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2333-1

Workshop on Science Applications of GNSS in Developing Countries
(11-27 April), followed by the:
Seminar on Development and Use of the Ionospheric NeQuick Model
(30 April-1 May)

11 April - 1 May, 2012

Evolution to Modernized GNSS Ionospheric Scintillation and TEC Monitoring

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Evolution to Modernized GNSS Ionospheric Scintillation and TEC Monitoring

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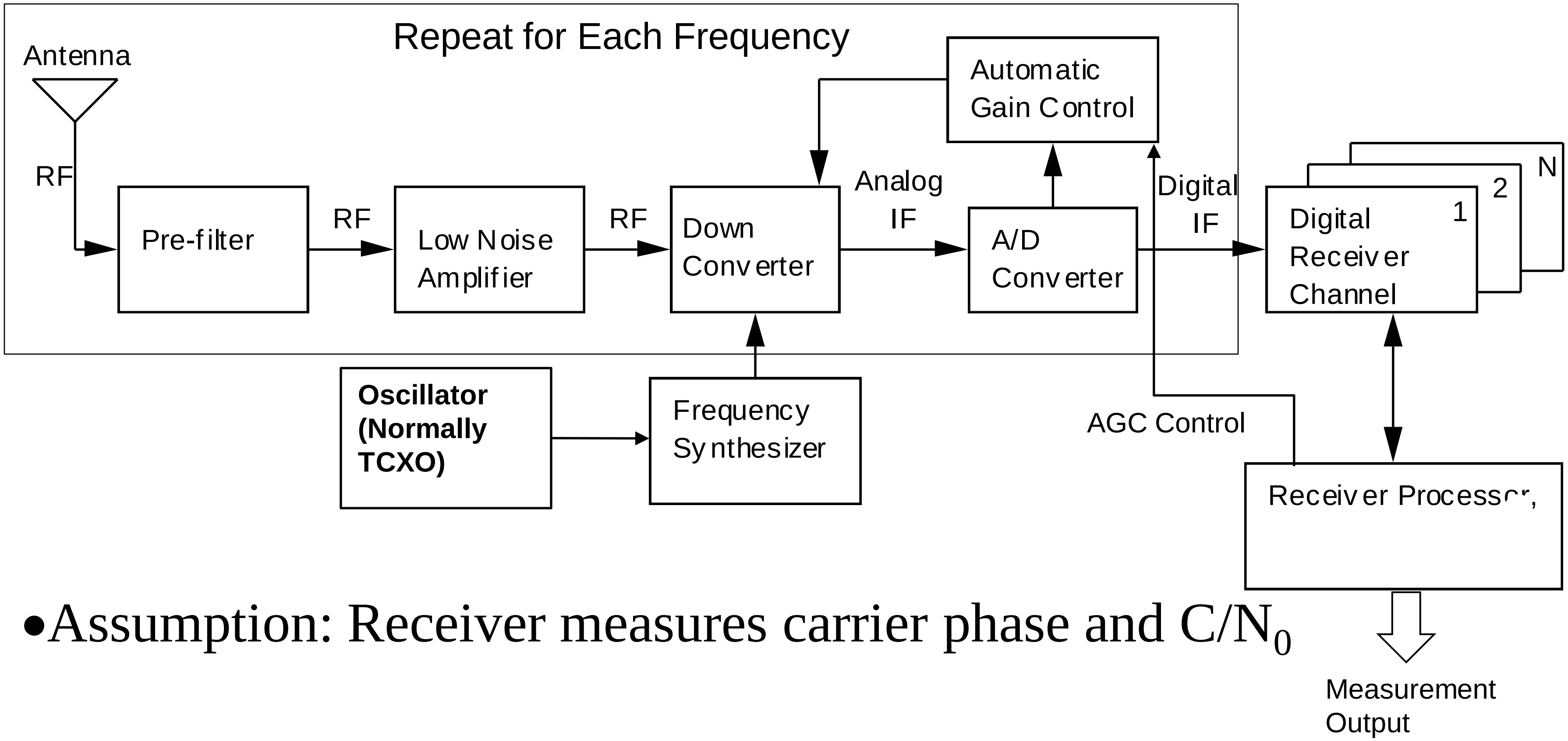
Tutorial Outline

- 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

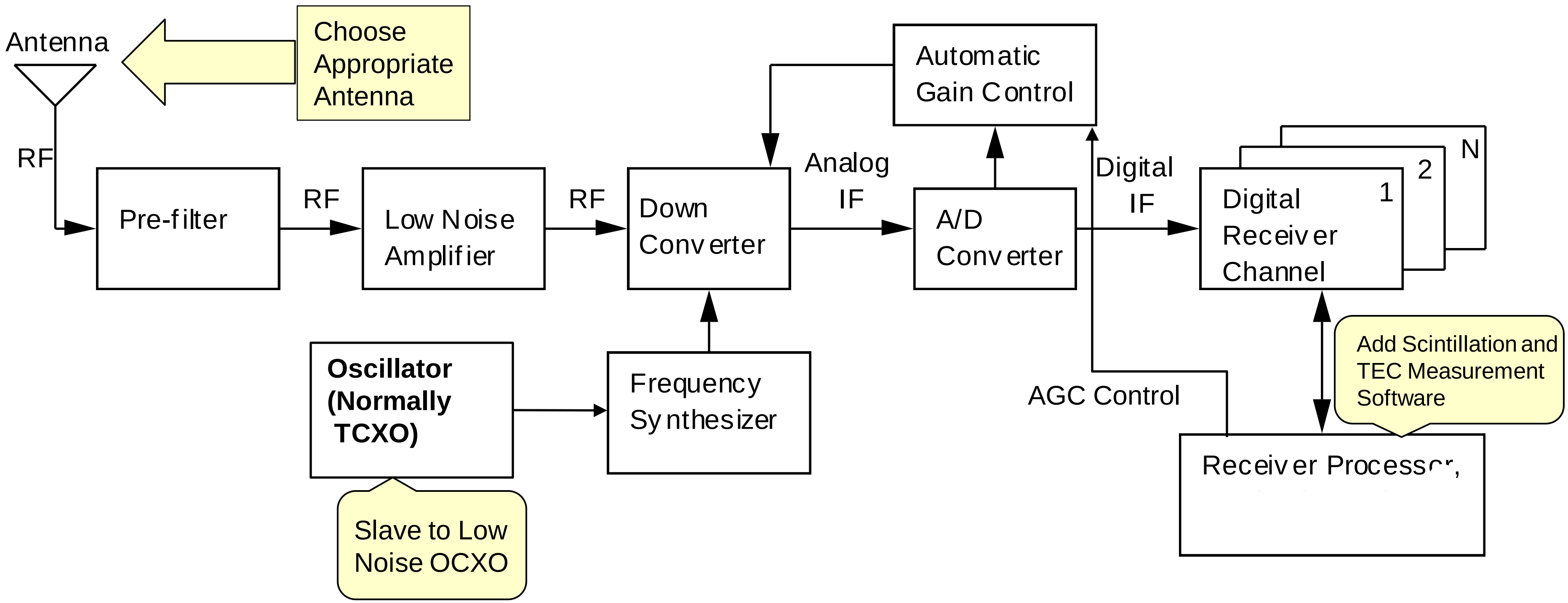
Multiple Frequency GNSS Receiver Functional Block Diagram



- Assumption: Receiver measures carrier phase and C/N_0

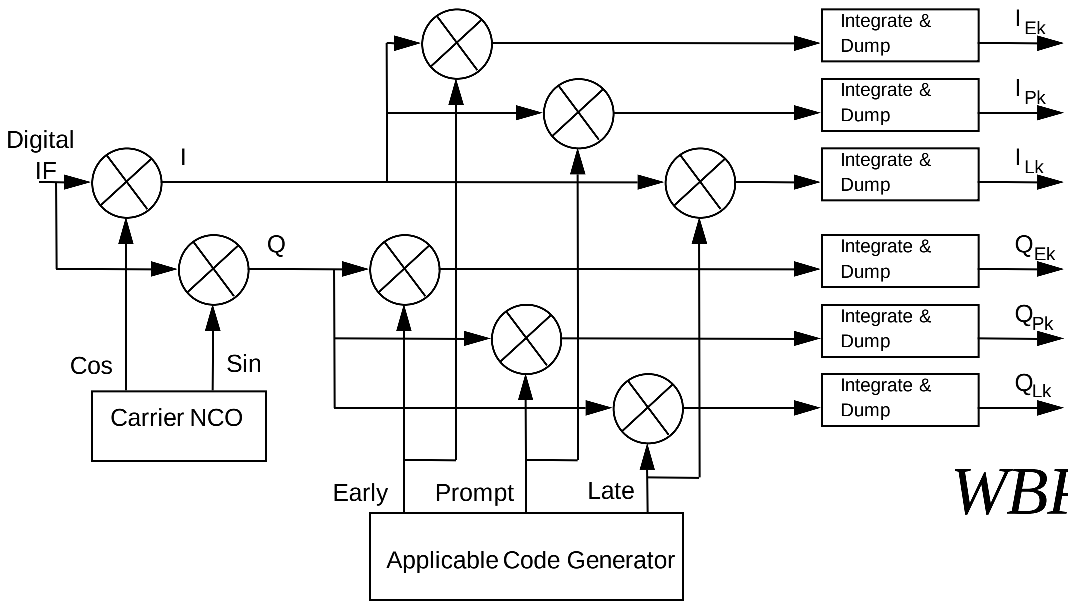
GNSS Receiver Modifications for Scintillation Monitoring

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 between NBP and WBP is proportional to received 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)

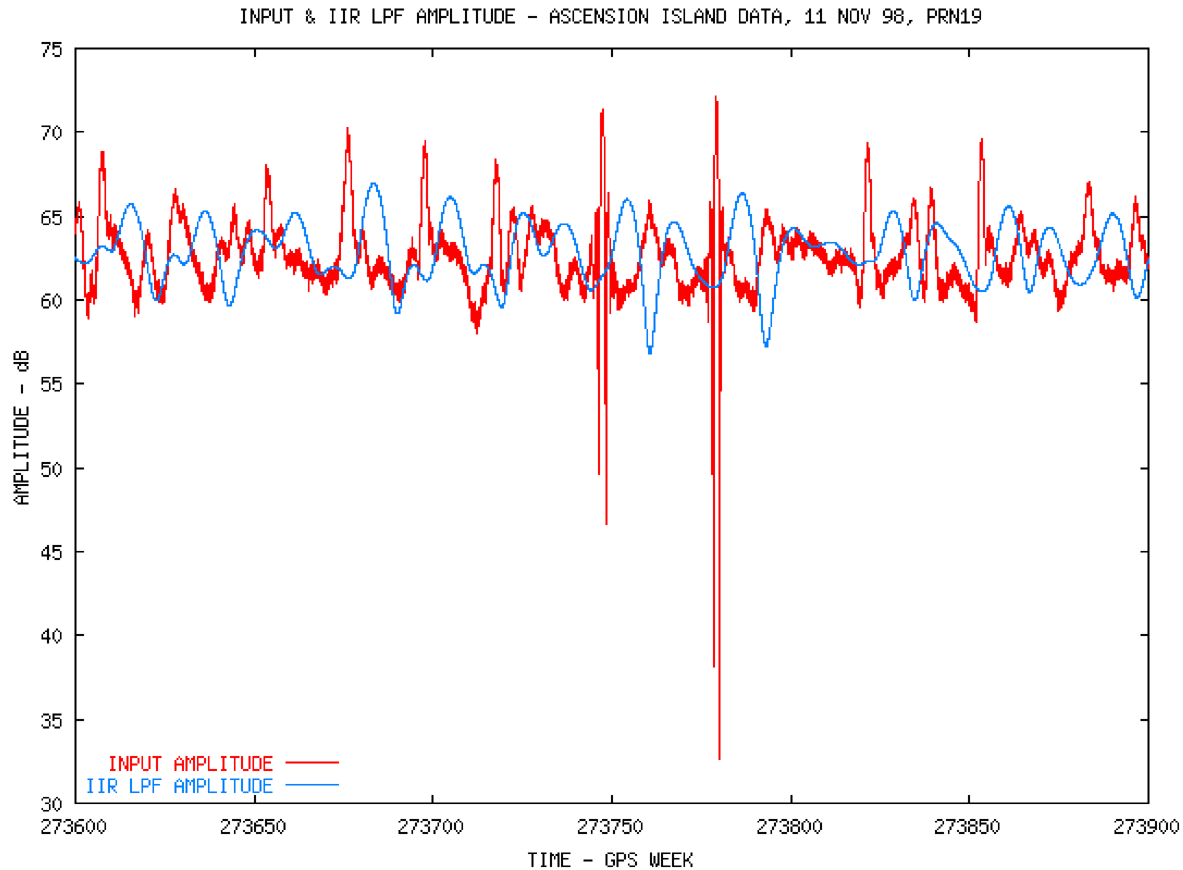
- Total S4 is standard deviation of normalized Signal Intensity
  - $$S4_{Total} = \sqrt{\frac{\langle SI_k^2 \rangle - \langle SI_k \rangle^2}{\langle SI_k \rangle^2}}$$
  - Scale factor of Signal Intensity is ambiguous, but this normalization with average value over 60 seconds takes care of that
- 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 any 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

- In low-passed version (denominator) does not line up with raw version, increasing the variance
- Possible to correct for the delay, but requires raw data buffering that is not desirable



Measuring Amplitude Scintillation Summary

- Amplitude Scintillation
  - Measure GNSS 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
    - Detrending using averaging proves to be more stable than filtering, but results in higher S4 due to multipath fading

Measuring Phase Scintillation

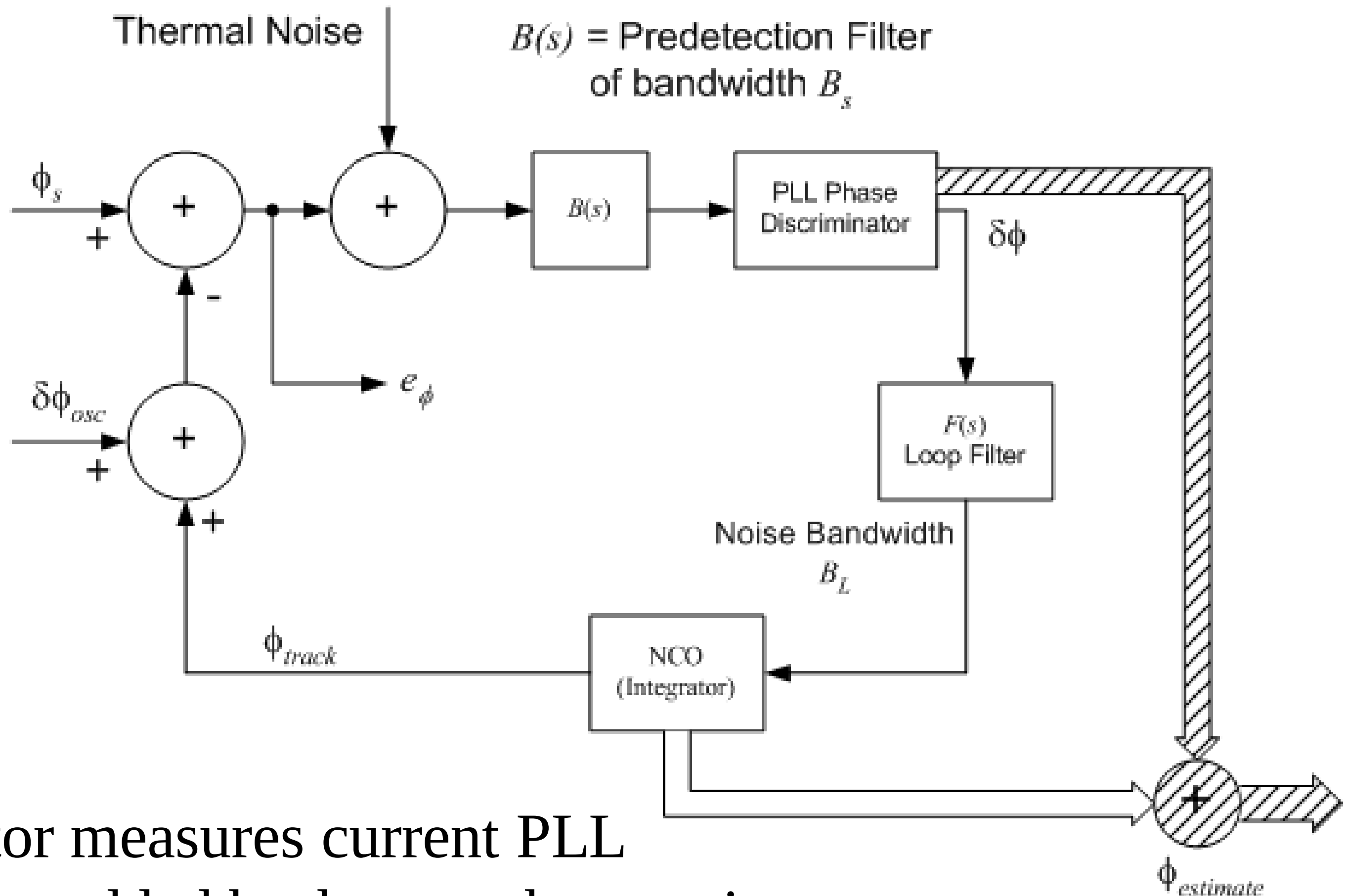
Some History Relative to Measuring Phase Scintillation Effects

- GPS Silicon Valley inherited commercialized scintillation monitoring technology from a US 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 provide good phase 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)
  - Normally, weakest link in a GPS receiver
  - Measurements include perturbations of receiver and satellite oscillators
    - Mostly, these perturbations cannot be removed with “detrending”
  - Longer-term 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 higher-frequency 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



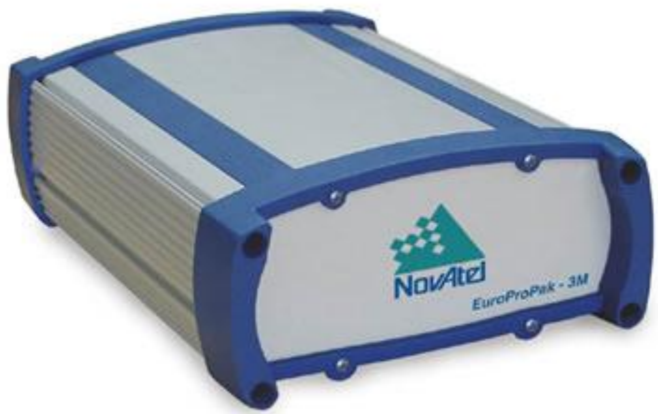
- Phase Discriminator measures current PLL 50-Hz phase error – added back onto phase estimate

Legacy Measurements of TEC

- Measure difference of GPS PN code phase on L1 and L2, smoothed against negative L1/L2 difference in carrier phase
  - Legacy monitors use "semi-codeless" technique to measure on L2
  - Does not enhance ability to measure scintillation
  - Semi-codeless L2 has 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) and receiver and antenna L1/L2 biases
- Real-time accuracies on the order of 1 – 2 TECU, after calibration
  - Also, very much affected by multipath

Evolution to Modernized GNSS

Legacy GSV 4004B & Antenna

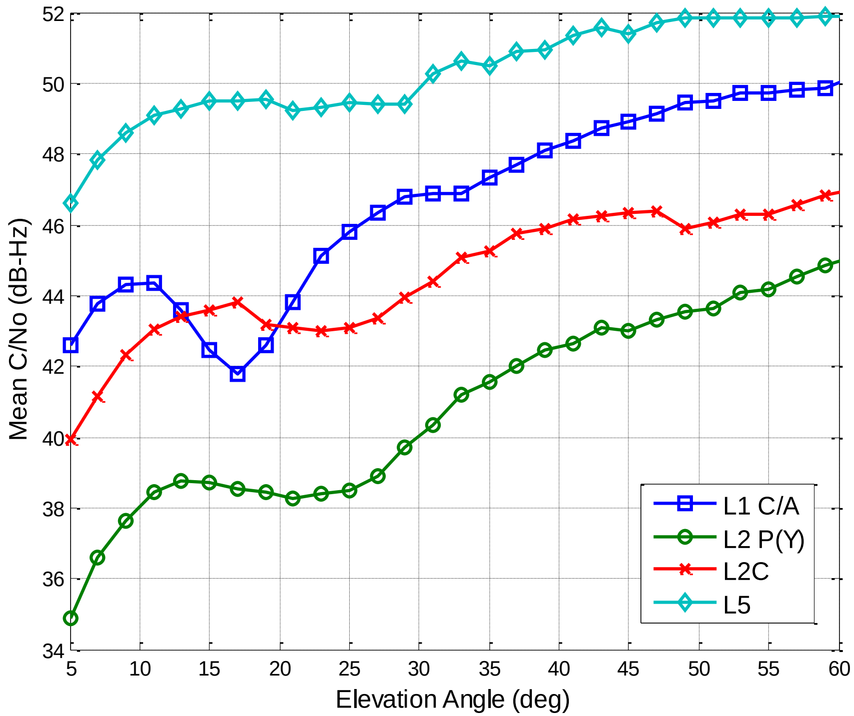


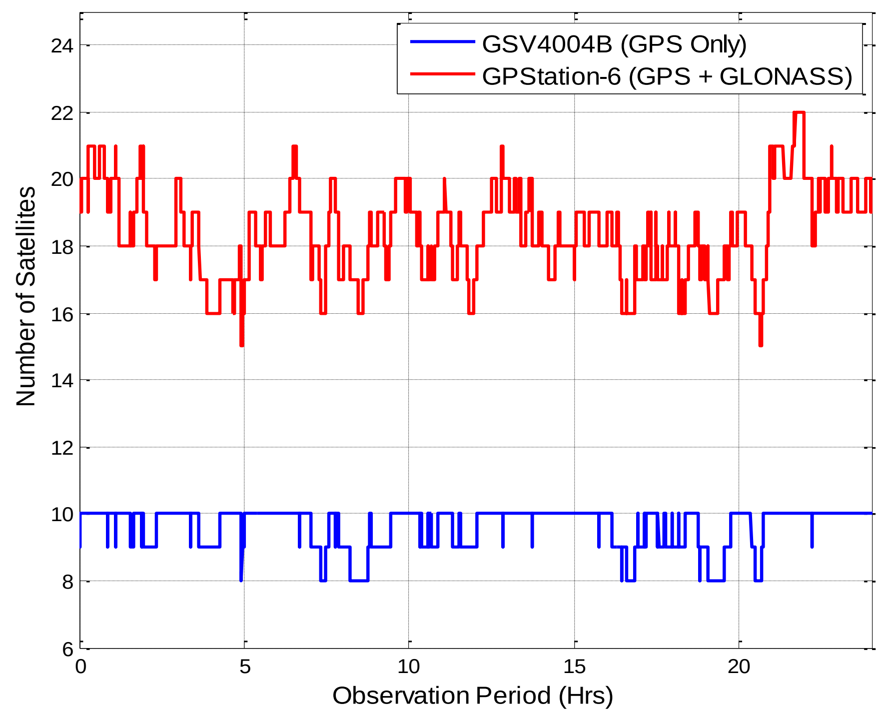
GSV4004B GPS IONOSPHERIC SCINTILLATION AND TEC MONITOR AND OPTIONAL GPS702GG ANTENNA

Features of GPStation-6 GISTM

Features	GISTM Receiver **(Bold Red Indicates New Features)**
Channel Configuration	**120** independent channels
Signal Tracking	GPS (L1, semi-codeless L2P, **L2C, L5**) **GLONASS (L1, L2-C/A, L2P)** **Galileo (E1, E5A/B, E5 Altboc)** SBAS (L1, **L5**), **Compass (Upgradable)**
Ionospheric Measurments	50 Hz phase and amplitude data (raw or detrended-raw)
Scintillation Indices	GPS (L1 C/A, **L2C, L5**), **GLONASS (L1, L2)** **Galileo (E1, E5)**, SBAS (L1, **L5**)
TEC (Code and Carrier)	GPS (L1/L2P, **L1/L2C, L1/L5**), **GLONASS (L1/L2)** **Galileo (E1/E5A), SBAS (L1/L5)** (1 Hz raw and 4/minute smoothed)
Communication Interface	**USB**/RS-232/RS-422 , I/O (PPS, Event, Position Valid)

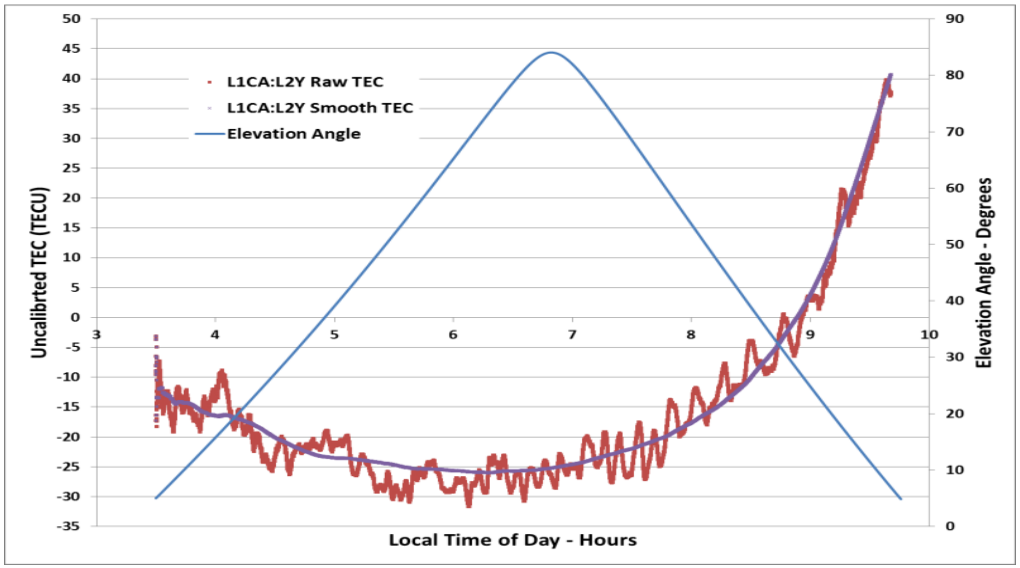
Improvements by Adding L2C and L5

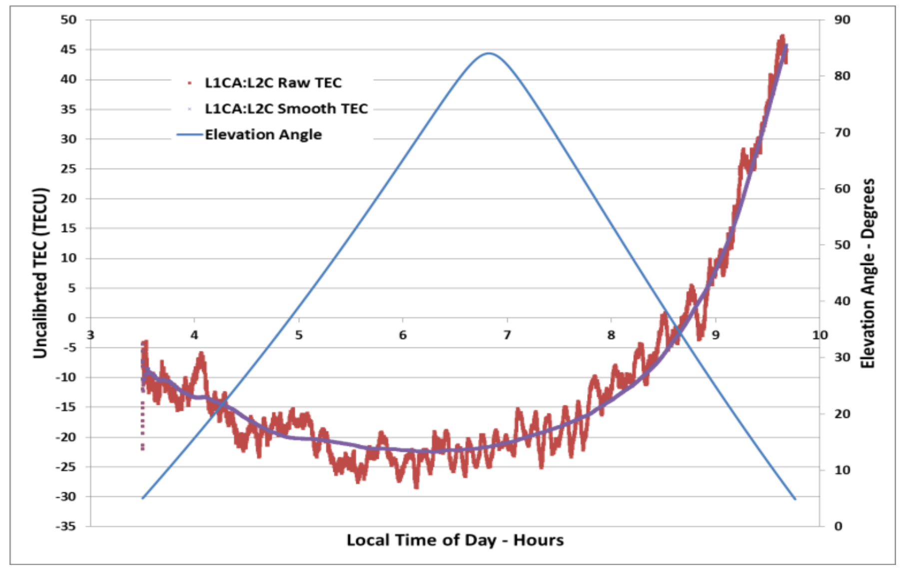




- Measured at Calgary, AB, Canada
- GPS Modernization improves Signal Quality – C/N_0
- Adding Constellations increases Number of Ionospheric Pierce Points

Comparison of L1C/A - L2C and L1C/A - L2P(Y) for Measuring TEC



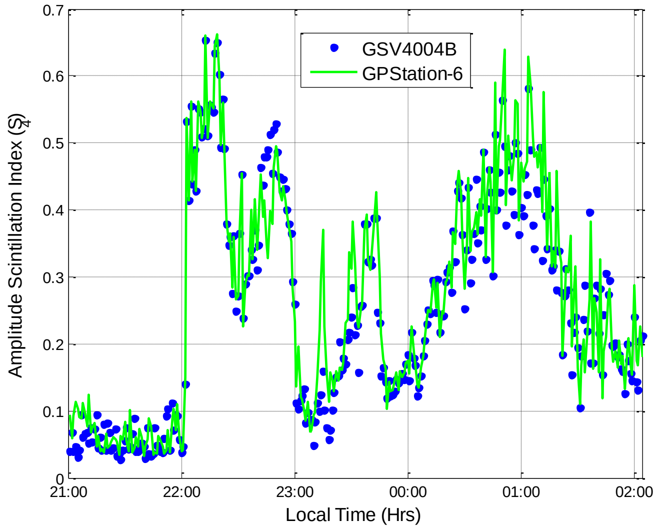


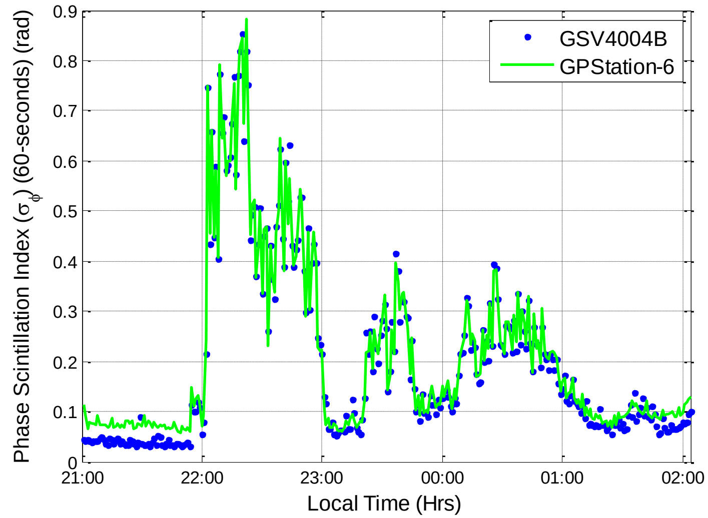
- Negative TEC because receiver is not delay calibrated

L2P(Y)/L2C TEC Performance Differences

- Not much difference in displayed performance
  - 3 dB loss in L2C I/Q multiplexing
  - Wider tracking loop bandwidth on L2C
  - Multipath errors dominate – lower chipping rate on L2C
- However, L2C tracking much more robust and less dependent on L1 aiding
- Larger TEC bias using L2P(Y)
  - More filter delay of wideband signal

GPS Scintillation Measurement Comparisons

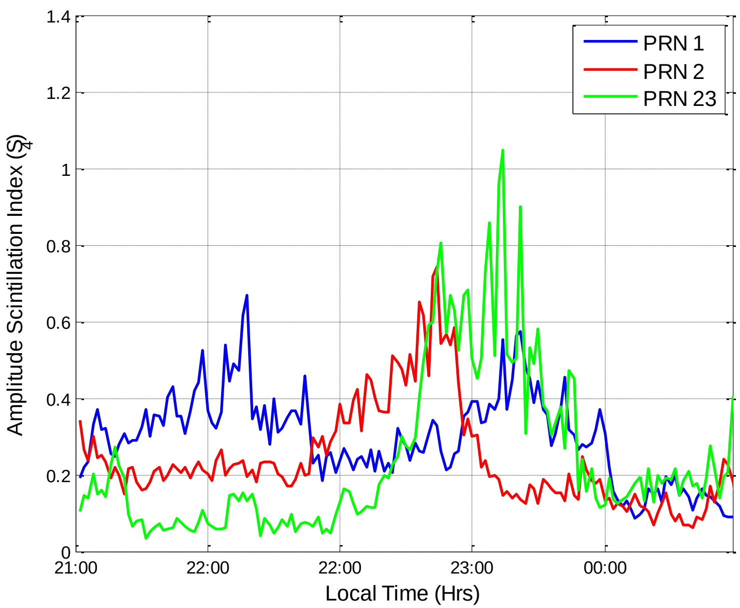


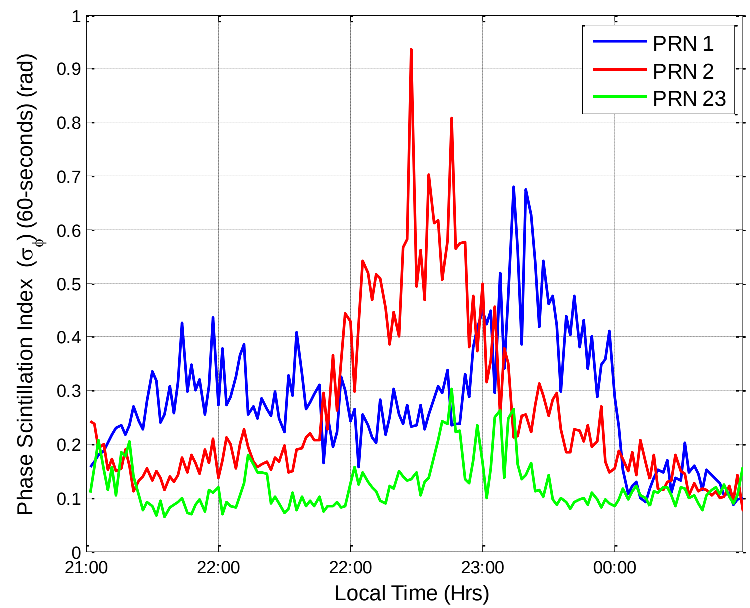


- Calama, Chile
- S4 – Legacy vs Modernized
- σ_ϕ – Legacy vs Modernized

- Comparison shows excellent backward compatibility

Modernized Monitor Includes GLONASS



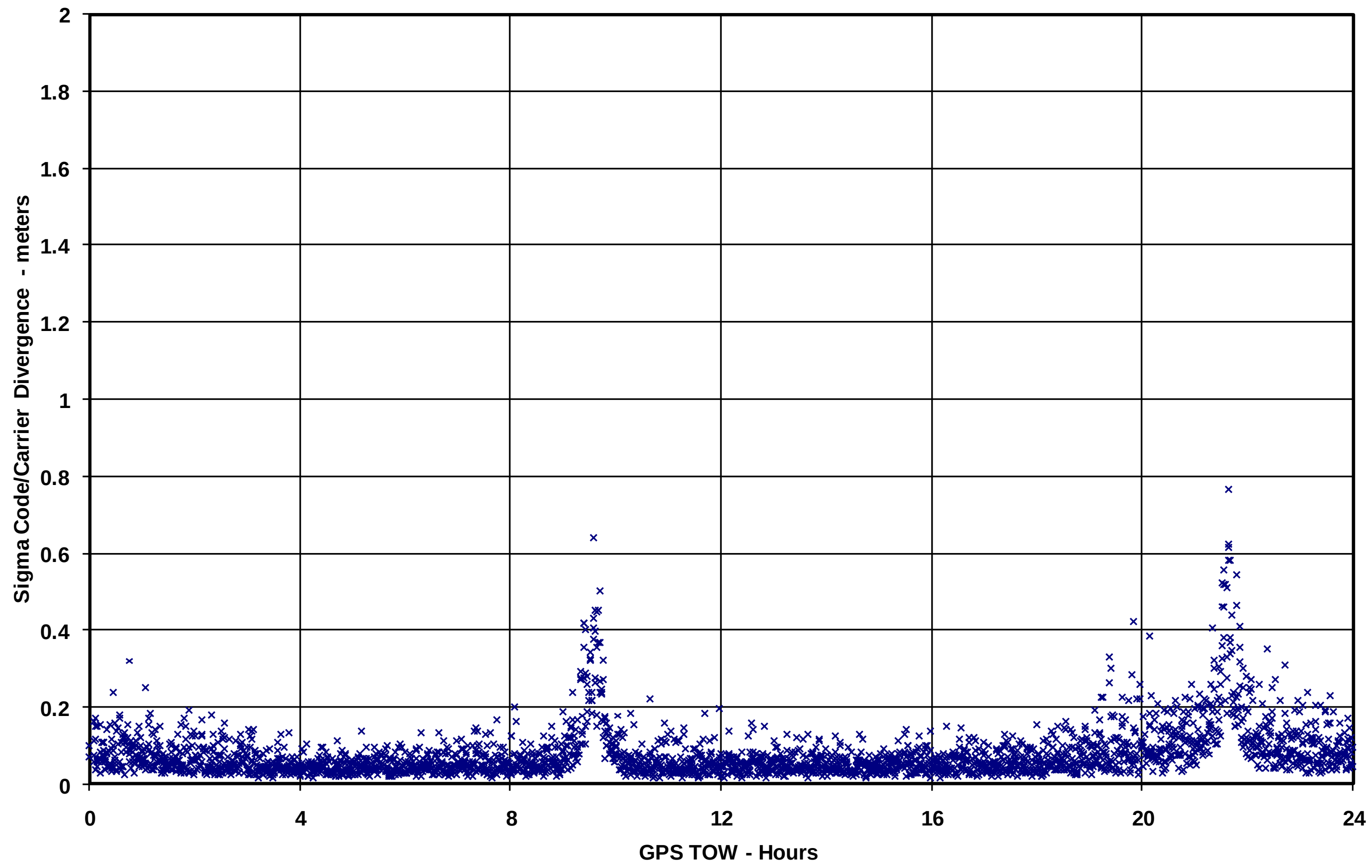


- S4
- σ_ϕ

SBAS GEO Measurements

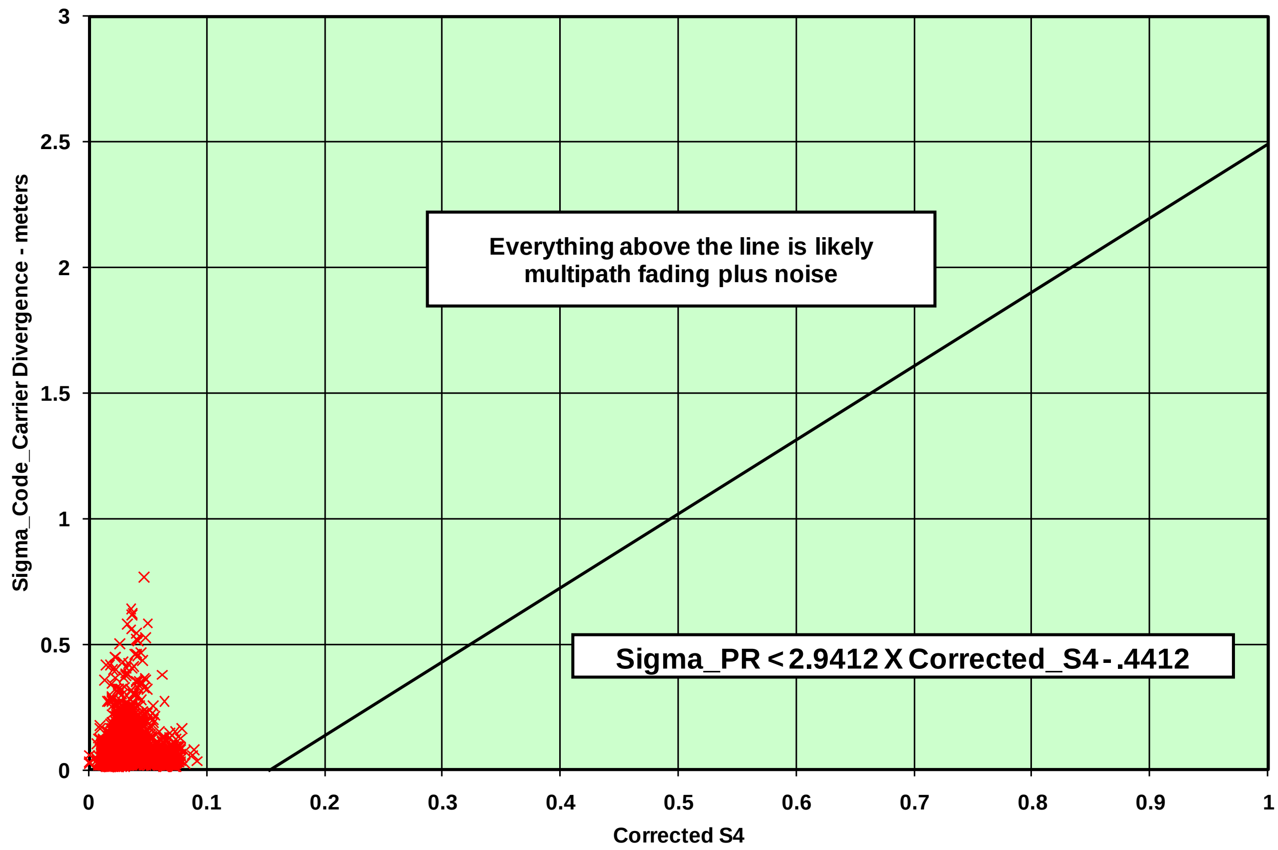
Legacy SBAS S4 Measurements in Non-Scintillating Environment

- Standing wave multipath detrends out very well
- Code/carrier divergence due to crossing Doppler of 2 GEOs

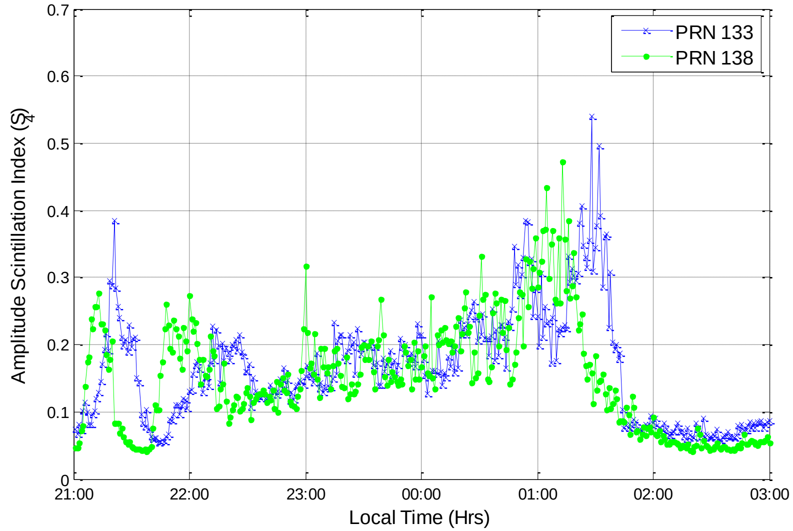


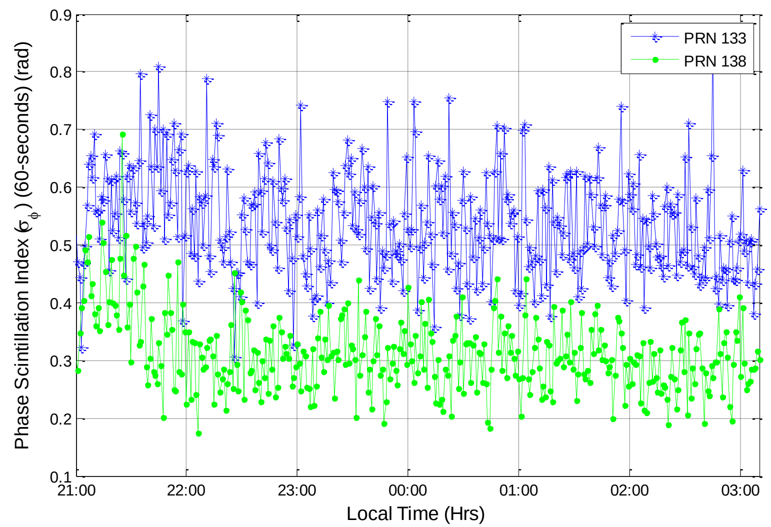
Easy to Distinguish between Multipath and Amplitude Scintillation from GEOs

- No scintillation
- Slow varying standing wave multipath



Modernized SBAS Measurements – Same Performance as Legacy Receiver





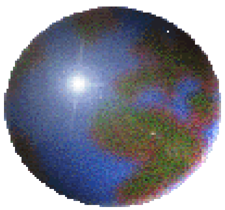
- S4
  - Time difference is due to pierce point location difference

- σ_ϕ
  - Noise is due to GEO payload transponder phase noise
  - Some phase scintillation observable between 9 and 10 pm

Scintillation Monitoring Limitations That Apply to Both Legacy and Modernized Monitors

General GNSS Receiver Limitations in Scintillation Environment

- Phase Scintillation
  - Generally, not a problem at L1 or L5, or on L2C
    - Unless a very narrow tracking bandwidth is used
    - No worse than low-grade TCXO typically found in GPS Receivers
    - Requires relative wide bandwidth PLL for phase tracking
  - Larger problem for "semi-codeless P(Y)" on L2
    - Very narrow bandwidth PLL coupled with erroneous (required) aiding with L1 phase (doesn't agree with Doppler aiding)
- Amplitude Scintillation
  - Primary culprit for loss of phase lock
    - 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

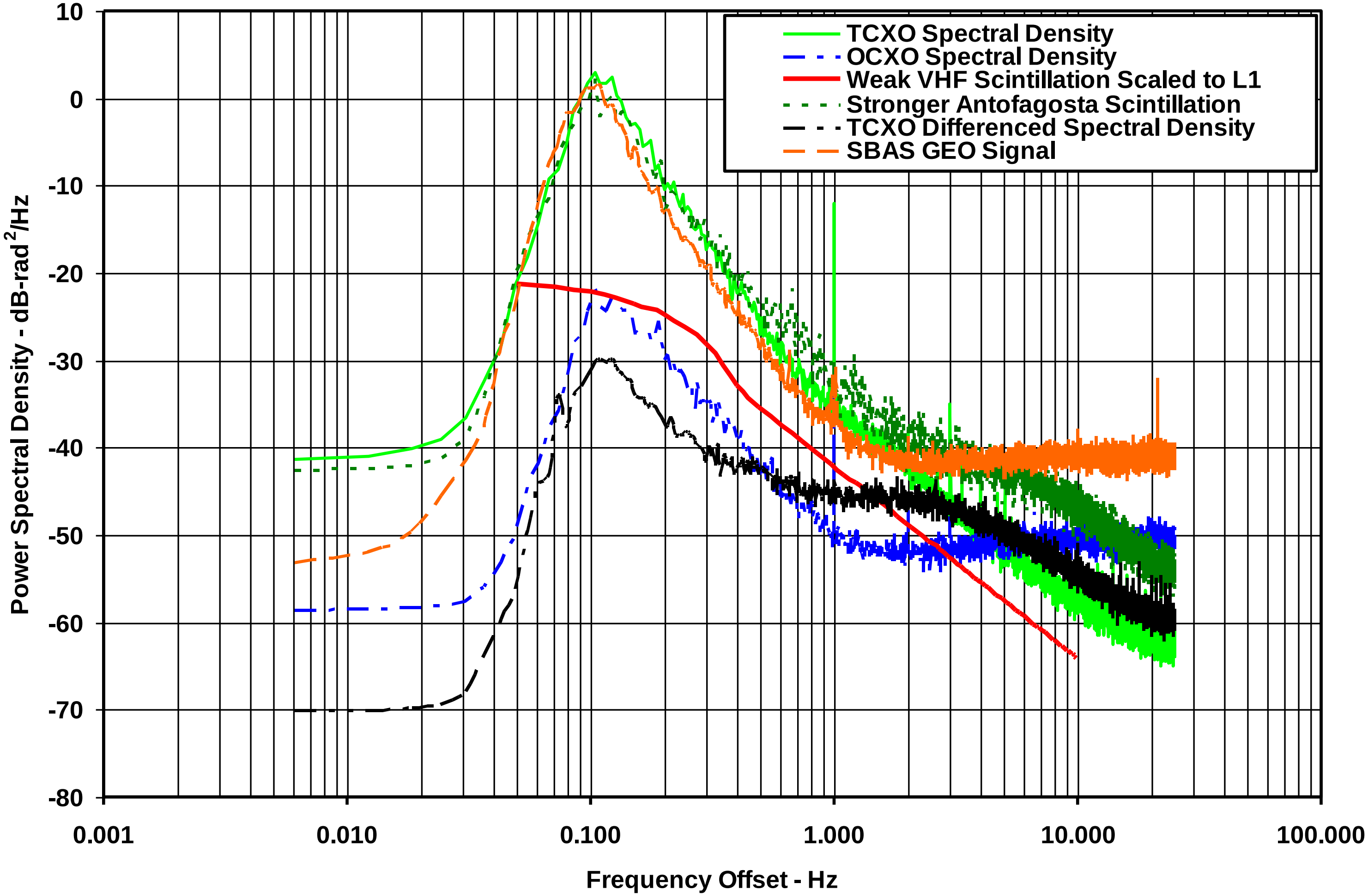


Phase Scintillation Limitations

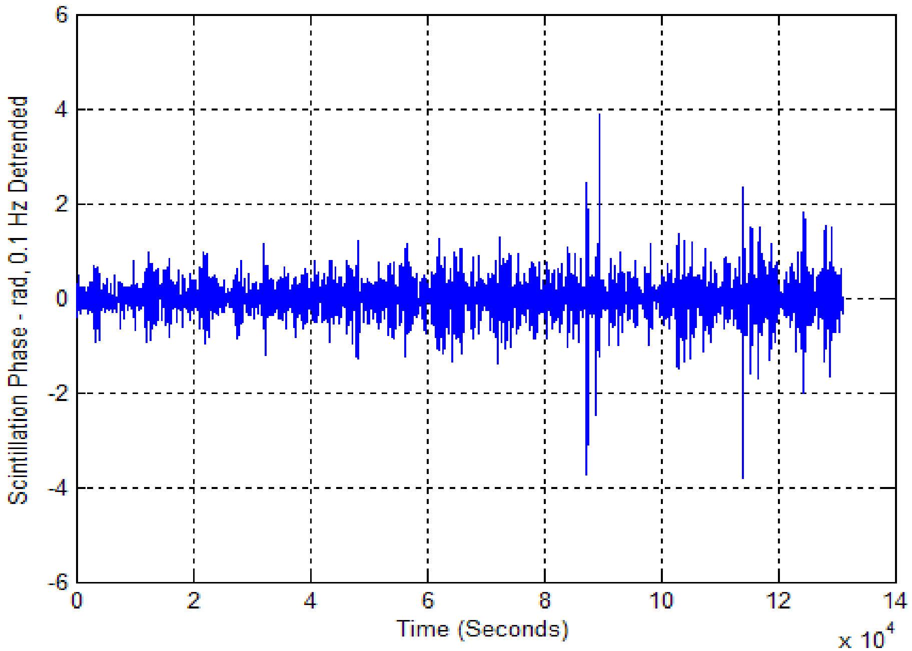
GNSS Scintillation Monitor Limitations in Phase Scintillation Environment

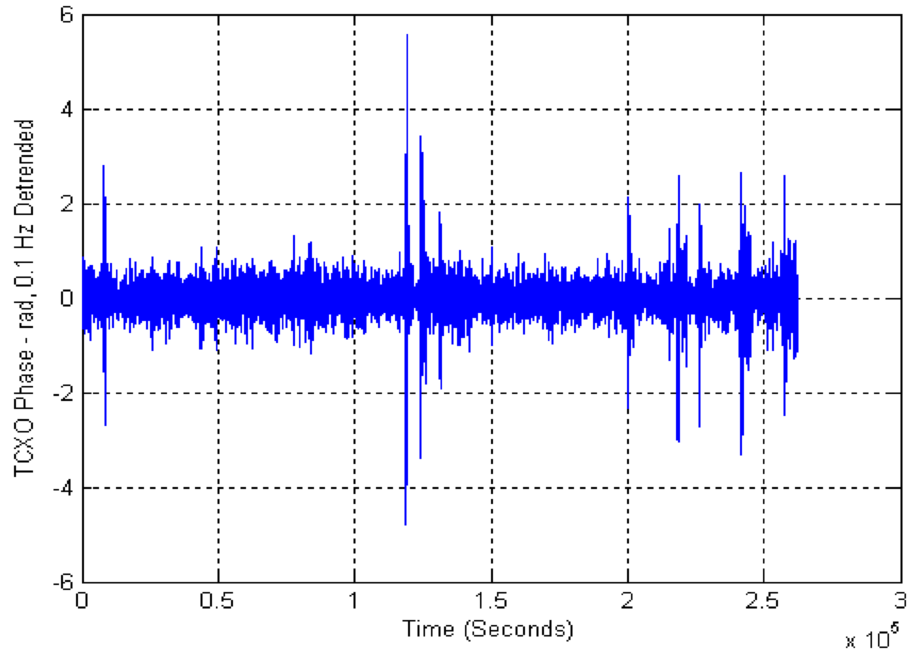
- Can't measure scintillation at "semi-codeless" L2 P(Y) – Loop bandwidths too narrow
- Measurement limitations on coded signals (L1, L2C and L5) dominated by receiver oscillator
  - Typical receiver oscillator phase noise masks phase scintillation (See PSDs and plots in next charts)
  - Thermal Noise 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





σ_ϕ = 0.396 radians

σ_ϕ = 0.46 radians

Tradeoffs Regarding Using Low-Noise Oscillators (OCXOs)

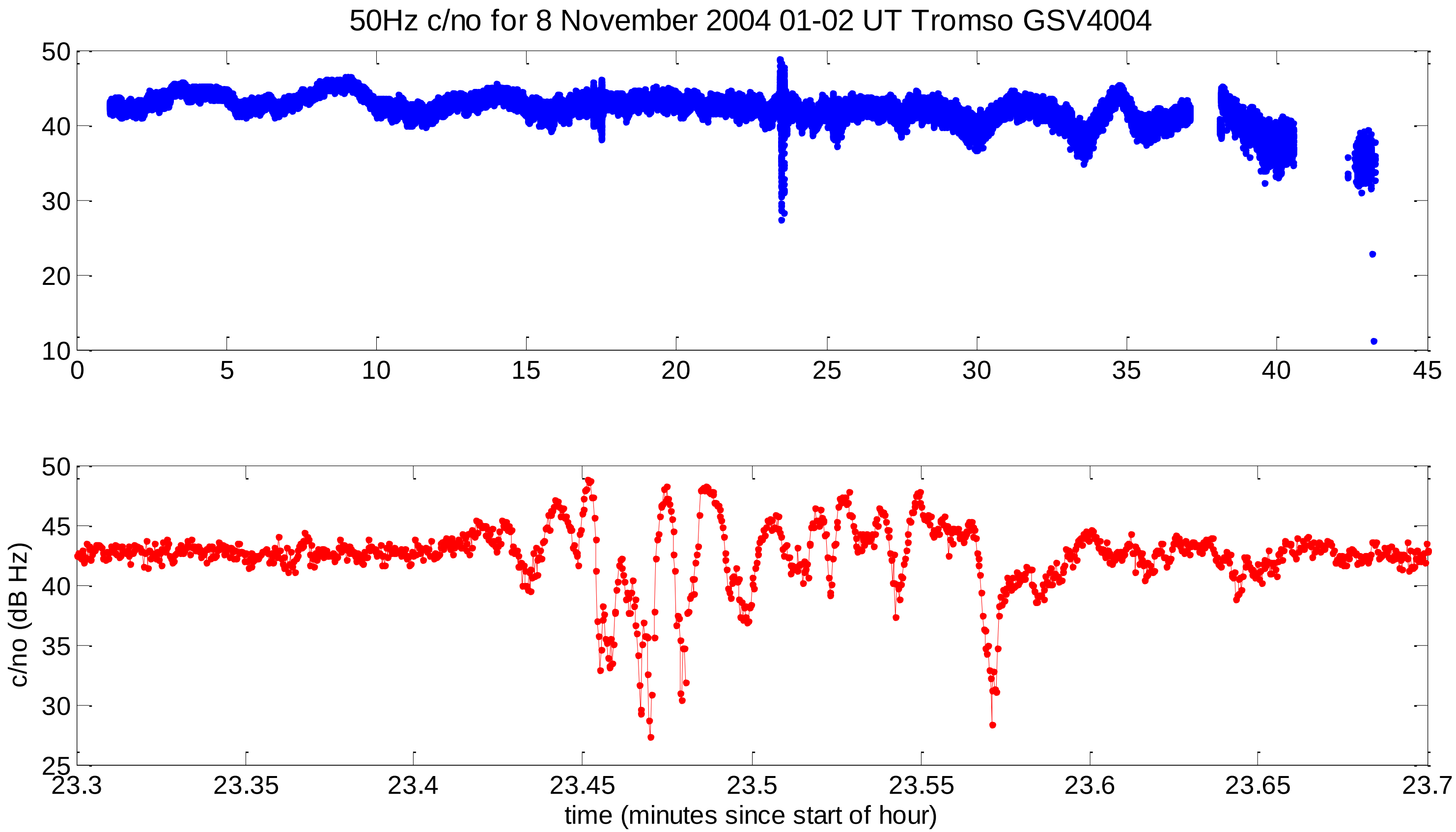
- Cost of low-noise OCXOs has diminished somewhat over recent years
  - The cost driver is their packaging with the receiver (low-volume quantities)
    - This packaging must also meeting international radiation and conductive emission (CE) requirements
- As stated, TCXO noise can be eliminated by differencing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

Amplitude Scintillation Limitations

Scintillation Monitor Limitations in Amplitude Scintillation Environment

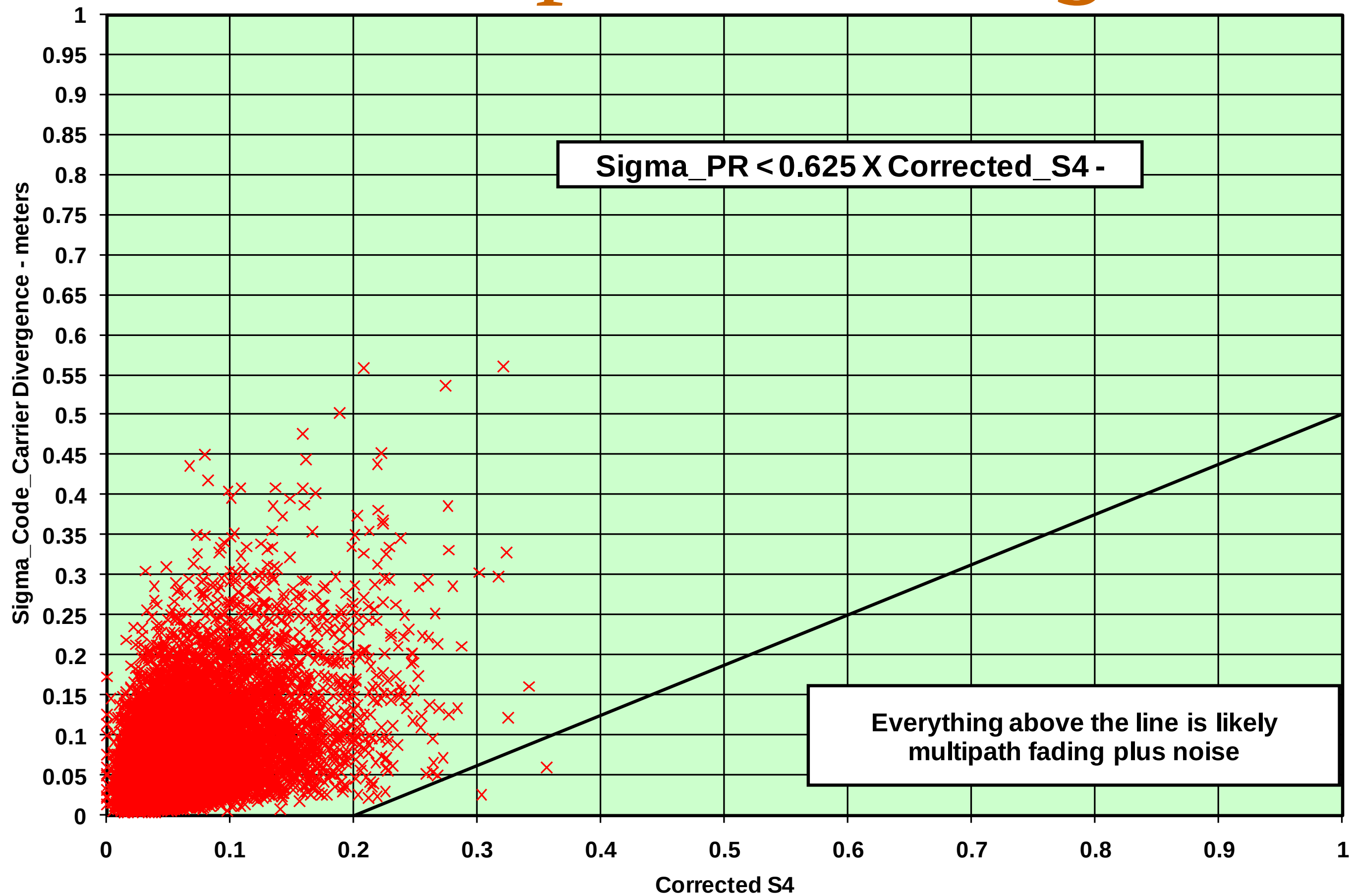
- Amplitude Scintillation
  - High S4 can cause loss of phase lock
    - S4 is still usually valid – it is based upon non-coherent power measurements, at least for short to medium length fades
    - See state diagram
  - Multipath fading limits minimum S4 capability
    - Longer duration, but shallow 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



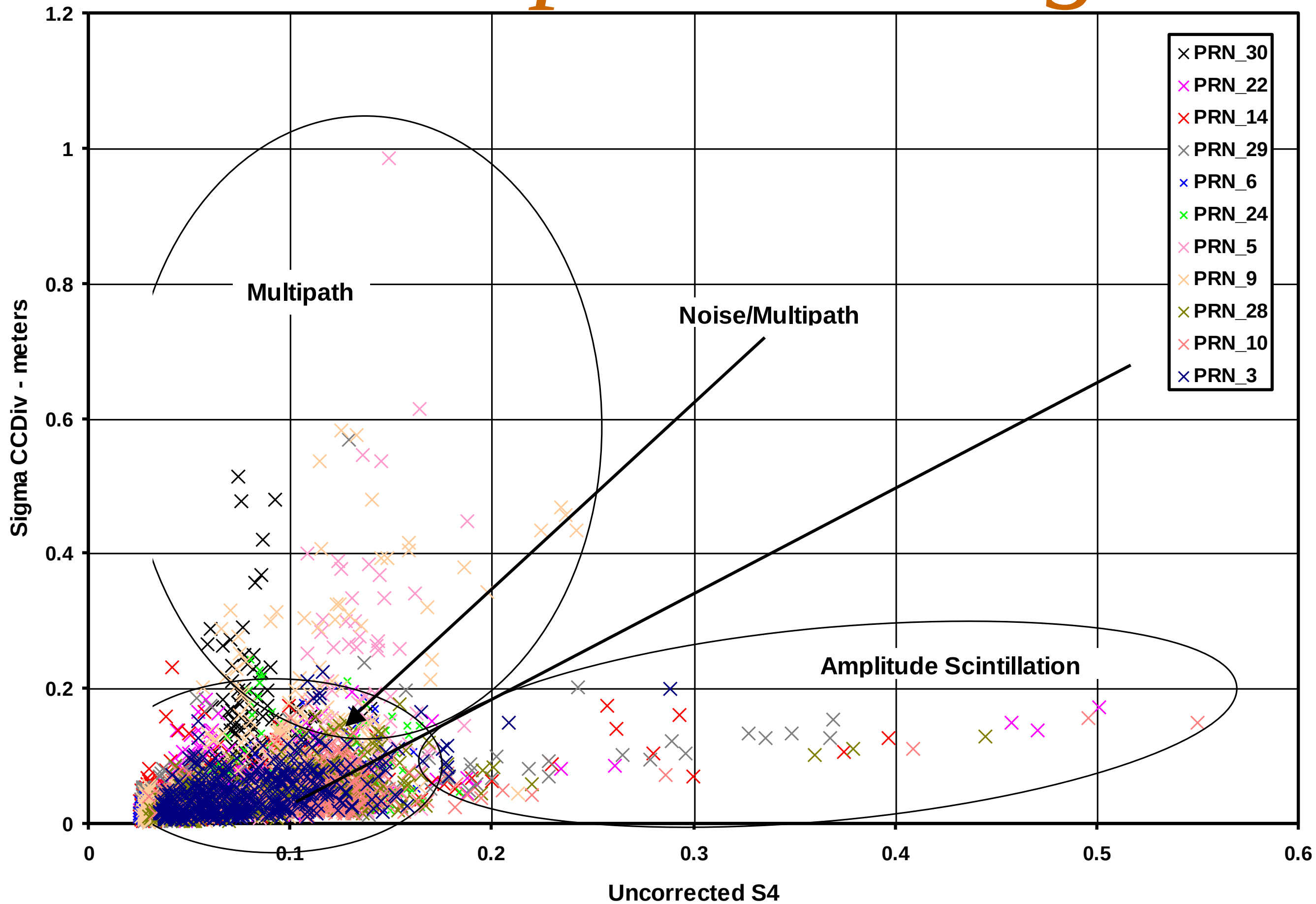
Distinguishing Between Amplitude Scintillation and Multipath Fading

- No Scintillation
- Varying Multipath
- All GPS Satellites



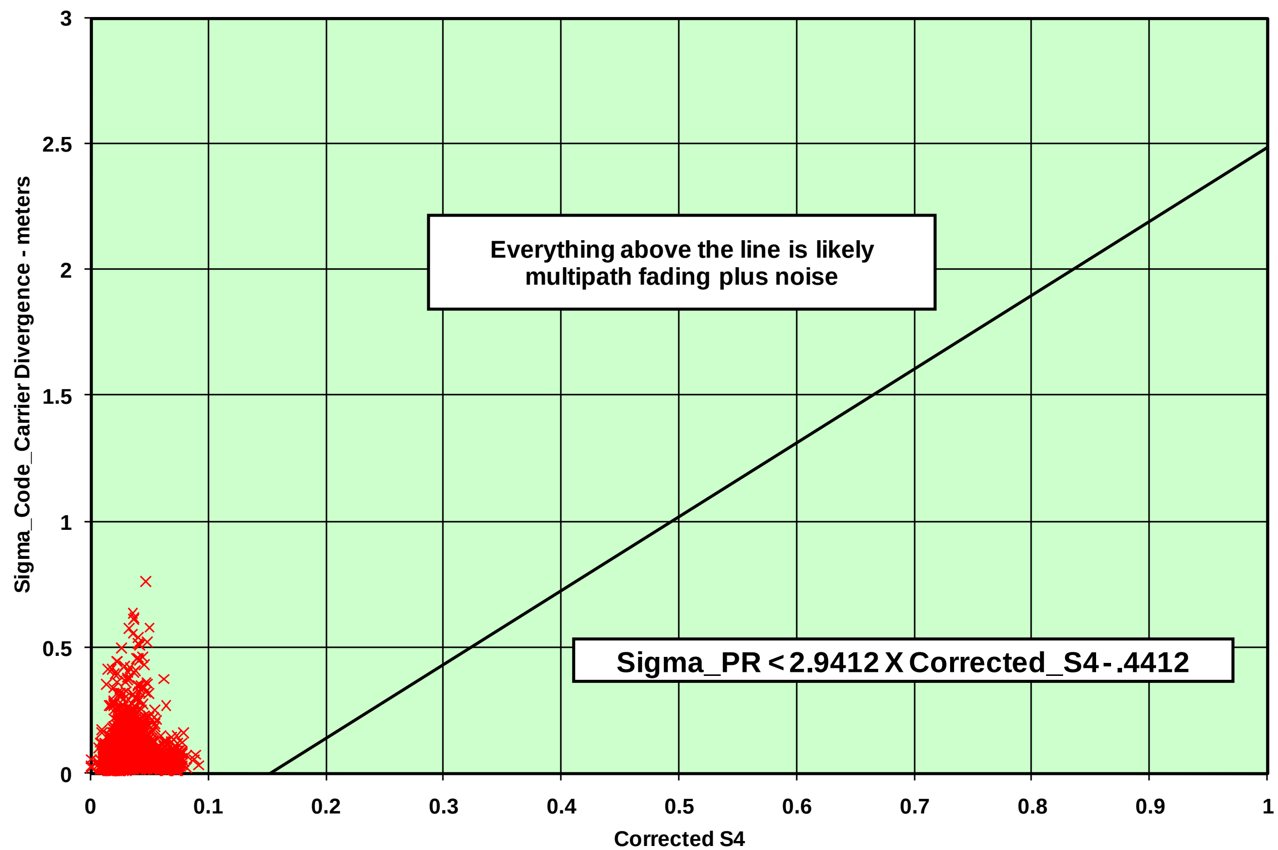
Distinguishing Between Amplitude Scintillation and Multipath Fading

- Moderate Scintillation
- Varying Multipath
- All GPS Satellites

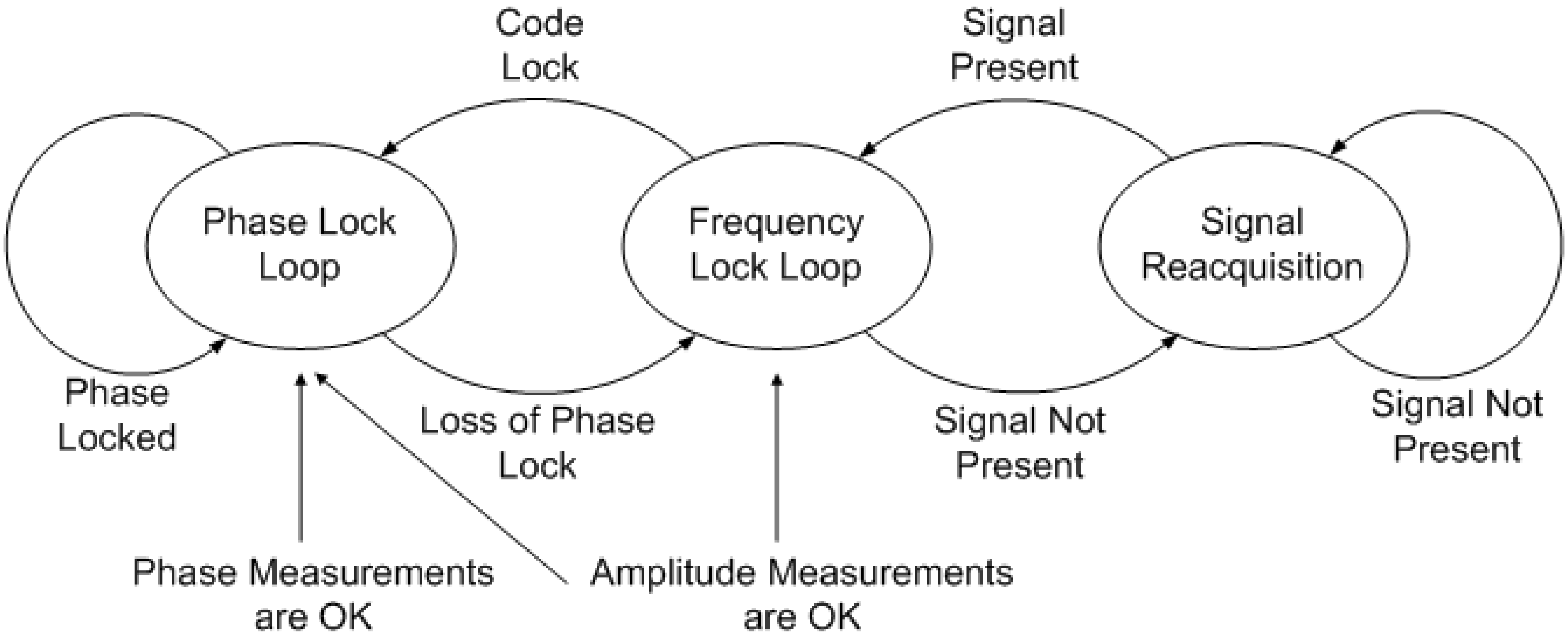


Multipath Fading Tracking SBAS Signals

No Scintillation,
Slow Varying Multipath
2 SBAS Geostationary Satellites



Signal Tracking State Diagram

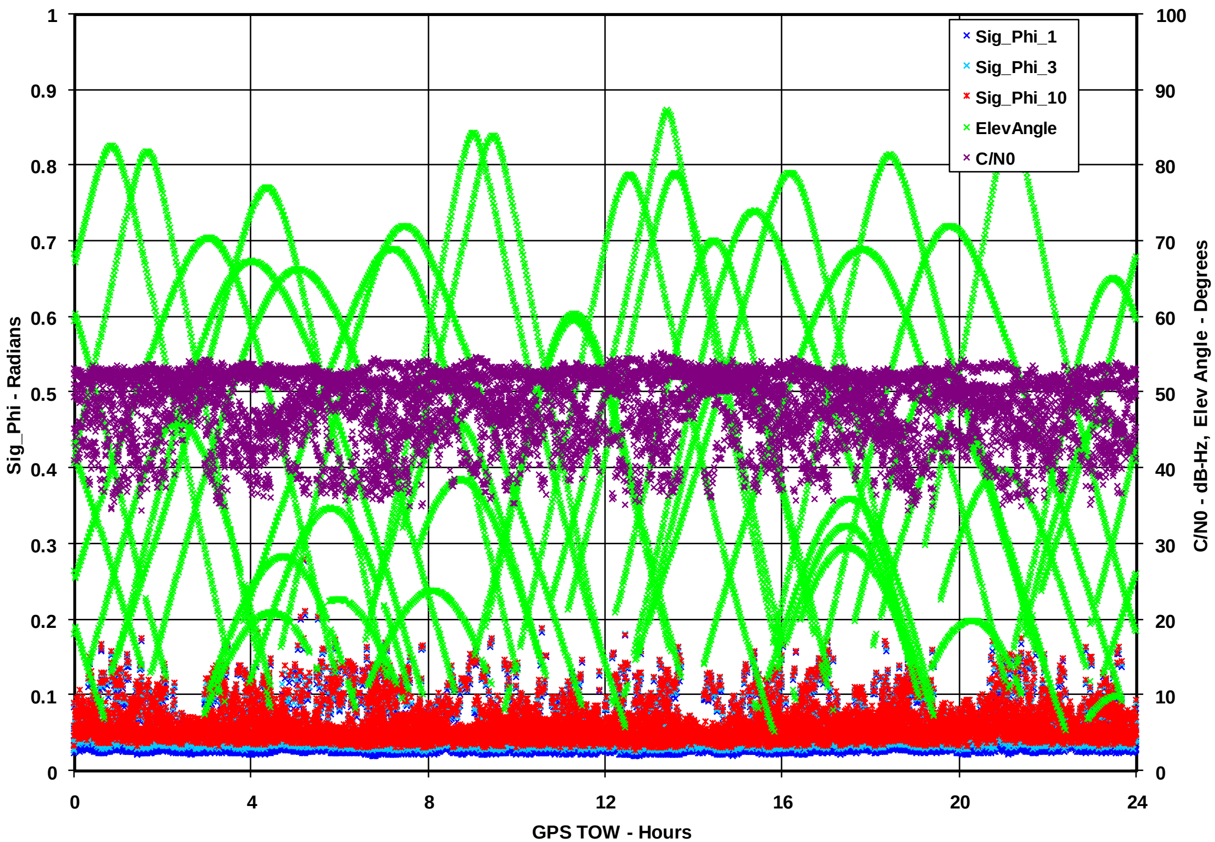


- Not necessarily implemented in all receivers, but is in Scintillation Monitors described here

Example Phase Measurements Collected in San Francisco Area

Non-Scintillation Environment

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



SBAS GEO Phase Measurements

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