On the behavior of quiet-time GNSS scintillation observed by a monitor deployed in Puerto Rico: Seasonal and solar flux effects

Minori T. Kikuchi[1,*], Josemaria Gomez Socola[1], Alexander A. Massoud[1], Carlos Perez[2], Pedrina Terra[3], Christiano G. M. Brum[3], and Fabiano S. Rodrigues[1]

1. The University of Texas at Dallas | 2. Citizen scientist | 3. Florida Space Institute, University of Central Florida

*mtk230001@UTDallas.edu

1. ABSTRACT

- Puerto Rico (PR) has been often described as located in a region that is transition between low and mid latitudes. Previous studies showed that quiet-time ionospheric scintillation observed by a GNSS-based monitor in PR occurred more frequently than previously anticipated [1]. Previous studies also indicated a significant solar flux effects on scintillation activity observed from PR [2]. Here, we utilize new, uninterrupted observations of scintillation made over 3 years to better understand the scintillation conditions experienced by a GNSS receiver in PR. More specifically, we present results related to spatial distribution, occurrence rates and magnetic latitude extent of amplitude scintillation.

2. BACKGROUND AND MOTIVATION

- Strong scintillation events observed at low latitudes are attributed to equatorial plasma bubbles (EPBs) and elevated background ionospheric densities associated with the equatorial ionization anomaly (EIA) [1,3].
- Among other things, we seek a better understanding of the variability in the magnetic latitudinal extent of scintillation.
- A new set of routine, long-term observations made by a ScintPi scintillation monitor deployed in Quebradillas, PR (~24.5° N dip latitude) contribute to advances in our understanding.

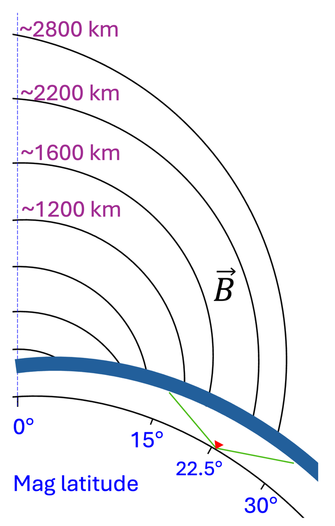

Figure 1. Sketch illustrating the relationship between the EPB apex height at the magnetic equator and magnetic latitude. This relationship assumes that EPBs extend along geomagnetic field lines [3].

3. SCIENCE QUESTIONS

- **SQ1.** What is the quiet-time behavior of scintillation observed by a monitor deployed in PR, a region often considered transition between low and latitudes?
- **SQ2.** How is the quiet-time scintillation behavior impacted by changes in solar flux conditions?

4. METHODOLOGY

- ScintPi 3.0 [4] monitors Global Navigation Satellite System (GNSS) signals transmitted at two frequencies (L1 ~ 1.6 GHz and L2 ~ 1.2 GHz). Here, we perform analysis on L1 signals measured by a ScintPi monitor deployed in Quebradillas, PR. See **Figure 2**.
- Scintillation severity is quantified using the signal intensity (I) derived from ScintPi observations and the S_4 index:

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}} \qquad \text{[Eq. 1]}$$

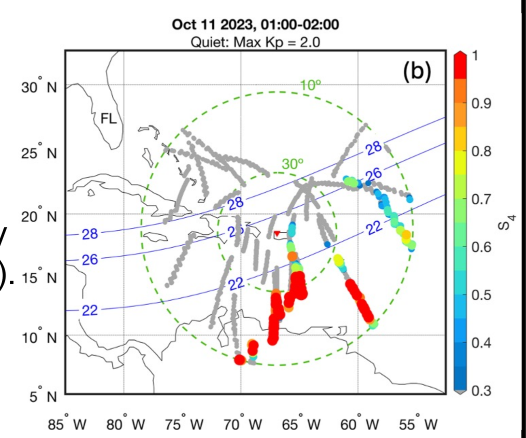

Figure 2. Field of view of the ScintPi monitor located in Quebradillas, PR. Also shown are ionospheric pierce points (IPPs) of GNSS signals coded by severity of scintillation (quantified by S_4). ScintPi is located at 66.91°W, 18.46°N, 24.5°N mag latitude.

5.1 ONE THE OBSERVATIONS, INTERANNUAL VARIABILITY AND SOLAR FLUX EFFECTS

- In this study we analyzed measurements made between Dec. 2021 and Nov. 2024 by the Quebradillas ScintPi. **Figure 3(a)** shows the solar activity during the period of interest. **Figure 3(b)** summarizes the maximum S_4 per minute during the same period.
- It can be seen in **Figure 3(b)** scintillation events exhibit significant interannual variability with increased scintillation occurrence during Equinox and December Solstice periods, and a much lower occurrence rate during June Solstice. The observations also show a larger number of strong scintillation during higher solar flux conditions.
- In the following analyses and results, data between Nov. 7 and Feb. 4, Feb. 4 and Mar. 21, and Sep. 21 and Nov. 5 were selected to represent Dec. Solstice, Mar. Equinox, and Sep. Equinox, respectively. Also, only data where Kp ≤ 3.0 during observations and preceding 24 hours were considered (i.e., geomagnetic quiet days).

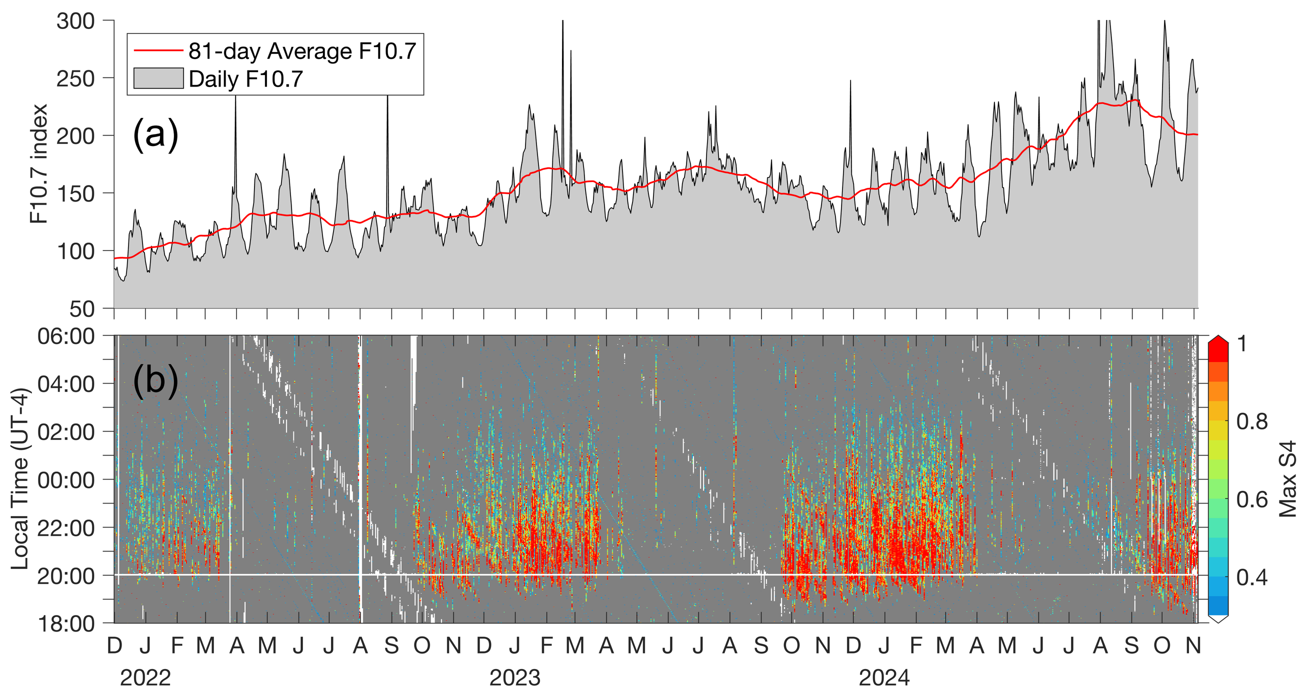

Figure 3. (a) Solar activity represented by the F10.7 index. (b) Maximum L1 S_4 index every minute. A 10° elevation mask is used.

5.2 ON SPATIAL DISTRIBUTION

- **Figure 4** shows the IPPs of the observations for different seasons (rows) and years (columns). It shows the spatial (latitude versus longitude) distribution of the observations for different seasons and solar flux conditions. White markers indicate the locations of IPPs. Scintillation events ($S_4 \geq 0.3$) are indicated as red markers.
- The results in Figure 4 show that scintillation occurs predominantly southeast of Quebradillas and confirm that observed scintillation events are a manifestation of EPBs. A few cases of high S_4 to the west of Quebradillas were caused by multipath.
- The results in Figure 4 also illustrates how the spatial distribution of scintillation responds to changes in solar activity in each season.

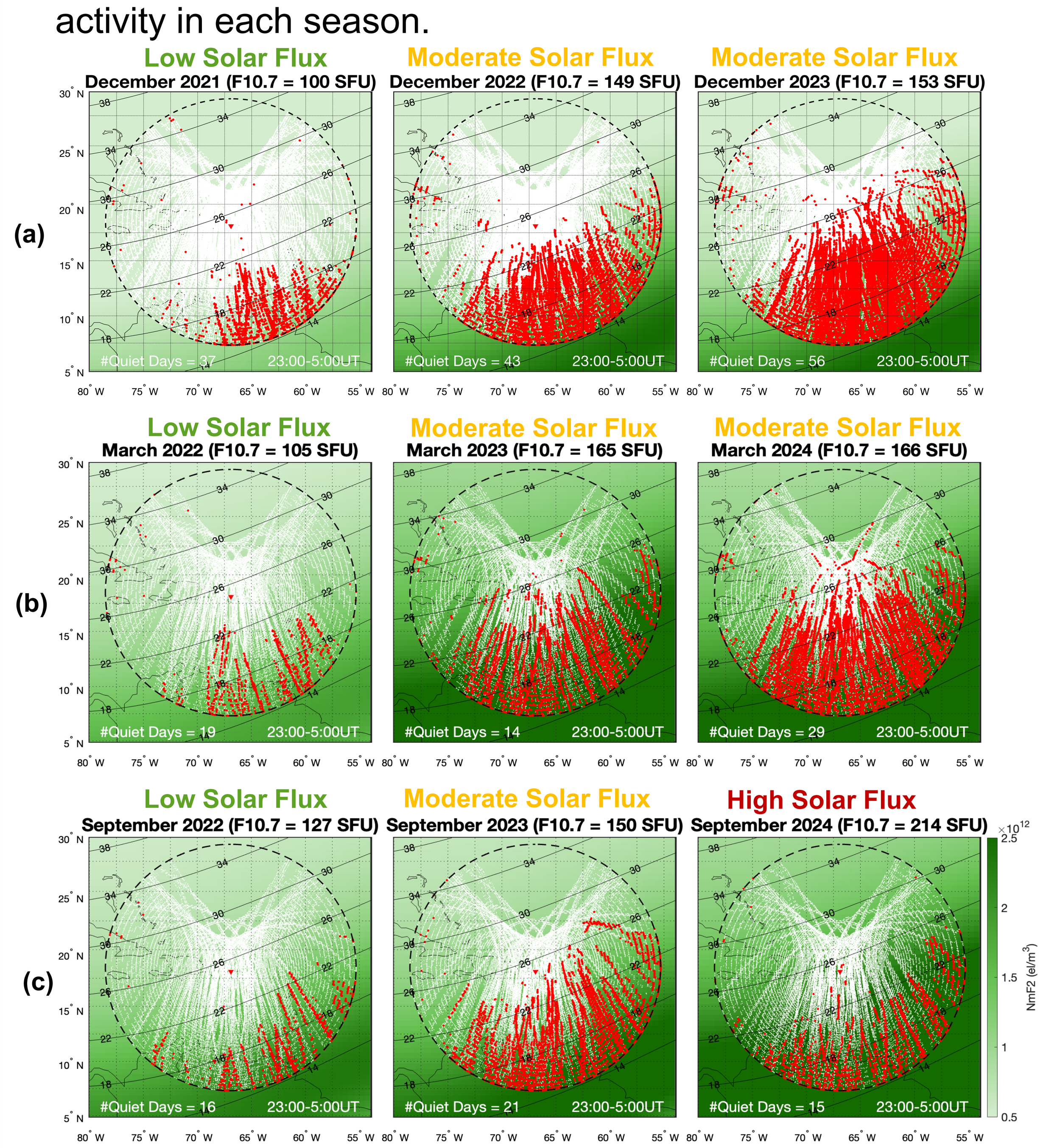

Figure 4. ScintPi observations during (a) Dec. Solstice 2021-2023, (b) Mar. Equinox 2022-2024, and (c) September Equinox 2022-2024. Only observations made between 23:00 and 5:00 UT (19:00 and 01:00 LT) are considered. White (red) markers indicate $S_4 < 0.3$ ($S_4 \geq 0.3$). Mean F10.7 is indicated in each panel. Mag. dip latitude lines calculated using IGRF-13 are also indicated. Green shading represents F-region peak densities from the International Reference Ionosphere (IRI) model.

5.3 ON SPATIAL OCCURRENCE RATES

- **Figure 5** shows the spatial distribution of scintillation occurrence rates (ORs) computed using the quiet-time observations presented in Figure 4. Scintillation ORs were computed as the ratio of observed scintillation cases ($S_4 \geq 0.3$) over the total number of observations.
- The results in Figure 5 show that during low solar flux conditions, ORs remains mostly below ~30% anywhere in the FOV of the monitors. During moderate and high solar flux conditions, however, ORs can be as high as ~70% at the lowest dip latitudes.
- The results in Figures 4 and 5 also indicated that the latitudinal extent of scintillation increased substantially from year 1 to year 2. This change, however, is not clearly seen from year 2 to year 3. In fact, the latitudinal extent seems to have decreased in September equinox.

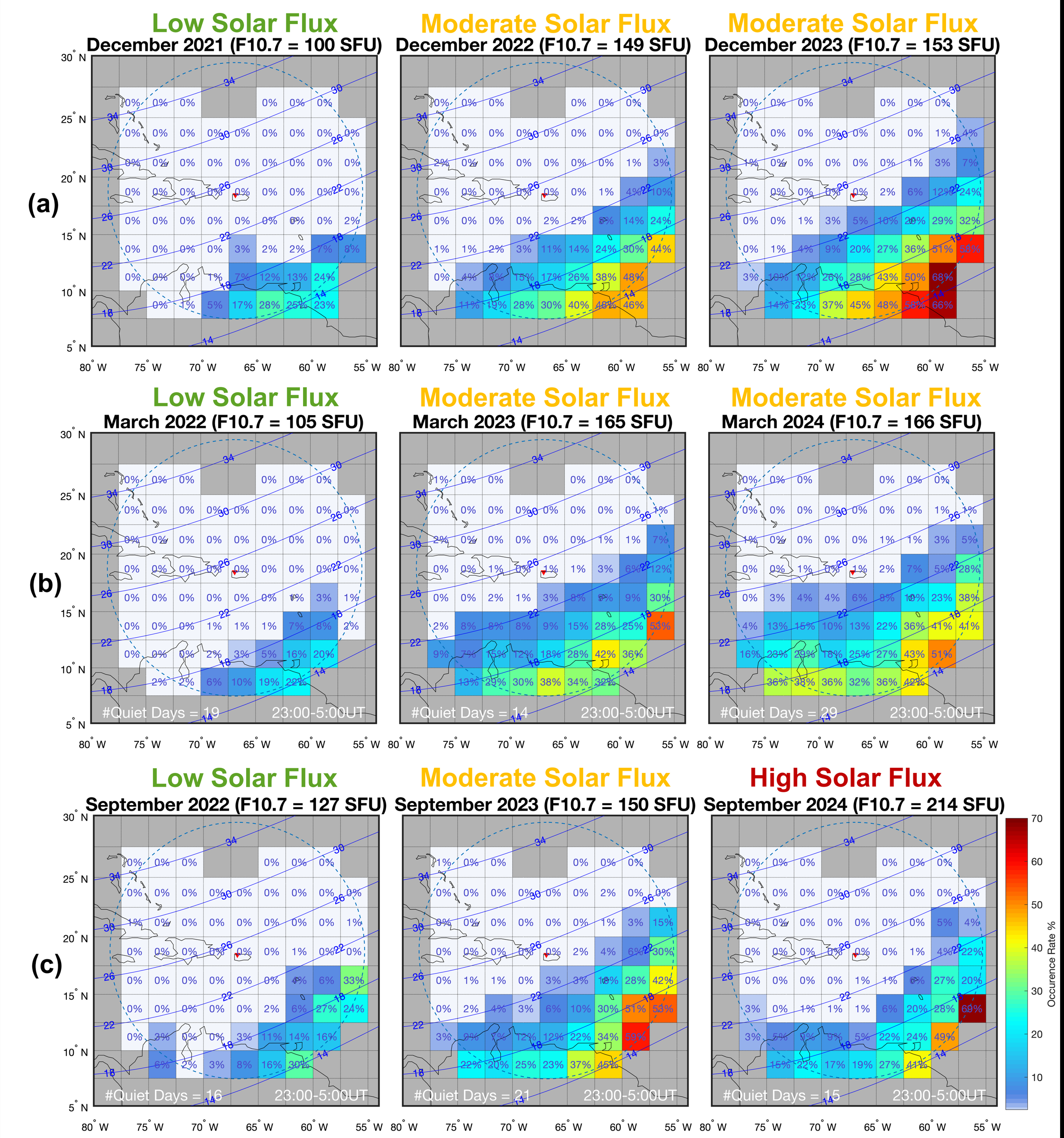

Figure 5. S_4 occurrence rates for (a) December Solstice 2021-2023, (b) March Equinox 2022-2024, and (c) September Equinox 2022-2024 **between 23:00-5:00 UT.** Blue lines correspond to magnetic latitude. Bins with less than 100 total observations are shaded in gray, and occurrence rates less than 2.5% are in white.

5.4 ON LATITUDE EXTENT

- To better quantify the distribution of the magnetic latitude extent of scintillation observed from PR, we summarized our observations using box plots. The results are show in **Figure 6**.
- The results confirm that changes in solar flux from year 1 (low) to year 2 (moderate) cause a clear change in the maximum latitude of scintillation. However, the box plots also show that a large increase in solar flux activity from year 2 to year 3 during September Equinox was not accompanied an increase in the maximum latitude extent.

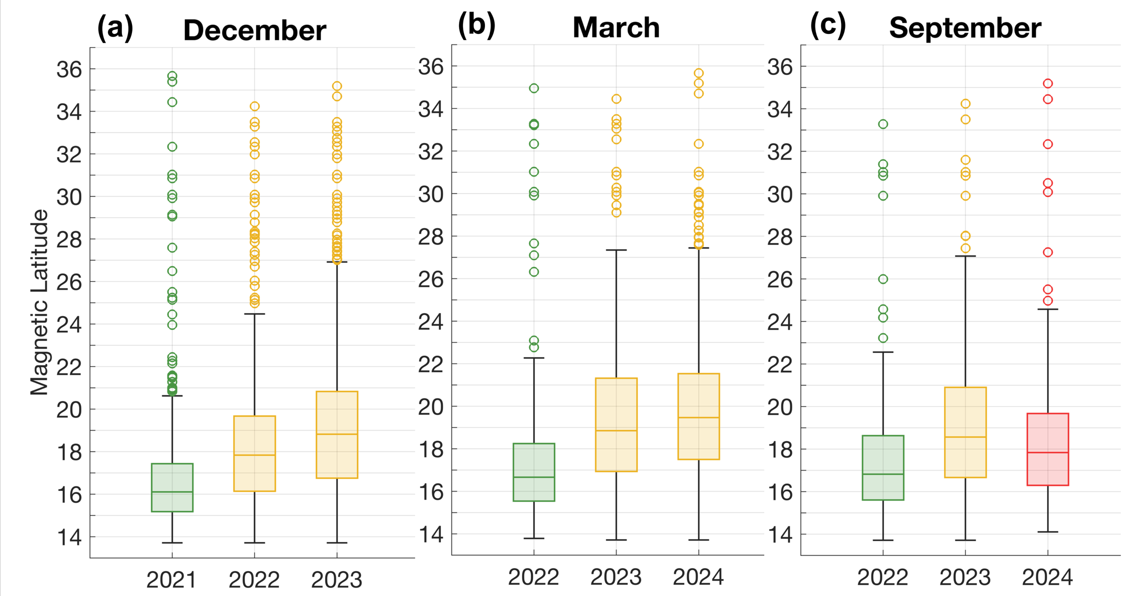

Figure 6. Box plot of the magnetic latitude of points with S4≥0.3 for (a) December Solstice 2021-2023, (b) March Equinox 2022-2024 and (c) September Equinox 2022-2024 between 23:00-5:00 UT Colors correspond mean quiet-time solar activity: low in green, medium in yellow, and high in red.

6. MAIN FINDINGS

- ✓ The results in **Section 5.1** show that, in the transition region, scintillation occurrence shows clear interannual (seasonal) variations. The results also show variations, from year to year, in severity, onset time, and duration in the observed scintillation events [**SQ1**].
- ✓ The results in **Section 5.2** show scintillation events occur southeast of PR and are associated with EPBs [**SQ1**].
- ✓ The results in **Section 5.3** show that an increase in solar flux conditions from year 1 (low) to year 2 (moderate) are accompanied by a clear increase in the occurrence and maximum magnetic latitude of scintillation [**SQ2**].
- ✓ Finally, the results also show that a substantial increase in solar flux in September (from year 2 to 3) was not followed by an increase in magnetic latitude extent. This is better quantified in the box plot in **Section 5.4**. This interesting result has motivated ongoing additional analyses [**SQ2**].

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REFERENCES

[1] Gomez Socola et al., On the quiet-time occurrence rates, severity and origin of L-band ionospheric scintillations observed from low-to-mid latitude sites located in Puerto Rico, Journal of Atmospheric and Solar-Terrestrial Physics, Volume 250, 106123, ISSN 1364-6826, https://doi.org/10.1016/j.jastp.2023.106123, 2023.
[2] Kikuchi, M. T., Gomez Socola, J., Massoud, A. A., Perez, C., Terra, P. Brum, C. G. M. and F. S. Rodrigues, On the spatio-temporal behavior of quiet-time GNSS scintillation observed in Puerto Rico: Seasonal and solar flux effects, 2025 CEDAR Workshop, Des Moines, IA, June 22-27, 2025.
[3] de Paula, E. R., F. S. Rodrigues, K. N. Iyer, I. J. Kantor, M. A. Abdu, P. M. Kintner, B. M. Ledvina, and H. Kil, Equatorial Anomaly Effects on GPS Scintillations in Brazil, Advances in Space Research, 31(3), 749- 754, 2003.
[4] Gomez Socola, J. and F. S. Rodrigues, ScintPi 2.0 and 3.0: low-cost GNSS-based monitors of ionospheric scintillation and total electron content, Earth Planets Space 74, 185, https://doi.org/10.1186/s40623-022-01743-x, 2022.