Training on GNSS and Space Weather in Africa in the framework of the North-South scientific network GIRGEA

Christine Amory-Mazaudier [1,2], Rolland Fleury [3], Frédéric Masson [4], Sharafat Gadimova [5], Emran Anas [6]

[1] LPP, CNRS/Ecole Polytechnique/Sorbonne Université/Université Paris-Sud/Observatoire de Paris
[2] T/ICT4D Abdus Salam ICTP,
[3] Lab-STICC, UMR 6285, Institut Mines-Telecom Atlantique, site de Brest,
[4] Institut de Physique du globe de Strasbourg, Ecole et Observatoire des Sciences de la Terre,
[5] Office for Outer Space Affairs, United Nations Office at Vienna
[6] CRASTE-LF, Rabat, Morocco

E mail (christine.amory@lpp.polytechnique.fr).

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Abstract: This paper presents the successful setting up of a research and teaching network for space weather in developed and fragile countries. This development took nearly a quarter of a century with the help of international cooperation. Numerous studies have been developed in different domains of Space Weather concerning the impact of solar events on the ionosphere and the Earth's magnetic field, ionospheric electric currents and the induced currents in the ground (GIC) Other studies have also been conducted on climate change, lightning and the movement of tectonic plates. We underline the importance of Global Navigation Satellite Systems [GNSS] for the development of space weather research and capacity building during the last decades

Key words: Capacity building, GNSS, Space Weather, Sun Earth's relation, Geomagnetism, Atmosphere

1. Introduction

It was in 1987 that the International Association for Geomagnetism and Aeronomy (IAGA), at the request of the Interdivisional Commission of Developing Countries (ICDC) defined the International Equatorial Electrojet (IEEY) project to develop research centered on the magnetic Equator (Mazaudier et al., 1993) This project ran from 1992 to 1994, and so began our experience on developing research capabilities in developed and fragile countries. Then the International Heliophysical Year (IHY-http://ihy2007.org), from 2007 to 2009, reinforced this approach and advocated the deployment of inexpensive instrument networks in these countries (Harrison et al., 2005; Davila et al., 2007; Kitamura et al., 2007). The Global Positioning System (GPS) receivers have thus been deployed in Africa in particular. From 2010 to 2012, as part of the International Space Weather Initiative (ISWI) project, efforts led to the establishment of an international research network (www.iswi-secretariat.org). The three projects IEEY, IHY and ISWI are part of the United Nations Basic Space Science Initiative program (http://www.oosa.unvienna.org). During the last decade the GPS network has become the main network of scientific instruments deployed on Earth (more than ten thousand receivers). This article presents in its second section some use of GNSS for research. The third section describes the evolution of the training of the scientists using GNSS in the North-South scientific network GIRGEA (International Research Group Europe Africa) (www.girgea.org). The fourth section is devoted to the setting up of a GNSS master in the United Nations-affiliated African Regional Centre for Space Science and Technology - in French Language (CRASTE-LF), in Rabat, Morocco. Finally, the fifth section is dedicated to the International Committee on GNSS (ICG), established in 2005 under the umbrella of the United Nations, which promotes voluntary cooperation on matters of mutual interest related to civil satellite-based positioning, navigation, timing, and value-added services.

2. On the use of GNSS by Scientists

The GPS system designed primarily for positioning has proved to be an important instrument for different researches.

The first modern global satellite navigation system is GPS (Global Positioning System) has thirty GPS satellites, in almost circular orbit, scrolling at 20200 km altitude with a period close to 12h. A receiver placed on the ground can acquire two types of measurements: time measurements based on the codes transmitted and translated into distances (pseudo-range) and relative phase measurements. The frequency accessible to all unprotected civilian applications is the L1 frequency (1575.42 MHz). However, manufacturers have been able to develop dual-frequency receivers although the P (Y) code is encrypted on the L2 frequency (1227.60 MHz).

As early as 1992, an international group (IGS for International GPS Service) around scientists was quickly created to propose a recording format for dual-frequency measurements, independent of the manufacturers: the RINEX format (Receiver INdependent EXchange). The daily measurement files are archived at NASA / CCDIS (Crustal Dynamics Data Information System) and SOPAC (Scripps Orbit and Permanent Array Center) with copies to regional centers. Since then, the network has grown steadily to include about 400 stations today

Other positioning systems have been set up as the GLObal NAvigation Satellite System (GLONASS) by the Russian Federation, the European GNSS (GALILEO) by the European Union, BeiDou satellite navigation system (BDS) by China. In addition, the regional navigation satellite system (NavIC) and Quasi-Zenith Satellite Systems (QZSS) are being developed by India and Japan respectively to provide satellite-based navigation services.

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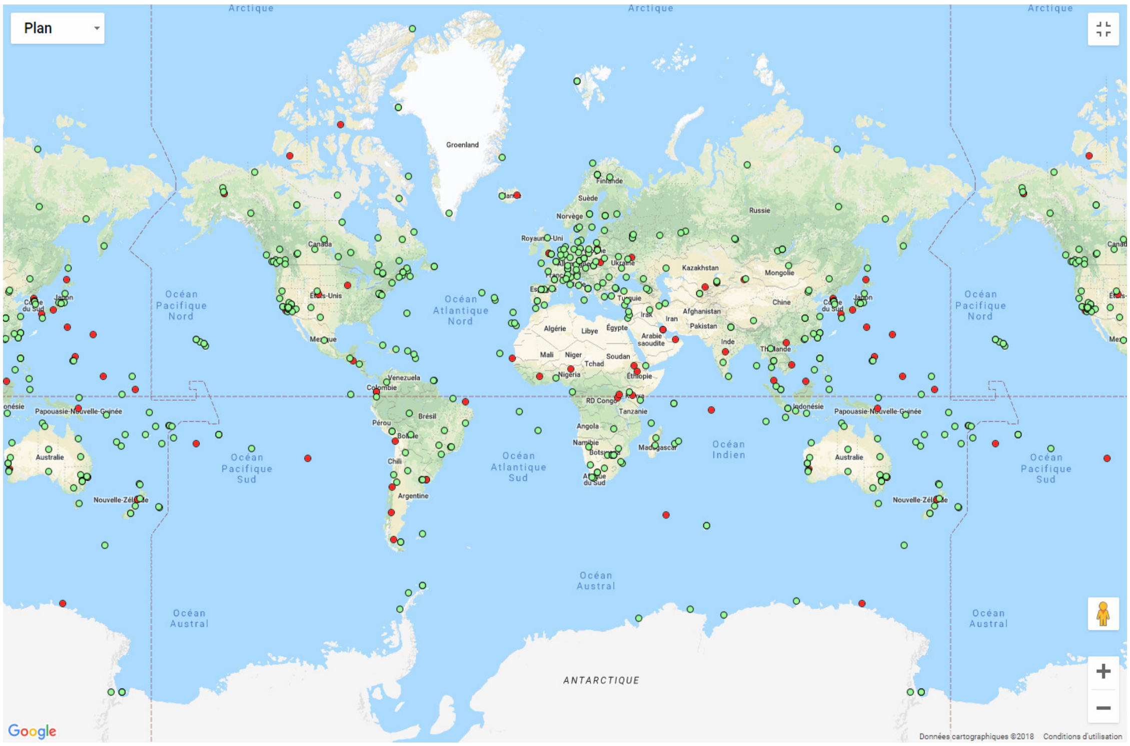

Figure 1: IGS network of GPS

Measurements were progressively made on the other navigation systems as they progressed. The letter 'G' of IGS has become the symbol of 'G' in GNSS. The mission of the IGS is to strengthen this network, to ensure the quality of the measures provided and their universal access. In the following paragraphs we will present the different uses for GNSS science.

2.1 GNSS for study of Plate Tectonics

GPS appeared in the early 1990s in Earth Sciences. First, it was used to characterize tectonic plate movement rates (Sella et al., 2002) and rigidity (Tregoning, 2003), as well as tectonic deformations at plate boundaries (McClusky et al., 2000) This was done (and still is done) by installing permanent GPS stations, or by conducting repeated measurement campaigns over time. Today, thanks to the multiplication of this type of measurement, global velocity and deformation maps of the earth's surface are regularly updated and published (Kreemer et al., 2014). From the beginning of GPS, researchers also saw the potential of this tool to estimate the velocity of tectonic faults. This is why dense networks have been installed around large faults such as the San Andreas Fault, the North Anatolian Fault, the Dead Sea Fault or the Sagaing Fault (Vernant, 2015). The Izmit earthquake in 1999 also showed the potential of GPS to study seismic events (Delouis et al., 2002) and since then GPS has become a highly appreciated tool by seismologists. Networks have also been set up around rifting areas such as Iceland (Arnadotti et al., 2001) and Afar (Vigny et al., 2006). Since the early 2000s, GPS has shown its power to characterize the behaviour of subduction zones. Precursory work on the coupling between the plates involved in subduction has been developed in Japan in an attempt to anticipate the most potentially seismic zones (Mazzotti et al., 2000). Some countries in North Africa and East Africa are in areas subject to tectonic plate movement. As part of the GIRGEA network, a thesis in the DRC is in progress on this topic.

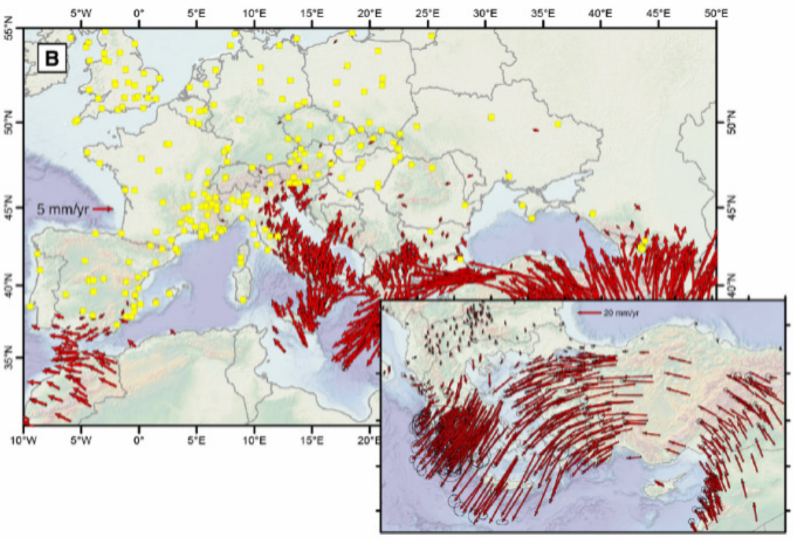

Figure 2: from Nocquet (2012) GPS velocity field from the Euro Mediterranean region, relative to Eurasia. Yellow squares indicate velocities below 1 mm/yr. The inset illustrates the westward movement of Anatolia relative to Eurasia.

GPS allowed the discovery of a fundamental process in active tectonics, called slow earthquakes. In the early 2000s, the fact that very regularly the subduction interface slides slowly without making an earthquake was highlighted in the Cascades subduction zone (Dragert et al., 2001). Instead of occurring abruptly in a few seconds or minutes, the slip is slow, and spreads slowly along the subduction plane. Then, this type of phenomenon was observed on most subduction zones.

From the Sumatra earthquake in 2004, and especially from the seismic sequence in South America (Chile, Ecuador) and Japan, the combination of GPS data before earthquakes (to study the pre-seismic properties of the subduction zone and in particular its coupling), during earthquakes (to study the co-seismic slip with high-rate GPS observables (e.g. at 1 Hz)) and after the earthquake (to study the post-seismic shift), combined with slow seismic observations, has allowed a renewed understanding of the earthquake cycle (Nocquet et al., 2017) Today, previous models with the notion of a characteristic earthquake repeated more or less identically at regular intervals, are completely challenged.

GPS is also useful in many other areas of Earth science. GPS is useful in Volcanology, since it can track the uplift related to eruptions. GPS also allows the study of the vertical movements of the Earth and the relative movement of sea level, landslides, among others. In 20 years, GPS has become an indispensable tool in Earth science.

2.2 GNSS for ionospheric studies => Space weather

Total Electron Content: TEC

The ionosphere is the partially ionized region of the upper atmosphere between 80 and 2000 km altitude. The ionosphere is mainly created by the photoionization of the atoms and molecules of the atmosphere by the X and UV radiation of the sun. The TEC is the total number of electrons contained in a cylindrical volume of surface 1 m^2 and in length the line of sight (LOS) between the receiver and the satellite. Its unit is the TECU (TEC Unit) which corresponds to 10^{16} el / m^2.

With a large number of ground stations, several organizations provide daily TEC charts. Figure 3 illustrates an example produced by the Astronomical Institute of the University of Bern (AIUB) for the 14/03/2015 at 13UT.

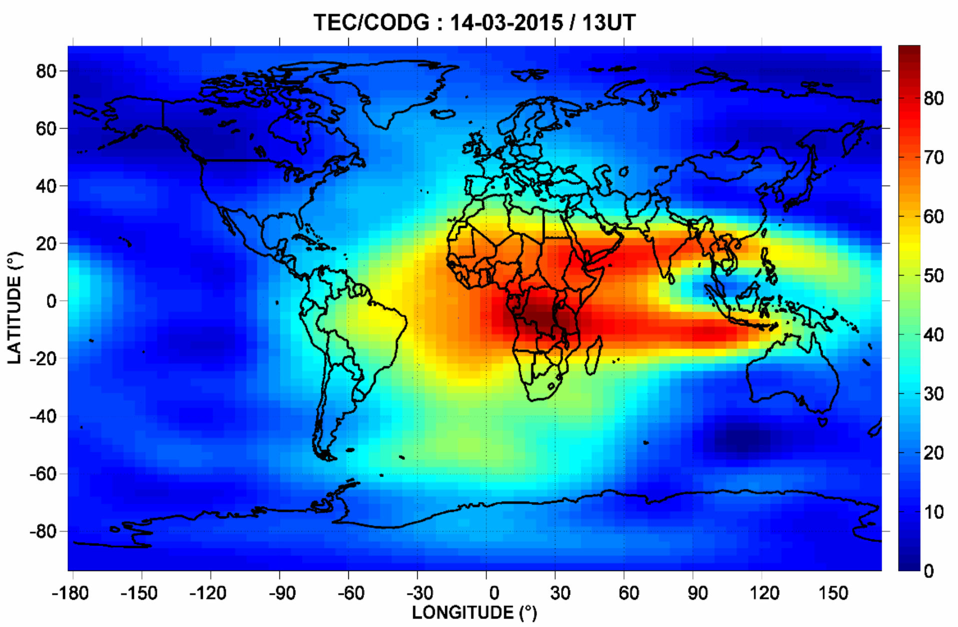

Figure 3: Post-processed ionospheric map of TEC from CODE on 14/03/2015 at 15UT (reference: http://www.aiub.unibe.ch/research/code___analysis_center/index_eng.html)

In general, when non-perturbed conditions are given, the night TEC values are small (as an example, see left side of the figure). After sunrise (towards longitude ~ -90 ° E), the TEC increases strongly with a strong gradient between high and low latitudes. The maximum is located on both sides of the equator (equatorial, or Appleton-Hartree, anomaly) to longitude 15 ° E (14LT). The TEC then decreases more slowly towards the night values. For the coming years, it is planned to have in real time this type of maps with a minimum network of ground stations in order to follow the evolution of the ionosphere state as part of the space weather (Krankowski et al., 2010) and thus to provide relevant information to different users requiring high location accuracy (Rovira-Garcia et al., 2014) (Roma Dollase et al., 2018).

Solar flare effect on TEC

The excess of radiation in X and UV bands during a solar flare causes an increase of the TEC (typically between 1-10 TECU) in the daylight sector, with a variable duration between a few minutes and about 1 hour. Recall that the impact occurs about 8 minutes after the start, a value that corresponds to the travel time of the Sun-Earth distance. Figure 4, from Yasyukevich et al. (2018) illustrates the example of the very strong eruption in September 6, 2017 that started at 11:53 and peak at 12: 02UT.

At 12: 00 there is no particular variation. At 12:20, the variation of the TEC is greater than 0.4 TECU / min on all the measurements in the illuminated part and the values decrease towards the sunrise and sunset times (continuous gray curves)

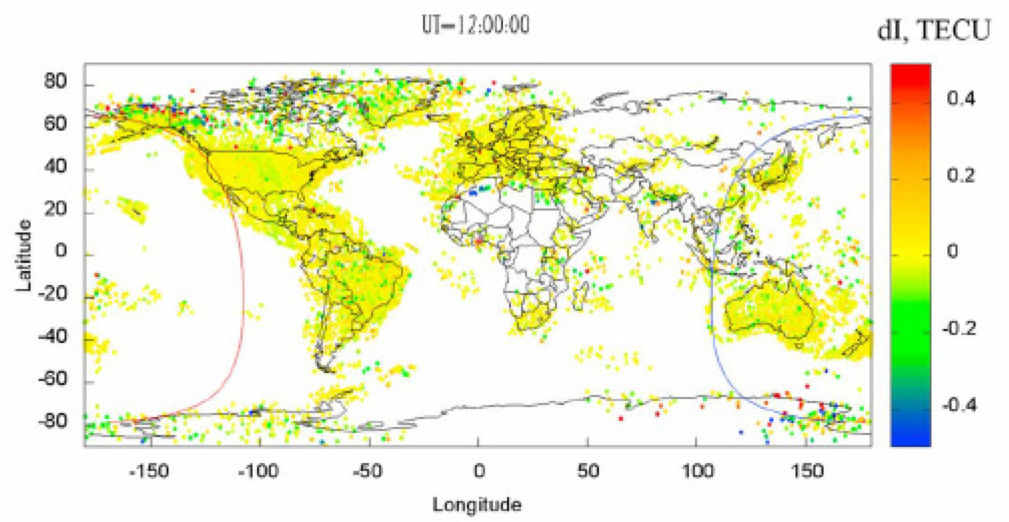

Figure 4b: Map of TEC during the solar flare

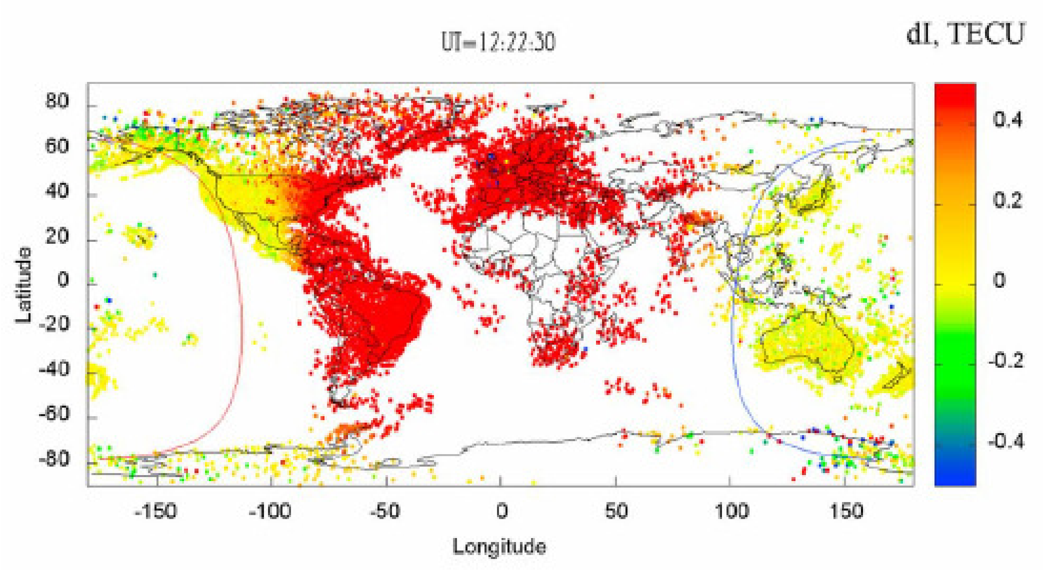

Figure 4a: Map of TEC before the solar flare

Scintillation

The ionosphere is not a homogeneous medium. Irregularities of ionization appear in the form of turbulent zones. GNSS signals diffracted when traversing such structures. On the ground, the signal varies rapidly with short periods. The phenomenon is observable on amplitude measurements and on TEC measurements calculated from GNSS phase observables. At high latitudes, they are related to the precipitation of the ionized particles of the plasma cloud emitted by the Sun. Figure 5 illustrates the variation in the amplitude of the signal received on both frequencies during the visibility of PRN # 08 over the Yellowknife station in Canada. Shortly before 21UT and until 21:45, the amplitude starts to oscillate quickly. It can double and / or go down to low levels up to the loss of the signal. In this extreme case, positioning performance could be impacted by the decrease in the number of satellites tracked. Specific receiver networks make it possible to track the phenomenon (Jayachandran et al., 2009).

At low latitudes, scintillations are mainly caused by plasma ionized bubbles known by the acronym EPB for Equatorial Plasma Bubbles, which rise at altitude in the ionosphere over the hours following sunset. There are multiple causes of scintillations. The bubbles is the main one. There are others that are unknown. What it is true is that if there are bubbles, there will be scintillations.

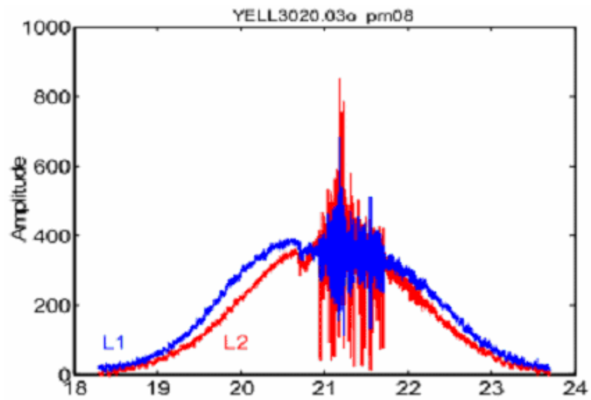

Figure 5: Variation on the amplitude of the PRN # 08 signal over Yellowknife

Many PhD, outside our network, have been supported on the variability and modeling of the ionosphere from GNSS measurements: Komjathy (1997) in Canada, Schaer (1999) in Switzerland, Moeketsi (2007) in South Africa, Bidaine (2007) in Belgium, Nohutcu (2009) in Turkey, Seo (2010) in the United States, Murti (2015) in Singapore, Jin (2016) in Norway. All the theses supported in the GIRGEA network are cited on the website (www.girgea.org) in the theses section.

2.3 GNSS for Atmospheric studies

What is the contribution of GNSS in this case? Unlike the ionospheric term, the tropospheric one does not depend on frequency. Direct estimation with GPS measurements is not possible. The tropospheric delay is due to the presence of neutral molecules and the water vapor content. The fine analysis of the tropospheric delay is based on the separation of these two origins: one distinguishes respectively a dry part which contributes for 90% of the delay and a wet part. The first is the vertical hydrostatic delay (Zenithal Hydrostatic Delay, ZHD), the second is the vertical wet delay (Zenithal Wet Tropospheric ZWD). The sum constitutes the total tropospheric delay noted ZPD (Zenithal Path delay) or ZTD (Zenithal Total Delay).

The ZTD tropospheric product can only be based on phase measurements where the noise is very low. Determining ambiguity constants and detecting and correcting phase jumps requires networking to perform single, double, triple phase difference calculations. Specific post-processing scientific software (BERNESE, GAMIT) is used to provide tropospheric term estimates for stations in the IGS network. These products are archived in certain data centers distributed world-wide with a delay of a few days compared to the current date (for example, at NASA's CDDIS).

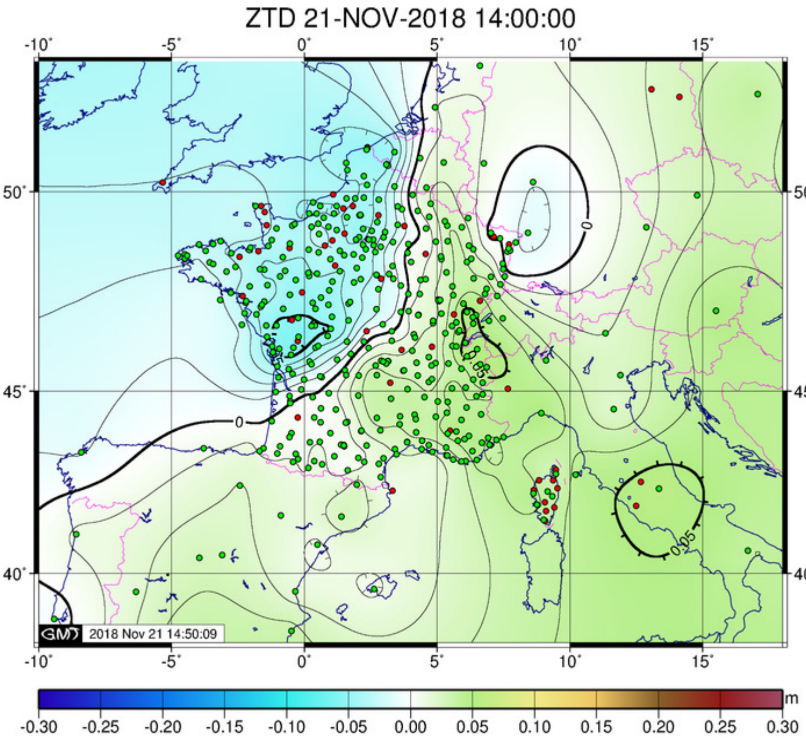

Figure 6: ZTD values over France on 21/11/2018 at 14: 00UT

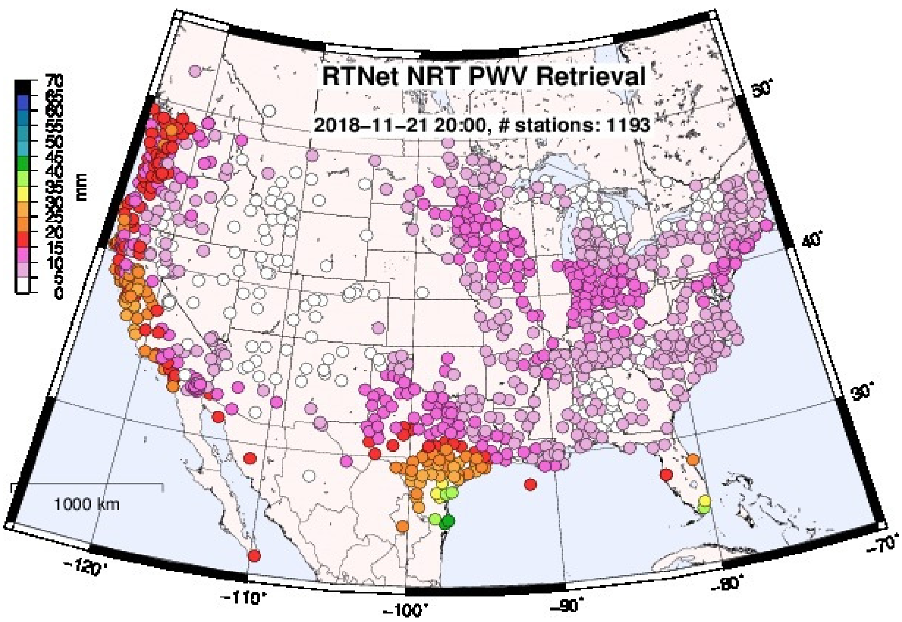

Figure 7: Values of the PWV parameter over the United States on 21/11/2018 at 20UT (https://gps-solutions.com/gnss_meteorology)

Table 1: PhD [update June 2019]

Countries	PhD [1992-2018] [with GNSS]	PhD in Progress [with GNSS]
Algeria- 2010	3	3 [2] / 1 PhD GPS => for Climate study
Benin-1990	1	
Burkina Faso-2006	9 [1] 2014	4
Cameroon-2015	1	
Cote d'Ivoire-1990	13 [1]	5 [3]
Egypt-2010	3 [1] 2015	
Spain-1990	1	
France-1990	3	
Guinea Conakry-2016		1
India-2007	1	
Nigeria-1990		1
Malaysia-2018	1	
Morocco-2013	1 [1] 2016	4 [3]
Nepal-2018		2 [2]
RC-2009	1	1 [1]
DRC-2011	4	5 [1] / 1 PhD GPS=>plate tectonics motions
Senegal-1990	2	
Tunisia-2017	1	
Vietnam-2006	6 [1] 2014	2 [1]
total	48 [5] 5 PhD on ionospheric studies	31 [13]

In dense regional networks, some organizations present ZTD deadlines in the form of cards. This is the case of the IGN in France, where Figure 6 shows the differences between the time obtained and the application of the Saastamoinen model with standard values (T = 15 °, P = 1015.25hPa, Humidity = 50%) as recommended by the European program E_GVAP. In this case, the differences are less than 15 cm and are mainly due to the wet contribution. This map of ZTD is from the website: http://rgp.ign.fr/PRODUITS/tropo.php

What is of interest to meteorologists is the integrated amount of water vapor rated IWV (Integrated Water Vapor) which is expressed in kg / m2 or the 'Precipitable Water Vapor' (PWV) which is the IWV quantity divided by the density of the water. 'water.

IWV is linearly related to ZWD with a proportionality coefficient estimated using empirical laws.

The PWV quantity is nowadays estimated in real time with dense networks and a network infrastructure allowing quick archiving of measurements. This product is operational above the United States as shown in the mapping of Figure 7 for 21/11/2018 at 20 UTC (Figure captured at 21:05).

These are the values of the IWV can be integrated into the weather forecast. This assimilation of data is the subject of many scientific studies because many parameters are estimated and subject to evolution while meteorologists are looking for mesoscale structures of water vapor that escape the current survey techniques.

Numerous PhD have been put forward on the impact of delay modeling on localization precision and using the dense network tomography method: Flores (1999) in Spain, Kleijer (2004) in the Netherlands, Braun (2004) in the United States, Champollion (2005) in France, Antonini (2013) in Italy, Qian (2016) in Germany, Atta (2016) in Ghana

3. Evolution of studies in GIRGEA due to the use of GNSS

As part of the international scientific projects IEEY, IHY, and ISWI, the GIRGEA (Groupe International de Recherche en Géophysique Europe Afrique: www.girgea.org/ IRGGEA: International Research Group of Geophysics Europa Africa) research network has been created. The work methods of this sharing-based network have been described previously (Amory-Mazaudier, 2012). In this paper we will present the evolution, during the last decade, of the studies made in this research network mainly due to the use of GNSS.

Table 1 gives the status of the PhD supported since 1992 (studies having started in 1990). The first column gives the country and the year for which the country started to work in the GIRGEA network. The second column gives the number of supported PhD (in black) and those who used the GPS data (in red) with the year of defense of these PhD. In 28 years of study 46 PhD were supported in 16 different countries. Of these 48 PhD, 5 of them have used GPS receivers from 1992 until today. Since 2015, 31 PhD are in progress 43% of them use GPS data. It is important to note that for each country, the GIRGEA network tries to answer to the needs of the country and thus our fields of research have extended to many disciplines: Sun Earth Relations, Space Weather, Geomagnetism, Study of the Ionosphere and Atmosphere, Seismicity, Atmospheric Electricity, Climate, Computer Science etc. In this context, GNSS-based techniques allow covering many scientific fields.

Table 2: Research topics of the various PhD supported

Topic	Number of PhD
Ionosphere studies with GPS	5
Ionosphere studies with Ionosonde, radar HF or SID	17
Earth's magnetic field regular Sq and disturbances	12
Earth's magnetic field GIC / Telluric electric field	3
Cosmic muons	1
Lightening/Atmosphere	1
Dynamic of mass in the Congo Basin/hydrology	1
Model of seismic activity Electromagnetic signal post seism	3
MSTID/ Satellite Demeter	1
Irradiation photo pile Effect of Energetic particle on space craft	2
Monsoon/Climate	1
Information System	1

In GIRGEA there are also countries in which there are only professors who have supervised PhD, this is the case for Argentine, Gabon, Reunion Island and USA. The 48 PhD supported correspond to 46 students, as 2 students supported 2 PhD. Of these 46 students, 44 had a position in their country. Two students have left their country for personal family reasons. PhD were mostly supported in the country of the student (43 out of 48).

Different languages are used by students to defend their PhD: Spanish/1, Vietnamese/2, English/4 and French /41.

Table 2 gives the areas of research for the 48 PhD already supported. The majority of these PhD, 17 out of 48, concern the study of the ionosphere using ionosonde. 12 PhD are related to studies of the Earth's magnetic field. The 48 PhD were based on articles published in international scientific journals with peer review. Theses work has been presented in two review papers, Amory-Mazaudier et al., 2005 and Amory-Mazaudier et al., 2017.

The first GIRGEA School was held in Abidjan from 16 to 28 October 1995. The group photo of this school is on Figure 8. This school brought together participants from Benin, Burkina Faso, France, Ivory Coast, Nigeria and Senegal. Since 2009, other schools have been organized in different African countries of the GIRGEA network, the reports of these schools are on the website www.girgea.org. To conclude, it is important to point out that the 2 PhD starting in Nepal have been initiated through the international cooperation developed under the ICG programmed on GNSS application.

Figure 8: First school of GIRGEA/Abidjan 1995

4. CRASTE-LF / Master in GNSS

The CRASTE-LF http://crastelf.org.ma, [Centre Regional Africain des Sciences et Technologie de l'Espace en langue Francaise / African Centre for Space Science and Technology in French Language] was established in Morocco on 23 October 1998 under the initiative of the UNOOSA /UN General Assembly Resolution - 45/72 of 11 November 1990 and - 50/27 of 6 December 1995.

13 Member States adhered to the CRASTE from its creation: Algeria – Cameroon - Cape Verde - Central African Republic - DR Congo - **Côte d'Ivoire** - Gabon Morocco – Mauritania – Niger - **Senegal** – Togo – Tunisia.

The objectives of the Centre are:

*To **increase knowledge** in Space Sciences and Technologies by organizing Postgraduate and/or Short courses, Seminars, Workshops, Conferences at a regional level.

*To improve the technical **competences** of the **experts, teachers, decision-makers** and to hold them informed about technical progress and to hold them informed about technical progress.

*To **assist** the countries of the region on the development of endogens capacities in space tools.

*To **Strengthen** the Local and Regional Capacities.

*To promote **Cooperation** between the **Developed Countries and States Members** as well as among **these States**.

*To develop **expertise** in Space Sciences and Technology.

***Provide advisory services to Member States** and regional institutions that have made the request.

* **Collect and disseminate information** related to space and space technologies

In 2012, the CRASTE-LF created a Master in GNSS. From 2016, the Master is accredited in partnership with the Institut Agronomique et Veterinaire (IAV) Hassan II. All the courses of CRASTE-LF since 2000 are given in table 3 as well as the number of sessions and the trainees and table 4 shows the number of participants in the GNSS training from 2013.

Table 3: Number of sessions and trainees since 2000

Course	sessions	trainees
Remote sensing & GIS	14	257
Satellite Meteorology & Global Climate	6	62
Satellite Communications	3	38
Space Science and Atmospheric	0	0
GNSS (since 2013)	4	53
Space Law	0	0

Table 4: Number of participants to the GNSS master since 2013

Year	2013	2016	2017	2018	All years
All	32	17	37	42	128
GNSS	12	17	12	12	53

The 53 participants in the GNSS master programs are from Algeria: 2, Cameroon: 6, Central African Republic: 5, Côte d'Ivoire: 1, Morocco: 25, Niger: 4, Senegal: 4, Togo: 1, Tunisia: 5.

In addition, CRASTE-LF organized between 2010 and 2018 sixty-six (66) regional activities in space technologies (short courses, seminars, workshops and conferences) in several African French-Speaking Countries, benefiting 2593 participants from 43 countries. 12 of these activities were carried out in the field of GNSS, took place in 5 African countries (Burkina Faso, Cote d'Ivoire, Morocco, Senegal and Togo).

Thus, at the margin of the current progress experienced by space technologies and their major contribution to societal benefits, CRASTE LF-as all Regional Centre for Space Science and Technology Education- in French Language, affiliated to UN, takes a considerable effort at the capacity-building in the field of space technologies, including GNSS (Emran, 2018).

Figure 9: 8th session of CRASTE-LF Governing Board Meeting, 8 June 2018

5. International Committee on Global Navigation Satellite Systems and its activities

The International Committee on Global Navigation Satellites Systems (ICG) was established in 2005 under the umbrella of the United Nations and has conducted annual meetings since its establishment to review and discuss developments in GNSS. In 2007, a Providers' Forum was established within ICG to discuss issues of compatibility and interoperability among systems. Participation in ICG is open to all countries and entities that are either GNSS providers or users of GNSS services and are interested and willing to actively engage in ICG activities.

To date, ICG has played its role as an important platform for international cooperation and coordination in achieving compatibility and interoperability among GNSS providers (United Nations Document, ST/SPACE/75, 2018), and it greatly contributes to the overall aim of achieving efficient interaction in one of the most important fields of space applications. Of particular note have been the productive discussions in ICG, in which providers of space and ground-based navigation systems work together to address their differences (United Nations Document, ST/SPACE/55, 2011), including protection of the GNSS spectrum, addressing orbital debris and orbit de-confliction. Meanwhile, the leadership of the United Nations Office for Outer Space Affairs (UNOOSA) has contributed significantly to the organization of and planning for the meetings of ICG and the activities undertaken in its capacity as Executive Secretariat of ICG.

For developing countries, GNSS applications offer a cost-effective way of pursuing sustainable economic growth while protecting the environment (Gadimova, 2010). Satellite navigation and positioning data are now used in a wide range of areas that include mapping and surveying, monitoring of the environment, precision agriculture and natural resources management, disaster warning and emergency response, aviation, maritime and land transportation and research areas such as climate change and ionospheric studies.

Capacity building efforts in space science and technology are considered as a major focus of the activities of UNOOSA and of specific interest to ICG. Such efforts are to provide support to the regional centres for space science and technology education, affiliated to the United Nations, which also act as the ICG information centres, and work further towards fostering a more structured approach to information exchange in order to fulfil the reciprocal expectations of a network between ICG and each regional centre, and hence to connect the institutions involved or interested in GNSS applications with GNSS providers. The regional centres are located in Morocco and Nigeria for Africa, in Brazil and Mexico for Latin America and the Caribbean, and in India for Asia and the Pacific (United Nations Document, ST/SPACE/59, 2012).

To support the work of ICG and its program on GNSS applications, UNOOSA, as Executive Secretariat of ICG, is organizing regional workshops, training courses and international meetings focusing on capacity-building in the use of GNSS-related technologies in various rapidly growing fields of science and industry, as well as deploying instruments for the International Space Weather Initiative. All these activities bring together a large number of experts, including those from developing countries, to discuss and act on GNSS-related issues that are also highly relevant to ICG.

The successful completion of the work of ICG, particularly in establishing interoperability among the global systems, will allow a GNSS user to utilize one instrument to receive signals from multiple systems of satellites. This will provide additional data, particularly in urban and mountainous regions, and greater accuracy in timing or position measurements. To benefit from these achievements, GNSS users need to stay abreast of the latest developments in GNSS-related areas and build the capacity to use the GNSS signal.

As we move forward in the 21st century, governments and business in developing and industrialized countries are exploring potential growth areas for their national economies. Almost without exception, the most promising option seems to be outer space, and, in particular, satellite positioning, navigation and timing, and its potential and future almost universal applications (Haubold, 2010).

ICG will, therefore, continue to strengthen its role as a major player in the multilateral arena, given that satellite positioning becomes more and more a multinational cooperative venture. The detailed information is available at:

http://www.unoosa.org/oosa/en/ourwork/icg/icg.html

6. Conclusions

In this article we presented the use of GNSS by multiple scientists. This trans disciplinary technique can be used in many areas of Earth physics. On the other hand, it is a great tool for developing research capacities in developing countries that combines basic research and application to the daily life. We have also shown how international cooperation under the umbrella of the United Nations has been and is a powerful factor in developing research and capacity building, particularly in Africa and all over the world.

The deployment of GNSS receivers and access to free data on the web, such as data from the IGS network, allows isolated researchers who do not have local measurement instruments to carry out research. Our GIRGEA network, which began mainly with studies of the ionosphere and the Earth's magnetic field, continues growing with more and more subjects to study and the GNSS-based applications helps in the hold.

Work with United Nations centres is indispensable and fruitful. These centres can develop courses that can be followed by students from the different countries covered by them. It is difficult for small countries to develop courses on subjects using modern techniques such as from GNSS. In this context such type of centres make it possible to develop contacts between the different countries and to initiate new research.

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