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# Coordinates

Volume XX, Issue 3, March 2024

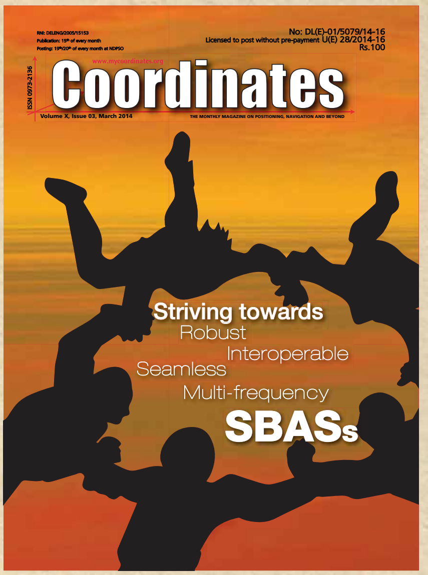
THE MONTHLY MAGAZINE ON POSITIONING, NAVIGATION AND BEYOND

## The next layer: Towards open padagogy in Geospatial education

## The dynamics of ERA5 and GNSS-Derived precipitable water vapour in the climatic zones of Nigeria

# In Coordinates

## 10 years before...




mycoordinates.org/vol-X-issue-3-March-2014

## Retrospective Gap Filling – the Easy-OBU Way

**Florian Kressler,** AustriaTech, Federal Agency for Technological Measures Ltd, Vienna, Austria
**Hannes Stratil,** Director of Engineering - R&D EFKON AG, Graz, Austria
**Jörg Pfister,** Managing Director, PWP-systems GmbH, Bad Camberg, Germany
**Roman Srp,** Executive Director, Czech and Slovak Intelligent Transport Systems and Services, Praha, Czech Republic
**Zuzana B linová,** Assistant Professor, Department of Transport Telematics, Czech Technical University in Prague, Praha, Czech Republic

In this paper, the basic concept of a system for retrospective gap filling was presented. This system is based on an on-board unit fitted out with low costs sensors. In the event of loss of satellites data from these sensors are stored in the on-board unit and, once satellite visibility is available again, transferred to a back office were these data are used to calculate the route using non-causal filtering operations.

## SBASs: Striving towards seamless satellite navigation

GAGAN has provided the capability for continuous real time monitoring and recording of GPS/ GAGAN data and is able to provide the users the advance predictability required for flight planning purposes.

**V Somasundaram**
Member Air Navigation Services (ANS), Airports Authority of India

WAAS has experienced episodes of interference at several reference station locations but due to the distributed nature of the WAAS reference stations and the data validation and integrity monitors, WAAS service availability has not been impacted.

**Deane Bunce**
The Federal Aviation Administration (FAA) Wide Area Augmentation System (WAAS) Program Manager

The current MSAS provides horizontal navigation only due to the ionosphere problem.

**Takeyasu Sakai**
Chief Researcher, Electronic Navigation Research Institute (ENRI), Japan

The K-SBAS is expected to be declared operational for open service in the year 2018

**Gi Wook Nam**
PM of K-SBAS Program, Korea Aerospace Research Institute

IWG targets the development of dual frequency multi constellation (DFMC) SBAS

**Frédéric LECAT**
Regional Officer Communication, Navigation, Surveillance, International Civil Aviation Organization (ICAO), Asia and Pacific (APAC) Office

## Geospatial data sharing in Pakistan: Possibilities and problems

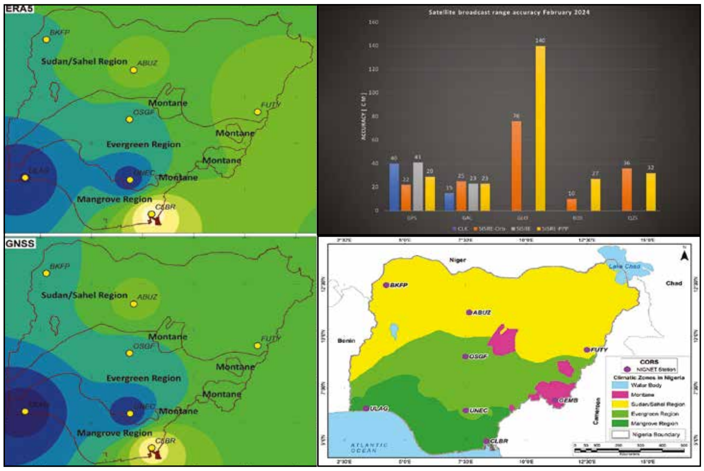
**Asmat Ali and Munir Ahmad**
Survey of Pakistan

In Pakistan, geospatial data is not being shared due to various institutional and technical problems. The findings of this study reveal that the institutional issues include; lack of data policy and legal framework, data management, lack of coordination among organizations and relatively high cost of the data itself.

## Potential use of GBAS techniques to improve SBAS signal quality monitoring

**Markus Schenk, Keerthi Narayana and Hua Su**
Thales Alenia Space Deutschland GmbH

The paper demonstrates that the advanced techniques of Signal Quality Monitoring of GBAS, with respect to antenna type used, can be applied to meet the SBAS needs. In this paper, SBAS is considered as EGNOS. The adaptations are also focussed to gain maximum benefit with low impact on the cost especially regarding extensive re-certification.




# In this issue

Coordinates Volume 20, Issue 3, March 2024

## Articles

**GNSS constellation specific monthly analysis summary: February 2024** Narayan Dhital 5
**The next layer: Towards open pedagogy in geospatial education** David Ray Abernathy 8 **The Dynamics of ERA5 and GNSS-Derived Precipitable Water Vapour in the Climatic Zones of Nigeria** Ojegbile, B.M., Okolie, C.J., Omogunloye, O.G., Abiodun, O.E. and Olaleye, J.B. 17

## Columns

**Old Coordinates** 2 **My Coordinates** Editorial 4 **News** GIS 30 GNSS 30 Imaging 31 LBS 31 UAV 32 Industry 32 **Mark Your Calendar** 34

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Abiodun, O.E., David Ray Abernathy, Narayan Dhital, Ojegbile, B.M., Okolie, C.J., Olaleye, J.B. and Omogunloye, O.G.; SBG System, and many others.

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# A(I) landmark development

The European Parliament has approved the EU AI Act on 13th March 2024.

The first of its own kind.

The Act envisions to prohibit AI with unacceptable level risks.

A few more countries are likely to follow the suit

May be with different approach and focus.

If the focus of the EU is on safe AI with

The goals of healthcare improvement and environment protection,

The USA emphasis is on standards for safety, critical infrastructure and cybersecurity.

Japan opts for a human-centricity, privacy and innovation approach,

Canada emphasises on moral values and transparency.

And a few more..

As several templates emerge,

There also emerges a need of an international regulatory body.

For the overall development and roll out of AI.

It is work in progress!

**Bal Krishna, Editor**
**bal@mycoordinates.org**

# GNSS constellation specific monthly analysis summary: February 2024

The analysis performed in this report is solely the author's work and his opinion. State Program: U.S.A (G); EU (E); China (C) "Only MEO- SECM satellites"; Russia (R); Japan (J); India (I)

**Narayan Dhital**
Actively involved to support international collaboration in GNSS-related activities. He has regularly supported and contributed to different workshops of the International Committee on GNSS (ICG), and the United Nations Office for Outer Space Affairs (UNOOSA). As a professional employee, the author is working as GNSS expert at the Galileo Control Center, DLR GfR mbH, Germany.

## Introduction

The article is a continuation of monthly performance analysis of the GNSS constellation. **(Dhital et. al, 2024a, and Dhital et. al, 2024b)** provides previous months analysis. In this month's issue, the monitoring of Galileo satellite attitude maneuver during low beta angle is the only addition.

## Analyzed Parameters for February, 2024

(**Dhital et. al, 2024**) ) provides a brief overview of the necessity and applicability of monitoring the satellite clock and orbit parameters.

a. Satellite Broadcast Accuracy, measured in terms of **Signal-In-Space Range Error (SISRE) (Montenbruck et. al, 2010).** Due to the data latency of 2 weeks for precise satellite clocks and orbits, at the time of current analysis, only 01-18 February, 2024 time frame is used.

**b. SISRE-Orbit** ( only orbit impact on the range error), SISRE (both orbit and clock impact), and **SISRE-PPP** (as seen by the users of carrier phase signals, where the ambiguities absorb the unmodelled biases related to satellite clock and orbit estimations. Satellite specific clock bias is removed) (Hauschlid et.al, 2020)

**c. Clock Discontinuity:** The jump in the satellite clock offset between two consecutive batches of data uploads from the ground mission segment. It is indicative of the quality of the satellite atomic clock and associated clock model.

**d. URA:** User Range Accuracy as an indicator of the confidence on the accuracy of satellite ephemeris. It is mostly used in the integrity computation of RAIM.

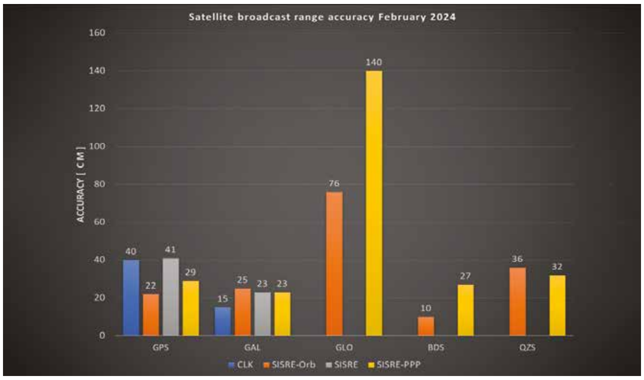
**e. GNSS-UTC offset:** It shows stability of the timekeeping of each constellation w.r.t the UTC

**f. ERPs Accuracy (xp, yp and UT1):** It shows the prediction accuracy of the linear model at 1 day interval (or the discontinuity between two batches of data) and the accuracy w.r.t precise products from IERS **(IERS et. al, 2024)**. Due to the required latency of IERS C04 products, Jan 17, 2024 to Jan 29, 2024 time frame is selected.

**g. Satellite Yaw Maneuver:** It shows the behavior of satellites that are operating under the low sun angle w.r.t the orbital plane and their yaw rate to quickly align the solar panels towards the sun direction (Liu et. al, 2022)

Note:- for India's IRNSS there are no precise satellite clocks and orbits as they broadcast only 1 frequency which does not allow the dual frequency combination required in precise clock and orbit estimation; as such, only URA and Clock Discontinuity is analyzed.

### (a), (b) Satellite Clock and Orbit Accuracy (monthly RMS values)



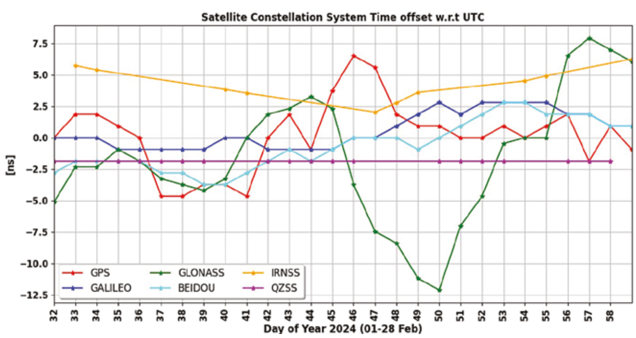

### (c) Satellite Clock Jump per Mission Segment Upload

| Const | Mean [ns] | Max [ns] | 95_ Percentile [ns] | 99_ Percentile [ns] | Remark (Best and Worst 95 %) |
|---|---|---|---|---|---|
| IRNSS | 3.46 | 144.7 | 6.37 | 24.47 | Best I03 (3.16 ns) Worst I06 (14.06 ns) |
| GPS | 15.06 | 168133.59 | 0.96 | 2.82 | Best G23 (0.45 ns) Worst G08 (9.34 ns) Larger discontinuity for G10 during 09-13 Feb; and for G08 during 25-26 Feb |
| GAL | 13.25 | 910319.96 | 0.17 | 0.38 | Best E21 (0.13 ns) Worst E03 (0.19 ns) Larger discontinuity on 09 Feb for E30 |

### (d) User Range Accuracy (Number of Occurances in Broadcast Data 01-28 Feb)

| IRNSS-SAT | 2 [m] | 2.8 [m] | 4.0 [m] | 5.7 [m] | 8 [m] | 8192 [m] | 9999.9 | Remark Other URA values (frequency) |
|---|---|---|---|---|---|---|---|---|
| I02 | 5710 | 9 | - | - | 2 | - | 6 | - |
| I03 | 849 | 1 | - | - | 1 | - | - | - |
| I06 | 1030 | 9 | - | - | 3 | - | - | - |
| I09 | 1034 | 18 | 5 | 2 | 2 | - | - | - |
| I10 | 867 | 1 | 1 | 1 | 4 | 1 | - | URAs 11.3 (1), 16 (1), 32 (2), 64 (1) and 128 (1) |

### (e) GNSS-UTC Offset




### (f): Broadcast Earth Rotation Parameters (Discontinuity and Accuracy in RMS)

Unit: xp, yp in mas. dUT1 in msec

| Quality Indicators | GPS | | | BDS | | | QZSS | | | IRNSS | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | xp | yp | dUT1 | xp | yp | dUT1 | xp | yp | dUT1 | xp | yp | dUT1 |
| Discontinuity | 1.30 | 0.57 | 0.47 | 1.15 | 0.55 | 0.11 | 0.65 | 0.43 | 0.27 | 0.89 | 0.45 | 0.11 |
| Accuracy | 4.17 | 2.05 | 0.46 | 1.69 | 0.62 | 0.09 | 0.27 | 0.26 | 0.10 | 1.02 | 0.47 | 0.08 |

Note:- Mission segment upload rates are GPS: 1 day; BDS: up to 20 days; QZSS: 1 hour & 1 day (1 day selected in the analysis); IRNSS-1 day. The analyzed period is 17-29 January, 2024.

**Remark:** The introduction to the ERPs and the broadcast navigation format are available in **(Steigenberger et. al, 2022 and IGS et.al, 2021)**. Regarding the performance obtained by analyzing the 13 days of data, it can be observed that the accuracy of GNSS broadcast ERPs does not have drastic differences among the constellation and remain consistent to the results reported in January **(Dhital et. al, 2024b)**. A special mention is needed for GPS accuracy due to its reference epoch in broadcast data not matching the IERS C04 (00 h UTC) reference epoch. As the IERS reference epoch is propagated with a simpler linear model, without accounting for semidiurnal tidal effects, and whereas the GPS ICD specifies the consideration of such variations, the direct comparison with GPS data will have a bias. **(Steigenberger et. al, 2022)** shows such bias could be in the range of 1 mas for polar coordinates and upto 0.5 msec for dUT1. When the bias is subtracted from the accuracy for GPS, the values will be at least similar, if not better, to other constellations (QZSS and IRNSS). The only interesting difference in this analysis is a relatively larger values for GPS in comparison to what was observed in **(Dhital et. al, 2024b)**. The relatively lower accuracy and higher discontinuities of BDS are attributed to the lower update rate of the ERP prediction model from the mission segment. It is observed that the update period ranges up to 7 days or even more in some cases. The overall performance looks similar to the results provided in the literature **(Liu M et. al, 2023; Liu W et. al, 2023)**.

Note:- ERPs are introduced only in RINEX version 4. Galileo and GLONASS do not provide ERPs in the broadcast messages.

### (g): GNSS satellite nominal and non-nominal yaw attitude (GPS and Galileo)

The basic introduction to the orientation of GNSS satellites is provided in **(Dhital et. al, 2024b)**. It also covers the relation between the Sun elevation angle (beta angle) and the nominal yaw angle of the satellite.

In February, there were no GPS satellites under the low beta angle ( > -1° and < 1°). However, there were Galileo satellites from orbital plane C with lower beta angle and hence, undergoing noon and midnight turn maneuver.

**E03, E04, E05, E07, E08, E09, and E19** from 01 Feb until 07 Feb had beta angle > -4° and < 4° and from 02 to 04 Feb > -1° and < 1°.

As presented in different literature **(Cao et. al, 2018; Liu et.al, 2022, Sylvain et. al, 2021)**, the yaw rate of the Galileo satellites depends on the satellite type and the beta angle. The nominal yaw rate is close to 0.01°/sec and during the orbit noon and midnight maneuver, the rate increases to 0.07°/sec depending on the beta angle. The lower the beta angle higher the yaw rate. To monitor the yaw rate of the identified satellites undergoing the midnight and noon maneuver, two cases are monitored. In the first case, a day is selected with beta angle below 1°. In the second case, a day is selected with beta angle above 4° but below 6°. Galileo E05 satellite is examined for both cases and is shown in Figure (g). The yaw rate is close to 0.07°/sec on the 3rd of Feb where the beta angle is below 1°. Similarly, the yaw rate reduces below 0.03°/sec when the beta angle began to go above 4°.

### Monthly Performance Remarks:

1. Satellite Clock and Orbit Accuracy

- For GPS, the satellite clock and orbit accuracy shows consistent performance in comparison to January 2024 (Dhital et. al, 2024b). There were multiple satellites (G02, G08, G10 and G27) in maneuvers and non-healthy status. As a result, large satellite clock discontinuities and orbit degradation were observed. G27 became usable again for the first time since the 30th December 2023.
- For Galileo, a large satellite clock discontinuity was observed for E30 on the 9th of February. Other parameters showed consistent performances in comparison to January.
- For GLONASS, no large clock offsets were detected unlike in January. The performance looked only marginally better in February.
- For BDS and QZSS, the performance looks very much the same as in December 2023. For QZSS, there are days with better orbit quality and some days with degraded performance. A 24 hours periodic degradation is seen for J03 from 08 to 10 Feb.
- For IRNSS, the overall constellation clock discontinuity and the URA statistics look similar to the performance in January. I10 consistently broadcast a few epochs with varying confidences in the ephemerides.

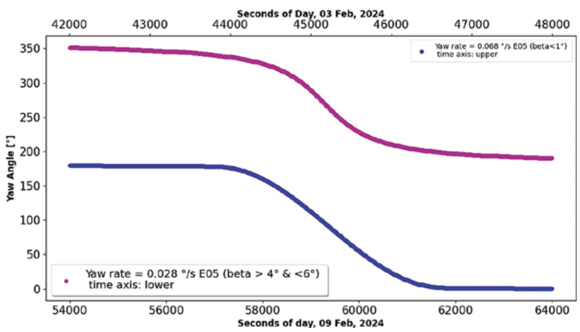


Fig: (g)

2. UTC Prediction (GNSS-UTC):

Among the GNSS, Galileo and GLONASS showed more variations in comparison to January 2024. That being said, the GAL-UTC prediction is still kept within 3 ns.

## References


Cao X, Zhang S, Kuang K, Liu T (2018) The impact of eclipsing GNSS satellites on the precise point positioning, Remote Sensing 10(1):94

Dhital N (2024a) GNSS constellation specific monthly analysis summary, Coordinates, Vol XX, Issue 1 pages 20-22

Dhital N (2024b) GNSS constellation specific monthly analysis summary, Coordinates, Vol XX, Issue 2 pages 9-12

Hauschlid A, Montenbruck O (2020) Precise real-time navigation of LEO satellites using GNSS broadcast ephemerides, ION

IERS C04 (2024) https://hpiers.obspm.fr/iers/eop/eopc04/eopc04.1962-now

IGS (2021) RINEX Version 4.00 https://files.igs.org/pub/data/format/rinex_4.00.pdf

Li M, Wang Y, Li W (2023) performance evaluation of real-time orbit determination for LUTAN-01B satellite using broadcast earth orientation parameters and multi-GNSS combination, GPS Solutions, Vol 28, article number 52

Li W, Chen G (2023) Evaluation of GPS and BDS-3 broadcast earth rotation parameters: a contribution to the ephemeris rotation error Montenbruck O, Steigenberger P, Hauschlid A (2014) Broadcast versus precise ephemerides: a multi-GNSS perspective, GPS Solutions

Liu T, Chen H, Jiang Weiping (2022) Assessing the exchanging satellite attitude quaternions from CNES/CLS and their application in the deep eclipse season, GPS Solutions 26(1)

Montenbruck O, Steigenberger P, Hauschlid A (2014) Broadcast versus precise ephemerides: a multi-GNSS perspective, GPS Solutions

Steigenberger P, Montenbruck O, Bradke M, Ramatschi M (2022) Evaluation of earth rotation parameters from modernized GNSS navigation messages, GPS Solutions 26(2)

Sylvain L, Banville S, Geng J, Strasser S (2021) Exchanging satellite attitude quaternions for improved GNSS data processing consistency, Vol 68, Issue 6, pages 2441-2452


## Data sources:

https://cddis.nasa.gov (Daily BRDC); http://ftp.aiub.unibe.ch/CODE_MGEX/CODE/ (Precise Products); BKG “SSRC00BKG” stream; IERS C04 ERP files

(The monitoring is based on following signals- GPS: LNAV, GAL: FNAV, BDS: CNAV-1, QZSS:LNAV IRNSS:LNAV GLO:LNAV (FDMA))

# The next layer: Towards open pedagogy in geospatial education

This article documents one such transition in an undergraduate course on GIS, arguing that OP is the logical next step for enhancing creativity and innovation in GIS education

**David Ray Abernathy**
Department of Global Studies, Warren Wilson College, Asheville, North Carolina, USA

## Abstract

Open-source software and open data are becoming increasingly popular in the teaching and learning of geographic information science. The cost savings that are derived from using free software over proprietary software are one driving factor, yet the move from "closed" to "open" represents much more than financial austerity it signifies a broader shift in educational philosophy. This article documents the gradual transition of an introductory undergraduate course in geographic information systems from an entirely closed course to one that has become increasingly open. Having completely adopted the first three layers of open software, data, and educational resources the course is now turning toward the next layer: embracing the philosophy of open pedagogy.

## Introduction

Over the past two decades, there has been an increasing propensity for openness and sharing among those responsible for the creation and management of geospatial data. Not coincidentally, there have also been parallel trends in related avenues of open, including open-source software, open science, and open educational resources (OERs). This collective movement toward openness has been a boon to geospatial education, as the tools, data, and educational materials necessary for teaching and learning GIS have become much more democratized, accessible, and affordable. Students and educators today do not have to be bound by expensive software licenses, proprietary data, or the limited perspective of an individual textbook.

In addition to making geospatial education more accessible and affordable, these recent trends in openness have laid a solid foundation for rethinking not only what we teach but also *how* and *why* we go about teaching and learning geospatial science. Building on this foundation, we are beginning to see the next "layer" of openness: open pedagogy (OP). Open-source tools, open data, and OERs can certainly enhance the traditional lab assignment, research paper, syllabus, and weekly course structure, but they also allow us to rethink what those traditional syllabi and assignments could and should look like. How can this burgeoning toolkit of openness give us an opportunity to teach and learn in important new ways?

This article documents the steady transition of an introductory undergraduate course in geographic information systems from an entirely "closed" course to one that has become increasingly open. Having completely adopted the first three layers of open software, data, and educational resources the course is now turning toward embracing the philosophy of OP. As such, the course structure, assignments, and learning outcomes are all being re-examined as the benefits and challenges of moving away from a surveillance model of education to a more participatory and collaborative one are investigated.

The main objective of this article is to build upon the large and growing literature on open GIS (Coetzee et al., 2020; Osaci-Costache et al., 2017; Sui, 2014) by integrating the emerging research on the value of OP (Hegarty, 2015; Tietjen & Asino, 2021). As the benefits of transitioning to "all things open" (https://www.allthings open.

org/; McKiernan et al., 2016) are made increasingly clear, incorporating OP into GIS education becomes imperative. This article documents one such transition in an undergraduate course on GIS, arguing that OP is the logical next step for enhancing creativity and innovation in GIS education.

## Anatomy of a "closed" course

I began teaching an introductory GIS course at a small liberal arts college in 2003, modeling the course after ones I had taken in my graduate studies: obtain proprietary GIS software, assign a textbook that included a CD of tutorial data, create lab assignments with the tutorial data, write quizzes and a midterm exam, and assign a final mapping project. Since my institution is one of a handful of work colleges in the country, meaning that all students worked from 8 to 20 h a week on campus, I was also able to establish a student GIS work crew. The crew was responsible for keeping the GIS lab open, reporting any problems with hardware and software, and serving as informal teaching assistants for the students needing additional help on assignments.

Most of the students in the class dutifully completed their assignments, and some became enthusiastic enough about GIS to want to apply it to other projects. But after a couple of years, I noticed that the students who were the most excited about GIS, and the ones who were actually getting jobs in GIS after graduation, were the students on the work crew. A couple of the student crew members had not even taken the introductory course, yet they still displayed a desire to learn and saw the potential for applying geographic information science in their own academic work.

The lab itself consisted of 16 desktop computers, an instructor computer, and a shared storage drive. These machines themselves were "closed," as students could not alter the operating system or any of the installed software— they could only work on projects that were then saved to the shared drive. This setup was helpful in keeping the lab in good working order but was certainly detrimental to student learning and frustrating for the student crew. In 2005, we received a small grant that allowed us to install a separate workstation for crew use. This workstation was set up as a dual-boot computer so that students could have access to both Windows and Linux operating systems, and they could tinker to their hearts' content. The proprietary GIS software we used in class could not be installed on Linux, but before long one of the crew members had begun installing open-source software to see if he could perform some basic GIS operations. We even began to explore the idea of "GIS on a stick," since it was becoming possible to install an entire operating system and necessary software on a small USB drive (e.g., see https://live.osgeo.org).

Seeing the enthusiasm with which my student crew went about tinkering with open source, and noting that there was a growing community of open-source geospatial software developers, I began to consider the possibility of teaching an introductory GIS course with open-source software. Little did I know that what I considered to be merely a shift from costly to free software would lead to a reconsideration of my entire pedagogical approach to GIS education.

## Transitioning to open-source software

In 2002, Gary Sherman began developing Quantum GIS, a free and open-source GIS software platform that was officially released as version 1.0 in 2009. Licensed under the GNU General Public License version 2 (https://gnu.org/licen ses/old-licenses/gpl-2.0.en.html) and eventually renamed as simply QGIS (https://qgis. org/en/docs/index.html), the software began to attract users due to its user-friendly interface and its extensibility. Users were free to use, modify, share, and study the software code, and over the next few years, the software's features expanded considerably. With the release of version 2.0 in 2013, the popularity of QGIS began to grow, and over the next few years, it was available for multiple operating systems. Importantly, the software also began to include software plugins and interfaces with other geospatial toolkits such as the Geographic Resources Analysis Support System (GRASS, https://grass.osgeo.org) and the System for Automated Geoscientific Analyses (SAGA, https://saga gis.sourceforge.io/en/index.html), both of which are also open source and freely available.

It was the integration of an interface with GRASS tools that made QGIS a viable alternative to the proprietary software being used in my undergraduate GIS course at the time. The course is primarily populated with students in the natural sciences, and, therefore, raster analysis is quite common; having access to a robust set of raster tools in GRASS made it possible to replicate my existing lab assignments that previously required access to an expensive software extension. As such, in 2015 I made the decision to test the waters by offering a course entirely focused on free and open-source software.

At the time, the GIS software in use at my institution was limited to 25 "seat licenses," meaning that no more than 25 copies of the software could be running simultaneously on campus. Furthermore, most of these licenses were to be restricted to one computing laboratory. This meant that students could only work on projects when the lab was open and available, which did not include nights and weekends. Limiting access to desktop computers in a single lab significantly inhibited the amount of work that could be assigned to students, and, therefore, limited students' opportunities to learn. Transitioning to open-source software not only eliminated the expense of purchasing software and paying annual maintenance fees, it provided the flexibility and freedoms that Richard Stallman insists are a "moral duty" of educational institutions (Stallman, n.d.). The benefits of the move to QGIS at my institution can be summarized by what I refer to as the "five E's," which are briefly described below.

## Expense

This is considered as the "low-hanging fruit" in terms of justifying a transition to open-source GIS software, as institutions are always looking for ways to reduce expenses without unduly harming their underlying educational mission. Given that open-source software had matured enough by 2015 that the introductory course learning objectives could be met just as easily as with proprietary software, the reduction in annual expenses was met with enthusiasm by the administration.

## Ethos

Students apply to my institution because they are excited to become collaborative members of a work college community. They understand that in addition to academics, they are expected to work each week as part of a work crew and also participate in community engagement activities. In addition, the campus has a working farm and garden, a blacksmith shop, a fine woodworking shop, and a 650-acre working forest. Most of the students consider themselves "makers" of sorts, preferring to create and produce resources rather than simply rely on store-bought consumer products. Open-source software meshes well with this ethos, as students prefer working with a set of tools developed by a community rather than produced by members of a corporate hierarchy. Many of our students are studying the natural sciences, where the scientific method is the norm; they understand, then, the argument that reproducible science requires that you be able to look at the software code being used in scientific research (Ince et al., 2012).

## Extensible

Students not only appreciate being able to "look under the hood" of the software they use, but they also recognize the power of extensibility. If the software being used does not have a tool readily available to take on a particular task, there is a good chance that some sort of extension or plugin exists that can be downloaded and added to the program. In the event that the plugin does not exist, a student with the desire to create it can learn the skills necessary to do so. There are currently more than 150 plugins available for download on the QGIS repository, and more features in the core software are being added with each new version release. In addition, not being wed to one particular suite of expensive software means that students can search for solutions across multiple software tools. Many of our students often turn to the R statistical programming language, for example, which at the time of this writing has almost 20,000 available packages that can be downloaded and added to the core program.

## Expandable

Not only does open-source geospatial software offer opportunities for extending its functionality through additional plugins and packages, but it also makes possible the expansion of the spaces and time in which the software can be used. No longer confined to the limited number of machines in the limited capacity of a single laboratory, open-source software allows for a much wider distribution of the necessary tools across and beyond campus. Once our course shifted to open-source GIS, we were able to add the software to computers in the library and students were able to download and install it on their own computers. This had a much greater impact than we originally thought suddenly we found that students were working on projects in the library, in the cafeteria, and late at night in their dorm rooms. This increased accessibility made it possible to assign more complex projects that required time outside of class and lab hours, and the students readily embraced this work. While there was also some added complexity as students grappled with installing and troubleshooting software on their own operating systems, this seemed like an important educational component as well. Students were not walking into a lab that had been set up for a generic learning environment; rather, they were learning to get the tools they needed up and running on their own computers. And of course, when the class abruptly shifted online amid the COVID-19 pandemic, having access to the software on individual student computers became essential.

## Employment

Many students end up enrolling in a GIS class because they view it as providing them with an employable skill set. Many of the organizations listing entryl evel positions use a popular proprietary suite of software. Yet learning how to work with open-source tools should not be viewed as an inferior alternative to learning the proprietary software instead, it can be argued that learning to apply open-source software to tackle geographic information science provides a more robust introduction to the field. Indeed, one of our students was hired by the City of Asheville after he graduated precisely because of his experience with open-source tools. The manager of business and public technology with the city at that time made it known that his office preferred hiring people with open-source software experience, as they often seemed to have a better knack for solving problems. Similarly, several of the students who learned the fundamentals of geographic information science using open-source software in class went on to participate in the NASA Develop program, which frequently makes use of proprietary GIS software. These students were able to successfully complete their work, as the concepts and skills they learned were applicable across different GIS platforms.

Taken together, these "five E's" demonstrate the value in emphasizing the use of free and open-source software in education. All the concepts and skills typically covered in an introductory GIS class visualizing vector and raster data, geoprocessing, SQL, map algebra, composing map layouts, batch processing and more can be just as easily applied with open-source software as they can with proprietary tools. Perhaps more easily, since access to the software was significantly enhanced by not being limited to a single laboratory environment. While the producers of proprietary geospatial software have made efforts to incorporate open-source tools in their suites of software applications (Cheraghi, 2018), the emergence of fully open geospatial software tools has revolutionized GIS education and paved the way for the application of open-source principles to other important aspects of higher education.

## Open and affordable educational resources

The many benefits of open-source software outlined above can also be found in the adoption of OERs. While there is no shortage of GIS textbooks on the market, these tend to be expensive and often bundled with (unnecessary, as we will see below) tutorial data. Furthermore, these textbooks can be viewed by students as too much like a cookbook for a specific software program (point-and-click guides to GIS operations), or as too theoretical and not a practical resource for hands-on learning. Therefore, switching from costly, copyrighted textbooks to OER is a logical next step after adopting open-source software for GIS education.

OERs, as defined by UNESCO, are "learning, teaching and research materials in any format and medium that reside in the public domain or are under copyright that have been released under an open license, that permits no-cost access, re-use, re-purpose, adaptation and redistribution by others" (http://unesco.org/en/communication-information/open-solutions/open-educational-resourses). Many OERs are licensed under the Creative Commons system of copyright, which can be considered analogous to the GNU General Public license used for open-source software. This means that, unlike with the standard published textbook, OER users are free to make copies, adjust the resources for their needs, and combine the content with other resources. Instead of the "five E's" described above, OER can be explained through the "five R's": retain, reuse, revise, remix, and redistribute (Wiley & Hilton III, 2018).

Similar to the transition from proprietary software to open source, the most immediate benefit of a transition from traditional textbooks to OER is financial. Several studies have found that textbook price increases have steadily outpaced the rate of inflation for decades (Pollitz & Christie, 2006; see also Everard & St Pierre, 2014). In rapidly changing fields like geographic information science, used textbooks are typically not a viable option and often have little resale value. As a result, students often avoid purchasing an assigned textbook or have to work extra hours to be able to afford it (Hanson, 2021). The financial benefit to OER can be seen as a social justice issue, as it helps create more equitable access to education.

When my introductory GIS course focused primarily on proprietary software, I tried different textbooks each year as I struggled to find one that I thought was the most useful without being exorbitantly expensive.

Nevertheless, students complained about the cost and several avoided purchasing it. Those who did purchase it often had the complaints mentioned above: one book felt like a recipe book that led to students mindlessly following along with the exercises, while another felt too theoretical and did not offer much in the way of practical exercises to help students learn. Ultimately, I was not satisfied with any of the textbooks and decided to make the switch to OER.

Most college or university libraries will have at least one librarian who is well versed in OER, and there are many online resources available for accessing quality resources. The MERLOT (https://merlot.org) repository contains thousands of curated resources, as does the Openly Available Sources Integrated Search (OASIS, https://oasis. genes eo.edu). Openstax (https://opens tax.org) and the Open Textbook Library (https://open.umn.edu/opent extbooks) are two additional popular repositories for textbooks, while OER Commons (https://oerco mmons.org) includes access to other materials such as labs, datasets, and case studies.

In addition to these resources, many individual schools, school systems, and states are forming online resources and networking opportunities for faculty to learn more about OER. In my state, for example, NC Live (https://nclive.org) has formed Open Education North Carolina, and the Appalachian College Association started Open Appalachia (https://www.acaweb.org/collaborations/oar) to promote OER adoption across its member schools.

For my introductory GIS course, I opted to use a GIS textbook from the Open Textbook Library (Campbell & Shin, 2011). While not containing practical lab assignments, I felt the text did a good job of covering many of the necessary concepts needed in the early weeks of the course. Because I was not forcing students to pay an exorbitant price for the book, I did not feel required to teach every chapter. Instead, I could pick and choose the chapters that worked best for my particular course and could assign them in an order I saw fit. I designed the lab assignments for the course, but there are plenty of tutorials online that could also be incorporated into a course to supplement labs and exercises (Gandhi, n.d., see also https://qgis.org).

Another benefit of using OER is that you are not limited to a single textbook. If another resource has a single chapter or a handful of chapters that suit the needs of a particular course, it can easily be assigned in addition to the primary text. A chapter from one book can be assigned for 1 week, chapters from another for the next week, and creative commons licensed articles and YouTube videos for the next week. This is one example of the benefit of "remixing" from the "five Rs" described earlier, and demonstrates the benefits of OER for allowing for a more diverse collection of voices in the course materials.

## Open data

One concern that GIS educators may have when switching to OERs is that an OER text may not have an accompanying website, lab materials, and/or tutorial data. This may be of particular concern for instructors and students in an introductory GIS course, where basic, cleaned datasets are valuable for use in the early weeks as students first begin to learn the fundamentals. For those who have been teaching and working in GIS for decades, the memories of how hard (and often expensive) geospatial data was to create and obtain are quite vivid.

In the last decade or so, however, this has begun to change. Data, in parallel with open-source software and OER, have increasingly become open and accessible. Data locked behind paywalls and buried in PDFs can now be easily obtained through data portals and dashboards. The petabytes of data being collected by NASA's Earth Observing System's fleet of satellites are available to anyone without restriction.

As someone who has taught GIS for 20 years, I have witnessed this transition from closed to increasingly open data– and have seen how it has transformed teaching and research. For example, around 2005 I had a student hired to work on a funded grant project in which the goal was to create a single cadastral map for approximately 40 counties in Western North Carolina. The student contacted individual county governments and requested polygon vector data files for property boundaries if available. The responses varied tremendously. While some counties were more than happy to share, this sharing often took the form of compact discs or another storage medium, which the student then had to travel to retrieve or pay to be shipped. Other counties were more reticent, offering the data for a substantial fee or not offering it at all. One county only had centroid data available. In all, the project took the student several months and a not insignificant portion of the grant budget to complete.

A few years later, the US Environmental Protection Agency awarded a grant to the North Carolina Department of Environment and Natural Resources to begin building the "Integrated Cadastral Data Exchange" (https://www.ncone map.gov/pages/ parcels). At this same time, a statewide data portal for North Carolina, NC OneMap (https://ncone map.gov), was created to serve as a statewide geospatial data repository. Among many other datasets, NC OneMap provides access to a seamless parcel layer for all of North Carolina (https://www.ncone map.giv/pages/ parcels). In short, what took a student several months in the early 2000s now takes a student mere minutes.

This is but one example of the benefits of open data. It underscores the rationale of organizations like Code for America, a nonprofit organization whose vision is that "government can work for the people, by the people, in the digital age" (https://codef orame rica.org/about us/ vision-and-values/). As governments and nonprofits increasingly began to see the value in open data, portals and repositories began springing up in dozens of cities, states, and at the federal level. My students, for example, now have access to data at the municipal and county level (via the Asheville Open Data Portal, https://data-avl.opend ata.arcgis.com/), state level (http://ncone map. gov) and federal level (https://data.gov). The open data movement has unquestionably ushered in an unprecedented amount of available data to anyone—i ncluding students in their first GIS class.

Another benefit of open data in GIS education, in addition to it being freely available and untethered from an expensive textbook, is that it gives students useful skills in identifying and downloading useful datasets. In my introductory GIS course, I provide students with a handful of basic vector layers to get them started, but by the second week of the course, I have students searching open data portals for their own spatial data. This typically leads to an interesting discussion as students run into various hurdles (e.g., "I only wanted the streets for my hometown but had to download the whole county," or "I found two layers for my state but they don't overlap") that can then be used as lessons later in class (in these two cases, how to filter data to a desired geographic extent, and how to work with data in different projections). It can even be a gentle (or sometimes not so gentle) introduction to data cleaning, depending on the datasets uncovered by the students.

Some may feel that having students download geospatial data instead of relying on ready made textbook data so early on in a GIS course might lead to frustration and inhibit students' desire to learn. I would argue the opposite: that showing students the diversity of data out there sparks their imaginations and gets them doing the important work of asking spatial questions. It also prepares students to be problem solvers rather than recipe followers. Having students face common issues such as differing projections or the need for data cleaning during the second week of an introductory course sets them up to anticipate problems and to consider the possible solutions. It also sets them up to want to experiment, even if they fail at first, rather than to just simply follow directions from a textbook. This is an important first step in having students understand that they are not expected to simply "consume" knowledge but also to co-create it and to contribute to the learning of others. It is, in other words, a gateway to applying the principles of OP to GIS education.

## The next layer: toward open pedagogy

Using the common metaphor of "layers" used in GIS to describe multiple datasets in the same geographic extent, we can consider the approaches to openness described above (open-source software, OERs, and open data) to be layers that build on one another in GIS education. Open-source software provides the "basemap" for open GIS education, as it democratizes access to geospatial software and makes it freely and easily available to anyone who wishes to use it. OERs make up the next layer, as they similarly provide anyone access to materials that may have previously only been available behind an expensive paywall or through the purchase of a copyrighted textbook. The third layer, open data, opens up the possibilities for asking spatial questions by making an incredible diversity of data freely and easily available for anyone with internet access. These layers most certainly overlap, as questions about cost, ownership, equality, accessibility, and knowledge acquisition are embedded in each. Taken together, these layers build a solid foundation for adding the next layer: OP.

What exactly "OP" means is still being debated, and no set definition has been agreed upon. There are, however, some common elements across multiple definitions, as described by Tietjen and Asino (2021) in their research seeking commonalities across these multiple definitions. They developed a "five-circle framework" to identify the key components of OP, including (1) OP welcomes diverse learners as design partners, (2) OP is a participatory pedagogy, (3) open licenses are essential to foster practices such as remixing, (4) OP encourages all learners, inside and outside the school setting, to contribute to building a knowledge community, and (5) OP fosters a culture of collaboration through sharing and editing (Tietjen & Asino, 2021).

The idea of OP builds off of other pedagogical approaches to learning that encourage the movement away from the standard classroom structure of active instructors and passive students. Sometimes referred to as "student-centered" pedagogy, "experiential learning," "active learning," and other expressions of what we might include within the larger umbrella of "inquiry-based" learning (Biswas-Diener & Jhangiani, 2017; Khalaf & Mohammed Zin, 2018; Pedaste et al., 2015), the concept of OP draws from a substantial literature on the educational value and importance of shifting away from the more "traditional" form of classroom instruction.

At its simplest, OP urges us to depart from what Freire calls the "banking model" of education (Freire, 2000), instead working toward a model in which students are active participants in their own learning. It requires questioning of what David Wiley calls the "disposable assignment," considering instead educational activities that add value to the world (Wiley, n.d.). In GIS education, it beckons the instructor to move beyond lab assignments that encourage pointing and clicking in lieu of thinking, or written assignments that get seen and evaluated only by the individual assigning them. It asks that we move away from "here's how you do it" to "what do we want to do, and why?"

Yet, this next layer of open may seem more daunting than the previous three. It is one thing to switch from a DVD of prepackaged data to open data on the internet, but quite another to transform course assignments and projects to more fully embrace OP. What might this look like in an introductory GIS course? In practice, OP might take several forms— from "crowdsourcing" a syllabus to creating a podcast to having student projects focus on a "deliverable" for an outside client. The point is that students need to be viewed as co-creators, not empty receptacles, and that the work and learning being produced is done so for the production of knowledge, not simply a letter grade.

In my introductory GIS course, I have begun to look at ways to incorporate the principles of OP into the teaching and learning environment. While the course is by no means an exemplary model of what good OP looks like, it does demonstrate some of the early steps being taken to create an environment where students are producers of knowledge, not merely consumers. Below are some examples of steps being taken to foster a knowledge community around geographic information science.

## Collaborative assignments

Students are encouraged to work together on daily assignments, which are to be posted to the class site on our learning management system (LMS) by the end of the class session. These posts are then viewable by all participants in the class, not just the instructor. The knowledge that one's peers, and not just the instructor, will be able to see the work provides an additional incentive to do well, and the fact that students are able to work collaboratively ensures that they see this exercise as more of a learning process rather than simply an assignment for a grade.

Our institution uses the open-source Moodle LMS for course management, which includes tools and resources for sharing work that is viewable by everyone in class. An online forum, where students can easily post their map layouts and comment on the work of others, becomes our shared repository for daily work. These in class assignments focus on one or two specific GIS concepts, such as SQL, table joins, map algebra, or geoprocessing, and typically require students to submit a map layout that demonstrates the successful application of the assigned concepts. Here again, students can get immediate feedback on their work by examining the work of others and/or soliciting feedback from their peers. These concepts and skills are then reinforced with longer lab assignments, which are turned in for instructor feedback and assessment.

## Critical GIS paper

Early on in an introductory GIS course, students often express amazement at the power of database querying or geoprocessing tools. It seems important, therefore, to have them simultaneously think critically about GIS as a technoscientific human construct. GIS is more than just software and hardware—i t is also a science, a set of social practices, and a complex collection of unequal power relationships. Its history is embedded in a larger history of military strategy, surveillance, colonialism, and territoriality. In the course, I ask students to read about GIS as a set of social practices, then identify a specific artifact (map, book, news article) to critically examine. We then use these analyses as the basis for class discussion on the potential benefits and problems of geographic information science.

### Tutorial modules

There are typically several tools and techniques in GIS that get used repeatedly, yet until students have had the benefit of learning by repetition the application of these tools can be difficult to recall. Students often ask for a "refresher" on how to use a specific tool if they have not had a chance to use it in the past week or two. Given this, I asked students to produce a tutorial module as one of their written assignments. Each student took a particular tool (e.g., creating a buffer) and created a document that addressed the following: (1) what is the end result that this tool will achieve, and why would I use it?, (2) define the tool, using appropriate vocabulary, (3) describe a specific example of the tool in use, including screenshots, and (4) explain the desired outcome after applying the tool. The collection of tutorial modules was then compiled for use in future GIS classes. Knowing that they were making contributions to a collection of tutorials that would be used by students in the future, the class worked hard to develop clear and thorough documentation.

### Individual student research project

The introductory course culminates with each student conducting a research project. The students have complete control over the research question being asked in the assignment; they are only given some basic parameters and shown some past examples of good student work. Students are strongly encouraged to identify an outside "client" for their work. This might take the form of a student doing some preliminary geographic exploration and mapping for their senior thesis project, or it might be a project specifically requested by a faculty member in another department, or perhaps even a project for an organization off campus. Since our campus has a working farm and forest, project requests often come to students in the class who are also engaged in work in those environments. The key point here is that they are producing a deliverable for a client, not just turning in an assignment for the course instructor.

## A question of scale: Observations on the challenges ahead

While the early evidence— student course evaluations, student success in graduate programs and early career positions, my own assessment of student learning—i ndicates that the transition to a fully open GIS course provides positive outcomes, there remain several challenges to "scaling up" this effort more broadly. There are still some aspects of the class that are difficult to fully shift to open, and the nature of my specific institution may foster a transition from closed to open that is not easily replicable at other institutions. Each of these challenges is briefly addressed below.

For the current course, one area that remains challenging is in web based geospatial visualization and analysis. Students learn how to export vector data to Keyhole Markup Language (KML) for viewing on Google My Maps (https://www.google.com/maps/about/mymaps) and Google Earth (https://earth.google.com), which are free (but not open source) web based mapping platforms. Students also learn how to edit OpenStreetMap (https://www.openstreetmap.org), which is both free and open source but limited in terms of its utility beyond serving as a basemap. The more enterprising and curious students might explore using other open-source web tools, including R Shiny (https://shiny.posit.co), OpenLayers (https://openl ayers.org), Leaflet (https://leafl etjs.com), and Open Data Kit (https://getodk.org), but the open-source online geospatial world is constantly evolving and can prove daunting to students in an introductory course.

Another ongoing set of challenges— which is perhaps the flip side to the "E" that represents expandability— are the difficulties that arise in a transition from a traditional computer laboratory to a "bring your own device" laboratory. Again, students enjoy having the ability to install free software on their own computers and the freedom that provides for doing work outside of the limited time and space of formal class instruction. Yet it also potentially exposes a sense of inequality between those students who can afford expensive laptops and those who cannot. We can partially address this by making desktop computers available to those students who do not have an appropriate computing device, but this still puts those students at a disadvantage since they have much more limited access to the software. At our institution, we have tried to further address this by making open-source GIS software available on the computers in the library room that is open 24/7, yet there is still a question of equity that we have not fully been able to answer.

It is also clear that some dimensions of my particular educational institution— small class sizes, only one GIS instructor, a work program, and an educational curriculum that fosters a "maker mentality"— have made the transition to a fully open class much easier than it might be at institutions that look quite different. A new instructor inheriting an existing lab and program, or an instructor who rotates teaching GIS with other instructors, might find it difficult to make these same sorts of transitions. Similarly, an instructor in an upper-level geospatial course may use proprietary software and expect that students enrolled in the course be familiar with that same software from earlier introductory courses. In such cases, perhaps an instructor could engage open concepts by adopting additional readings that are OER, creating a lab assignment or teaching module on open-source geospatial software, providing students with examples of open data portals, or transitioning an assignment from one that asks students to follow a recipe to one that fosters inquiry based learning. While it may be necessary to mainly stick with proprietary GIS in these settings, at least in the short term, simply exposing students to the possibilities of openness might spark their interest and catalyze their own efforts to learn more about open tools, resources, data, and pedagogy.

## Summary and concluding remarks

While the assignments mentioned previously can be viewed as baby steps toward a truly inclusive classroom of mutual knowledge production, they have begun to change the classroom culture from "what do I have to do and when is it due" to "how might I harness the power of GIS to ask— and perhaps answer—i nteresting questions." In practice, OP can often feel uncomfortable, as there is a requisite shift in the power dynamic between instructor and student, as the specter of letter grades is overshadowed by the larger goal of knowledge creation, and as the walled garden of textbooks with packaged data is replaced with OER and open data. Yet my preliminary efforts along these lines seem to line up with other examples of the perceived benefits of OP (Bonica et al., 2018).

Taken together, these four layers of open— open-source software, OERs, open data, and OP— can create dynamic new teaching and learning environments for GIS in higher education. Rather than teaching recipe driven assignments using expensive textbooks and proprietary software, we should be encouraging students' curiosity and freely giving them the tools and resources they need to satisfy that curiosity. As a former student once shared with me as we reflected on that semester's class:

If you want to build a ship, don't drum up people together to collect wood and don't assign them tasks and work, but rather teach them to long for the endless immensity of the sea.[1]

This quote gets at one of the key aspirations of OP. If we work with students as co-creators of knowledge, if we give them tools and resources that they can tinker with and remix, if we replace disposable assignments with useful projects, and if we devalue letter grades in favor of deeper reflection and evaluation– we may help foster the intrinsic self-motivation that truly enriches learning.

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## Conflict of interest statement

The author declares no conflict of interest.

## Data availability statement

All data and resources used in the production of this manuscript can be made available.

## Endnote

[1] Typically associated with the author of the Little Prince, Antoine de Saint-Exupéry.

## References

Biswas-Diener, R., & Jhangiani, R. (Eds.) (2017). Open: *The philosophy and practices that are revolutionizing education and science.* Ubiquity Press.

Bonica, M. J., Judge, R., Bernard, C., & Murphy, S. (2018). Open pedagogy benefits to competency development: From sage on the stage to guy in the audience. *The Journal of Health Administration Education, 35*(1), 9.

Campbell, J. E., & Shin, M. (2011). *Essentials of geographic information systems*. https://www.saylor.org/books/

Cheraghi, F. (2018). Esri association with open source: Is it free too? In N. N. Srivastava (Ed.), *Emerging trends in open source geographic information systems* (pp. 73– 96). IGI Global. https://doi. org/10.4018/978-1-5225-5039-6.ch004

Coetzee, S., Ivánová, I., Mitasova, H., & Brovelli, M. (2020). Open geospatial software and data: A review of the current state and a perspective into the future. *ISPRS International Journal of Geo-Information, 9*(2), 90. https:// doi. org/10.3390/ijgi9 020090

Everard, A., & St Pierre, K. (2014). A case for student adoption of open textbooks. *Journal of the Academy of Business Education, 15*, 66.

Freire, P. (2000). *Pedagogy of the oppressed* (30th anniversary ed.). Continuum.

Gandhi, U. (n.d.). *QGIS tutorials and tips*. https://www.qgist utori als.com/en/

Hanson, M. (2021). *Average cost of college textbooks.* https:// educa tiond ata.org/avera ge-cost-of-college-textbooks

Hegarty, B. (2015). Attributes of open pedagogy: A model for using open educational resources. *Educational Technology, 55*(4), 3– 13. https:// www.jstor.org/stabl e/44430383

Ince, D. C., Hatton, L., & Graham-Cumming, J. (2012). The case for open computer programs. *Nature*, 482, 485– 488. https:// doi.org/10.1038/natur e10836

Khalaf, B. K., & Mohammed Zin, Z. B. (2018). Traditional and inquiry-based learning pedagogy: A systematic critical review. *International Journal of Instruction, 11*(4), 545– 564. https:// doi.org/10.12973/ iji.2018.11434a

McKiernan, E. C., Bourne, P. E., Brown, C. T., Buck, S., Kenall, A., Lin, J., McDougall, D., Nosek, B. A., Ram, K., Soderberg, C. K., Spies, J. R., Thaney, K., Updegrove, A., Woo, K. H., & Yarkoni, T. (2016). How open science helps researchers succeed. *eLife, 5*, e16800. https:// doi.org/10.7554/eLife.16800

Osaci-Costache, G., Cocos, O., & Cocos, A. (2017). Geography students' perception related to the use of GIS open source software in geographic higher education. *Romanian Review of Geographical Education, 6*(1), 93–113. https://doi. org/10.23741/ rrge1 20175

Pedaste, M., Mäeots, M., Siiman, L. A., De Jong, T., Van Riesen, S. A., Kamp, E. T., Manoli, C. C., Zacharia, Z. C., & Tsourlidaki, E. (2015). Phases of inquiry-based learning: Definitions and the inquiry cycle. *Educational Research Review, 14,* 47– 61. https://doi.org/10.1016/j.edurev.2015.02.003

Pollitz, J. H., & Christie, A. (2006). The high cost of textbooks: A convergence of academic libraries, campus bookstores, publishers? *Electronic Journal of Academic and Special Librarianship, 7*(2), 69. https://digit alcom mons.unl.edu/ejasl journ al/69

Stallman, R. (n.d.). *Why schools should exclusively use free software.* https://www.gnu.org/educa tion/ edu-schoo ls.en.html Sui, D. (2014). Opportunities and impediments for open GIS. Transactions in GIS, 18(1), 1– 24. https://doi.org/10.1111/tgis.12075

Tietjen, P., & Asino, T. I. (2021). What is open pedagogy? Identifying commonalities. *The International Review of Research in Open and Distance Learning, 22*(2), 185– 204. https:// doi.org/10.19173/ irrodl.v22i2.5161

UNESCO. (n.d.). *Open educational resources*. https://www.unesco.org/en/ commu nicat ion-information/open-solutions/open-educational-resources

Wiley, D. (n.d.). *Killing the disposable assignment.* The non disposable assignment: Enhancing personalised learning. https://wordp ress.viu.ca/ enhan cingp erson alize dlear ning/2017/09/11/ killing-the-dispo sable-assignment-by-david-wiley/

Wiley, D., & Hilton, III, J. L. (2018). Defining OER-enabled pedagogy. *The International Review of Research in Open and Distributed Learning, 19*(4), 133– 146. https://doi.org/10.19173/ irrodl.v19i4.3601



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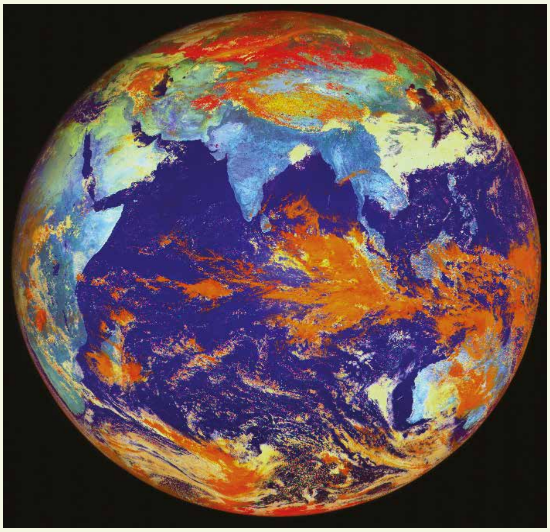
# INSAT-3DS begins imaging the Earth

INSAT-3DS, the meteorological satellite, has initiated Earth imaging operations. The first set of images by the meteorological payloads (6-channel Imager and 19-channel Sounder) was captured on March 7, 2024.

The satellite was launched on February 17, 2024. After completing orbit-raising operations, the satellite reached the designated geostationary slot for the In Orbit Testing (IOT) on February 28, 2024. As part of Meteorological Payload IOT, the first session of imaging for Imager and Sounder payloads was carried out on March 7, 2024. The payload parameters are found to be nominal, complying with payload specifications. Thus, all the payloads of INSAT-3DS have been tested to perform nominally.



Imager and Sounder payloads onboard 3DS are similar to the payloads flown on 3D and 3DR. Significant improvements have been achieved in radiometric accuracy, black body calibration, thermal management, and imaging throughput, among others. The payloads are designed and developed at the Space Applications Centre (SAC), Ahmedabad. The first images are processed and released at the Master Control Facility, Hasan.

The 6-channel imager equipment captures images of the Earth's surface and atmosphere across multiple spectral channels or wavelengths. The use of multiple channels allows for gathering information about various atmospheric and surface phenomena, such as clouds, aerosols, land surface temperature, vegetation health, and water vapour distribution. The imager could be configured to capture specific features of interest. The 19-channel sounder captures radiation emitted by the Earth's atmosphere through channels carefully chosen to capture radiation emitted by different atmospheric constituents and properties like water vapour, ozone, carbon dioxide, and other gases, while others may be designed to measure temperature variations in different layers of the atmosphere.

These Payloads generate over 40 geophysical data products such as Sea Surface Temperature, Rainfall (precipitation) Products, Land Surface Temperature, Fog Intensity, Outgoing Longwave Radiation, Atmospheric Motion Vectors, High-Resolution Winds, Upper Tropospheric Humidity, Cloud Properties, Smoke, Fire, Mean Surface Pressure, Temperature Profiles, Water Vapor Profiles, Surface Skin Temperature, Total Ozone, etc., for the user community. The data collected derive information about the vertical structure of the atmosphere, crucial for weather forecasting, climate monitoring, and understanding atmospheric processes. *https://www.isro.gov.in*

# The dynamics of ERA5 and GNSS-Derived precipitable water vapour in the climatic zones of Nigeria

This study has proven the utility of the ERA5 PWV for mapping and monitoring the water vapour content and for long- term climate studies over Nigeria

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## Abstract

*Precipitable water vapour (PWV) is a crucial atmospheric parameter that measures the amount of water vapour in the atmosphere above a specific location. The analysis of PWV variation is required to improve the understanding of climatic variability. The state-of-the-art fifth generation of the European Centre for Medium-Range Weather Forecasts (ERA5) which provides historical PWV records has gained prominence in the research community. The ERA5 dataset requires validation using in-situ ground observations such as Global Navigation Satellite Systems (GNSS). However, there is a limited understanding of the climatic and seasonal variability of ERA5 PWV over Nigeria. The sparse GNSS data coverage in previous studies has also limited their potential for correlating the PWV variations with significant or severe weather occurrences. This study investigates the spatio-temporal and seasonal correlation of ERA5 PWV with the GNSS-derived PWV over Nigeria between 2011 and 2016, using GNSS observations from the Nigerian GNSS Network (NIGNET). The GNSS observations were processed using Precise Point Positioning software to derive the Zenith Tropospheric Delay and its products. Subsequently, the PWV was derived from the Zenith Wet Delay. The quantitative analysis was facilitated using spatial interpolation and statistical metrics. The findings reveal a very close correlation between ERA5 PWV and the GNSS-derived PWV across all climatic regions in Nigeria, with the highest correlations occurring in the Sudan/ Sahel region (r: 0.96 - 0.98). In the dry season, there is a decrease in PWV from lower to higher latitudes. During the wet season of 2012 which recorded severe precipitation and flooding, the highest PWV content occurred in the mangrove and evergreen climatic regions located in south-west and south-eastern Nigeria. This study has proven the utility of the ERA5 PWV for mapping and monitoring the water vapour content and for long-term climate studies over Nigeria.*

## 1.0. Introduction

Precipitable water vapour (PWV) is a crucial atmospheric parameter that measures the amount of water vapour in the atmosphere above a specific location (Kelsey *et al.*, 2022). It represents the depth of water that would result if all the water vapour in a vertical column above that location were condensed and falls as precipitation (Ojrzyńska *et al.*, 2022). PWV has a wide range of applications in severe weather forecasting/ prediction, climate studies, water resource management, satellite communications, aviation and transportation, environmental studies and disaster monitoring. Thus, the measurement of its spatiotemporal distribution and variation has been a subject of interest in several studies (e.g., Khaniani *et al.*, 2021; Wang *et al.*, 2022; Dong *et al.*, 2023; Pipatsitee *et al.*, 2023; Sarkar *et al.*, 2023).

The measurement and monitoring of PWV improves the understanding of Earth's atmospheric dynamics and its influence on weather and climate, as well as human activities that are impacted by the content of the atmospheric water budget (Daniela, 2001; Isioye *et al.*, 2019). There are several methods for measuring and mapping PWV such as: radiosondes, microwave radiometers, infra–red sensors, light detection and ranging (LiDAR) sensors, and global navigation satellite systems (GNSS). Recently, the practice of deriving PWV from numerical weather prediction models (NWPs) such as the ERA5 dataset has gained wide prominence.

ERA5 is a state-of-the-art global atmospheric reanalysis dataset that contains a comprehensive and consistent record of historical weather and climate variables produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), and launched in July 2017 to succeed the ERA–interim reanalysis (Amangabara and Obenade, 2023). ERA5 is the fifth generation of this kind of dataset from ECMWF and it represents a significant improvement over its predecessors in different ways. Its high temporal and spatial resolution, wide range of variables, and extensive data assimilation make it a valuable resource for researchers and organisations worldwide working on climate and atmospheric science, weather forecasting, and environmental studies (Bosco *et al.*, 2020; Ying et al, 2022; Li *et al.*, 2023; Peng *et al.*, 2023).

GNSS is highly regarded as one of the most reliable sources of PWV and has repeatedly outperformed other methods in several studies (Jiang *et al.*, 2016; Isioye *et al.*, 2017; Shejule and Sreeja, 2022). This is due to its high spatio-temporal resolution, all-weather operability, continuous monitoring, interoperability of datasets, cost-effectiveness and high operational reliability. In Africa, several GNSS reference networks have been established under different initiatives such as the African Geodetic Reference Framework (AFREF) and the Nigerian Geodetic Reference Network (NIGNET). Isioye (2017) demonstrated that NIGNET observations were adequate for GNSS meteorology. Mayaki (2019) used NIGNET observations for deriving GNSS zenith tropospheric delay (ZTD) which were identified to have the potential for climatic studies. In another study using NIGNET, Bawa *et al.* (2021) mapped the PWV over Nigeria using GNSS observations. Bala (2022) also adopted NIGNET data for studying the spatial variation of PWV in Nigeria.

Despite the high reliability and high temporal resolution (data logging interval) of GNSS observations, their sparse distribution in the African continent is a serious limitation and a confounding factor for PWV analysis. In contrast, NWPs such as ERA5 which have a higher spatial resolution enable more robust analysis over wider territories. Moreover, the historical records available for ERA5 are more extensive than most of the recently established GNSS stations. Several studies have assessed the relationship between numerical weather prediction models and GNSS-derived PWV. For example, Nemaoui *et al.* (2017) found the difference between the GNSS-derived PWV and the ERA-interim PWV to be an average of 4.0 mm in Algeria. A handful of studies have assessed the accuracy of the ERA5 dataset in Nigeria and Africa (e.g., Bawa *et al.*, 2022; Nzelibe *et al.*, 2023). Abimbola *et al.* (2017) found that the root mean square error (RMSE) of the difference between the GNSS-derived PWV and the National Centre for Environmental Prediction (NCEP) II for three GNSS stations in Nigeria range between to be 3.2 and 9.9mm. Isioye *et al.* (2017) found this difference to be ~ -1.2 mm on daily average over Nigeria for five NIGNET stations. Compared to other numerical weather models, the ERA–interim PWV was found to be superior in terms of the daily, monthly and seasonal variation (Isioye *et al.*, 2016; Isioye *et al.*, 2017).

The accuracy of long-term reanalysis datasets such as ERA5 varies in different parts of the world and responds to changes in weather and climate. Validating ERA5 measurements in West Africa is a serious challenge due to the sparse coverage of continuously operating GNSS reference stations (CORS) in the region. The seasonal variation of PWV is closely tied to the wet and dry seasons in Nigeria and this often has significant implications for agriculture, water resources, and climate monitoring. Nigeria has distinct wet and dry seasons because of its proximity to the equator and the influence of the West African Monsoon. Significant variations in rainfall, temperature, and atmospheric conditions define these seasons (Ibebuchi and Itohan, 2023). The wet season, typically between April and October is the period the country experiences the West African Monsoon, which brings heavy rainfall (Onafeso, 2023). The West

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African Monsoon retreats during the dry season, which runs from November to March. This results in lower rainfall and the peculiar harmattan season, which is marked by a dry and dusty trade wind that blows throughout West Africa and originates in the Sahara Desert (Ojigi and Opaluwa, 2019; Kendon *et al.*, 2023). Understanding the seasonal variations in PWV has great potential for improved climate resilience and weather forecasting in Nigeria (e.g., Ekpe, 2014; Ojigi and Opaluwa, 2019; Wang *et al.*, 2022; Dong *et al.*, 2023; Pipatsitee *et al.*, 2023).

Despite their modest achievements, several of the existing studies were limited by the spatial and temporal coverage of the datasets. Moreover, the influence of climatic variability on the accuracy of PWV over Nigeria has not yet been holistically investigated. Sayne (2011) opined that "Nigeria's climate is likely to see growing shifts in temperature, rainfall, storms, and sea levels throughout the twenty-first century and poor adaptive responses to these shifts can fuel violent conflict in some areas of the country." A year later (i.e., 2012), severe rainfall among other issues led to serious flooding in 33 states of Nigeria (Ajaero *et al.*, 2016).

Thus, a spatiotemporal understanding of the PWV over the nation's troposphere can be a major factor in understanding the dynamics of flooding and other hydrological disasters. The present study addresses the historical analysis of the relationship between ERA5 and GNSS-derived PWV in Nigeria, and the seasonal variations of PWV in various climatic zones of Nigeria.

## 2.0. Methodology

The workflow diagram of the methodology is shown in Figure 2, and the various stages are discussed in the following sections.

### 2.1 Study area

Nigeria is geographically situated in the West African tropical region within latitudes 4oN - 14oN and longitudes 3oE - 15oE, and has a land area of about 910,770 km$^2$. The country has a vast stretch of coastline along the Gulf of Guinea to the south, vast savannas, dense rainforests, plateaus, and a central belt of hills and mountains, among other diverse geographical features. Important geological features include the northeastern Chad Basin and the Central Benue Trough. Nigeria's diverse ecosystems, including mangroves, wetlands, grasslands, and highlands, contain much of the country's rich biodiversity. The geographical regions all experience different climatic seasons. The dry season, which typically lasts from November to March, is characterised by wind from the Sahara Desert that is dry and dusty, with lower humidity and lower temperatures (World Bank Group, 2021). During the rainy season, which lasts from April to October, there is a lot of rain, especially in the southern and central parts of the country, which promotes lush vegetation and agricultural activity. In general, during August, there is a seasonal transition from long rain campaign to short rain campaign which lasts till October (Ibebuchi and Itohan, 2023). The country has three distinct climatic zones: a tropical monsoon climate in the south extending over the entire Mangrove region; a tropical guinea savannah climate throughout most of the middle areas – evergreen and a hot, semi-arid Sudan/Sahel climate in the north (Ogunsote *et al.*, 2002; World Bank Group, 2021). The depth of the precipitation in Nigeria follows a south-to-north decrease in gradient. Heavy rainfall events are often experienced during the rainy season in the south which could be anytime within the wet season (April to October). After this, the dry season (November to March) arrives with the Sahara wind with dusty harmattan often strong in the north and very brief in the south (Tolulope and Pourvahidi, 2020; World Bank Group, 2021). The annual rainfall in the Mangrove region during the wet season is typically above 2,000 mm and can exceed 4,000 mm in the Niger Delta. However, during the dry season in the Evergreen region, annual average rainfall may be as high as 1200 mm, whereas only 500 to 750 mm of rain or less, falls in the north from June to September. The annual variability of rainfall in northern regions often results in flooding and sometimes droughts towards the north-eastern end (Ekpe, 2014; Ogunsote *et al.*, 2002; Tolulope and Pourvahidi, 2020; World Bank Group, 2021; Ibebuchi and Itohan, 2023).

**Table 1: Datasets acquired for this study**

| Datasets | Format | Sources | Application | Duration |
|---|---|---|---|---|
| GNSS: Receiver Observation Data + associated metadata | Observation data in RINEX format together with all associated metadata that aids fast and appropriate post-processing | Nigeria GNSS Permanent Reference Network (NIGNET) CORS data + Script Orbit and Permanent Array Centre (SOPAC) | Applied as input for GNSS processing using GAPS | 2011 – 2016 |
| ERA5 Reanalysis | Network Common Data format (NetCDF) | European Centre for Medium-Range Weather Forecasts (ECMWF) | Comparison with GNSS PWV | 2011 – 2016 |

**Table 2: Details of the selected NIGNET CORS**

| S/N | Station Name | Latitude (°N ) | Longitude (°E) | Ellipsoidal Height (m) | Location | % volume of processed data 2011 – 2016 |
|---|---|---|---|---|---|---|
| 1 | ABUZ | 11.15 | 7.65 | 705.06 | Zaria | 73.72 |
| 2 | BKFP | 12.47 | 4.23 | 250.00 | Birni - Kebbi | 79.20 |
| 3 | CLBR | 4.95 | 8.35 | 57.17 | Calabar | 66.70 |
| 4 | FUTY | 9.35 | 12.50 | 247.40 | Yola | 81.98 |
| 5 | OSGF | 9.03 | 7.49 | 532.64 | Abuja | 56.89 |
| 6 | ULAG | 6.52 | 3.40 | 44.56 | Lagos | 43.70 |
| 7 | UNEC | 6.42 | 7.50 | 254.40 | Enugu | 73.08 |

## 2.2 Datasets

The main datasets used in this study include GNSS observations from the Nigerian GNSS Reference Network (NIGNET), and the ERA5 datasets. The datasets used and their characteristics are shown in Table 1.

### 2.2.1 GNSS observations

NIGNET was set up in 2009 by the Office of the Surveyor General of the Federation as a network of sixteen (16) Continuously Operating Reference Stations (CORS) in line with the mandate of the African GNSS Reference Framework (AFREF) (Adebomehin, 2016; Nwilo *et al.*, 2016; Ayodele at al., 2019). Seven of these ground–based CORS including ABUZ, BKFP, CLBR, FTY, OSGF, ULAG and UNEC (shown in Figure 1) were selected for this study based on the volume of consistent times series of data available, data logged and latency of data transmission archived for each station (Ayodele *et al.*, 2019).

The volume of GNSS data available at each of the seven CORS is presented in Table 2.

The NIGNET data was downloaded from the NIGNET ftp server and processed using the GNSS Analysis and Positioning Software (GAPS) Precise Point Positioning (PPP) package developed by the University of New Brunswick. GAPS provides users with highly precise point positioning with varied options for exploring both the static and kinematic modes of data capture (Mayaki *et al.*, 2019; Urquhart *et al.* 2014).

### 2.2.2 ERA5 PWV

The ERA5 PWV was downloaded in hourly temporal resolution in Network Common Data Format (NetCDF). The gridded data covering Nigeria was downloaded from the ECMWF database (ECMWF, 2023). Within ArcGIS Pro, the data was extracted at points coinciding with the seven functioning NIGNET CORS and saved in comma-separated value (.csv) format. The spatial resolution of the ERA5 dataset is 0.25° by 0.25° and it covers the period from 2011 to 2016. This ensured that the ERA5 PWV was consistent with the GNSS-derived PWV in terms of the period of coverage.

## 2.3 Data processing

The NIGNET raw GNSS data was post-processed using GAPS PPP. The accurate satellite clock was applied, along with orbit corrections, and metadata requirements were adequately adhered to. The Scripps Orbit and Permanent Array Centre (SOPAC) performed the data quality checks and cleaning. This process ensures reliable results by mitigating noise, interference, and atmospheric effects, enhancing the accuracy of PPP analysis within the UNB system's advanced capabilities.

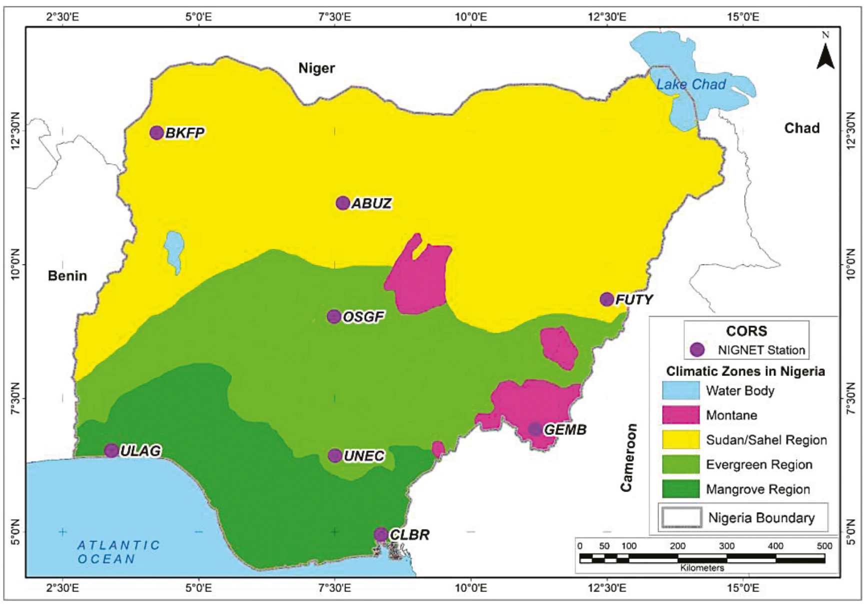



**Figure 1: Map showing the seven selected NIGNET stations and climatic zones in Nigeria**

The delay along the path of travel, S, of the GNSS signal is called Zenith Tropospheric Delay (ZTD) given by:

$$ZTD = \int_S N(s)\ ds \quad (1)$$

Where, $N(s)$ is the atmospheric refractivity of any radio wave expressed as:

$$N(s) = 10^6(n(s) - 1) \quad (2)$$

and $n(s)$ refers to the refractive indices in the media along the path.

The ZTD is often divided into Zenith Wet Delay (ZWD), which depends on water vapour and temperature and the Zenith Hydrostatic Delay (ZHD), which depends on surface pressure, latitude and height of the receiver station (Bawa *et al.*, 2021). In this study, the GAPS PPP version 6.00 was used as the precise point positioning engine in static mode to estimate ZTD based on parameters preset as shown in Table 3. The a-priori modelling of the tropospheric delay was carried out by a combination of the Niell Mapping Function (NMF) and Saastamoinen model (Mayaki, 2019).

The ZTD obtained was in a 30-second time interval. To derive an hourly dataset from time series ZTD, the mean of ZTD values for every 120 consecutive time points were aggregated using a simple MatLab code. This process provides a consolidated overview of the ZTD on an hourly basis.

The GAPS estimates the station position, receiver clock, zenith wet delay, and an ambiguity per satellite based on epoch, using a sequential weighted least squares filter. The surface meteorological variables used empirically in GAPS to compute the ZHD is the Vienna Mapping Function 1 (VMF1) and the obtained ZHD is then used for the derivation of the ZWD through the PPP estimated ZTD following Equations 3 and 4.

$$ZHD = 0.002277 \times \frac{P}{1-0.00226\times\cos(2\varphi)-0.00000028\times H} \quad (3)$$

Where, P is the surface pressure, H is the ellipsoidal height and $\varphi$ is the latitude of the CORS

$$ZWD = ZTD - ZHD \quad (4)$$

The PWV was estimated from the GAPS estimated ZWD following Equation 5 as stated by Bevis *et al.* (1992) for GNSS meteorology.

$$PWV = \Pi \times ZWD \quad (5)$$

Isioye et al (2017) derived Equation 6 for the conversion factor $\Pi$ for adoption as a function of surface temperatures, $T_s$ for GNSS meteorological application in Nigeria

$$\Pi = \left(\frac{0.5245T_s+132.12}{0.0053499T_s+1739.07624}\right) \quad (6)$$

Since the units of the ZWD are in millimetres, the PWV was derived for all the stations in millimetres.

## 2.4 Spatial interpolation of PWV maps

Maps showing the spatial distribution of PWV were prepared using geographic information system (GIS)-based inverse distance weighted (IDW) interpolation.

IDW is a common deterministic spatial interpolation model with a relatively fast and easy computation and straightforward interpretation (Yu and Wong, 2008; Maleika, 2020; Ohlert *et al.*, 2023). Summarily, IDW estimates the unknown value ŷ ($S_0$) in location $S_0$, given the observed y values at sampled locations $S_i$ (Yu and Wong, 2008):

$$\hat{y}(S_0) = \sum_{i=1}^{n} \lambda_i y(S_i) \quad (6)$$

The estimated value in $S_0$ is a linear combination of the weights ($\lambda_i$) and observed y values in $S_i$ where $\lambda_i$ is usually defined as (Yu and Wong, 2008):

$$\lambda_i = \frac{d_{0i}^{-\alpha}}{\sum_i^n d_{0i}^{-\alpha}} \quad (7)$$

In Equation (7), the numerator is the inverse of distance (d0i) between S0 and Si with a power α, and the denominator is the sum of all inverse-distance weights for all locations i (Yu and Wong, 2008). The spatial interpolation was implemented using the IDW tool of the 3D Analyst extension within the ArcGIS 10.8.1 software environment. ArcGIS is a software that provides contextual tools and services for mapping and spatial analysis (ESRI, 2023).

## 2.5 PWV validation and quantitative analysis

It is a standard practice to validate reanalysis dataset such as ERA5 PWV by comparison with in-situ observations such as radiosondes or GNSS (Chen *et al.*, 2021; Zhang *et al.*, 2019; Zhao *et al.*, 2019; Zongwan *et al.*, 2020). Due to the wide availability and proliferation of GNSS data across the globe, it is increasingly being adopted for validating reanalysis datasets such as ERA5 (e.g., Bawa *et al.*, 2022, Nzelibe *et al.*, 2023). In this study, the ERA5 PWVs were validated using estimated PWV from the selected NIGNET CORS over a period of 6 years (2011 - 2016). Additionally, the variation of PWV in the different climatic zones of Nigeria was assessed. To compare the PWV generated from ERA5 and GNSS, the following statistical metrics were adopted in the quantitative analysis: mean, minimum, maximum, mean bias (MB), mean absolute error (MAE), root mean square error (RMSE), correlation coefficient (r) and coefficient of determination (R2) as shown in Equations 8 - 12.

**Table 3: Options selected for the GAPS PPP post-processing**

| Items | Selected Option on GAPS |
|---|---|
| Observation | GPS un-differenced, ionosphere – free linear combination of L1 and L2 carrier phase and pseudo range |
| Processing Mode | Static |
| Elevation cut – off | 10o |
| Tropospheric Delay | Vienna Mapping Function 1 (VMF1) |
| Phase – windup effect | Applied |
| Ambiguities | Estimated as real numbers |
| Reference frame | International Terrestrial Reference Frame 2008 (ITRF 2008) |
| Mapping Function | Vienna Mapping Function (VMF) |
| Station displacement | Solid Earth tide, ocean tide loading IERS Convention 2010 |
| Satellite Antenna | Phase Centre Offset (PCO) and Phase Centre Variation (PCV) corrected. |
| Receiver Antenna | PCO and PCV |
| Orbit and Clock products | IGS final product |

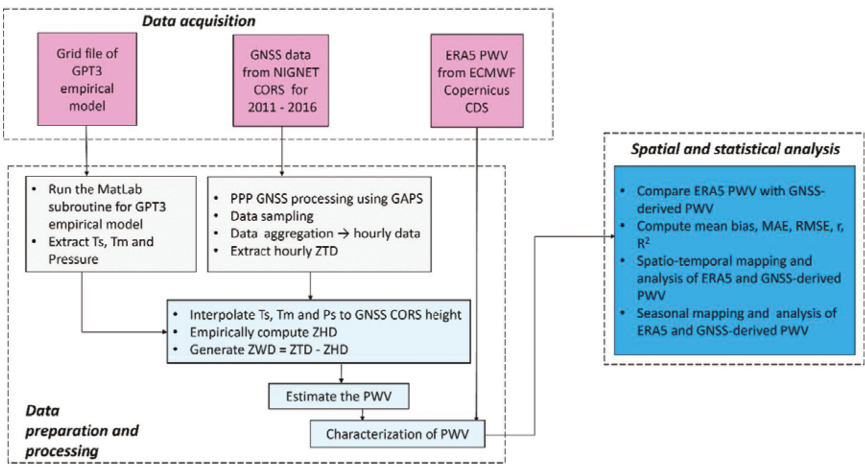



**Figure 2: Workflow diagram of the methodology**

The coefficient of determination ($R^2$) is a statistical measurement that examines how differences in one variable can be explained by the difference in a second variable when predicting the outcome of a given event (Scott *et al.*, 2023). It ranges from 0 to 1, where 0 shows no relationship and 1 a perfect fit.

$$MB = \frac{1}{N}\sum_{i=1}^{n}(y_i - \hat{y}_i) \tag{8}$$

$$MAE = \frac{\sum|y_i - \hat{y}_i|}{N} \tag{9}$$

$$RMSE = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{N}} \tag{10}$$

$$r = \frac{N(\sum y_i\hat{y}_i) - (\sum y_i)(\sum \hat{y}_i)}{\sqrt{[N\times(\sum(y_i)^2 - (\sum y_i)^2)]\times[N\times(\sum(\hat{y})^2 - (\sum \hat{y}_i)^2)]}} \tag{11}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \bar{y}_i)}{\sum_{i=1}^{n}(\hat{y}_i - \bar{y}_i)} \tag{12}$$

Where $y_i$ = GNSS PWVs, $\hat{y}_i$ = ERA5 PWVs, $\bar{y}_i$ = mean values of GNSS-derived PWVs for N = number of observations.

## 3.0 Results and Discussion

### 3.1 Relationship between ERA5 and GNSS-derived PWV

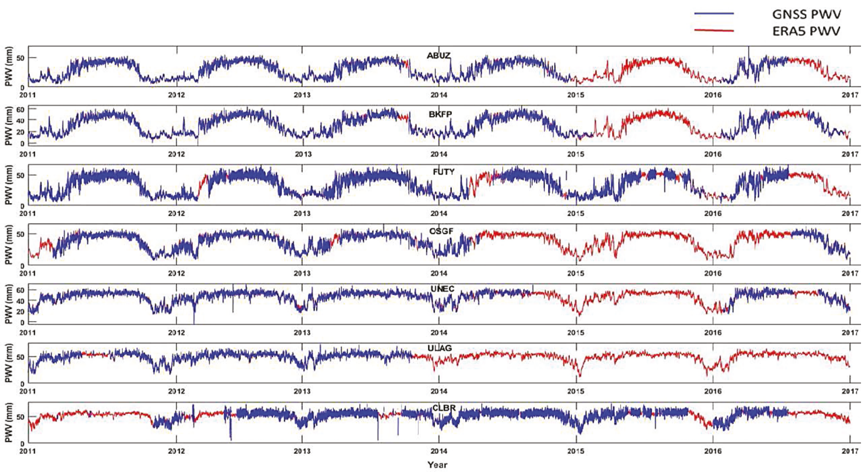
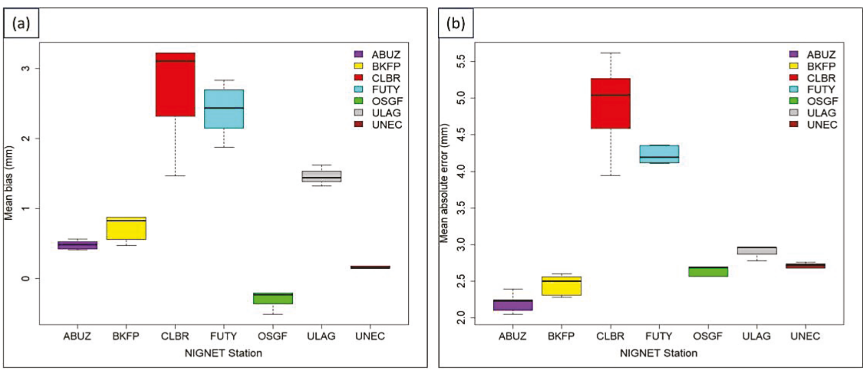



**Figure 3: Graphical comparison of ERA5 and GNSS PWVs at the seven NIGNET stations, 2011–2016**



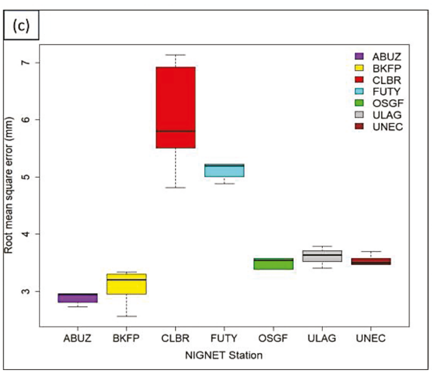




**Figure 4: Boxplots of the (a) mean bias (b) mean absolute error, and (c) root mean square error of the ERA5 PWVs, 2011 – 2016**

The global state-of-the-art ERA5 PWV was validated using the GNSS-derived PWV. The time series plots of the ERA5 reanalysis and the GNSS PWV are shown in Figure 3. The ERA5 PWV is closely aligned with the GNSS-derived PWV. Generally, the PWVs are lowest at the beginning and end of the year, and this corresponds with the dry season months (November to March) which have lower precipitation (rainfall). The highest PWVs are generally observed in the wet season months from April to October. There are several perturbations in the PWV values during the dry season months which are likely signatures of the influence and interaction of the tropical continental air mass from the Sahara and maritime tropical air mass from the Atlantic Ocean (e.g., Nicholson, 2013). However, the trend line is generally smoother during the wet season. The gaps in the graph are due to gaps in the data coverage (i.e., seasons where there is no data logged for GNSS observation).

Figures 4a - c present boxplots of the mean bias, mean absolute error, and the root mean square error of the ERA5 PWV for the period 2011 to 2016. Generally, mean bias values from 2011 to 2016 are lowest at OSGF and UNEC respectively (Figure 4a). However, the MAE and RMSE values from 2011 to 2016 are lowest at ABUZ and BKFP (Figure 4b and 4c). CLBR which has the least accurate ERA5 PWV estimates is in the mangrove climatic region. The rainfall pattern in Calabar has been reported to be irregular, with January and September having the lowest and highest number of rainy days respectively (Ogbozige, 2022).

Figures 5 and 6 present Pearson's correlation heatmaps of the ERA5 and GNSS PWVs at the seven stations for the period, 2011 - 2013. Due to excessive data gaps, the periods from 2014 to 2016 were not included in this initial correlation analysis. The correlations of the ERA 5 and GNSS-derived PWV for all stations are generally above 0.90 except for CLBR with a correlation of approximately 0.8. This may be caused by the anomalous nature of the tropical air mass in this region (e.g., Ekpe, 2014; Ogbozige, 2022).

From Figure 6, it is observed that all the ERA5 PWVs have a very high positive correlation in the Sudan/Sahel region, For example, the correlation between PWV at Zaria (ABUZ) and Kebbi (BKFP) is 0.96; Zaria (ABUZ) and Yola (FUTY) is 0.94; and Kebbi (BKFP) and Yola (FUTY) is 0.91. In the evergreen climatic region, Abuja (OSGF) has a very high positive correlation with Enugu (UNEC), with a correlation coefficient of 0.92. In the mangrove climatic region, the correlation between Lagos (ULAG) and Calabar (CLBR) is very high at 0.87. However, the correlation between Calabar (CLBR) and Enugu (UNEC) is 0.94 which is an indication of the direction of the tropical maritime air mass passing through the direction of the monsoon as it emanated from the southwest following the assertion of Helen (1991).

Regression analysis was carried out between the numerical reanalysis source of PWV and the ground-based GNSS observations at 95% confidence interval and the linear relationship between them at each of the selection stations is given by the following relations.

ABUZ: $GNSS_{PWV} = (0.96165 \pm 0.00372) \times ERA5_{PWV} + (0.98007 \pm 0.00008)$

BKFP: $GNSS_{PWV} = (0.95157 \pm 0.00346) \times ERA5_{PWV} + (1.34570 \pm 0.00010)$

CLBR: $GNSS_{PWV} = (1.01770 \pm 0.00580) \times ERA5_{PWV} + (0.30867 \pm 0.00017)$

FUTY: $GNSS_{PWV} = (1.06180 \pm 0.00590) \times ERA5_{PWV} + (0.62852 \pm 0.00015)$

OSGF: $GNSS_{PWV} = (0.99467 \pm 0.00614) \times ERA5_{PWV} - (0.47593 \pm 0.00022)$

ULAG: $GNSS_{PWV} = (1.07660 \pm 0.00640) \times ERA5_{PWV} - (2.72520 \pm 0.00030)$

UNEC: $GNSS_{PWV} = (1.03870 \pm 0.00730) \times ERA5_{PWV} - (1.93000 \pm 0.00040)$

Table 4 presents the coefficient of determination ($R_2$) between ERA5 and GNSS-derived PWV at the seven NIGNET stations. There is a good fit between the

**Table 4: Coefficient of determination (R2) between ERA5 and GNSS-derived PWV at the NIGNET stations**

| Year | ABUZ | BKFP | CLBR | FUTY | OSGF | ULAG | UNEC |
|---|---|---|---|---|---|---|---|
| **2011** | 0.96 | 0.964 | 0.378 | 0.903 | 0.924 | 0.882 | 0.92 |
| **2012** | 0.957 | 0.956 | 0.476 | 0.909 | 0.915 | 0.8 | 0.875 |
| **2013** | 0.945 | 0.949 | 0.302 | 0.858 | 0.886 | 0.743 | 0.839 |
| **2014** | 0.945 | 0.951 | 0.527 | 0.721 | 0.795 | - | 0.886 |
| **2015** | - | 0.371 | 0.592 | 0.889 | - | - | - |
| **2016** | 0.94 | 0.946 | 0.736 | 0.874 | 0.948 | - | 0.885 |

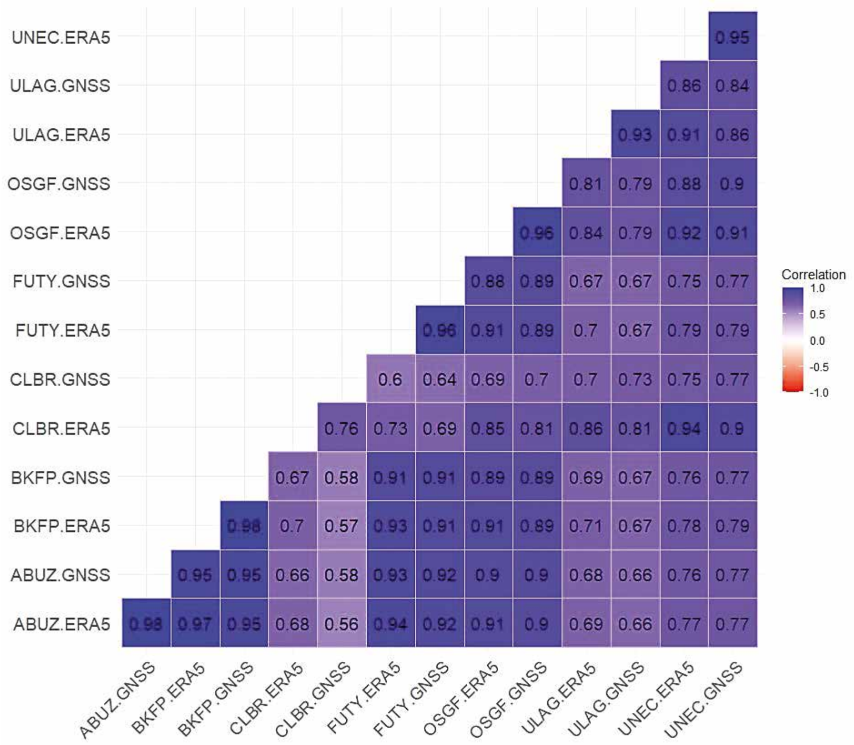



**Figure 5: Correlation heatmap of the ERA5 and GNSS PWVs at the seven NIGNET stations, 2011 – 2013**

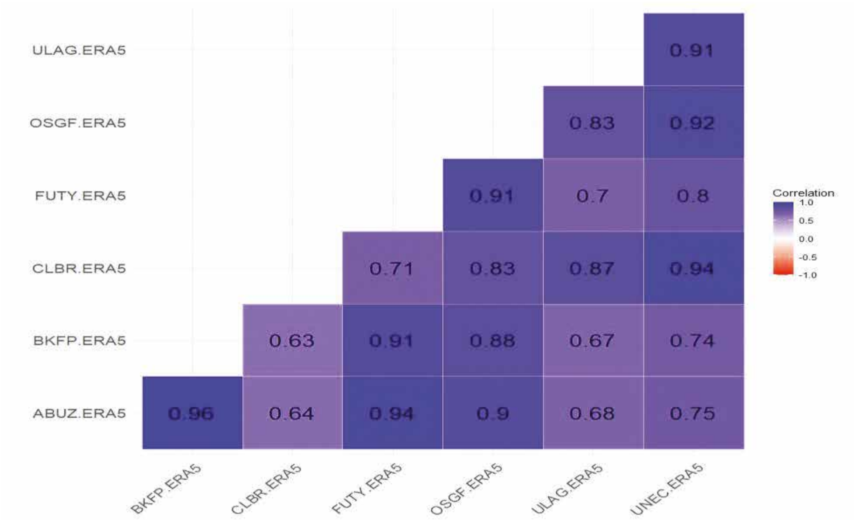



**Figure 6: Correlation heatmap of the ERA5 PWVs at the seven NIGNET stations, 2011 – 2016**

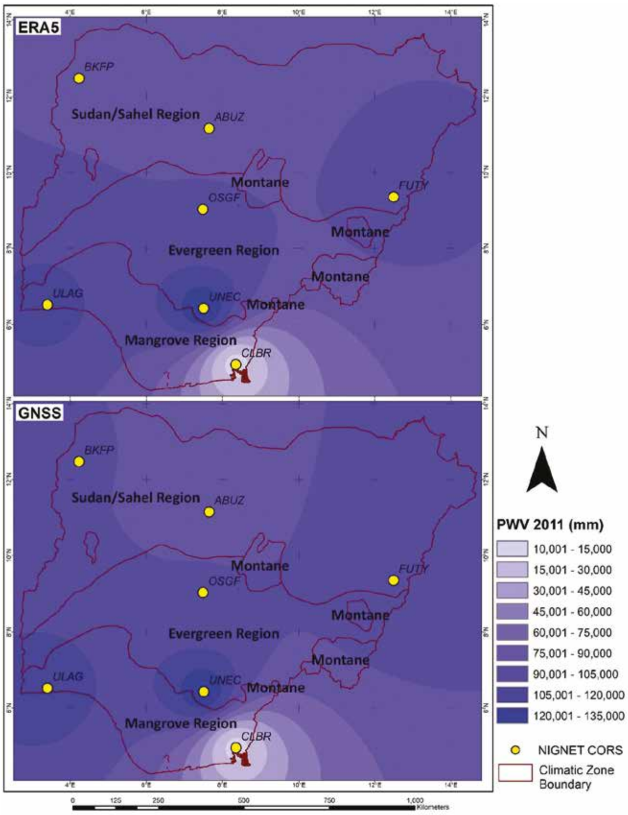



Figure 7: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2011

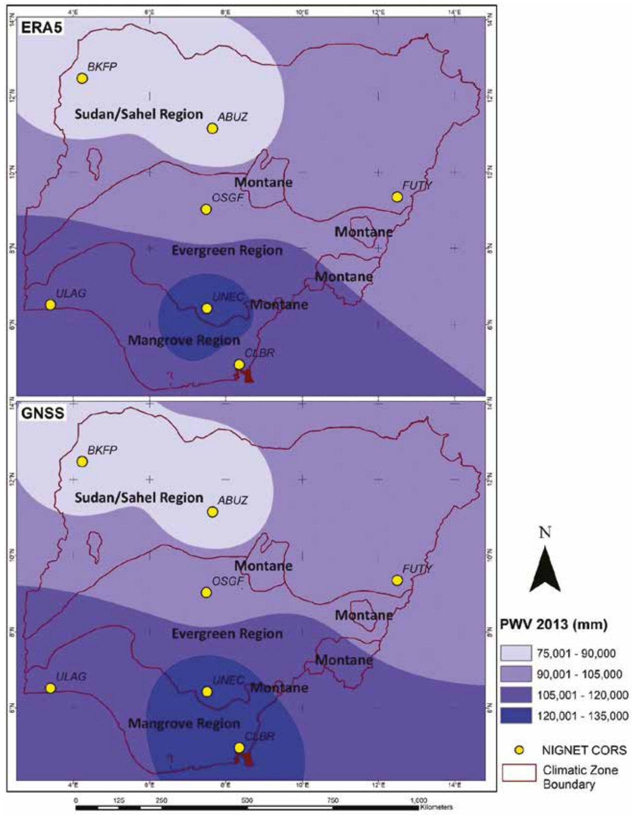



Figure 9: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2013

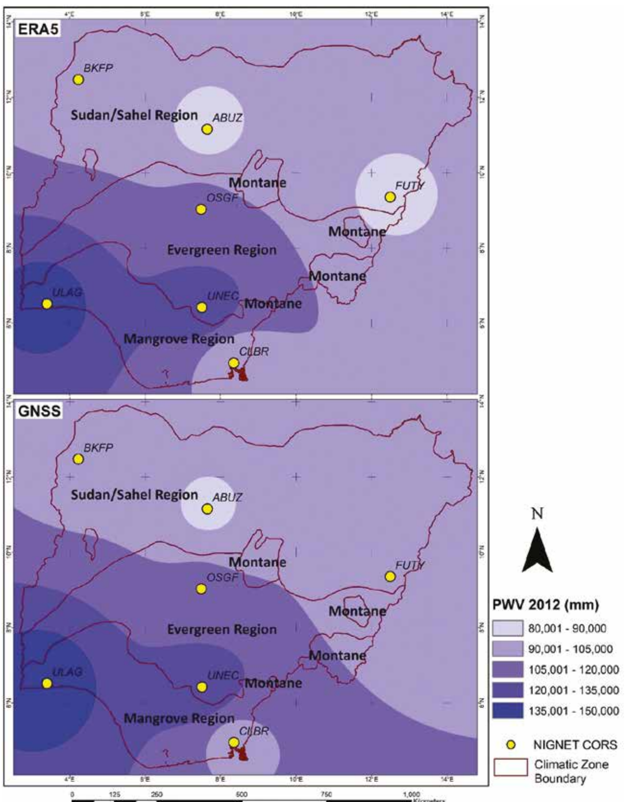



Figure 8: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2012

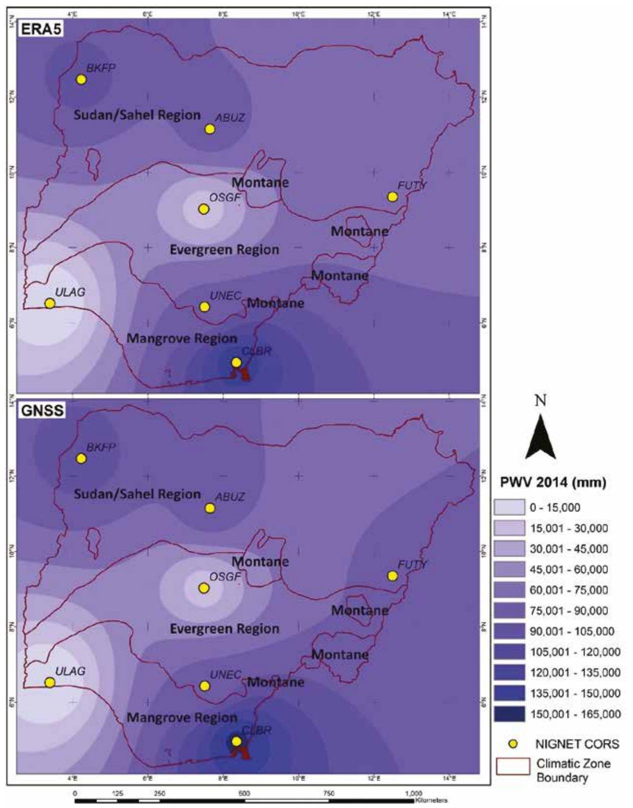



Figure 10: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2014

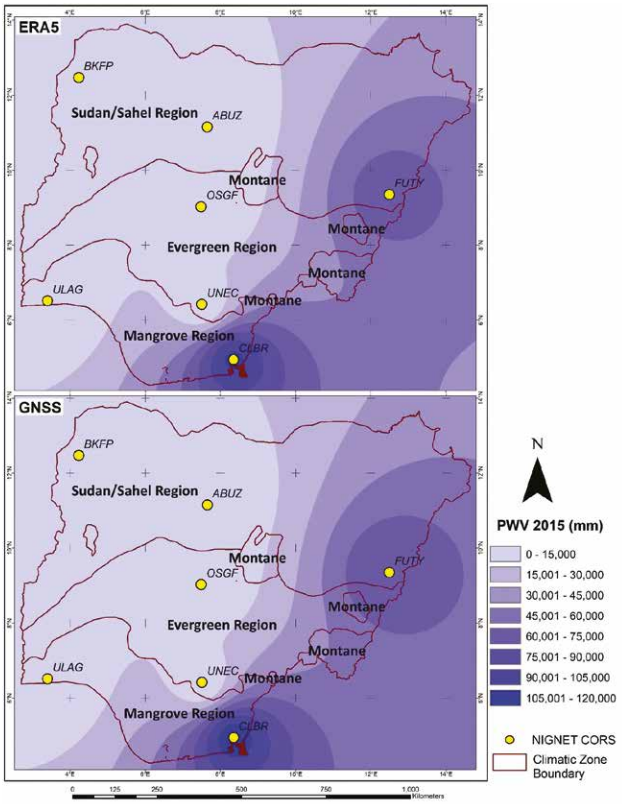



Figure 11: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2015

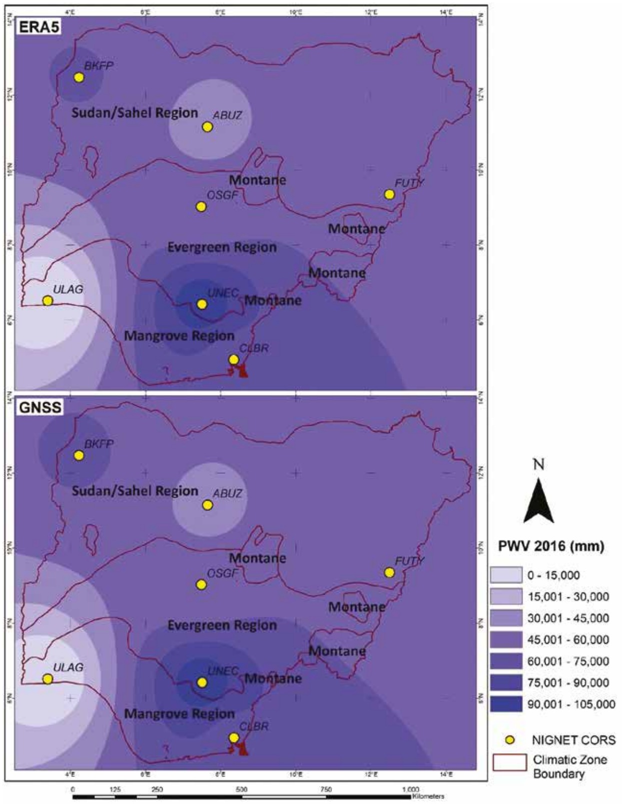



Figure 12: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, 2016

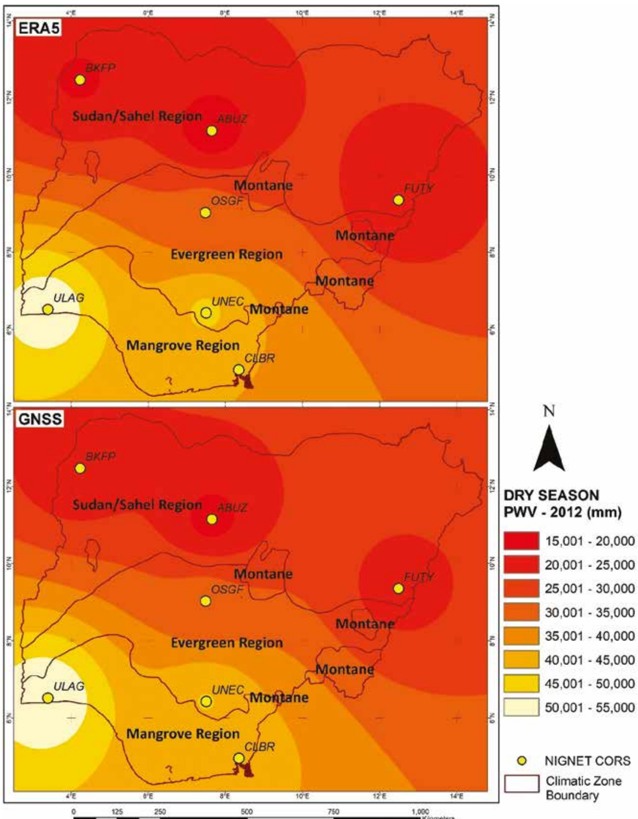



Figure 13: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, dry season 2012

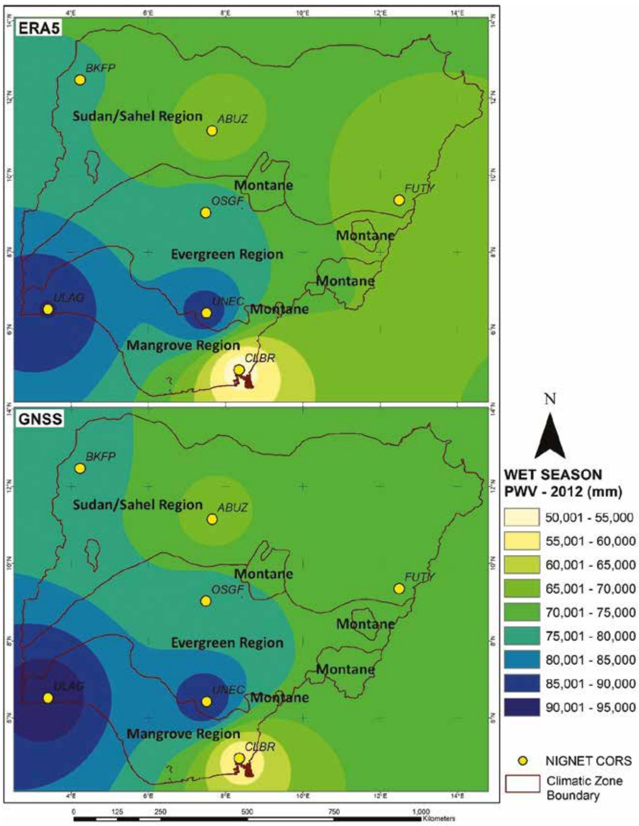



Figure 14: Spatial variation of ERA5 and GNSS PWV across the Nigerian climatic zones, wet season 2012

ERA5 and GNSS-derived PWVs in all the climatic regions where R2 is above 0.7. Thus, ERA5 PWV can be a good predictor of estimated PWV from GNSS observation especially when long-term monitoring is required, and even when the GNSS station distribution is sparse.

### 3.2 PWV variation in Nigerian climatic zones

In this section, the PWV variation in the different climatic zones is investigated. The importance of assessing the variability of PWV in different climatic zones lies in its potential to offer insights into regional atmospheric dynamics. Such an understanding can indicate the moisture content of the atmosphere which influences weather patterns and precipitation, and fuel the development of targeted strategies for water resource management and disaster preparedness in specific regions.

Figures 7 - 12 present the spatial and temporal variation of ERA5 and GNSS PWV across the Nigerian climatic zones, from 2011 to 2016. In this analysis, the PWVs in the climatic regions are generalised from the PWVs of the respective stations. In the year 2011, the PWV was highest over the station UNEC (Evergreen region) and lowest at CLBR (Mangrove region).

Summarily in 2011 (Figure 7), there was similar spatial distribution between ERA5 and GNSS-derived PWV in the mangrove and evergreen regions, with slight variance in the Sudan/Sahel region. In the year 2012 (Figure 8), the Mangrove climatic region had the highest PWV content over Nigeria, followed by the Evergreen region and the Sudan/Sahel region. There are slight differences in the spatial distribution between ERA5 and GNSS at Yola (FUTY). The high PWV in the mangrove region especially Lagos (ULAG) is possibly a consequence of the disastrous 2012 flooding that occurred in Nigeria. The flooding started in Lagos due to heavy rainfall in July and continued with heavy downpours in the southwestern states (Mangrove region). The flooding that occurred around Adamawa, Taraba, and Benue states sometime around September 2012 was largely due to the opening of Lagdo Reservoir with little contribution of rainfall (NEMA, 2013; Amangabara and Obenade, 2015). The 2012 map shows water vapour content variation in the direction of the flooding experienced in 2012 with a slight variation in water vapour content over Yola (FUTY) where ERA5 was lower than the GNSS estimates

In the year 2013 (Figure 9), ERA5 and GNSS PWV were highly correlated in all the climatic zones with very slight variation in the Monsoon area of the Mangrove region (CLBR) where ERA5 captured less PWV content than the ground-based GNSS. In the years 2014 (Figure 10), 2015 (Figure 11) and 2016 (Figure 12), the spatial pattern of the ERA5 and GNSS-derived PWV maps are similar with significant correlations. Although the ground-based GNSS-derived PWV depicts spatio-temporal variations more accurately, the analysis shows that ERA5 can be utilized as a proxy or alternative dataset to fill in GNSS coverage gaps, or in areas where GNSS data is sparse or non-existent.

### 3.3 Seasonal variability of PWV in Nigeria

Given the severity of the 2012 rainfall in Nigeria and the associated flooding in 33 states of the federation (Ajaero *et al.*, 2016), this section focuses on the seasonal variability of PWV in the year 2012. Figures 13 and 14 show the seasonal variations of PWV in all the climatic regions of Nigeria during the dry and wet (rainy) seasons of 2012 as captured by the state-of-the-art ERA5 reanalysis and the NIGNET CORS.

In the dry season (Figure 13), the ERA5 PWV ranged from 17, 316.42 – 52, 939.03 mm, while the GNSS-derived PWV ranged from 18, 423.70 to 54, 413.07 mm. There is a considerable similarity in the spatial distributions of the ERA5 and GNSS-derived PWV. The Mangrove region (which is closest to the Atlantic Ocean) recorded the highest PWV. In the northern region where the influence of the continental air mass is the strongest, the PWV is lowest. The map shows a trend in which the PWV decreases at higher latitudes. From Lagos (ULAG), the PWV decreases radially outwards and this is an indication of the direction of the movement of the tropical air mass. Summarily, there is a close consonance in the PWV differentials in both ERA5 and GNSS for the dry season.

The wet season map (Figure 14) reveals PWV variabilities within and between climatic regions. Within the Mangrove region, the highest PWV was recorded in Lagos (ULAG) while the lowest PWV was recorded at Calabar (CLBR). The same spatial pattern was also observed in the evergreen region at Enugu (UNEC) with a PWV of about 88, 517.24 mm, and other parts of the evergreen region where PWV ranged from 60,000 – 80,000 mm.

The situation is not different in the Sudan/Sahel region where the station at Kebbi (BKFP) recorded the highest PWV in the range of 66, 296.91 – 75, 221.66 mm (Figure 14). Summarily, the ERA5 and GNSS-derived wet season maps have similar spatial patterns. This further validates the importance of ERA5 PWV as a proxy or alternative to in-situ GNSS-derived PWV estimates, especially in areas where GNSS data is sparse or non-existent.

## 4.0 Conclusion

The global state-of-art ERA5 reanalysis dataset which records the total column of water vapour (i.e., precipitable water vapour) has gained wide popularity among climate researchers. Its peculiar variation in Nigeria's climatic regions has been addressed in this study. The GNSS-derived PWV has been underscored to have a higher spatio-temporal and all-weather accuracy in all the climatic regions of the country. During dry and wet seasons, the PWV is highest at lower latitudes in Nigeria, especially in the mangrove region which adjoins the Atlantic Ocean.

The detailed analysis has revealed a high correlation between ERA5 and GNSS-derived PWV at several locations and climatic regions of Nigeria. PWV is a valuable parameter for long-term weather and climate monitoring. More so, PWV acquired from the ERA5 reanalysis can serve as a good substitute to the classic GNSS-derived PWV in understanding historical climatic trends and dynamics.

The need to adequately understand the dynamics of emerging severe weather events is increasing in the face of global climate change. A comprehensive and consistent long-term historical record of climatic parameters that can enhance this understanding and improve emergency preparedness is of utmost importance. The historical database of PWV mapped by ERA5 is viable for long-term studies of PWV over Nigeria for several applications such as hydrological analysis, water resource management, agricultural irrigation and climate change studies. The ERA5 PWV is also valuable for mapping the signature of the West African Monsoon, which is a critical meteorological phenomenon that brings seasonal changes in winds and rainfall to West Africa. The ERA5 PWV also maps the uniqueness of the Intertropical Convergence of the continental and maritime air masses of the Nigerian tropical climate.

Due to the country-wide coverage by ERA5, it is recommended for macro-scale modelling and analysis of PWV over large territories. It can also contribute to the understanding of the dynamics of historical meteorological parameters and peculiar distinctive features of weather and climate. The capability of ERA5 PWV for studying severe weather events has been identified in this study, for example, the case of the 2012 heavy downpour in Nigeria and the associated flooding. Due to the irregular rainfall and PWV variability at Calabar (Monsoon region), a longer time series dataset is recommended for a more comprehensive understanding of the ERA5-GNSS relationship in that region. The observed correlations between PWV and climatic seasons as revealed in this study provide key insights requiring further investigation. The diurnal, monthly and seasonal trend of PWV with rainfall will be investigated in another study.

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The authors appreciate the Office of the Surveyor General of the Federation (OSGOF), in Nigeria, for allowing them access to the NIGNET data. The researchers at the Department of Geodesy and Geomatics Engineering, University of New Brunswick in Canada, who used the offline version of GAPS to batch process the CORS data, are also well acknowledged by the authors. We also appreciate the journal reviewers and our colleagues who assisted with reviewing the paper.

## References

Aaron Sayne (2011). *The Climate Change: Adaptation and Conflicts in Nigeria*. United States Institute of Peace Special Report 274.

Abimbola, O. J., Falaiye, O. A., and Omojola, J. (2017). *Estimation of precipitable water vapour in Nigeria using NIGNET GNSS/GPS, NCEP-DOE Reanalysis II and surface meteorological data*. Journal of Physical Science, 28(2), 19–29. https://doi.org/10.21315/jps2017.28.2.2

Adebomehin, A.A. (2016). *The State and Utilization of the Nigeria CORS Network*. A presentation given at the International Training Workshop on Global Navigation Satellite Systems (GNSS), Ile-Ife, Nigeria.

Ajaero, I. D., Okoro, N. M., and Ajaero, C. K. (2016). Perception of and Attitude Toward Mass Media Reportage of the 2012 Flood in Rural Nigeria. SAGE Open, 6(3). https://doi.org/10.1177/2158244016666887

Amangabara G. T., and Obenade M., *"Flood Vulnerability Assessment of Niger Delta States Relative to 2012 Flood Disaster in Nigeria."* American Journal of Environmental Protection, 3(3), 76-83. doi: 10.12691/env-3-3-3.

Ayodele, E.G., Okolie C.J., Mayaki, O.A. (2019). *An Assessment of the Reliability of the NIGNET Data.* Nigerian Journal of Environmental Sciences and Technology, 3(1): 18 – 29.

Bala I. A. (2022). *Analysis of Precipitable Water Vapour in Nigeria using GNSS Observations.* MSc Thesis, University of Beira Interior, Covilha, Portugal.

Bawa S., Isioye O. A., Moses M., Abdulmumin L. (2022). *An Appraisal of the ECMWF Reanalysis 5 (ERA5) Model in Estimating and Monitoring Atmospheric Water Vapour Variability Over Nigeria.* Geodesy and Cartography ISSN 2029-6991 / eISSN 2029-7009 2022 Volume 48 Issue 3: 150–159, Vilnius Gediminas Technical University. https://doi.org/10.3846/gac.2022.14777

Bawa S., Usman S., Adamu B., Aliyu A., Adamu A. Musa, N. (2021). *Modelling Precipitable Water Vapour (PWV) Over Nigeria from Ground-Based GNSS.* Geoplanning: Journal of Geomatics and Planning, 8(1), 41-50 DOI: 10.14710/geoplanning.8.1.41-50.

Bevis, M., Businger, S., Herring, T.A., Rocken, C., Anthes, R.A., Ware, R.H. (1992). *GPS Meteorology: Remote Sensing of Atmospheric Water Vapor Using the Global Positioning System.* Journal of Geophysical Research, 97(D14): 15787 - 15801.

Chen, B., Yu, W., Wang, W., Zhang, Z., & Dai, W. (2021). *A global assessment of precipitable water vapor derived from GNSS zenith tropospheric delays with ERA5, NCEP FNL, and NCEP GFS products.* Earth and Space Science, 8, e2021EA001796. https://doi.org/10.1029/2021EA001796

Dong Ren, Yong Wang, Guocheng Wang, Lintao Liu (2023). Rising trends of global precipitable water vapor and its correlation with flood frequency. Geodesy and Geodynamics 14, 355 – 367. https://doi.org/10.1016/j.geog.2022.12.001

ECMWF (2023). ERA5 hourly data on single levels from 1940 to present. https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form (Date accessed: 16th September, 2023).

Ekpe, Itita Augustine (2014). *Rainfall Anomalies and Trend in Calabar: An Imperative for Human Adaptation to Climate Change.* Unpublished MSc. Thesis submitted to Department of Geography and Environmental Science University of Calabar-Calabar, Nigeria

ESRI (2023). ArcGIS https://www.esri.com/en-us/arcgis/about-arcgis/overview (Date accessed: 23 September, 2023).

Helen Chapin Metz, ed. Nigeria: *A Country Study.* Washington: GPO for the Library of Congress, 1991. https://countrystudies.us/nigeria/33.htm

Ibebuchi CC and Itohan O.A. (2023). *Rainfall variability patterns in Nigeria during the rainy season.* Science Report, 13(1), 78 - 88.

Ifechukwu Ugochukwu Nzelibe, Herbert Tata and Timothy Oluwadare Idowu (2023). *Assessment of GNSS zenith tropospheric delay responses to atmospheric variables derived from ERA5 data over Nigeria.* Satellite Navigation (2023) 4:15 https://doi.org/10.1186/s43020-023-00104-7

Isioye O.A., Combrinck L., Botai J.O. (2016). *Modelling Weighted Mean Temperature in the West African Region: Implications for GNSS Meteorology.* Journal of Meteorological Applications, 23(4), 614-632, December 2016. http://dx.doi.org/10.1002/met.1584

Isioye, Olalekan Adekunle (2017). *An Investigation of Ground-based GNSS Atmospheric Remote Sensing Techniques for Weather and Climate Monitoring in Nigeria.* PhD Dissertation in Geoinformatics (Geodesy Option) University of Pretoria South Africa.

Isioye O. A., Combrinck L. & Botai J.O. (2017). *Retrieval and Analysis of Precipitable Water Vapour based on GNSS, AIRS, and Reanalysis Models over Nigeria.* International Journal of Remote Sensing https://doi.org/10.1080/01431161.2017.1346401

Isioye O.A., Botai J.O., Combrinck L., Moses, M. (2019). *Assessing the Impact of Variations in Atmospheric Water Vapour Content over Nigeria from GNSS Measurements.* South African Journal of Geomatics, 8(1), March 2019. http://dx.doi.org/10.4314/sajg.v8i1.3

Jacob, Daniela. (2001). The Role of Water Vapour in the Atmosphere: *A Short Overview from a Climate Modeller's Point of View.* Phys Chem Earth P A-Solid E G. 26. 523-527. 10.1016/S1464-1895(01)00094-1.

Jiang, P., Ye, S., Chen, D., Liu, Y., Xia, P. (2016). *Retrieving Precipitable Water Vapor Data Using GPS Zenith Delays and Global Reanalysis Data in China.* Remote Sensing, 8, 389. https://doi.org/10.3390/rs8050389

Kelsey, V., Riley, S., and Minschwaner, K. (2022). *Atmospheric precipitable water vapor and its correlation with clear-sky infrared temperature observations, Atmos.* Meas. Tech., 15, 1563–1576, https://doi.org/10.5194/amt-15-1563-2022.

Kendon, E.J., Stratton, R.A., Tucker, S. *et al.* (2019). *Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale.* Nat Commun 10, 1794. https://doi.org/10.1038/s41467-019-09776-9

Khaniani, Ali Sam, Motieyan, Hamid, Mohammadi, Atefeh (2021). *Rainfall forecast based on GPS PWV together with meteorological parameters using neural network models. Journal of Atmospheric and Solar-Terrestrial Physics, 214,* 1364-6826. https://doi.org/10.1016/j.jastp.2020.105533

Maleika, W. (2020). *Inverse distance weighting method optimization in the process of digital terrain model creation based on data collected from a multibeam echosounder.* Applied Geomatics 12, 397–407 https://doi.org/10.1007/s12518-020-00307-6

Mayaki, A.O., Nikolaidou, T., Santos, M., Okolie C.J. (2018). *Comparing the Nigerian GNSS Reference Network's Zenith Total Delays from Precise Point Positioning to a Numerical Weather Model.* International Association of Geodesy Symposia. Springer, Berlin, Heidelberg. https://doi.org/10.1007/1345_2018_43

Mayaki, A.O. (2019). *Evaluation of Precise Point Positioning Derived Zenith Total Delays from the Nigerian GNSS Reference Network.* MSc Thesis, Department of Geodesy and Geomatics Engineering, The University of New Brunswick, Canada, April 2019.

Namaoui, H., Kahlouche, S., Belbachir, A. H., van Malderen, R., Brenot, H., & Pottiaux, E. (2017). *GPS water vapor and its comparison with radiosonde and ERA-Interim data in Algeria.* Advances in Atmospheric Sciences, 34(5), 623–634. https://doi.org/10.1007/s00376-016-6111-1

Nicholson, S. E. (2013). *The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability.* Int. Sch. Res. Not. 2013. https://doi.org/10.1155/2013/453521

National Emergency Management Agency, NEMA (2013). *South-south lost 2.51trillion to floods in 2012.* https://nema.gov.ng/south-south-lost-n2-51trn-to-floods-in-2012-says-nema/ [Accessed 26th September, 2021].

Nwilo, P.C, C.J. Okolie and C.U. Onwuzuligbo. (2016). *Technological Advancements in Geodetic Infrastructure: The Nigerian Adaptation.* Paper presented at the Nigerian Association of Geodesy 2016 General Assembly/Conference, Enugu Nigeria, 1-15.

Ogbozige, F.J. (2022). *Modelling Monthly Rainfall of Calabar, Nigeria*

*Using Box-Jenkins (ARIMA) Method.* Tanzania Journal of Engineering and Technology 2022, 41(2):131-140. DOI: 10.52339/tjet.v41i2.786

Ogunsote, O.O., Prucnal-Ogunsote, B. (2002). *Defining Climatic Zones for Architectural Design in Nigeria: A Systematic Delineation.* Journal Environmental Technology 1, 14.

Ohlert, P.L., Bach, M. and Breuer, L. (2023). *Accuracy assessment of inverse distance weighting interpolation of groundwater nitrate concentrations in Bavaria (Germany).* Environ Sci Pollut Res 30, 9445–9455. https://doi.org/10.1007/s11356-022-22670-0

Ojigi, L. M., and Opaluwa, Y. D. (2019). *Monitoring atmospheric water vapour variability over Nigeria from ERA-Interim and NCEP reanalysis data.* SN Applied Sciences, 1(10), 1159. https://doi.org/10.1007/s42452-019-1177-x

Ojrzyńska, H., Błaś, M., Kryza, M. (2022). *Precipitable Water Content Climatology over Poland. Atmosphere* 2022, 13, 988. https://doi.org/10.3390/atmos13060988

Onafeso, O.D. (2023). *The Climate of Nigeria and Its Role in Landscape Modification.* In: Faniran, A., Jeje, L.k., Fashae, O.A., Olusola, A.O. (eds) Landscapes and Landforms of Nigeria. World Geomorphological Landscapes. Springer, Cham. https://doi.org/10.1007/978-3-031-17972-3_2

Piyanan Pipatsitee, Sarawut Ninsawat, Nitin Kumar Tripathi, Mohanasundaram Shanmugam, Patsharawadee Chitsutti (2023). *Estimating daily potential evapotranspiration using GNSS-based precipitable water vapor,* Heliyon, (9) e17747, https://doi.org/10.1016/j.heliyon.2023.e17747

Richard Cliffe Ssenyunzi, Bosco Oruru, Florence Mutonyi D'ujanga, Eugenio Realini, Stefano Barindelli, Giulio Tagliaferro, Axel von Engeln, Nick van de Giesen, (2020). *Performance of ERA5 data in retrieving Precipitable Water Vapour over East African tropical region,* Advances in Space Research, 65(8), 1877-1893, https://doi.org/10.1016/j.asr.2020.02.003

S. Sarkar, J. Kuttippurath and V. K. Patel (2023). *Long-term changes in precipitable water vapour over India derived from satellite and reanalysis data for the past four decades (1980–2020).* Environ. Sci.: Atmos., 3, 749. https://doi.org/10.1039/d2ea00139j

Scott Nevil, David KIndness and Suzanne Kvilhaug (2023). *Coefficient of Determination: How to calculate it and interpret the result.* (Date accessed: 23 September, 2023). https://www.investopedia.com/terms/c/coefficient-of-determination.asp

Shejule Priya Ashok and Sreeja Pekkat (2022). *A systematic quantitative review on the performance of some of the recent short-term rainfall forecasting techniques*. Journal of Water and Climate Change Vol 13 No 8, 3004 doi: 10.2166/wcc.2022.302.

Tolulope Dorcas Mobolade and Parastoo Pourvahidi (2020). *Bioclimatic Approach for Climate Classification of Nigeria.* Sustainability 2020, 12, 4192, doi:10.3390/su12104192

Urquhart L, Santos MC, Garcia CA, Langley RB, Leandro RF (2014). *Global assessment of UNB's online precise point positioning software.* IAG Symp Ser 139:585–592. https://doi.org/10.1007/978-3-642-37222-3_77

Wang, Haishen, Yubao Liu, Yuewei Liu, Yunchang Cao, Hong Liang, Heng Hu, Jingshu Liang, and Manhong Tu. 2022. *Assimilation of GNSS PWV with NCAR-RTFDDA to Improve Prediction of a Landfall Typhoon.* Remote Sensing 14, no. 1: 178. https://doi.org/10.3390/rs14010178

World Bank Group (2021). *Climate Change Knowledge Portal for Development, Practitioners and Policy Makers.* Nigeria - Climatology | Climate Change Knowledge Portal. (Date accessed: 23 September, 2023).

Yu, G.L., and Wong, D.W. (2008). *An adaptive inverse-distance weighting spatial interpolation technique.* Computers & Geosciences 34(9), 1044-1055. https://doi.org/10.1016/j.cageo.2007.07.010

Zhang, Y., Cai, C., Chen, B., & Dai, W. (2019). *Consistency evaluation of precipitable water vapour derived from ERA5, ERA-Interim, GNSS, and radiosondes over China.* Radio Science, 54, 561–571. https://doi.org/10.1029/2018RS006789

Zhao, Q., Yao, Y., Yao, W. & Zhang, S. (2019) *GNSS-derived PWV and comparison with radiosonde and ECMWF ERA-interim data over mainland China.* Journal of Atmospheric and Solar Terrestrial Physics, 182, 85–92.

Zhihao Wang, Peng Chen, Rong Wang, Zhiyuan An, Xueying Yang (2023). *Performance of ERA5 data in retrieving precipitable water vapor over Hong Kong,* Advances in Space Research, 71(10), 4055-4071. https://doi.org/10.1016/j.asr.2022.12.059

Zongwan Li, Changzeng Tang, Shihua Tang, Yue Zhang (2020). *Comparison of GNSS PWV and ERA5-Derived PWV based on GNSS PWV in Hong Kong, China.* The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-3/W10, 2020 International Conference on Geomatics in the Big Data Era (ICGBD), 15–17 November 2019, Guilin, Guangxi, China https://doi.org/10.5194/isprs-archives-XLII-3-W10-987-2020

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## Dharavi redevelopment to kickstart with survey

The Dharavi Redevelopment Project Pvt Ltd (DRPPL), a joint venture between the government of Maharashtra and the Adani Group, recently announced that a survey would be launched to collect data from the lakhs of slum dwellers living in Dharavi. The data will be used by the government to determine the rehabilitation eligibility of the residents. The survey will also create, for the first time ever, a 'Digital Dharavi,' an advanced library of one of the world's largest informal settlements.

The survey will begin from Kamla Raman Nagar, with a unique number being allotted to each slum tenement. This will be followed by laser-mapping of the respective lanes, known as a 'Lidar Survey'. A trained team will visit every tenement with an indigenously developed application to scan documents.

Dharavi encompasses several thousand industrial and commercial units manufacturing garments and leather items. *www.hindustantimes.com*

## UNCTAD-AIR initiative to harness geospatial technology

UNCTAD has partnered with the Atlantic International Research (AIR) Centre, a non-profit organization, to help Brazil and South Africa boost their earth observation capabilities.

The joint work will arm both countries with much-needed data to support evidence-based urban planning and management, and to report on their progress towards the Sustainable Development Goals. The initiative was announced at a global workshop on Earth observation held in the Azores, Portugal in January. *unctad.org*

## Kongsberg Geospatial adds Echodyne Radar to IRIS Terminal

Kongsberg Geospatial has partnered with Echodyne to accelerate and extend Beyond Visual Line of Sight (BVLOS) operations for Advanced Air Mobility (AAM) applications. The collaboration will provide enhanced situational awareness to Unmanned Aircraft System (UAS) operators by visualizing all airspace movement, cooperative and noncooperative, to ensure safe and reliable UAS operations. *www.echodyne.com*

## Amini and Zindi collaboration

A new partnership between Zindi, a data science company in Africa, and Amini, a pioneering data solutions provider, marks a significant step forward in the quest for agricultural innovation. This strategic alliance aims to harness on-the-ground data sources, creating and collating new agricultural datasets across the continent. *www.amini.ai*

## Contract awarded for Mumbai's digital twin

Genesys International secured a contract worth Rs 155 crore with the Brihanmumbai Municipal Corporation (BMC) to develop a 3D city model and map stack for Mumbai. This project is a significant development in applying advanced mapping technology to develop a highly accurate Mumbai 3D model, creating a unified mapping platform with multiple layers. The project aims to provide an elaborate and comprehensive overview of the city's landscape to enable precise planning and collaboration among various stakeholders. *www.timesofindia.con*

## Mosaic, Movella improve mobile mapping and geospatial analysis

Mosaic has joined forces with Movella to introduce a revolutionary integration that promises to redefine precision and efficiency in mapping and 3D reconstruction projects. This collaboration merges Mosaic's cutting-edge Mosaic 51 and Mosaic X camera systems with Movella's XVN, enhancing GIS platform integration and supporting extensive 3D reconstruction with unprecedented precision. *www.movella.com*



## EGNOS Safety of Life Assisted Service for Maritime Users

EGNOS, Europe's regional satellite-based augmentation system (SBAS), is adding a new service to its repertoire: The EGNOS Safety of Life Assisted Service for Maritime Users (ESMAS).

DGNSS, short for Differential Global Navigation Satellite System, is an enhancement to GNSS that was developed to correct errors and inaccuracies in the GNSS system and thus allow for more accurate positioning information.

Because it does not require any additional infrastructure, ESMAS is well-positioned to support navigation in ocean and coastal waters, including harbour approaches and entrances. All that is needed to utilise the service is an SBAS-enabled GNSS receiver developed according to the International Electrotechnical Commission (IEC) standards. With such a receiver onboard, a vessel can navigate with increased accuracy and can receive alerts signalling errors on GNSS with the objective to avoid unsafe situation. Furthermore, EGNOS interfaces NAVAREA coordinators, to timely provide Maritime Safety Information (MSI) - the navigational warnings and other urgent safety related messages - that could be broadcast to the ships using conventional channels.

Although the service targets merchant vessels, the ESMAS signal is available free of charge to all SOLAS-conforming vessels from EU Member States, Iceland, Norway and Switzerland.

The ESMAS offers a service tailored to maritime users to enable marine navigation in harbour entrances, harbour approaches and coastal waters of the European Union Member States and EGNOS contributing countries (Iceland, Norway and Switzerland) in line with the IMO Resolution A.1046. *www.euspa.europa.eu*

## Arabsat and Aldoria collaborate on space safety

Arabsat and Aldoria have announced the signing of a MoU to collaborate on enhancing space safety and security. This MoU sets the stage for expanded collaboration on key strategic initiatives and potential ventures. Under this agreement, Aldoria would provide its advanced space solution to Arabsat and its member countries, enhancing their capabilities in safeguarding space assets. Furthermore, the partnership includes plans for the establishment of one of Aldoria's sensor systems in an Arabsat member country, further strengthening space security measures in the region. *www.arabsat.com*

## StriX-3 reaches its target orbit

Synspective announced that StriX-3, its fourth SAR satellite, has successfully reached its target orbit and spread its wings. It was successfully deployed into a Sun-Synchronous Orbit (SSO) at an altitude of 561 km by Rocket Lab's Electron rocket from the Rocket Lab Launch Complex 1 on New Zealand's Mahia Peninsula.

StriX-3 is not a newly developed and designed satellite but was manufactured based on the same conceptual design as StriX-1. To successfully build the desired satellite constellation, parallel production, or the capability to concurrently produce several satellites, is necessary. *synspective.com*

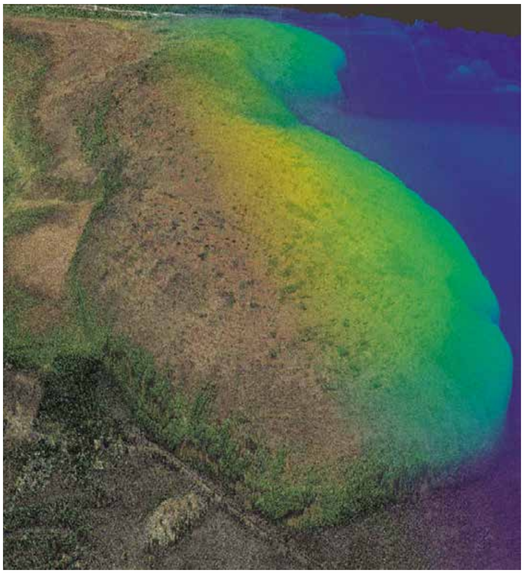
## Eyeonic Vision System Mini

SiLC Technologies, Inc. (SiLC) launched the Eyeonic™ Vision System Mini (Eyeonic Mini), a groundbreaking advancement in LiDAR technology. This innovative system, integrating a full multi-channel FMCW LiDAR on a single silicon photonics chip and an integrated FMCW LiDAR System-on-Chip (SoC), sets a new industry benchmark in precision. *www.silc.com*

## Researchers develop method to measure carbon stored in bogs

Researchers at Singapore-MIT Alliance for Research and Technology (SMART), MIT's research enterprise in Singapore, and Nanyang Technological University, Singapore (NTU Singapore), have developed a method that can accurately measure the amount of carbon stored in bogs. It uses satellite data and reduces the need for on-site sampling to derive the three-dimensional shapes of raised peatlands, also known as bogs, and hence the amount of carbon it contains.

The new mathematical model replaces earlier models whose accuracy is limited to specific bog conditions and was developed with collaborators from the Massachusetts Institute of Technology, University of Potsdam, Stanford University and the University of Minnesota.



Measuring carbon stocks in raised peatlands is challenging. The variable shape of bogs and varying depths of their carbon-rich soil known as peat, combined with their inaccessibility and vast size in many tropical regions, makes obtaining accurate data difficult, say the team of researchers. *https://smart.mit.edu*

## Omnispace tests LEO tech with Africa's biggest telco

Omnispace is testing its plan to use 600 low Earth orbit (LEO) satellites to deliver connectivity directly to smartphones and other devices in Africa. They will be partnering with MTN, the largest mobile network operator in Africa, to conduct these tests.

The network will rely on S-band spectrum to provide connection to mobile users even in areas with no cell tower coverage. *Omnispace.com*

## OxTS enhances autonomous vehicle validation solution

OxTS' GNSS-aided inertial navigation systems (INS) are now supported on the NVIDIA DRIVE autonomous vehicle (AV) development platform. The software plug-in, developed in-house by OxTS using the NVIDIA DriveWorks SDK, runs on the NVIDIA DRIVE AGX Orin developer kit.

The plug-in gives developers using NVIDIA DRIVE the ability to feed OxTS GNSS/INS data directly into the platform to access accurate reference localization data as ground truth and validate the performance of the other sensors or algorithms under test. *www.oxtx.com*

## Vodafone Turkey deploys Adtran optical cesium solution

Adtran has announced that Vodafone Turkey has deployed its Oscilloquartz optical cesium atomic clock technology to bring new levels of resilient timing to its nationwide network. It's first-to-market solution will deliver robust protection against disruptions to GNSS signals. By combining its existing Adtran Oscilloquartz core grandmaster clock devices with the new optical cesium atomic clock technology, Vodafone Turkey has an ePRTC+™ solution that guarantees accurate network synchronization during any possible GNSS unavailability. *www.adtran.com*

## DroneAcharya to train Adani Group in DGCA certified drone operations

DroneAcharya Aerial Innovations, a listed drone startup secured a significant service order from the Adani Group. This involves providing certified drone pilot training for DGCA (Directorate General of Civil Aviation). *financialexpress.com*

## Inertial Labs and E38 Company partnership

Inertial Labs and E38 Company have announced a strategic partnership that will see the integration of Inertial Labs' RESEPI Payload LiDAR technology into E38's advanced E455 drone platform.

RESEPI (Remote Sensing Payload Instrument) is a sensor-fusion platform for accuracy-focused remote sensing applications. It utilizes a high-performance Inertial Labs INS (GPS-Aided Inertial Navigation System) and a high-accuracy single or dual-antenna GNSS receiver integrated with a Linux-based processing core and data-logging software.

The E455 is an innovative fixed-wing vertical takeoff and landing (VTOL) UAS designed to operate on battery power with a maximum takeoff weight of up to 65 lbs. *inertiallabs.com*

## Partnership for cross-border drone delivery services

Aerodyne Group and DroneDash Technologies a leading air mobility company headquartered in Singapore have signed an agreement to introduce cross-border drone delivery services between Malaysia and Singapore. Under this partnership, UAVs will navigate through regulatory landscapes to secure necessary permits for establishing shore-to-shore operations along the Malaysia-Singapore corridor. The initiative focuses on safe navigation through congested maritime and aerial paths by offering a navigation system supported by satellite communications and 5G roaming. www.dronesworldmag.com

## Trimble, DroneDeploy collaborate on UAV mapping

Trimble has collaborated with DroneDeploy to integrate the Trimble Applanix POSPac Cloud post-processed kinematic (PPK) GNSS positioning service into DroneDeploy's UAV mapping and data collection platform. The partnership aims to provide DroneDeploy users with centimeter-level accuracy and a more efficient workflow for reality capture projects.

The integration uses Trimble Applanix POSPac Cloud PPK service and CenterPoint RTX post-processing to achieve high-accuracy positioning based on dual-frequency observables logged by UAVs. *www.trimble.com*

## UAV Navigation-Grupo Oesía unveils GNSS-denied navigation kit

UAV Navigation-Grupo Oesía has released its GNSS-denied navigation kit designed to offer navigation capabilities in challenging environments.

The kit combines UAV Navigation's attitude and heading reference system (AHRS), the POLAR-300, with its Visual Navigation System, the VNS01, designed to offer unmatched dead reckoning navigation capabilities with minimal drift.

The technology offers users improved navigational accuracy, with error rates as low as 0-1% over covered distances. As technology advances and geopolitical challenges emerge, the demand for reliable and secure navigation for UAVs intensifies. *www.uavnavigation.com*

## SimActive used for 3D mapping from oblique cameras

SimActive Inc. has announced the use of its Correlator3D™ product with multi-camera drone payloads for improved 3D mapping. The software allows users to import oblique and nadir camera configurations to develop better 3D mapping products. *www.simactive.com*

## Non-GPS Navigation for GPS-denied environments

Scientific Systems has announced that it is continuing development of ImageNav™, the company's non-GPS, image-based, precision navigation software. The company has recently extended and demonstrated its image-based solution during flight operations ranging from 25,000 feet down to 200 feet.

For many air vehicle flights, the military relies on the GPS for navigation, risking exposure to electronic jamming in contested environments. ImageNav software computes both absolute and relative navigation position updates by fusing the output of three different algorithms: stereo terrain correlation, image-based feature matching, and feature-based velocity estimation. *www.ssci.com*

## Iridium to expand as a Global Alternative PNT

Iridium Communications Inc. has announced that it had entered into an agreement to acquire Satelles, Inc., that complement and protect GPS and other GNSS-reliant systems. The service, named Satellite Time and Location (STL), is an easy-to-adopt, highly secure solution that increases the efficiency and reliability of timing systems for digital infrastructure like 5G base stations, data centers, and other critical infrastructure and protects against GNSS vulnerabilities using low-cost hardware that doesn't require outdoor antennas. This acquisition continues Iridium's philosophy of investing in differentiating technologies uniquely suited to its network that significantly outperform competing solutions. *www.iridium.com*

## SECO launches Qualcomm-based SOM-SMARC modules

SECO has released its first Smart Mobility Architecture (SMARC) System on Modules (SoMs) based on Qualcomm QCS6490 and Qualcomm QCS5430 application processors. These new modules are the first results of SECO's strategic collaboration with Qualcomm Technologies. The SOM-SMARC-QCS6490 is designed to simplify the use of the Qualcomm QCS6490 processor. The chipset offers support for artificial intelligence (AI) and computing, robust performance at low power and expanded interfaces and peripherals catering to diverse industrial use cases. *www.seco.com*

## Enhancing U.S. Navy's MQ-25A UAS

BAE Systems has been selected by Boeing to upgrade and modernize the vehicle management system computer (VMSC) for the U.S. Navy's MQ-25 unmanned aerial refueling system. The technology refresh will increase computing power and address obsolescence issues, providing the unmanned aerial tanker with an integrated solution that improves aircraft performance and allows for future capability growth. *www.baesystems.com*

## Leica Geosystems launches TerrainMapper-3

Leica Geosystems has introduced the Leica TerrainMapper-3 airborne lidar sensor. It features new scan pattern reconfigurability to support a variety of applications and requirements in a single system.

The system offers three scan patterns, which allow users to customize the sensor's performance to fit specific applications. Its circle scan patterns are designed to improve 3D modeling of urban areas or steep terrains. The ellipse scan patterns use data capture for more traditional mapping applications. Skew ellipse scan patterns are aimed at improving point density for infrastructures and corridor mapping applications. *leica-geosystems.com*

## Stonex launches hybrid mobile mapping solution

Stonex has launched the X70GO SLAM laser scanner. It combines mobile scanning with a stationary mode to scan with high resolution to enhance overall surveying capabilities. It is a real-time 3D model reconstruction device that integrates an inertial navigation module, high-performance computer and storage system. It is equipped with a 360° rotating head, which, combined with the SLAM algorithm, can generate high-precision point cloud data. The system comes with a hybrid scanning capability. The X-Whizz mode combines the advantages of SLAM mode with the resolution of a static scan, which eliminates the need for multiple scan stations. *www.stonex.it*

## Fairview Microwave announces military-grade antennas

Fairview Microwave has announced the launch of its advanced military-grade antennas. The new products include ruggedized GPS, manpack omni, and vehicle omni antennas designed to excel in mission-critical applications such as vehicle navigation, personnel communications, vehicle communications, electronic warfare and jamming. *www.fairviewmicrowave.com*

## GMV improves airport navigation performance

The European Organization for the Safety of Air Navigation (EuroControl) has awarded GMV a contract for the evolution of AUGUR, a free service for pilots, airspace users and air navigation service providers.

AUGUR is a web-based service that makes it possible to predict the availability of the GPS and receiver autonomous integrity monitoring (RAIM) navigation solution for a wide range of air operations. The RAIM processing algorithm, which is standardized and incorporated into most aeronautical GPS receivers, allows operators to check the integrity of GPS satellite signals by exploiting the redundancy of measurements offered by the current constellation.

Although only four satellites in view are needed to calculate the position and time of the aircraft, the current GPS constellation has 31 active satellites, meaning that the receivers are getting signals from more than four satellites much of the time. The RAIM technique takes advantage of these additional measurements to check the integrity of the satellites and ensure the position obtained is correct within the alarm limits established for each operation.

The improvements made to the AUGUR include RAIM GPS availability displayed on a map and the integration of the planned Navigation Integrity Category (NIC), which measures the quality of the aircraft navigation position transmitted via automatic dependent surveillance–broadcast (ADS-B). It also issues space weather warnings such as solar flares, geomagnetic storms and coronal mass ejections (CME) and has options to import or export geographic data in industry-standard formats. *www.gmv.com*

## CHC Navigation Unveils RS10

CHC Navigation has launched the RS10, handheld SLAM LiDAR laser scanner integrated with a full RTK GNSS receiver. Designed to improve the efficiency across a wide range of mapping and surveying applications, it provides professionals with a versatile, all-in-one tool for capturing rich 3D geospatial data in both outdoor and indoor environments. By combining survey-grade GNSS RTK receiver with the handheld LiDAR SLAM system, the RS10 simplifies workflows without compromising accuracy or flexibility.

## First UltraCam Osprey 4.1 in the Middle East

The Centre for Geographic Information Systems (CGIS), the State of Qatar's official geospatial agency under the Ministry of Municipality, acquired the very first UltraCam Osprey 4.1 photogrammetric nadir and oblique aerial camera system in the region. The advanced mapping and survey equipment solution purchased by CGIS goes beyond the UltraCam Osprey 4.1 system, encompassing the entire UltraMap processing suite, which includes five modules. Additionally, CGIS acquired a RIEGL laser scanner 780II-S and a RIEGL 880-GII bathymetric sensor for installation in a new DA62 MPP Survey Star from Diamond Aircraft.

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**GISTAM 2024**
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Angers, France
**https://gistam.scitevents.org**

**IGRSM Conference 2024**
29 - 30 April
Kuala Lumpur, Malaysia
**https://conference.igrsm.org**

### May 2024

**GeoIgnite 2024**
14-15 May 2024
Ottawa, Canada
**https://geoignite.ca**

**FIG Working Week 2024**
19 - 24 May
Accra, Ghana
**www.fig.net/fig2024/Welcome.htm**

**National Surveyors' Conference**
21 –24 May 2024
Cardigan, PE Canada
**https://www.acls-aatc.ca/nsc-2024**

### June 2024

**GEO Business 2024**
05 - 06 June
London, UK
**https://www.geobusinessshow.com**

### July 2024

**Esri User Conference**
15 - 19 July 2024
San Diego, CA, USA
**www.esri.com**

### August 2024

**International Geographical Congress 2024**
24 - 30 August
Dublin, Ireland
**https://igc2024dublin.org**

### September 2024

**ION GNSS +**
16-20 September
Baltimore, USA
**https://www.ion.org/gnss/index.cfm**

## ESA–JRC opens registration for GNSS summer school

The European Space Agency (ESA) and the European Commission's Joint Research Centre (JRC) are collaborating to host the 15th edition of the International Summer School on Global Navigation Satellite Systems (GNSS). The course is scheduled to take place in Novo Mesto, Slovenia, from July 15 to 26, 2024.

The summer school invites graduate students, Ph.D. candidates, postdoctoral researchers, engineers and academics from both the industry and agencies to attend. The wide range of attendees offers a dynamic environment conducive to learning and networking. *www.esa-jrc-summerschool.org*

## Geely launches LEO satellites

Chinese automaker, Geely has launched its second set of low-Earth orbit (LEO) satellites in its effort to enhance navigation capabilities for autonomous vehicles. The 11 satellites were launched from the Xichang Satellite Launch Center in Sichuan, China province.

## 1Spatial bags contract in Belgium

1Spatial have secured a three-year contract with a leading Distribution System Operator for electricity and gas networks in Belgium, following a competitive tender. The project will enable the utility company to carry out a wide range of activities including distribution network management, connection works and repairs, in a more efficient, cost-effective manner, ensuring the safety of its team and customers. *1spatial.com*


**FORM IV**

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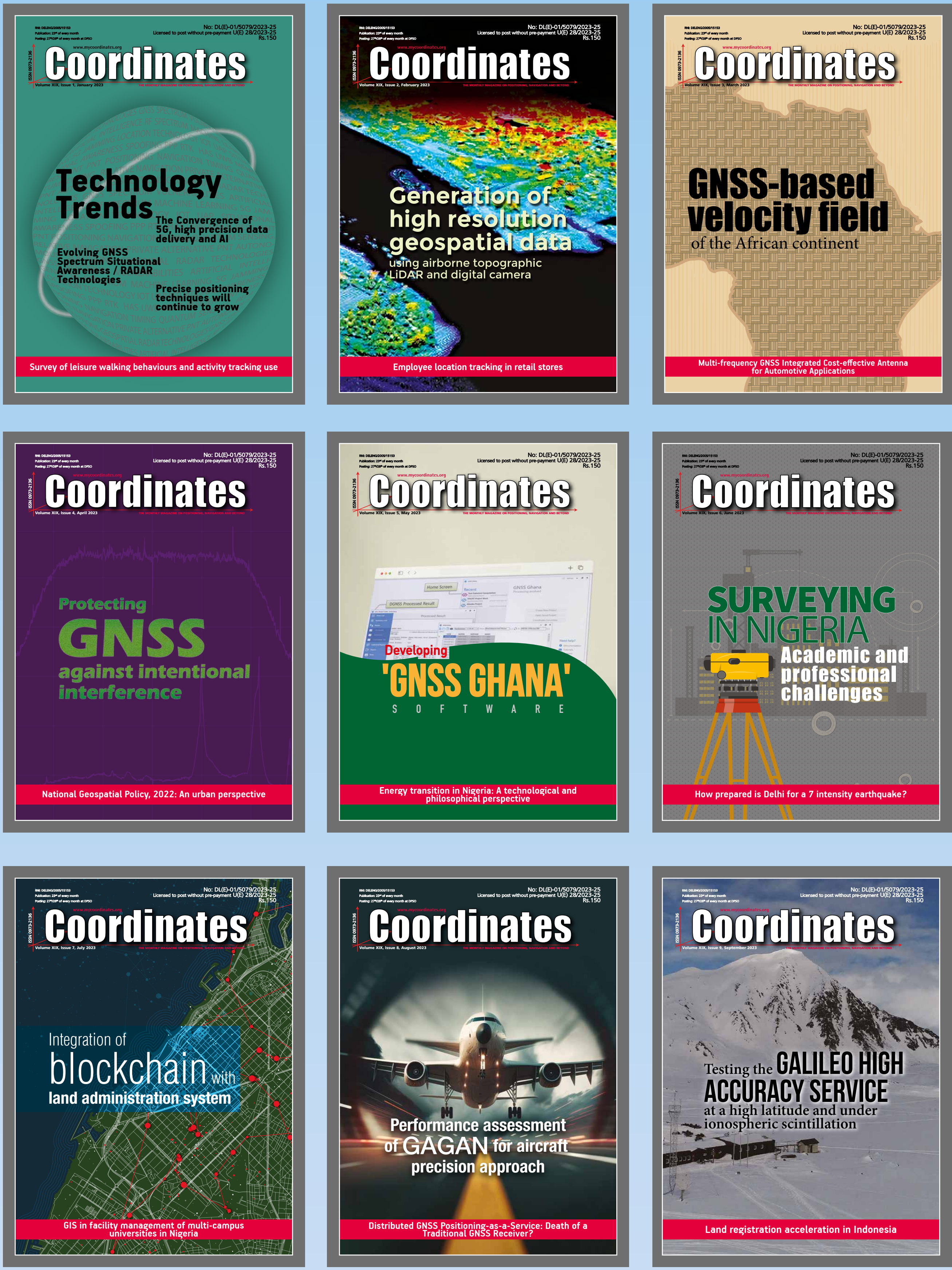
March 1, 2024 — Signature of publisher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