Filling the gap between physical ionosphere models and scintillation models in equatorial region

IES 2017

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Introduction

- Scintillation model aims
  - Link budget estimation for TTC (from HF to L band)
  - GNSS performance evaluation (L band)
  - SBAS evaluation performance
- State or the arts
  - GISM [ITU-R.531]: ok for low latitude and elevation > 30°, 100Mhz – 2Ghz
  - TIRPS: VHF, UHF band (no L band)
  - WBMOD: ionospheric medium parameters and scintillation indices, not adapted for high latitude (2D propagation model)
- We need a global scintillation model for all frequencies, equatorial and polar region

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- Fill the gap between physical and stochastic model
- Validation
- Conclusions

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Scintillation Model: stochastic approach

- Principle: electronic density modeled by a stochastic process

$$\mathrm{Ne}(\vec{r},t) = \underbrace{\langle Ne(\vec{r},t)\rangle}_{\text{Mean delay (NeQuick)}} + \underbrace{\Delta Ne(\vec{r},t)}_{\text{Stochastic process}}$$

- Space correlation at t:

$$< \Delta N_e(\vec{r},t)\Delta N_e(\vec{r}',t) >= B^{3D}_{\Delta N_e}(\vec{r},\vec{r}') = B^{3D}_{\Delta N_e}(\vec{r}-\vec{r}')$$

- Spectrum:

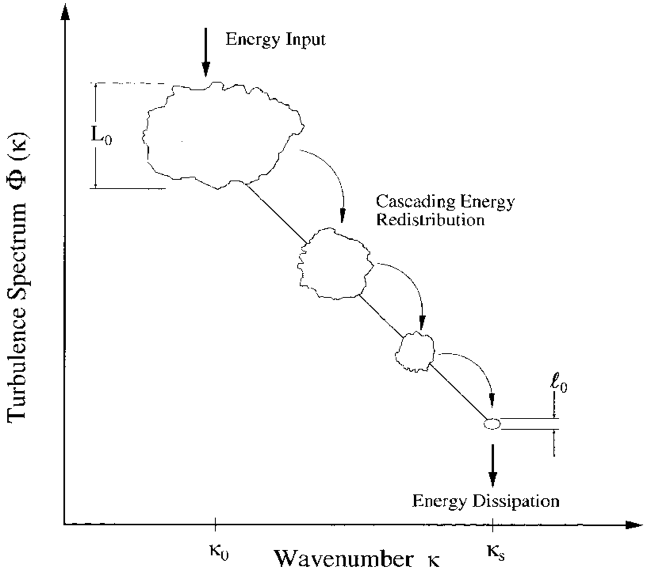
$$S^{3D}_{\Delta N_e}(\vec{K}) = (2\pi)^{-3}\iiint B^{3D}_{\Delta N_e}(\vec{r})\, e^{-i\vec{K}.\vec{r}}d\vec{r}$$

Scintillation Model : stochastic approach

- Turbulence spectrum [Schkarofsky, 1968]

$$S_{\Delta N_e}^{3D}\left(\left|\vec{K}\right|\right) = C_s\,(K^2 + K_0^2)^{-p}$$

  - Cs scintillation strength
  - L_0 Outer scale (biggest size of the ionospheric turbulent eddies)
  - l_0 Inner scale (smallest size of the ionospheric turbulent eddies)
  - P spectrum slope



$$K_0 = \frac{2\pi}{L_0}$$

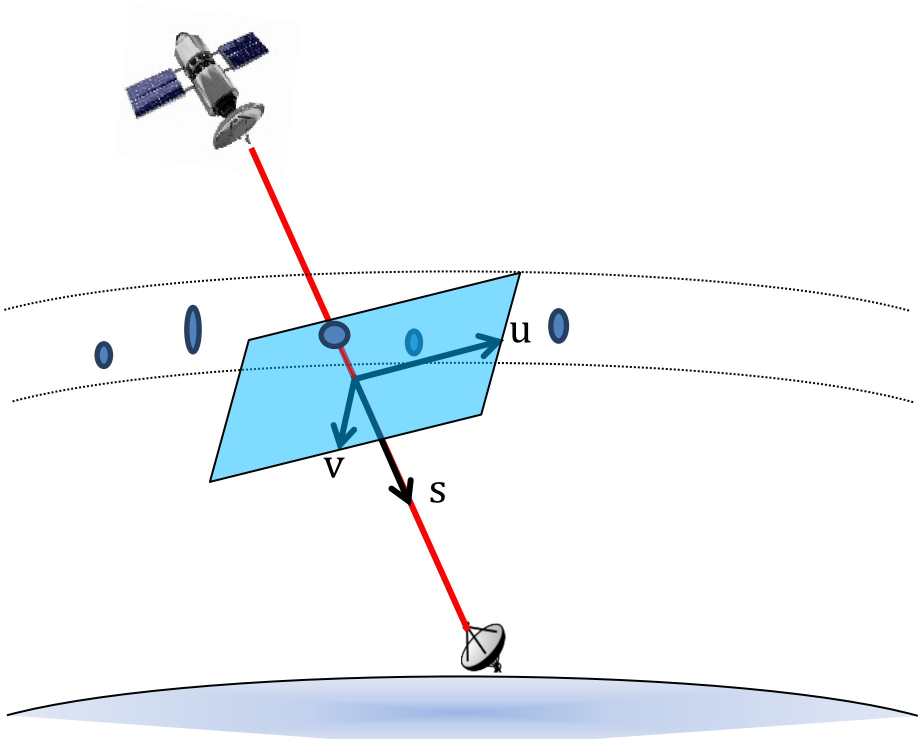
$$K_i = \frac{2\pi}{l_0}$$

Scintillation Model : stochastic approach

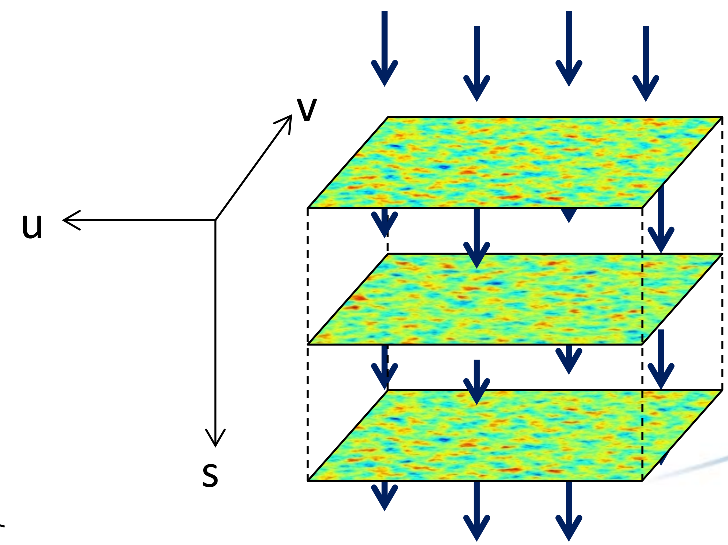
From Ne to phase fluctuation:

$$S_\phi(K_u, K_v) = 2\pi \left(\frac{r_e \lambda}{k_o}\right)^2 \delta s . S_{\Delta N_e}(K_u, K_v, K_s = 0)$$

Propagation tool: Parabolic Waves Equation (PWE)

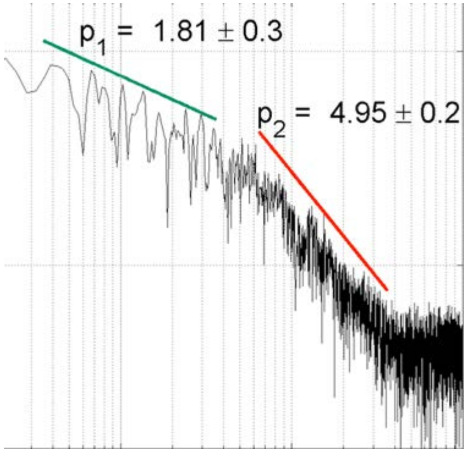


3D-PWE/2D-MPS



Scintillation Model : stochastic approach

- Models limitations:
  - Need a high number of input parameters
    - Geometry: LOS propagation and Magnetic / electric field direction (~ ok geomag soft)
    - Turbulence Spectrum parameters: Cs, p, L_0, l_0, anisotropy ratio (WBMOD ????) → <u>How define Schkarofsky spectrum ?</u>
    - Ionosphere description: layer altitude (~ok), drift velocity (???)
  - We assume spectrum with one slope, recent work show spectrum with 2 slopes (Carrano-Rino[2016])

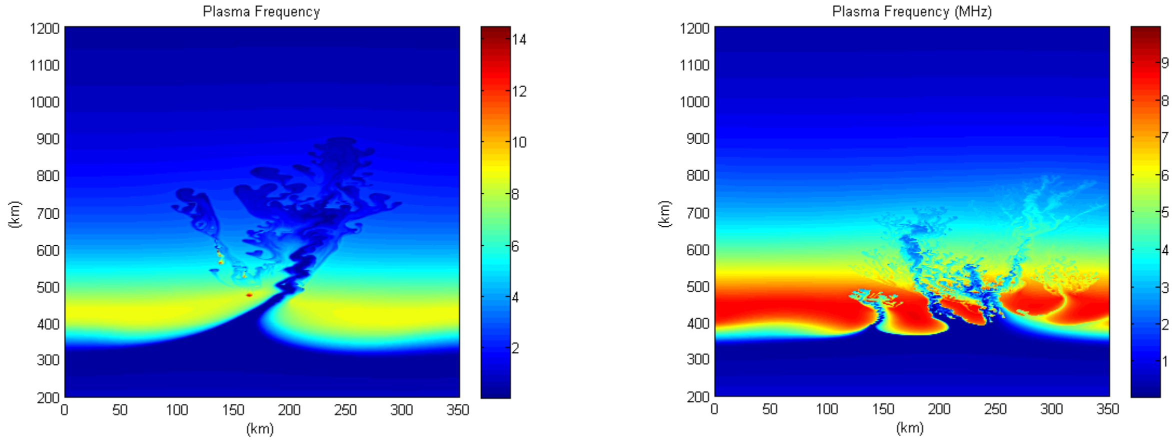


$$S_\phi(q) = \begin{cases} C_1 q^{-p_1} & q > q_0 \\ C_2 q^{-p_2} & q < q_0 \end{cases}$$

  - **How can we extract Turbulence spectrum parameters from data**

Scintillation Model : physical approach

- High resolution model of plasma bubbles: Dr Yokoyama san model
  - plasma density continuity equation
  - current continuity condition to obtain the electrostatic potential
- A physics based model of the scintillation



- Yokoyama, T., H. Shinagawa, and H. Jin, Nonlinear growth, bifurcation and pinching of equatorial plasma bubble simulated by three-dimensional high-resolution bubble model, *J. Geophys. Res. Space Physics*, 119, 10,474-10,482, 2014.
- Yokoyama, T., H. Jin, and H. Shinagawa, West wall structuring of equatorial plasma bubbles simulated by three-dimensional high-resolution bubble (HIRB) model, *J. Geophys. Res. Space Physics,* 120, 8810-8816, 2015.
- Yokoyama, T., and C. Stolle, Low and midlatitude ionospheric plasma density irregularities and their effects on geomagnetic field, *Space Sci. Rev.*, doi:10.1007/s11214-016-0295-7, 2016.

Scintillation Model : physical approach

- Computation challenge to use physical model in propagation
  - PWE can reproduce the effect the scintillation only if the sampling step of the phase screen is smaller than the Fresnel range ($L_{Fresnel} = 2\sqrt{\lambda L_V}$)
  - The phase screen size should be large enough to catch all the irregularities (>1000 km in the horizontal direction, >800 km in the vertical direction
  - Thus, the output of the physical model should provide a density with a grid (pixel 2D or Voxel 3D) smaller than Fresnel range on a large range

  - Example
    - HF (30MHz), $L_{Fresnel} \approx 3\ km$ → 111556 Ne samples
    - L (1.5GHz), $L_{Fresnel} \approx 100\ m$ → 100020001 Ne samples

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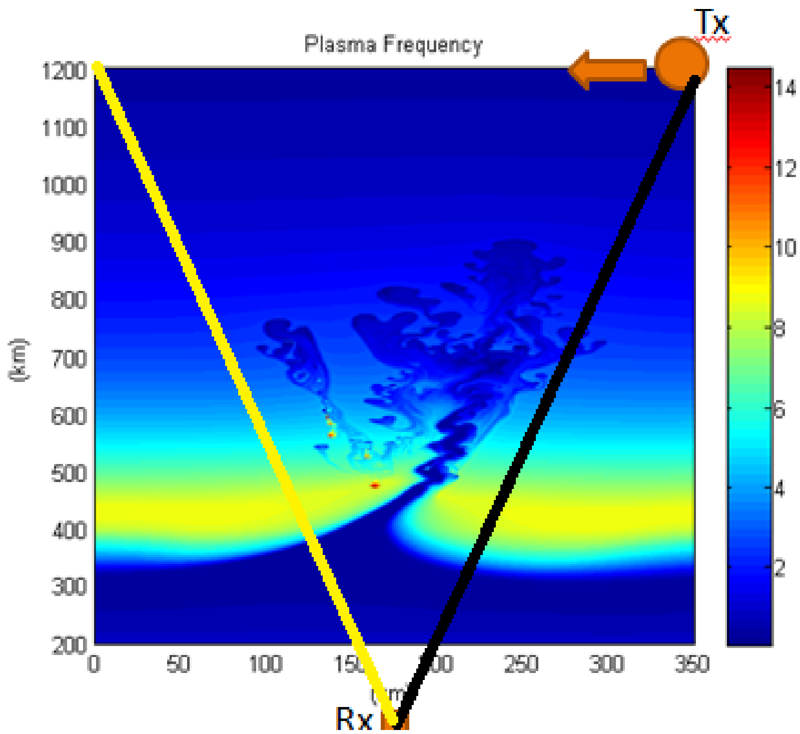
Fill the gap between stochastic and physical scintillation model

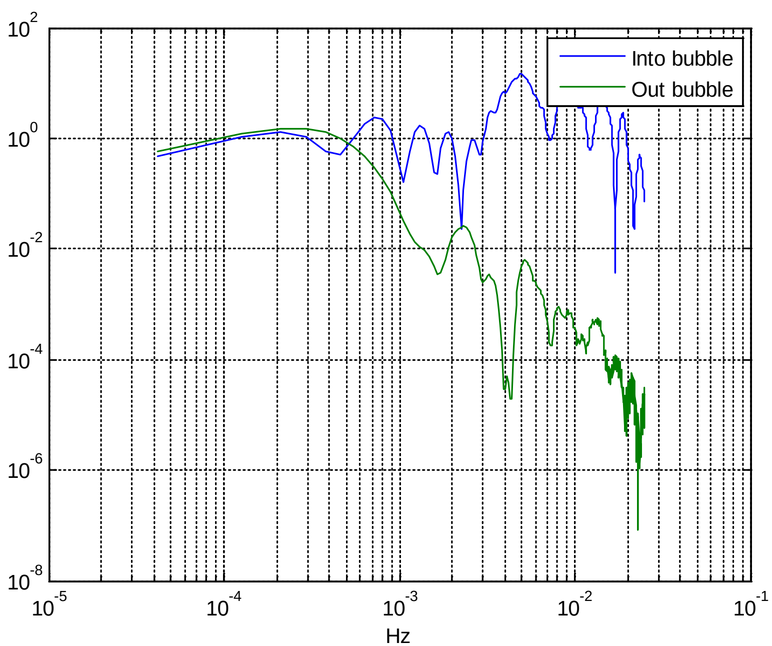
- We use 3D ionospheric model (NICT model)
  - Receiver at d = 180km
  - Satellite at h = 1200 km, from d = 350 to 0 km
  - Pixel size ~ 1 km

NICT: Yokoyama et al

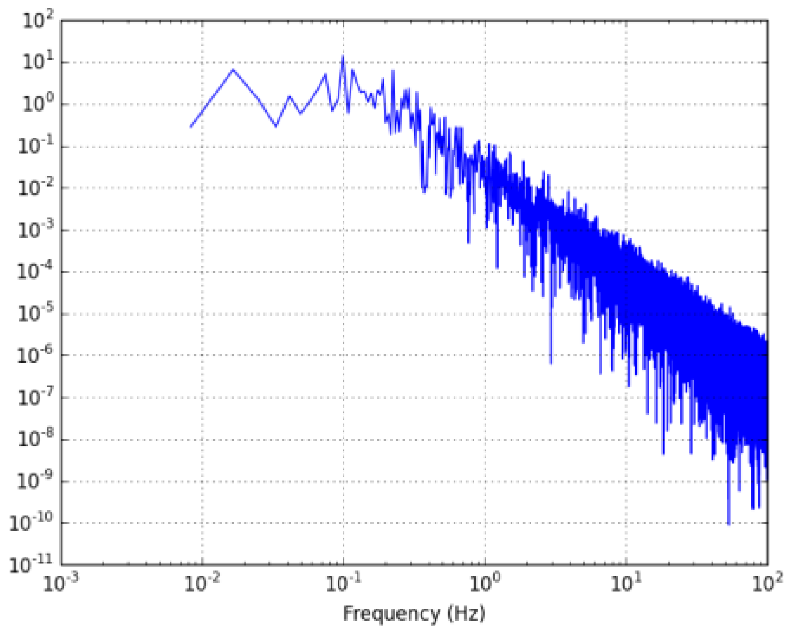


Fill the gap between stochastic and physical scintillation model

- What about scintillation: define phase screen base on NICT model
  - PWE use: the Ne scale sould be smaller than the Fresnel range $2\sqrt{R\lambda} \sim 300m$ for L1 → <u>scale issue</u>



From NICT model
(with v = 100m/s)



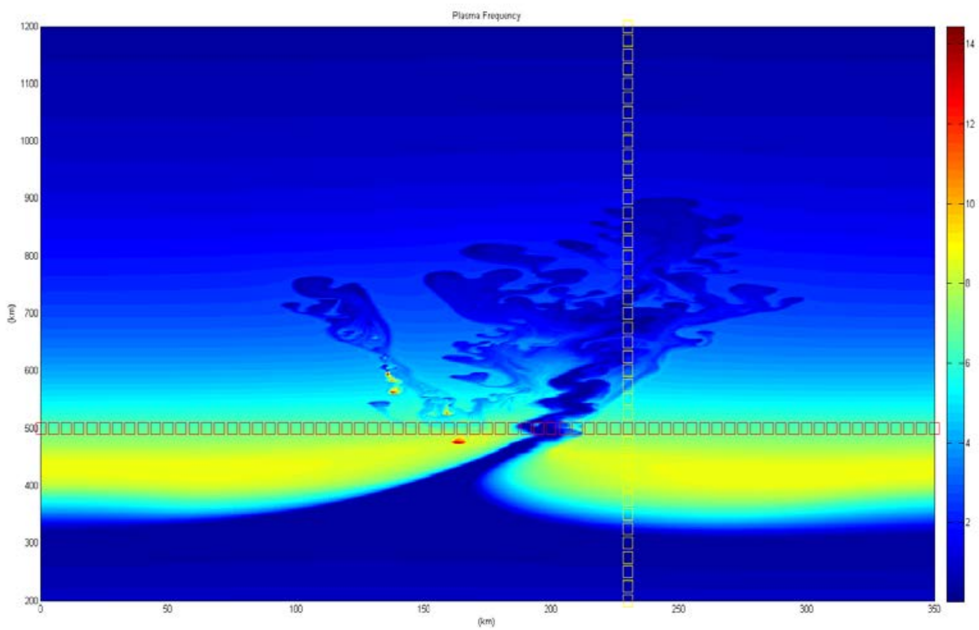
Typical input of scintillation model

Fill the gap between stochastic and physical scintillation model

- How to solve scale issue ?
  - Medium scanning to catch the « sub-bubbles » location coordinates
  - On each «sub-bubbles», evaluation of the σ_{N_e} parameter (scintillation strength is function of

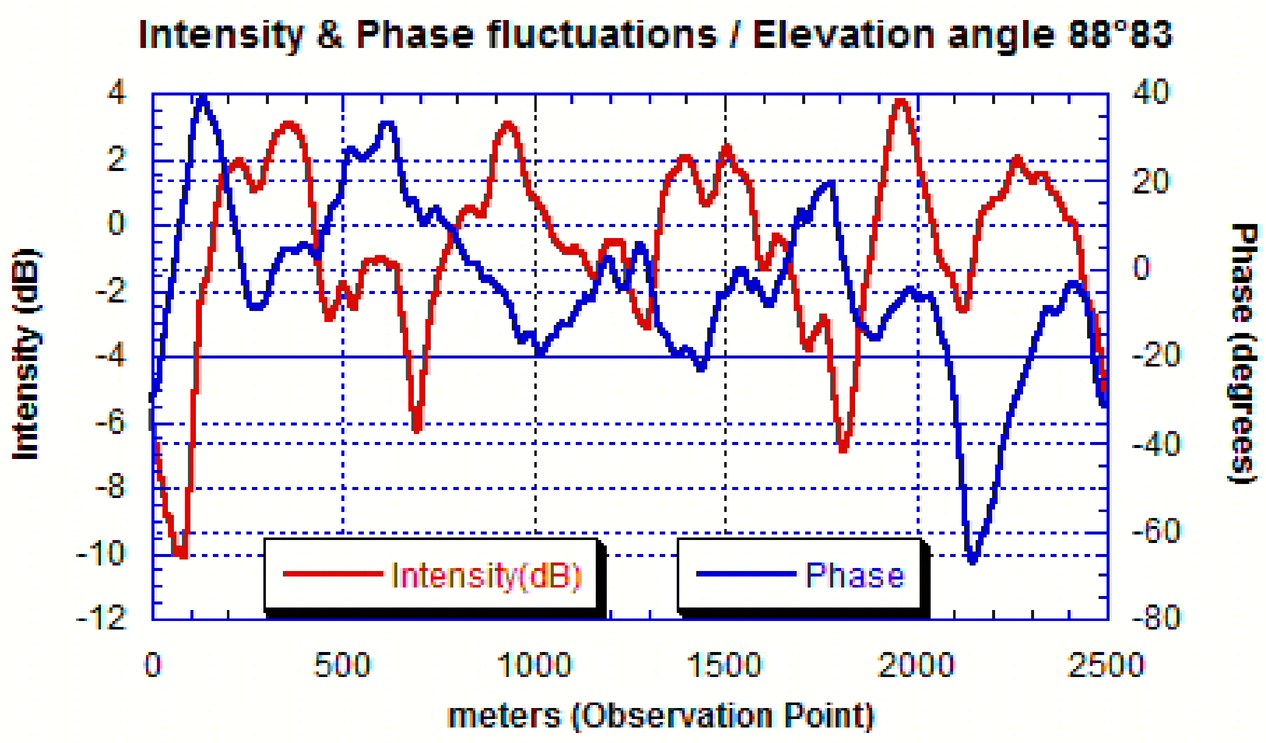
$$\sigma_{N_e}\colon\ C_S = \frac{{\sigma_{N_e}}^2 {K_0}^{p-3} \Gamma\left(\frac{p}{2}\right)}{\pi^{\frac{3}{2}} \Gamma\left(\frac{p-3}{2}\right)})$$

  - Creat a random phase screen ⊥ to propagation direction (follow the Schkarofsky spectrum, appropriate sampling for PWE, size equal to the grid research)



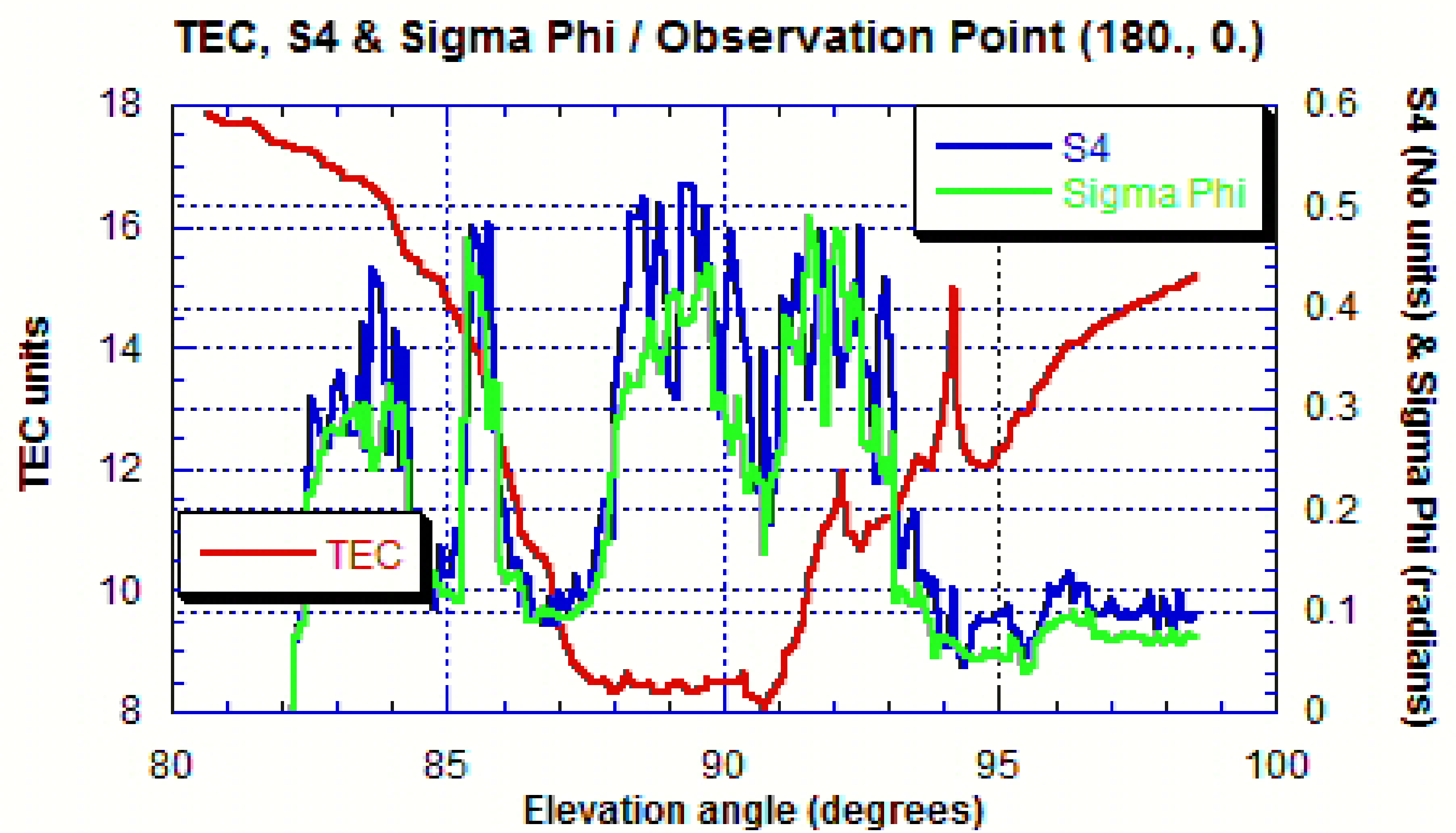
Fill the gap between stochastic and physical scintillation model

- How to solve scale issue ?
  - amplitude and phase series



Fill the gap between stochastic and physical scintillation model

- How to solve scale issue ?



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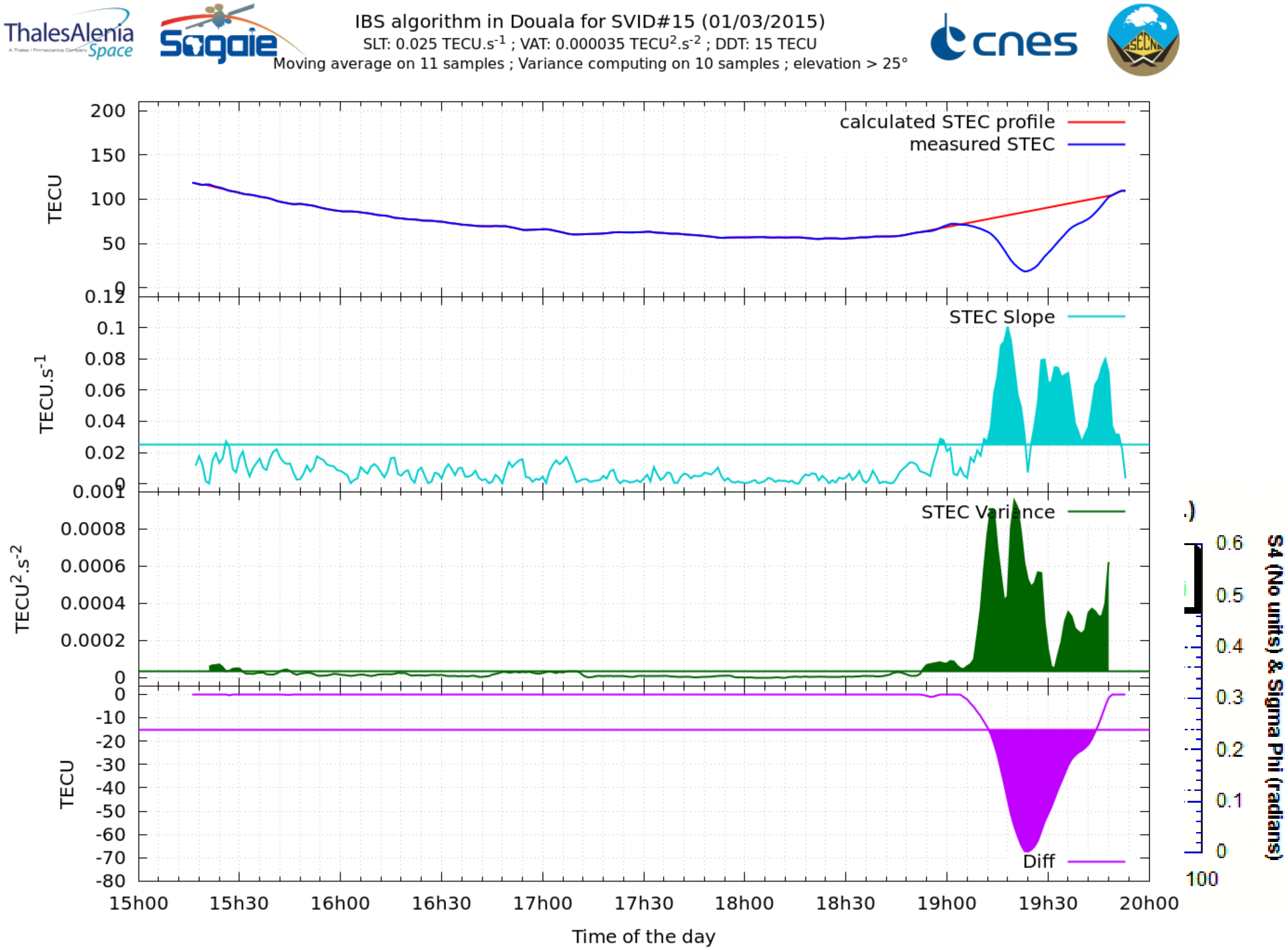
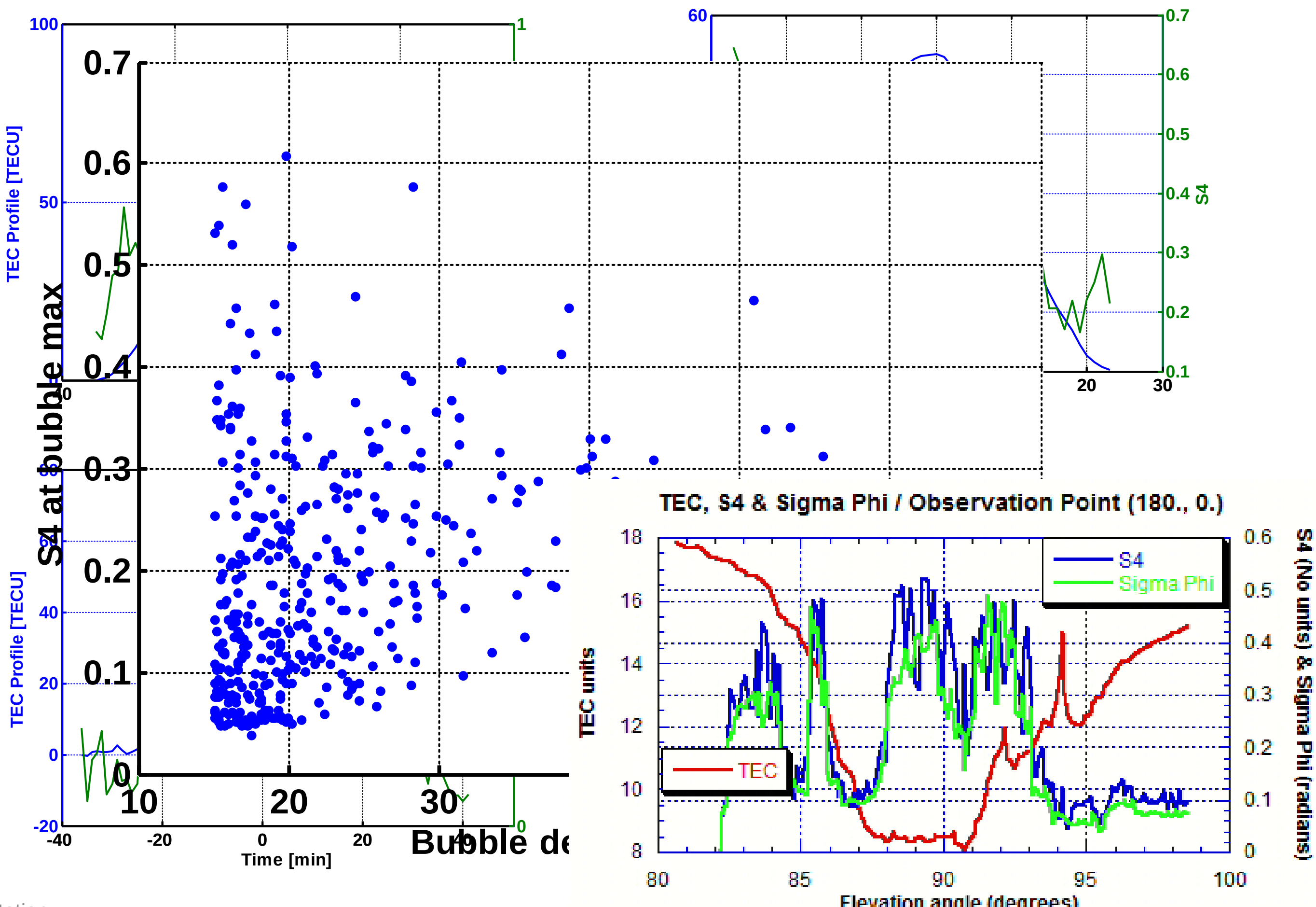
Validation

- Bubble seeker



Validation

- On data, no real correlation between the bubble size and the S4



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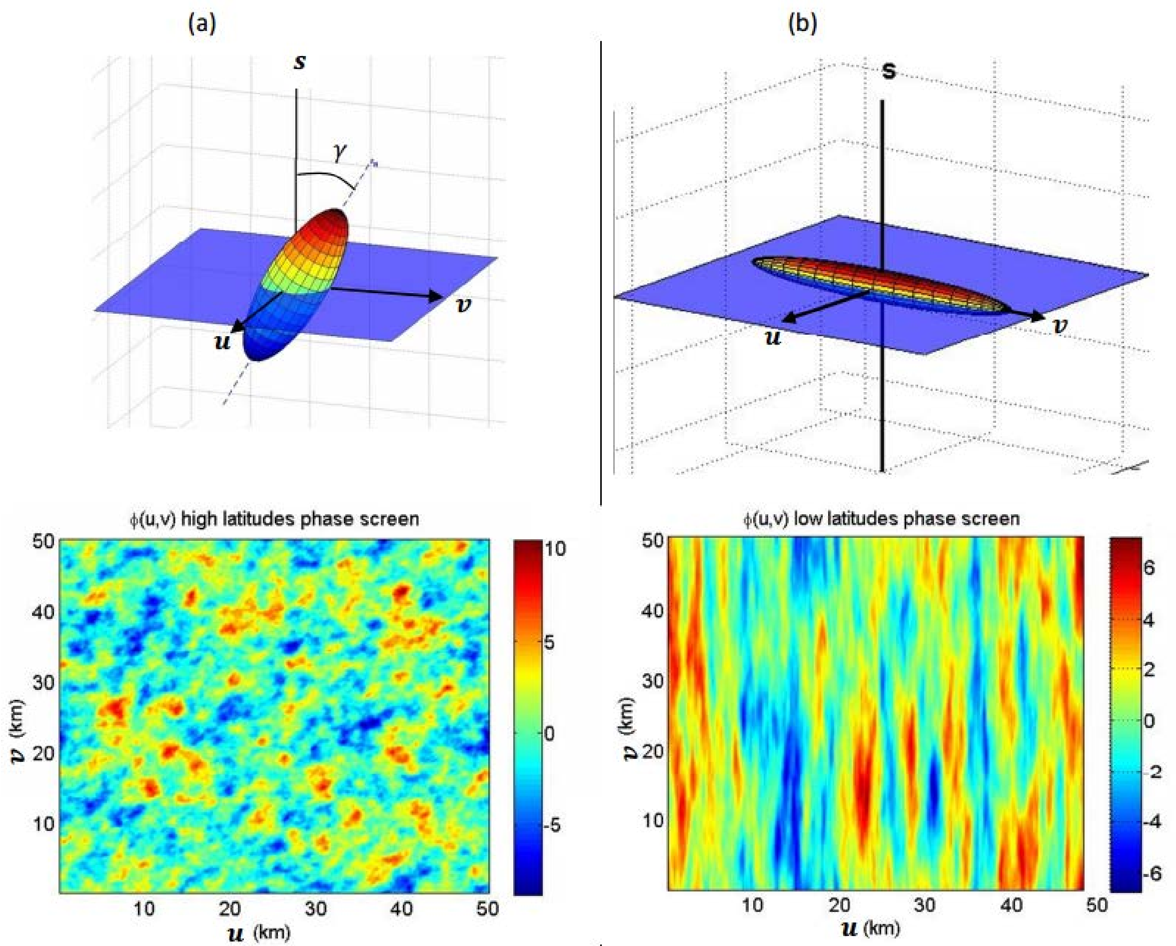
Conclusions

- Scintillation on L1 signal is model by a stochastic process reliable for equatorial and polar region (3D Anisotropy, 2D propagation)
- Howerver, we need to improve the knowlege of the ionospheric medium, and more particulary the turbulence structure knowledge
- To find more information about the medium, we propose a link with the physical ionospheric model from NICT (Yokoyama bubble model)
- Main problem: scale issue (from 1km to 100m) and computation challenge
- To solve this issue, we assume scintillation in all the bubble envelop and we introduce stochastic turbulence as a function σ_{Ne}
  - + easy and fast to implement
  - - If we compare to data, we might over estimate the scintillation → here, the proposed approach gives the worst case
- Hardly to validate the propagation approach with one shot, need a statistical analysis with several physical montecarlo simulation

Scintillation Model

- Exemple of phase screen in space domain for low and high latitude

Polar region:
2D simplification not possible
→ variation along v ~ variation along u



Equatorial region:
2D simplification possible
→ variation along v << variation along u

Annexe: PWE equation

- Propagation in a 3D environnement (Helmholtz equation, depolarization effects neglected)

$$\nabla^2 \vec{E}(\vec{r}) + k_0^2 n(\vec{r})^2 \vec{E}(\vec{r}) = \vec{0}\,,$$

  - In the LOS frame (u,v,s) and planar wave assumption

$$\Psi(u,v,s) = e^{ik_0 s} E(u,v,s)$$

$$\frac{\partial^2\Psi}{\partial u^2} + \frac{\partial^2\Psi}{\partial v^2} + \frac{\partial^2\Psi}{\partial s^2} - 2ik_0\frac{\partial\Psi}{\partial s} + 2k_0^2\left(n(\vec{r})^2 - 1\right)\Psi = 0$$

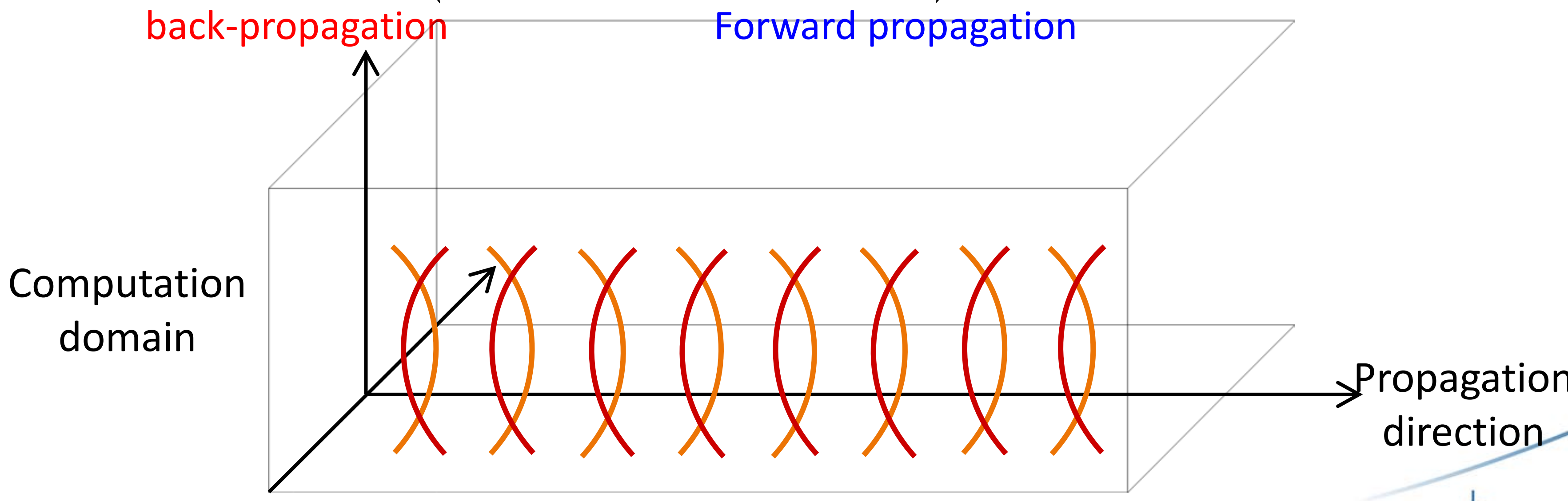
Annexe: PWE equation

- Propagation decomposition

$$\left(\partial_s + i\sqrt{\partial_u^2 + \partial_v^2 + k_0^2\varepsilon_r}\right)\left(\partial_s - i\sqrt{\partial_u^2 + \partial_v^2 + k_0^2\varepsilon_r}\right)\Psi = 0$$

- back-propagation not tacking into account

$$\left(\partial_s - i\sqrt{\partial_u^2 + \partial_v^2 + k_0^2\varepsilon_r}\right)\Psi = 0$$

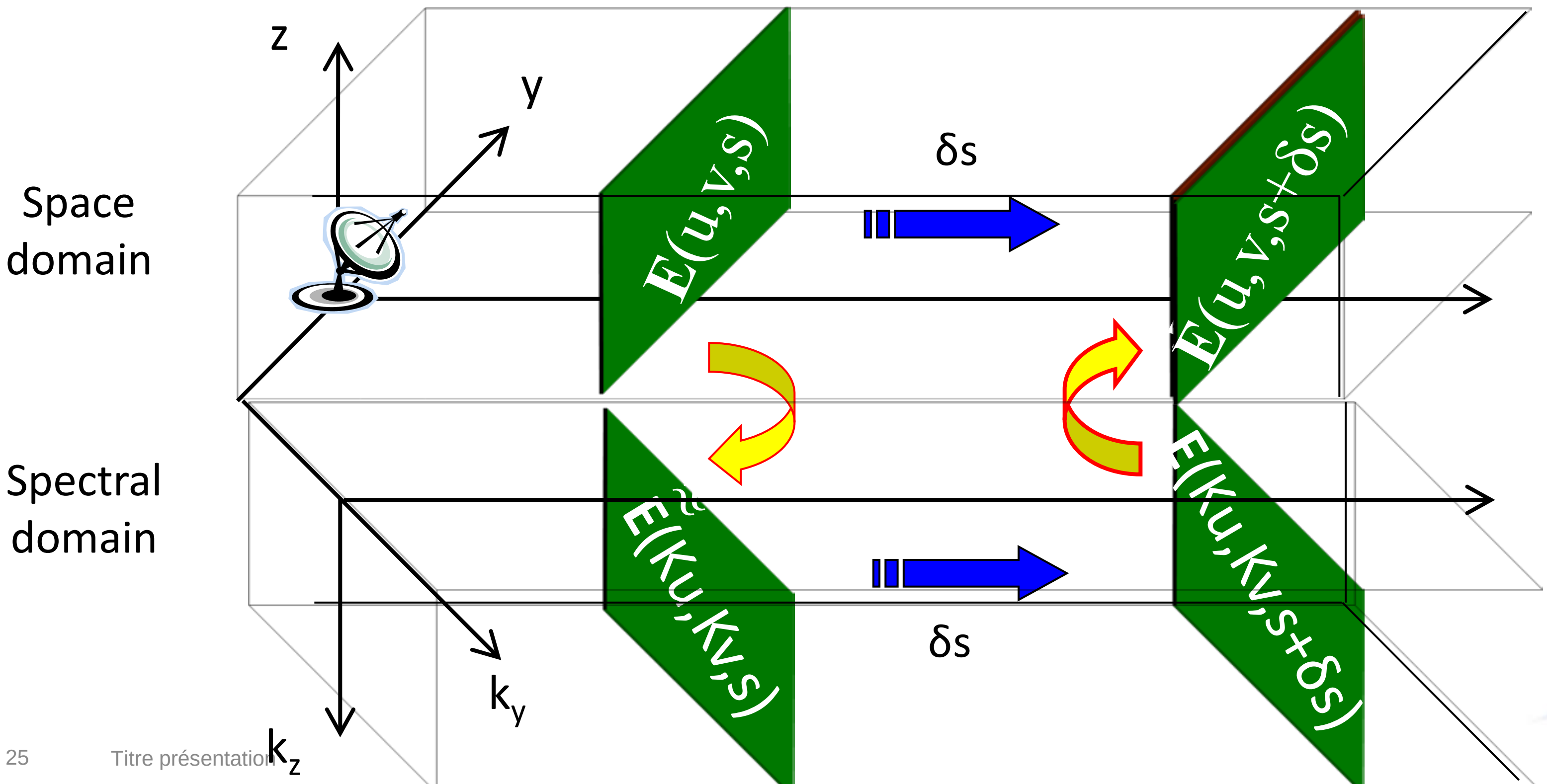


Annexe: PWE equation

- Propagation in the spectral domain along phase screen

$$E(u,v,s+\delta s) = e^{ik_0\phi(u,v)}\,\mathrm{TF}^{-1}\left\{e^{i\sqrt{k_0^2-K_u^2-K_v^2}\,\delta s}\,\mathrm{TF}[E(u,v,s)]\right\}$$

$$\phi(u,v) = \int_{s}^{s+\delta s} n(u,v,\xi)^2 d\xi - 1$$



From Ne to n

- Appleton–Hartree equation:

$$n^2 = 1 - \frac{X}{1 - iZ - \frac{\frac{Y^2}{2}\sin^2\theta}{1 - X - iZ} \pm \frac{1}{1 - X - iZ}\left(\frac{1}{4}Y^4\sin^4\theta + Y^2\cos^2\theta\,(1 - X - iZ)\right)^{\frac{1}{2}}}$$

$X = \frac{{\omega_0}^2}{\omega^2}$, with $\omega_0 = 2\pi f_p = \sqrt{\frac{Ne^2}{\epsilon_0 m}}$

Y= $\frac{\omega_H}{\omega}$ with $\omega_H = 2\pi f_H = \frac{B_0 e}{m}$(need geomegnetic model)

Z= $\frac{\eta}{\omega}$ with η the electron collision frequency (available by NICT model ?)

- Appleton–Hartree equation (simplification at L band, w>>w0, Y=Z=0)

$$n \quad = 1 - \frac{40.3Ne}{f^2}$$

From ΔNe to Δn

- Propagation in a 3D environnement (Helmholtz equation, depolarization effects neglected)

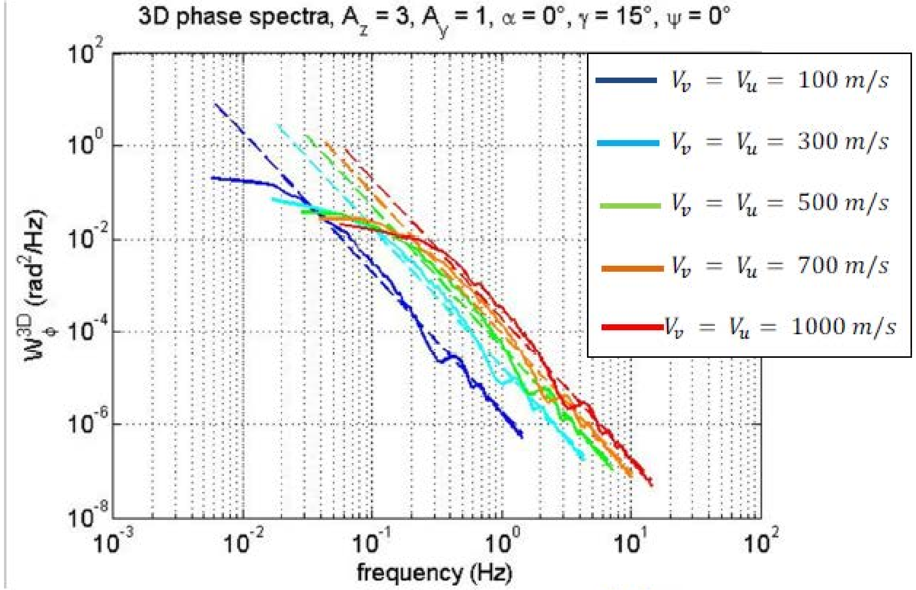
$$\nabla^2 \vec{E}(\vec{r}) + k_0^2 \varepsilon_r(\vec{r}) \vec{E}(\vec{r}) = \vec{0} \, ,$$

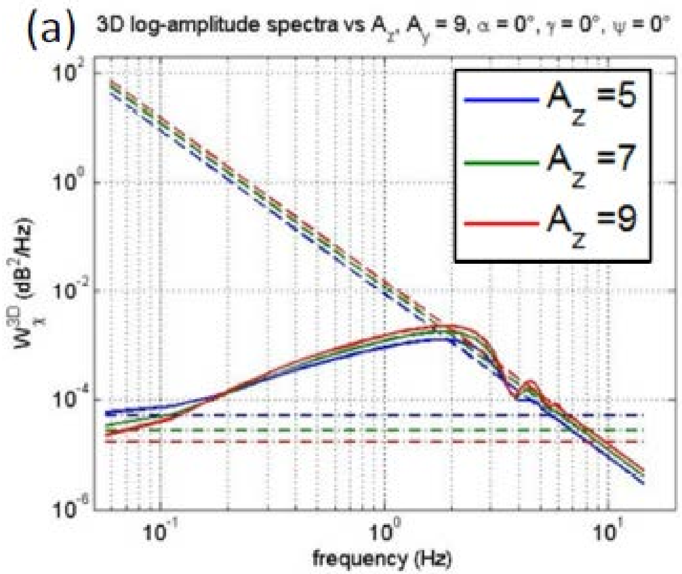
$$\varepsilon_r(\vec{r}) = 1 - \frac{N_e(\vec{r}) e^2}{\varepsilon_0 m \omega^2} \, .$$

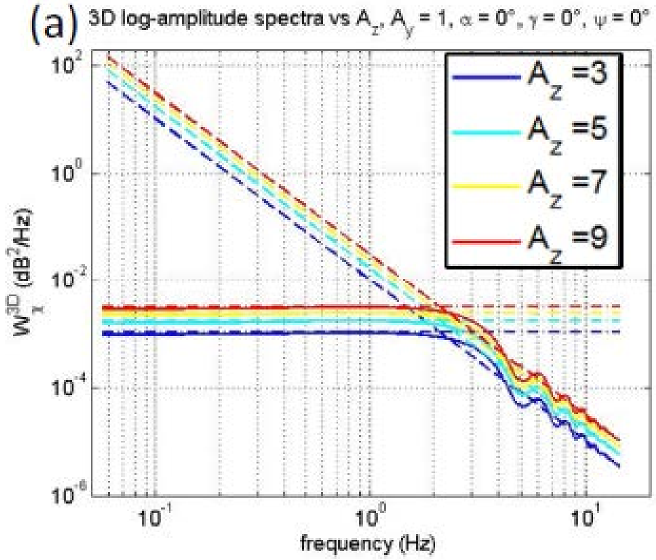
  - Assumption: frequency >> MUF (first order of the Appleton-Hartree equation)

$$\varepsilon_r = < \varepsilon_r > + \Delta\varepsilon_r = 1 + 2\Delta n(\vec{r}) = 1\text{-}2 \, \frac{\Delta N_e \lambda r_e}{k_o}$$

Annexe: Spectrum shape

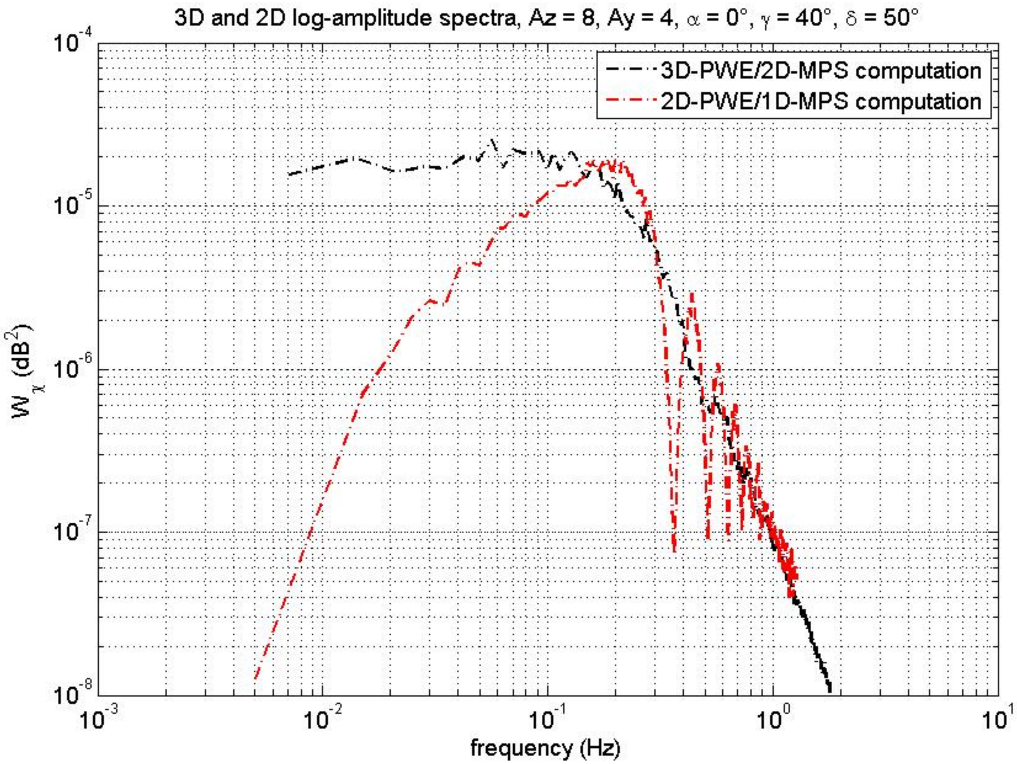


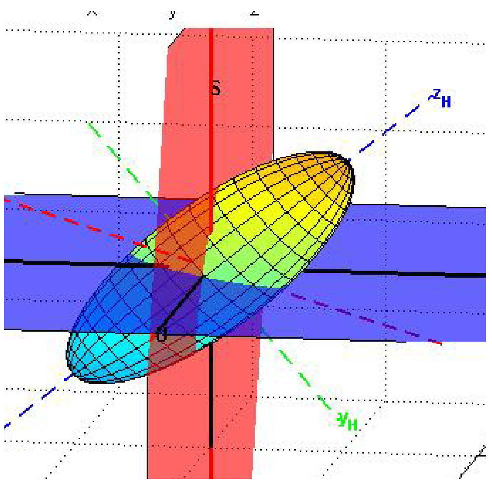




Scintillation Model: 3D vs 2D

- With a drift speed assumption (Vu, Vv), conversion of the phase screen in amplitude an phase times series





Introduction (SAGAIE project)

Main question :

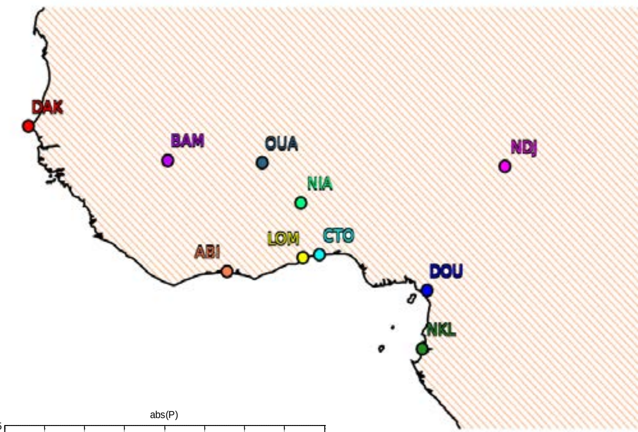
- *Is a Mono-Freq SBAS service possible in the west African equatorial region (ASECNA zone) ?*

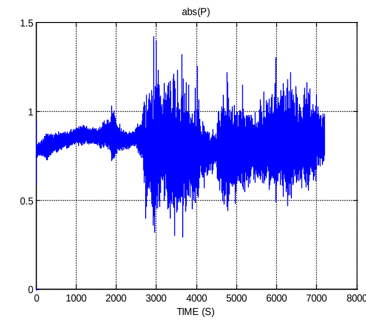
Main issues of this zone compared to mid-latitude SBAS :

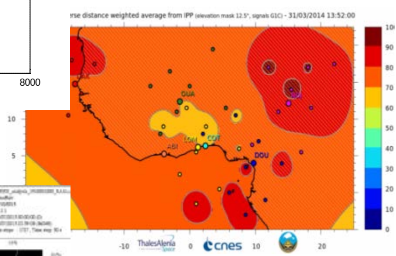
- Ionosphere scintillation (may cause LoL of RIMS and user receivers)
- TEC gradients and bubbles (may cause correction errors due to MOPS iono grid size and update rate)

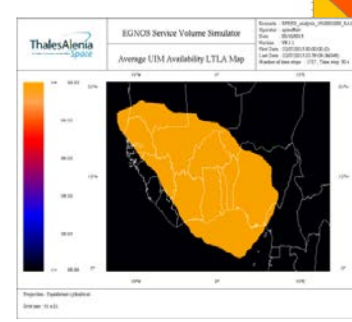
Rational approach :

- Deploy a network of station in the ASECNA zone and ensure its maintenance (SAGAIE1 and MONITOR2 extension)
- Quantify the reality of scintillation, TEC gradients and bubbles in the zone
- Provide an indicative performance of an SBAS system in the zone and conclude or at least provide strong arguments to the feasibility

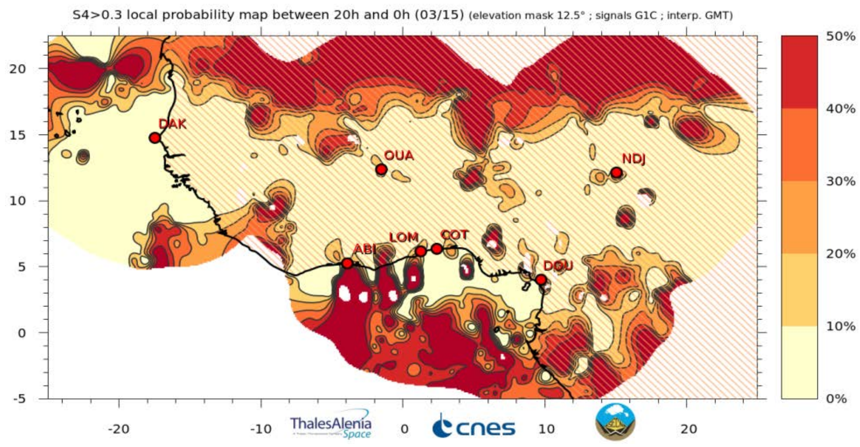


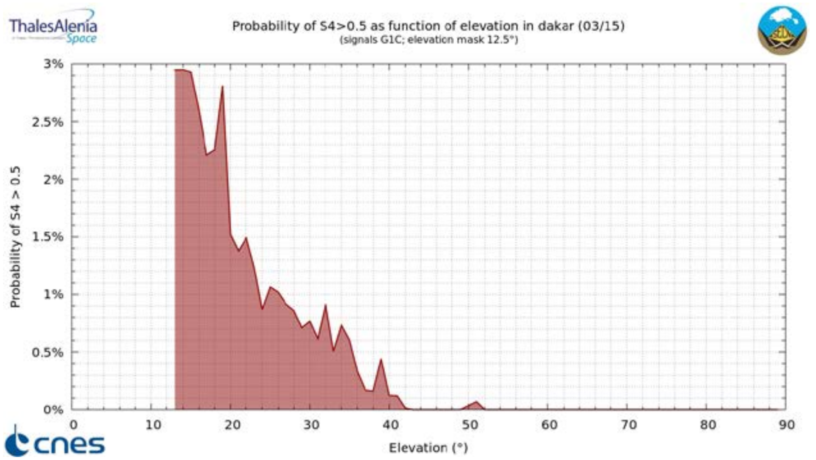


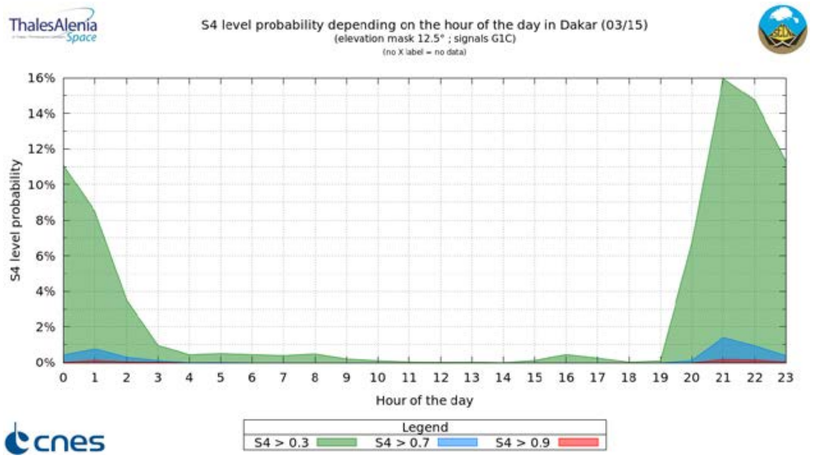


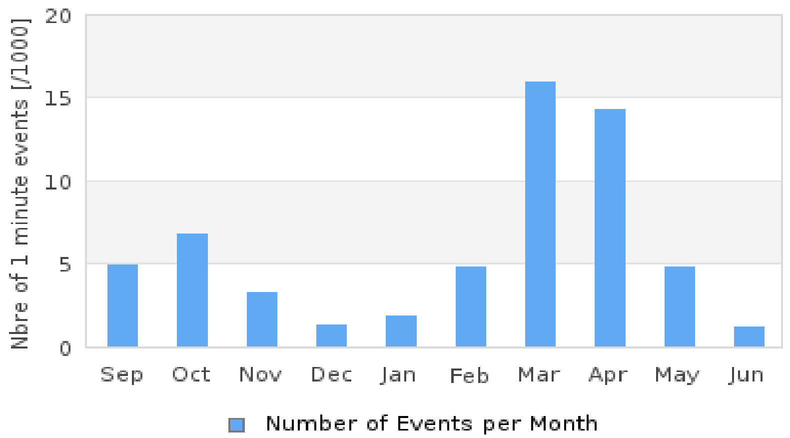


SAGAIE: statistical analysis of scintillation









Introduction (SAGAIE: Indicative SBAS performance)

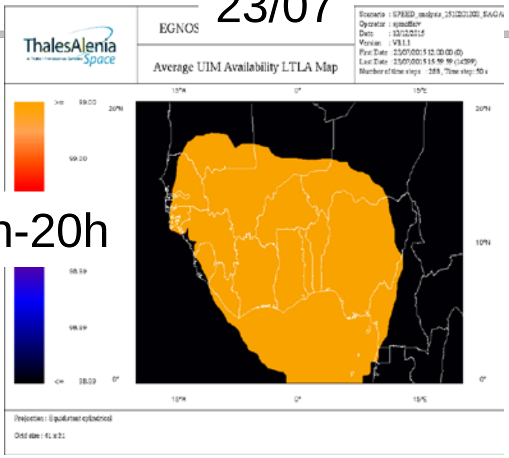
EV241m

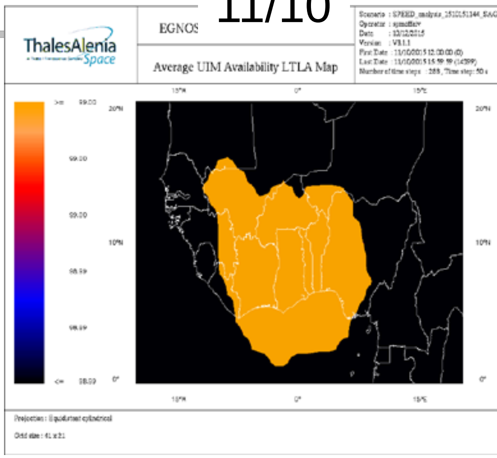
- Only 9 stations ! (i.e. few IPP near each IGP)
- Sensitive to LoL → <u>Scintillation issue</u>

23/07

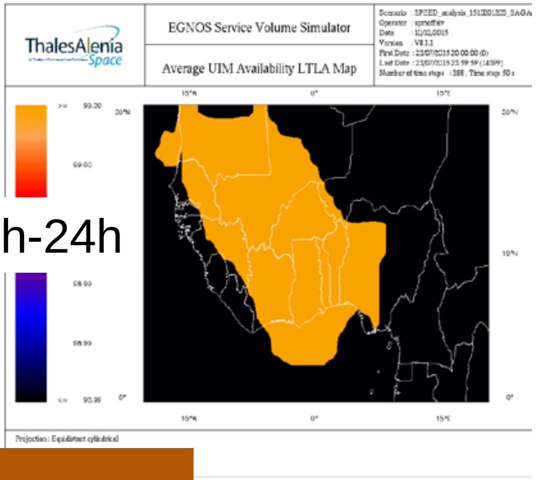
11/10

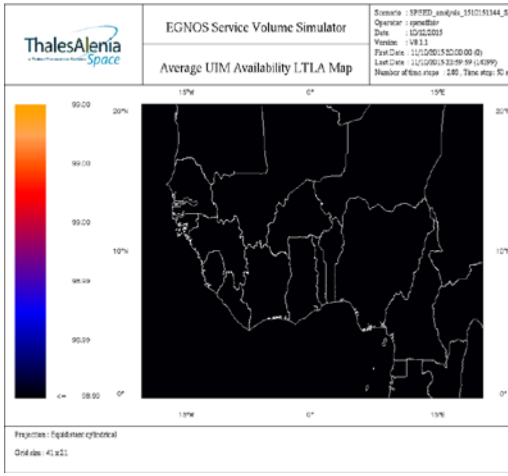
16h-20h





20h-24h



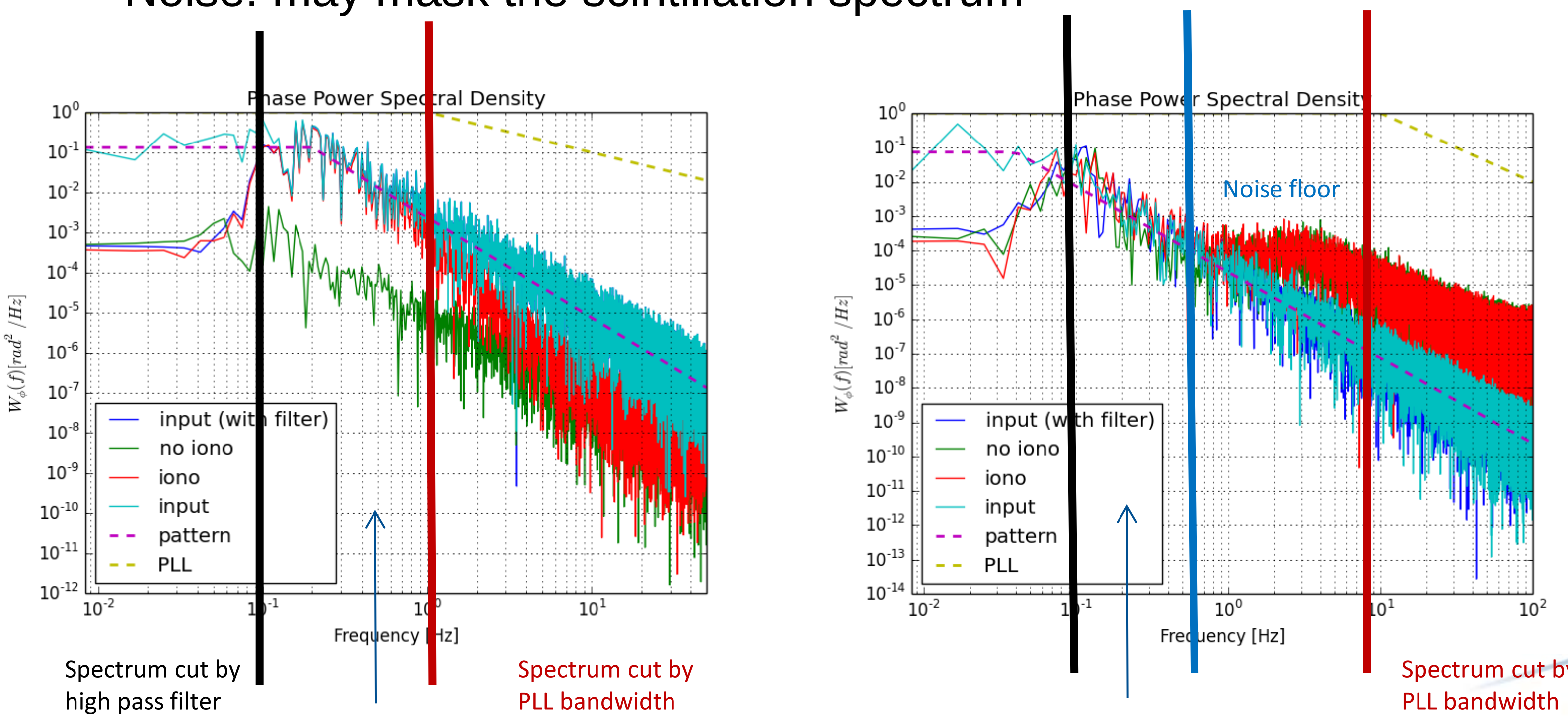


- Gradient are not an issue
- Not so far from having good perf
- With more RIMS (more IPP) and better handling of LoL, it will work !

Scintillation Model

- Scintillation spectrum hardly observable
  - Sampling rate: limit the high part of the spectrum (max fs/2)
  - Observation time: limit the low part of the spectrum (min 1/T)
  - GNSS receiver and estimator tunning
  - Noise: may mask the scintillation spectrum

C/N0 = 60dBHz



C/N0 = 40dBHz

Spectrum portion where phase scintillation is observable