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GNSS TEC and Scintillation Receivers and Receiver Demonstration.

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GNSS TEC and Scintillation Receivers and Receiver Demonstration

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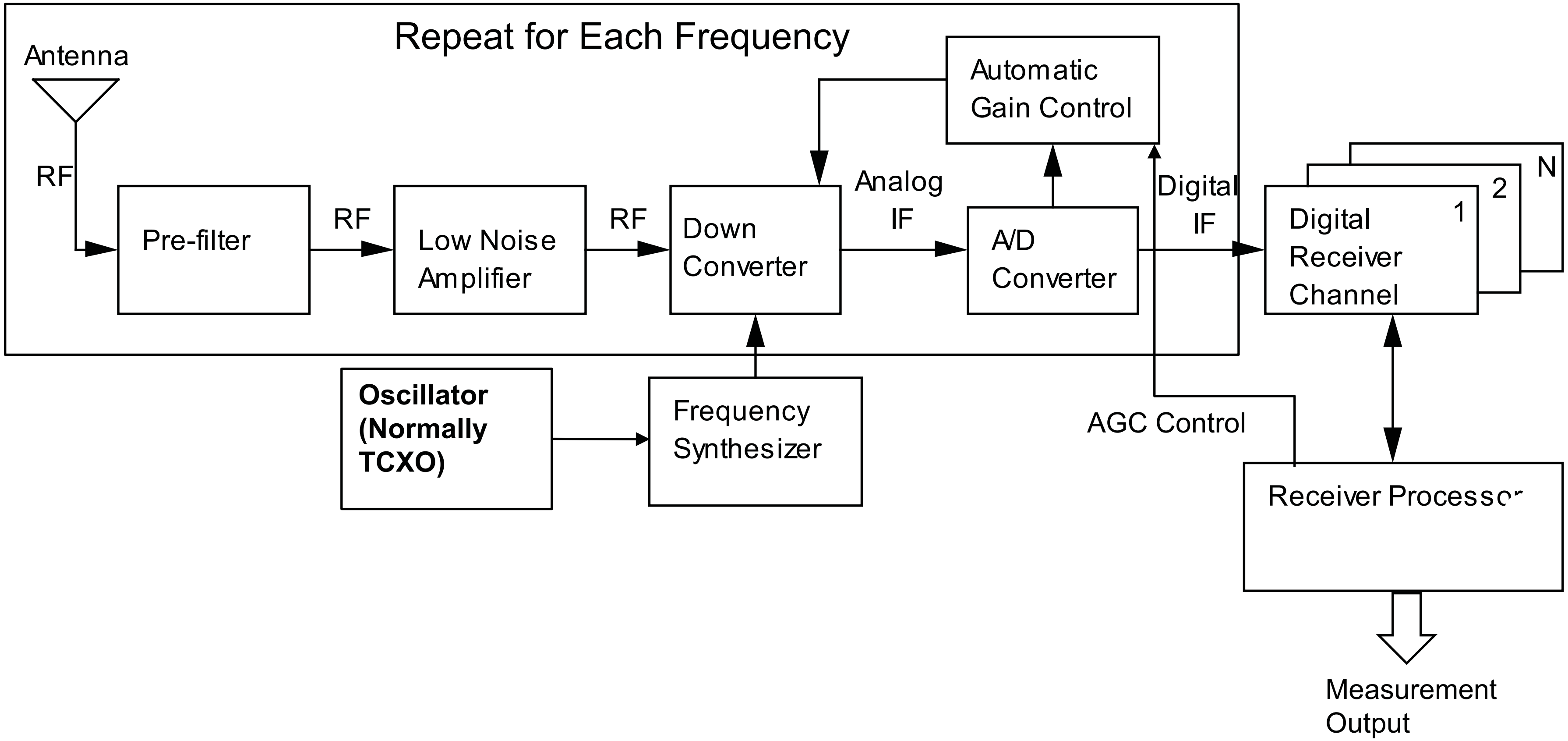
Tutorial Outline

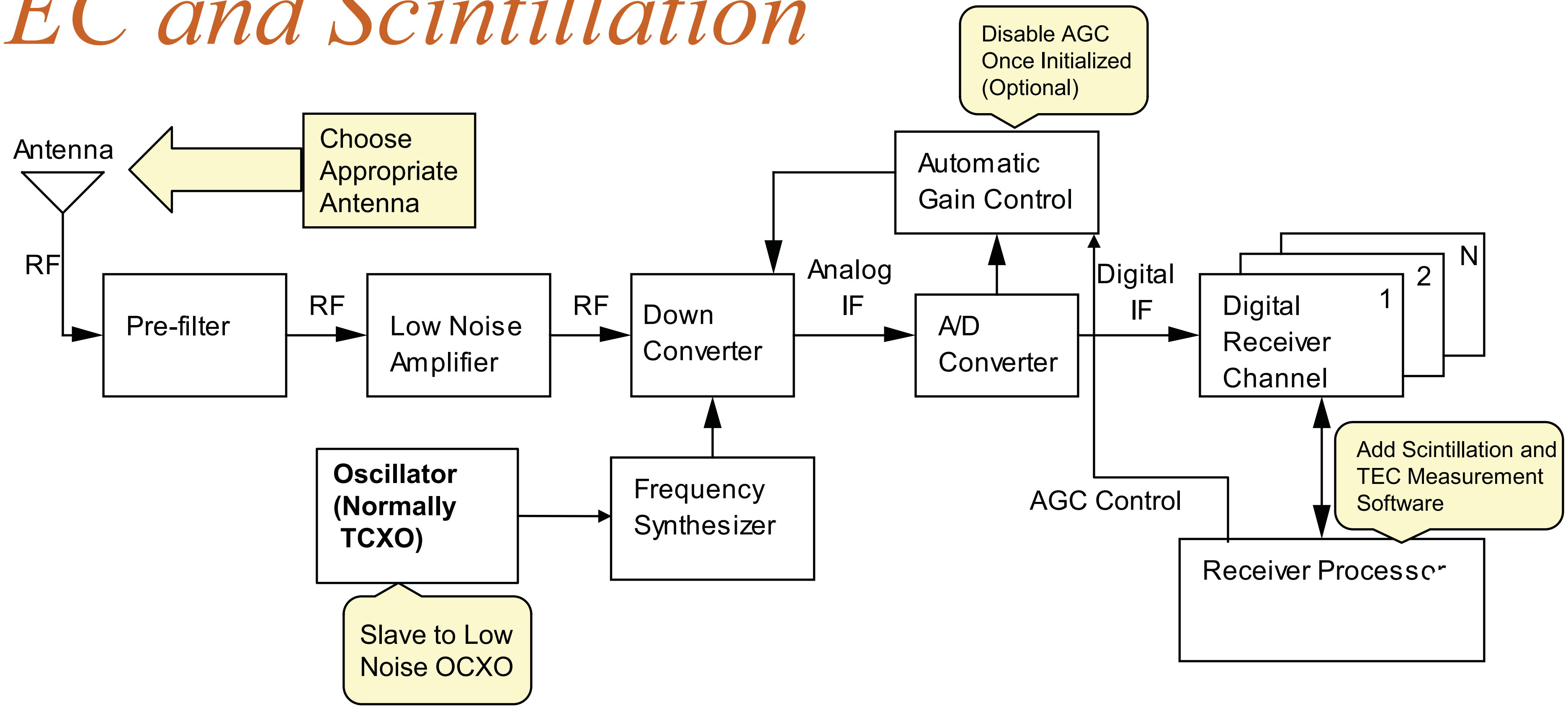
- Short Review of GPS Receivers
  - Emphasizing what functions are affected by scintillation
  - Emphasizing modifications implemented for measuring scintillation effects
- Amplitude and Phase Scintillation Measurements
- Measurement Limitations
  - How well does the receiver perform in a scintillation environment?
  - How can a GNSS receiver be designed to better operate in a scintillation environment?
- TEC Measurements
  - Measuring TEC or satellite and/or receiver inter-frequency biases?
- Example Measurements
  - GPS Satellites
  - SBAS Geostationary Satellites

Standard Multiple Frequency GPS Receiver Functional Block Diagram



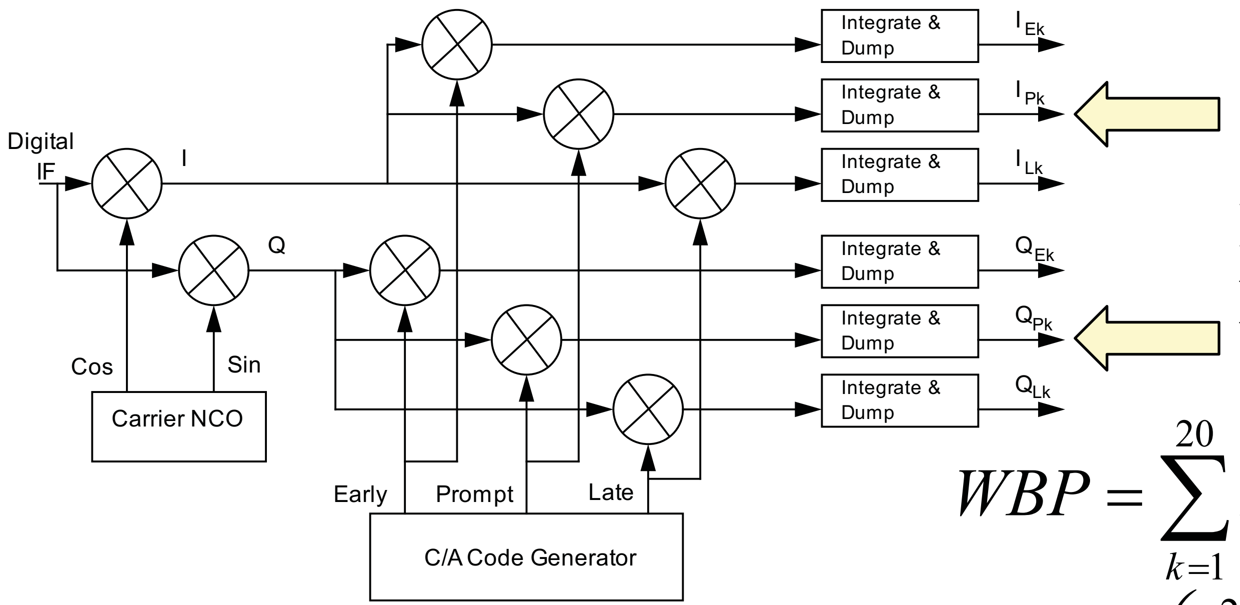
GPS Receiver Modifications for Scintillation Monitoring

Receiver Modifications to Measure TEC and Scintillation



Measuring Amplitude Scintillation

Typical Receiver Channel for Amplitude (Power) Measurements



Only use Prompt I and Q Samples for Power Measurements

$$WBP = \sum_{k=1}^{20} I_{Pk}^2 + Q_{Pk}^2$$

$$NBP = \left(\sum_{k=1}^{20} I_{Pk} \right)^2 + \left(\sum_{k=1}^{20} Q_{Pk} \right)^2$$

Signal Intensity Samples

- Signal Intensity samples are based upon Narrowband (NBP) and Wideband (WBP) Power Measurements (50 samples/second)
  - $SI_k = NBP_k - WBP_k$
  - Difference is proportional to signal power
    - Theoretically cancels noise power in the mean
      - Practically, it doesn't completely – correction made later
- Samples collected and stored over 60 seconds
  - Thus, 3000 samples every minute
  - These 50 sps samples are available as an output

Computing S4 (1)

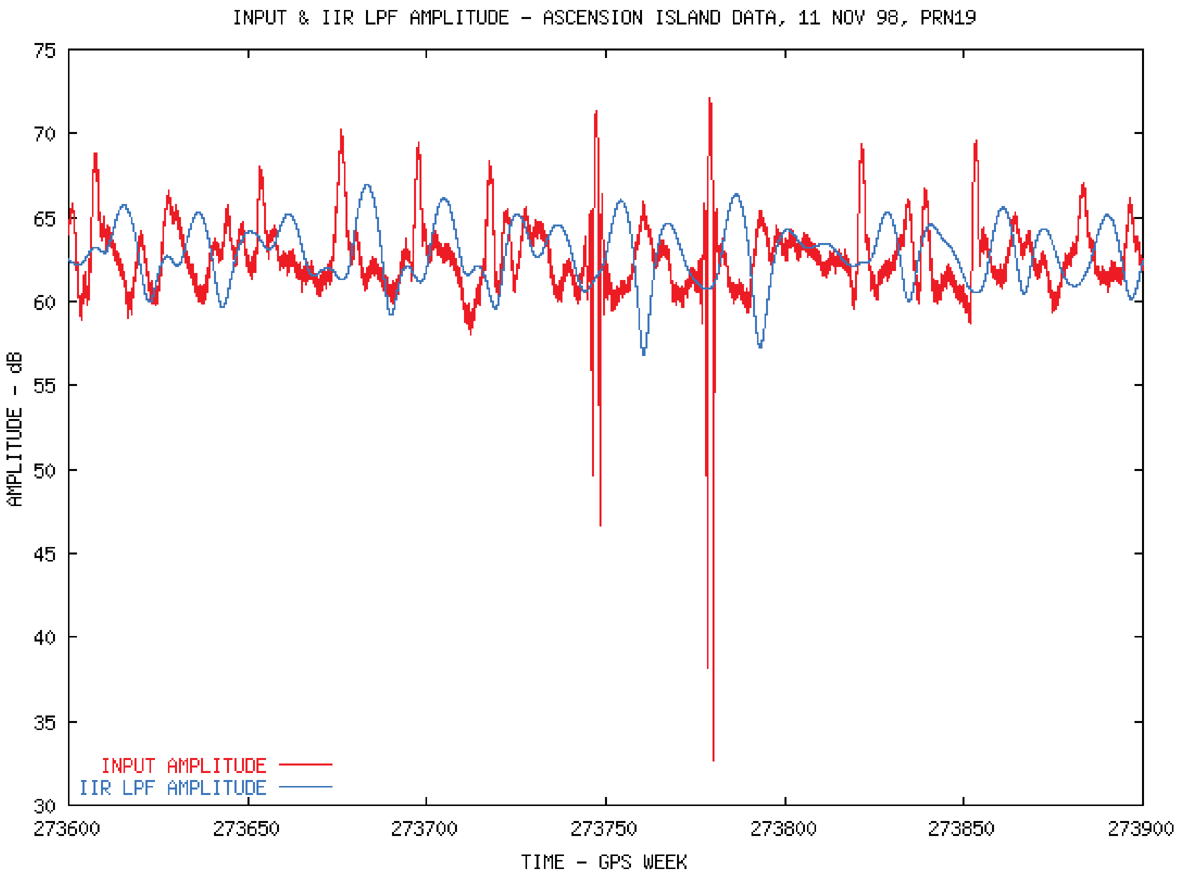
- Total S4 is standard deviation of normalized Signal Intensity
  - $$S4_{Total} = \sqrt{\frac{\langle SI_k^2 \rangle - \langle SI_k \rangle^2}{\langle SI_k \rangle^2}}$$
  - Scale factor of Signal Intensity is ambiguous, but this normalization with average value over 60 seconds takes care of that
- Desirable to remove the effects of receiver noise, theoretically computed as
  - $$S4_{N_0} = \sqrt{\frac{100}{\hat{S}/N_0}\left[1 + \frac{500}{19\,\hat{S}/N_0}\right]}$$
  - This is square root of expected value of $S4^2$, given noise only
- $\hat{S}/N_0$ is average measured signal-to-noise density over 60 second period – also an output, as well as the above noise contribution

Computing S4 (2)

- Noise contribution is removed as follows:
  - $$S4_{Corrected} = \sqrt{\frac{\langle SI_k^2 \rangle - \langle SI_k \rangle^2}{\langle SI_k \rangle^2} - \frac{100}{\hat{S}/N_0}\left[1 + \frac{500}{19\,\hat{S}/N_0}\right]}$$
  - If square-root argument is negative, set to 0 (means noise dominates amplitude scintillation)
  - This corrected value is computed off-line
- Option also exists to compute average value of SI_k as low-pass filtered value
  - This presents potentially unstable normalization because of filter delay – results in inflated $S4$ values

Low-Pass Filtering Introduces Delay in Normalization

- Low-passed version (denominator) does not line up with raw version



Measuring Amplitude Scintillation Summary

- Amplitude Scintillation
  - Measure GPS signal-plus-noise power
  - Remove, as well as one can, noise power
  - Relatively straight-forward
    - Some “detrending” issues separating scintillation fades from multipath fading – a detrending bandwidth issue
    - Averaging proves to be more stable than filtering, but results in higher S4 due to multipath fading

Measuring Phase Scintillation

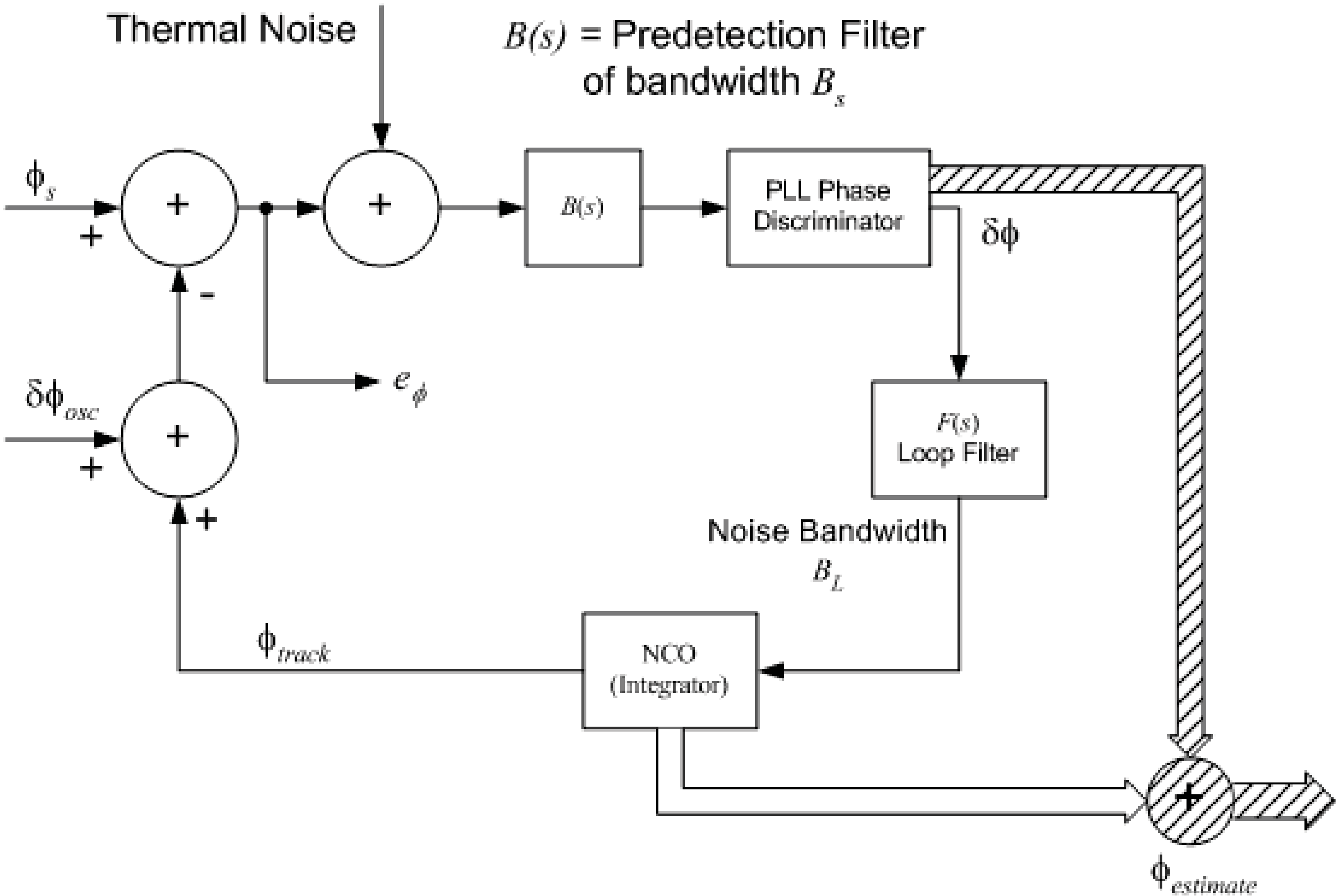
Some History Relative to Measuring Phase Scintillation Effects

- GPS Silicon Valley inherited commercialized scintillation monitoring technology from an Air Force Small Business Innovation Research (SBIR) program
  - Toughest challenge on that program was measuring phase scintillation with standard GPS receivers using Temperature Compensated Crystal Oscillators (TCXOs)
    - TCXO phase noise masked phase scintillation effects
    - Problem solved using good Oven Controlled oscillators (OCXOs)
- These upgraded receivers are relatively expensive
  - But, provide good scintillation measurements
  - Even then, there are limitations to operation in a scintillation environment

Measuring Phase Scintillation Effects

- To measure phase scintillation, GPS receiver must track signal phase using a phase lock loop (PLL)
  - Weakest link in a GPS receiver
  - Measurements include perturbations of receiver and satellite oscillators
    - Mostly, these perturbations cannot be removed with "detrending"
  - Phase includes signal Doppler, multipath and ionosphere TEC (and oscillator frequency offset), mostly removed with "detrending"
- Typically, measurement bandwidth is the PLL loop bandwidth
  - Wide bandwidth makes loop more sensitive to amplitude fading, and thus, loss of lock
  - Narrow bandwidth makes loop more robust, but filters out phase scintillation effects
- Loop can be configured to have narrow loop bandwidth for robustness, but still provide wide bandwidth phase data

PLL Model with Wideband Phase Estimator



Measuring TEC

- Measure difference of PN code phase on L1 and L2, smoothed against negative difference in carrier phase
  - Use "semi-codeless" technique to measure on L2
  - Does not enhance ability to measure scintillation
  - 15 to 35 dB less signal power recovery than L1
  - However, can use very low bandwidth PLL, aided with L1 Doppler phase, regaining 14 to 17 dB, depending upon C/N_0
- Limitations
  - Typically not available if L1 C/N_0 drops below 38 dB-Hz
  - Must contend with L1/L2 biases
    - Satellite biases (Tau_GD and C/A-to-P)
    - Receiver and antenna biases
- Real-time accuracies on the order of 1 – 3 TECU, after calibration
  - Also, very much affected by multipath

GPS Receiver in a Scintillation Environment

General GPS Receiver Limitations in Scintillation Environment

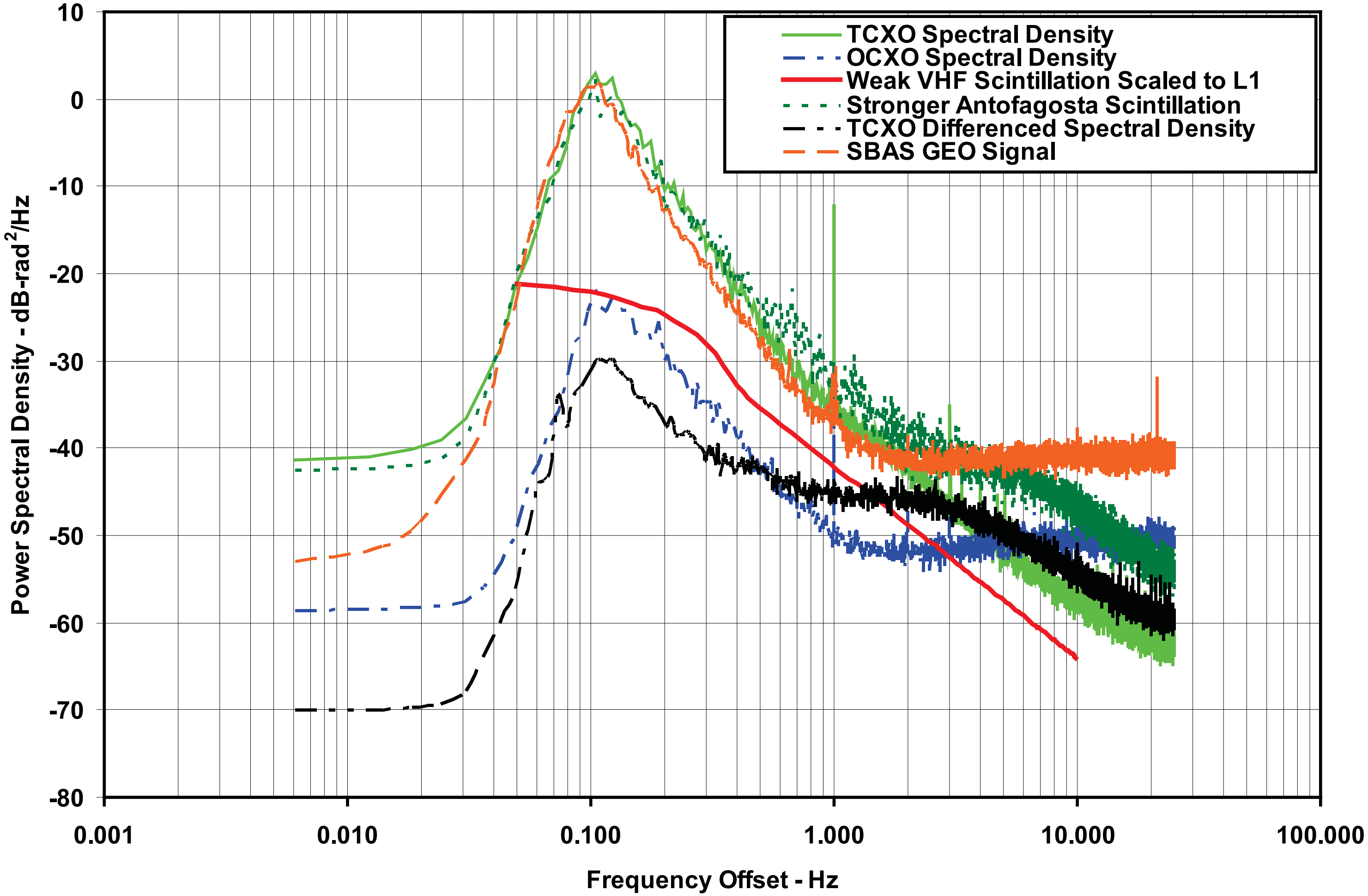
- Phase Scintillation
  - Generally, not a problem at L1
    - Unless a very narrow tracking bandwidth is used
    - No worse than low-grade TCXO typically found in GPS Receivers
  - Severe problem for "semi-codeless" L2
    - Very narrow bandwidth PLL coupled with erroneous aiding with L1 phase (doesn't agree with Doppler aiding)
- Amplitude Scintillation
  - Primary culprit for loss of phase lock at L1
    - Deep and long fades steal signal from PLL
    - Narrower bandwidth is better, but could require a better oscillator, and may lose lock due to strong phase scintillation
    - False alarms from lock detectors during fades (apparent loss of lock)
  - Loss of data (symbols) from SBAS signals

Phase Scintillation

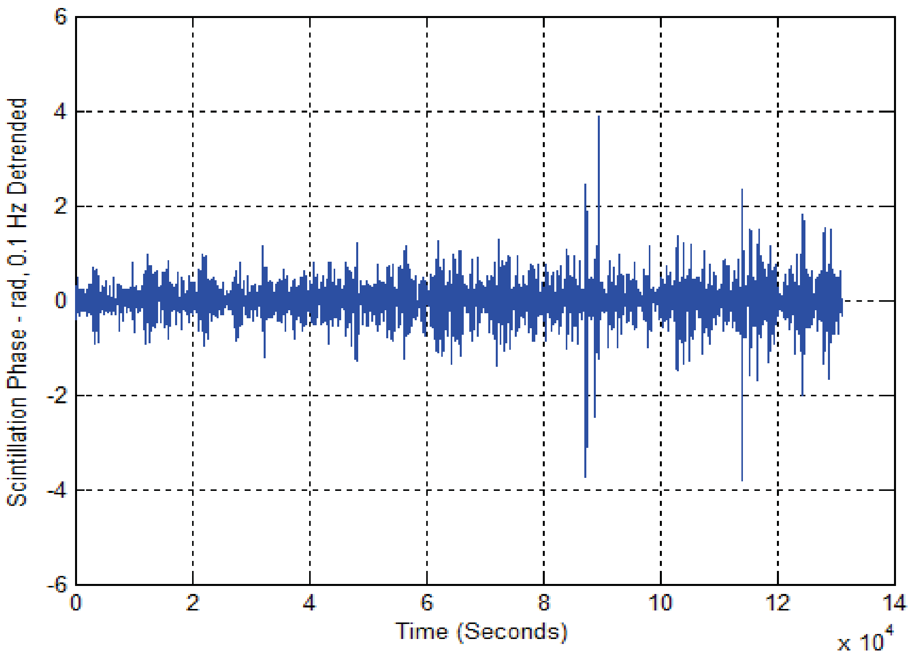
GPS Scintillation Monitor Limitations in Phase Scintillation Environment

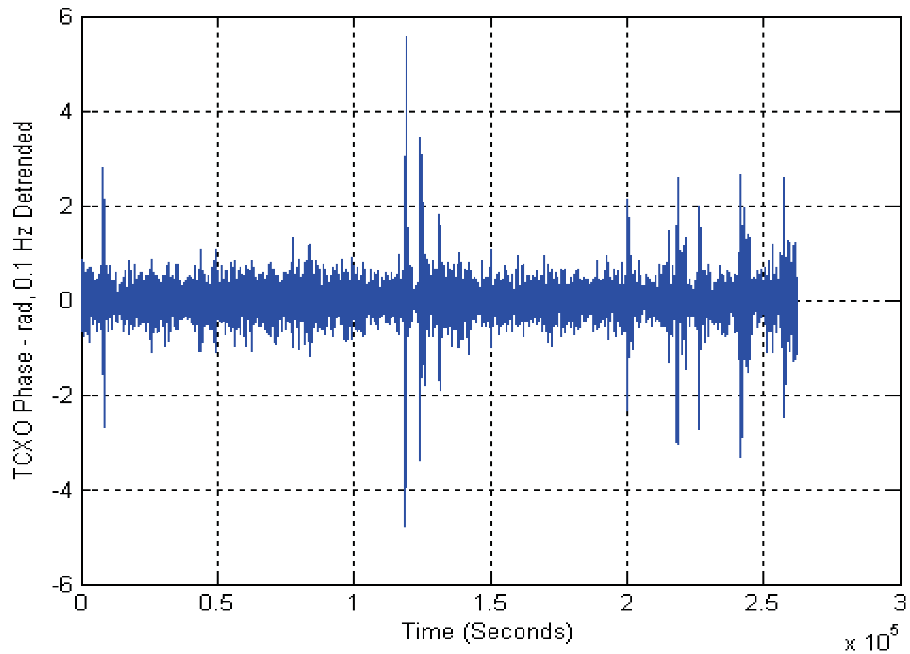
- Phase Scintillation
  - Can't measure scintillation at L2
  - Measurement limitations at L1 dominated by receiver oscillator
    - Typical receiver oscillator phase noise masks phase scintillation (See PSDs and plots in next charts)
    - Thermal Noise limitation is about 0.1 radian @ 30 dB-Hz
    - OCXO phase noise typically better than 0.05 radians
  - Limitation can be overcome by differencing phase between satellites
    - Creates a requirement for high-rate data collection and substantial post processing

Phase Noise PSD Comparisons



Antofagosto Phase Scintillation vs. TCXO Phase Noise





$\sigma_\phi = 0.396$ radians

$\sigma_\phi = 0.46$ radians

Tradeoffs Regarding Using Low-Noise Oscillators (OCXOs)

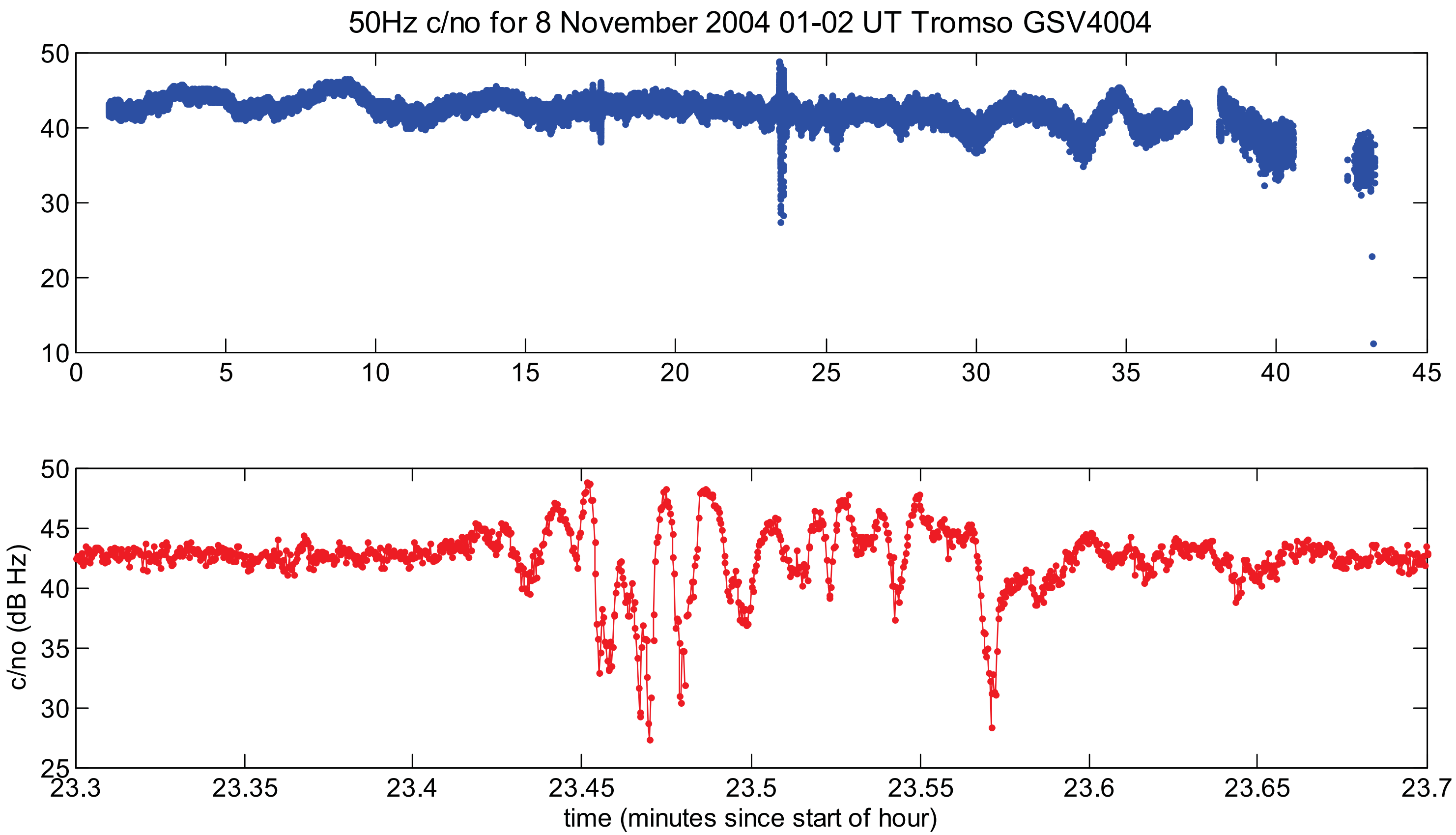
- Cost of low-noise OCXOs has diminished somewhat
  - The cost driver is their packaging with the receiver (low-volume quantities)
    - This packaging must also meeting international radiation and conductive emission (CE) requirements
- As stated, TCXO noise can be eliminated by differencing phase across satellites
  - Creates a data storage and post-processing burden
  - Receiver tracking bandwidth must be kept high, preventing tracking in noisy conditions

Amplitude Scintillation

GPS Scintillation Monitor Limitations in Amplitude Scintillation Environment

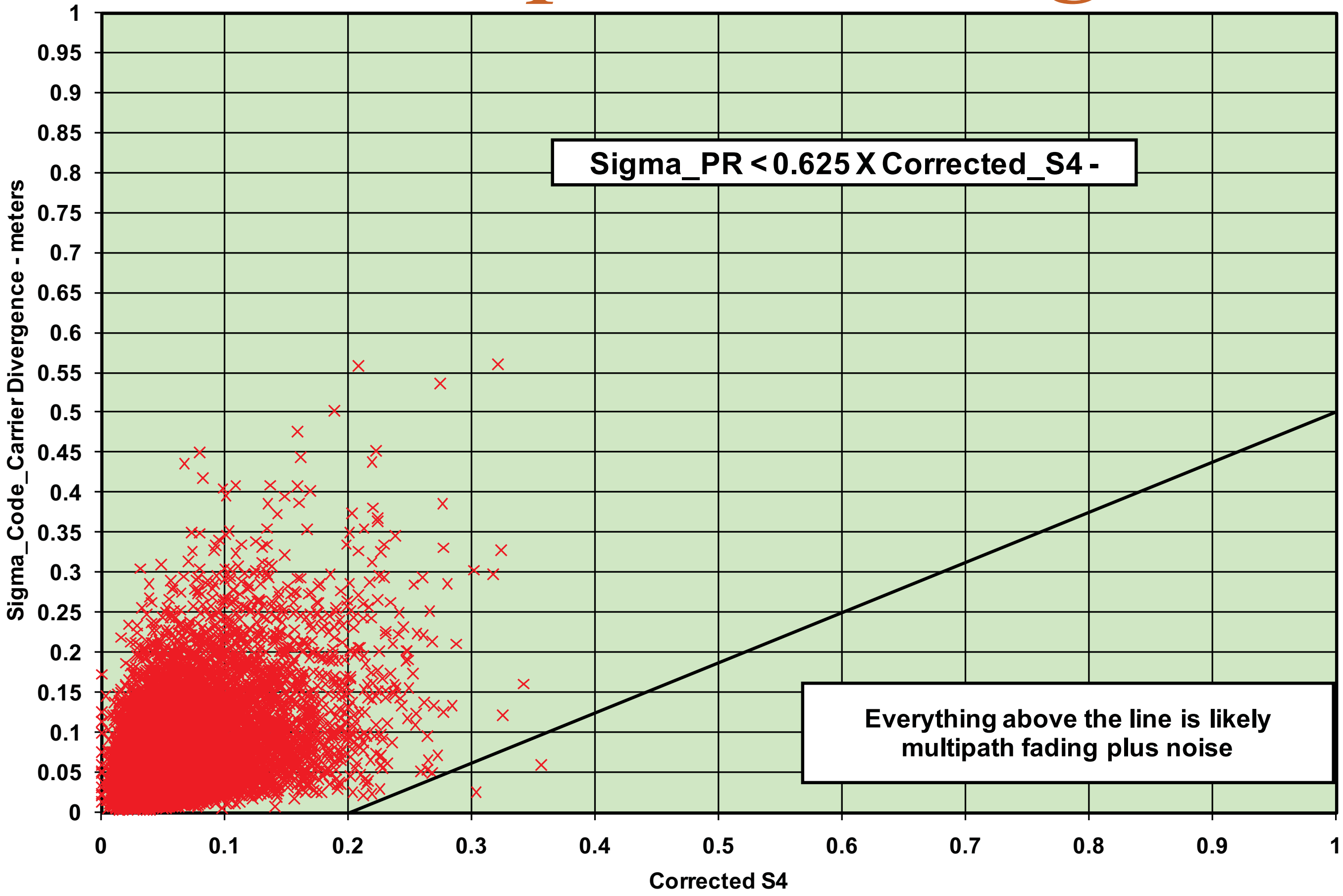
- Amplitude Scintillation
  - High S4 can cause loss of phase lock
    - Of course, that is still information
    - S4 is still usually valid – it is based upon non-coherent power measurements, at least for short to medium length fades
    - See state diagram
  - Multipath fading limits minimum S4 capability
    - Longer duration, but shallow fades
    - Can be detected and eliminated because multipath also causes code/carrier phase divergence – scintillation does not

Fade Depths and Widths Using 50 Hz Amplitude Samples



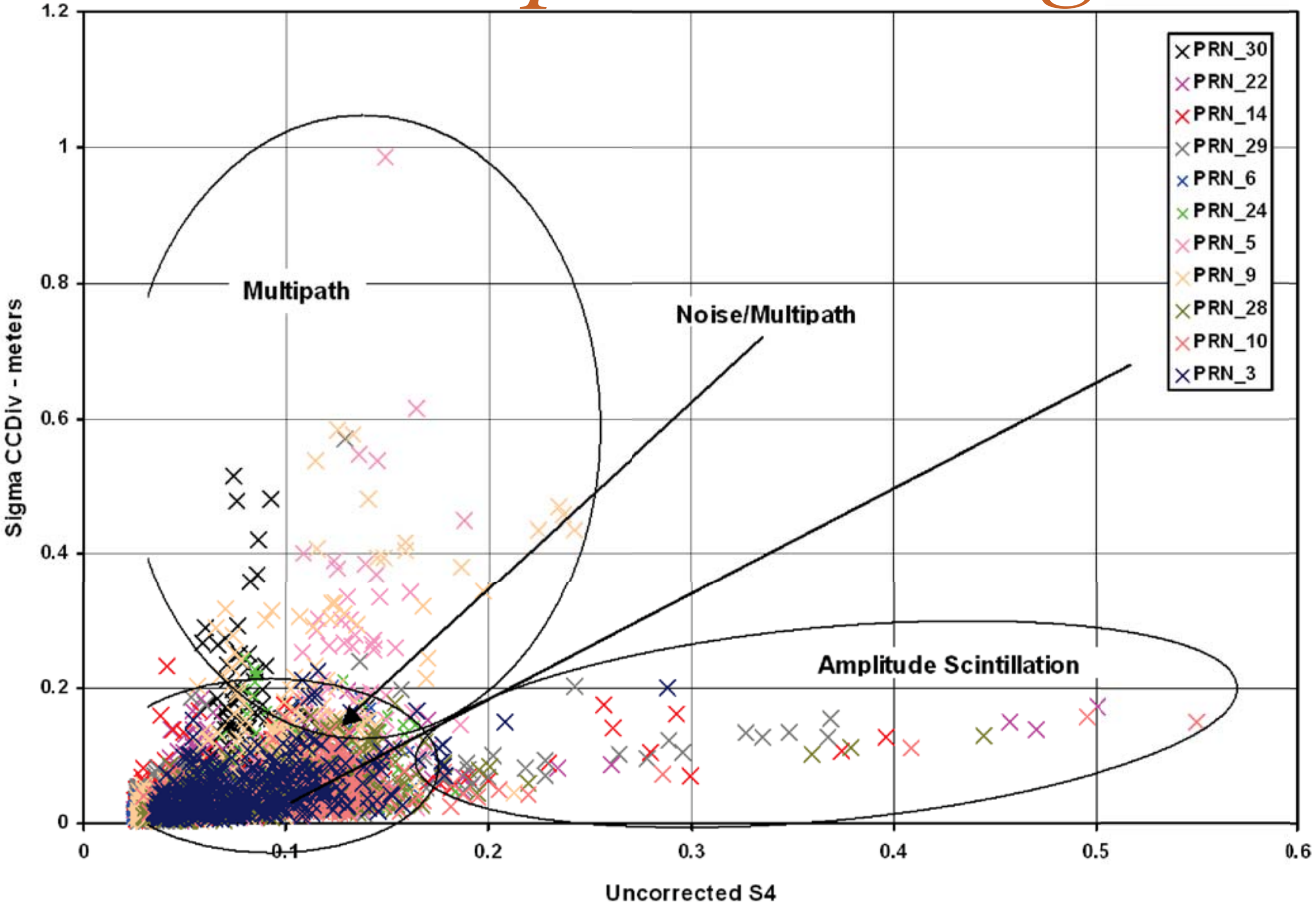
Distinguishing Between Amplitude Scintillation and Multipath Fading

- No Scintillation
- Varying Multipath
- All GPS Satellites



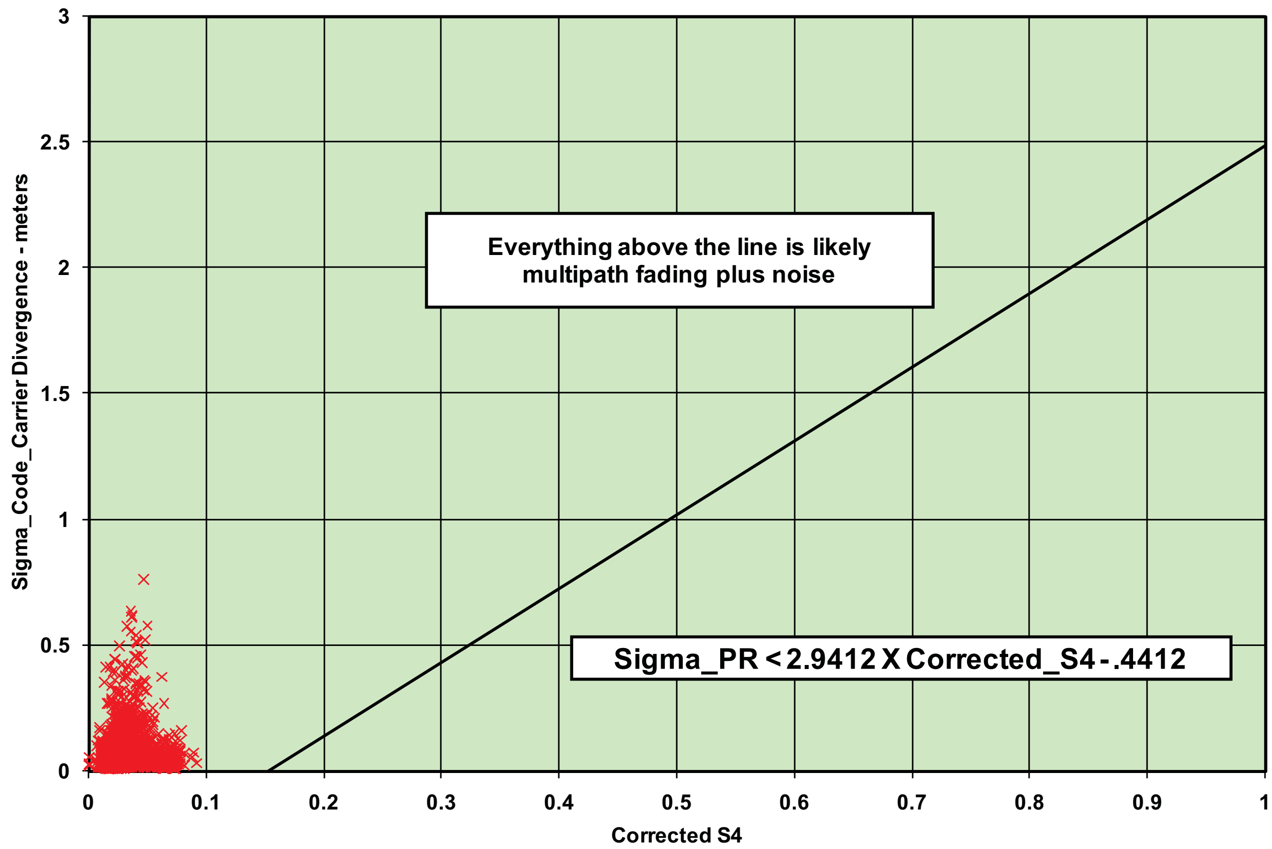
Distinguishing Between Amplitude Scintillation and Multipath Fading

- Moderate Scintillation
- Varying Multipath
- All GPS Satellites

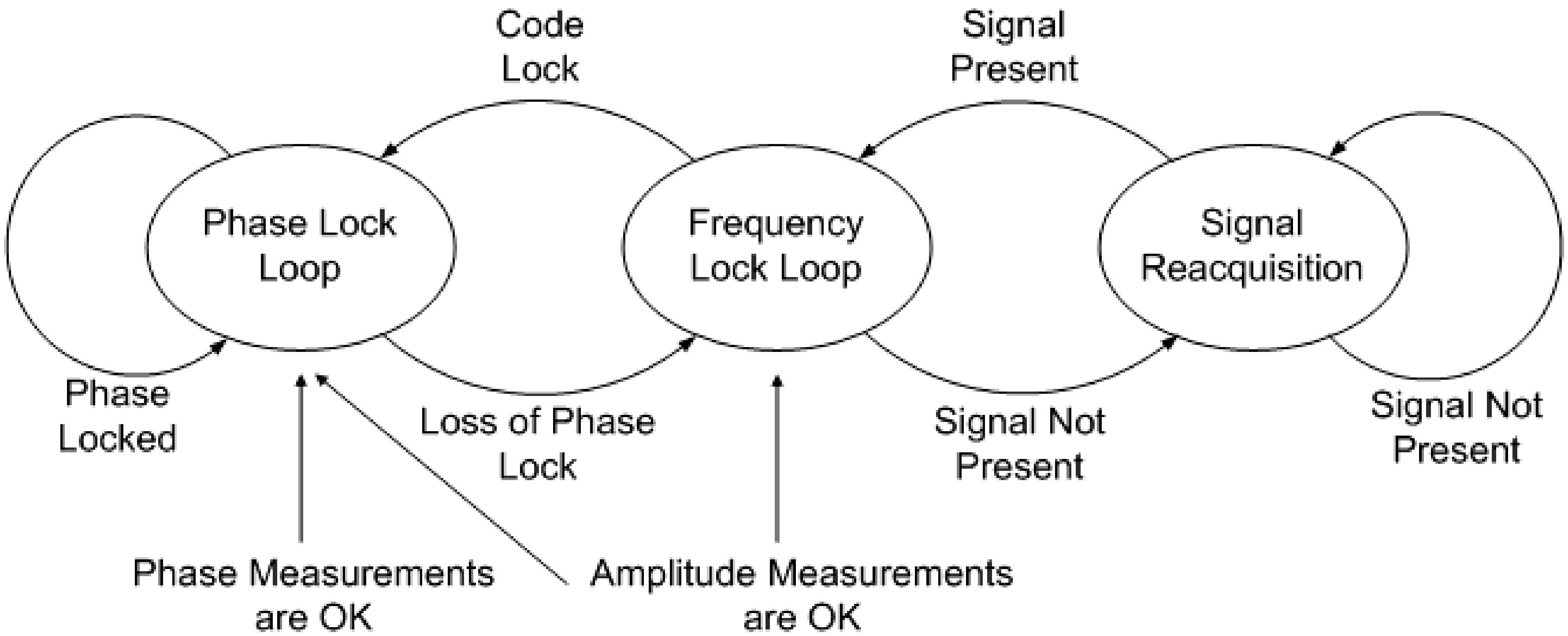


Distinguishing Between Amplitude Scintillation and Multipath Fading

No Scintillation
Slow Varying Multipath
2 SBAS Geostationary
Satellites



Signal Tracking State Diagram

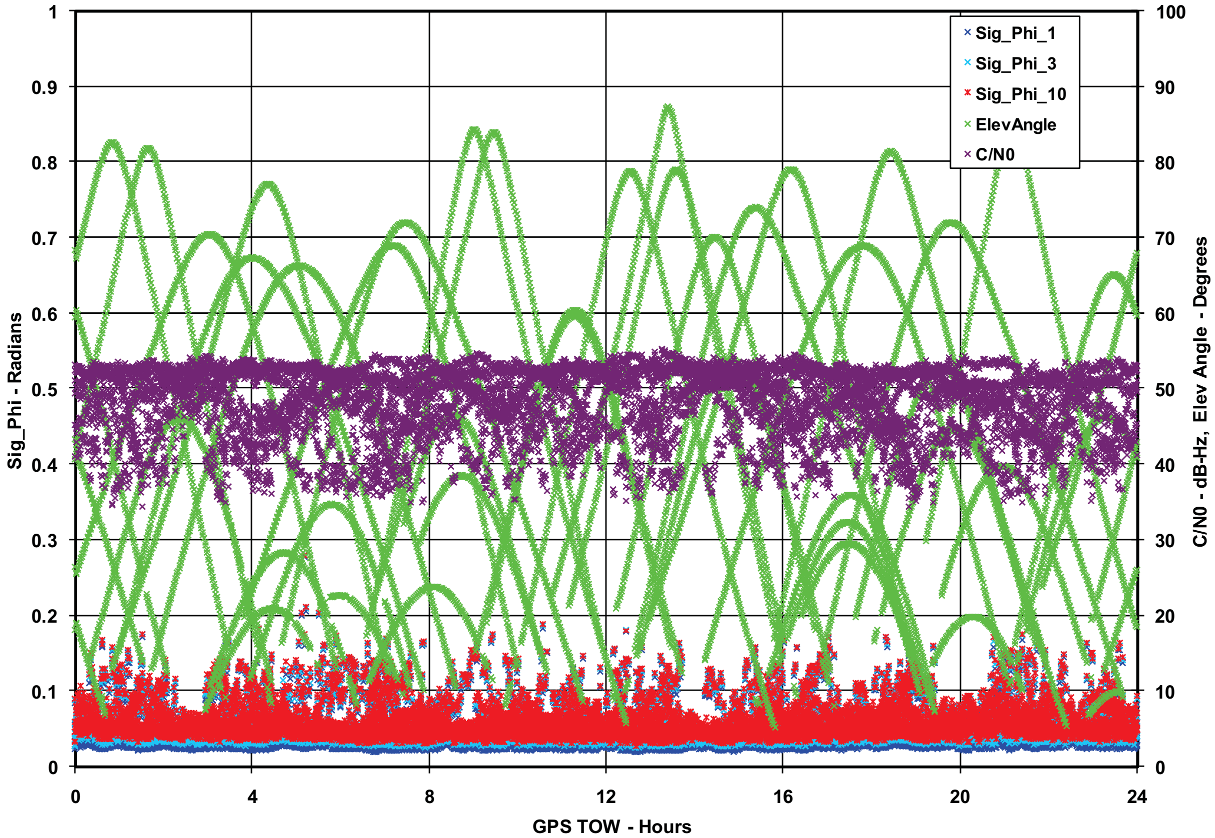


- Not necessarily implemented in all receivers, but is in Scintillation Monitors described here

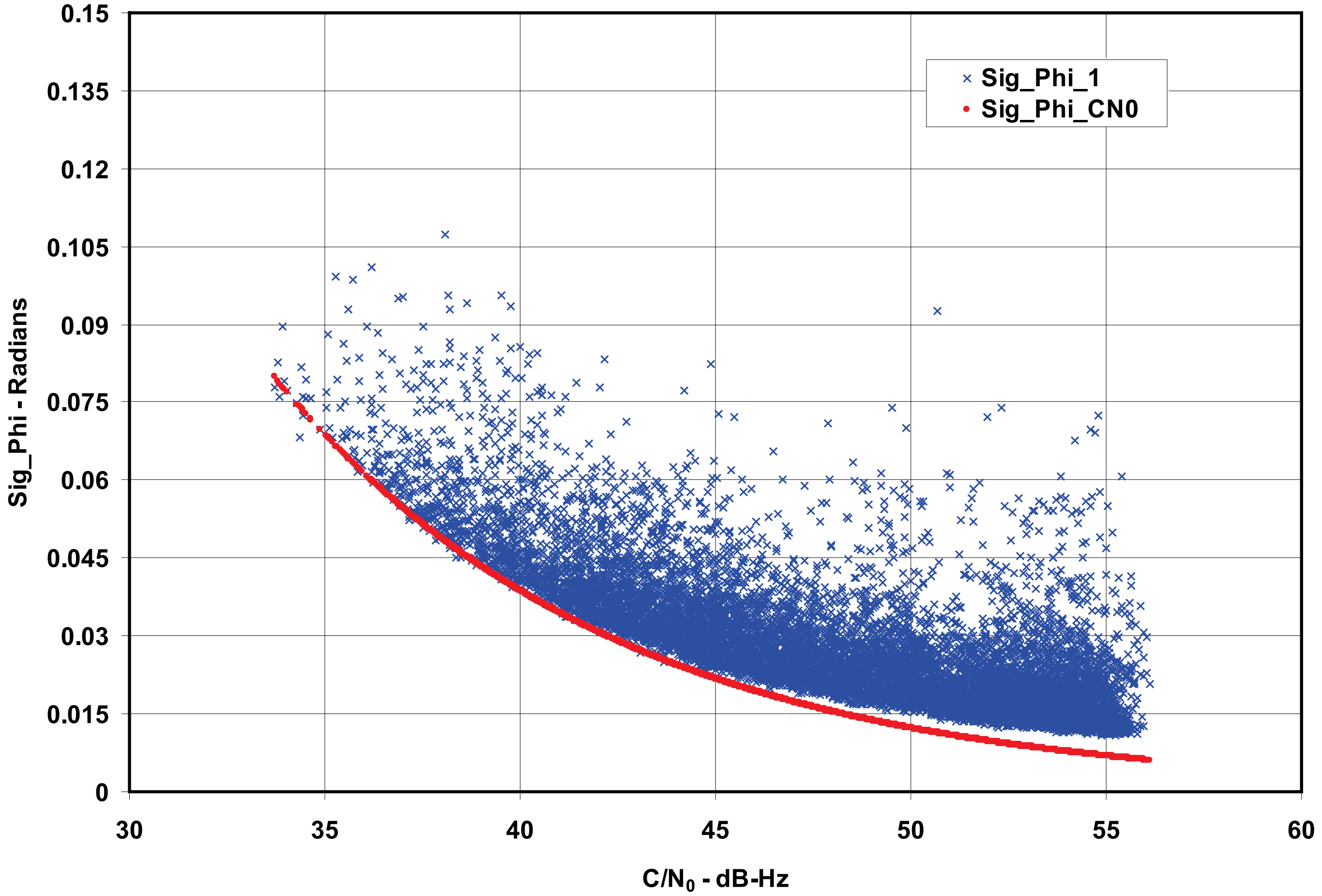
Example Measurements taken in San Francisco Area

GPS Satellites

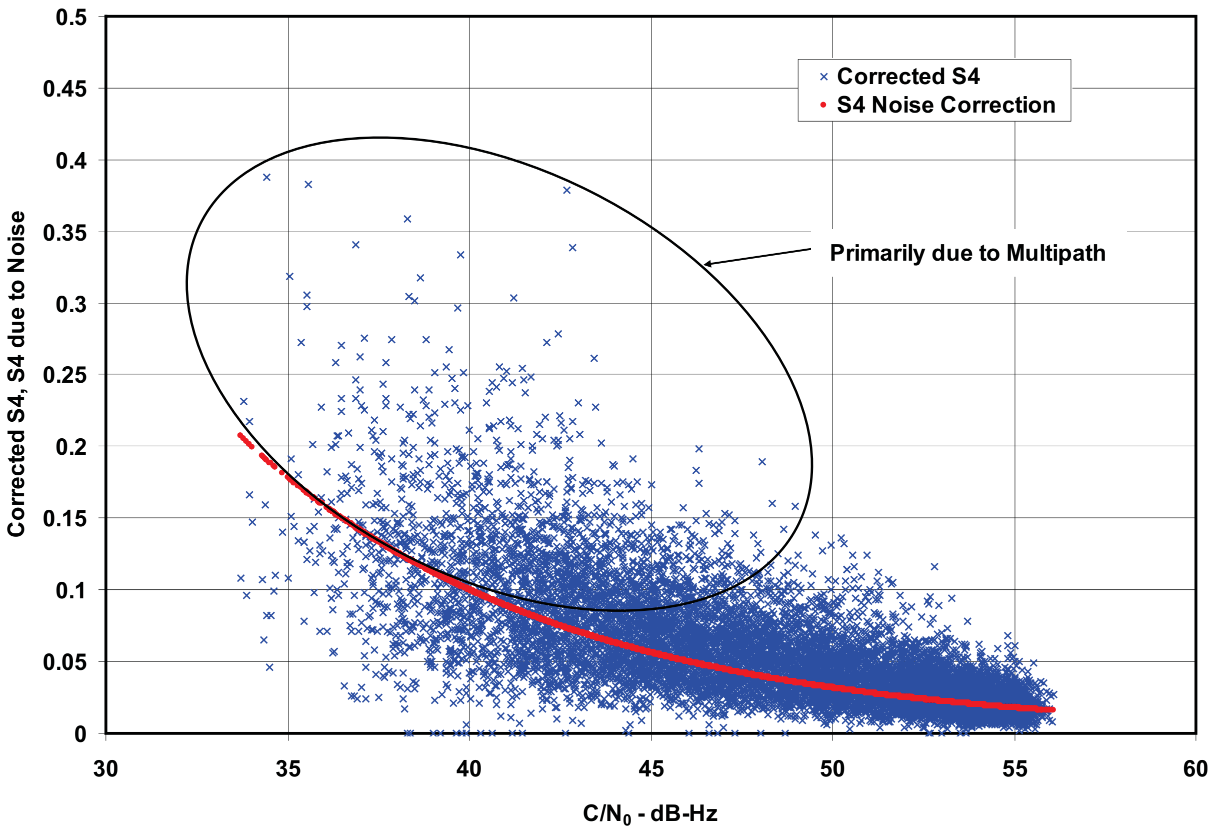
Typical Plot of 1, 3 and 10 Second Sigma-Phi from All Satellites in View



Thermal Noise (C/N_0) Effects Versus Theoretical Sigma-Phi Phase Scintillation Parameters



Thermal Noise (C/N_0) Effects Versus Theoretical S4 Amplitude Scintillation Parameter

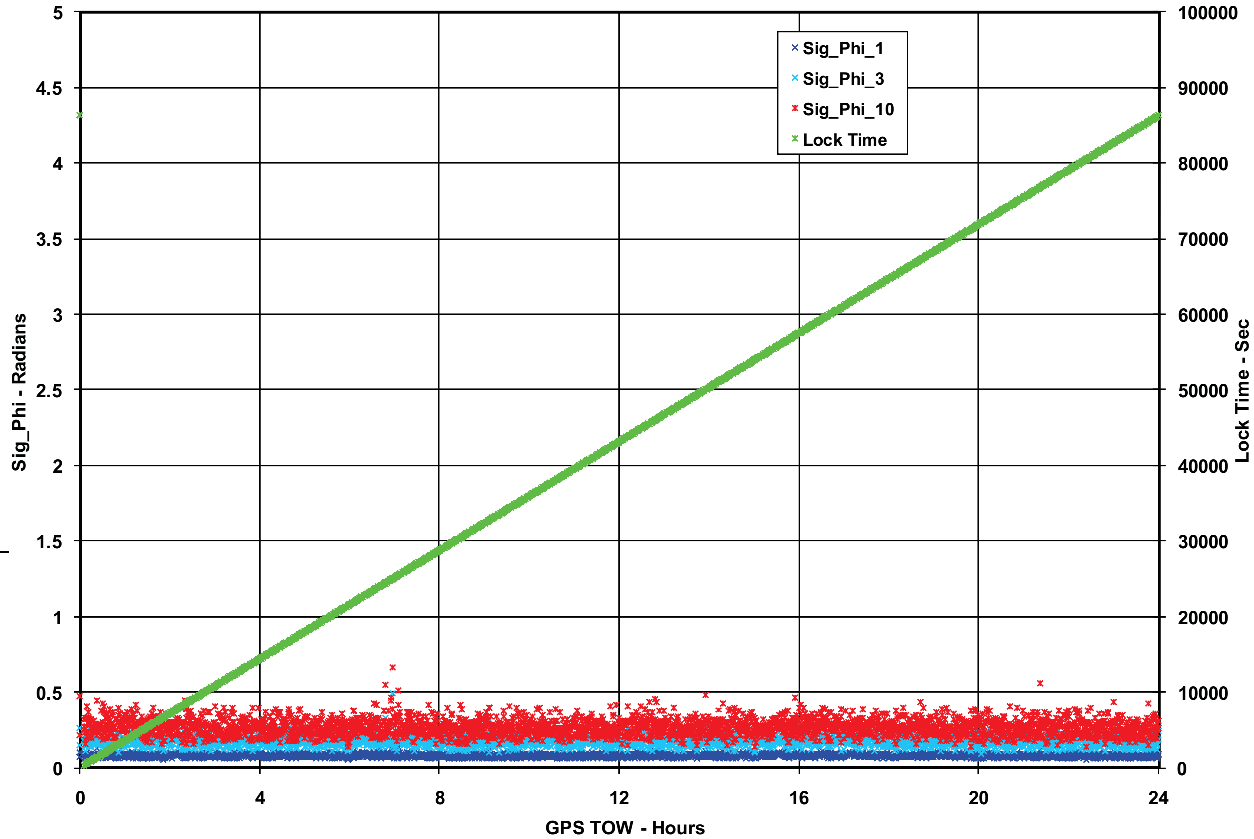


Example Measurements

SBAS Geostationary Satellites

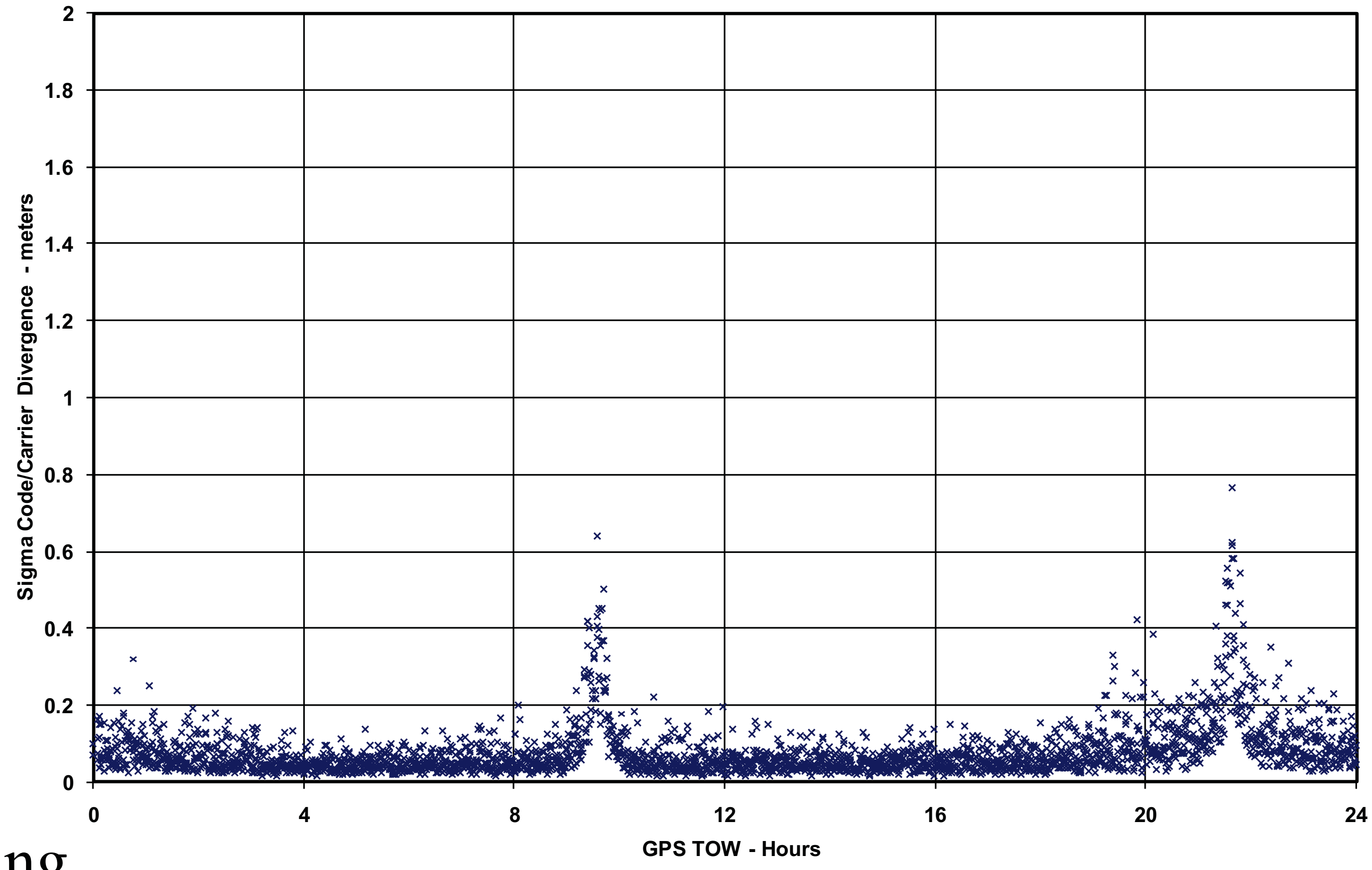
SBAS GEO Phase Measurements

- Phase Degraded by GEO Transponder Code/Carrier Control
- However, constant 45 degree elevation – no multipath effects



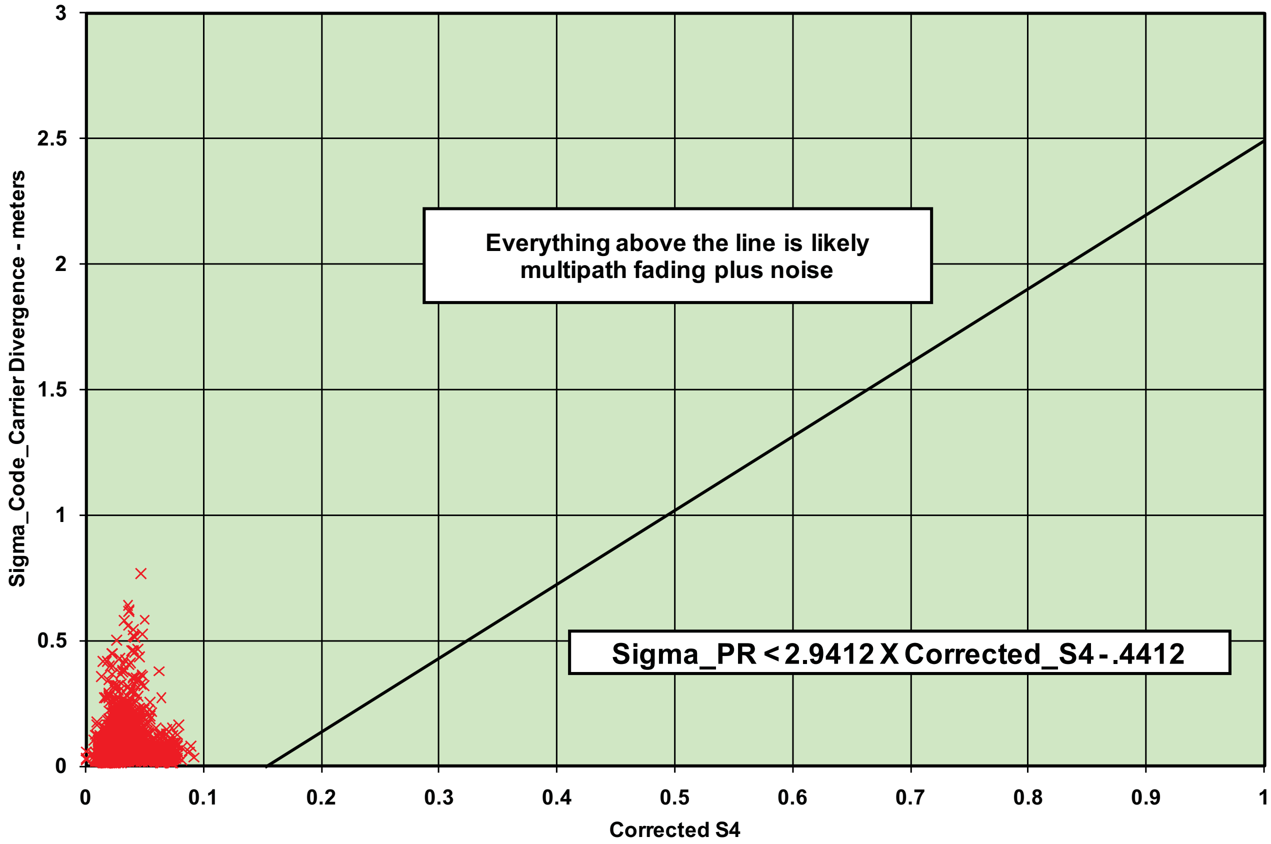
GEO Amplitude Measurements

- Standing wave multipath detrends out very well
- Code/carrier divergence due to crossing Doppler of 2 GEOs
- May be some scintillation during late evening



Easy to Distinguish between Multipath and Amplitude Scintillation from GEOs

- No scintillation
- Slow varying standing wave multipath



Receiver Demonstration

GSV4004B GPS Ionospheric Scintillation and TEC Monitor

GSV 4004B & Antenna

GSV4004B GPS IONOSPHERIC SCINTILLATION AND TEC MONITOR AND OPTIONAL GPS702GG ANTENNA

GPS IONOSPHERIC SCINTILLATION AND TEC MONITOR (GISTM) FEATURES - 1

- Tracks and reports scintillation and TEC measurements from up to 10 GPS satellites and 3 SBAS GEO(s) in view (no TEC on SBAS GEOs).
- A 25 Hz raw signal intensity noise bandwidth and a 25 Hz phase noise bandwidth insures that all the spectral components of both amplitude and phase scintillations are measured. Phase data and amplitude data are sampled at a 50 Hz rate.
- Single frequency (L1) satellite carrier phase is compared against a stable ovenized crystal oscillator (OCXO) to insure that all phase scintillation effects are recorded, not merely the 1/f refractive component measured by dual-frequency differential systems. The stable OCXO also allows tracking with a narrowband phase-lock-loop (PLL) to provide more robust tracing in scintillating environments.

GPS IONOSPHERIC SCINTILLATION AND TEC MONITOR (GISTM) FEATURES - 2

- Software is included in the GISTM to automatically compute and log the amplitude scintillation index, S_4, and phase scintillation index, σ_ϕ, computed over 1, 3, 10, 30 and 60 seconds. In addition, TEC and TEC phase are each logged every 15 seconds. Phase and amplitude data, either in raw form or detrended (to remove systematic variations), can also be logged at a 50-Hz
- Scintillation measurements from the GISTM can easily be scaled to the frequencies of the new, L-band and C-band low-orbit personal telecommunications satellites to predict the magnitude of scintillation effects on those commercial systems. These measurements can also be scaled to lower frequencies typical of older military and commercial systems.
- Utility software is included: 1) Script Logging utility for controlling the receiver and requesting data logs, 2) Various data parsing utilities for extracting data from the logs and converting to ASCII data, 3) A utility to view logs collected at a 1/60-sec rate. Standard NovAtel windows-based utilities (GPSolution4 and Convert4) can also be used for real-time viewing of receiver status and for data parsing.

Specific GSV4004B Data Logs

LOG	ID	BYTE COUNT	DESCRIPTION
RAWSINB	327	H + 4 + (n * 420)	GISTM 50-Hz phase and amplitude data, and 1-Hz TEC data (rate = 1 per sec)
DETRSINB	326	H + 4 + (n * 420)	GISTM detrended RAWSINB data (rate = 1 per sec)
ISMRB	274	H + 4 + (n*152)	GISTM main data record (rate = 1 per 60 sec)

The Future

Future GPS, SBAS and Galileo

- Added GPS frequencies will enhance both scintillation and TEC monitoring
  - GPS will add open-coded L2C (at L2) and L5 (1176.45 MHz) signals as satellites are replenished
    - L2C on 8 Block IIR-M satellites
    - L2C and L5 on all subsequent Block IIF satellites
    - L1C on GPS III satellites
    - L1F and E5 on Galileo satellites
  - SBAS GEOs will broadcast at L1 and L5
    - WAAS has two on orbit
    - Inmarsat-4s are on orbit, but not yet operational
  - Galileo will have open-coded signals at L1 and at L5, but not L2