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Performance of 6 Different Global Navigation Satellite System Receivers at Low Latitude Under Moderate and Strong Scintillation

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Abstract After sunset, in the equatorial regions ionospheric plasma irregularities are generated due to the generalized Rayleigh-Taylor instability. Under favorable conditions these irregularities develop in the equatorial region while mapping along the magnetic field lines giving rise to large plasma depletions structures called Equatorial Plasma Bubbles with embedded smaller structures on their walls. The global navigation satellite system (GNSS) L1 band frequency is sensitive to irregularities of the size of 300–400 m in the first Fresnel zone, which cause scattering and diffraction of the signal and produce amplitude and/or phase scintillation. Severe scintillation of GNSS signals can in turn cause loss of lock of the receiver code and/or carrier loops. As a result, GNSS navigation and positioning solution can be adversely affected by the ionospheric scintillation. There are multiple GNSS receivers designed to monitor scintillations. These receivers are based on different hardware designs and use different methodologies to process the raw data. When using simultaneous data from different GNSS scintillation monitors it is important to evaluate and compare their performances under similar scintillation conditions. The scintillation monitoring techniques may be useful for many applications that use GNSS signal. The aim of this work is to evaluate the performance of six different GNSS receivers located at São José dos Campos (23.1°S, 45.8°W, dip latitude 17.3°S) during moderate and strong scintillation activity. The amplitude (S4) and phase (σϕ) scintillation indexes from these receivers were analyzed and compared for the nights February 20–21 and November 27–28, 2013.

1. Introduction

The Equatorial plasma bubble irregularities occur with scale sizes ranging from centimeters to hundreds of kilometers. Those plasma density irregularities with scale sizes of hundreds of meters cause scattering and diffraction of radio waves propagating through these unstable ionospheric regions and can produce large amplitude and/or phase scintillation on the received signals (Yeh & Liu, 1982). The scintillation strength is strongly dependent of the local time, season, solar flux, propagation path, magnetic location and geomagnetic conditions (de Paula et al., 2019; Moraes, Vani, Costa, Abdu et al., 2018; Moraes, Vani, Costa, Sousantos et al., 2018; Muella et al., 2017; Sousasantos et al., 2018). The fades on the GNSS signals due to scintillations caused by irregularities with scale sizes between 300 and 400 m can be deep and long enough to cause GNSS receivers to lose lock, thus affecting the positional and navigational accuracy. Also, as pointed out by several authors (Doherty et al., 2004; Skone et al., 2001; Zou & Wang, 2009), rapid phase variations can modify the Doppler shift in the GPS signal, causing it to exceed the bandwidth of the phase lock loop, resulting in a loss of phase lock. Therefore, statistical characterization of scintillation patterns can help to improve the robustness of GNSS receivers (C. S. Carrano & Groves, 2010; Kintner et al., 2001, 2007; A. O. Moraes et al., 2017, 2014, 2012) and to mitigate their effects on the navigation and positioning systems.

Many different scintillation monitors with multi-frequency and multi-constellation possibilities have been developed in the last decade. Devices from different manufacturers have been used in different studies and sometimes data analysis involves using data from different equipments (Alfonsi et al., 2018;
A question that arises is how closely the results of these equipment can agree. This aspect is important to ensure, for example applications including fusion of data from different sources of scintillation monitors. The main objective of this work is to compare the performance of six different receivers under moderate and strong scintillation conditions using GPS L1 frequency and to compare and contrast their $S_4$ and $\sigma_\phi$ parameters. It is straightforward to compute $S_4$ and $\sigma_\phi$ based on their definitions as the standard deviations of normalized intensity and phase fluctuations, respectively. However, both the intensity and phase measured by the receiver include contributions from non-ionospheric origins including terrestrial multipath, thermal noise, geometric phase, and cycle slips. These non-ionospheric contributions must be removed prior to quantifying the signal modulation caused by ionospheric scintillation in terms of compute $S_4$ and $\sigma_\phi$. Since different receivers attempt to mitigate these non-ionospheric contributions using different techniques (some of which are proprietary), the values of $S_4$ and $\sigma_\phi$ reported by different receivers may not be the same. A goal of this paper is to quantify these differences, so that scientific studies conducted using these GPS scintillation measurements can be properly informed of the uncertainties involved. Phase and amplitude parameters are important to supply models or algorithms to mitigate scintillation effects on positioning. The high-rate data can be applied to estimate scintillation-induced error terms at the output of the tracking loops of the GNSS receivers, providing necessary input information to modified functional and/or stochastic models (Vani et al., 2019; Veettil et al. 2020).

The rest of the paper is structured in the following way. Section 2 describes the scintillation monitor networks in Brazil and provides details about their technical specifications. In Section 3, detailed description of the scintillation monitors and of the methods for estimating $S_4$ and $\sigma_\phi$ scintillation indexes are presented and discussed. Section 4 describes in details the experimental setup and the measurements performed in real time and post processing are presented. The comparison between scintillation indexes in the different receivers is also presented. Finally, Section 5 summarizes the performance verification, discussing the agreement between the scintillation monitors and presenting concluding remarks.

2. Scintillation Monitor Technical Specifications and Data Characteristics

2.1. Scintillation Monitor Networks in Brazil

Brazil in 2013 had at least 3 ionospheric scintillation monitoring networks working. The SCINTEC project was created to monitor and generate real time maps of ionospheric scintillation. In this network, scintillation data is acquired through GPS receivers CASCADE (GEC-Plessey GPS card—single frequency) developed by Cornell University (T. L. Beach, 1998; T. L. Beach & Kintner, 2001; de Paula et al., 2007; Rezende et al., 2007). Another scintillation network is Low-Latitude Ionospheric Sensor Network (LISN) from Valladares and Chau (2012) that consists of scintillation monitors, magnetometers and ionosondes. This network is not only concentrated in the Brazilian territory, but also includes sensors spread throughout the South American continent. LISN operates with Novatel GSV 4004B—G2 receivers. The third network is the CIGALA/ CALIBRA project, a joint initiative between Nottingham University from United Kingdom, the National Institute of Geophysics and Volcanology (INGV) from Rome, the University of Nova Gorica from Slovenia, the company Septentrio from Belgium and leading in the Brazilian side by the UNESP and ConsultGEL company. This network was funded by ESA (European Space Agency) and the focus of the project is to monitor and characterize the effects of scintillation on positioning. More information can be found in Vani et al. (2017). This network operates with Septentrio POLARxS PRO scintillation monitor receiver.

All of these networks have a receiver installed in the Aeronomy Division of INPE at its headquarters in São José dos Campos. Additionally, this INPE’s Division also had under operation in São José dos Campos, through technological and scientific cooperation, a CASES receiver from Atmospheric & Space Technology Research Associates (ASTRA) company, a Novatel GPSTATION6 from Boston College and a prototype software defined radio (SDR) from Stanford University. This scenario with six different receivers deployed in the same facility created a unique opportunity for a comparative study between the performances of different receptors under the effects of moderate and strong scintillation events.
2.2. Scintillation Monitor General Technical Specifications

Table 1 lists the characteristics of the GNSS receivers, their antennas and respective cables used in each monitor. The antennas are set few meters apart with same sky visibility. As mentioned before, these receivers are: Cornell Scintillation Monitor (CSM), ASTRA Connected Autonomous Space Environment Sensor (CASES), Novatel GSV 4004B, Novatel GPStation6, Septentrio PolaRxS Pro, and Stanford University Ionospheric Software Defined Receiver (SU IONO SDR), and from now on we will refer to them as CSM, CASES, GSV 4004B, GPStation6, Septentrio, and SU IONO SDR, respectively. Besides different receivers, antennas and cables, these scintillation monitors have different data processing methodologies as will be discussed in detail in Section 3.

2.3. Scintillation Monitor Data Characteristics

Even though GNSS signals are sampled/acquired at a rate of the order of MHz, they are processed within the receiver tracking loop, integrated (i.e. averaged) and amplitude and phase information are obtained in a lower rate like 50 or 100 Hz. Of these six receivers, the CASES receiver acquired amplitude and carrier phase data at 100 Hz for the calculation of $S_4$ and $\sigma_\phi$ indexes, while for all the other receivers this rate was 50 Hz.

CSM monitor is the only one that does not have the necessary features for phase scintillation index extraction. Despite having the ability for carrier phase acquisition, the SU IONO SDR receiver was not configured for it in this campaign. The scintillation indexes were calculated using data accumulated over 60-s intervals, except for the CASES receiver that was configured to use a 100-s interval.

The $S_4$ and $\sigma_\phi$, depending on the manufacturer and receiver model, may be calculated online during reception, which is namely the real time mode, or after acquisition, which is the post-processing mode using raw data. Both procedures use manufacturer’s proprietary tools. Table 2 summarizes these capabilities for each receiver.
different raw data for this computation. The GSV 4004B and GPStation6 monitors based on GPS receiver architecture implemented by hardware estimate the signal intensity based on the narrowband-wideband power ratio method, which is extensively reported in the GPS literature. This method is a C/N0 estimator based on the observable from the prompt correlator (Falletti et al., 2011). The CSM receiver which is a simplified version, for the S4 index computing uses only signal measurements from wide band power (WBP) and a noise channel (T. L. Beach, 1998). In the ASTRA, Septentrio, and SU IONO SDR receivers, the signal is decomposed in two components, $I_c$ (In-phase) and $Q_c$ (Quadrature), and the intensity is obtained directly from these components. Table 3 summarizes the type of signal measurement availability for the listed receivers of Table 1. Receivers that have wideband power available are identified by WBP, while the receivers with $I_c$ and $Q_c$ components are identified by $I_c/Q_c$. The $I_c$ and $Q_c$ signal components and the WBP are used to calculate $S_4$ following the standardized methodology described at Section 3.6. The $\sigma_\varphi$ can be determined using the carrier phase cycle counting extracted from the raw binary files and the detailed methodology is described in Section 3.7.

3. Description of the Scintillation Monitors and of Their Scintillation Indexes

3.1. The ASTRA CASES

ASTRA’s CASES GPS receiver is a dual-frequency (L1 and L2) GPS receiver, developed as a low-cost alternative for monitoring ionospheric scintillation and total electron content (Azeem et al., 2013; Crowley et al., 2011). The receiver software includes several features: advanced triggering techniques to accurately determine the onset of ionospheric scintillation, buffering of data to allow for observation of the onset of scintillation, data-bit prediction and wipe-off for robust tracking, and eliminating local clock effects by differencing (O’Hanlon et al., 2011). The CASES receiver implements all signal processing functions (i.e., those downstream of its analog radio frequency (RF) front end) from correlation to navigation solution, in a general-purpose Digital Signal Processor. This approach provides the following benefits: flexibility to accommodate specialized signal processing schemes like the scintillation-robust tracking loops, remote re-configurability, full control over receiver behavior, products, and cadences, and reduced cost.

The CASES receiver software is designed to output the raw in-phase and quadrature accumulations at 100 Hz. The scintillation parameters ($S_4$ and $\sigma_\varphi$) are computed inside the receiver and output at a cadence that can be adjusted in the configuration file. Processing periods may vary, but for this study a 100-s interval was used for calculating scintillation indexes.

While other scintillation monitors may include oven-controlled crystal oscillators (OCXO), CASES utilizes a less-expensive temperature-compensated crystal oscillator (TCXO) without sacrificing the data quality. It does so by exploiting a non-scintillating carrier signal as a phase reference, a technique referred to as CDGPS-based phase referencing (where CDGPS refers to carrier phase differential GPS) (O’Hanlon et al., 2011). CASES does provide an option to be paired with an external OCXO. For example, in dense-array applications, one CASES receiver can be anchored to an OCXO while the other CASES in the array, each with an inexpensive TCXO, can be phase-synchronized to the anchor unit in a relative sense via carrier-phase differential techniques. This technique can greatly reduce the cost of implementing the array.

In the CASES GPS receiver, the amplitude and phase scintillation indexes are calculated on-board in real time. CASES $S_4$ calculations are performed on a 100 s cadence using the 100 Hz In-Phase ($I_c$) and Quadrature ($Q_c$) accumulation samples according to the following procedure:

1) First the 100 Hz amplitude is computed and the noise floor subtracted
2) $I_c^2 + Q_c^2 - N_0^2$, then its run through a 12-point averaging to remove thermal noise. The averaged noise-free amplitude for the $k$th bin is given by

| Table 3 | Raw Data Availability |
|---|---|
| Receiver | Method | WBP | Phase cycle counting |
| ASTRA CASES | $I_c/Q_c$ | No | Yes |
| CSM | WBP | Yes | Yes$^a$ |
| Novatel GSV 4004b | WBP$^b$ | Yes$^b$ | Yes$^b$ |
| Novatel GPStation6 | WBP | Yes | Yes |
| Septentrio PolaRxS PRO | $I_c/Q_c$ | No | Yes $^c$ |
| SU IONO SDR | $I_c/Q_c$ | No | Yes $^d$ |

ASTRA, Atmospheric & Space Technology Research Associates; CASES, Connected Autonomous Space Environment Sensor; CSM, Cornell Scintillation Monitor; SU IONO SDR, Stanford University Ionospheric Software Defined Receiver; WBP, wide band power.

$^a$Phase is acquired at 10 Hz rate. $^b$The raw binary files were not available, since GPS-SCINDA was not set to campaign mode. $^c$The phase data was not recorded in this work.
where \( N_0 \) is the receiver noise floor.

3) Sample amplitudes (A) over the 100 s interval are detrended using a first-order polynomial fit \( P_f \) to account for the changing range and antenna pattern. Equation 2 shows the final detrended intensity measurements used for estimating \( S_4 \).

\[
A' = A - P_f + \langle A \rangle.
\]  

where \( <> \) is the DC component of the signal intensity over the 100 s scintillation window.

The \( S_4 \) index is then computed according to Van Dierendonck et al. (1993):

\[
S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}.
\]  

where \( I = A^2 = I_c^2 + Q_c^2 \) is the signal intensity, \( A \) is the amplitude of the received signal, \( I_c \) and \( Q_c \) are the signal intensity in-phase and quadrature components respectively and \( <> \) is ensemble average. So the \( S_4 \) index is the standard deviation of signal intensity divided by the mean value of intensity.

CASES \( \sigma_{\phi} \) calculations are performed on a 100 s cadence using the 100 Hz carrier phase data. CASES uses a third order polynomial subtraction to remove all low-frequency phase variations (e.g. those due to receiver-satellite geometry) and uses polynomial fits to filter out the high frequency noise. Following the detrending, the standard deviation of the residual signal is calculated using equation (Van Dierendonck et al., 1993):

\[
\sigma_{\phi} = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2},
\]  

where the \( \phi \) is the unwrapped and detrended carrier phase.

For this study, the CASES phase scintillation index was calculated using a 100 s averaging window.

### 3.2. The CSM GEC-Plessey Builder-2

The CSM is a modification of a commercial GPS development system, the Plessey GPS Builder-2 card (T. L. Beach, 1998; T. L. Beach & Kintner, 2001) with special firmware to measure the amplitude scintillations. The hardware is based on the Zarlink IC GP2015 for RF downconversion and IC GP2021 with 12 Fully Independent Correlation Channels for GPS code detection and processing. No phase scintillation or TEC were calculated with this system since its designed just for the L1 frequency. The Plessey development system consists of a 16-bit Personal Computer card containing RF and correlator chips with accompanying receiver source code written in C and Assembly language. All receiver functions above the level of code correlation, including code and carrier tracking, devolve upon the PC. The advantage of using the Plessey development system is that the code correlator outputs are not buried within an onboard microcontroller as is the case in most commercially available GPS receivers. Averaging the “raw” correlations provides a known, albeit uncalibrated, measurement of signal strength. The Cornell scintillation monitor outputs signal strength data at 50 Hz for each satellite tracked, with data collection synchronized to the data bits of the GPS navigation message. The scintillation monitor also provides phase data at 10 Hz, although finding phase scintillations with the current receiver design, amid oscillator and tracking loop noise and large background trends, has proven problematic. So it is not advisable to use CSM carrier phase measurements. The CSM was developed to try to maintain lock during most scintillation conditions. Therefore, it can measure the amplitude of the GPS signal when most standard GPS receivers would have lost lock. This CSM has a 12-channel correlator that allows the tracking of...
signals from up to 11 GPS satellites, simultaneously. One channel is dedicated to noise estimation. The CSM provides measurements of both the L1 (1.575 GHz) wide band power (WBP) and wide band noise at a 50 Hz sampling rate.

The $S_4$ index is computed using CSM measurements of the WBP ($P = \text{WBP}$), Noise WBP (N) and the respective low-pass filtered versions $\langle P \rangle$ and $\langle N \rangle$. According to T. L. Beach (1998) the filtered versions are obtained using a sixth order low-pass Butterworth filter with a cutoff frequency of 0.1 Hz. The filtering is used to remove fluctuations in the signal measurements caused by non-geophysical sources.

Conceptually, the $S_4$ calculation based on Equation 3 consists of dividing the standard deviation of the scintillating signal by the mean received power. This procedure can be obtained from the CSM using the following methodology. First, the WBP $P$ and its filtered version $\langle P \rangle$ are used to estimate the real signal strength variance over a one-minute period by the following expression (T. L. Beach 1998):

$$\sigma^2 = \frac{1}{M} \sum_{k=1}^{M} (P_k - \langle P \rangle_k)(P_k - \langle P \rangle_k). \quad (5)$$

where $M = 3,000$ is the total number of samples $k$, during one minute interval. The mean signal power ($\hat{S}$) for the same period can be obtained using the filtered versions of WBP $\langle P \rangle$ and Noise WBP $\langle N \rangle$ by the following expression:

$$\hat{S} = \frac{1}{M} \sum_{k=1}^{M} (\langle P \rangle_k - \langle N \rangle_k). \quad (6)$$

Finally, the computed $S_4$ index will be given by

$$S_4 = \frac{\sigma^2}{\hat{S}}. \quad (7)$$

3.3. The Novatel Systems GSV-4004B and GPStation6

The GSV 4004B GPS receiver provides measurements of L1 signal power and phase at 50 Hz and also L2 C/N0 and phase at 1 Hz. A total of 24 channels are used to monitor GPS L1 and L2 signals, a noise channel, and up to three Space-Based Augmentation System (SBAS) satellite signals. Power measurements on L1 are provided as the difference between narrow band and wide band power measured over the same 20 millisecond periods (Van Dierendonck et al., 1993). L2 measurements are provided using semi-codeless techniques, and are therefore generally unsuitable for scintillation analysis. The receiver incorporates an Oven Controlled Crystal Oscillator (OCXO) for low phase noise (C. S. Carrano & Groves, 2019).

The $S_4$ index is derived from the detrended intensity of signals received from satellites. Differently from the other receivers shown in Table 1, in the Novatel methodology, the intensity measurement is considered as the difference between Narrow Band and Wide Band Power components (NBP and WBP) are given by:

$$\text{WBP} = \sum_{i=1}^{20} I_i^2 + Q_i^2, \quad (8)$$

and

$$\text{NBP} = \left( \sum_{i=1}^{20} I_i \right)^2 + \left( \sum_{i=1}^{20} Q_i \right)^2. \quad (9)$$

where $I_i$ and $Q_i$ as previously mentioned are respectively the In-phase and Quadrature components of the signal, sampled at 1 kHz. In this case, the detrended signal intensity is estimated based on Van Dierendonck and Arbesser-Rastburg (2004):
where \( \langle \text{NBP} \rangle \) and \( \langle \text{WBP} \rangle \) are the low-pass filtered versions of NBP and WBP, with a cutoff frequency of 0.1 Hz. Additionally, the contribution of ambient noise in \( S_4 \) estimation is not removed. According to Van Dierendonck and Arbesser-Rastburg (2004), the \( S_4 \) index calculated using detrended signal intensity of Equation 10 and taking into account the effect of the ambient noise is given by

\[
S_4 = \sqrt{\frac{(SI^2) - \langle SI \rangle^2}{\langle SI \rangle^2}} - \frac{100}{S / N_0} \left[ 1 + \frac{500}{19S / N_0} \right]^{1/2},
\]

where \( S / N_0 \) is the signal-to-noise density of the received signal and it is typically updated every 60 s.

According to Van Dierendonck and Arbesser-Rastburg (2004), the phase scintillation monitoring is accomplished by monitoring the standard deviation of the detrended carrier phase from signals received from satellites. The detrending methodology uses a sixth-order high-pass digital Butterworth filter with a frequency cut-off of 0.1 Hz. This value can be selected by the operator. Then Equation 4 is used for real-time estimates of \( \sigma_\phi \).

The receiver GPStation6 was designed incorporating to the proven GSV4004 B receiver with the ability to track multi-constellation, multi-frequency, GNSS measurements (Shanmugam et al., 2012).

Both the GSV4004B and GPStation6 compute \( S_4 \) and \( \sigma_\phi \) and STEC in real time during data acquisition and these values are stored inside binary Ionospheric Scintillation Monitor (ISM) records. Then these parameters are extracted from these ISM binary records to produce ASCII or CSV files. The ISM records contain only previously computed statistics like \( S_4 \) and \( \sigma_\phi \) and not the raw amplitude and phase data that would be necessary to compute them. NovAtel provided programs to extract the raw (50 Hz) amplitude and phase values. From this data, one can compute one's own \( S_4 \) and \( \sigma_\phi \) values in post-processing but no software is provided by NovAtel to do this (C. S. Carrano & Groves, 2019).

### 3.4. The Septentrio PolarRxS Pro

The Septentrio PolaRxS receiver used in this study can monitor satellites from the following constellations: GPS, GLONASS, Galileo, and SBAS. Using 136 channels, it can track the L1, L2, L1P, L2P, L2C, L5, and E5ab/AltBOC satellite signals. The current version of the receiver (PolaRxS5) also supports the E6 band and all BeiDou signals. While this receiver is capable of providing power and phase measurements at 100 Hz, it was operated at 50 Hz. The signal intensity was computed from the post-correlator In-phase (I) and Quadrature (Q) samples acquired during 20 millisecond intervals.

Multipath, tracking noise, jamming and interference are known to introduce amplitude and phase variations that can mask the actual physical scintillation. Septentrio PolaRxS receivers use advanced signal processing techniques to mitigate the impact of those error sources on the scintillation indices. In addition, to observe phase scintillations on individual signals and satellites, the receiver clock jitter must be as small as possible. The receiver incorporates a high-quality OCXO, resulting in a \( \sigma_\phi \) “noise floor” lower than 0.03 radians.

The \( S_4 \) and \( \sigma_\phi \) parameters can be output in real-time, or they can be obtained in post-processing using the company’s sbf2ismr utility. \( \sigma_\phi \) is provided with averaging over 1, 3, 10, 30 or 60 s with a user-selectable detrending cutoff frequency. This study used the \( \sigma_\phi \) value averaged over 60 s with a detrending high pass filter cutoff at 0.1 Hz. Next to \( S_4 \) and \( \sigma_\phi \), other parameters such as the spectral slope and strength are also reported.

### 3.5. The Stanford University Ionospheric Software Defined Receiver SU IONO SDR

The SU IONO SDR is a custom instrument for ionospheric monitoring consisting of: UBlox6 GPS L1 receiver, a GTEC GPS L1/L2/L5 raw Intermediate Frequency (IF) data logger, a notebook PC, with custom software and external storage. This is depicted in the Figure 1.
This system logs raw IF data on GPS L1, L2, and L5 from 6 p.m. until 2 a.m. local time. A bandwidth of 20 MHz is captured on each of the bands. At the end of each collection period, the uBlox C/N0 data for each Pseudo Random Noise (PRN) was compared to a reference set, utilizing a historical record as a function of elevation angle, to determine a “scintillation intensity.” The “scintillation intensity” is computed on each satellite on an hourly basis. Based on this detection criteria, various 1 h data segments of raw IF data were saved for post processing. This was required to minimize data volumes as a result of the resulting size, 144 GB, of each hour of raw IF data recorded. A later modification computes the $S_4$ directly based on the $C/N_0$ measurements from the uBlox GPS L1 receiver. Post-processing of the raw IF data was used to validate and refine this $S_4$ computation.

Next it will be described the methodology used in this work to estimate $S_4$ and $\sigma_\phi$ indexes from the raw data.

### 3.6. Amplitude Scintillation Index $S_4$ Calculation Standardized Methodology

As stated before all receivers used a 50 Hz data acquisition except the CASES that used 100 Hz in this analysis.

From the raw amplitude data (with noise) at a rate of 50 Hz or 100 Hz, WBP and $I_c/Q_c$ components were used for $S_4$ estimation. As presented in Equation 3, $S_4$ is computed based on the signal intensity.

When available, WBP was read from those receivers that provide it (see Table 3). The next step was to resample the data at the same rate used during acquisition (50 Hz or 100 Hz) followed by a linear interpolation to fill data gaps due to losses of lock. Next, the intensity was detrended to remove intensity trends due to the changing range to the satellite, and to partially suppress the contribution from terrestrial multipath. To detrend the intensity, the following steps were taken. First, a 60-s moving average is performed to obtain the intensity trend. This trend is subtracted from the resampled and not interpolated intensity data, expressed in units of dB-Hz. Converting the detrended intensity back to linear units, the $S_4$ values are estimated for each minute of data using Equation 3, where $I$ (signal intensity) is a vector of 3,000 or 6,000 signal intensity samples, depending on the data acquisition rate of the receiver. When the total number of samples due to data gaps in each 1 minute interval exceeds 1/4 of the total samples, the value of $S_4$ is not calculated for that minute. The purpose of discarding intervals with many missing samples is to avoid spurious results due to insufficient statistics.

### 3.7. Phase Scintillation ($\sigma_\phi$) Calculation Standardized Methodology

In this work the phase scintillation calculations were performed using the methodology of C. S. Carrano and Groves (2019). Carrier phase is a measure of the range between the satellite and receiver expressed in
units of cycles at the carrier frequency, and typically converted to radians. GPS receivers measure phase by integrating the Doppler frequency. This is why the carrier phase measurement is frequently referred to as accumulated Doppler range. To extract the phase fluctuations caused by the ionosphere, the carrier phase measurements must be detrended to remove the significantly larger contribution from the changing range to the satellite (geometric Doppler). Before the phase measurements can be detrended, however, cycle slips and data gaps must be detected and repaired, otherwise the detrending filter produces spurious oscillations. The carrier phase is detrended by first repairing cycle slips and then applying a sixth order Butterworth high-pass filter with 3 dB cutoff at frequency 0.1 Hz. This cutoff frequency was chosen for consistency with the real-time results presented in this paper, since all of the receivers considered used a cutoff frequency of 0.1 Hz when detrending the phase fluctuations to provide real-time estimates of $\sigma_\phi$. Once the phase fluctuations due to scintillation have been extracted according to the methodology described above, we compute $\sigma_4$ as the standard-deviation of the detrended phase in each 60 s interval using Equation 4.

4. Measurement Setup

The six receivers described in Section 2 were installed at São José dos Campos (23.1°S, 45.8°W, dip latitude 17.3°S), a station under the southern crest of the equatorial ionization anomaly. The $S_i$ and $\sigma_4$ indexes data from these receivers are analyzed for the geomagnetically quiet (Kp < 3) nights February 20–21, 2013 for the PRN 19 and November 27–28, 2013 for the PRN 25. For geomagnetically disturbed nights the scintillation normally presents high variability (de Paula et al., 2019), so for this study it was selected these two magnetically quiet nights. The daily averaged F10.7 cm solar fluxes for the days February 27, February 28, November 27, and November 28 on 2013 were 111.0, 106.2, 125.6, and 129.3 sfu, respectively, where 1 sfu = 10$^{-22}$Wm$^{-2}$ Hz$^{-1}$. During the February 20–21 night, the average $S_i$ was about 0.5 until 02:40 UT (LT = UT−03) on day 21, and then increased to an average of about 0.7 up to 03 UT and afterward it presented a sharp decrease. For this night the scintillation can be considered moderate. On the November 27–28 night the $S_i$ index was almost at zero level up to 00:30 UT on day 28 and increased sharply to an average level of 0.8 up to about 01:50 UT and reaching 1.0 in the average after this time. Some short lived $S_i$ spikes larger than 1.2 were observed during this night. The scintillation level for the November night was larger than for February night and can be considered strong scintillation. The $S_i$ behavior for this night, with a sharp $S_i$ increase, is a typical case when a well-developed ionospheric structure (bubble) moves across the line of sight from the GNSS satellite to the receiver. In this work it was considered ionospheric scintillation only when $S_i > 0.15$. The elevation mask of 10° was used for data collection, however in the data analysis elevations larger than about 20° should be considered to minimize the effects over the signal of non-geophysical sources such as low S/N and multipath. Amplitude scintillation index $S_i$ from these six different GNSS receivers and phase scintillation index $\sigma_4$ from three of those receivers were analyzed to compare their values and to analyze their performance during these two nights.

The CASES, GSV4004B, and GPStation6 scintillation monitors provide the $S_i$ parameter calculated internally in real time by their receivers. The CSM and the Septentrio monitors provide $S_i$ post-processing their raw data using their own proprietary codes. High rate raw data from CASES, CSM, GPStation6, Septentrio, and SU IONO SDR were provided allowing the post-processing of $S_i$ parameters. In this work this parameter was calculated using a standardized procedure described in Section 3.6. For the GSV 4004B, $S_i$ was calculated by GPS-SCINDA tools from LISN using raw data at the rate of 50 Hz. All of the GPS-SCINDA or LISN systems use $C/N_0$ (converted to linear units) as a proxy for signal intensity, and this signal intensity is not detrended prior to computing the $S_i$ index (C. Carrano, 2008).

The CASES, GSV 4004B, and GPStation6 scintillation monitors provide also the RT $\sigma_4$ parameter calculated by their receivers, however RT GSV4004B phase data was too noisy to be used. At this work $\sigma_4$ was also calculated using phase raw data for the CASES, GPStation6 and Septentrio and following the methodology described in Section 3.7. No high rate raw phase data were available for the GSV 4004B, for the SU IONO SDR and for the CSM scintillation monitors. In the SU IONO SDR system they could have used the $I/Q$ data to extract higher rate data, however their priority at that time was more comparing to what they could extract from standard receivers.

In this work the first step was to present the proprietary real time $S_i$ and $\sigma_4$ indexes, when available, from these different systems. The next step was to repeat this procedure for the proprietary post-processed data.
Finally, S₄ and σₕ indexes were post-processed according to Sections 3.6 and 3.7, respectively. Sections 4.1–4.7 present results from these procedures and detailed comments and discussions are presented in Section 5.

4.1. Real Time S₄ Index Directly Read from the Receivers

Figure 2 (panels a, c and e) shows real time S₄ index (blue line) directly provided by the receivers CASES, GSV 4004B and GPStation6 for the night February 20–21, 2013, and for the night November 27–28, 2013 (panels b, d, and f). Black line is the satellite elevation and green line is the amplitude scintillation threshold of S₄ = 0.15. The gaps are losses of lock. Excellent S₄ agreement was observed between these 3 receivers during February 20–21 while more data gaps were observed mainly for the GSV 4004B and GPStation6 receivers during November 27–28 during more severe scintillation conditions. Larger S₄ variability was observed for the GSV 4004B and GPStation6 receivers compared to CASES receiver.

4.2. Post-processed S₄ Using Proprietary Methodology

Figure 3 shows the S₄ index for the Septentrio and CSM post-processed by their own proprietary methodologies, for the two nights. S₄ indexes, although having similar patterns for these two receivers, were larger for CSM during both nights. CSM data were lost after about 01:20 UT for lower satellite elevation during the 27–28 night.

4.3. Post-processed S₄ Using Raw Data and Standardized Methodology

Figure 4 presents in the left panels (a, c, e, g, and i) the S₄ indexes (blue), the satellite elevation (black), the number of lost samples per minute (gray vertical histograms) and the raw WBP signal (blue) for the CASES, CSM, GSV 4004B, GPStation6, and Septentrio for the night 20–21 of February 2013. No SU IONO SDR data...
were available for this night. In the right panels (b, d, f, j, and l) same parameters, for all six receivers, are presented for the night 27–28 of November 2013. No raw data was available from the GSV 4004B and its S₄ was obtained from the LISN site where this parameter was calculated using GPS-SCINDA tools. Only the CSM lost S₄ data after 01:50 UT when satellite elevation dropped below than 30° on the night 27–28 November and presented smaller WBP amplitude incursions and a large lost samples/minute (mainly on the night 27–28 of November) compared to the other receivers. S₄ good agreement was observed for the (five) six receivers during the February 20–21 and November 27–28 nights. The GPStation6 occasionally reported very large spurious spikes in the power measurement (up to several orders of magnitude). These spikes in power tended to coincide with cycle slips in the L1 carrier phase. Unless removed, these spurious spikes in the power will cause artificially large S₄ values. Following Carrano’s personal communication, we removed these spikes by normalizing the WBP signal by the median and then discarding values above 10 linear units. After detrending, the WBP it was again normalized by the median and values above eight linear units were discarded before calculating the S₄ index. Manual inspection of the data confirmed that this processing successfully removed the spurious power spikes but not the high-frequency signal fluctuations due to scintillation. Subsequently, we discovered that the simpler approach of finding intensity values which exceed a 60-s running average of intensity by more than 10 times is equally effective at identifying these power spikes. Replacing these spikes with the value of the 60-s running average yields nearly identical results to those presented here.

4.4. Real Time σ₂ Index Directly Read from CASES and GPStation6 and Post-processed by Septentrio Own Methodology

Figure 5 (panels a, c) presents the RT phase scintillation σ₂ for the night February 20–21 and at Panels b, d for November 27–28 provided directly from the CASES and GPStation6 receivers. Panels e and f present this parameter post-processed by the Septentrio own methodology for these two nights. Gaps in the plots are due to σ₂ values larger than 2 radians that were not considered. σ₂ reasonable agreement was observed during the night February 20–21, however the receivers GPStation6 and Septentrio lost a large amount of data during the night November 27–28.
Figure 4. $S_4$ index (blue), satellite elevation (black), WBP (blue), and lost samples per minute (gray histograms) for the six scintillation monitors. The green line is the amplitude scintillation index $S_4$ threshold of 0.15. WBP, wide band power.
4.5. Post-processed $\sigma_\phi$ Using Raw Data and Standardized Methodology

Figure 6 (panels a, c, and e) presents the post-processed phase scintillation $\sigma_\phi$ for the night February 20–21 and at panels b, d, and f for the night November 27–28 for the CASES, GPStation6 and Septentrio, following the standardized methodology described at Section 3.7. Compared to the RT $\sigma_\phi$ (Figure 5) the post-processed $\sigma_\phi$ (Figure 6) calculation improved substantially the data availability. Very good $\sigma_\phi$ agreement was observed for the three receivers and for two nights.

4.6. Comparison of $S_4$ and $\sigma_\phi$ Indexes Post-processed Using Standardized Methodologies

Figure 7 (panel a) shows the $S_4$ data available from five scintillation monitors for the night 20–21 and for all the six scintillation monitors for the night 27–28 (panel b). Panels c and d present $\sigma_\phi$ data for these two nights from CASES, GPStation6 and Septentrio scintillation monitors. These $S_4$ and $\sigma_\phi$ parameters were determined according to the methodologies described in Sections 3.6 and 3.7 respectively.

Complementing the comparative analysis of the performance of the receivers, Pearson’s linear correlation coefficient $r$ was computed between pairs of receiver’s indexes. Figures 8 and 9 present these $S_4$ analyses for February 20–21, 2013 and for November 27–28, 2013 respectively. The receivers are identified in the diagonal of the matrix. For each pair of receivers, the comparative $S_4$ plots are shown below the diagonal, while the correspondent $S_4$ correlation coefficients $r$ are found above the main diagonal. SU IONO SDR data were not available for the 20–21 night. Detailed discussions about these results will be provided at Section 5.

Similarly to the correlation analysis presented in Figures 8 and 9, Figure 10 shows the $\sigma_\phi$ pairwise correlation coefficients $r$ on February 20–21, 2013 (a) and on November 27–28, 2013 (b). Only $\sigma_\phi$ data for Cases, GPStation6 and Septentrio were available. Larger $\sigma_\phi$ dispersion (see plots below the diagonal) and smaller $r$ coefficients for all pairs of receivers were observed for the night 27–28 with larger scintillation intensity compared to the night 20–21.

Another quantitative analysis of how much the $S_4$ values of the pairwise receiver indexes differ in average (avg) and in maximum (max) values was performed. For each 1 minute the $S_4$ differences from each pair
Figure 6. Post-processed $\sigma_\phi$ using raw data and standardized methodology.

Figure 7. $S_4$ and $\sigma_\phi$ indexes for the two nights of 2013, calculated from the raw WBP data ($S_4$) and phase raw data ($\sigma_\phi$) and using standardized methodology. WBP, wide band power.
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of receivers is calculated and the average and the maximum values are determined. Only \( S4 \) values existing simultaneously for each pair of receivers for each 1 min were considered in the analysis. Figures 11 and 12 are Heatmaps for the avg and max parameters respectively. The data for the night 20–21 are below the diagonal and for the 27–28 night are above the diagonal. The \( S4 \) average differences color bar is below the plot and these values increase from light to dark colors. The receiver pairs with the lowest avg (0.021) are Septentrio/GPStation6 and highest avg (0.045) are both GSV 4004 B/CSM and GSV 4004 B/CASES for the 20–21 night, while for the 27–28 night the lowest value (0.019) is for Septentrio/SU IONO SDR and highest (0.053) for CSM/GSV 4004B, CSM/Septentrio and CSM/SU IONO SDR. In most cases larger avg values were observed for the 27–28 night.

Figure 12 shows that the lowest value (0.134) of the parameter max is for the station pair Septentrio/CASES and the highest value (0.519) for the GSV 4004 B/CSM for the 20–21 night. For the 27–28 night, the lowest max value (0.128) is for the CASES/SU IONO SDR and the highest (0.476) is for GSV 4004 B/GPStation6.

Similar study was performed for the \( \sigma_4 \) values of the pairwise station differences in average (avg) and in maximum (max) and the results are presented in Figure 13a for the avg parameter and in Figure 13b for the max parameter for both nights. Note that the color scales for these two figures are different. Both avg and max parameters increased substantially from the 20–21 night to the 27–28 night that has a higher scintillation level.

4.7. Comparison of \( S4 \) and \( \sigma_4 \) Indexes Using Manufacturer Proprietary Tools and Post-processed Standardized Methodologies from the Same Receiver

The comparison between the \( S4 \) computed using the manufacturer proprietary tools and using the standardized methodology from the same receiver was performed using the Pearson's linear correlation, providing one idea about how important is the standardized methodology to compute these indexes. Similar

![Figure 8. Comparative \( S4 \) plots for each pair of receivers (below the diagonal) and correspondent \( S4 \) correlation coefficients \( r \) for the five receivers (in the diagonal) available on February 20–21, 2013.](image-url)
procedure was adopted for the $\sigma_4$ index. Figure 14 presents the results of this analysis. The larger contributions to improve the indexes calculation using the standardized methodology were for CASES with the smaller correlation coefficients $r$ for $S_4$ (0.871) and $\sigma_4$ (0.667) for the two nights. From another perspective, the best agreement between the two methodologies was for the Septentrio with $r$ values larger than 0.995.

Figure 9. Same of Figure 8 for the six receivers available on November 27–28, 2013.

Figure 10. Comparative $\sigma_4$ plots for each pair of receivers (below the diagonal) and correspondent $S_4$ correlation coefficients $r$ for the three receivers (in the diagonal) available on February 20–21, 2013 (a) and on November 27–28, 2013 (b).
5. Discussions and Conclusions

Our results, even though being just for two nights, are representative of a site under the Equatorial Ionization Anomaly southern crest, where the amplitude and phase scintillations are larger than from other magnetic latitudes. They are for two nights with moderate solar activity (110–129 sfu) and for low geomagnetically disturbed conditions ($Kp < 3$). For geomagnetically disturbed nights, the scintillation presents high variability, so our choice was to make our study for these two geomagnetically quiet nights. These two

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**Figure 11.** $S_4$ average differences avg between pair of receivers for the 20–21 night (below the diagonal) and for the 27–28 night (above the diagonal).

**Figure 12.** $S_4$ maximum differences max between pair of receivers for the 20–21 night (below the diagonal) and for the 27–28 night (above the diagonal).
night scintillations cover a large range of $S_4$ amplitudes occurrences during summer solstice conditions. The comparative $S_4$ analysis (Figures 8–10) points out a linear relation for each pair of receivers from low to strong $S_4$ values, so it is expected similar performance of these six receivers for different sites and different times with different $S_4$ levels. Anyway, these two nights were the only ones when all receivers good quality data were available. A study of pairs of receivers with data for longer concurrent periods would be beneficial but it is outside the scope of this article.

It was observed a good agreement between RT $S_4$ indexes from the CASES, GSV 4004B and GPStation6 scintillation monitors (see Figure 2, panels a, c, and e) for the 20–21 night. Larger $S_4$ variability was observed for the Novatel receivers whose averages are for each 60 s, compared to CASES with 100 s averages. In Figure 2 (panels b, d, and f) for the 27–28 night, under higher $S_4$ values, even though there is a good $S_4$ agreement, the Novatel receivers presented more losses of lock, mainly the GPStation 6, compared to the CASES receiver.

As it can be observed in Figure 3, the post-processed $S_4$ from the Septentrio and CSM using their proprietary methodologies were in good agreement for the two nights, however larger $S_4$ values for the CSM were observed for the two nights. When applying the method (Equations 5–7) outlined in T. L. Beach (1998) to calculate $S_4$, we have observed that the reported $S_4$ values seem high relative to other scintillation receivers. We recommend using the methodology of Section 3.6 instead. Besides presenting more losses of lock for both nights the CSM scintillation monitor does not provide data for the 27–28 night (see panel d of Figure 3) after 01:20 UT. It could be a function of the relatively unsophisticated tracking algorithms copied from the original Plessey development kit used in the CSM.

When post-processing raw data (see Figure 4) from the six scintillation monitors using the standardized methodology of C. S. Carrano and Groves (2019) during these nights, there is a better $S_4$ agreement between them.

The $S_4$ correlation analysis from the pairs of receivers (see Figures 8 and 9) presented very strong correlations for the two nights ($r > 0.965$). Similarly to the real time $S_4$ values there are no CSM $S_4$ values after about 01:50 UT for this post-processed methodology (see upper part of panel d in Figure 4). Large number of lost samples per minute (gray histograms) was observed only for the CSM, mainly for the 27–28 night. Smaller amplitude fadings were observed in the CSM WBP compared to the other five scintillation monitors (see panel c and d lower parts of Figure 4). Probably, this is mostly a result of the CSM FLL tracking loop, that does not allow the receiver to follow rapid fades to very low levels. The SU IONO SDR amplitude scintillation data were available just for the 00:30 UT to 02:00 UT on the night 27–28 of November 2013 and their WBP and $S_4$ parameters were in very good agreement with CASES ($r = 0.997$) and Septentrio ($r = 0.997$) receivers (see Figure 9).

The RT $S_4$ provided directly from the CASES and GPStation6 scintillation monitors were in reasonable agreement (see Figure 5, panels a, b, c and d), however a large lack of data is observed for the GPStation6
for the 27–28 night under higher scintillation level (see panel d) for low elevation angles. Post-processed Septentrio $\sigma_\phi$ (Panels e and f) using their own methodology is in reasonable agreement with the other RT $\sigma_\phi$ from panels a, c for the 20–21 night, however $\sigma_\phi$ values (Figure 5, panel f) were larger and lost more values after about 01:20 UT with elevation angles smaller than 30°, compared to CASES values (Panel b).

When phase data is post-processed using the standardized methodology described at Section 3.7, strong correlations ($r > 0.888$) for the 20–21 night and good correlation ($r > 0.746$) for the 27–28 night were observed in the $\sigma_\phi$ correlation analysis for the CASES, GPStation6 and Septentrio (see Figure 10), pointing out that when processing phase data, it is necessary to have a careful procedure to reconstruct the phase before calculating $\sigma_\phi$. The spikes in $\sigma_\phi$ are due to cycle slips on L1 or loss of lock on L1, which also results in a cycle slip [Carrano, personal communication]. A scintillation monitor must detrend the phase in order to remove

Figure 14. Comparison between the $S_4$ and $\sigma_\phi$ computed by the same receiver using the manufacturer proprietary tools and using the standardized methodology described in Sections 3.6 ($S_4$) and 3.7 ($\sigma_\phi$) for the two nights.
the purely geometrical contribution due to satellite motion before computing $\sigma_\phi$. An unrepairs cycle slip causes large oscillations in the detrended phase, which results in a spike in $\sigma_\phi$. There are two remedies for this: 1) detect and correct the cycle slips before detrending, or 2) accept the fact that $\sigma_\phi$ will have a jump whenever a slip occurs and simply discard this data afterward. The best option is 1), but this is seldom attempted in real-time due to the difficulty involved. The Novatel receivers documentation suggests that one should discard $\sigma_\phi$ values for 4 min following each loss of lock or cycle slip event.

The $S_4$ and $\sigma_\phi$ indexes post-processed using standardized methodologies, which are plotted at Figure 7 for all available receivers, presented a good agreement for both nights. These data were also used to perform the Pearson’s linear correlation coefficient analysis between pairs of receivers which indicates a very strong $S_4$ correlation between all pairs of receivers as can be observed at Figures 8 ($r > 0.965$ for the 20–21 night) and 9 ($r > 0.977$ for the 27–28 night). It is worth noting that the GSV 4004B, that does not use the same algorithm employed for the others receivers in the $S_4$ estimation, presents a slightly lower correlation. The results for $\sigma_\phi$ (Figure 10) show a strong correlation between station pairs (0.888, 0.914, and 0.943) for the February night and a good correlation (0.746, 0.864, and 0.834) for the November night, pointing out that phase scintillations were more affected during larger scintillation intensity when compared to amplitude scintillations.

Considering the results for all station pairs from Figures 11 to 13, much larger $\sigma_\phi$ average differences (avg) and maximum differences (max) were observed for the 27–28 night (larger scintillation intensity) compared to the night 20–21. Larger $S_4$ avg values were also observed for the 27–28 night compared to the 20–21 night, but not for the max values when they were larger for most station pairs for the 20–21 night. The avg and max differences in $S_4$ and $\sigma_\phi$ values between receiver pairs would become larger as the scintillation strength increases. Since $S_4$ and $\sigma_\phi$ measure the standard deviation of a random process (i.e. normalized intensity fluctuations and phase fluctuations, respectively), as these measures increase (stronger scintillation) the absolute differences between receivers, e.g. avg (abs ($S_4_{rx1}—S_4_{rx2}$)), max (abs ($S_4_{rx1}—S_4_{rx2}$)), will typically increase as well. Additional effects come into play when the scintillation is strong, namely loss of lock events and cycle slips. Since different receiver models use different tracking loop designs, each receiver will experience a different number of data gaps and cycle slips as a result of the scintillation. The standardized methodology attempts to detect and repair cycle slips before computing the standard deviation of phase. So, as the scintillation strength increases, one would expect larger differences in $\sigma_\phi$ values between receivers that use different tracking loop designs to track the phase, since different numbers of slips have had to be repaired. The standardized methodology uses interpolation to fill in data gaps due to loss of lock, and different receiver models will experience different numbers of loss of lock events causing data gaps of different lengths. This may also contribute to larger differences in values between different receivers when the scintillation is strong. This does not point out a deficiency in the standardized methodology for computing sigma-phi. In fact, one might argue that it becomes even more important to use the same (standardized) technique for detecting and repairing cycle slips under strong scintillation conditions, since different proprietary algorithms for doing so would likely contribute to further differences in sigma-phi values between the different receiver models.

The comparison of $S_4$ and $\sigma_\phi$ indexes using manufacturer proprietary tools and post-processed raw data using standardized methodologies (see Figure 14) from the same receiver pointed out that the larger contributions to improve the indexes calculation using the standardized methodology were for the CASES, mainly for the $\sigma_\phi$ calculations, when the correlation coefficient $r$ was 0.667, while the best agreement between the two methodologies was for the Septentrio with $r$ larger than 0.995.

Key findings of this work are:

- when using the standardized methodology to post-process the $S_4$ and $\sigma_\phi$ indexes there is a much better agreement between the values of these parameters for the six receivers.
- The real-time phase data for the CASES, GSV 4004B, and GPStation6 (also Septentrio post-processed phase using their own methodology) were substantially affected during the upper scintillation level in the November 27-28 night.
- The raw data (WBP) for the GPStation6 presented very large abnormal upward fluctuations (incursions) and it was necessary to apply the data processing methodology described in Section 4.3 to improve the $S_4$ calculations.
The CSM presented smaller amplitude fadings, larger S4 values and many losses of lock during scintillations mainly when satellite elevations were lower than 30°.

The ASTRA, Septentrio, and SU IONO SDR scintillation monitors were the most robust for amplitude and phase calculations during scintillation conditions.

Lower S4 average differences between pairs of receiver were for Septentrio/GPStation6 (0.021) for the night 20–21 and Septentrio/SU IONO SDR (0.019) for the night 27–28. The lower S4 maximum differences were for CASES/Septentrio (0.134) in the night 20–21 and for CASES/SU IONO SDR (0.128) in the night 27–28.

For all station pairs analyses much larger σϕ average differences avg and maximum differences max were observed for the night with larger scintillation intensity (27–28). Similar behavior was also observed for the S4 average differences, but not for the maximum differences since they were larger for most station pairs during the night 20–21.

When comparing the index calculations using the standardized methodology with the manufacturer proprietary tools for the same receiver, the larger contribution to improve the indexes calculation using the standardized methodology was for CASES mainly for σϕ calculations, while the best agreement between these two methodologies was observed for the Septentrio.

Based on this work we can point out that, under some few operational constraints, simultaneous S4 data from all the six analyzed scintillation monitors, even though having different receivers, antennas, cables (see Table 1) and different data processing methodologies, presented a reasonable agreement (see Figure 7, panels a and b). So their data could be simultaneously used to develop global S4 maps and scientific researches giving support to many geodetic applications, like precise agriculture and air navigation oriented by GNSS signals, during ionospheric scintillations.

Some planned future work includes:

- To develop a S4 model based on real scintillation data, and using a GNSS simulator to apply this simulated signal to these six different receivers. This procedure will eliminate the influence of different antennas and cables and data processing methodologies.
- To extend this work to the Septentrio PolaRxSS, Topcon Net-G3, software-designed radio (SDR) and low cost scintillation monitors like the one proposed by Rodrigues and Moraes (2019) and to extend the study for more events of scintillation conditions.

Data Availability Statement

The data from the CSM, GSV 4004B, GPStation6, Septentrio, and SU IONO receivers used in this paper are available on a public repository https://doi.org/10.5281/zenodo.3922909. The CASES data supporting this research are available from Dr Geoff Crowley at ASTRA, with a mutually executed NDA, and are not accessible to the public or research community without a prior agreement. The F10.7 cm solar fluxes and Kp values were obtained from https://omniweb.gsfc.nasa.gov/form/dx1.html and http://wdc.kugi.kyoto-u.ac.jp/kp/index.html, respectively.

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