Opportunistic Frequency Stability Transfer for Extending the Coherence Time of GNSS Receiver Clocks

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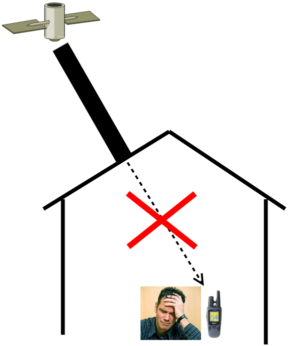
The Problem

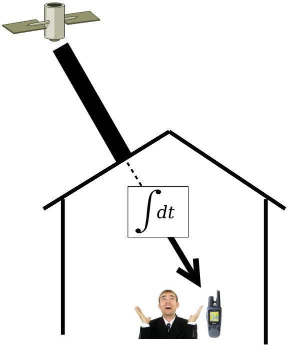
GNSS signals attenuate **30–50 dB** in indoor environments



GNSS receivers can't acquire or track indoors
with a $\mathbf{C/N_0 \approx 7}$ **dB-Hz**

A Possible Solution

Coherently integrate long enough to recover signal power!



How long do we have to wait to acquire?

Rule-of-thumb from detection theory:

$$\mathbf{SNR} \;=\; \frac{C}{N_0} \cdot T \;\geq\; \mathbf{14\ dB}$$

for fixed $P_{\mathrm{d}} = 0.95$ and $P_{\mathrm{fa}} = 0.001$

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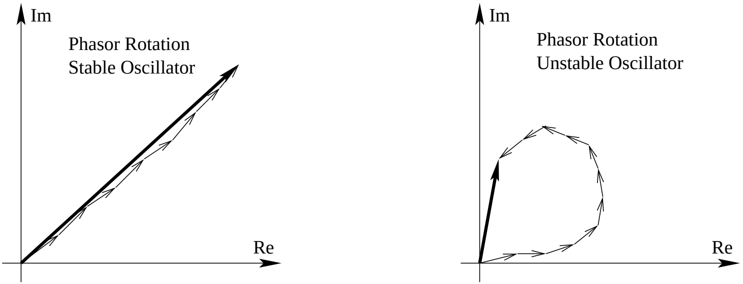

"Now's the time, the time is now"
-Led Zeppelin

.01 s/s

0.1 s/s

10^{-5} s/s

10^{-12} s/s

10^{-6} s/s

10^{-9} s/s

What Are Our Options?

1. Carry an atomic clock $\longrightarrow$
2. Use chip-scale atomic clocks in RX
3. Use small, portable OCXOs

leapsecond.com/pages/atomic-bill

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Oscillator Model

Oscillator generates **sinusoidal output** voltage:

$$v(t) = \cos(2\pi\nu_0 t + \phi(t))$$

where ν_0 is nominal frequency and $\phi(t)$ is time-varying phase.

Ideal oscillators are deterministic:

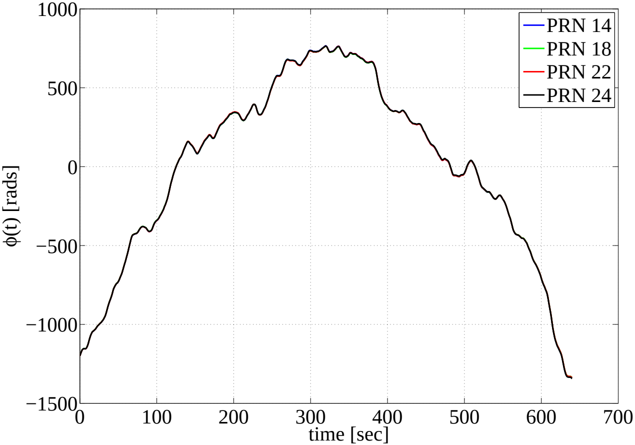
$$V(t) = \cos(2\pi\nu_0 t) \qquad \text{(no offset)}$$
$$V(t) = \cos(2\pi\nu_0 t + \Phi) \qquad \text{(constant offset)}$$

Oscillator Comparison Experiment

- Estimated phase using receiver driven by TCXO and OCXO
- Removed deterministic component due to satellite orbit leaving:
  1. ionospheric errors
  2. ephemeris errors
  3. timing errors in range computation
  4. receiver position errors
- Linear fit removes 2, 3, and 4
- Remaining phase represents phase history of the driving oscillator

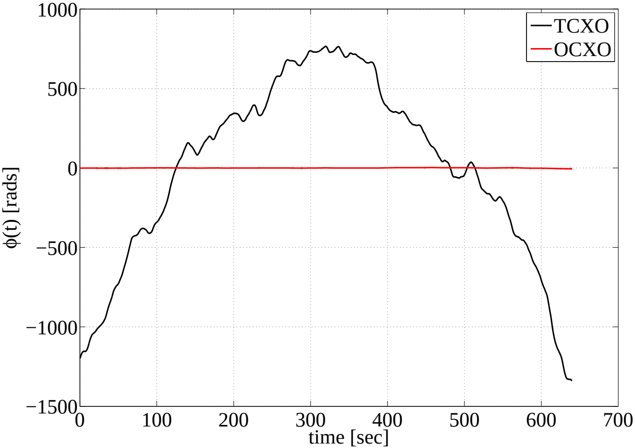
TCXO Referenced Carrier Phase Observable

$$\lambda\phi(t) = r(t) + c\left[\delta \mathbf{t_R}(t) - \delta t_S(t)\right] + \lambda(\gamma_0 - \psi_0) + \epsilon_{\mathrm{atmo}}(t) + \lambda n_\phi$$



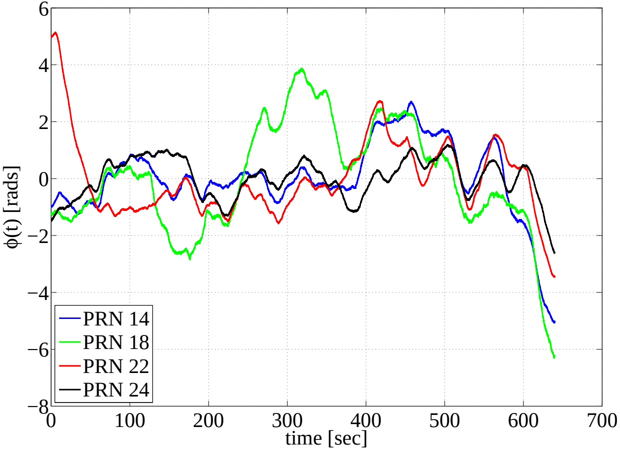
TCXO & OCXO Referenced Carrier Phase Observables

$$\lambda\phi(t) = r(t) + c\left[\delta t_R(t) - \delta t_S(t)\right] + \lambda(\gamma_0 - \psi_0) + \epsilon_{\text{atmo}}(t) + \lambda n_\phi$$

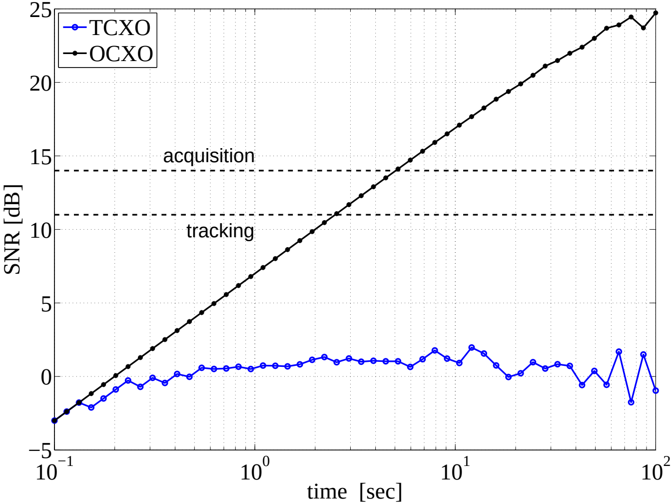


OCXO Referenced Carrier Phase Observable

$$\lambda\phi(t) = r(t) + c\,[\delta\mathbf{t_R}(t) - \delta\mathbf{t_S}(t)] + \lambda(\gamma_0 - \psi_0) + \epsilon_{\mathbf{atmo}}(t) + \lambda n_\phi$$

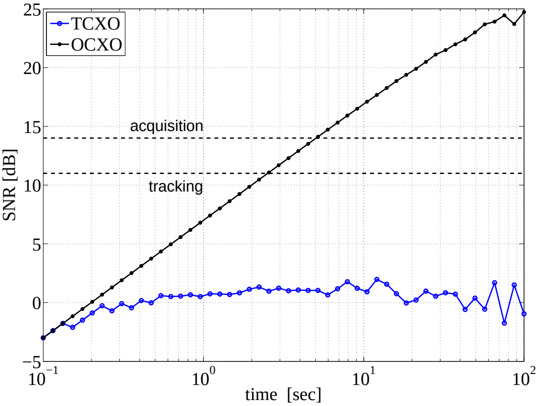


TCXO vs. OCXO



TCXO
OCXO
acquisition
tracking
SNR [dB]
time [sec]
25
20
15
10
5
0
−5
10^{-1}
10^{0}
10^{1}
10^{2}

TCXO vs. OCXO



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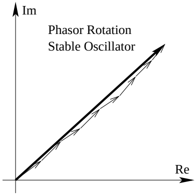
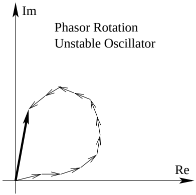


Im
Phasor Rotation
Stable Oscillator
Re

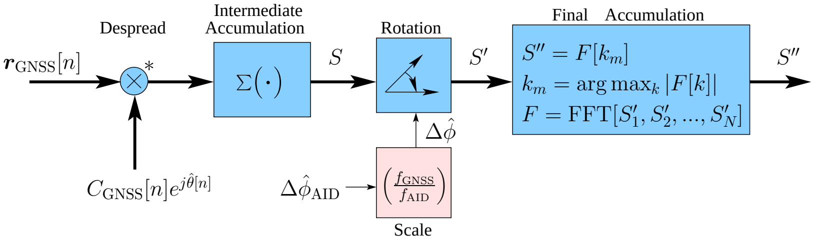


Im
Phasor Rotation
Unstable Oscillator
Re

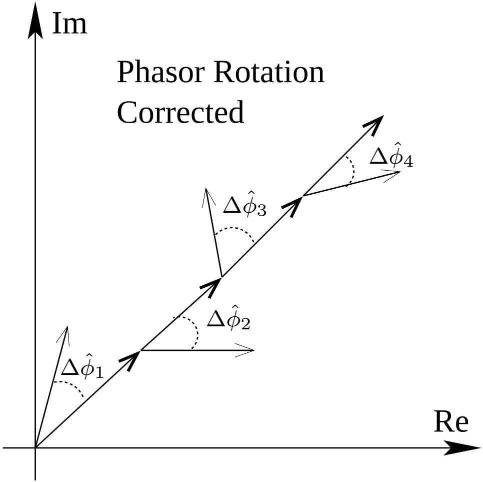
Frequency Stability Transfer Model

Rotate GNSS phase by the change in aiding signal's phase relative to local oscillator over jth intermediate accumulation interval:

$$\Delta\phi = \left(\frac{f_{\mathrm{GNSS}}}{f_{\mathrm{AID}}}\right) \cdot \left(\phi_{\mathrm{AID}}[n_j] - \phi_{\mathrm{AID}}[n_{j-1}] + n_\phi\right)$$

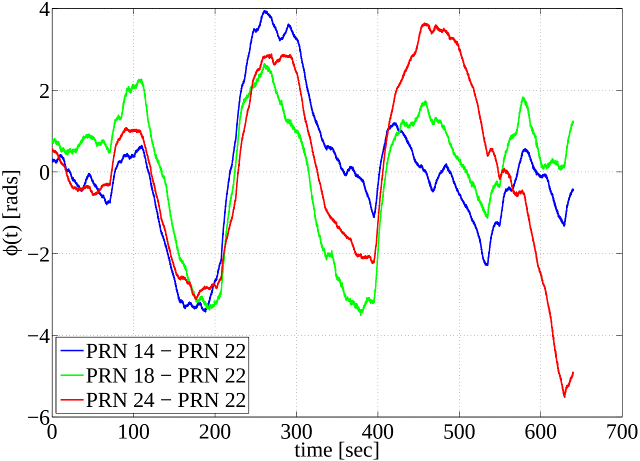


Frequency Stability Transfer Phasor "Fix-Up"



Synthetic Oscillator Phase History

Create synthetic oscillator via single differencing: $\Delta\hat{\phi}_{\mathrm{AID}} = \phi_{\mathrm{PRN\,22}}$



Ambient Stable Signals

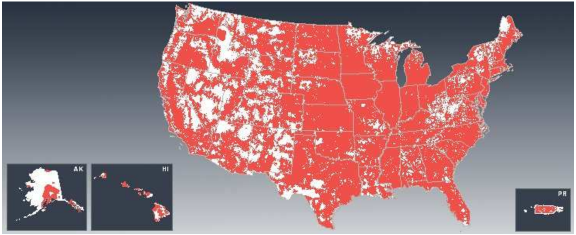
1. WWVB
   - broadcast from NIST in Colorado
   - designed to synchronize time
   - only stable locally due to ground wave propagation
   - 60 kHz broadcast

2. High-Definition TV (HDTV)
   - available in major metropolitan areas
   - signal is designed to penetrate buildings
   - approx. 700 MHz broadcast

3. Cellular Code Division Multiple Access (CDMA)

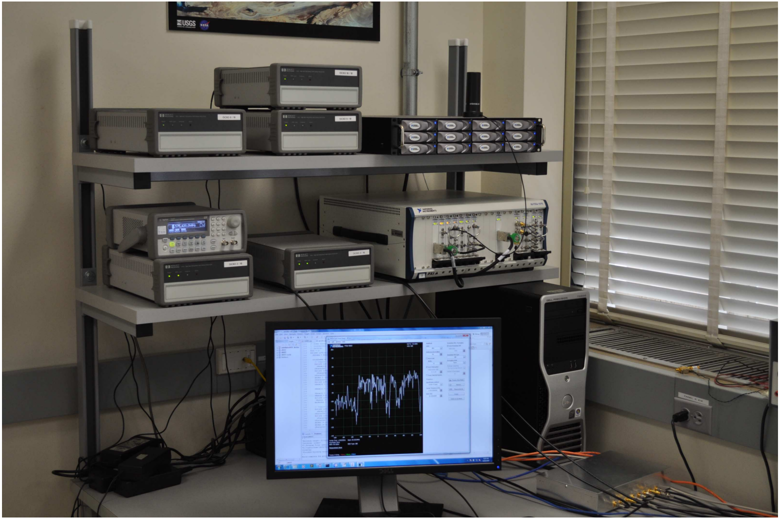
Why CDMA?

- CDMA is similar to GPS from receiver standpoint
- Widely available in U.S.
- Base station clocks very stable and synched to GPS
- UHF Band 1930–1990 MHz (tends to attenuate phase noise)
- Dataless pilot channel allows direct computation of phase

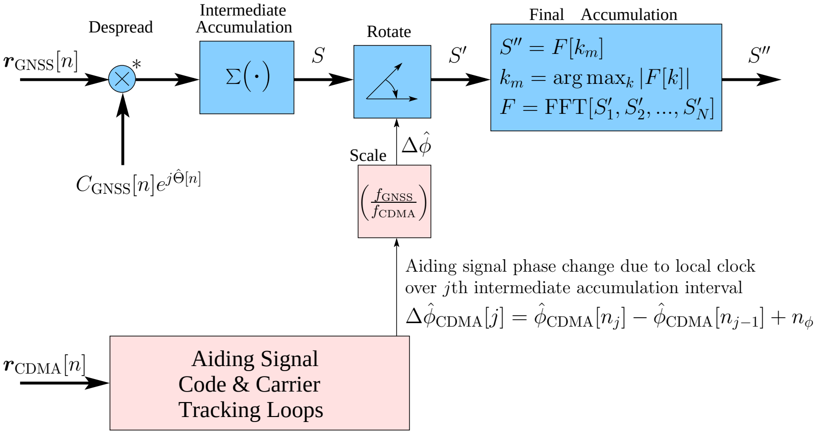


Verizon Wireless Coverage Map, 2010

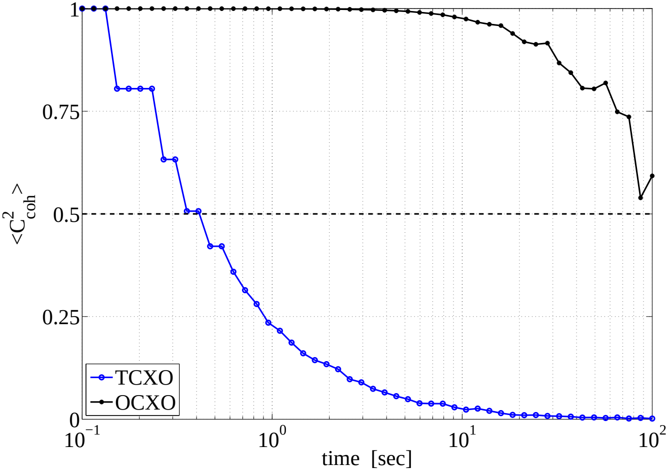
CDMA Laboratory Setup



Frequency Stability Transfer Block Diagram



Oscillator Coherence



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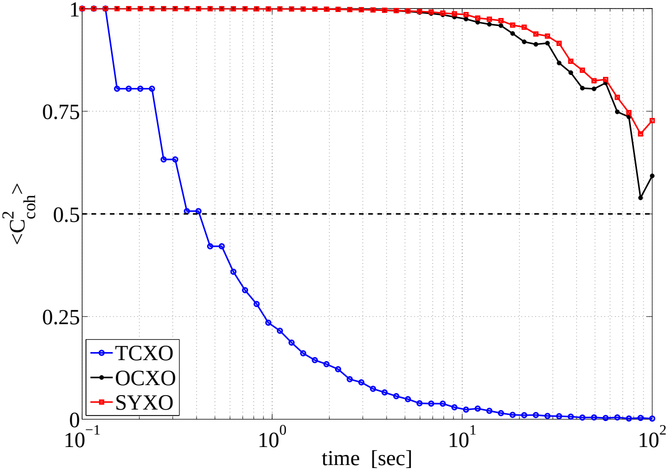

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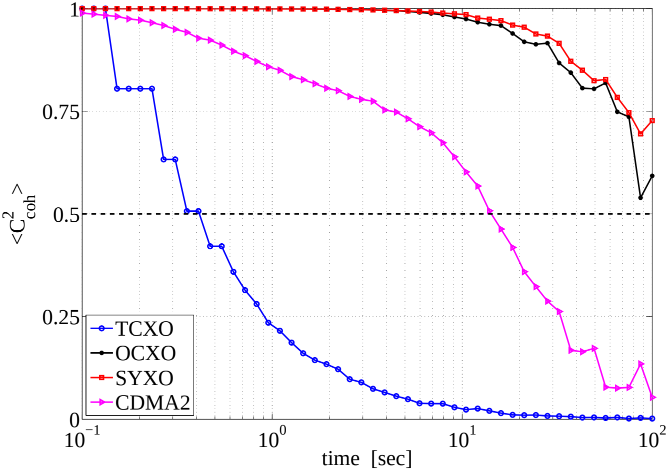
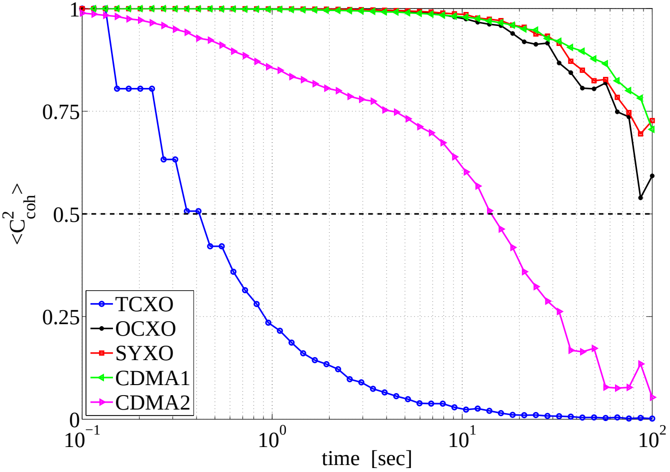
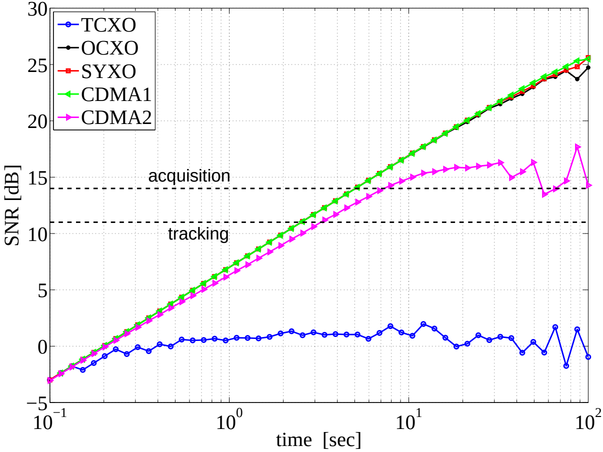


Oscillator Coherence



Coherence and SNR Relation

$$\mathrm{SNR}(t) = \langle C_{\mathrm{coh}}^2(t) \rangle \cdot t \cdot (C/N_0) \qquad \text{for fixed } C/N_0$$



Conclusion

Indoor GNSS tracking and acquisition is possible with **commercial GNSS receivers** using **stable signals of opportunity** if you're willing to hold still for a few seconds!