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The Development of Cost-Effective GPS Receiver for Ionospheric Scintillation Monitoring Aided with IoT System

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ABSTRACT

One of the applications of GPS receiver is to detect and measure the irregularities in satellites communication. Many of the studies conducted the research to analyses the transmission data through ionosphere layers. One of the subjects of the research is scintillation. One of the ionosphere scintillation parameters used for measuring the irregularities is amplitude scintillation (S4). However, the survey-grade or GISTM receiver, which is expensive, was commonly used to monitor the parameter. The other alternative is to used common geodetic GPS receiver that capable of collecting the parameters. This study used ZED-F9P with ANN-MB antenna and Raspberry Pi as the prototype to operate. The data collected during the autumnal equinox showed a pattern of strong ionospheric scintillation effects in the post-midnight hours. The study demonstrates the feasibility of using low-cost GNSS receivers for ionospheric monitoring, which has important implications for various applications such as navigation, communication, and space weather monitoring.

Keywords:
GNSS; GPS; GLONASS; GALILEO; BEIDOU; ionosphere scintillation; low-cost GNSS; amplitude scintillation (S4); raspberry Pi 4; ZED-F9P GNSS receiver

1. Introduction

One of the main applications of Global Navigation Satellite System (GNSS) is to determine the location and movement of the target object with precision and high accuracy. The GNSS constellation also can be used to track and study the satellite communication affects in ionosphere, one of the atmosphere's layers which cause most delay in radio signal. The study by researchers is usually based on the survey-grade receivers or GISTM to collect and measure the ionospheric parameters but both of these options are expensive and very scarce [1,2]. Thus, by using a common geodetic receiver that is more accessible and cost-effective, the low-cost GNSS receiver was used to evaluate their performance in monitoring the ionosphere layer [3-6].

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The ionosphere is part of earth's atmosphere layers that have a high concentration of electrons and ions [7,8]. It is formed by the interaction of solar radiation and space weather within many layers of the atmosphere [9]. The ionosphere layers existed by collecting electrons and ions that range from 50 km to 1000 km in earth's latitude, and in Figure 1 show the division of regions based on ion density [10]. These regions included D-region (50 km to 90 km), E-region (90 km to 140km) and the region with the highest intensity is F-region [11,12]. The F-region has a very high density of ions and also divided into F1 and F2 layers where the latter have a most scintillation event due to the intense of electron and ion activity [13].

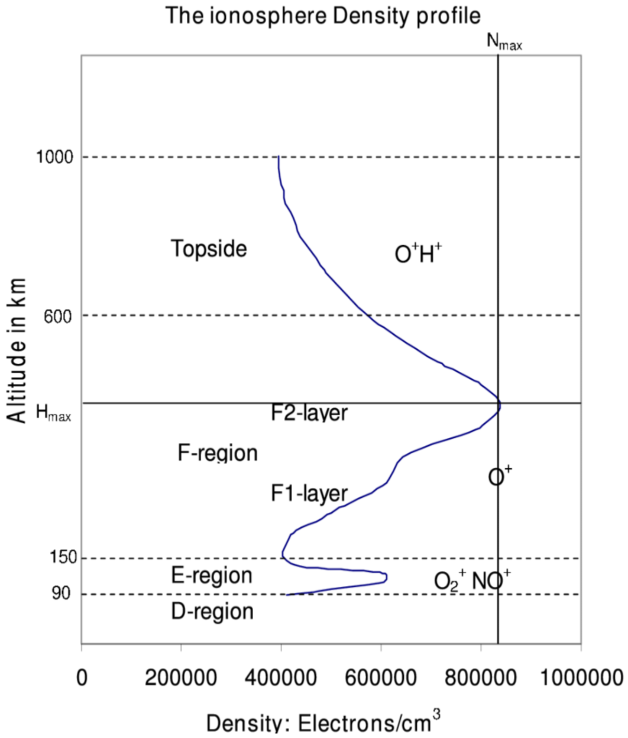


Fig. 1. The ionosphere's region [10]

The ionosphere's ionized layers can cause signal transmission fluctuations from satellites and known as ionospheric scintillation. This phenomenon occurs due to rapid changes in' signal amplitude and phase as it passes through the ionosphere [14]. One way to measure this is through the amplitude scintillation parameter (S4), which determines the level of power fluctuation and noise exposure during transmission. The other is phase scintillation (σϕ) used to analyse receiver clock errors or cycle-slips [15]. The S4 index is derived by detrending the intensity of the received signal and can be categorized into four types, as shown in Table 1 [16]. While phase scintillation used standard deviation of the detrending of carrier-phase measurement.

Table 1
Type of scintillation index [16]

Scintillation index	Types of scintillation
S4< 0.2	Negligible
0.2 ≤ S4< 0.3	Weak scintillation
0.3 ≤ S4< 0.4	Moderate scintillation
S4 ≥ 0.4	Strong scintillation

This phenomenon compromises GNSS navigation by creating substantial changes of electron distribution in the amplitude and carrier-phase of GNSS measurements, causing the increased of noise or even a lock loss in the GNSS receiver's tracking loop. Although the occurrences of ionospheric event were global phenomenon, the scintillation is mostly observed near the low latitudes and both polar regions. The disruptions in GNSS caused by the ionosphere are linked to space weather occurrences like geomagnetic storms at high latitudes and the formation of plasma bubbles after sunset across equatorial latitudes [17].

The Global Positioning System (GPS) is the most well-known GNSS constellation system, which been maintained by United States government and support by any device that accessible with GPS receiver [18]. There several other GNSS systems is used around the globe, including GLONASS (Russia), Galileo (Europe), and BeiDou (China). The most commonly used GNSS system in Malaysia and the equatorial region is the GPS system. However, due to the unique positioning and environmental challenges presented by the equatorial region, other GNSS systems are also increasingly being used [19].

Internet of Thing (IoT) technologies entering a new phase with wide application was built around the system amid to the pandemic. The usefulness of IoT system is that can be used to connect the physical devices, such as GPS, embedded into the network, which enable them to exchange and record the data within other devices over the internet [20]. IoT applications in recent researchers' projects are primarily used to monitor and control research prototypes in real time across an interconnect network, saving money and time [21,22].

This paper will be discussing the application of a low-cost receiver instead of survey-grade geodetic receiver. The prototype will be embedded with IoT application to store and plot the real-time parameters collect by cost-effective receiver. The GPS constellation data only be used on the data recording with 10 Hz sampling rate. The parameter focused on the S4 index only. In this paper, section 2 provides the details of chosen component for the prototype and introduction into the methodology. The result and discussion of the parameters in section 3.

2. Methodology

This paper will be discussing the application of a low-cost receiver instead of survey-grade geodetic receiver. The prototype will be embedded with IoT application to store and plot the real-time parameters collect by cost-effective receiver. The GPS constellation data only be used on the data recording with 10 Hz sampling rate.

The U-Center software and RTKLIB program were employed as external software tools. The U-Center software is the official program for managing U-Blox GNSS receivers, and it was used to configure the initial settings for the ZED-F9P, including the message protocol type [23]. On the other hand, the RTKLIB is an open-source program that was utilized to handle the GNSS data for processing [24]. This program is portable and supported on both Windows and Linux systems, whereas the latter is essential for running in the Raspberry Pi 4 operating system.

The raw GPS data collected and recorded inside the Raspberry Pi 4 storage using the sub-program from RTKLIB, the STR2STR to continuously running. While at the same time the other sub-program, CONVBIN used for translating and convert the raw data to readable RINEX message. RINEX or Receiver Independent Exchange Format message is standard format for satellite navigation system. This message contains observation and navigation file, where each observation file provides the measurements from satellite signal include the signal arrival time, the satellite identifier, the carrier phase, and the pseudo range, among others, while the latter contains navigation message of the orbit and satellites’ clock data.

Then, the RINEX file will be extracted into table in Python for further calculation. For the S4 index, signal intensity and signal-to-noise ratio (SNR) was extracted. The flowchart in Figure 2 explained in simple form about the process.

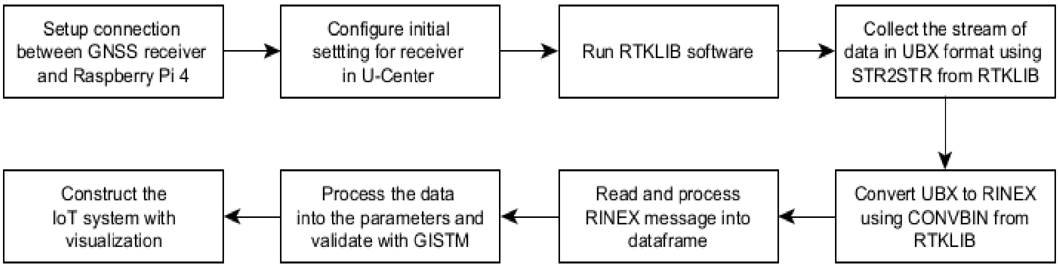


Fig. 2. The flowchart for retrieve the parameters from the prototype

The parameters used sample of 60S for both σφ and S4 index.

$$S_{4T} = \sqrt{\frac{\langle SI^2 \rangle - SI^2}{\langle SI \rangle^2}} \tag{1}$$

The *SI* stand for signal intensity received. $<SI^2>$ is mean of signal strength while $<SI>^2$ is standard deviation of signal strength and normalized by its mean over 60 seconds [15,25].

$$SI = \log_{10}(C/N_0) \tag{2}$$

The C/N_0 measurement of the carrier noise density in dB-Hz and calculated into *SI*, signal intensity. The experiment represents both parameters collected by ZED-F9P receiver and ANN-MB antenna from GPS constellation. The raw data used the sampling rate of 10 Hz (0.1s) while averaging of 60s.

For the IoT system, it can categorize into three part, IoT device, IoT gateway and IoT cloud server. The IoT device is the physical sensor that used to connect through IoT gateway and store the data in cloud server. For the IoT device, the prototype consists of the ZED-F9P receiver and ANN-MB antenna. It operated by Raspberry Pi which capable to connect to internet through Wi-Fi connection for IoT gateway. The cloud server in this paper was InfluxDB time series [26].

3. Results

3.1 The Prototype

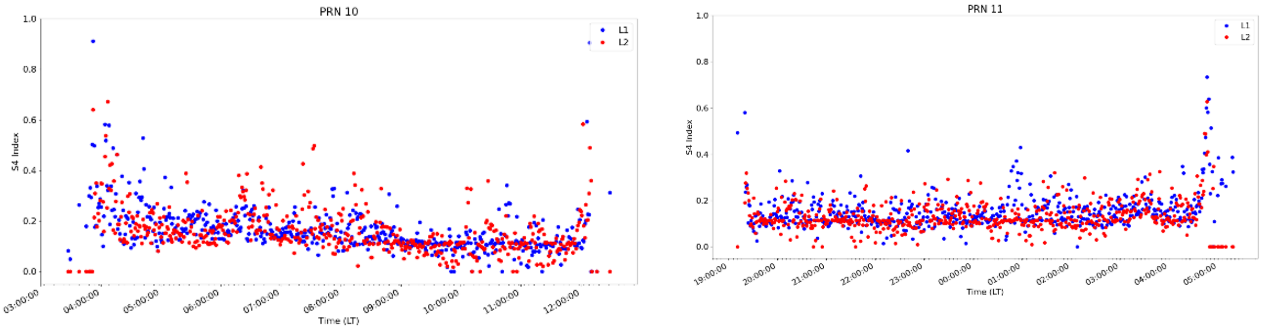
The assembly of the prototype was plain and simple. The connection between the ZED-F9P receiver and the Raspberry Pi was made using a micro-USB cable connector with an ANN-MB antenna, as shown in Figure 3. The Raspberry OS was utilised as the primary operating system, and Python was used as the programming language. The receiver's default sampling rate is 1 Hz, although the GISTM or survey-grade geodetic receiver can support data rates of up to 50 Hz. The prototype can be adjusted up to 10 Hz while using only one constellation (GPS) without errors.

(a) (b)

Fig. 3. The prototype (a) Connection between Raspberry Pi 4 and ZED-F9P receiver (b) with ANN-MB antenna

3.2 The Amplitude Scintillation (S4)

Data for the parameter was gathered on the local time of autumnal equinox, which was September 23, 2022. The data was collected with a sampling rate of 10 Hz (0.1 second) over a period of 36 hours. The degree of amplitude scintillation can be categorized as weak, moderate, or strong scintillation. The Figure 4 show the initial result of S4 index for from PRN 10 and PRN 11 for L1 (1575.42 MHz) and L2 (1227.6 MHz) frequency.



(a) (b)

Fig. 4. The S4 index for (a) PRN 10 (b) PRN 11

The parameter calculated using Python first, and then it sent to IoT cloud for storing and visualize the data in real-time. This study used the data from PRN 2, 10, 11, 13, 19, and 20 on autumnal equinox. The findings from the study revealed strong ionospheric scintillation effects that were observed post-midnight. This was confirmed through the data presented in Figure 5, which indicated a clear pattern of an upsurge in amplitude scintillation for variables corresponding to PRN 2, 10, 11, 19, and 20. According to the collected data, the parameters of ionospheric scintillation started to rise gradually from midnight until 01:00. By this time, the scintillation had intensified to a level of strong amplitude, indicating significant fluctuations in the GNSS signal. The scintillation parameters then began to decrease, reaching a relatively weak scintillation by 06:00. The majority of the data points were concentrated between the time periods of 02:00 to 05:00, where the scintillation effects were most prominent. These results suggest that the ionospheric conditions during this time frame are particularly challenging for GNSS receivers and may impact the accuracy and reliability of positioning and navigation services.

However, it was observed from the data collected during daylight hours that it ranges from weak to moderate level scintillation while rapidly rise after sunset shown in PRN 13 at 07:00. But there some few increments during daytime because of the occurrence of scintillation is bit higher during autumnal equinox compare to vernal equinox [27].

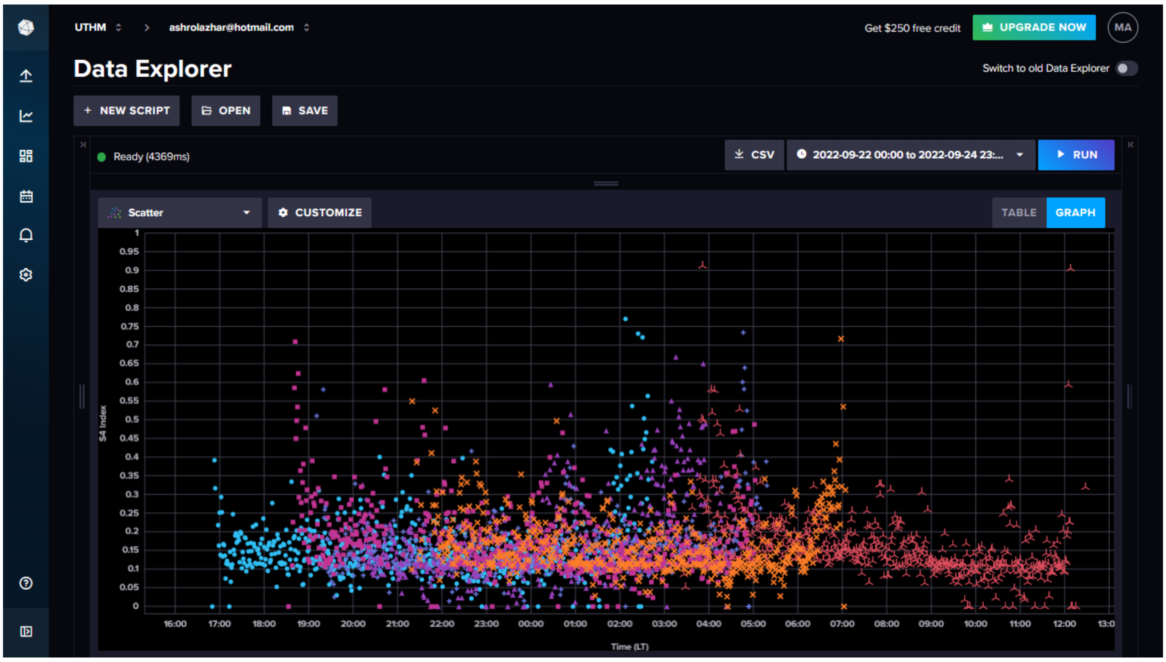


Fig. 5. The plotted graph of the S4 index in IoT platform, InfluxDB

4. Conclusions

The conclusion from the study conducted using a low-cost GNSS receiver, ZED-F9P controlled by Raspberry Pi, and ANN-MB antenna from U-Blox, it was found that strong ionospheric scintillation effects were present in the post-midnight hours during the autumnal equinox on September 23, 2022. The data indicated a rise in parameters from midnight until 01:00, reaching strong scintillation, and then steadily decreasing until 06:00, whereas concentrate between 2:00 and 5:00. The result obtained demonstrate capability of the cost-effective solution to monitor the S4 index parameter especially in areas where there is a lack of sophisticated infrastructure. Furthermore, it was very flexible in-term using the open-source program, such as RTKLIB and portable solution for data processing, which can be run on a Raspberry Pi, an independent mini-computer with connection to IoT system. Overall, this study provides values insights into the potential implementation of low-cost GNSS receivers and open-source software for ionospheric monitoring, which has substantial implications for a variety of applications including aviation, maritime, and telecommunications.

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