Ionospheric Scintillation Effect on GNSS

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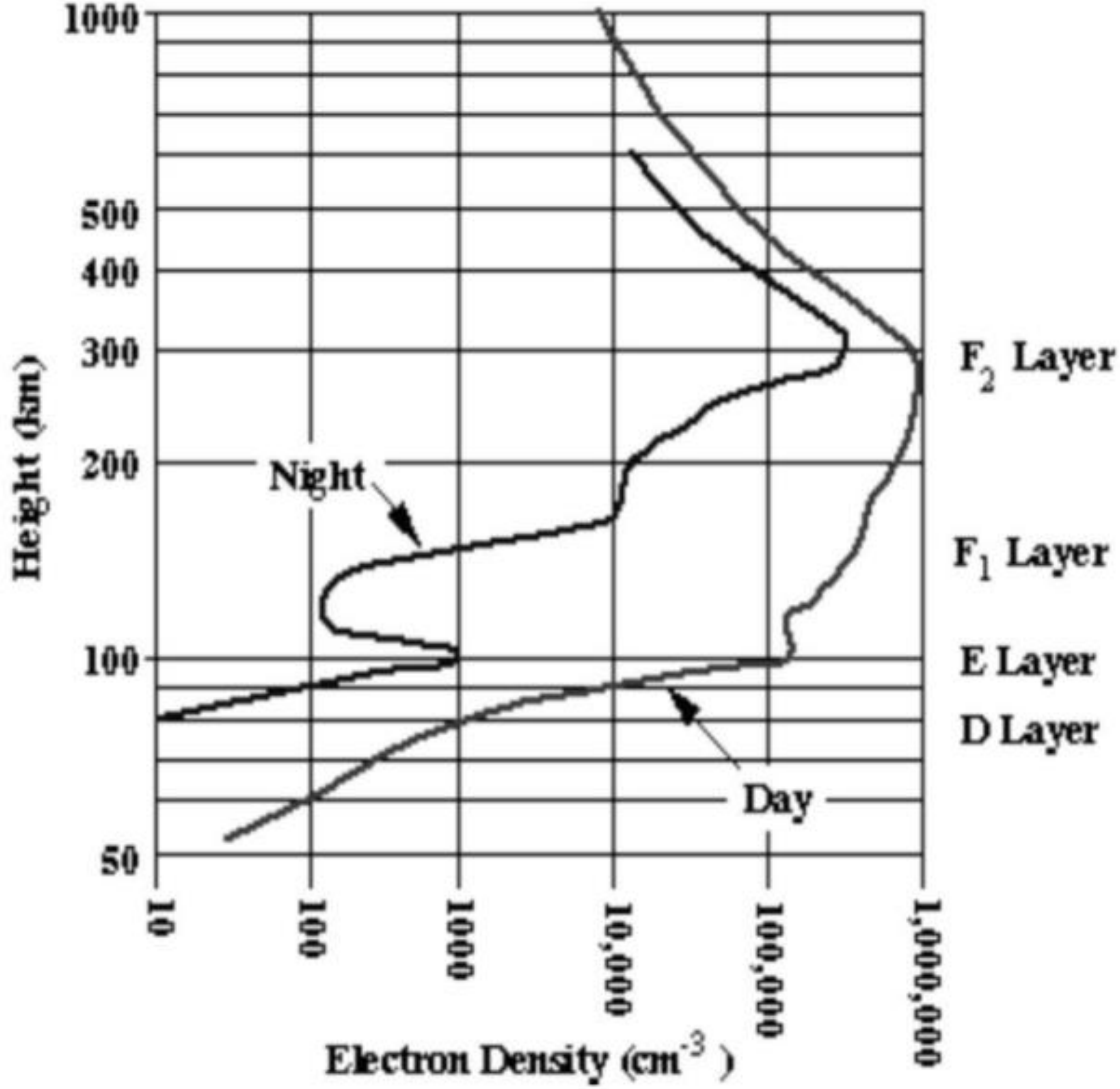
Contents

- Introduction to ionospheric scintillation;
- Generation mechanisms of equatorial scintillation;
- Scintillation effects on the GNSS signal;
- Statistical model of scintillation;
- Costas loop and cycle slip;
- Conclusions.

Ionospheric scintillation

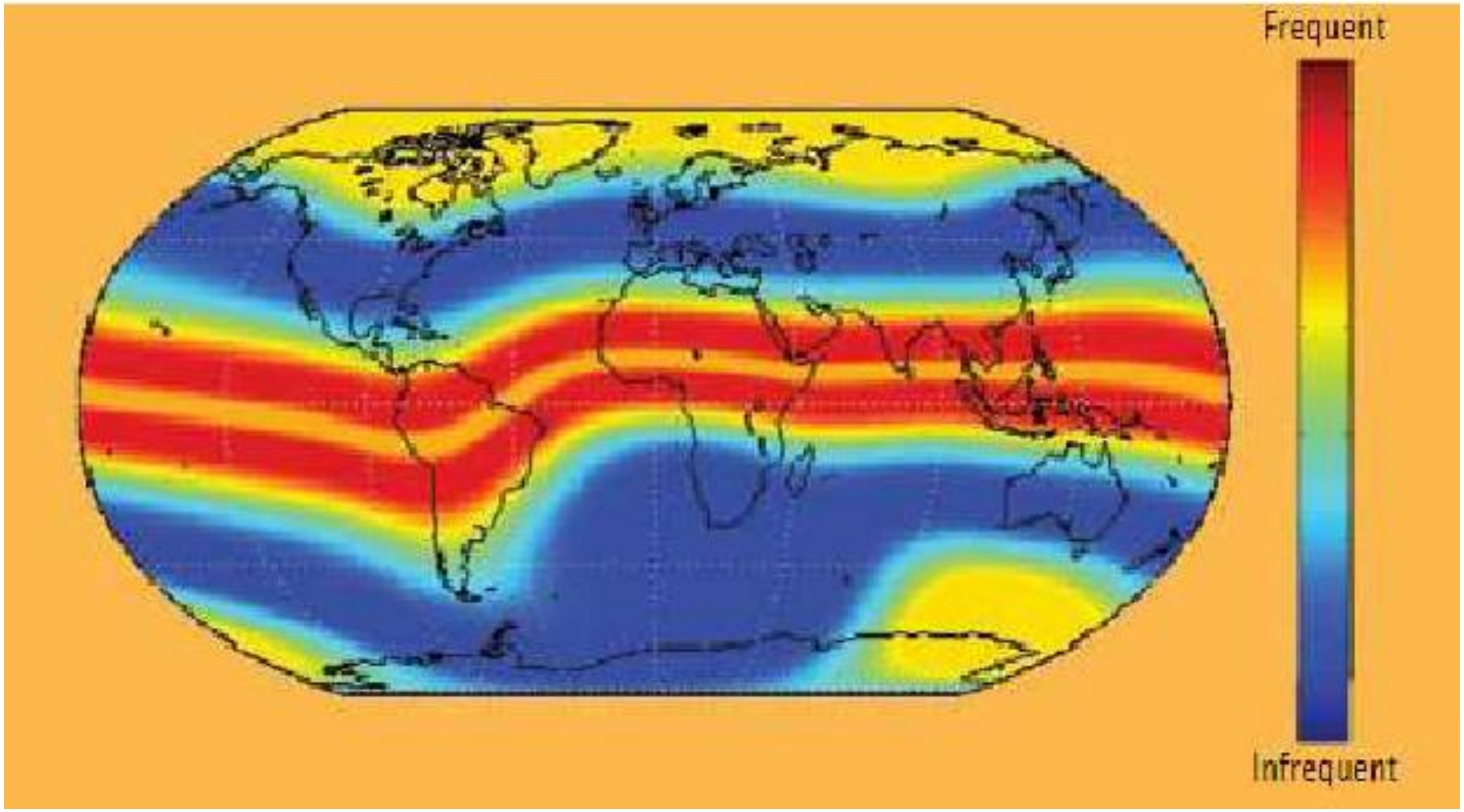
- Ionospheric scintillation are rapid fluctuations in the amplitude and phase of transionospheric signals;
- These distortions are caused by irregularities in the density of electrons (TEC) in the ionosphere through which the signal propagates;
- The phenomenon is more intense and frequent in regions around the magnetic equator (equatorial scintillation) and in the aural and polar regions;
- It significantly affects communications in the VHF and UHF bands;
- The occurrence of ionospheric scintillation depends on the season and the 11-year solar cycle.

Ionospheric layers



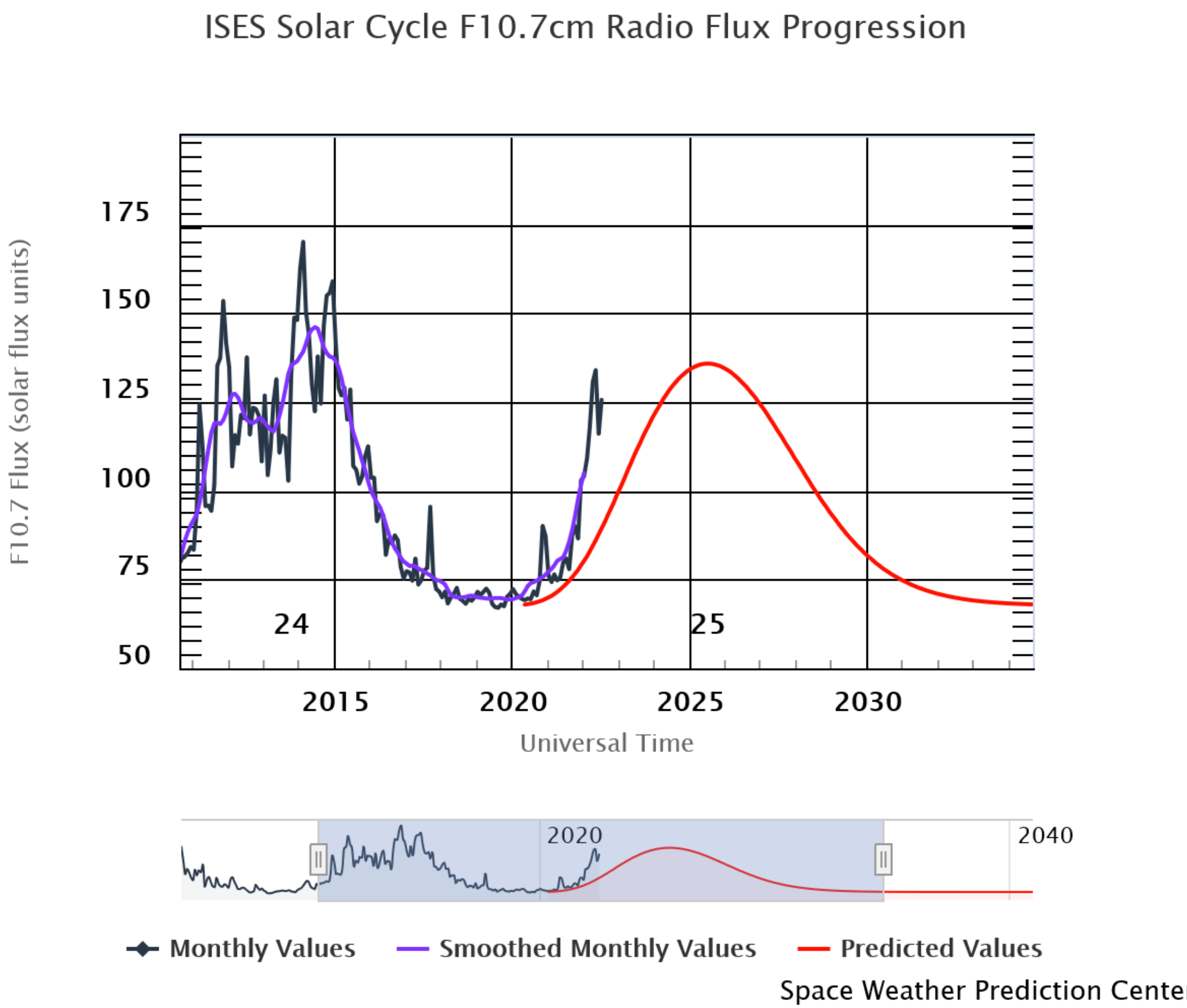
(Moraes, A. O. et al., 2009)

Frequency of scintillation by geographic regions



(Kintner et al.,2009)

Eleven-year solar cycle



(https://www.swpc.noaa.gov/products/solar-cycle-progression)

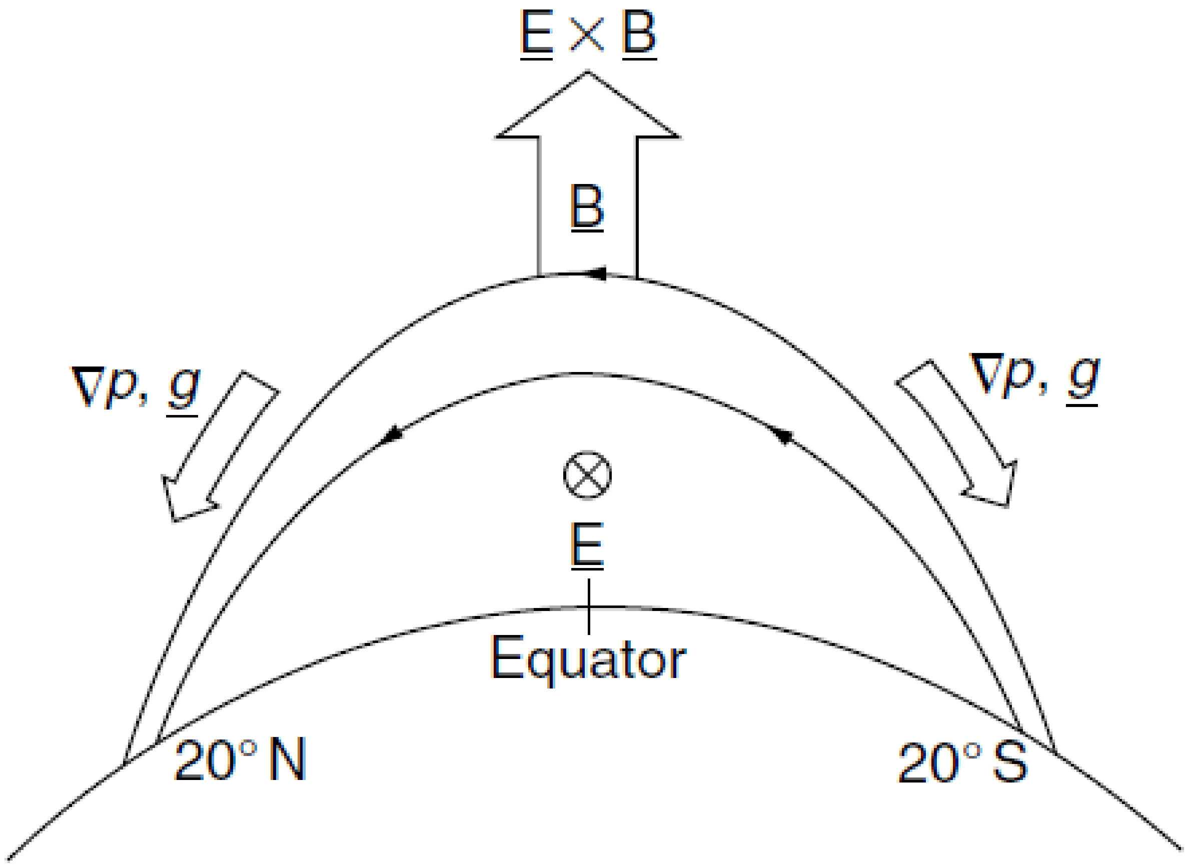
Equatorial ionospheric scintillation

- It usually occurs after sunset;
- It results from the irregularities of the electronic density in the ionosphere caused by plasma bubbles in the equatorial anomaly (EA);
- Its intensity increases with magnetic latitude, being maximum at the anomaly crest;
- It depends on the seasons and occurs more frequently at the equinoxes (September and March);
- Its intensity and frequency depend on solar activity.

About equatorial anomaly

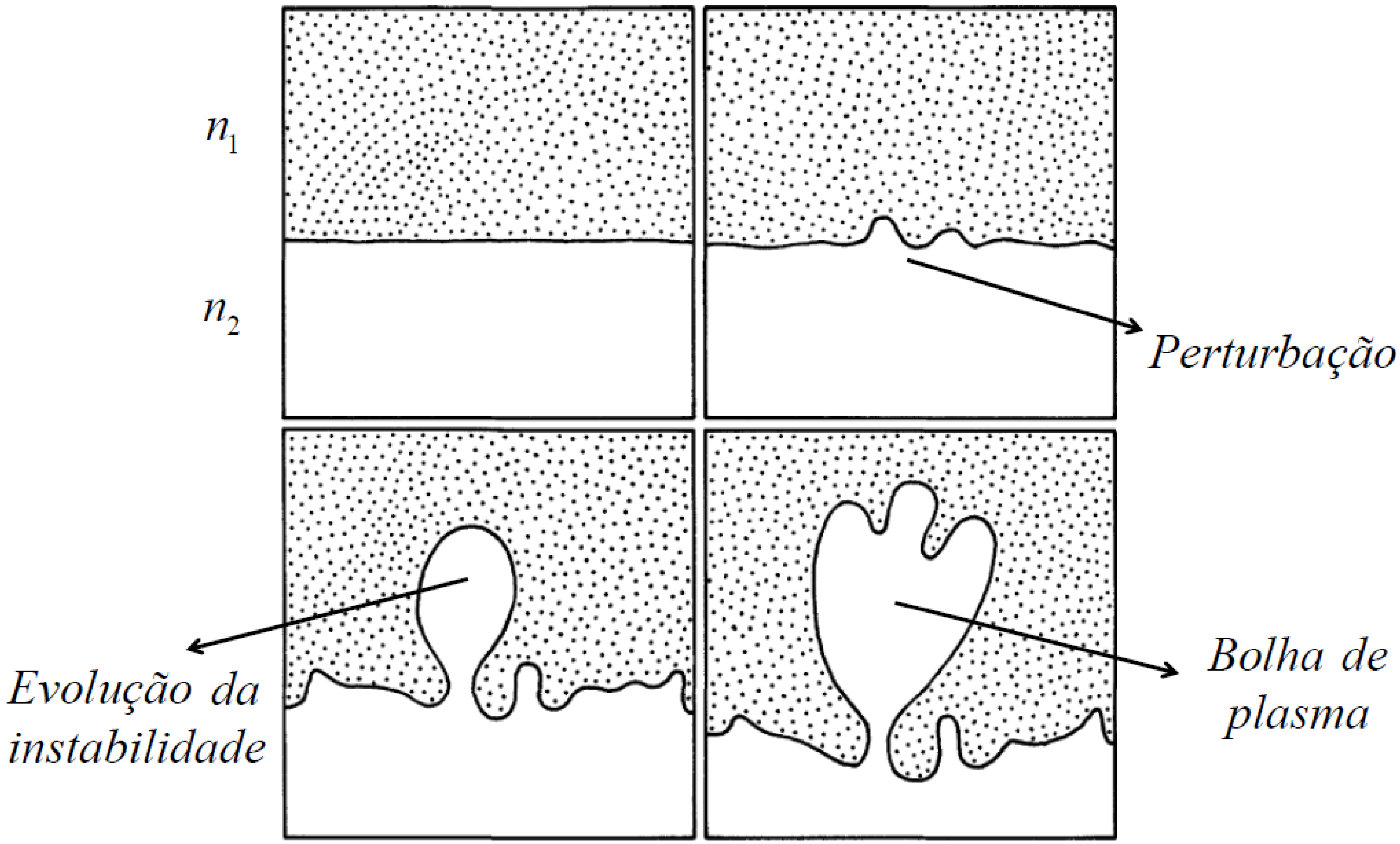
- **Characteristic:** It is characterized by the ionization of the ionosphere with maximum intensity at approximately +/- 20° of magnetic latitude and minimum ionization at the equator;
- **Dynamics in the anomaly:** During the daytime, the plasma generated by the solar ionization in the F layer is raised by the action of the electric and magnetic fields;
- Then, by the action of gravity and the pressure gradient, the ions move along the lines of the geomagnetic field, intensifying the TEC at +/- 20° latitude;
- At sunset, recombination in the E layer creates a low-density plasma layer;
- Due to Rayleigh-Taylor instability, low density plasma bubbles are formed at the base of the F layer.

Generation of equatorial anomaly (Foutain effect)



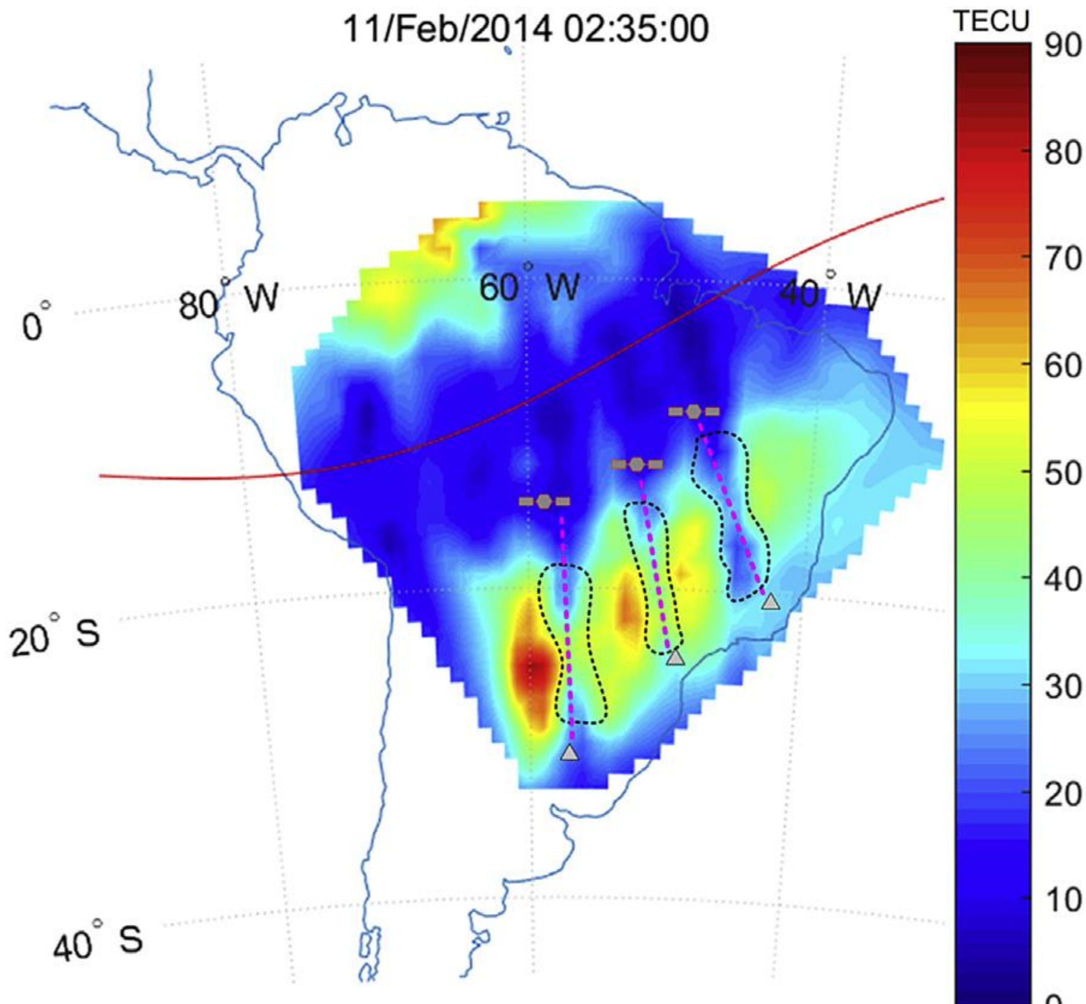
(Silva, D. B., 2017)

Formation of equatorial plasma bubbles due to Rayleigh-Taylor instability (RTI)



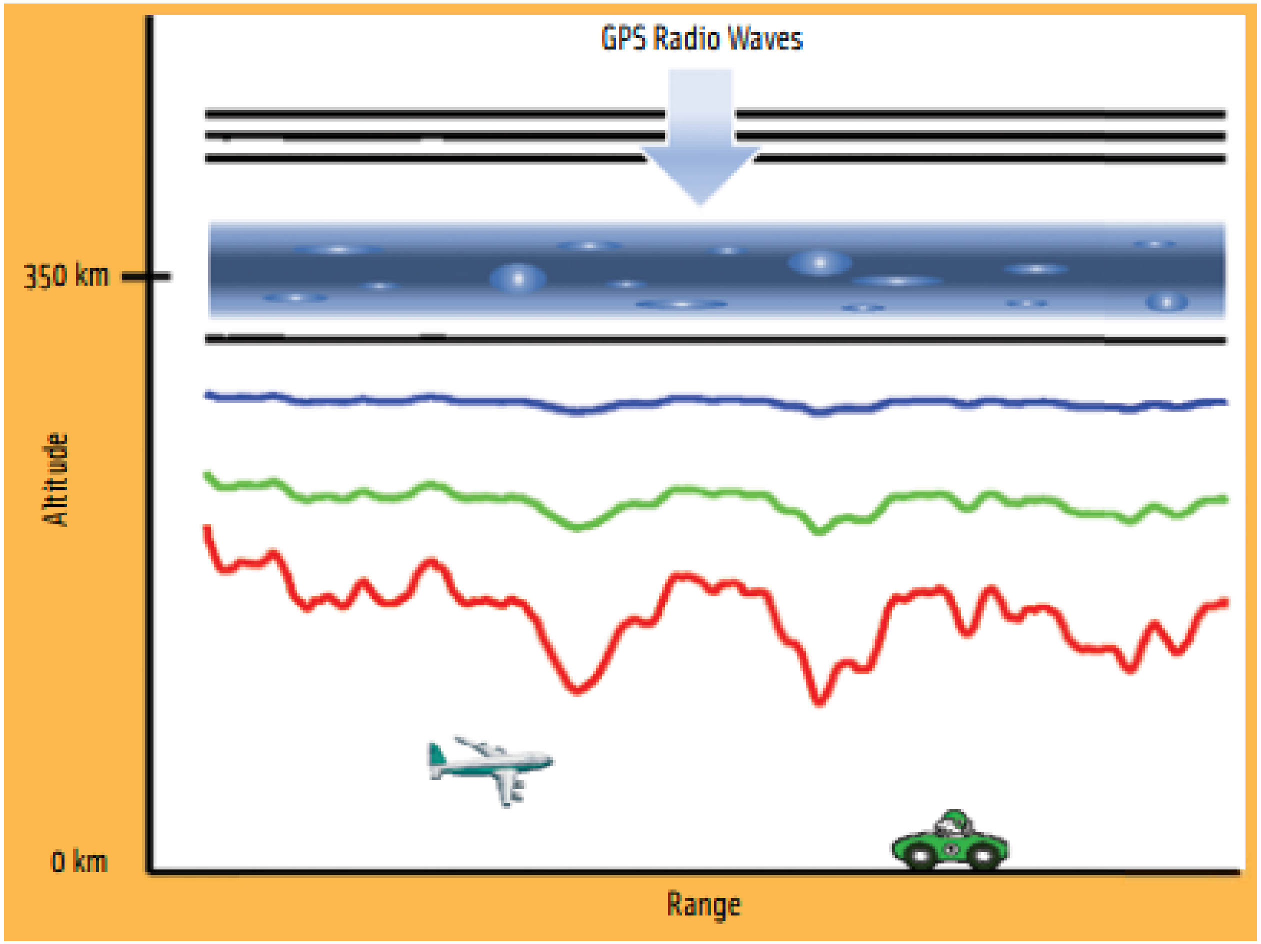
(Silva, D. B., 2017)

TEC map on the Brazilian territory



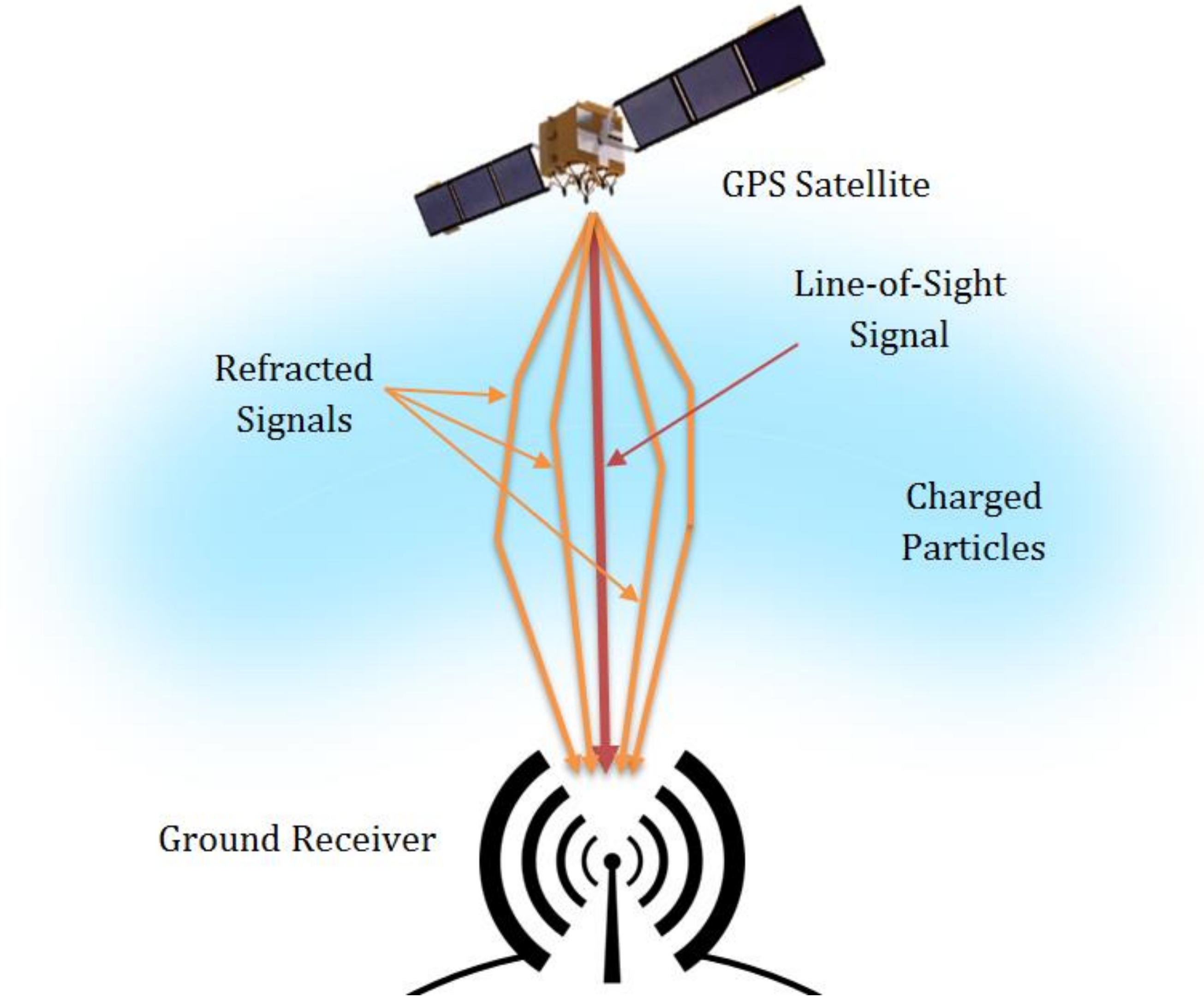
(Vani, B. C. et al, 2021)

Effect of TEC irregulaties over GNSS radio waves



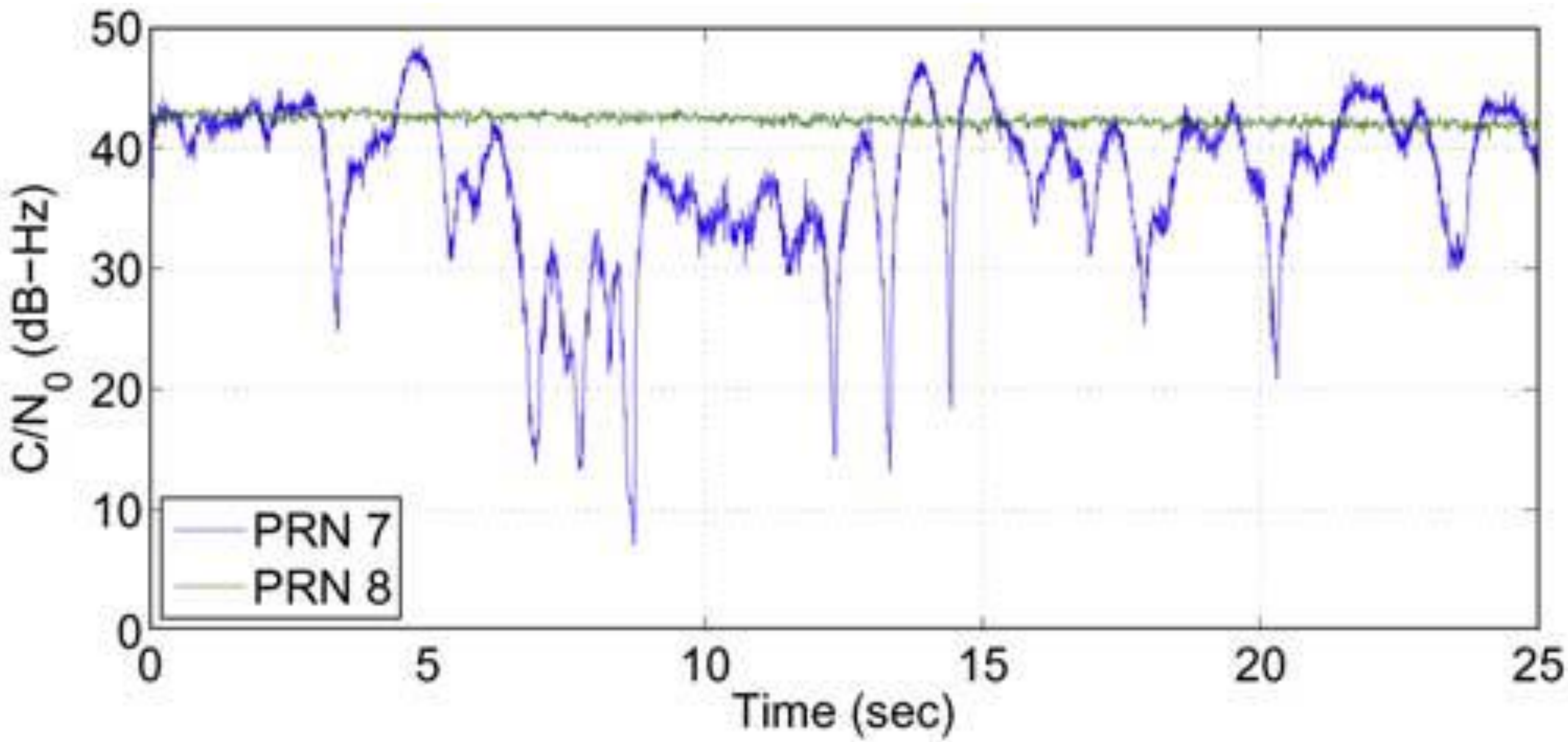
(Kintner et al.,2009)

Multipath due to ionopheric scintillation



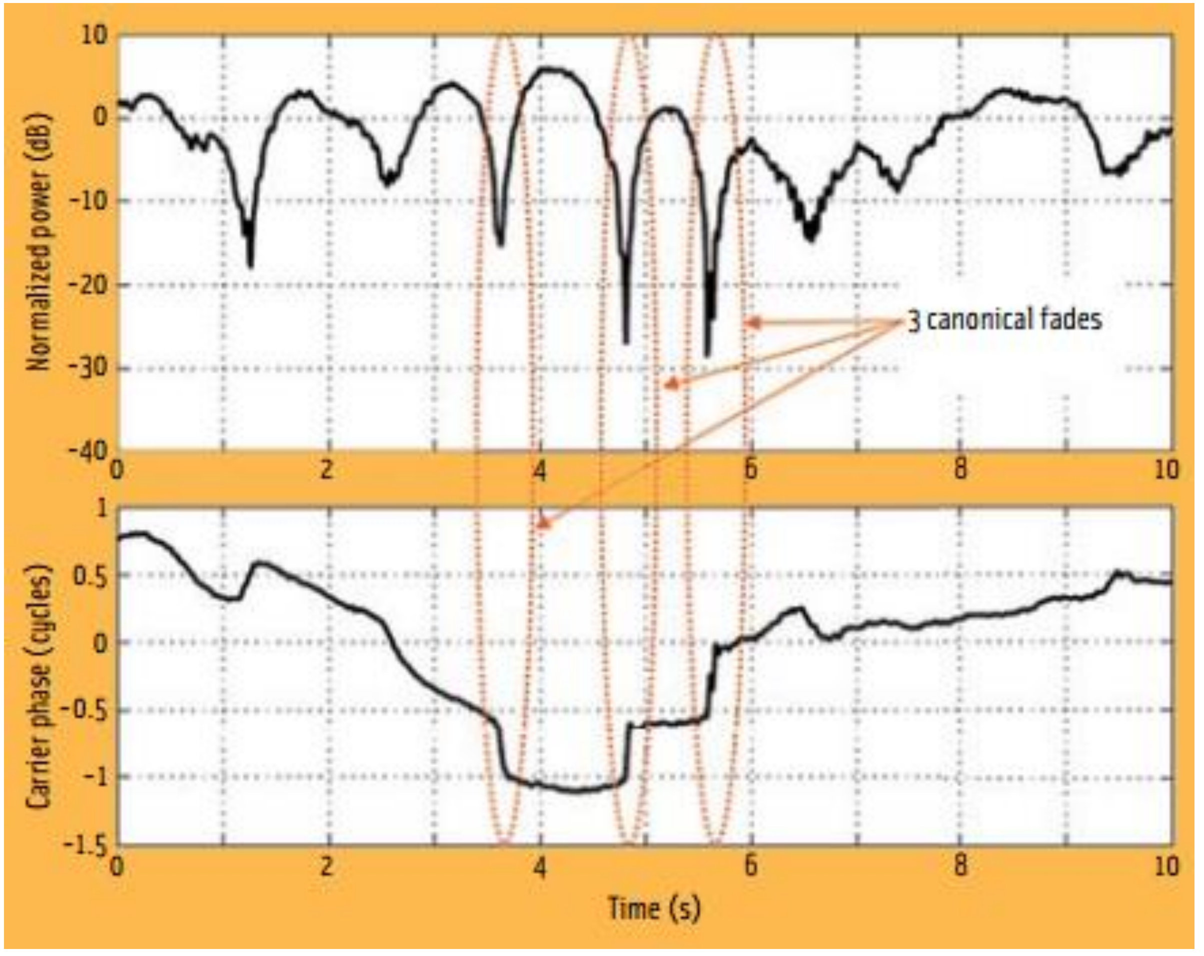
(Olivarez, N., 2013)

Magnitude of received GNSS signal with scintillation and scintillation free



(Kintner et al.,2007)

Effect of scintillation on magnitude and phase of the received GNSS signal



(Kintner et al.,2009)

Consequencies of scintillation in the GNSS system

- Possibility of loss of lock in the receiver's carrier recovery loop;
- Degradation in the accuracy of phase and delay measurements;
- Reduction in positioning accuracy due to the decrease in available satellites;
- In Brazil, it can cause disruption to services such as precision agriculture, offshore operations and navigation;
- The operation of the GBAS (Ground-Based Augmentation Service) system to support civil aviation operations is not available in Brazil.

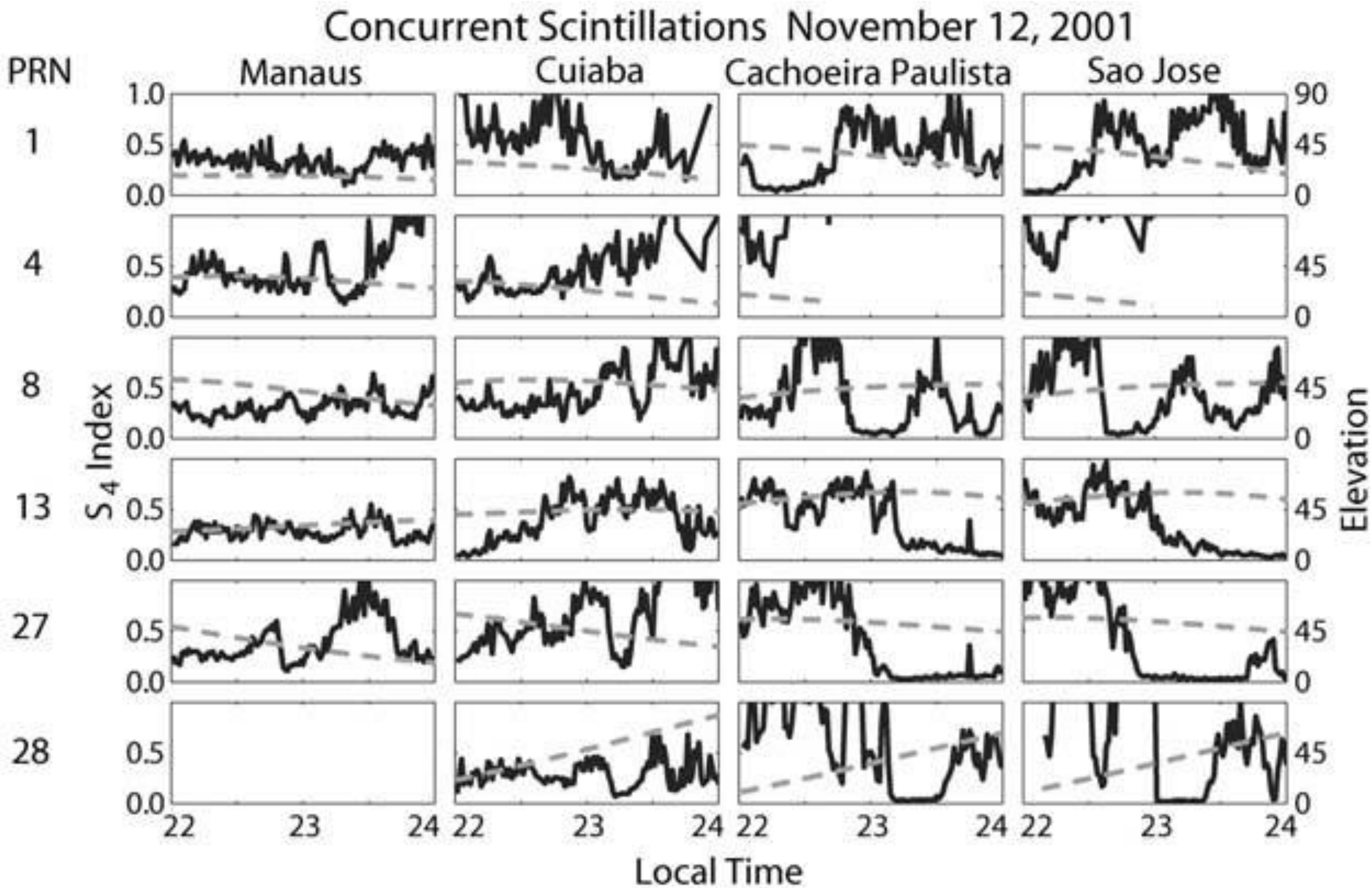
Intensity characterization of the scintillation

- The S_4 index describes the scintillattion intensity in terms of amplitude. It is defined by:

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

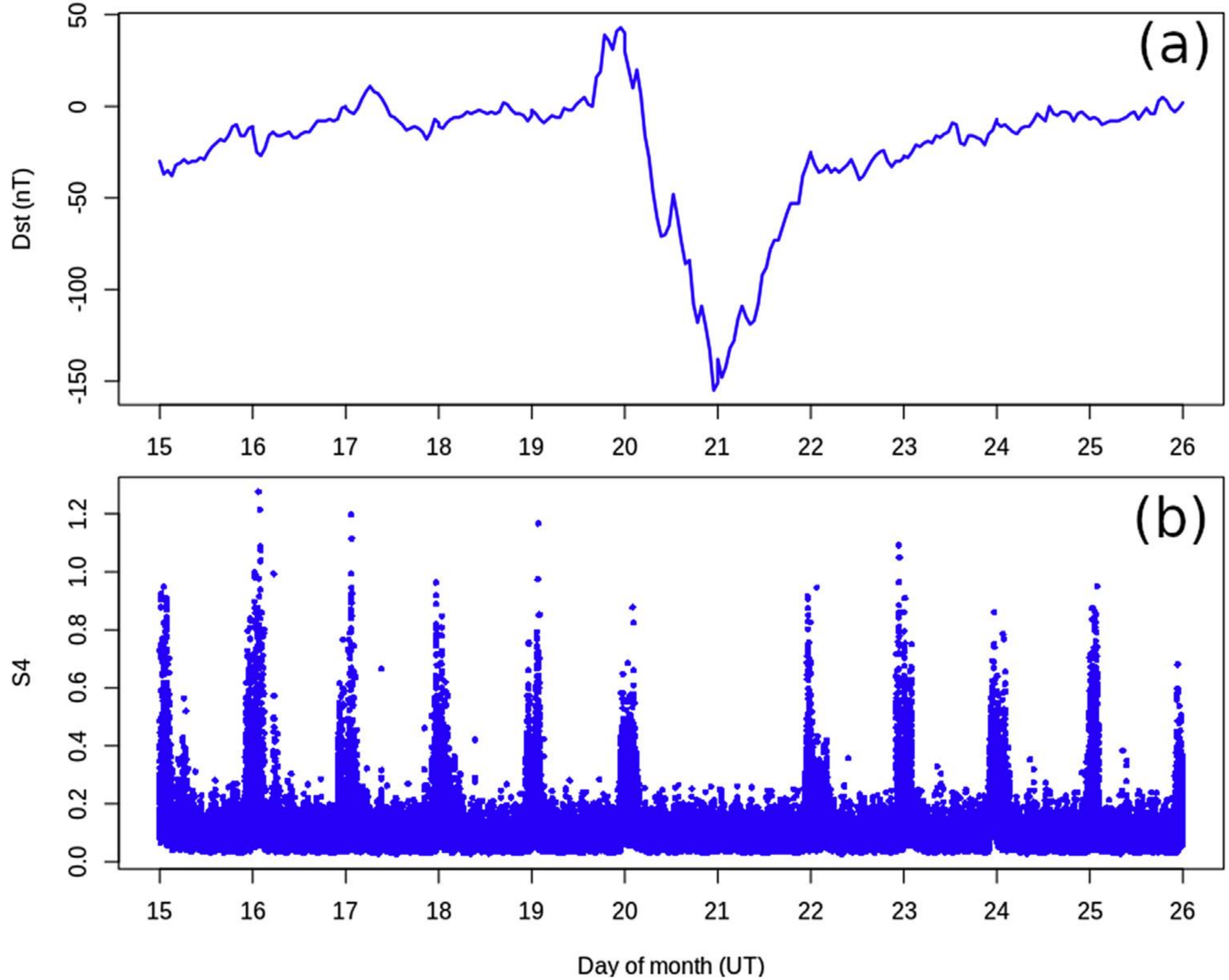
  where I is the square of the magnitude of the received signal and the operator $\langle . \rangle$ represents the time average;
- $S_4 < 0.3$ corresponds to low level of scintillation, $0.3 \leq S_4 < 0.5$ is moderate level and $0.5 \leq S_4 < 1$ represents high level;
- The intensity of the phase scintillation is measured by the index σ_ϕ which represents the standard deviation of the phase fluctuation caused by the scintillation.

S_4 measurements at stations in Brazilian territory



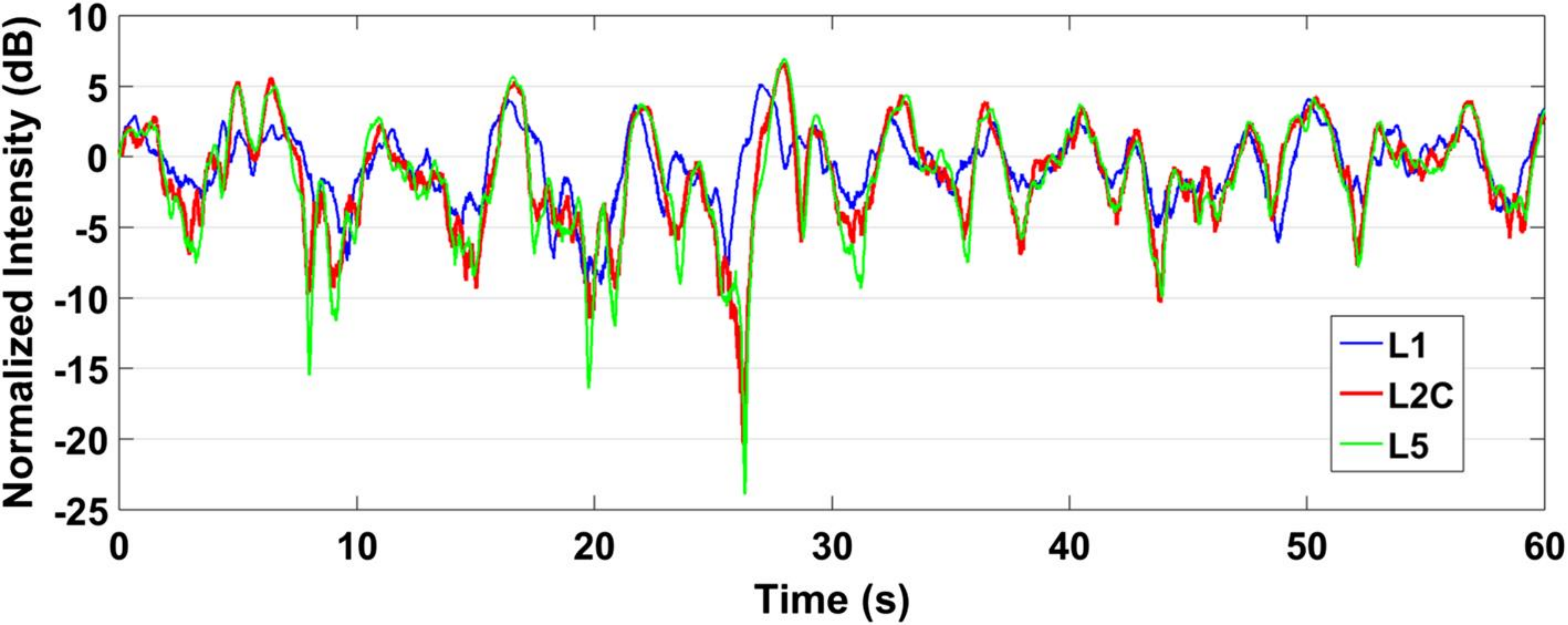
(Kintner et al.,2007)

S_4 measurements in Fortaleza (December 2015)



(Vani, B. C. et al, 2021)

Measurements of S_4 in São José dos Campos (day 13/11/2015)



(Salles, L. A. et al, 2021)

Statistical model of channel with scintillation (Cornell model)

- **Received signal:**

$$r_l(t) = a(t)e^{j\theta(t)}c(t)s_l(t-\tau) + n_l(t)$$

- **Scintillation effect:** Flat fade represented by $c(t)$:

$$c(t) = Ae^{\phi} + d(t),$$

A is a constant proportional to the amplitude of the part of the signal that reaches the receiver directly through the line-of-sight (specular component) and $d(t)$ is a complex Gaussian process with zero mean and variance $2\sigma^2$, associated with the part of the signal that undergoes dispersion (multipath component).

Probability Density Function (PDF) of the magnitude of $c(t)$ (Distribuição de Rice)

- The magnitude of $c(t)$ is $\alpha = |c(t)|$ whose PDF é

$$p_\alpha(\alpha) = 2\alpha(1+K)e^{-K-\alpha^2(1+K)} I_0\left[2\alpha\sqrt{K(1+K)}\right],$$

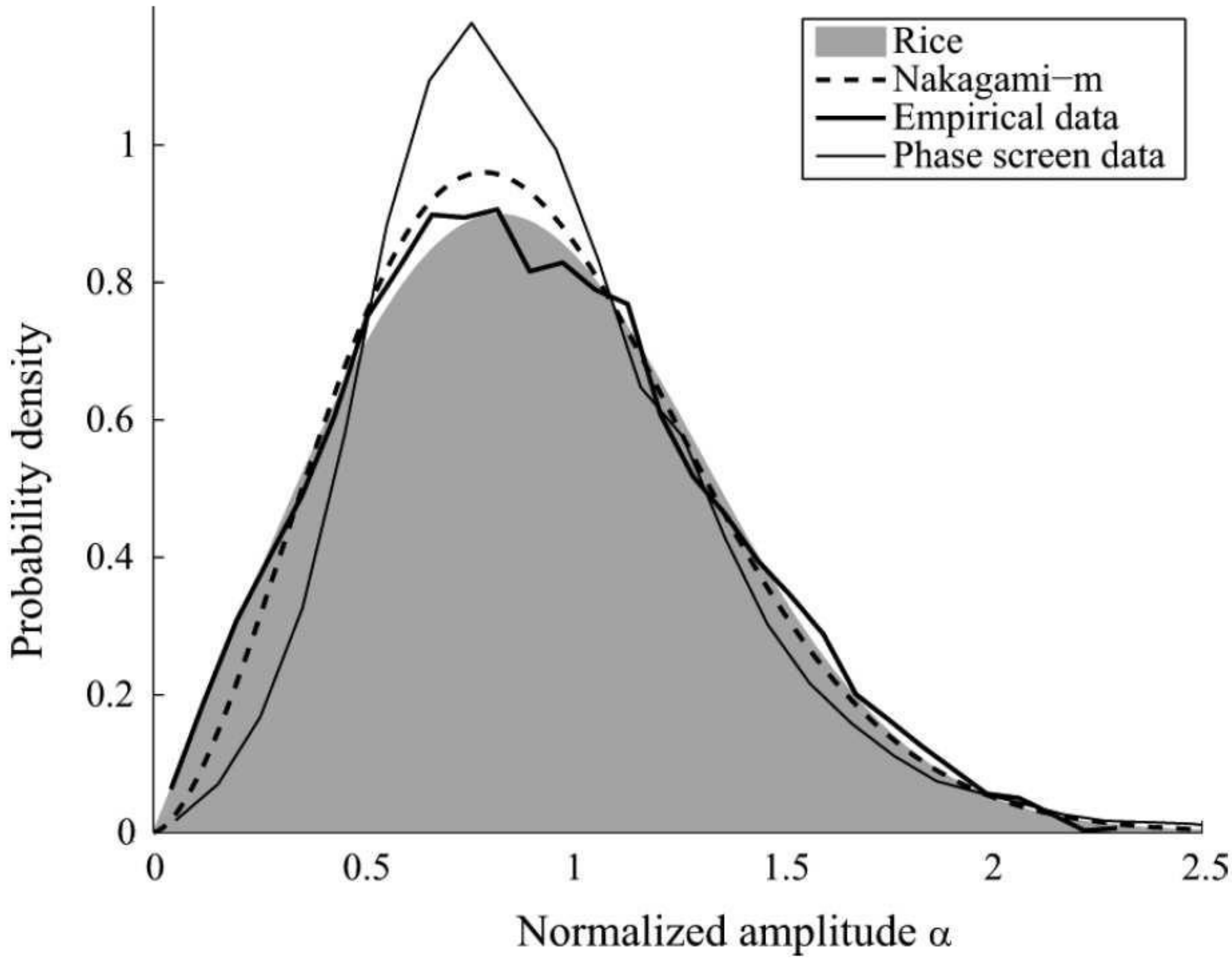
where

$$K = A^2/2\sigma^2$$

and

$$K = \frac{\sqrt{1-{S_4}^2}}{1-\sqrt{1-{S_4}^2}}.$$

Comparisons of Rice probability distribution



(Humphreys et al, 2008

Autocorrelation function of the process $d(t)$

- Expressions for the autocorrelation function of $d(t)$:

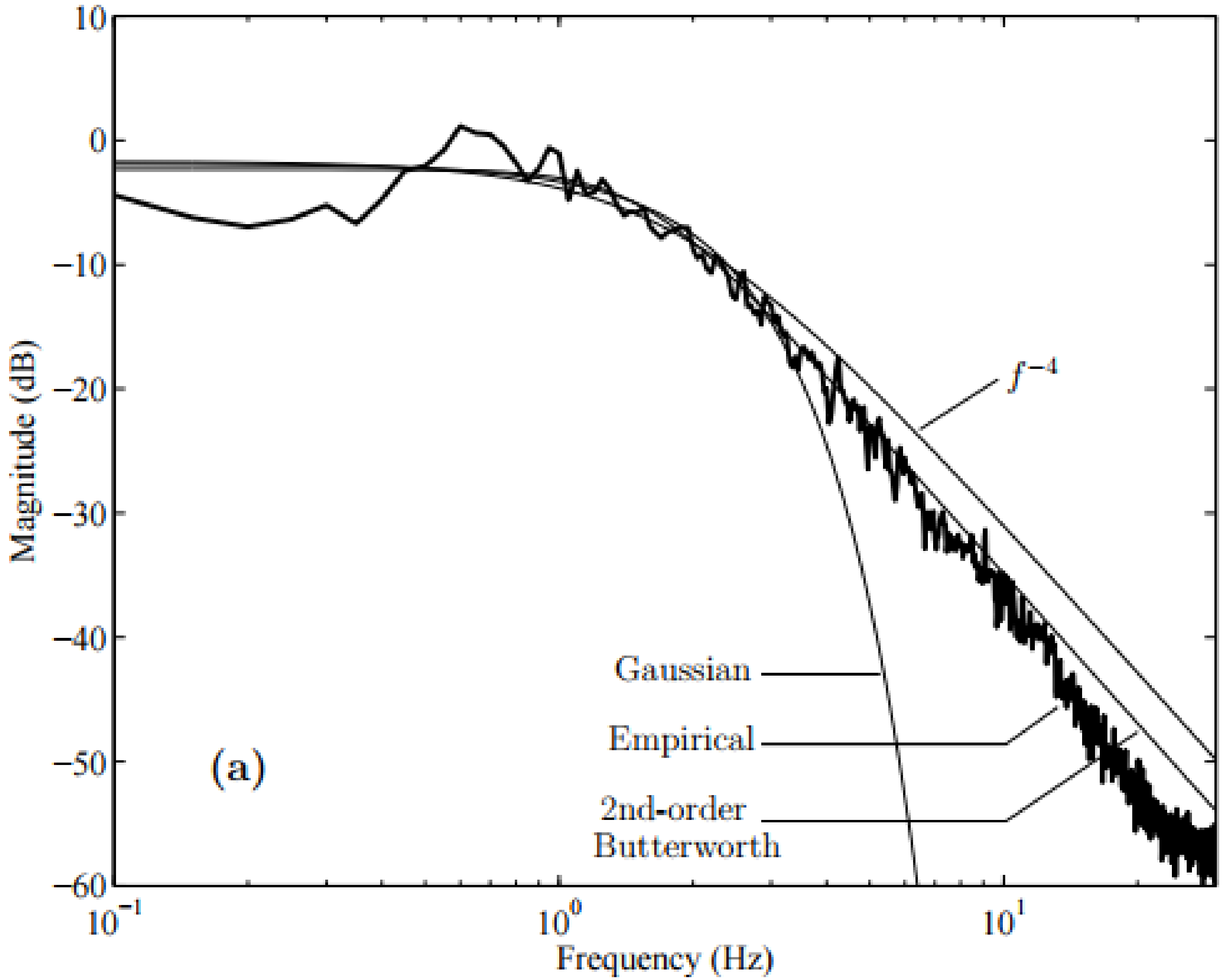
$$R_d(\tau) = E\{d(t)d^*(t+\tau)\},$$

$$R_d(\tau) = 2\sigma^2 \exp\left(-\frac{\beta\tau}{\tau_0}\right)[\cos({}^{\beta\tau}/_{\tau_0}) + sen({}^{|\beta\tau|}/_{\tau_0})],$$

β=1.239646 and τ_0 is the channel decorrelation time;

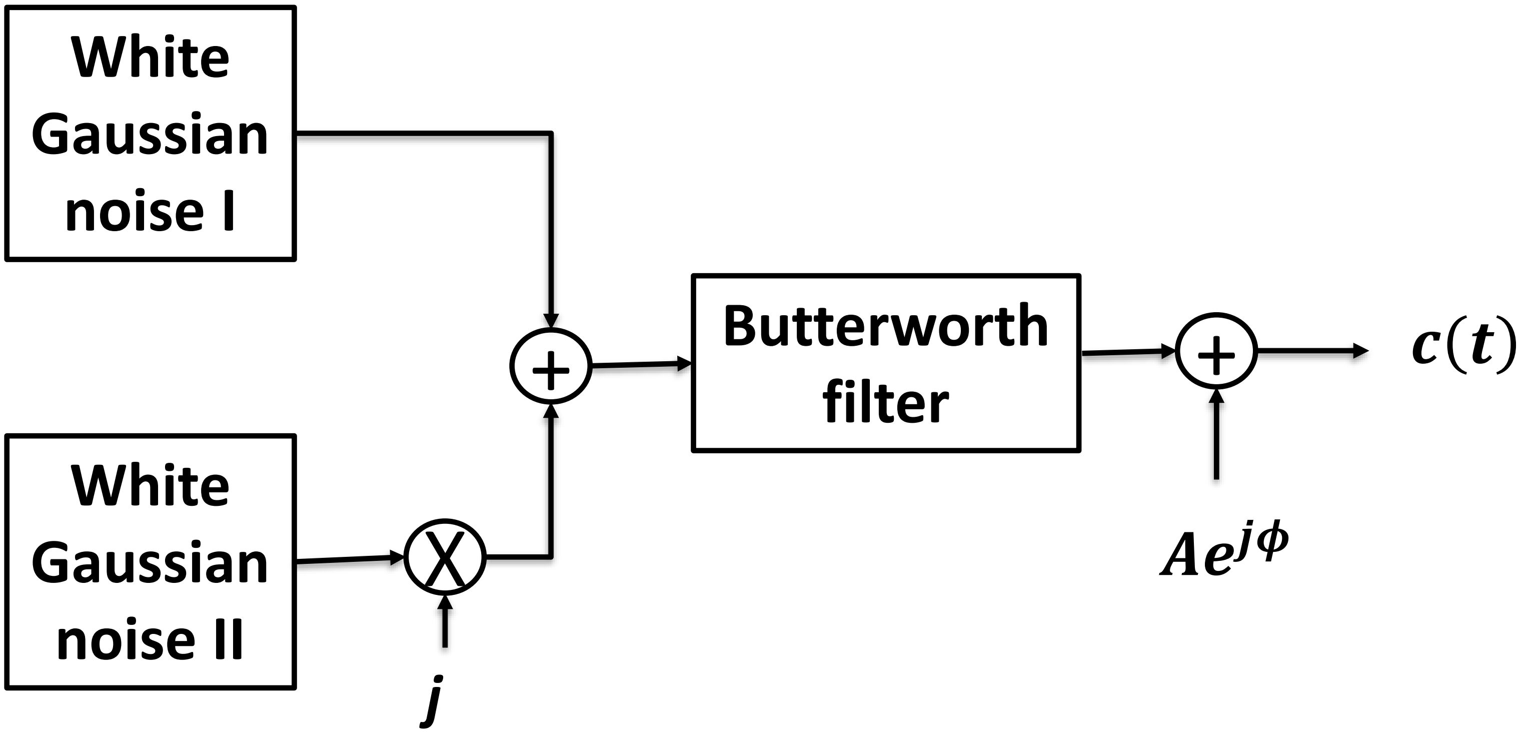
- A process with this autocorrelation function may be obtained by the passage of a Gaussian and white process through a second-order low-pass Butterworth filter.

Power spectral density of the process $d(t)$

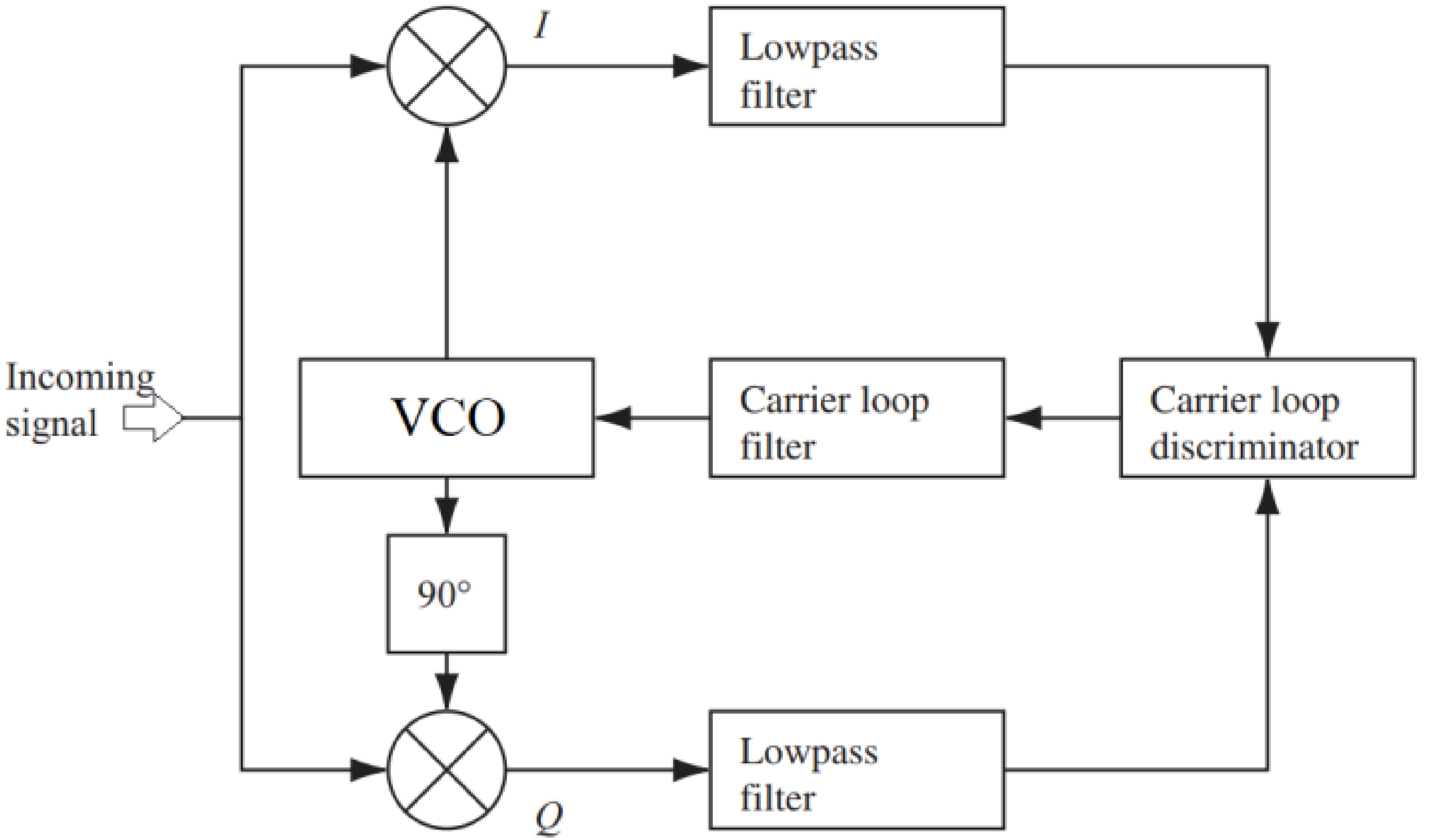


(Humphreys et al, 2008)

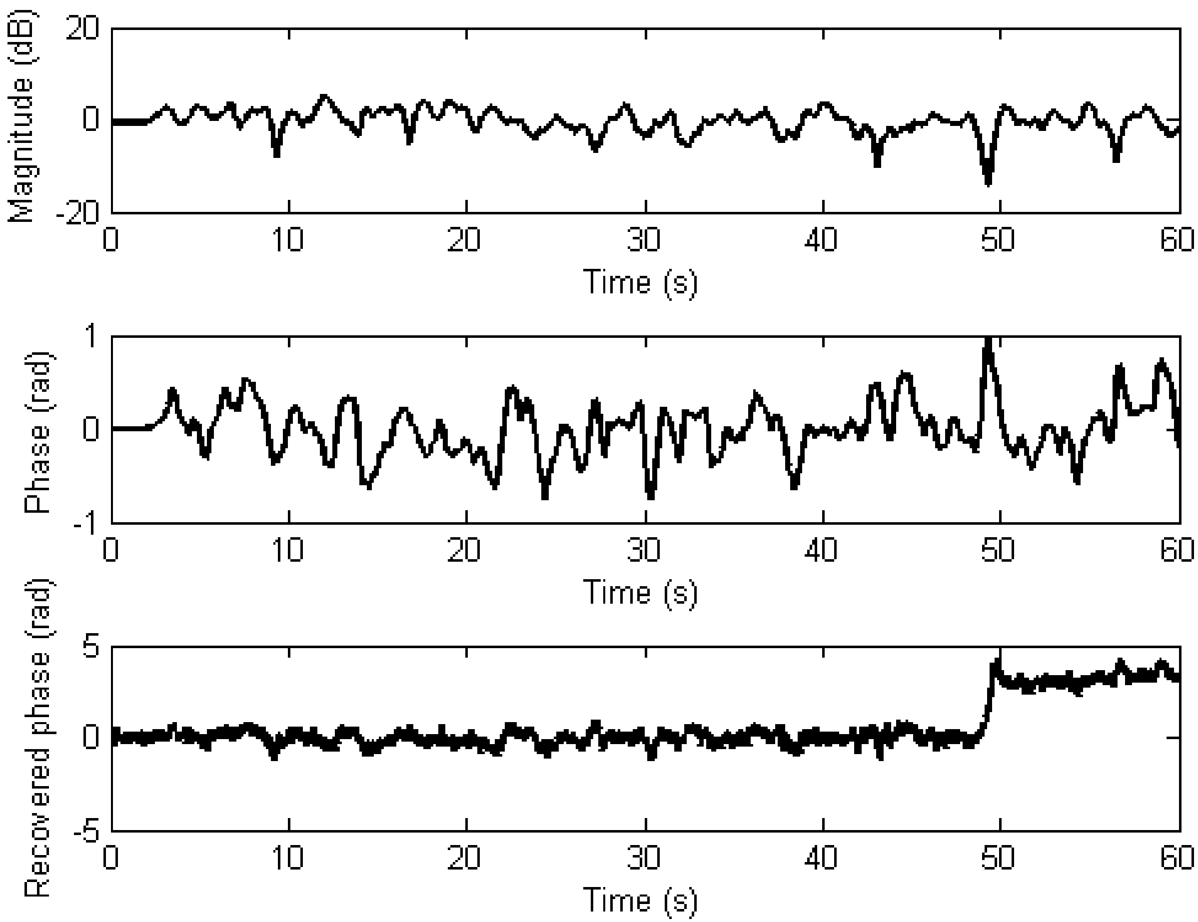
Mechanization of the scintillation model



Carrier phase recovery loop (Costas loop)



Phase recovered by a Costas loop with B_L=10 Hz, C/N_0=30 dB-Hz and S_4=0.5



Main conclusions

- Ionospheric scintillation occurs in equatorial and high latitude regions;
- In addition to geographic position, it also depends on signal frequency, solar activity, season and time of day;
- It distorts the amplitude and phase of transionospheric signals;
- The communication channel under scintillation can be modeled as a Rise channel;
- It mainly affects the carrier phase recovery of the receivers;
- It reduces the positioning accuracy of GNSS systems;
- Depending on its intensity, it can lead to complete interruption of some services.

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