Estimation of Ionospheric Scintillation Index S4 from Rate of Change of Total Electron Content Index (ROTI) in Low Latitudes

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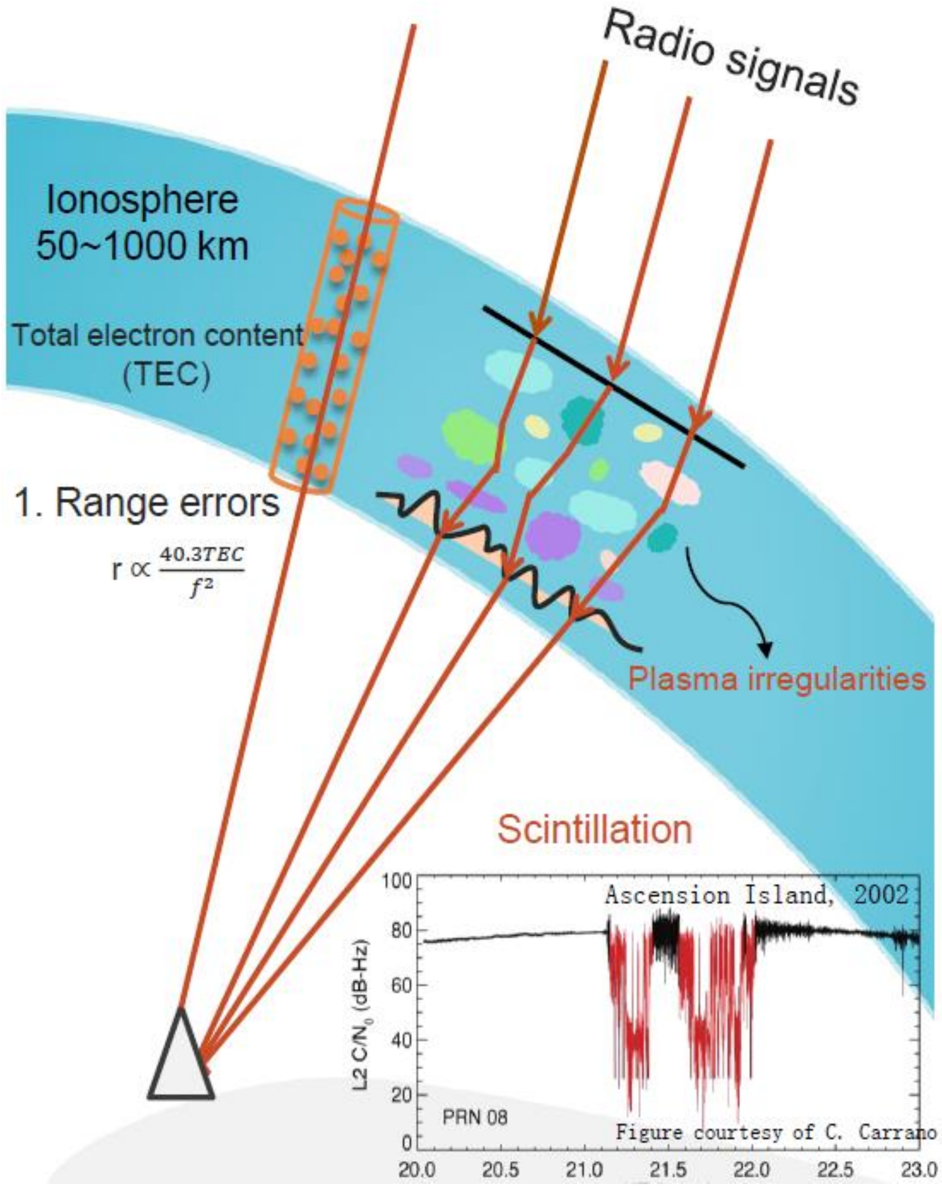
Outline

- Introduction
- Motivation
- Methodology
- Data
- Results
- Conclusions

Introduction

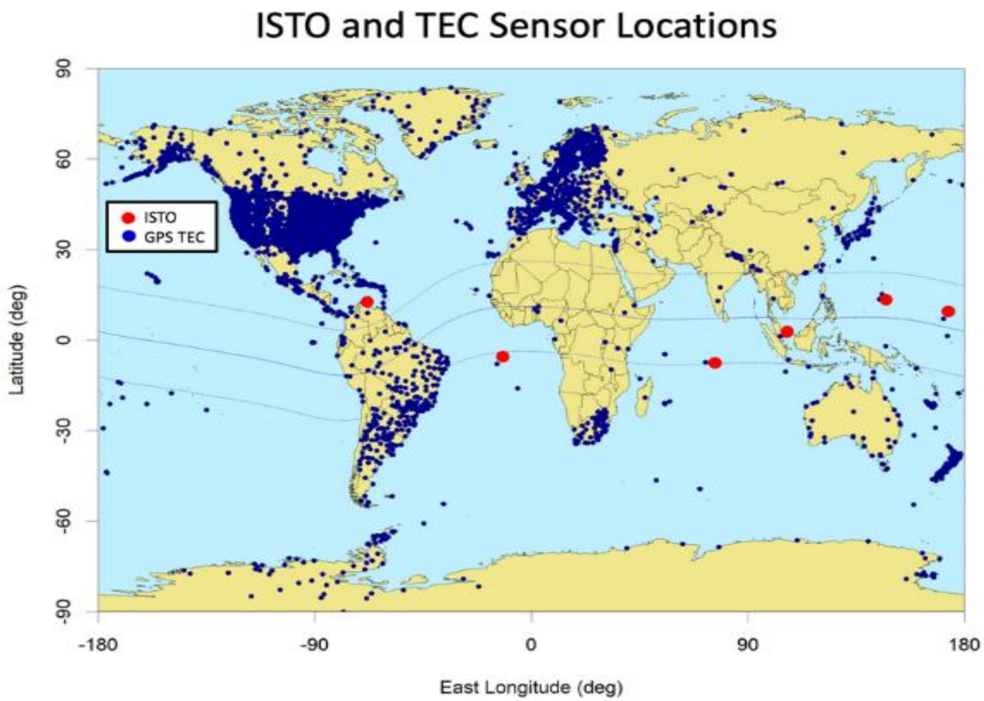
- The GNSS plays an important role in radionavigation systems.
- Ionospheric delays and scintillation cause positioning errors that degrade the accuracy, performance and availability of associated operations, particularly in the equatorial and low latitude regions.
- Ionospheric delays are propagation delays of GNSS signals and are associated to the Total Electron Content (TEC).
- Ionospheric scintillation are rapid fluctuations in both amplitude and phase of GNSS signals. Can create fading.



Motivation

- The International Civil Aviation Organization (ICAO) recently issued a request for real-time L-band scintillation parameters (S4 and σ_φ).
- Ionospheric irregularities can be assessed through the rate of change of TEC index (ROTI), which can be derived from dual frequency GNSS receivers.
- Specialized receivers that can generate the scintillation indices are not available all around the world, for this reason the ROTI calculated from inexpensive GNSS receivers could provide consistent scintillation diagnostics.

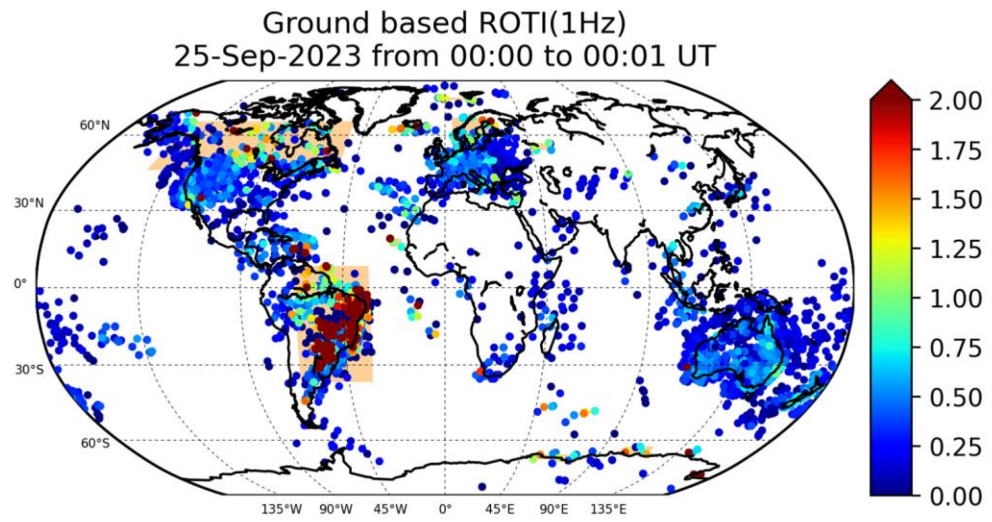
USA Space Weather Prediction Center (SPWC)



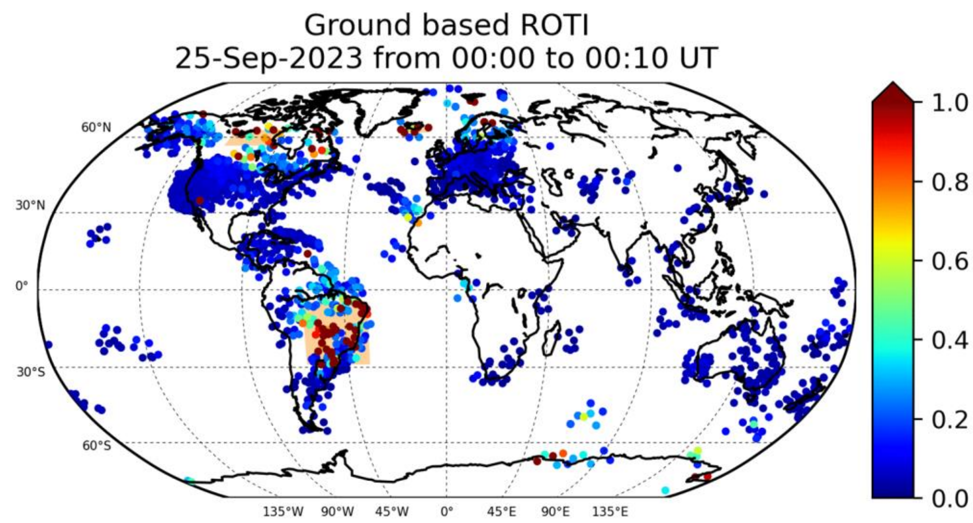
Motivation

ROTI Observations

ROTI(1Hz observations) => 1 min cadence



ROTI(30sec observations => 10 min cadence)



- High rate data captures variability on smaller temporal and spatial scales.

Motivation

- The relationship between ROTI and scintillation index S_4 has been widely studied to conserve the accuracy of GNSS applications.

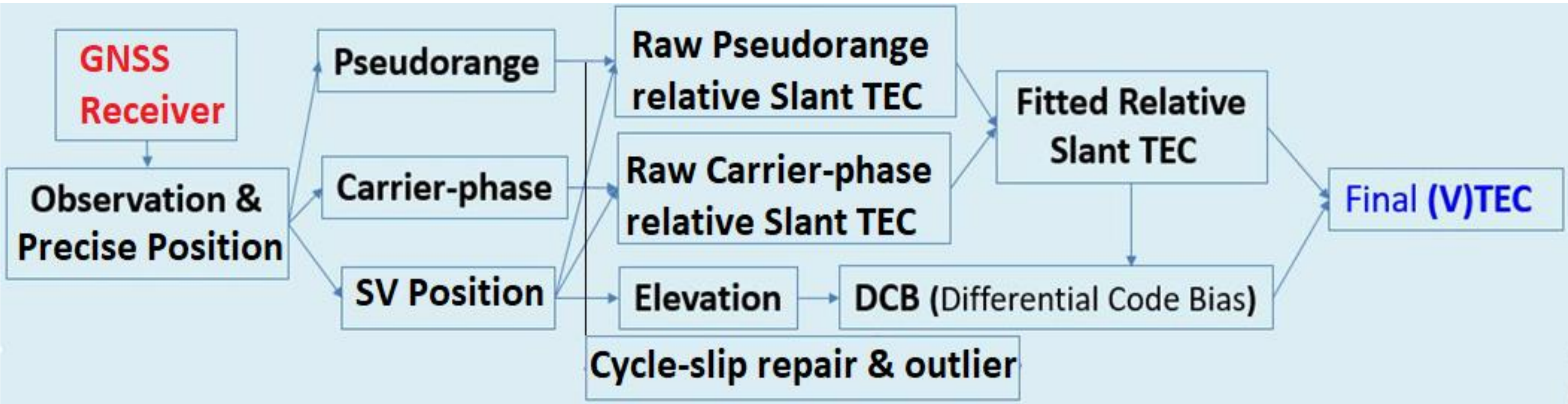
- **ROTI varies from satellite-to-satellite with the propagation geometry, and night-to-night & region-to-region with the irregularity drift**. The sampling rate affects its magnitude

- We focus on the equatorial region here (the most severe environment) and the underlying dynamics that give rise to intense irregularities.

- This work presents the estimation of ionospheric scintillation index S_4 from ROTI based on GNSS receivers located in low latitudes (Brazilian region). The **measured drifts** are used to estimate the effective scan velocity, when it is available. Additionally, samples of S_4 index are estimated using the **RISA drift climatology model**, varying the **sampling rate (1 sec and 10 sec) and GPS frequencies (L1, L2 and L5).**

Methodology

- Estimation of TEC:



- ROT can be estimated from the relation between the TEC and the sampling rate

$$ROT = \frac{TEC(t+\delta t) - TEC(t)}{\delta t}$$

Sampling rate
$\delta t = 1\ s, 10\ s$

- ROTI is the standard deviation of rate of TEC change (ROT)

$$ROTI = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(ROT - \overline{ROT})^2}$$

Methodology

- We applied the quantitative theory to estimate the S_4 using the relationship between ROTI/S_4 (Carrano et al., 2018)
- ROTI is a scaled version of the structure function of phase fluctuations.
- This theory applies the phase structure function developed by (Rino, 1979)

- Sampling interval
- Satellite motion
- Propagation Geometry
- Spectral Shape
- Strength
- Drift of the Irregularities

$$ROTI(\delta t)^2 = \frac{c^2}{\delta t^2}\left\{r_e^2\lambda^2\sec(\theta)\left(\frac{2\pi}{1000}\right)^{2\nu+1}C_K L\right\} G\,\frac{\Gamma(\nu-1/2)}{2\pi\Gamma(\nu+1/2)}\left[\frac{1-2\left|q_0 V_{eff}\,\delta t/2\right|^{\nu-1/2} k_{\nu-1/2}(q_0 V_{eff}\,\delta t)/\Gamma(\nu-1/2)}{q_0^{2\nu-1}}\right]$$

$$S_{4w}^2 = \left\{r_e^2\lambda^2\sec(\theta)\left(\frac{2\pi}{1000}\right)^{2\nu+1}C_K L\right\}\rho_F^{2\nu-1}F_S(\nu)\zeta(\nu)$$

θ: Propagation Angle

$C_K L$: Irregularity strength

G: Phase enhancement

q_0: Outer scale wavenumber

V_{eff}: Effective scan velocity

$\nu = p/2 \rightarrow p$: phase spectral index

ρ_F : Fresnel scale

$\zeta(\nu)$: geometry and propagation factor

$$S_{4w}^2 = \frac{\delta t^2}{c^2}\,\frac{\rho_F^{2\nu-1}F_S(\nu)\zeta(\nu)}{G}\,\frac{2\pi\Gamma(\nu+1/2)}{\Gamma(\nu-1/2)}\left[\frac{q_0^{2\nu-1}}{1-2\left|q_0 V_{eff}\,\delta t/2\right|^{\nu-1/2} K_{\nu-1/2}(q_0 V_{eff}\,\delta t)/\Gamma(\nu-1/2)}\right]\cdot ROTI(\delta t)^2$$

Correction based on a Rician statistic relation $S_4^2 \cong 1-\exp(-S_{4w}^2)$

Data

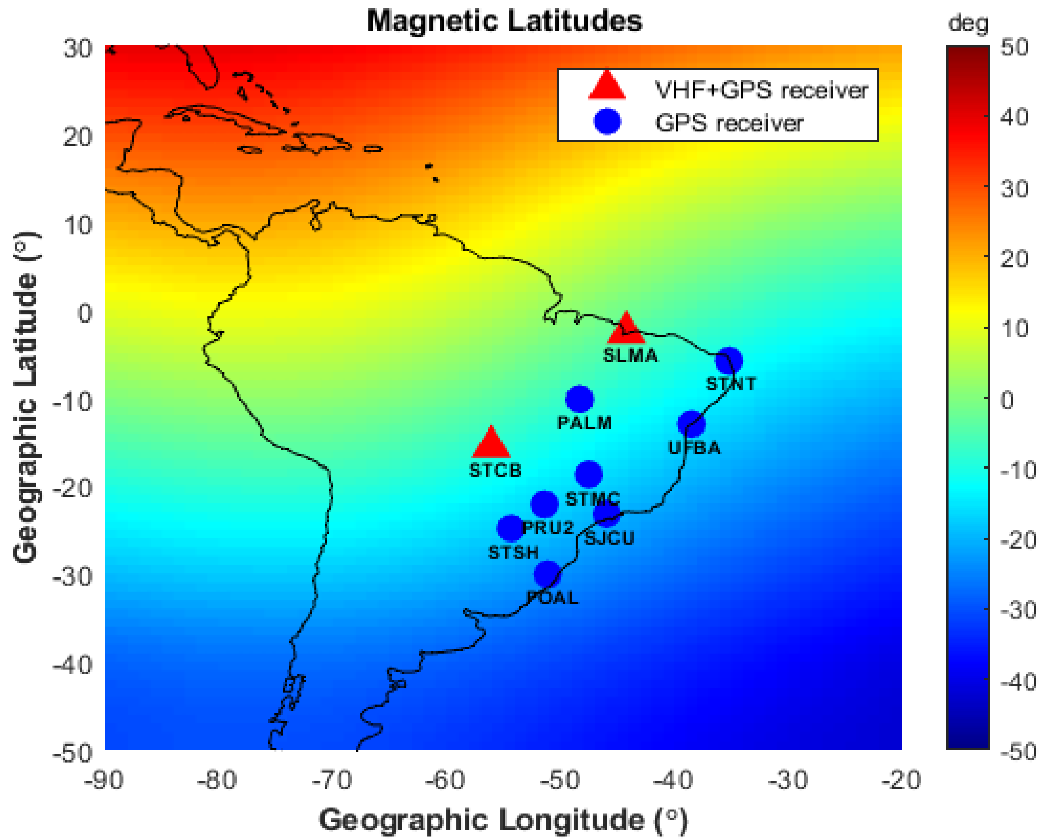
Stations located in Brazil

Stations located in different Dip latitudes

	Station	Lat	Lon	Dip lat
São Luís	SLMA	-2.57°	-44.22°	-2.7°
Palmas	PALM	-10.19°	-48.31°	-7.1°
Cuiabá	STCB	-15.55°	-56.06°	-7.8°
Natal	STNT	-5.84°	-35.19°	-10.7°
Salvador	UFBA	-12.92°	-38.51°	-14.6°
Monte Claros	STMC	-18.72°	-47.52°	-14.7°
Presidente Prudente	PRU2	-22.12°	-51.40°	-15.4°
Santa Helena	STSH	-24.84°	-53.34°	-16.4°
Sao Jose dos Campos	SJCU	-23.09°	-45.96°	-18.2°
Porto Alegre	POAL	-30.07°	-51.11	-22.5°

Some stations are located near of the southern crest of the equatorial ionization anomaly.

Sampling rate**:** 1 Hz
Cut-off Angle: 30°

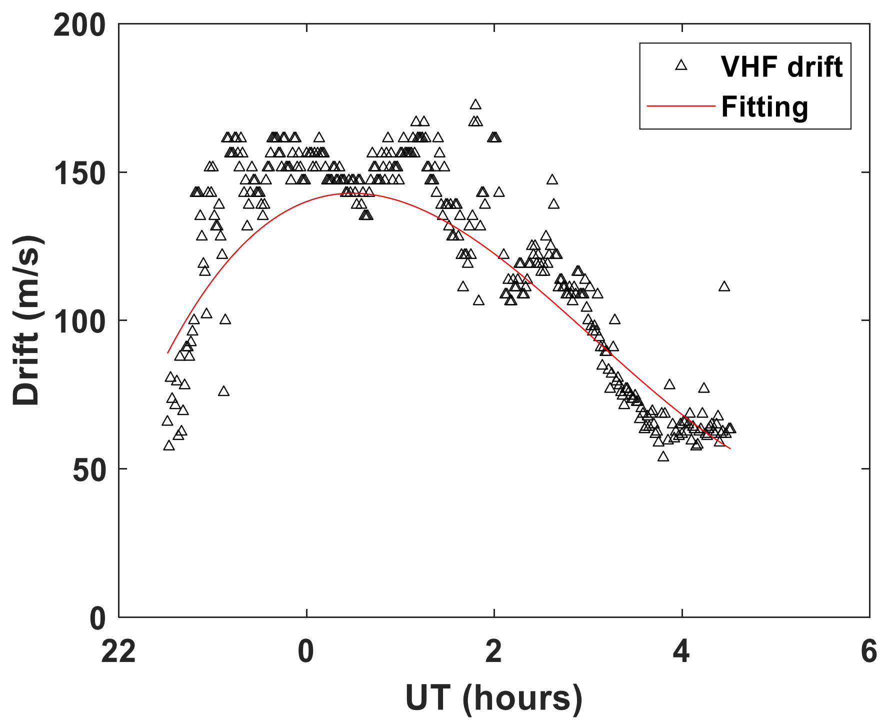


Data:
- GPS Observables (INCT-GNSS Network)
- Amplitude and Phase Scintillation (S_4, $\sigma\varphi$) Ionospheric scintillation monitor (INCT-GNSS Network) → Septentrio PolaRx
- Drift velocity (SCINDA, VHF receivers)
- Precise Satellite Position (IGS)

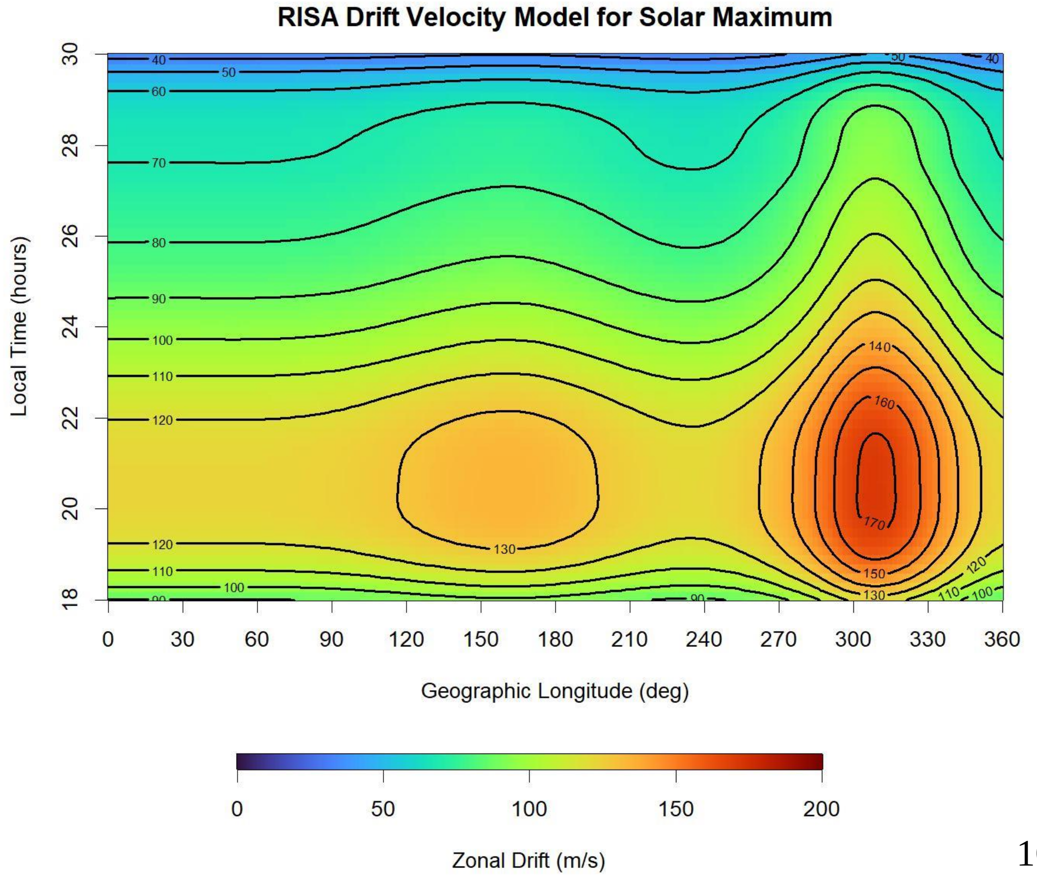
Drift Velocity

- We collected the VHF scintillation data from the SCINDA system to estimate the drift velocity and we applied linear/polynomial fitting for each evening.

Drift measured (São Luís)
March 13-14, 2022

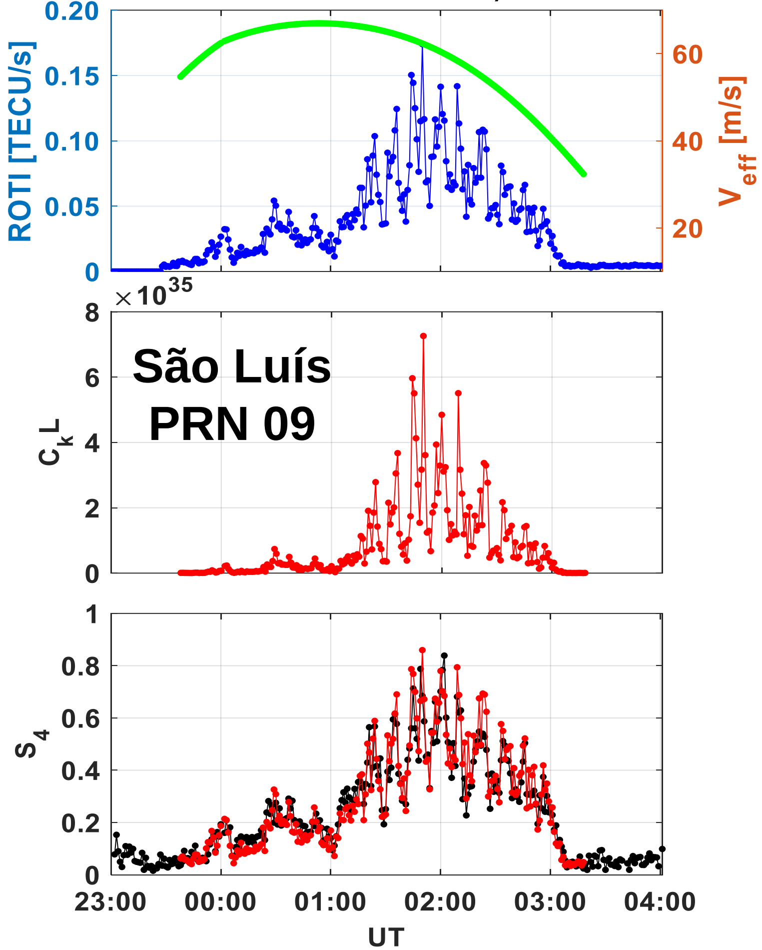


- ISR/BC recently developed a climatology model of the zonal irregularity drift from SCINDA data → RISA Model
- The model is a function of longitude, local time and solar cycle.



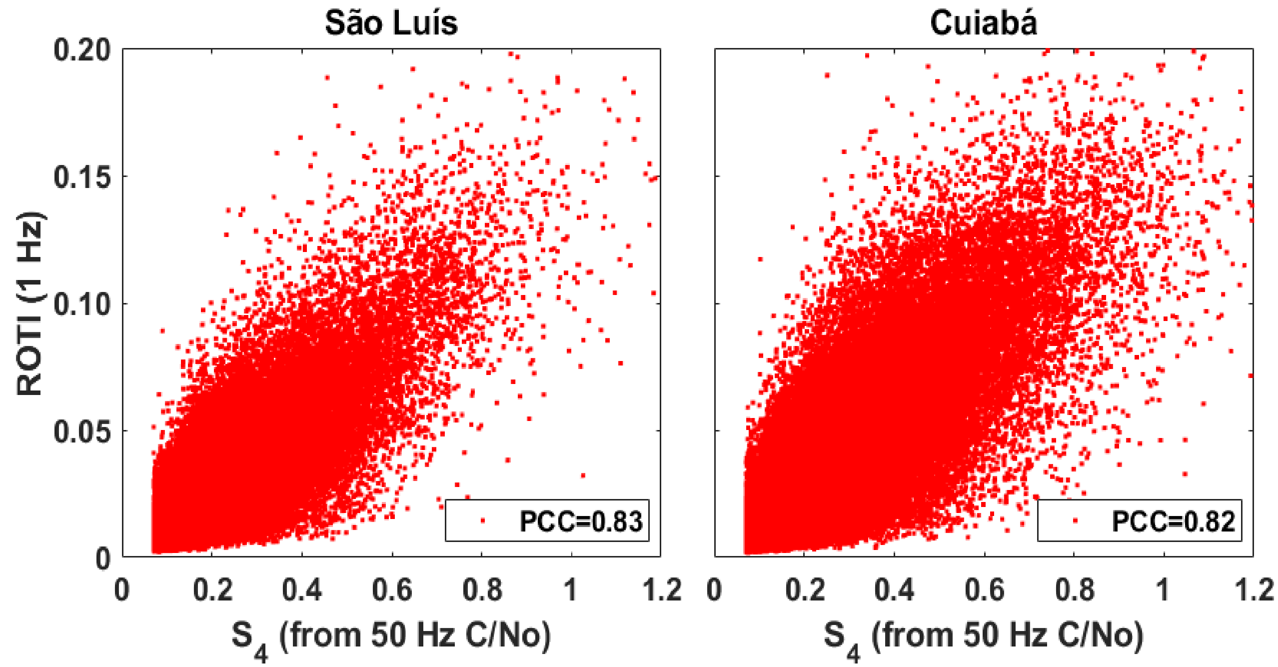
ROTI vs S_4 Estimation

November 13-14, 2022



Available Data: September - December 2022
Analysis: 85 nights

Scatter plot 1 Hz ROTI vs S_4(50 Hz)



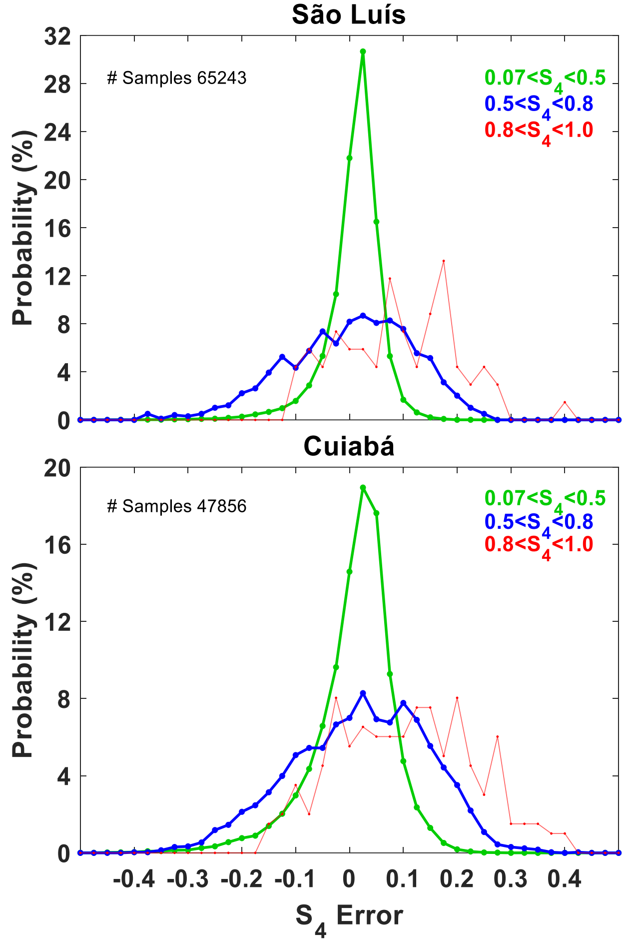
ICAO Thresholds for GNSS (Space Weather Advisories)

GNSS parameter	Weak	Moderate	Severe
Amplitude Scintillation Index (S_4 Index)	$0.07<S_4<0.5$	$0.5<S_4<0.8$	$0.8<S_4<1.0$
Phase Scintillation (σ_φ) [radians]	$\sigma_\varphi<0.4$	$0.4<\sigma_\varphi<0.7$	$0.7<\sigma_\varphi$
Vertical TEC [TEC units]	VTEC< 125	125<VTEC<175	175<VTEC

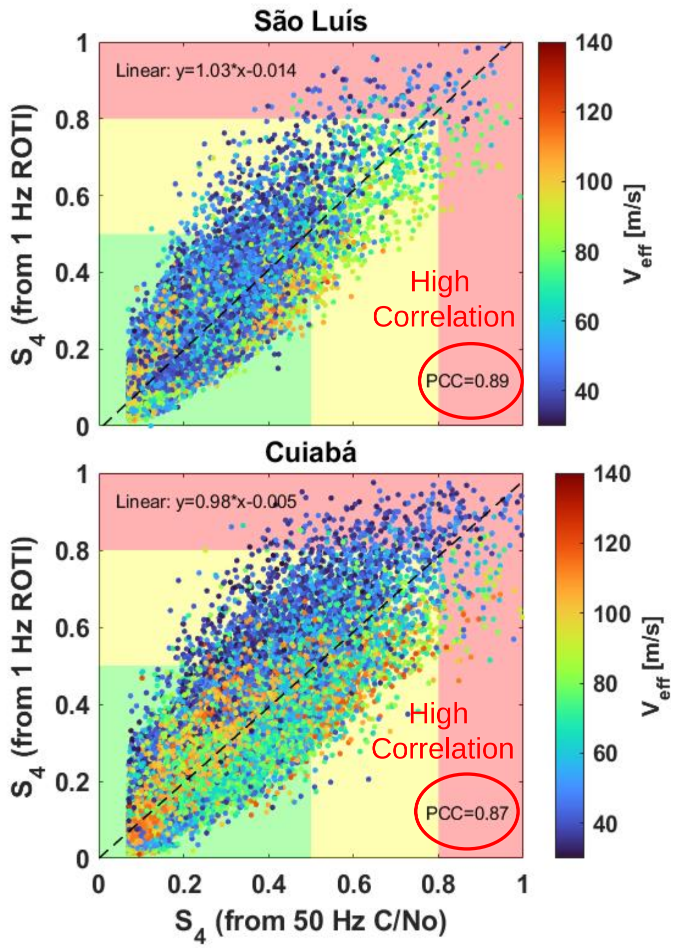
S_4 Estimation (Drift: Measurements)

Histogram

S_4 error=S_4(50 Hz) - S_4(1 Hz ROTI)



Scatter plot S_4(1 Hz ROTI) vs S_4(50 Hz)



These cases will be used as a reference for this study.

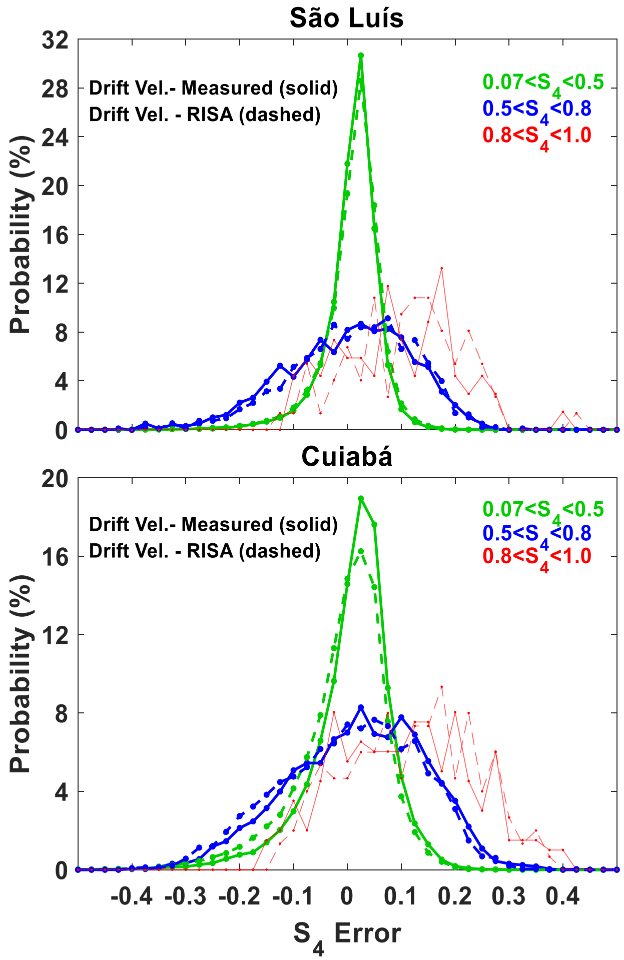
Station	Strength	Mean	SD	Median
São Luís	$0.07<S_4<0.5$	0.00	0.05	0.01
	$0.5<S_4<0.8$	0.00	0.11	0.01
	$0.8<S_4<1.0$	0.09	0.10	0.09

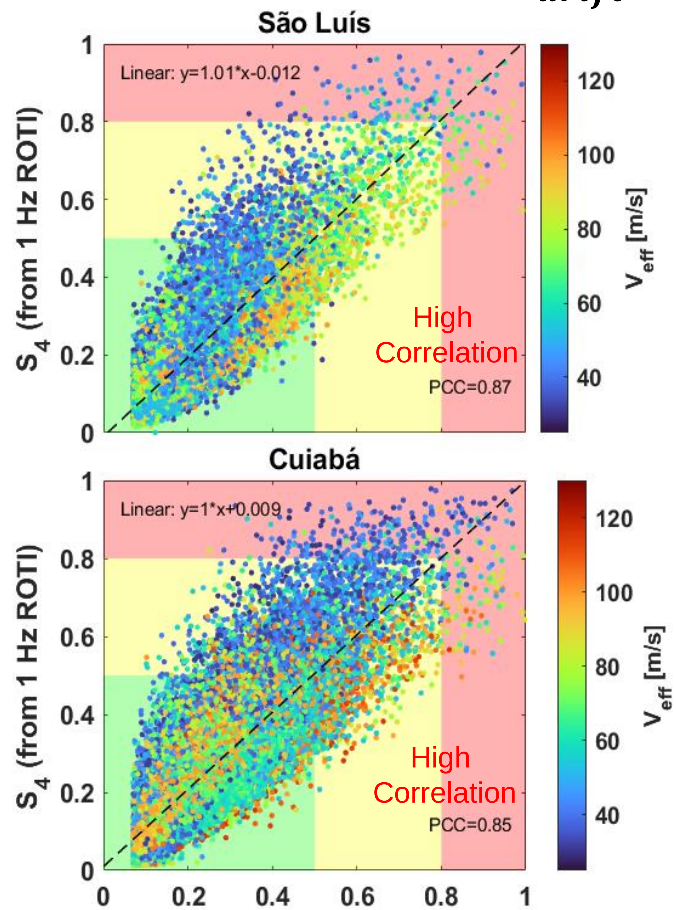
Station	Strength	Mean	SD	Median
Cuiabá	$0.07<S_4<0.5$	0.00	0.07	0.01
	$0.5<S_4<0.8$	0.01	0.12	0.02
	$0.8<S_4<1.0$	0.10	0.12	0.10

Variation of drift velocity source (Measurements and RISA model)

What happens when there are no drift measurements available??

$$V_{drift} = V_{RISA}$$





drift meas. Correlation coefficients:
São Luís PCC=0.89
Cuiabá PCC=0.87

Similar Correlation

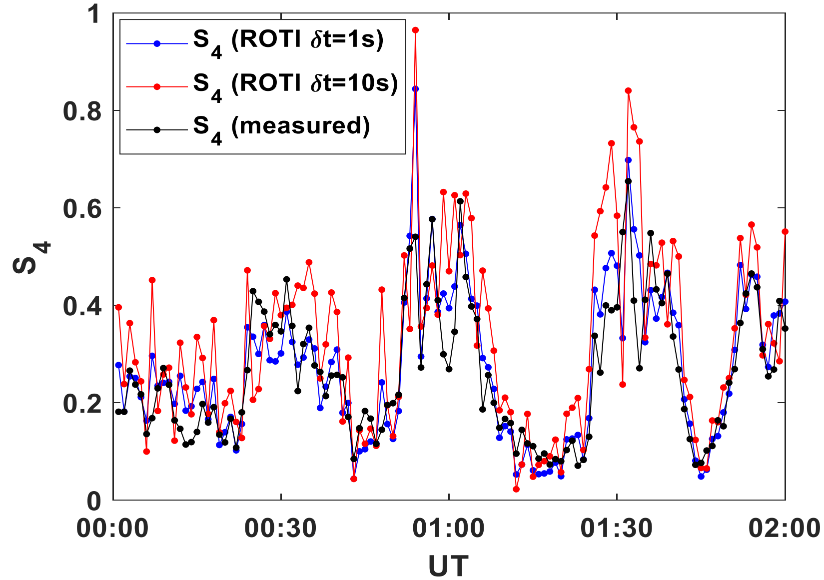
Station	Strength	Mean	SD	Median
São Luís	$0.07<S_4<0.5$	0.00	0.08	0.00
	$0.5<S_4<0.8$	0.01	0.13	0.02
	$0.8<S_4<1.0$	0.10	0.11	0.13

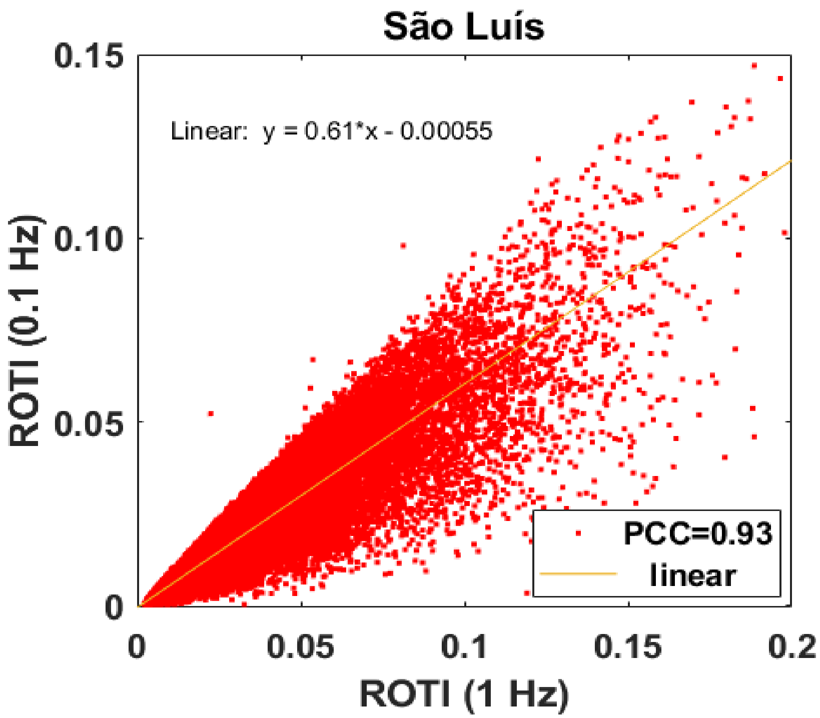
Station	Strength	Mean	SD	Median
Cuiabá	$0.07<S_4<0.5$	0.00	0.08	0.00
	$0.5<S_4<0.8$	0.01	0.12	0.02
	$0.8<S_4<1.0$	0.11	0.11	0.13

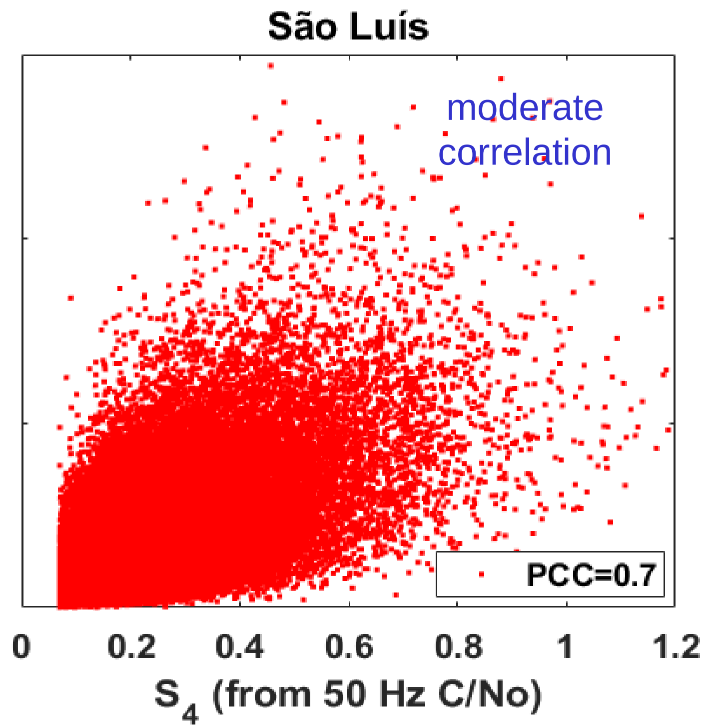
ROTI (1 sec) vs ROTI (10 sec)

What happens when there are receivers working at 10 s sampling rate??

The fundamental effect of the number of samples during a time interval (1 min) is then expected to be the smoothing of the signal, which reduce or remove short peaks and significantly raising the mean value.

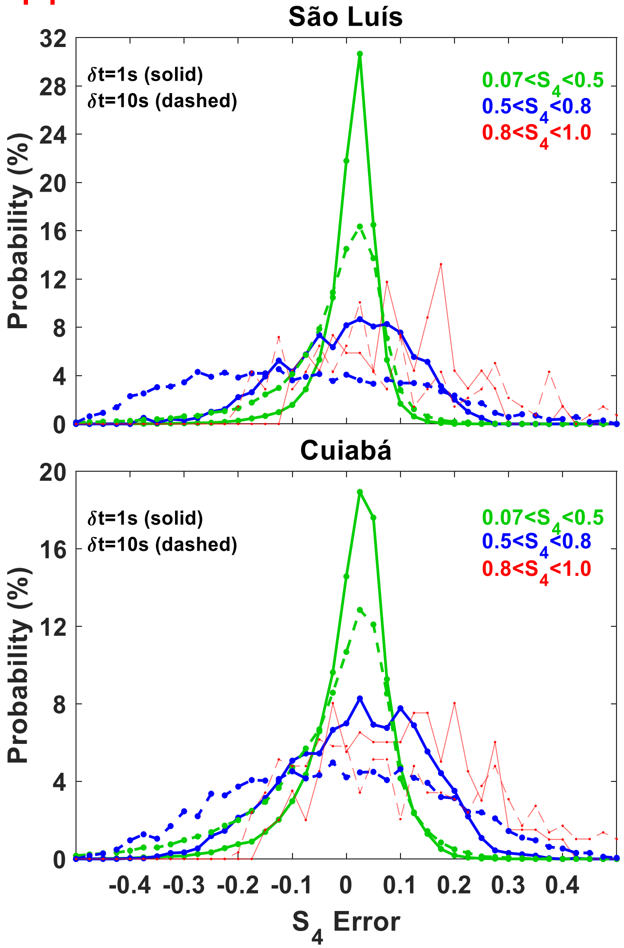


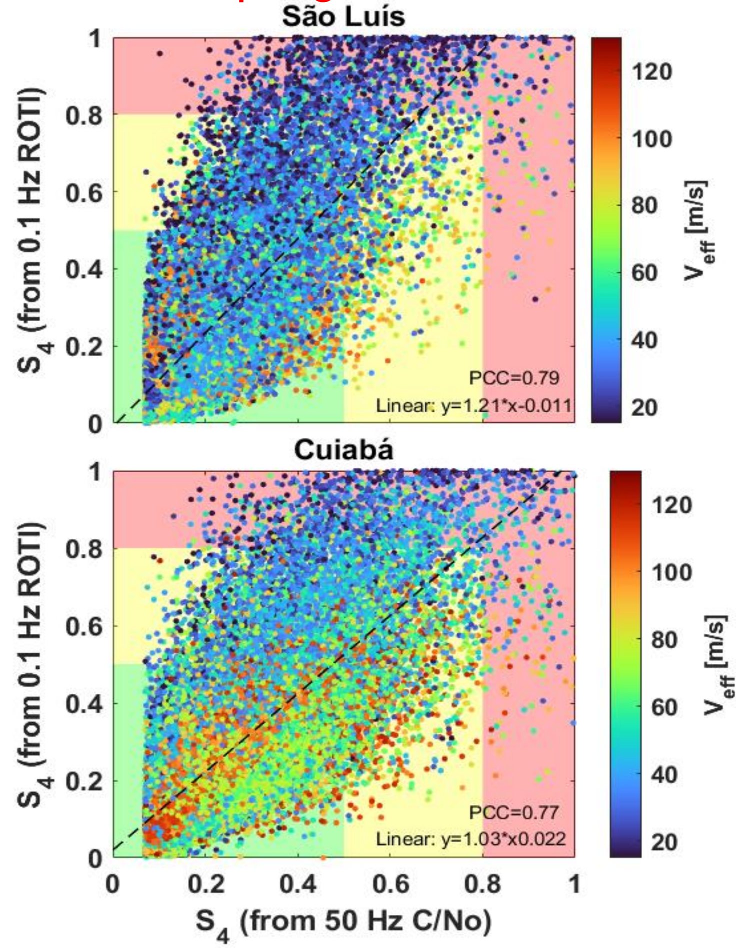




Variation of the sampling rate
$(\delta t = 1\ s\ and\ \delta t = 10\ s)$

What happens when there are receivers working at 10 s sampling rate??





Station	Strength	Mean	SD	Median
São Luís	$0.07<S_4<0.5$	-0.02	0.10	0.00
	$0.5<S_4<0.8$	-0.07	0.20	-0.08
	$0.8<S_4<1.0$	0.09	0.19	0.12

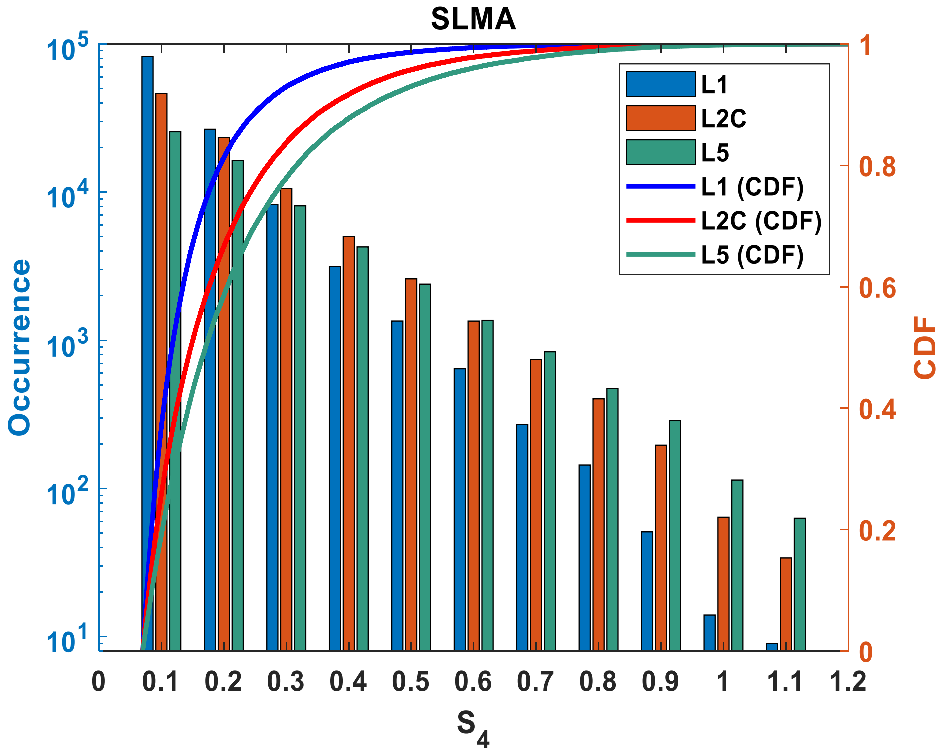
Station	Strength	Mean	SD	Median
Cuiabá	$0.07<S_4<0.5$	-0.03	0.12	0.00
	$0.5<S_4<0.8$	-0.02	0.19	-0.02
	$0.8<S_4<1.0$	0.11	0.20	0.07

S_4 from ROTI (δt =10 sec) presents low correlation and high Deviation Standard

Variation of the GPS frequency (L2 and L5 GPS)

How can we estimate the S4 for L2 and L5 GPS??

Histogram of occurrence and Cumulative Distribution Function from Scintillation index for São Luís station

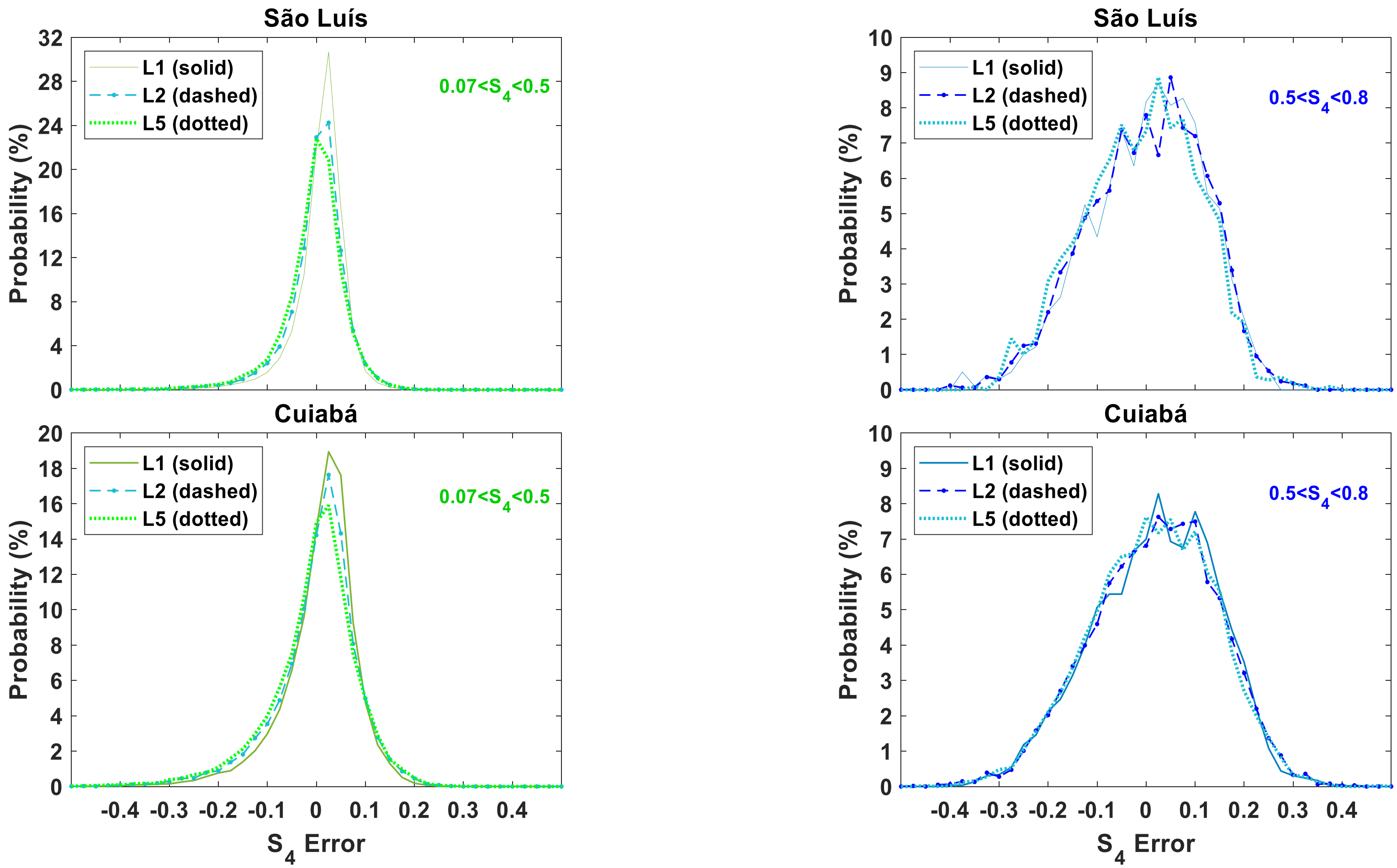


Frequency L5 presents more cases of strong scintillation for this interval

	0.07<S4<0.5	0.5<S4<0.8	0.8<S4<1.2
P_{L1} (%)	98.64	1.26	0.10
P_{L2} (%)	95.75	3.74	0.51
P_{L5} (%)	93.03	5.86	1.10

- The first stage of the routine takes ROTI (which depends on frequency) as an input and calculates the turbulence strength (which is frequency independent). The second stage takes the turbulence strength and calculates S4 at the L2 and L5 frequencies.

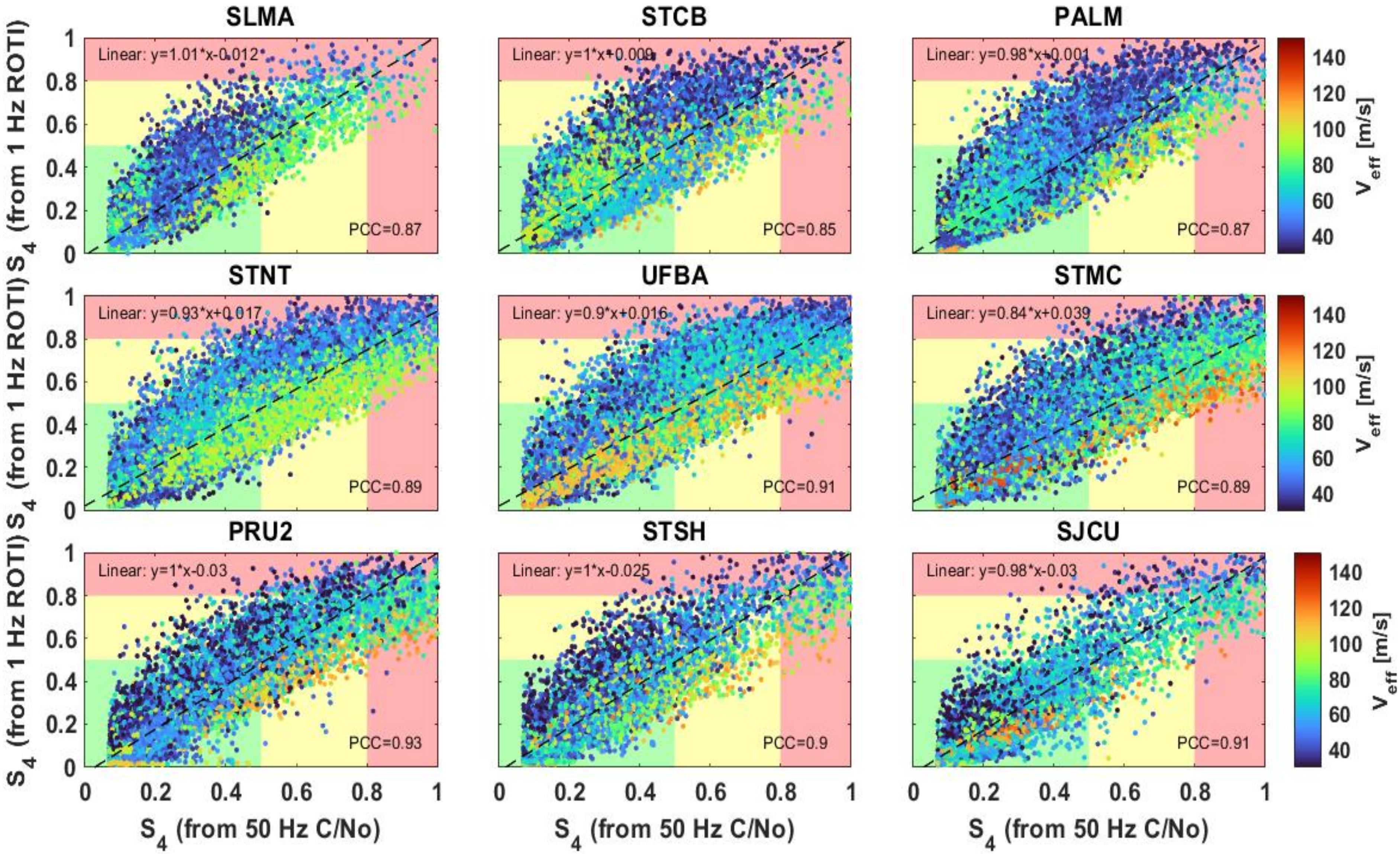
Variation of the GPS frequency
(L1, L2 and L5 GPS)



		L1			L2			L5		
station	Strength	Mean	SD	Median	Mean	SD	Median	Mean	SD	Median
São Luís	$0.07<S_4<0.5$	0.00	0.05	0.01	0.00	0.06	0.00	0.00	0.06	0.00
	$0.5<S_4<0.8$	0.00	0.11	0.01	0.00	0.11	0.00	0.00	0.11	0.00
	$0.8<S_4<1.0$	0.09	0.10	0.09	0.05	0.10	0.05	0.02	0.10	0.00

S_4 Estimation (Drift: RISA Model)

Comparison of S_4 computed from 1 Hz ROTI using RISA model and S_4 computed from 50 Hz intensity samples for Brazilian network



S_4 Estimation (Summarize)

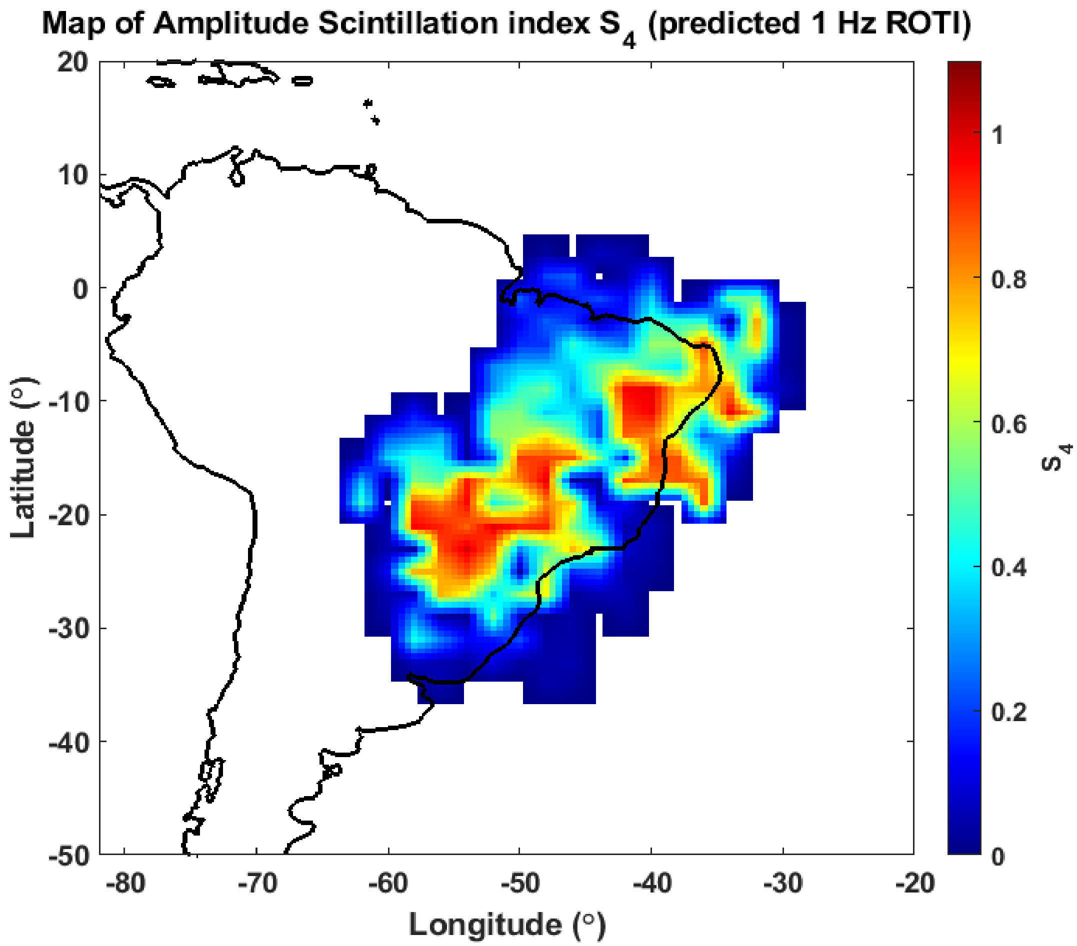
Comparison of S_4 computed from 1 Hz ROTI using RISA model and S_4 computed from 50 Hz intensity samples for Brazilian network

	Mean/SD	Mean/SD	Mean/SD	PCC
Station	**$0.07 < S_4 < 0.5$**	**$0.5 < S_4 < 0.8$**	**$0.8 < S_4 < 1.0$**	
SLMA (Measurements)	0.00/0.05	0.00/0.11	0.09/0.10	0.89
STCB (Measurements)	0.00/0.07	0.01/0.12	0.10/0.12	0.87
PALM (RISA)	0.00/0.07	0.01/0.12	0.09/0.11	0.87
STNT (RISA)	0.00/0.08	0.02/0.11	0.10/0.10	0.89
UFBA (RISA)	0.00/0.08	0.02/0.11	0.13/0.10	0.91
STMC (RISA)	0.00/0.09	0.04/0.12	0.15/0.11	0.89
PRU2 (RISA)	0.02/0.07	0.02/0.12	0.12/0.10	0.93
STSH (RISA)	0.02/0.08	0.02/0.13	0.11/0.11	0.90
SJCU (RISA)	0.03/0.08	0.03/0.14	0.10/0.09	0.91
POAL (RISA)	0.03/0.03	0.04/0.13	0.12/0.12	0.92

High Correlation

S_4 Estimation (Drift: RISA Model)

Brazilian Region
November 15, 2022



Conclusions

- The relationship between ROTI and S_4 make possible to predict S_4 from ROTI.
- When drift measurements are not available. The RISA model can be used to predict the S_4.
- The predicted S_4 using ROTI and the measured S_4 are highly correlated

  (Brazilian Network, PCC=0.87-0.93 → drift measurements and RISA model)

- The mean and standard deviation of the error in predicting S_4 from ROTI in strong conditions ($0.8<S_4<1.0$) presents large values because there are no enough cases, and the use of the Rician distribution.
- The S_4 estimated from 1Hz ROTI (δt =10 sec) presents weak correlation in comparison to ROTI(δt =1 sec). The best results are obtained when sampling TEC at 1 Hz. In this case, the S4 predictions show little bias, and the spread of the errors is reasonable.
- From the relation ROTI (L1/L2) is possible to estimate the S_4 for the L1, L2 and L5 GPS carriers based on strength of the irregularity.

Thank you!

Acknowledgements

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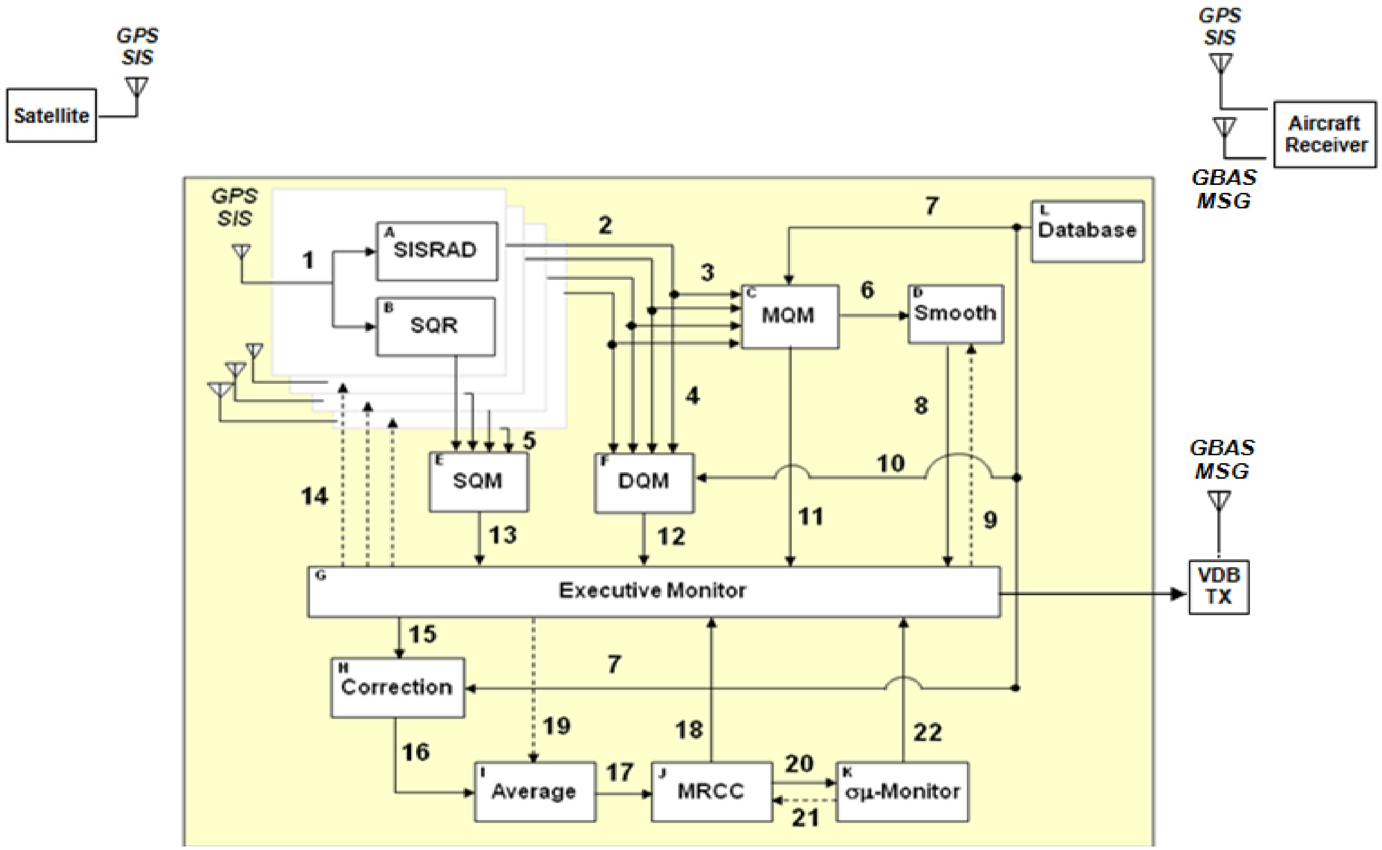
The effective scan azimuth parameter limit to the ordinary scan azimuth for normal propagation with respect to a possibly inclined magnetic field.

$$\alpha_{eff} = sin^{-1}(V_{eff}/V_h)$$

where V_h represent the horizontal component of the relative velocity between the irregularity drift and Ionospheric Pierce Point (IPP) location.

Application

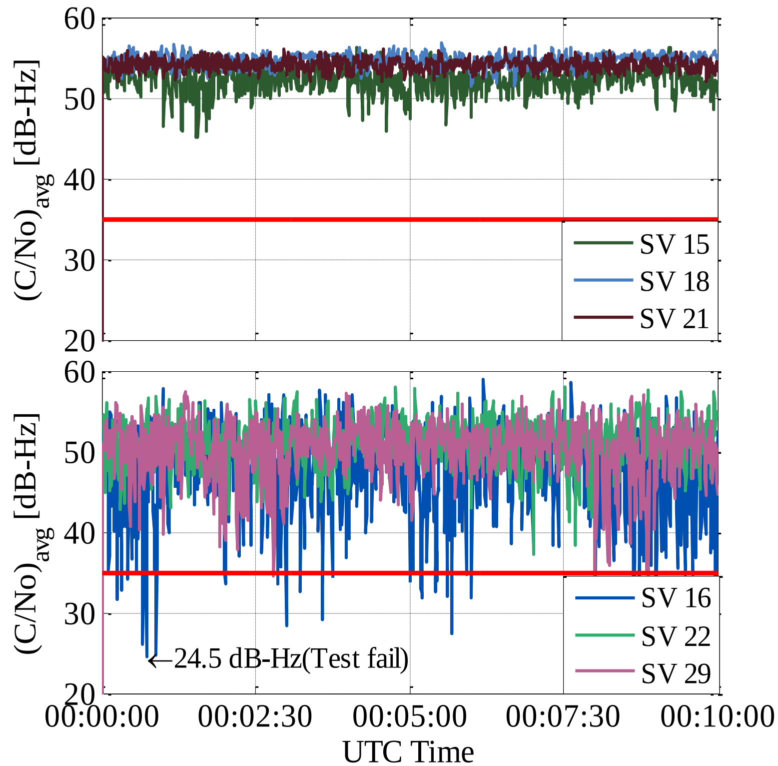
GBAS GROUND SYSTEM FUNCTIONAL FLOW DIAGRAM



- The relationship between ROTI and S_4 make possible to predict S_4 from ROTI.
- When drift measurements are not available. The RISA model can be used to predict the S_4.

Application

- SQM detects and identifies anomalies in the received GPS signal from each satellite, monitor signal power levels and ensure interoperability between different types of receivers in the GBAS.



Results for the RSMU1 GBAS receiver during TAM/JJ3839 flight