Eye on the Ionosphere: Measuring Ionospheric Scintillation Effects from GPS Signals

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From time to time, this column will include short contributions from invited guest contributors on specialized subjects pertaining to ionospheric effects on GPS signals. In this issue, Dr. A. J. Van Dierendonck discusses the required specifications of a civilian GPS receiver specially designed to make quantitative measurements of both ionospheric amplitude and carrier phase scintillation effects from GPS signals. © 1999 John Wiley & Sons, Inc.

GPS signals provide an excellent means for measuring ionospheric scintillation effects on a global basis. The signals are continuously available and can be measured through many points of the ionosphere simultaneously. GPS signals are themselves affected, but tracking through disturbances with a GPS receiver is usually possible with reasonably wide bandwidth tracking loops.

In the past, specially designed satellites have been launched for the purpose of monitoring ionospheric scintillation using satellite-radiated signals. In more recent years, the signals radiated from the GPS satellites have been used with success but, again, mostly experimental, and they have been done on a limited scale. This is because off-the-shelf GPS receivers do not provide the phase and amplitude information required for scintillation parameter extraction. Specially modified receivers have to be used to obtain accurate values of the scintillation parameters. In these past experiments, dual-frequency P-code receivers were used, measuring the difference between L1/L2 phase measurements. These differences cancel all systematic effects such as satellite motion, clocks, selective availability (SA), and the troposphere. Unfortunately, the cost of these receivers and the Anti-Spoof (A-S) cover on the P code has prevented this exploitation on an operational basis. Codeless cross-correlation receivers that will operate with A-S on are available, but their measurements are either far too noisy or are too bandwidth limited to be of use for ionospheric scintillation monitoring. We show here that the solution can be based on the latest commercial GPS receiver technology without relying on military receivers with their special P-code demodulation requirements. In the following, we present the requirements for an Ionospheric Scintillation Monitor based on that technology.

MEASURING PHASE SCINTILLATION

Phase scintillation monitoring can be accomplished by monitoring the standard deviation, $\sigma_{\Delta\phi}$, and the power spectral density of detrended carrier phase from signals received from the GPS satellites. The $\sigma_{\Delta\phi}$'s are computed during 1, 3, 10, 30, and 60-s intervals every 60 s. These five values, averaged for a minute and displayed or stored along with the Ionospheric Penetration Point at a mean ionospheric height where the irregularities that produce the scintillation effects are maximum, provide a map of a "poor man's" phase spectral density. For the power spectral density, Fast-Fourier-Transform (FFT) spectral lines, computed using detrended phase measurements, can define spectral parameters, strength ($T_{\phi1}$) and slope (p_ϕ), such that the phase spectral density is approximated as

$$\Phi_\phi(\nu) = T_{\phi1}\nu^{-p_\phi} \qquad (1)$$

in rad^2/Hz. As an option, one should be able to record raw detrended phase data for off-line analysis. The raw phase data should have a noise bandwidth of at least 15 Hz, which means that the carrier phase should be tracked with a 15-Hz bandwidth phase-lock-loop. A 50-Hz sample rate of the phase data is appropriate.

The key to using a single frequency GPS receiver with sufficient carrier phase bandwidth is the ability to remove the low-frequency systematic effects—SA, the troposphere, and satellite and receiver oscillator effects. In most off-the-shelf commercial receivers, the re-

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ceiver oscillator's phase noise by far dominates what would be expected of phase scintillation variations. This is because those receivers normally use a low-cost, temperature-compensated crystal-oscillator (TCXO) as a reference oscillator. All other systematic effects are easily removed. Fortunately, by replacing the TCXO with the output of a high-quality oven-controlled SC-cut crystal oscillator (OCXO), this dominant effect can be reduced to desired levels.

The method best used for detrending passes the phase measurements through a high-pass filter, which removes all low-frequency effects below its frequency cutoff (on the order of 0.1 Hz). This means that the oscillator effects should also be filtered out, except for high-frequency phase noise. The quality of the oscillator must be such that this unfiltered phase noise is low relative to the desired scintillation-monitoring performance.

Figure 1 shows the phase sigmas and the phase spectral density for a typical satellite pass when there is no scintillation, thus representing the phase noise of the oscillator and background thermal noise of the receiver. Note that the phase sigmas are at a level of 0.1 radians or less, while the spectral density at a 1-Hz offset is at a level of about −53 dB/Hz. This is measured at L1. When translated to the frequency of the oscillator, it agrees very well with the specified phase noise of the oscillator at a level of about −95 dB/Hz. At the beginning and at the end of the satellite pass, the thermal noise background (plotted base on C/N_0 measurements) dominates.

MEASURING AMPLITUDE SCINTILLATION

Amplitude scintillation monitoring is traditionally performed by computing the index *S4*. The *S4* index is derived from detrended signal intensity of signals received from satellites. Signal intensity is actually *received* signal power, which is measured in such a way that its value does not fluctuate with noise power. Because the *S4* index is normalized, the receiver's absolute gain is not important, as long as it is relatively constant during the detrending period. It is also important that the intensity measurement be linear with respect to the signal power over its entire range, including deep scintillation fades.

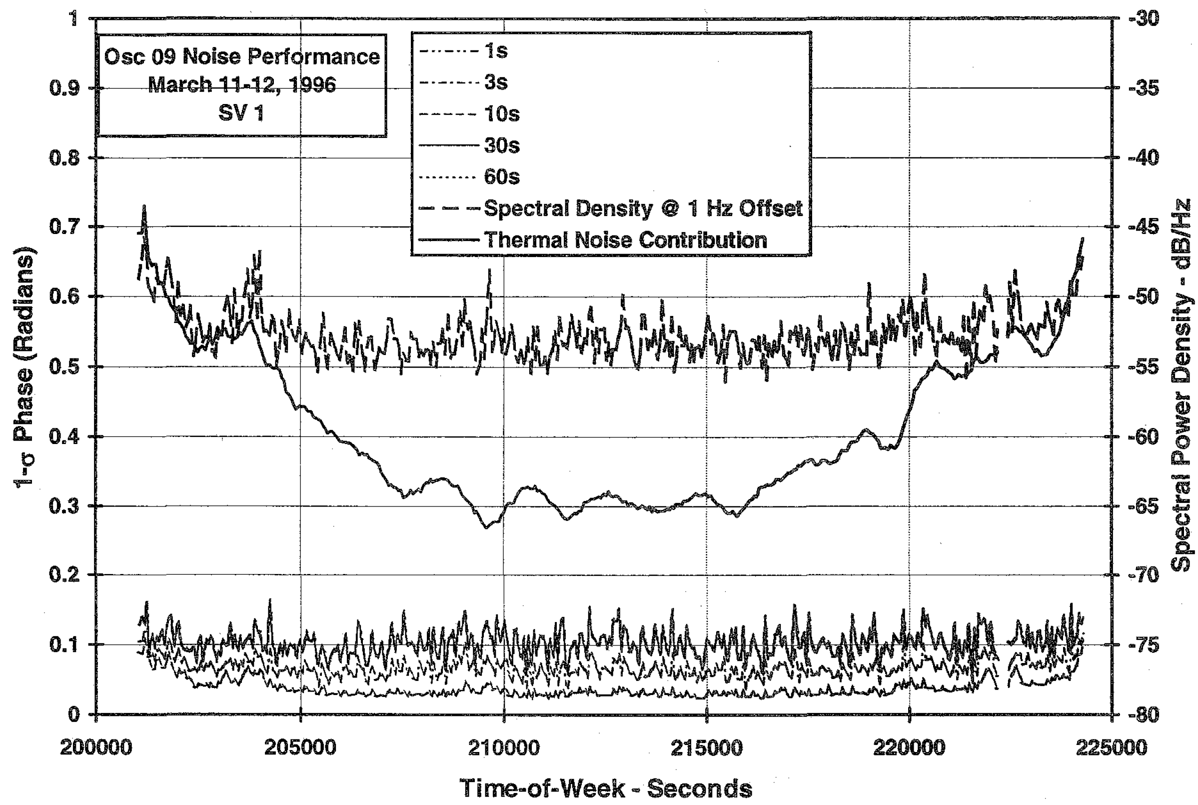

FIGURE 1. Phase scintillation parameters with no scintillation.

The total $S4$, including the effects of ambient noise, is defined as follows:

$$S4_T = \sqrt{\frac{\langle SI^2\rangle - \langle SI\rangle^2}{\langle SI\rangle^2}} \qquad (2)$$

where $\langle\bullet\rangle$ represents the expected (or average) value during the interval of interest (60 s) and where SI is signal intensity that is proportional to *received* signal power. SI is detrended by normalizing it to a low-passed version of SI, which removes the low-frequency variations below about 0.1 Hz.

$S4$ measured at L-band should have the effects caused by ambient noise removed. It is desired that the resulting $S4$ value be less than 0.05 for all received signal levels above −139 dBm.

The $S4$ values are normally computed during 60-s intervals. Raw detrended intensity data with a single-sided noise bandwidth of 25 Hz should also be collected for off-line analysis. The raw intensity data has a single-sided noise bandwidth of 25 Hz at a 50-Hz sampling rate.

For the power spectral density, FFT spectral lines, computed using detrended intensity measurements, can define spectral parameters, strength (T_{I1}), evaluated at a frequency ν of 1 Hz, ν_c, the scintillation rate parameter, and slope (p_I). The spectral density is defined such that it is approximated as

$$S_1(\nu) = 10\log_{10}[\Phi_I(\nu)] = S_{I0} + p_1(\log_{10}\nu) + p_2(\log_{10}\nu)^2 + p_3(\log_{10}\nu)^3 \qquad (3)$$

in dBc/Hz, as a cubic fit to the computed frequency line spectrum. The scintillation rate parameter is that frequency that maximizes Eq. (3). The slope parameter is the average derivative of Eq. (3) above a ν of 1 Hz ($-p_I$ is the slope parameter at 1 Hz). This fit should be done over the frequency range 0.2–5 Hz, where most of the scintillation power normally exists.

SCINTILLATION MONITORING RESULTS

The following figures show scintillation at Fairbanks, AK, on August 6, 1998. Figure 2 shows phase scintillation sigmas and phase spectral density. Figure 3 shows $S4$ and intensity spectral density. The higher endpoints of the passes are caused by lower C/N_0 and multipath, not necessarily scintillation. Note that there are two passes per day. During the second pass, the observation is over the pole, and that is when most of the scintillation occurs. During the first pass, the observation is more to the south, where there is minimal scintillation because of the lower geomagnetic

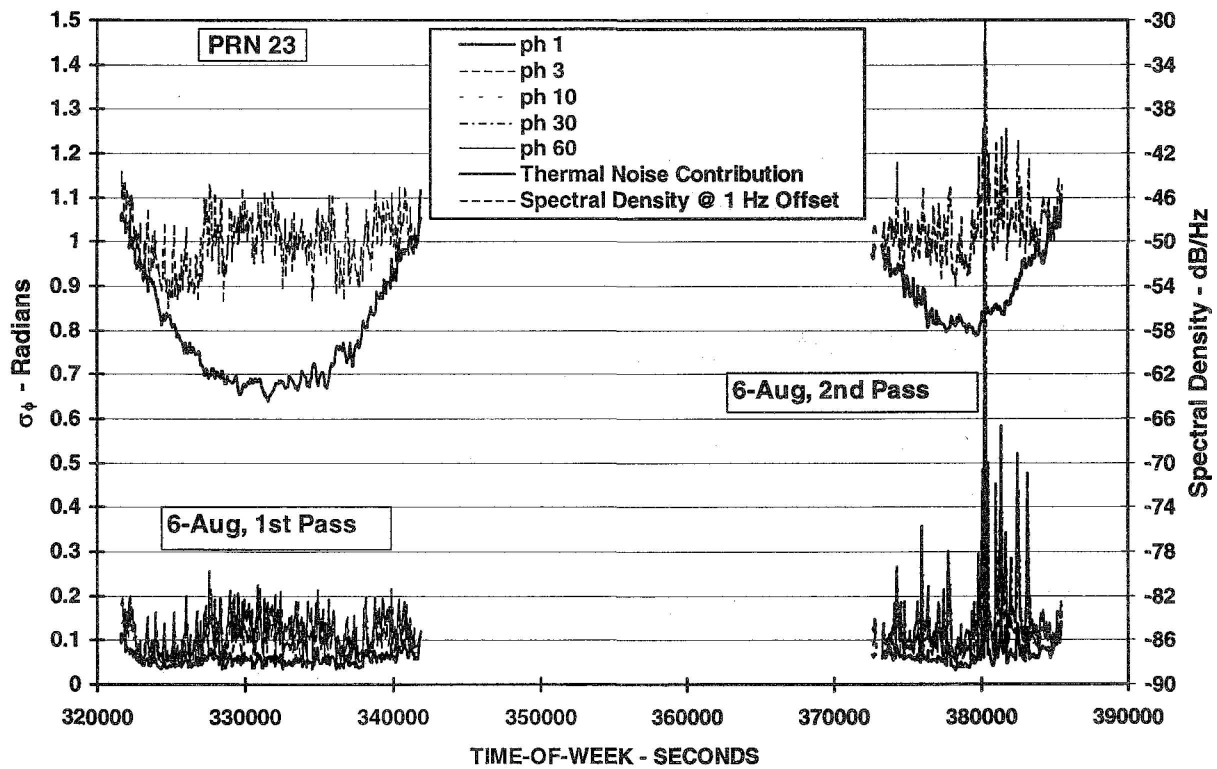

FIGURE 2. Phase scintillation at Fairbanks, AK on August 6, 1998.

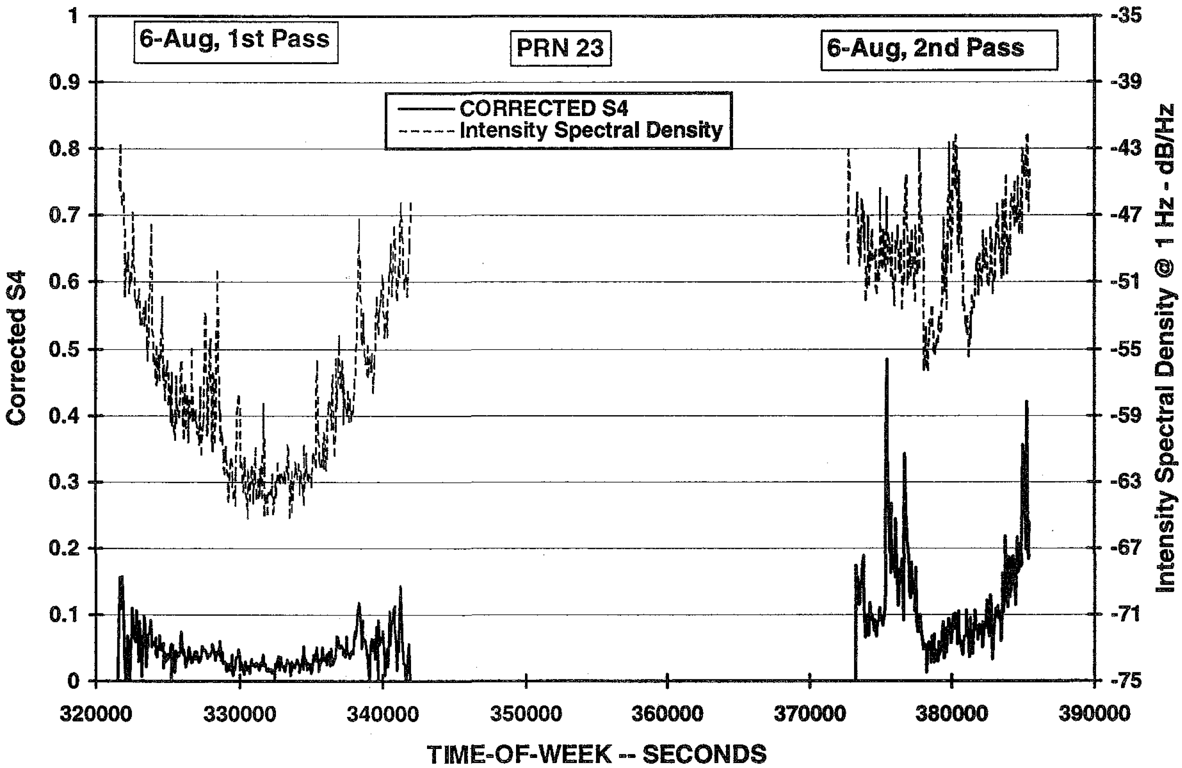

FIGURE 3. Amplitude scintillation at Fairbanks, AK on August 6, 1998.

latitudes of the ionospheric penetration point locations.

SUMMARY

Amplitude and phase scintillations can be measured by a properly designed civilian GPS receiver that operates using only the L1 frequency. The key to successful *single-frequency* phase scintillation measurements is having a suitable, phase stable, ovenized crystal oscillator against which the satellite carrier phase measurements are made. The phase scintillation bandwidth should be at least 15 Hz and have a 50-Hz sampling rate. Amplitude scintillation measurements require a well-calibrated, linear power response of the receiver with a single-sided noise bandwidth of approximately 25 Hz and a 50-Hz sampling rate. With such a receiver, the necessary scintillation parameters can be computed for all satellites in view. This is a powerful tool for real-time observations of ionospheric irregularities that can produce significant scintillation effects on GPS signals or on any satellite signals operating at frequencies from UHF to X-band, by suitable scaling to the frequency desired. ■

BIOGRAPHY

A.J. Van Dierendonck received a BSEE from South Dakota State University and MSEE and Ph.D. from Iowa State University. He has 25 years of GPS experience. Currently, he is self-employed under the name of AJ Systems and is a general partner of GPS Silicon Valley. In 1993, Dr. Van Dierendonck was awarded the Johannes Kepler Award by the Institute of Navigation Satellite Navigation Division for outstanding contributions to satellite navigation. For 1997, he was awarded the Institute of Navigation (ION) Thurlow award for outstanding contributions to the science of navigation. He is a Fellow of the Institute of Electrical and Electronic Engineers (IEEE).