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Full Length Research Paper

Extraction of ionospheric vertical total electron content (VTEC) using global navigation satellite system-continuously operating reference station (GNSS-CORS) data from station BF01 in Ouagadougou

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Numerous raw data concerning the ionosphere exist almost everywhere in Africa. However, these data are underexploited due to the lack of simple methods to extract ionospheric parameters from the data. This paper presents a method for extracting vertical total electron content (VTEC) using Global Navigation Satellite System-Continuously Operating Reference Station (GNSS-CORS) raw data recorded between 01/01/2013 and 12/31/2021 at station BF01 (Latitude = 12.3714 N and Longitude = -1.5197 W) in Ouagadougou, Burkina Faso, located at the trough of ionization in the West African equatorial zone. This station is one of the stations in Burkina Faso that recorded data better continuously during the period of this study. This work involves the determination of VTEC using dual-frequency GPS measurements. Thus, the raw GNSS-CORS data in "T02" format were first converted into "Receiver INdependent Exchange Format" (RINEX) into time files in steps of 1 s. These files were then reorganized into daily files with 30 s steps, before being used for VTEC extraction. For this purpose, scripts were developed and run in Matlab. The extracted VTEC is saved in text and graphics files. With the result obtained, it is possible to dimension some fundamental characteristics of the ionosphere at low latitudes. It is also possible to produce spatio-temporal maps of TEC variations over Burkina Faso and even for the whole of West Africa at least if the CORS networks of neighboring countries are known.

Key words: Global navigation satellite system-continuously operating reference station (GNSS-CORS), vertical total electron content (VTEC), Receiver INdependent Exchange Format (RINEX), ionosphere.

INTRODUCTION

The global navigation satellite system (GNSS) has been implemented to provide worldwide coverage to give the

position of any user anywhere at any time whatever the weather conditions. The global positioning system (GPS)

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is one of the GNSS systems used by scientists to study space weather in order to improve knowledge of the physical and chemical processes taking place in the upper atmosphere and beyond.

GPS satellites orbit the Earth at an altitude of around 20200 km (Sammuneh, 2003; Tachema, 2020) and emit signals that cross the ionosphere to reach receivers on the Earth's surface. In fact, each GPS satellite transmits two electromagnetic carrier waves L_1 and L_2 in the band L (Boutiouta et al., 2006). The frequencies of these two signals are respectively noted f_1 and f_2 and are each multiple of a fundamental frequency $f_0 = 10.23 \text{ MHz}$ generated by the internal clock of each satellite: $f_1 = 154f_0 = 1575.42 \text{ MHz}$, and $f_2 = 120f_0 = 1227.60 \text{ MHz}$. Free electrons in the ionosphere affect the propagation of these signals, altering their speed and direction of travel. This causes major errors in GPS positioning and navigation (Dubey et al., 2006). The total number of free electrons encountered by signals between a satellite and the ground receiver is called total electron content (TEC).

TEC is one of the important parameters extracted from GPS data for ionospheric studies. It represents the total number of free electrons contained in a cylinder of unit cross-section whose axis is the line of sight to the satellite and which extends along the path L separating the satellite from the receiver. It is therefore obtained by integrating the density of free electrons (N_e) in a cylinder with a cross-section of 1 m^2 and a height equal to the oblique signal path separating the station from the transmitting satellite, according to Equation 1 (Klobuchar, 1973).

$$TEC = \int_R^S N_e \cdot dL \quad (1)$$

where R and S are the receiver and satellite positions, respectively. TEC is expressed in TECU with the relationship $1 \text{ TECU} = 10^{16} \text{ electrons/m}^2$.

Knowledge of this TEC parameter makes it possible to assess errors in GPS positioning and navigation and to calculate corrections. Several works (Warnant and Pottiaux, 2000; Ya'acob and al., 2010; Ouattara et al., 2011; Marković, 2014) present methods for calculating TEC from Receiver INdependent Exchange Format (RINEX) files supplied by GPS stations. These TEC calculation methods can be grouped into three categories (Arikan et al., 2003; Abdullah et al., 2008; Ya'acob et al., 2010): (1) TEC calculation using pseudoranges; (2) TEC calculation using carrier phase delays; and (3) making a combination of pseudoranges and carrier phase delays. All these methods use RINEX file data to determine the TEC. However, in many GPS stations, the raw signal measurements are recorded in binary according to the proprietary formatting of the manufacturer who developed the receiver. As a result, they cannot be used directly because their storage structure is unknown. It is therefore necessary to find alternatives for converting the binary

data into RINEX format, which is the recording format adopted internationally by scientists for archiving observations independently of the type of receiver (<https://igs.org/wg/rinex/>, consulted on 18/02/2023). In most cases, the manufacturer offers software to post-process the binary files into RINEX files. Another possibility would be to finding a method for calculating the total electron content directly from the raw binary data. With this in mind in this paper we propose the process of extracting total vertical electron content (VTEC) from global navigation satellite system-continuously operating reference station (GNSS-CORS) raw data collected from the IGeographic Institute of Burkina Faso (IGB). The IGB has a network of GNSS-CORS reference stations. This network comprises 13 permanent GNSS-CORS receiving stations (https://www.igb.bf/?page_id=47, consulted on 12/05/2023). At these stations, measurements are archived in hourly files at 1 s intervals resulting in a lot of very large files. Initially, this high recording rate is not necessary to estimate the morphology of the TEC because the variation of the TEC between very close instants are not appreciable. In order to comply with other databases, a first step will be to retain only 30 s measurements (instants 00 and 30 s) and compact them into daily files. This work is limited to the BF01 permanent station of the BF-CORS network, located in Ouagadougou (Latitude = 12.3714 N and Longitude = -1.5197 W). It begins with a presentation of the data processing methodology, followed by a description of the data, and then present and discuss the results obtained. Finally, conclusion was drawn.

DATA PROCESSING METHOD

Dual-frequency method

In this work, the TEC was obtained by combining pseudorange measurements made on the two GPS signal frequencies. The frequencies of the two electromagnetic waves carrier of each GPS satellite contain code modulation, so that by comparing them with the reference code, we can measure the code travel time of the codes between satellite and receiver. Each satellite has its own code, independent of the others: this is the coding technique used to recognize a satellite identified by its 'Pseudo-Range Number' (PRN). The propagation speed of a signal is variable and depends on the conditions encountered as it passes through the medium. It is also unknown, and we assume that the signal moves at the speed (group speed) of light in a vacuum. Knowing the signal propagation time Δt and the speed c_0 of light, we deduce the distance between the receiver and the satellite, called the Pseudo-distance or Pseudo-Range (PR) by Equation 2.

$$PR = c_0 \cdot \Delta t \quad (2)$$

The expression for the pseudo-distance measurement performed on a frequency f is given by the relation (Equation 3) (Hofmann-Wellenhof et al., 2012):

$$P_r^s(f) = \rho_r^s + c_0[\delta t_r(f) - \delta t^s(f)] + T_r^s + I_r^s(f) + \varepsilon_r^s(f) \quad (3)$$

where $P_r^s(f)$: The pseudo-distance between the receiver and the satellite for frequency f ; ρ_r^s : The geometric (real) distance between the receiver and the satellite; c_0 : The speed of light in a vacuum; $\delta t_r(f)$: The receiver's clock error for frequency; $\delta t^s(f)$: The error of the satellite clock for frequency; T_r^s : The tropospheric delay independent of frequency; $I_r^s(f)$: The ionospheric delay for frequency; $\varepsilon_r^s(f)$: The residual measurement error for frequency f .

The indices r and s represent the GPS receiver and satellite, respectively. The ionospheric delay $I_{r,f}^s$ at time t is $I_r^s(f) = \frac{a}{f^2} N_s$ where $a = 40,3$; f = frequency 1 or 2 and $N_s = STEC$ (the slant TEC).

By replacing the frequency f of (Equation 3) with the two frequencies f_1 and f_2 , we obtain:

$$P_r^s(f_1) = \rho_r^s + c_0[\delta t_r(f_1) - \delta t^s(f_1)] + T_r^s + I_r^s(f_1) + \varepsilon_r^s(f_1) \quad (4)$$

$$P_r^s(f_2) = \rho_r^s + c_0[\delta t_r(f_2) - \delta t^s(f_2)] + T_r^s + I_r^s(f_2) + \varepsilon_r^s(f_2) \quad (5)$$

We eliminate ρ_r^s and T_r^s by doing Equation 4-Equation 5.

$$P_r^s(f_1) - P_r^s(f_2) = c_0[\delta t_r(f_1) - \delta t_r(f_2)] - c_0[\delta t^s(f_1) - \delta t^s(f_2)] + I_r^s(f_1) - I_r^s(f_2) + \varepsilon_r^s(f_1) - \varepsilon_r^s(f_2)$$

We posit $P_1 - P_2 = P_r^s(f_1) - P_r^s(f_2)$ and $b = c_0 \delta t$ and replacing $I_{r,f}^s$ by $\frac{a}{f^2} N_s$, we get:

$$P_1 - P_2 = \Delta b_r - \Delta b^s + a \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) N_s + \varepsilon_r^s(f_1) - \varepsilon_r^s(f_2) \quad (6)$$

Δb_r and Δb^s represent receiver bias (DCBr) and satellite bias (DCBs), respectively. DCB stands for differential code bias.

For an elevation β greater than 10° , $\varepsilon_r^s(f_1) - \varepsilon_r^s(f_2)$ is assumed to be negligible and Equation 6 becomes:

$$P_1 - P_2 = \Delta b_r - \Delta b^s + a \left(\frac{1}{f_1^2} - \frac{1}{f_2^2} \right) N_s \quad (7)$$

The slant TEC (STEC) can be deduced as follows (Fleury, 2017):

$$N_s = \frac{1}{a} \left(\frac{f_1^2 f_2^2}{f_2^2 - f_1^2} \right) [(P_1 - P_2) + (\Delta b^s - \Delta b_r)] \quad (8)$$

If $\Delta b_r = \Delta b^s = 0$, we obtain the relative STEC.

$$N_s = \frac{1}{a} \left(\frac{f_1^2 f_2^2}{f_2^2 - f_1^2} \right) (P_1 - P_2) = \frac{1}{40,3} \left(\frac{f_1^2 f_2^2}{f_2^2 - f_1^2} \right) (P_1 - P_2) \quad (9)$$

In N_s , $(P_1 - P_2)$ is expressed in meters; P_1 and P_2 are supplied by the RINEX file; the satellite bias Δb^s is supplied by the Centre for Orbit Determination in Europe Global Ionosphere Maps (CODE

GIM or CODG) organization (DCB files); the receiver bias Δb_r is also supplied by CODG if it is an IGS station (https://www.aiub.unibe.ch/research/code_analysis_center/index_eng.html, consulted on 25/05/2023).

Converting slant TEC (STEC) to vertical TEC (VTEC)

STEC is a quantity that depends on the geometry of the signal path emitted by the satellite in the ionosphere (Figure 1). It is therefore desirable to calculate an equivalent vertical value (VTEC) of STEC that is independent of the elevation of the signal path. To compare the electron content of trajectories with different elevation angles, STEC must be transformed into VTEC.

To convert STEC to VTEC, we adopted the ionospheric single-layer model, where the ionosphere is considered as a single layer concentrated on a spherical shell of infinitesimal thickness located at an altitude H above the Earth's surface (Fraile-Ordóñez, 1995; Schaer, 1999; Fleury, 2017; Mannucci et al., 1998) (Figure 1). This model assumes that free electrons are concentrated in the infinitesimal shell. The layer height H is therefore generally chosen to correspond to the height of the maximum electron density at the peak of F2 layer. The altitude of this peak varies from 250 to 350 km at mid-latitudes and from 350 to 500 km at equatorial latitudes (Ya'acob et al., 2008). In this work, where the study station is located in the equatorial zone, we take H equal to 450 km.

The point of intersection between the line of sight of the satellite and the spherical shell (ionospheric layer) is called the Ionospheric Pierce Point (IPP). In Figure 1, the angle α represents the zenith angle of the GPS satellite at altitude H , and β is its elevation angle at the receiver position.

Using the secant law, the slant TEC (STEC) is reduced to the vertical by the following relationship:

$$VTEC = k \cdot STEC \quad (10)$$

where k is the translation coefficient (MP for 'Mapping Function') between the VTEC and STEC, given by the relation (Schaer, 1999):

$$k = \left(\sqrt{1 - \left(\frac{R_T}{R_T + H} \cos \beta \right)^2} \right)^{-1} \quad (11)$$

By replacing k , we thus obtain the final relationship between slant and vertical TEC:

$$VTEC = STEC \left(\sqrt{1 - \left(\frac{R_T}{R_T + H} \cos \beta \right)^2} \right)^{-1} \quad (12)$$

$R_T = 6371.2$ km is the average radius of the Earth.

Figure 2 shows the position of the various Pierce points (IPP) in relation to the position of station BF01 on 03/01/2013. There is a marked asymmetry in the number of IPP points; there are more, numerous to the West of the station than to the East. This could be due to signals from the East being masked by nearby obstacle(s). The shape of the individual passages and a greater number of points to the South of the station are linked to the trajectory of the GPS satellites, which do not pass through the geographical poles.

VTEC calculation algorithm

To determine the VTEC, we used a Matlab script (tec_notigs.m)

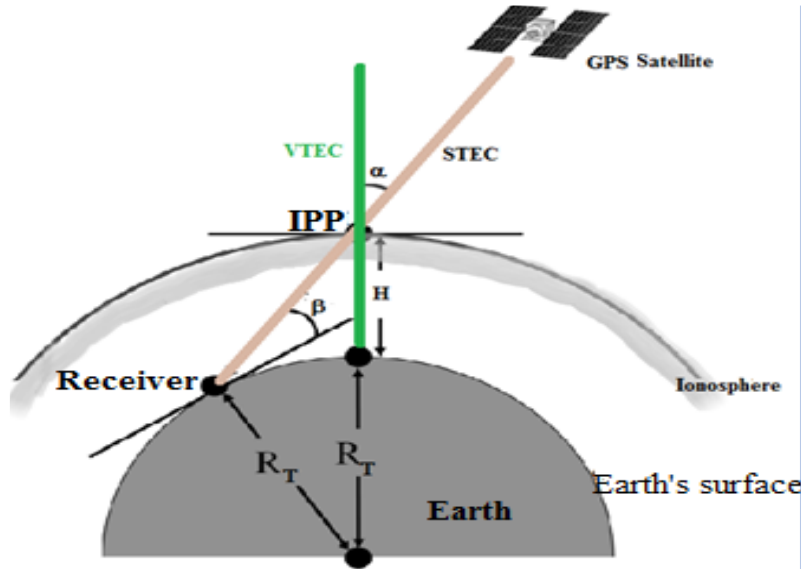


Figure 1. Geometric condition for converting slant TEC into vertical TEC in a thin-film hypothesis for the ionosphere.

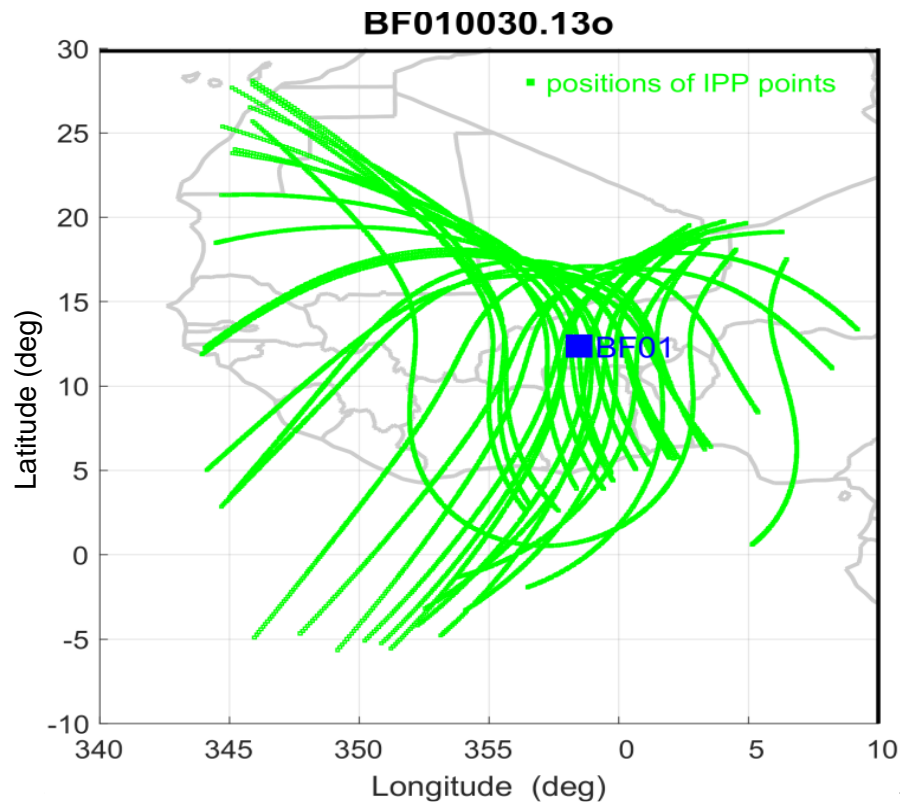


Figure 2. Geographical Positions of IPP points in relation to the position of station BF01 on 03/01/2013.

written by Fleury (2017). This program uses the two PR pseudo-distance measurements. It uses the daily RINEX files with 30 s

steps from station BF01, the satellite biases (DCB files), the Almanach (Yuma files) as input to calculate satellite positions and

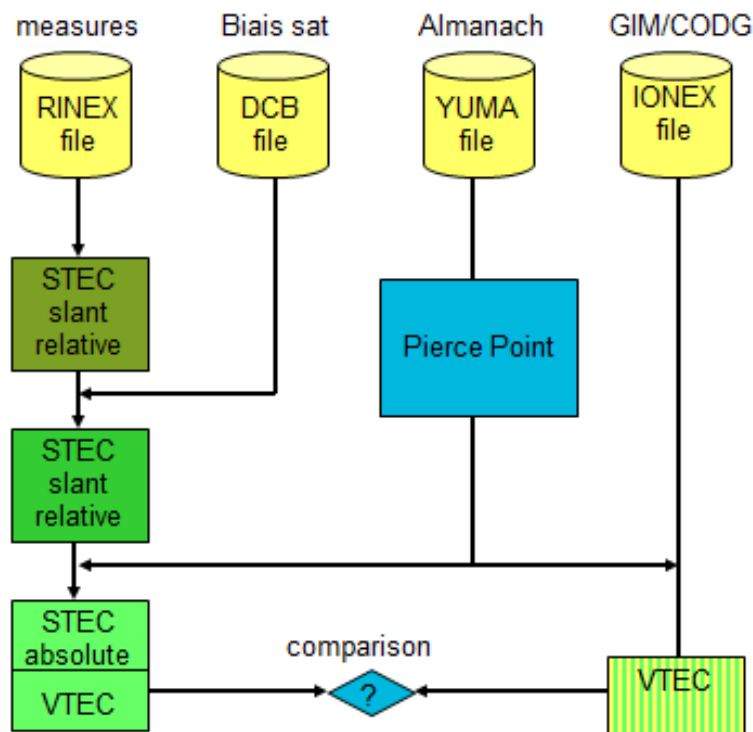


Figure 3. The stages of Rolland Fleury's programme.
Source: Fleury (2017).

the GIM/CODG model files. Figure 3 summarizes the algorithm used to determine the VTEC using `tec_notigs.m` in Matlab.

GNSS-CORS data

The raw satellite data used in this article are from GPS station BF01 in Ouagadougou (Latitude = 12.3714 N and Longitude = -1.5197 W) recorded between 2013 and 2021. They were obtained from the "Geographic Institute of Burkina Faso" (IGB). They can also be downloaded from www.bfcors.net website after registration. The receiver at the BF01 permanent station is a Trimble NETR8. The raw data are archived as hourly files with the extension "T02".

To obtain daily RINEX files with 30 s steps, the raw data underwent several pre-processing steps: conversion of raw data into RINEX, reorganization of data storage and creation of daily RINEX files with 30 s steps.

Conversion of raw data into RINEX

The raw data from station BF01 were not used directly to extract the ionospheric VTEC. They were first converted into RINEX files using the "Convert To Rinex" software acquired from the IGB. The Convert To Rinex software transforms raw binary data with the "T02" extension into RINEX format files. With this software, each "T02" format file produces three types of RINEX files: an observation file with the extension ".o", a navigation file with the extension ".n", and a GLONASS navigation file with the extension ".g". The observation files obtained are hourly files with data in 1 s steps.

Creation daily files with 30 s steps

The hourly RINEX files with 1 s steps are not used by the `tec_notigs.m` program, as it only performs the calculation with daily files and data sampled at 30 s intervals. To resolve this difficulty, an intermediate program "`cree_filejour_burkina.m`" was developed. This program takes the 24 files in RINEX format with 1 s steps for one day as input, concatenates them (keeping only one header in the RINEX structure) and outputs a daily file at 30 s intervals, also in RINEX format. This software can be run for one day, every day of the month or every day of the year. In all cases, the number of daily RINEX files with 30 s steps is equal to the actual number of days in the month or year.

To archive the new 30 s daily files, the files have been organized into a "year" folder and then into a "day of the year" sub-folder. For example, "C:\BF01\2013\001\" for the file for day 1 of the year 2013.

Daily RINEX file with 30 s steps

The 30 s daily RINEX files are observation files. There are 8 different measurements (line 13, Figure 4). The two (02) pseudo-range variables P1 and P2 used in the TEC determination expression (Equation 9) are circled in red.

Satellite biases (DCB files), almanacs (Yuma files) and GIM/CODG modelling (IONEX files)

The satellite biases (DCB files) are calculated on a daily basis, but to limit transfers, we have used the monthly files available at

1	2.11	OBSERVATION DATA				Mixed(MIXED)	RINEX VERSION / TYPE			
2	fichier journalier cree par R. FLEURY								COMMENT	
3	cnvtToRINEX 3.06.0				convertToRINEX OPR	28-Apr-22 11:39 UTC		PGM / RUN BY / DATE		
4	-----									
5	BF01								MARKER NAME	
6	BF01								MARKER NUMBER	
7	GNSS Observer				Trimble		OBSERVER / AGENCY			
8	5038K70648				TRIMBLE NETR8		4.48		REC # / TYPE / VERS	
9	TRM29659.00								ANT # / TYPE	
10	6228146.1213		-150832.4983		1363667.5436		APPROX POSITION XYZ			
11	0.0000		0.0000		0.0000		ANTENNA: DELTA H/E/N			
12	1	1	0	P1	P2	C1	C2	L5	C5	# / TYPES OF OBSERV
13	8	L1	L2	P1	P2	C1	C2	L5	C5	# / TYPES OF OBSERV
14	Forced Modulo Decimation to 30 seconds									
15	30.0000									
16	2013	1	1	0	0	0.0000000		GPS		TIME OF FIRST OBS
17	0									
18	16									
19	CARRIER PHASE MEASUREMENTS: PHASE SHIFTS REMOVED									
20	END OF HEADER									
21	13	1	1	0	0	0.0000000		0		16G02G09G12G15G18G24G25G26G29R01R07R09
22	R10R11R20R21									
23	127900582.372		99662843.981		0.000		24338683.258		24338677.961	
24	0.000		0.000		0.000		0.000		0.000	
25	116131090.278		90491841.151		0.000		22098989.941		22098982.555	
26	0.000		0.000		0.000		0.000		0.000	
27	112342013.070		87539344.918		0.000		21377977.992		21377971.641	
28	21377978.109		0.000		0.000		0.000		0.000	
29	110802885.583		86339988.510		0.000		21085083.102		21085077.078	
30	21085083.340		0.000		0.000		0.000		0.000	

Figure 4. Extract from the daily 30s RINEX file for 1st January 2013 from station BF01 in Ouagadougou.

<http://ftp.aiub.unibe.ch> website (consulted on 25/05/2023). For each year, we manually downloaded and decompressed 12 files.

GIM/CODG data are available at <http://ftp.aiub.unibe.ch/CODE/> (consulted on 25/05/2023). These are daily files. We downloaded and manually decompressed 365 or 366 files, depending on the year.

The almanac files in Yuma format are also daily files at <https://celestrak.org/GPS/almanac/Yuma/> (consulted on 25/05/2023). For each week, we downloaded the file with the time 319488 s and renamed them manually as yumaxxx.txt, where xxx is the GPS week number. This number is three characters long until September 2018, and four characters from that month onwards. A metric precision on the position of the satellites is sufficient for the calculation of the TEC, so this daily file is used for the entire GPS week which is running from Sunday at 00TU to the following Saturday at 24TU; the days are numbered from 0 to 6.

Figure 5 summarizes the various steps involved in extracting the VTEC from raw GNSS-CORS data from BF01 in Ouagadougou.

RESULTS AND DISCUSSION

The tec_notigs.m software developed in Matlab can process a year's worth of measurements in a single run. The output is three files for each day present: one (01) text file and two (02) graphics files.

The text file (Figure 6a) gives the VTEC values from the daily RINEX files with 30 s steps, and the VTEC values from the GIM/CODG files as a function of time. With these text results, it is possible to study the regular

and irregular (during disturbed periods) variability of the ionosphere above station BF01 in Ouagadougou.

The first graph (Figure 6b) shows the interpolated variation of the CODG VTEC (green dashed line) and the VTEC calculated from RINEX measurements (red line) for the station. This graph allows a comparative study of the VTEC extracted from the RINEX files with that of the CODG model.

On the second graph (Figure 6c), each red dot corresponds to the VTEC at the IPP. The black dots are an estimate of the VTEC by the Rolland Fleury model at station BF01. This graph is possible to verify that the receiver bias was correct, so as not to give "too many" negative VTEC values (particularly in the hours preceding sunrise). The individual VTEC values will be used (1) to estimate the horizontal ionization gradient (North-South and West-East in particular) and (2) for temporal monitoring of the position of the northern peak of the equatorial anomaly, due to the position of the BF01 station relative to the magnetic equator.

The results of the present study are similar to those of other previous works that have directly used RINEX files recorded at GPS stations. These include Ouattara et al. (2011) who used RINEX files from the Koudougou station in Burkina Faso, and Azzouzi (2016) who worked on 6 GPS stations located on a 50° latitudinal chain linking the middle and low latitudes of the Europe-Africa sector.

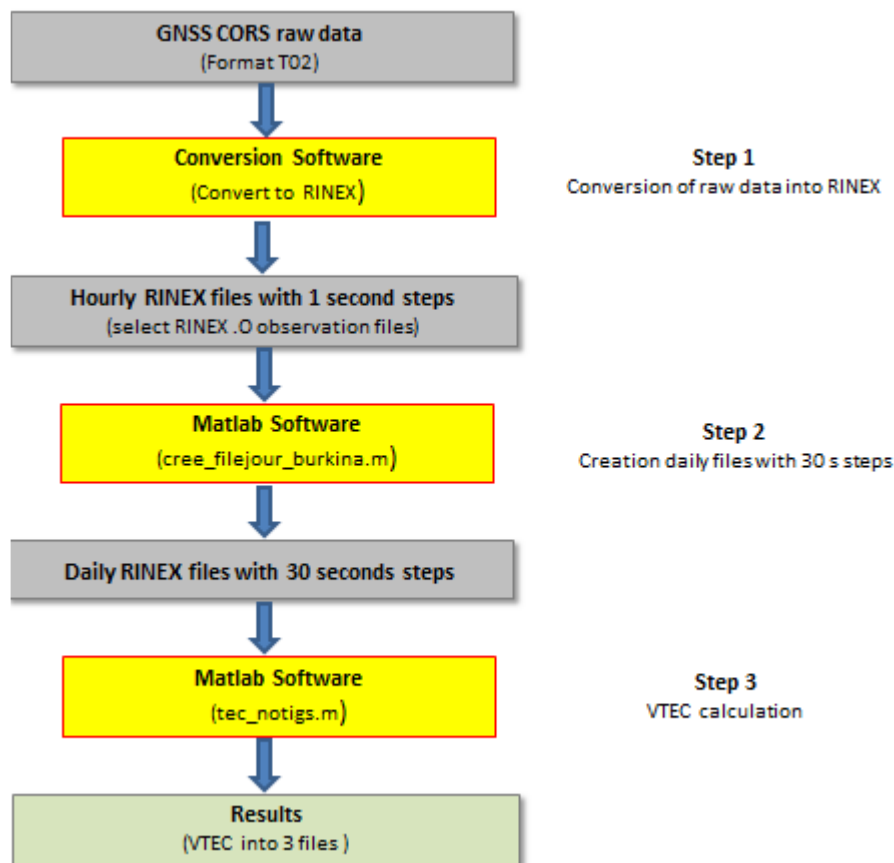


Figure 5. The various stages in extracting the VTEC from raw GNSS-CORS data for BF01 in Ouagadougou.

In view of the results, we consider that we have a method for extracting the VTEC at the BF01 station in Ouagadougou. This VTEC extraction method is applicable to all GPS stations whose data are archived in binary files with the extension "T02". It is thus possible to process each GNSS station in the CORS network in Burkina individually.

The present method has the advantage of using *in situ* data, so all parameters that could impact the ionosphere (even irregular phenomena) are taken into account in the extracted VTEC, unlike methods (Daniel et al., 2019; Lilian et al., 2019) using data from ionospheric models. Another advantage of our method is that it uses raw binary data in "T02" format directly, whereas most methods (Arikan et al., 2003; Ya'acob et al., 2010; Ouattara et al., 2011) use RINEX files as input, yet not all stations automatically convert their binary archives to RINEX format.

The major limitation of the method of the present study lies in the conversion of binary data with the 'T02' extension to RINEX format, where, at most, only the data of a single day can be converted in a single run. This is

too time-consuming for intensive data mining (at least one year).

Conclusion

The development of the CORS network in Burkina Faso is intended to provide national coverage for the positioning and mobility of the inhabitants of the country, as well as for geodesy. The archiving of measurements is important for scientific work that takes into account all the files. The Geographical Institute has made these measurements available to the scientific community of Burkina Faso. The existence of a long series of measurements between 2013 and 2021, unfortunately with a few off-periods, has enabled us to calculate the VTEC over the BF01 station in Ouagadougou.

In this work, we have given the expression of the TEC and clearly presented the process of extracting the VTEC from the raw GNSS-CORS data of the BF01 station.

With the result obtained, it is possible to dimension some fundamental characteristics of the ionosphere at

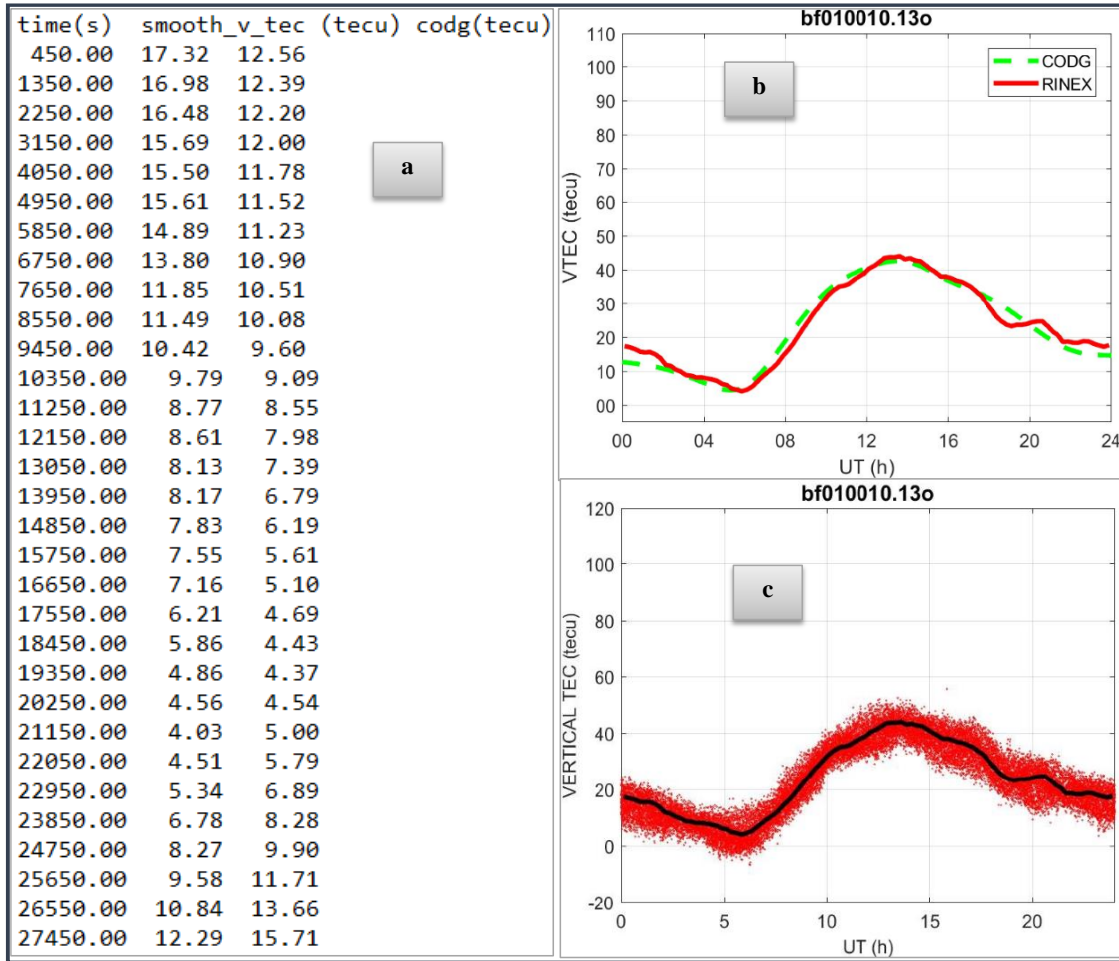


Figure 6. Extracts from BF01 data processing results files for 01/01/2013. a: extract from the text file; b. and c: graphics files.

low latitudes. It will also be possible to draw up spatio-temporal maps of VTEC variations over Burkina Faso, and at least for the whole of West Africa if the CORS networks of neighbouring countries are known. A study of the tropospheric contribution to these measurements will also be possible for future students in Burkina Faso. Studies will have to take into account the existing series of TEC variations to create an ionosphere model as accurate as possible, so that it can be integrated into future SBAS corrective systems over Africa.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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