On the Longitudinal Morphology of Zonal Irregularity Drift Measured using Networks of GPS Scintillation Monitors

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Abstract

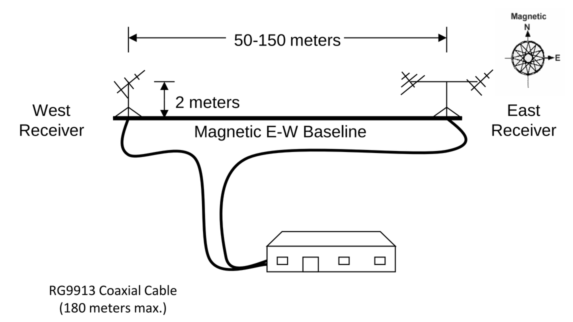
A complete characterization of field-aligned ionospheric irregularities responsible for the scintillation of satellite signals includes not only their spectral properties (power spectral strength, spectral index, anisotropy ratio, and outer-scale) but also their horizontal drift velocity. From a system impacts perspective, the horizontal drift velocity is important in that it dictates the rate of signal fading and also, to an extent, the level of phase fluctuations encountered by the receiver. From a physics perspective, studying the longitudinal morphology of zonal irregularity may lead to an improved understanding of the F region dynamo and regional electrodynamics at low latitudes. The irregularity drift at low latitudes is predominantly zonal and is most commonly measured by cross-correlating observations of satellite signals made by a pair of closely-spaced receivers. The AFRL-SCINDA network operates a small number of VHF spaced-receiver systems at low latitude stations for this purpose. A far greater number of GPS scintillation monitors are operated by AFRL-SCINDA (25-30) and the Low Latitude Ionospheric Sensor Network/LISN (35-50), but the receivers are situated too far apart to monitor the drift using cross-correlation techniques.

In this paper, we present an alternative approach that leverages the weak scatter scintillation theory [Rino, *Radio Sci.*, 1979] to infer the zonal irregularity drift from single-station GPS measurements of S_4, σ_φ, and the propagation geometry alone. Unlike the spaced-receiver technique, this technique requires assumptions for the height of the scattering layer (which introduces a bias in the drift estimates) and the spectral index of the irregularities (which affects the spread of the drift estimates about the mean). Nevertheless, theory and experiment show that the ratio of σ_φ to S_4 is less sensitive to these parameters than it is to the zonal drift, and hence the zonal drift can be estimated with reasonable accuracy. In this talk we validate the technique using spaced VHF antenna measurements of zonal irregularity drift from the AFRL-SCINDA network. Next, we discuss our future plans results to investigate the longitudinal morphology of zonal irregularity drift using the AFRL-SCINDA and LISN networks of GPS scintillation monitors.

Introduction

Most methods for estimating the zonal irregularity drift in the equatorial ionosphere are variations of the spaced-antenna technique [Vacchione et al., *Radio Sci.*, 1987; Spatz et al., *Radio Sci.*, 1988]. AFRL has installed several pairs of spaced-antennas that continuously monitor geostationary VHF beacons (the equipment setup is shown in the figure below).

When only a single receiver is available (or one located too distantly from other receivers in a network) the spaced-receiver technique cannot be applied. Nevertheless, previous attempts have been made to measure the irregularity drift using a stand-alone GNSS receiver by correlating observations of slant TEC between different satellites [Liang et al., 2009; Ji et al., 2011]. The difficultly with this approach is that the different scan directions of the GNSS satellites with respect to field-aligned irregularities generally results in a low correlation coefficient.



Here we describe an alternative approach that leverages the weak scatter scintillation theory [Rino, *Radio Sci.*, 1979] to infer the zonal irregularity drift from GNSS measurements of S_4, σ_φ, and the propagation geometry alone. We have applied the technique to a month of data (November, 2013) from three SCINDA stations where both GPS and VHF spaced-receiver data are available.

Geographic coordinates and magnetic dip angles for the three stations considered:

Station	Lat.	Lon.	Dip Angle
Bangkok (BKK)	14.1°N	100.6°E	14.0°N
Cape Verde (CVD)	16.73°N	22.9°W	18.5°N
Kwajalein (KWA)	9.4°N	167.5°E	8.5°N

Basic Concept

According to the weak scatter theory, both S_4 and σ_φ depend on the irregularity strength and propagation geometry, but only σ_φ depends on the irregularity drift through the effective scan velocity (a geometrical factor which maps irregularity spatial scales to the temporal frequencies at which they contribute in a spectrum of the measured time series). Our technique leverages this idea to infer the effective scan velocity from measurements of the ratio σ_φ / S_4. Once the effective scan velocity is known, the zonal irregularity drift can be calculated.

Amplitude scintillation: $S_4^2 = C_p \rho_F^{p-1} F_S(p) \wp(p)$

Phase scintillation: $\sigma_\varphi^2 = C_p F_\sigma(p) G \left[V_{eff} \tau_c \right]^{p-1}$

Table of Symbols

- C_p – phase spectral strength due to irregularities
- ρ_F – Fresnel scale = $[z \sec\theta / k]^{1/2}$
- p – phase spectral index
- k – signal wavenumber
- θ – propagation (nadir) angle
- z – vertical propagation distance
- $\wp(p)$ – combined geometry and propagation factor
- G – phase geometry enhancement factor
- $F_s(p)$ – a function only of p that appears in eqn. for S_4
- $F_\sigma(p)$ – a function only of p that appears in eqn. for σ_ϕ
- V_{eff} – effective scan velocity
- τ_c – time constant of the phase detrend filter

Theory – Measuring the Zonal Irregularity Drift

Divide σ_φ by S_4 so that irregularity strength (C_p) cancels. Rearrange to solve for V_{eff}:

$$V_{eff} = \frac{\rho_F}{\tau_c} \left[\frac{F_S(p)}{F_\sigma(p)} \frac{\wp(p)}{G} \frac{\sigma_\varphi^2}{S_4^2} \right]^{1/(p-1)}$$

From Rino's weak scatter theory:

Effective scan velocity

$$V_{eff}^2 = \frac{C V_{sx}^2 - B V_{sx} V_{sy} + A V_{sy}^2}{AC - B^2/4}$$

Scan velocity (assuming drift is purely zonal)

$$V_{sx} = -[V_{px} - \tan(\theta)\cos(\varphi) V_{pz}]$$
$$V_{sy} = V_D - [V_{py} - \tan(\theta)\sin(\varphi) V_{pz}]$$

Table of Symbols

- ψ – magnetic inclination angle
- φ – magnetic azimuth angle of propagation
- θ – propagation (nadir) angle
- V_{px} – magnetic north component of IPP velocity
- V_{py} – magnetic east component of IPP velocity
- V_{pz} – magnetic down component of IPP velocity
- A,B,C – coefficients of the transformation from propagation direction into principal axes
- V_D – zonal (magnetic eastward) irregularity drift

Combining the above and solving for the zonal irregularity drift gives

$$V_D = (V_{py} - \tan(\theta)\sin(\varphi)V_{pz}) - \frac{B}{2A}(V_{px} - \tan(\theta)\cos(\varphi)V_{pz}) \pm \frac{1}{A}\sqrt{[AC - B^2/4][A V_{eff}^2 - (V_{px} - \tan(\theta)\cos(\varphi)V_{pz})^2]}$$

Infinite axial ratio model: Taking the formal limit as the axial ratio becomes infinitely large gives $V_{eff} = \frac{\rho_F}{\tau_c} Q_\sigma(p) \left[\frac{\sigma_\varphi}{S_4} \right]^{2/(p-1)}$

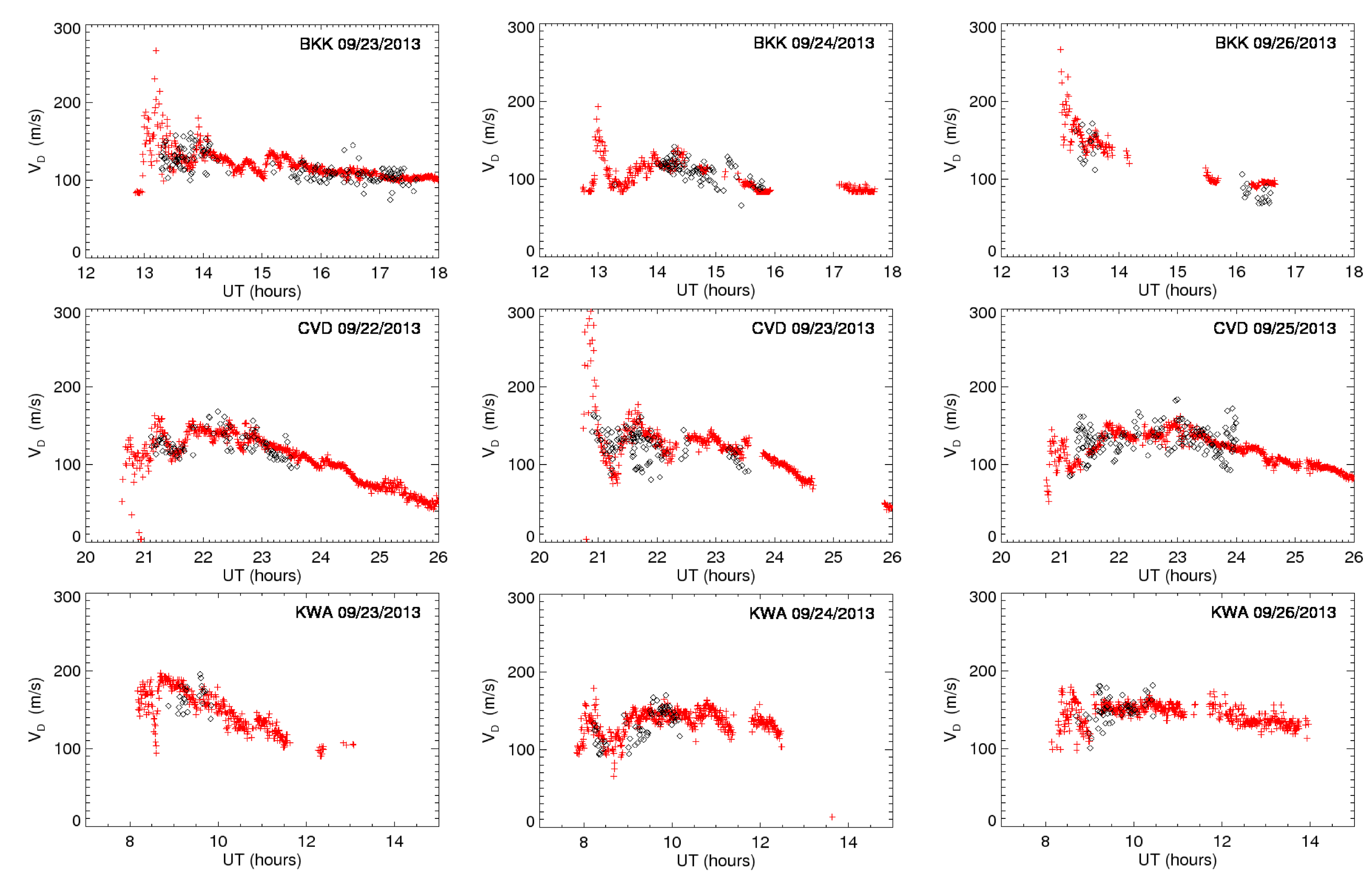
and the zonal irregularity drift becomes:

$$V_D \approx V_{py} + \frac{(V_{px}\sin\psi - V_{pz}\cos\psi)\sin\varphi\tan\theta}{\cos\psi - \cos\varphi\sin\psi\tan\theta} \pm \sqrt{1 + \frac{\sin^2\varphi\tan^2\theta}{(\cos\psi - \cos\varphi\sin\psi\tan\theta)^2}}\, V_{eff}, \qquad Q_\sigma(p) = \left[\frac{2^{(p+1)/2}\pi^{p-1/2}\Gamma[(5-p)/4]}{\Gamma[(1+p)/4]} \right]^{1/(p-1)}$$

This simpler model gives zonal drift estimates within ~ 5 m/s of the finite axial ratio model with a:b = 50:1 (used by WBMOD)

Example Results

The plots below compare estimates of zonal irregularity drift for three evenings at Bangkok (top), Cape Verde (middle), and Kwajalein (bottom) measured with a stand-alone GSV4004B GPS scintillation monitor (black diamonds) and VHF spaced-receivers (red crosses).

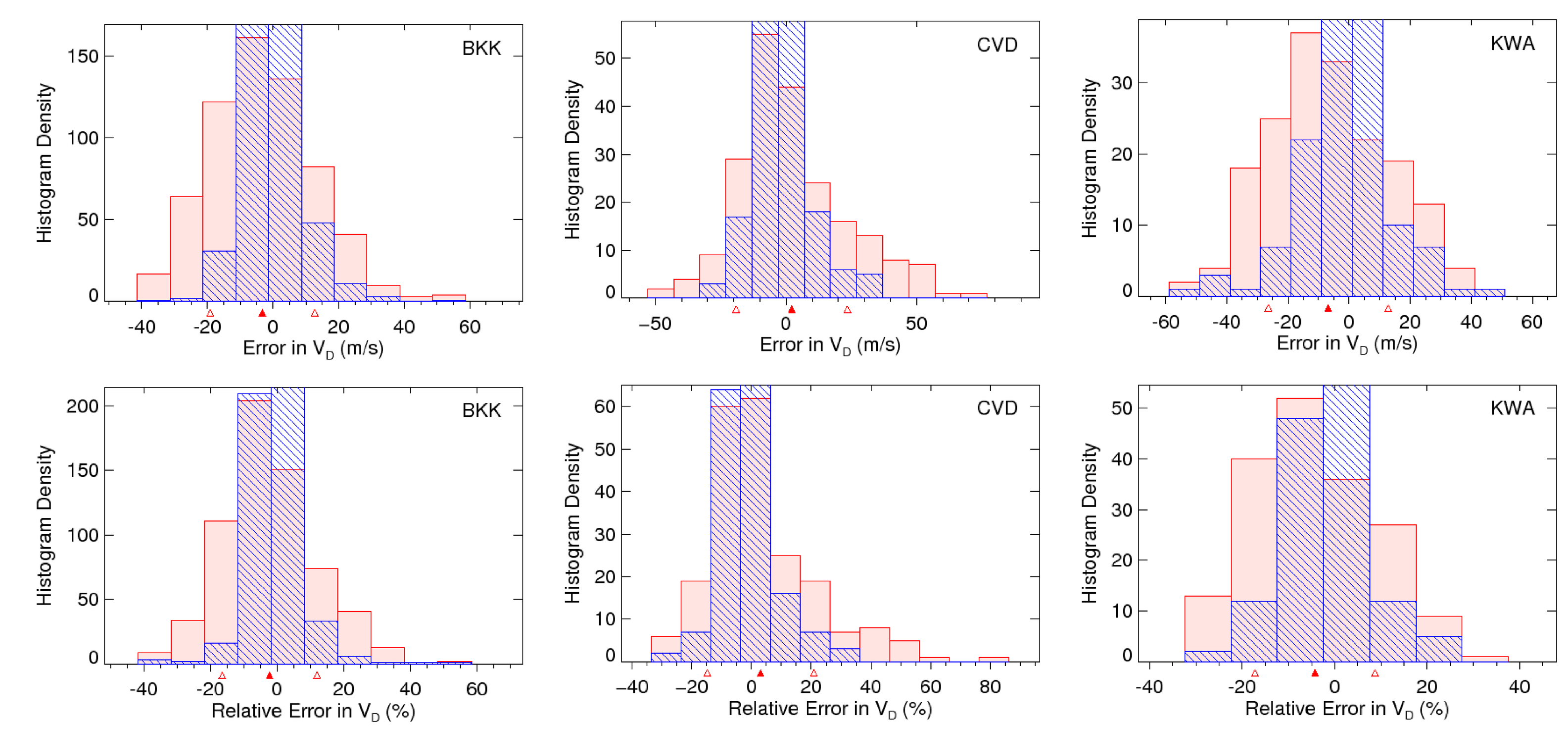


The VHF system can measure the drift longer into the evening because lower frequency systems are inherently more sensitive to scintillation. Nevertheless, when the GPS scintillation monitor can provide the zonal drift it agrees reasonably well with the VHF spaced-receiver drift.

For more information on this work, contact charles.carrano@bc.edu

Statistical Validation

We compared stand-alone GPS and VHF spaced-receiver estimates of the zonal drift at the three stations for all days with scintillation in November 2013. The histograms below show the difference (in m/s) between each sample and the median drift calculated from the VHF data using 5 minute bins. The filled and unfilled triangles near the abscissa scale shows the mean and +/- 1 standard deviation of the GPS drift estimates, respectively.



Red = GPS drift; Blue = VHF spaced-receiver drift

Interpretation

To assist with interpretation we introduce additional constraints which are *not* required to estimate the drift.

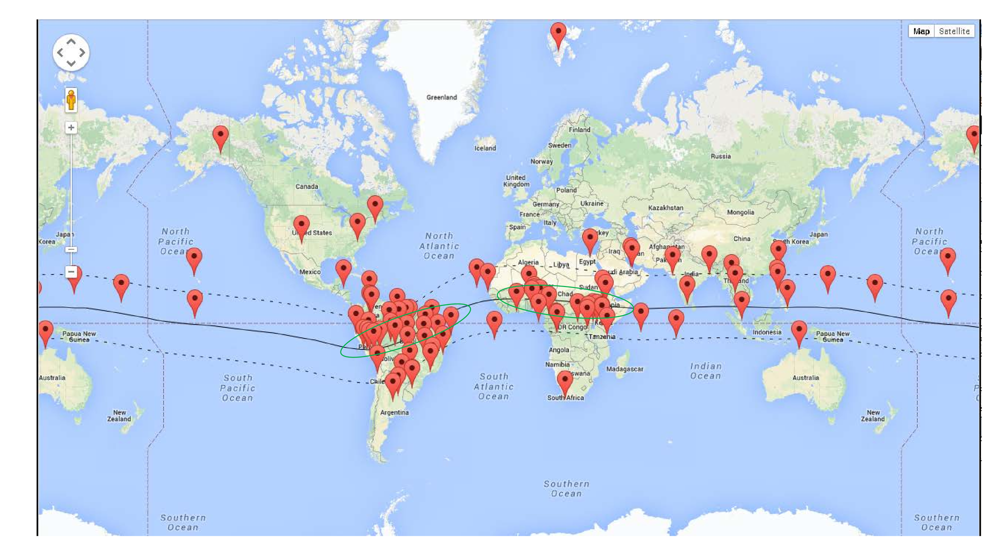
In the case of vertical propagation the infinite axial ratio model implies $V_D \approx V_{py} \pm \frac{\rho_F}{\tau_c} Q_\sigma(p) \left[\frac{\sigma_\varphi}{S_4} \right]^{2/(p-1)}$

If we also assume p=3 (typical) and τ_c = 10 sec (default for most scintillation monitors) then $\frac{\sigma_\varphi}{S_4} \approx \frac{V_D - V_{py}}{1.11\rho_F}$

- S_4 depends on the distance to the irregularities through the Fresnel parameter.
- σ_φ is proportional to the difference between the zonal irregularity drift and magnetic eastward IPP motion.
- The ionospheric perturbation strength affects both S_4 and σ_φ but not their ratio. If this ratio is measured and the distance to irregularities is known, we can infer the zonal drift.

Future Directions

The SCINDA and LISN networks include a large number of GNSS scintillation monitors suitable for estimating the zonal drift (figure at right). We hope to use continent-scale zonally distributed chains of receivers to unravel the complex longitudinal morphology of the zonal irregularity drift. Two such receiver chains in South America and Africa appear circled in green.



Summary

- By judicious selection of the scattering layer height and spectral index, we are able to obtain GPS estimates of the zonal irregularity drift that are unbiased and with a spread about the mean of 15-20 m/s (10-15%), which is about 35% higher than observed with the VHF spaced-receiver measurements.
- A simple error analysis of the technique suggests that errors in the assumed scattering layer height result in an overall drift bias, whereas the spread of the drift estimates is likely due to the natural variability of the phase spectral index at low latitudes.
- The simplified version of the model, which assumes infinitely elongated rod-like irregularities, provides drift measurements within 4 m/s (8 m/s) for satellites above 45° (30°) elevation compared with the more complex finite axial ratio model.
- While not intended to supplant direct measurements of the zonal irregularity drift made by spaced-receivers, the current technique should prove useful for the *vast majority* of GNSS scintillation monitors which are situated too distant from other neighboring scintillation monitors to apply the spaced-receiver technique.

Acknowledgements

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