study of the influence of solar events on GNSS positioning	Franck GRODJI University Félix Houphouët Boigny, Cocody, Abidjan franckgrodji@yahoo.fr
Democratic Republic of Congo	- The current situation is not known but some university lecturers have been attending GNSS workshops organized by ICTP and Boston College and the MAGDAS group. The lectures facilitated the deployment of a SCINDA GPS scintillation and TEC monitor in 2011.	Bruno KAHINDO University of Kinshasa bkahindo@gmail.com
Egypt	- Space weather forecasting and warning using artificial Intelligence - Installation of new equipment: Fluxgate Magnetometer and Telluric System CALLISTO Solar Radio Spectrometer GNSS TEC/Scintillation Monitoring Unit	Ayman MAHROUS Space Environment Research Lab at Egypt-Japan University of science technology(E-JUST) ayman.mahrous@ejust.edu.eg
Ethiopia	- Developing the state-of-the-art ionospheric TEC model for improved accuracy of positioning (applicable finally for agriculture, land management, and so on) - Understanding the triggering mechanism of the East African equatorial ionospheric post-sunset irregularities - Understanding the effect of geomagnetic storm time-driven ionospheric currents on low-latitude power grids	Melessew NIGUSSIE Washera Geospace and Radar Science Research Laboratory at Bahir Dar University melessewnigussie@yahoo.com

Table 11. *Cont.*

Country	Projects	Contacts
Guinea	No new initiatives	Rene TATO LOUA Direction Nationale de la Météorologie de Guinée lrenetatometeo@gmail.com
Kenya	- The 2022 event was planned and carried out at the ICTP in Italy during the first two weeks of October. The subsequent events in the years 2023 and 2024 are planned to be conducted at ICTP, Italy, and in Malindi, Kenya, respectively. These two workshops are planned in the framework of the NORISK project with the collaboration of the Italian Space Agency and the Kenyan Space Agency (ASI). - NORISK will install an ionosonde, a GNSS scintillation receiver, and ICT infrastructure for space weather data and product management in Malindi, and it will develop a nowcasting and forecasting model for TEC in the Eastern Africa region. - The Kenya Space Agency in the year 2020 disbursed about USD 30,000 to two universities for the installation of space weather monitors, and the work is still in progress. - Study of solar flares and geo-effectiveness and potential impact on GNSS systems.	Claudio CESARONI Istituto Nazionale di Geofisica e Vulcanologia claudio.cesaroni@ingv.it Local contact Joseph OLWENDO Pwani University j.olwendo@pu.ac.ke Director General, KSA Paul BAKI Technical University of Kenya
Morocco	- Measurements of thermospheric winds with Fabry–Perrot interferometer - Ionospheric irregularities analysis with an all-sky camera (PICASSO) - Analysis of GPS data from five GPS stations installed in Morocco - Analysis of satellite data (SWARM) - Use of simulation resources	Aziza BOUNHIR University Mohammed V of Rabat (and University Cady Ayyad of Marrakech) a.bounhir@uca.ma
Nigeria	- Studies on equatorial electrojet - Measurements of thermospheric winds with Fabry–Perrot interferometer - Measurements of thermospheric winds with Fabry–Perrot interferometer - Equatorial plasma bubbles with an all-sky camera - Analysis of GPS data during various scenarios such as geomagnetic storms, stratospheric warming, solar flares, etc. - Use of ground and satellite data for ionospheric studies - Complexities of the ionosphere using non-linear methods - Ionospheric irregularities studies	Scientists in various universities and research institutions including national space agencies tunderabiu@yahoo.com
Rwanda	-Space weather study through an analysis of solar radio bursts. -Kinematics of CMEs trough solar type II radio bursts and subsequent geo effectiveness -Empirical modelling of storms-time ionospheric TEC and other parameters.	Jean UWAMAHORO University of Rwanda—College of Science and Technology mahorojpacis@gmail.com
Republic Congo	- April 2022, National Week of Science: space technologies for sustainable development in Africa. - Contribution of solar wind parameters to the variation of ionospheric activity in the African equatorial zone	Bienvenue DINGA University Marien Ngouabi bvs_dinga@yahoo.fr

Table 11. *Cont.*

Country	Projects	Contacts
Senegal	- November 2017, installation of a GNSS station at the GLOSS tide gauge in Dakar - Installation of CORS (Continuously Operating Reference Stations) network in 2022, which will cover the country. This CORS network will define the Senegalese Datum - Project to launch a nanosatellite in 2023	Idrissa GAYE University Iba Der Thiam of Thiès idrissagaye3@hotmail.com
South Africa	- Space Weather Project in preparation for providing ICAO advisories for the aviation industry. We are currently developing products such as real-time TEC maps, scintillation products, and 3-dimensional electron density reconstruction maps. - Coupled with the one above, there has been a focus on the installation of GNSS receivers outside South Africa, such as in Kenya and Zambia. All of these are aimed at improving the accuracy of our space weather products. - The National Astrophysics and Space Science Program (http://www.nassp.uct.ac.za/) trains postgraduate students in Astrophysics and Space Science. Students who choose the Space Science stream conduct various projects in space physics, including space weather. This program has three nodes at the University of Cape Town, North West University, and the University of KwaZulu Natal	John Bosco HABARULEMA South African National Space Agency, Hermanus, South Africa jhabarulema@sansa.org.za
Tunisia	- 2006, installation of an AWESOME station at the Faculty of Sciences of Tunis - 2007, installation of the first SID station at the Faculty of Sciences of Tunis - Since 2009, several super-SID stations have been installed - Tunisia launched its first nanosatellite on Mars in 2021	Hassen GHALILA Faculty of Sciences of Tunis, University Tunis El Manar Hassen.ghalila@gmail.com
Uganda	- Developing an institute for space weather research at Busitema University	Patrick MUNGUFENI Physics Department, Muni University, Arua City, Uganda pmungufeni@gmail.com
Zambia	- Installation of Space Weather instrumentation - GNSS, total electron content (TEC), and scintillation monitor at Kwame Nkrumah University in Kabwe, Zambia, in March 2020 - Two (2) space-based augmentation (SBAS) reference receivers in the Northwestern District of Chavurah at the border with Angola and another in Kabwe at Kwame Nkrumah University in March 2020	Patrick SIBANDA Department of Physical Sciences, School of Natural Sciences, Kwame Nkrumah University sibandapatrick.ps@gmail.com

5. Conclusions and the Way Forward

In conclusion, we have gathered that:

(a) There is a huge infrastructure gap, so more instruments need to be deployed for space weather monitoring in Africa to fill in the gaps. This should not be left entirely to outsiders. There is a need for more African institutions/governments to invest in space weather research. To a small extent, this already happening, especially as an initiative by some space agencies in Africa, and perhaps the newly established African Space Agency should play a more proactive role in this.

(b) The community of space weather researchers in Africa is growing in number and competence, and this should encourage collaborations with other researchers from outside the continent. African and other researchers should team up and run more joint research projects, write proposals for funding, and carry out joint supervision of students.

(c) There is a need to develop thresholds of space weather threats on a variety of technological systems in Africa to inform space weather services in Africa.
(d) There is a need to create more awareness among the potential commercial stakeholders whose infrastructures and businesses could be impacted by space weather so that they put in place measures to mitigate space weather impacts. This could be one avenue for attracting the funding needed for research and development.
(e) We recommend that the African Space Agency (AfSA), when it becomes operational, takes up the challenge of improving space weather research infrastructure in the continent.
(f) Finally, it is well known that space weather prediction can only be possible by fully understanding the complex interactions and coupling occurring between the upper and the lower atmosphere, including the troposphere level. In this regard, the African continent offers a unique opportunity to have a global view as it is mostly composed of land areas spanning the northern mid-latitudes to the southern mid-latitudes. For this reason, the installation of different pieces of space-weather-monitoring equipment in Africa will have important and priceless benefits for the space weather field as a whole.

Author Contributions: Conceptualization: P.B. and C.A.-M.; Methodology: P.B., C.A.-M. and P.J.C.; software for plotting of figures: P.B. and P.J.C.; validation: P.B., C.A.-M., R.F. and P.J.C.; formal analysis: P.B., P.J.C., R.F., C.A.-M., C.C. and H.M.; investigation: all the authors were involved; resources: All the authors contributed information used in the research; data curation: P.B., P.J.C., C.A.-M., C.C. and H.M.; writing—original draft preparation: P.B. and C.A.-M.; writing—review and editing: P.B., P.J.C., R.F. and C.A.-M.; visualization: P.J.C.; supervision: C.A.-M.; project administration: P.B. and C.A.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflict of interest.

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