Onboard Processing and Real-Time Monitoring of Equatorial Ionospheric Scintillation and TEC - ScintPi

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1. MOTIVATION

- Ionospheric scintillation has been historically measured by **specialized** and relatively **high-cost** receivers. This is, in great part, due to their ability to sample intensity and phase measurements from Global Navigation Satellite System (GNSS) signals at high sampling rates and fidelity.
- The high cost of these professional-grade tools has **limited the deployment** of arrays scintillation monitors. As a result, scintillation monitoring coverage remains **sparse** over many regions of the world.
- ScintPi can be described as a series of **low-cost multi-constellation, dual-frequency** scintillation and total electron content (TEC) monitors [1,2]. It is an easy to install and maintain alternative developed by the UTD's UARS Lab for **educational** and **research** initiatives.
- Previous studies demonstrated the potential of ScintPi monitors for use in **autonomous, solar-powered stations** [3]. Applications of the station, however, were limited by the high bandwidth requirement of the receivers (several GB/day).
- In this project we contribute with the efforts related to (1) deployment of scintillation monitors at locations with limited internet availability and (2) delivery of scintillation measurements in real time.

2. PROJECT OBJECTIVES

Presented here is a student-led project with the following main objectives:

Objective 1: Compute **scintillation indices and Total Electron Content** (TEC) in **real-time** for ScintPi Monitors.

Objective 2: Develop a real-time **visualization tool** to assist space weather monitoring and early detection of scintillation events.

3. INSTRUMENTATION & SETUP

- ScintPi 3.0 provides **high-rate measurements** of signal strength (carrier-to-noise ratio, C/N_0) and phase at up to 20 Hz for all GNSS satellites in view.
- We deployed the real-time framework on a ScintPi 3.0 unit at **the Jicamarca Radio Observatory** as a test station with coordinates: 11.95° S, 76.87° W, 0 ° dip lat. Here **scintillation is known to occur commonly** especially near the locations of the equatorial ionization anomaly peaks.

Figure 1. (Left) Team member holding a ScintPi 3.0 scintillation monitor [2] used in this project. Cost of parts including antenna: ~600 USD. (Right) View of the Jicamarca Radio Observatory in Peru where the real-time system was implemented and tested.

4. METHODOLOGY

4.1 Data Products

- For each GNSS satellite, **the S_4 index** has been estimated using samples of the signal power (I) measured over 1-minute and the following relationship [4]:

$$S_4 = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle}$$

- The **TEC** has been estimated using **dual-frequency** (f_i) **carrier-phase observables** (Φ_i) :

$$TEC = \frac{1}{40.3} \frac{f_1^2 f_2^2}{f_1^2 - f_2^2} (\Phi_1 - \Phi_2)$$

4.2 Real-time Onboard Processing and Downsampling

- The **original ScintPi pipeline** used post-processing, **where raw 20 Hz GNSS data** were stored first, transmitted as compressed binary files, and **processed later.**
- **Real-time processing** was added by separating data acquisition and computation **using parallel processing in C**.
- Scintillation indices S_4 are computed onboard in 1-minute intervals from high-rate carrier-to-noise and **carrier phase is downsampled** to 1/60 Hz.

4.3 Cloud-Based Visualization and Internet Dashboard

- On the cloud service, **TEC is computed** using the **downsampled carrier phases**.
- A real-time web dashboard was developed using Dash, Plotly, and Azure App Services to continuously visualize incoming scintillation and TEC data streams with **automatic 5-minute updates**.

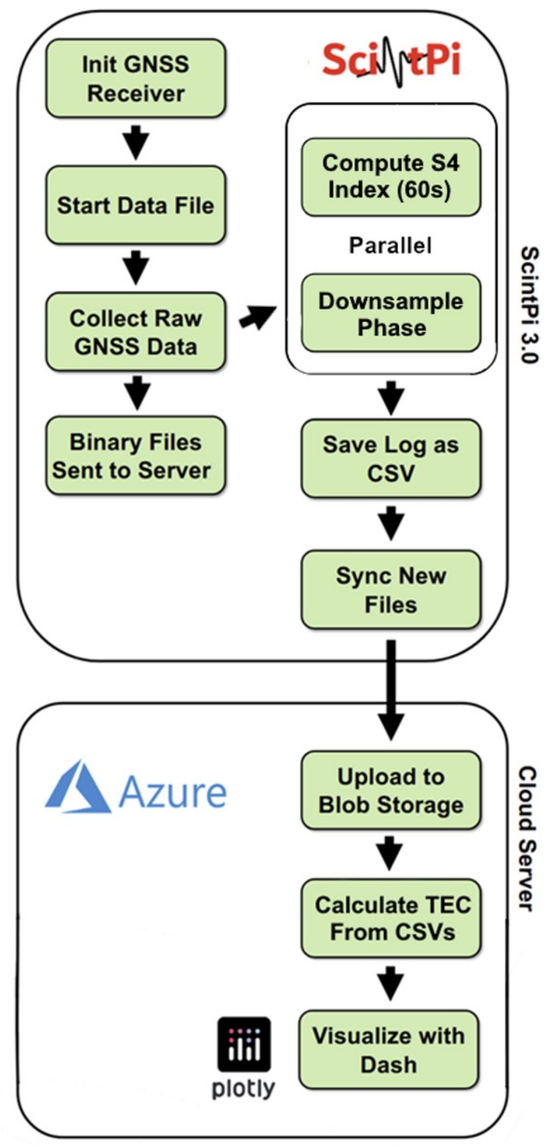

Figure 2. System architecture and real-time software pipeline. GNSS observations are collected on the receiver, where amplitude scintillation indices are computed and carrier phase is down-sampled. These products are stored locally in CSV format before being synchronized to Azure Blob Storage. Here, carrier phase measurements are processed to derive TEC. The results are served through a web dashboard built with Dash/Plotly and hosted on Azure App Services, providing interactive visualizations with updates every 5 minutes.

5. RESULTS AND DEMO

- We created and deployed an **interactive, online dashboard** that provides visualization of scintillation indices.
- The dashboard **support real-time visualization**, showing up to the last 24 hours of data. The site **updates every five minutes**, allowing accurate tracking of ionospheric events as they are happening.

Demo

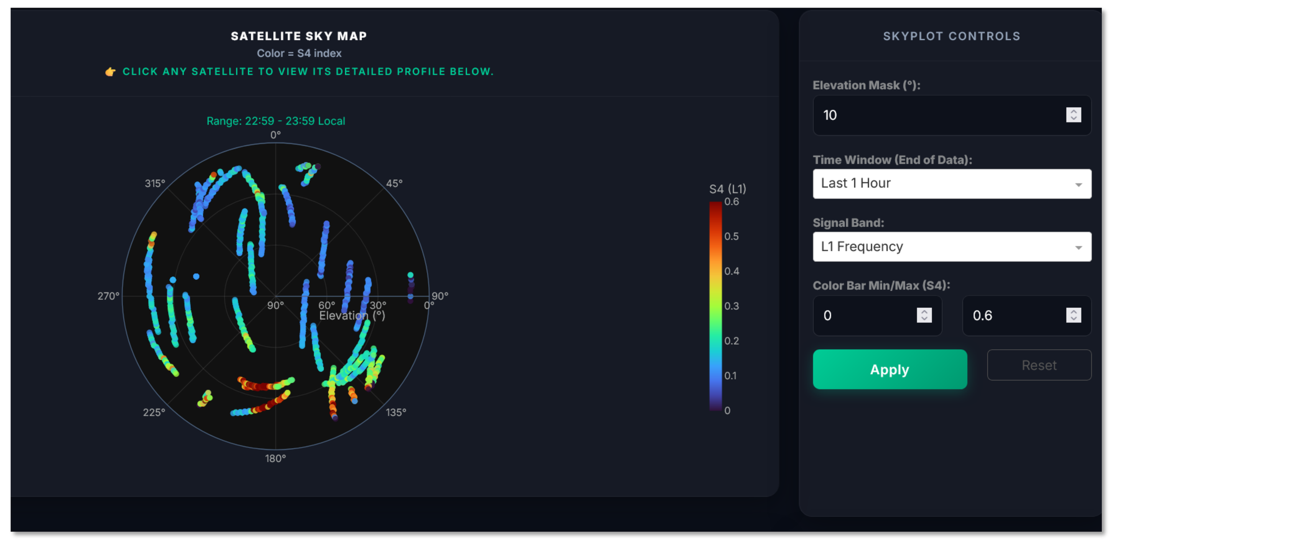

Figure 3. Example of the first panel that forms the web-based dashboard. The panel shows a sky map (or polar) plot GNSS satellite positions as a function of elevation and azimuth. The sky map is for the previous 1 hour of observations. The sky map also presents S_4 values for L1 signals transmitted by different GNSS satellites. The control panel on the right enables changing display settings including the time of observations, color bar limits, and frequency.

Figure 4. Example of the second panel that forms the web-based dashboard. It shows the current and previous several hours of measurements made using signals from GPS PRN 25. From top to bottom: L1 S_4, L2 S_4, slant TEC (1 TECU = 1 TEC Unit = 1×10^{16} electrons/m^2), elevation, and azimuth. The control panel on the right allows the user to select a specific satellite, time window, and elevation mask.

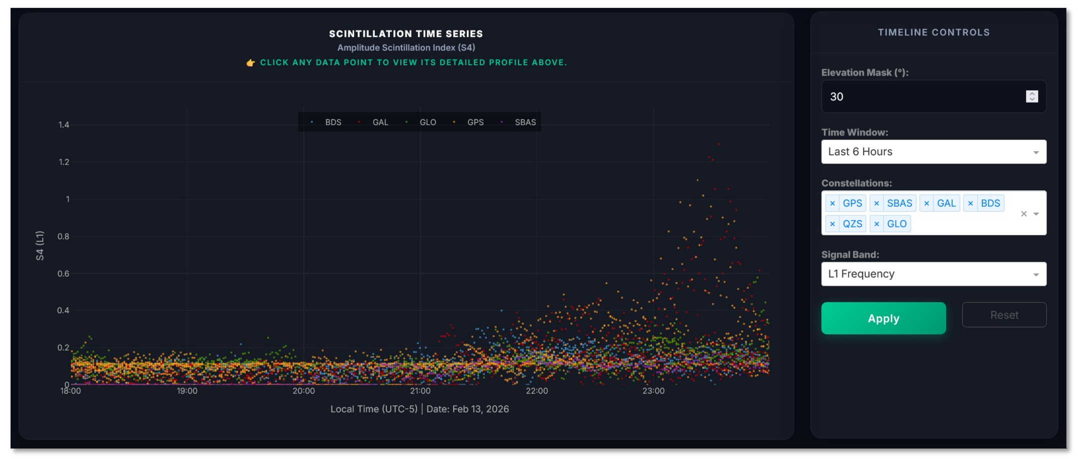

Figure 5. Example of the third panel that forms the web-based dashboard. It shows L1 S_4 indices observed at the time and for the previous several hours. Only S_4 indices for signals from satellites above the user-defined elevation mask are shown. The color of the data points represents the GNSS constellation (GPS-GPS, Beidou-BDS, Galileo-GAL, GLONASS-GLO, and SBAS-SBAS). This visualization enables quick identification of scintillation occurrence, duration, and intensity on a given day. The control panel on the right allows the user to select the signal frequency, elevation mask, satellite constellations, and adjust the observation time window.

6. EMPHASIZED RESULT AND DISCUSSION

- The scintillation dashboard **provides a helpful display of system health.**
- Real-time products produced by the system were compared with products from the nominal, post-processing pipeline, finding virtually identical values of S_4 and TEC.
- As shown in Table 1, onboard processing can **significantly reduce the bandwidth** required for scintillation monitoring by only transmitting the processed indices. In the case of Internet of Things (IoT) applications, the resulting files are small enough to be transmitted by most standard cellular plans.

	Raw Data	Real-Time Data
Daily Size	1.3 GB	3.2 MB
File Format	Compressed Binary	CSV
Sampling Rate	20 Hz	1/60 Hz
Data Interval	6 hours	1 minute
Upload Frequency	1/day	1/minute

Table 1. Comparison of raw and real-time data products generated by ScintPi 3.0. Daily size denotes the total data volume produced per station per day. Data interval represents the time spanned by each data file. Upload frequency specifies how often data are transmitted from the station.

7. CONCLUSIONS

- Our work demonstrates that ScintPi monitors **can support real-time operations providing scintillation and TEC information**. This has been achieved computing amplitude scintillation indices directly on the receiver and enabling real-time estimation of TEC using downsampled carrier phase measurements.
- This reduction in volume (from 1.3 GB to a few MB) **enables continuous operations** in bandwidth-limited environments using low-cost methods such as cellular telemetry. The results from a deployment at the Jicamarca Radio Observatory show that the real-time products are in excellent agreement with the post-processed measurements.
- This architecture advances previous scintillation approaches by **combining low-cost hardware, onboard processing, and scintillation and TEC monitoring within a single system**.

ACKNOWLEDGEMENTS AND REFERENCES

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