Investigation into the comparative amplitudes of phase and amplitude scintillation indices at low/equatorial and high latitudes

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Introduction

- Scintillation is a problem for global satellite systems such as GPS or Galileo as it can degrade the positioning, cause cycle slips or result, in the worst case scenario of strong scintillation, in the loss of lock of the receiver PLL.
- This problem is important for low latitudes (particularly in the equatorial anomaly regions) and at high (particularly polar and auroral) latitudes. Understanding the physical mechanisms of scintillation better and their effect on GNSS receivers should lead to improved mitigation strategies which to be optimum may well vary between low and high latitude applications
- It is well known that it is usual for ground based receivers at high latitudes to see significantly larger phase than amplitude scintillation for transionospherically propagated VHF/UHF signals from satellites whereas the opposite of larger amplitude than phase scintillation is generally seen at low or near equatorial latitudes.

There could be a number of reasons for this including

- detrending and Fresnel filtering effects
- geometrical factors
- Height distributions and differences in the irregularities (e.g. orientation, aspect ratio, spatial spectrum) in the two regions
- or a combination of two or more of these or other effects

Determining scintillation mechanisms

- Such an investigation should also yield light on the factors producing the scintillation in both cases.
- This is important because mitigation strategies to reduce scintillations effect may well vary depending on whether the scintillation is mainly in phase or amplitude or a combination of both.
- In order to determine the relative importance of all these effects, in this paper the ratio of the S4 index to the phase scintillation index will be determined to see which factors or parameters have the greatest effect in altering it, looking in particular for an effect that will minimise this ratio at low latitudes and maximise it at high latitudes and including variation with elevation, latitude (via dip) and properties of the individual irregularities and their anisotopic spatial spectrum.

Irregularity properties

- Variation of the following irregularity properties have been considered:-
- Their strength measured by the variance of their electron density
- Their aspect ratio(s): length to cross sectional radius.
- Their relative velocity perpendicular to the propagation path.
- Their outer scale
- The power law of their anisotropic spatial spectrum also considering a dual slope model with a variable break point.

The irregularities are always considered to be aligned along the local geomagnetic field direction.

They are superposed on a background vertical ionosphere profile given from equations (e.g Chapman layer), experimental measurements or IRI/ NeQuick models.

Methods of determining scintillation effects

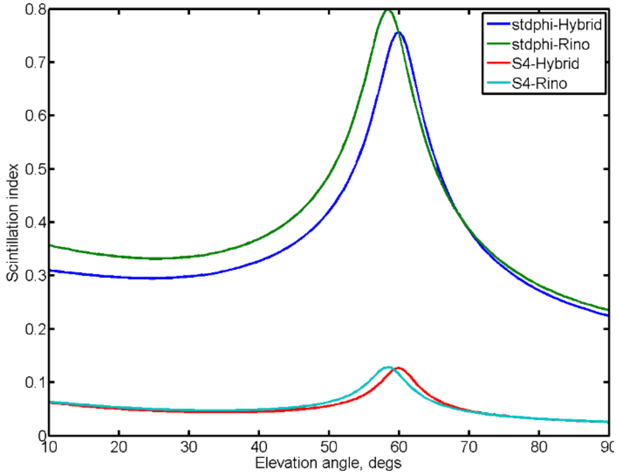
- Two different methods will be used to determine the scintillation indices σ_φ and S4; the weak scatter theory of Rino [3] and the Hybrid method of Gherm et al [4].
- Employing two different methods will ensure that the calculation are not too scintillation-determination-method specific.
- The equivalent phase screen method of Rino finds the fluctuations of both the phase and amplitude of the field below an equivalent phase screen which represents the diffracting effect of the entire ionosphere and in calculations it is normally placed near or a little above the height of the F region and commonly at 350 km altitude when this is not known.
- The Hybrid Scintillation Propagation Model (HPSM) method [4] uses the complex phase method in combination with the random screen technique. The parameters of the random screen (situated below the ionosphere) are determined as the result of a rigorous solution to the problem of propagation inside the ionosphere using the complex phase method. The random two-dimensional spatial spectrum at the screen is then transferred down to the Earth's surface employing the rigorous relationships of the random screen theory.

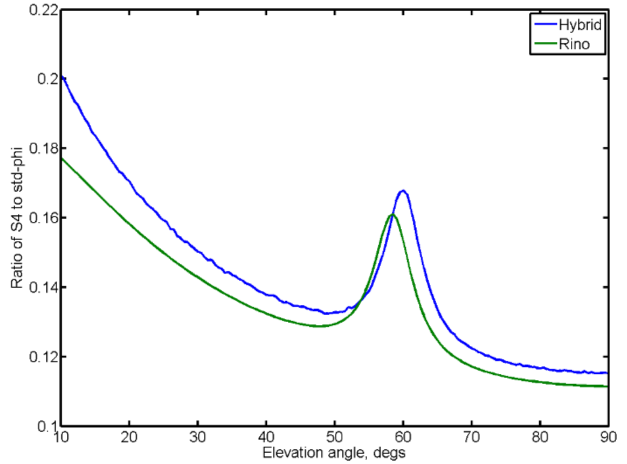
Geometrical and physical parameters used.

- The ratio of the amplitude (S4) to phase scintillation indices for the two methods was determined for a number of different parameters.
- When fixed, parameters generally took the following values:
- Normalised variance of the irregularity electron density: σ_N^2 : 0.001 (which was assumed to be height independent);
- the irregularities cross-field aspect ratio: 1 and longitudinal aspect ratio: (the length of the irregularities compared with their radius): 10;
- irregularity outer scale (L0): 10 km,
- the power law of the irregularity anisotropic spatial spectrum: 3.7 (then the slope of the received phase psd (on log log axes) for weak/moderate scintillation is 2.7);
- Velocity of irregularities: 300 m/s perpendicular to the propagation path.
- transmission frequency: 1575 MHz;
- azimuth of path :180 °;
- path elevation: 45°;
- geomagnetic field dip: 60°.
- The vertical electron density profile used for these calculations had a maximum of 4.63×10^{11} el m^{-3} at an altitude of 285 km and a TEC of 14.78.
- The signal was considered to be transmitted from an altitude of 20,000 km as from a GPS satellite.

Variation of scintillation with elevation angle

The scintillation indices for the two methods and the corresponding scintillation ratio of S4 to σ_φ plotted against elevation angle in the geomagnetic meridian





Both determination methods give fairly similar results and both show that the scintillation ratio varies significantly between high and low elevation angles (by a factor of about 0.6) and also increases by about 20% when the path elevation and dip angle are aligned. This would mean that at high latitudes where field aligned paths through the ionosphere are possible, the S4 index could be larger with respect to the phase index than for non-aligned paths. This cannot explain why there are lower amplitude (S4) than phase indices at high latitudes as this is the opposite effect.

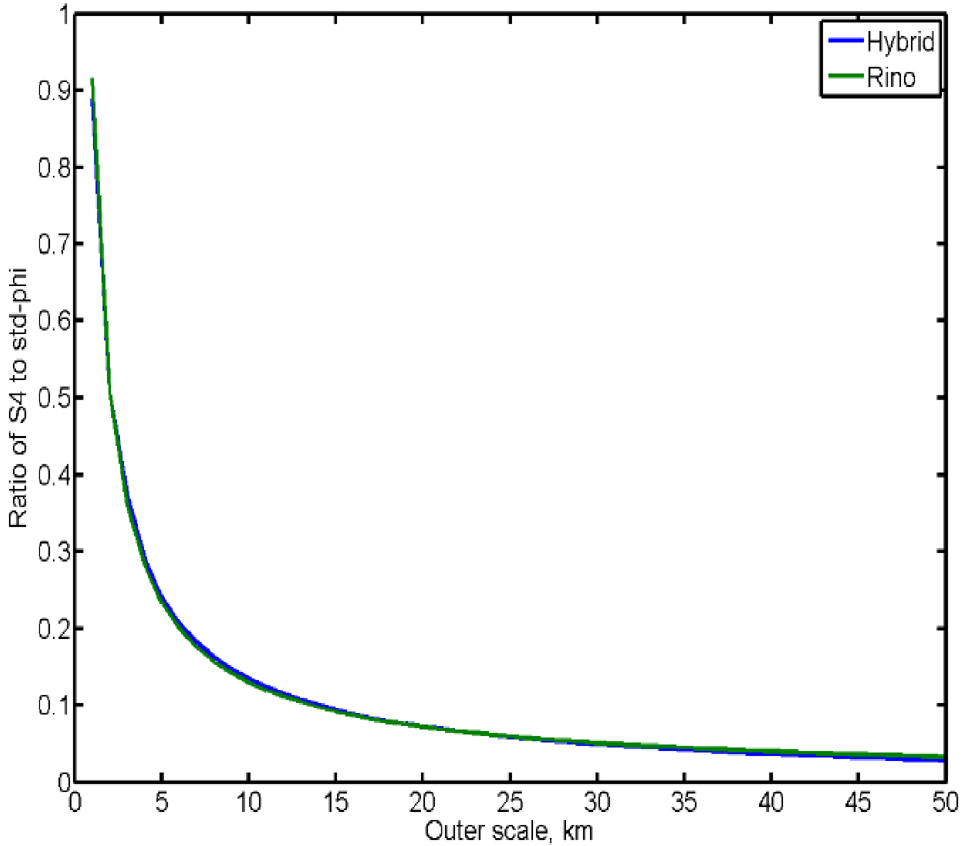
Variation of the ratio of the scintillation indices with outer scale

It is clear from the figure that there is a very appreciable dependence on the ratio with outer scale; this parameter varying from about 0.9 at 1 km to about 0.03 at 50 km.

This is because the increasing outer scale continually decreases the lower limit of the fading frequency range for which the phase scintillation is seen at the receiver.

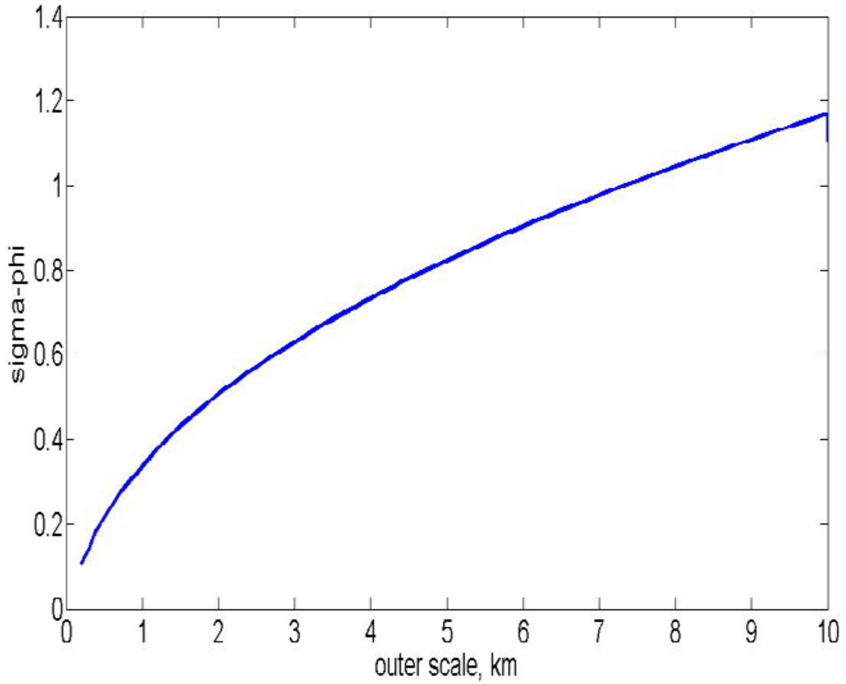
It does not have a corresponding effect on S4 because the lower frequency limit for this is already determined by the Fresnel frequency due to Fresnel filtering.

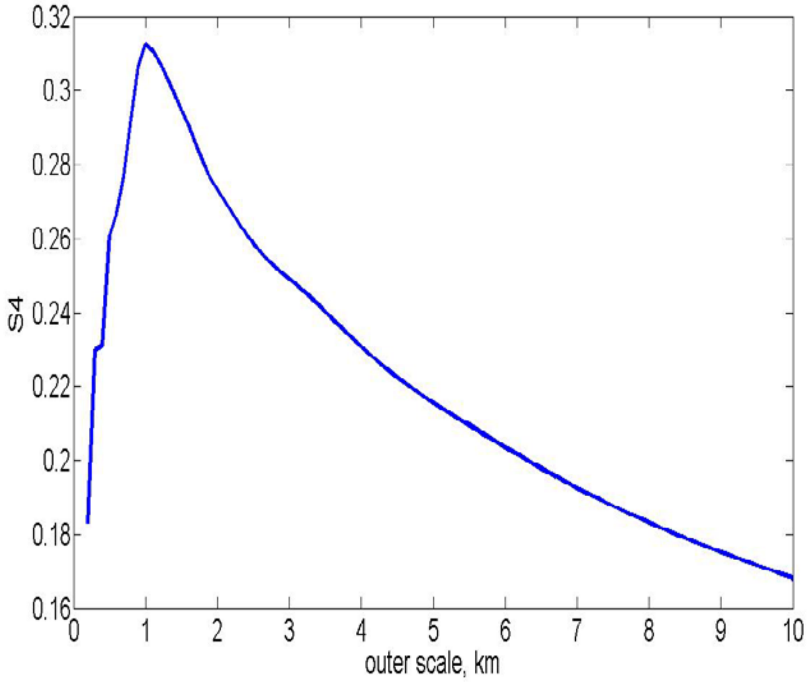
However the lowest fading frequency contributions to the phase scintillation index will often be lost in practice by the lower cut-of frequency introduced by the detrending.

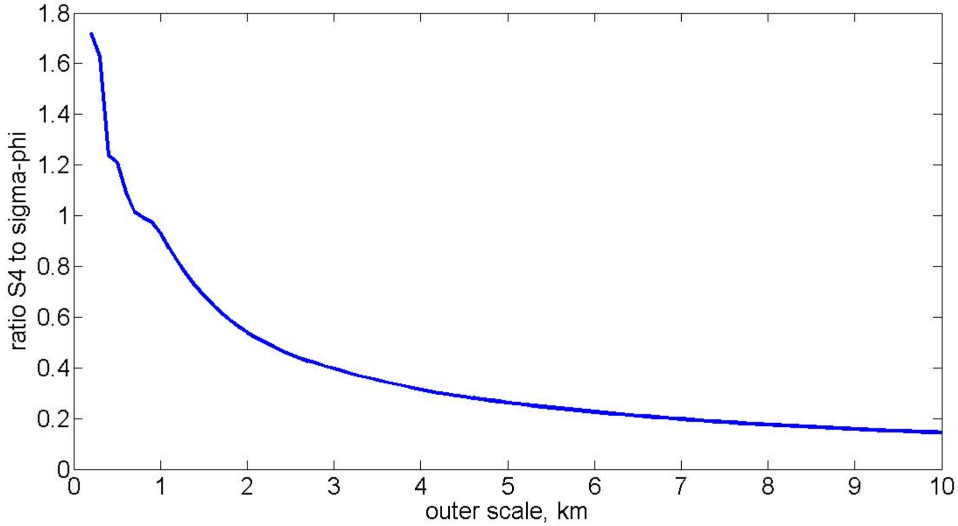


For all outer scales S4 is larger than σ_ϕ

Variation of S4/σ_φ ratio for outer scales less than 1 km





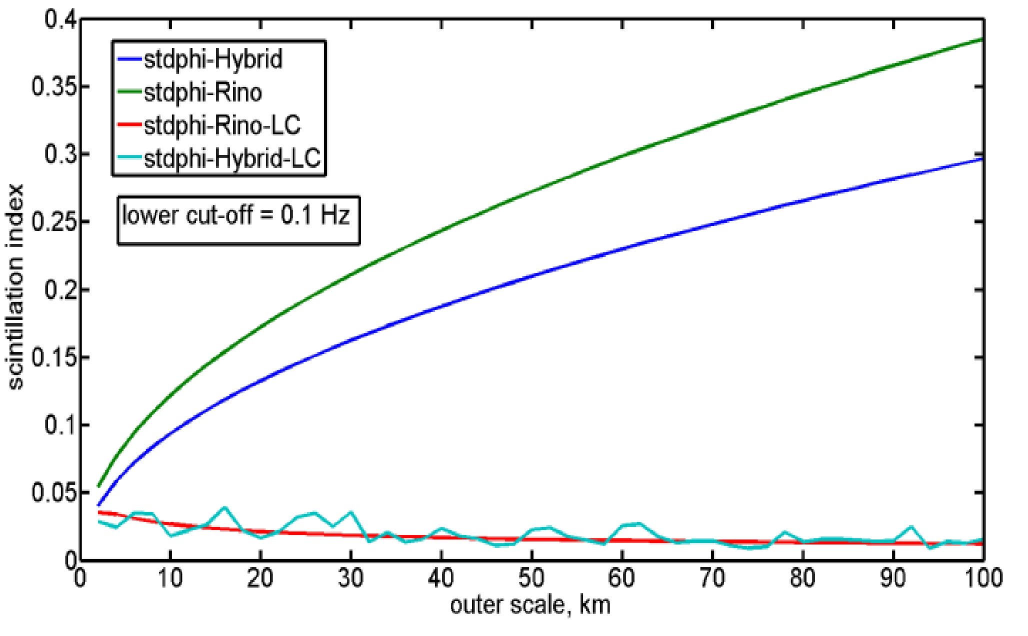


Ratios of S4/σ_φ > 1 for L0 < 1 km but will also depend on vector sum of satellite and irregularity velocity perpendicular to the path and the lower cut-off frequency of any detrending. Dual slope irregularity distributions with a shallower slope below the break point also produce higher S4/σφ ratios.

Effect of lower cut-off frequency

This is illustrated in this figure 3 where a low cut-off frequency of 0.1 Hz for the receiver/detrending is modelled and the variation of the scintillation indices with outer scale for both the Hybrid method and the Rino weak scatter theory is determined together with the corresponding determinations with no cut-off for comparison.

It is clear that the phase scintillation index is significantly reduced by a lower cut-off and actually slowly decreases with increasing outer scale rather than increasing with it, fairly similar in fact to the S4 variation with outer scale.



Discussion

When there is a low frequency cut-off, s4 would be much less affected than the phase scintillation index because Fresnel filtering would already have removed the lower fading frequencies below the Fresnel frequency which typically would be less than 0.1 Hz at low latitudes but could reach as high as 5 Hz for high latitudes due to the typically much faster irregularity drift velocity.

The ratio of the scintillation indices in the figure would be increased for large outer scales when the lower cut-off frequency was greater than v_{eff}/Lo where Lo is the outer scale and v_{eff} is the sum component of the satellite and irregularity velocities perpendicular to the path of propagation for isotropic irregularities but for anisotropic irregularities would also be reduced by the aspect ratio. This reduction would be modified by the relative direction of the path to the geomagnetic field direction (assuming the irregularities elongated in this direction).

Consideration of phase and amplitude psds

The difference between the two scintillation indices can best be understood with reference to the idealised psds for phase and amplitude shown.

The phase spectrum is modelled to have a single slope spectrum between its upper and lower limits on log-log axes.

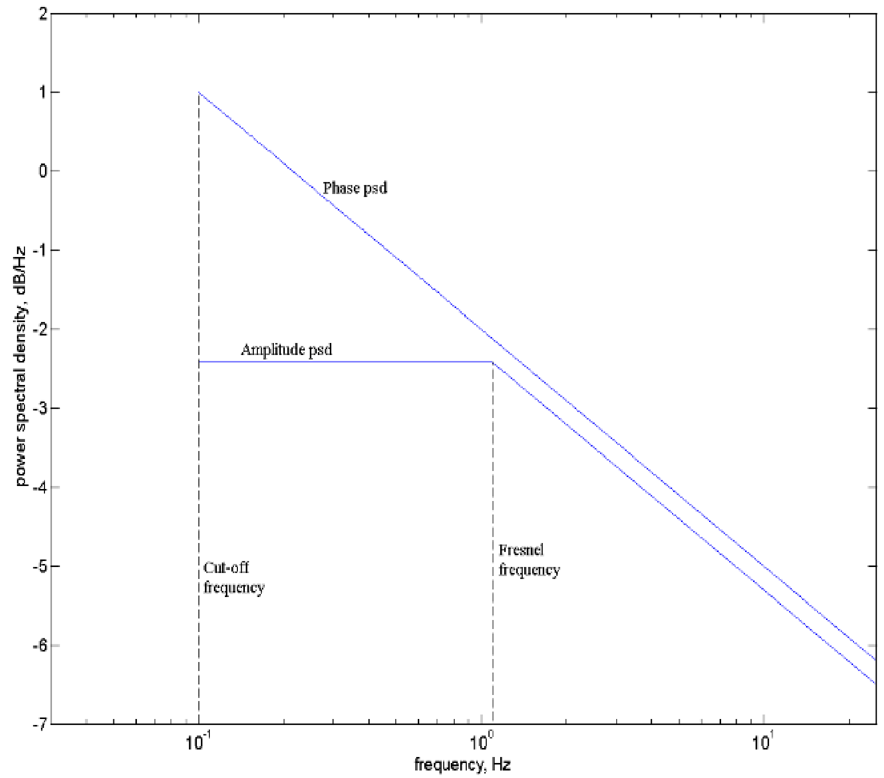
The amplitude spectrum is modelled similarly to the phase spectrum above the Fresnel frequency.

Below the Fresnel frequency, the amplitude psd is taken to be constant. σ_ϕ^2 is then equal to twice the area under the psd of the phase variation and σ_χ^2 equals twice the area under the psd of the log amplitude variation [6].

S4 would be approximately twice the amplitude psd, this depending a little on the amplitude distribution.

Then we can see that the difference between these two scintillation indices (σ_ϕ and σ_χ) corresponds to the triangular area bounded by the psds and the lower cut-off frequency.

It is clear that this difference will be reduced as the cut-off frequency is increased to approach the Fresnel frequency or the Fresnel frequency is reduced approaching the lower cut-off frequency.



From this we would expect that S4 can never exceed twice σ_ϕ but can be much less than it for high Fresnel frequencies corresponding to fast irregularity velocities. Also it is the larger irregularities which do not effect S4 which can enable σ_ϕ to be the larger index.

Discussion

The Fresnel frequency is given by $\nu/(2\lambda z)$ where ν is the relative drift velocity and z is the distance from the equivalent diffraction screen to the receiver.

Thus we can see the conditions that S4 will be larger than σ_ϕ will be those when the Fresnel frequency is low which corresponds to the lower irregularity drift velocities seen at low latitudes.

It is also clear from the equation that the Fresnel frequency will be reduced by a larger value of z which corresponds to a higher altitude for the irregularities (i.e F region rather than E region irregularities).

It is thought that most of the scattering of L band signals at low latitudes occurs within a thin layer surrounding the peak of the F layer in the equatorial region [7].

Depending on the solar activity, daytime and season, the peak density height may range from 350 to 500 km at equatorial latitudes and from 250 to 350 km at mid-latitudes [8]. The height of irregularities at auroral latitudes may well be lower depending on the auroral phenomenon.

For example, in [9], scintillation is shown to be well correlated spatially with aurora seen at both 120 and 200 km altitude.

Thus we can see that both the lower height and the higher velocity of the irregularity producing scintillations are likely at high latitudes and that both will increase the Fresnel frequency and thus decrease the S4 index compared with low latitudes.

Factors influencing the ratio of S4 to σ_ϕ

Three factors have been found which will tend to increase the ratio of S4 to σ_ϕ; lower values of the irregularity drift velocity and higher values of the altitude of the irregularities which are predominantly producing the scintillation, which both increase the Fresnel frequency and also lower values of the outer scale of the turbulence, particularly less than 1 km.

Whereas the former serve to increase S4 at low latitudes the latter reduces σ_ϕ.

For this to serve as one possible explanation for lower σ_ϕ at low/equatorial latitudes it would necessarily need to be shown that the outer scale of the turbulence is typically much smaller in this region than at auroral or polar latitudes (because of the importance of the ratio of ν/Lo in defining the low limit of the unfiltered fading spectrum). ν/Lo will be smaller at low than high latitudes even for similar values of the outer scale because ν chiefly depends on the irregularity drift velocity which will generally be considerable smaller at low/equatorial than high latitudes.

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