UTC Steering of Atomic Clocks

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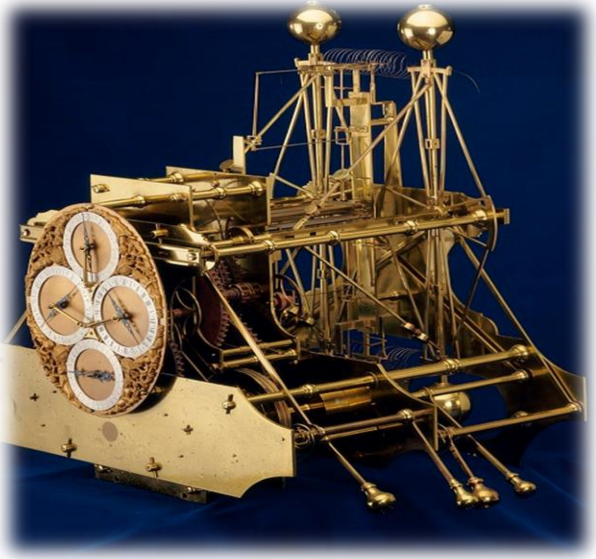
ITSF, Prague, November 1st 2016 – Session 4

V1.0 7-9-2106

Performance improvement

- Candidate for steering



Harrison's H1

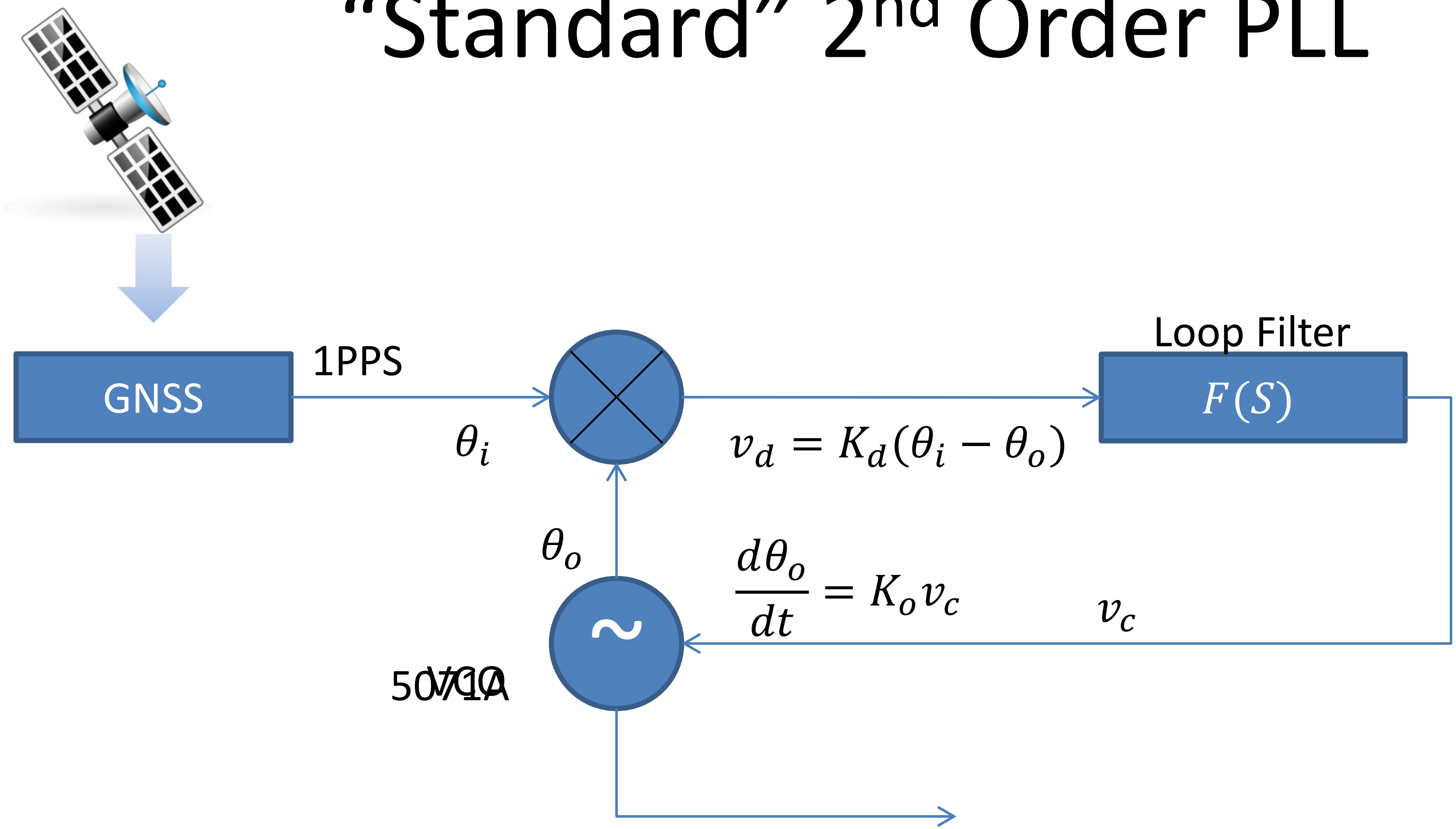
5071A Caesium
Harrison's H1

Caesium Fountain
Courtesy of NPL

5071A Basic Performance

Parameter		Standard Cesium Beam Tube. Values are within:	High-performance Cesium Beam Tube (Option 001).
Accuracy†		$\pm 1 \times 10^{-12}$	$\pm 5 \times 10^{-13}$
Frequency Change vs Environment		$\pm 1 \times 10^{-13}$	$\pm 8 \times 10^{-14}$
Warm-up Time: To normal operation status (typical) To full specifications (typical)		15 minutes 30 minutes	15 minutes 30 minutes
Reproducibility†		$\pm 1.0 \times 10^{-13}$	$\pm 1.0 \times 10^{-13}$
Long-term Stability			
Time domain Stability†	Averaging Time		
5- and 10-MHz outputs	10^4 seconds	$\leq 2.7 \times 10^{-13}$	$\leq 8.5 \times 10^{-14}$
	10^5 seconds	$\leq 8.5 \times 10^{-14}$	$\leq 2.7 \times 10^{-14}$
	5 days	$\leq 5.0 \times 10^{-14}$	$\leq 1.0 \times 10^{-14}$
	30 days	$\leq 5.0 \times 10^{-14}$	$\leq 1.0 \times 10^{-14}$
Flicker Floor Value†	Guaranteed	$\leq 5.0 \times 10^{-14}$	$\leq 1.0 \times 10^{-14}$
	Typical††	$\leq 1.5 \times 10^{-14}$	$\leq 5.0 \times 10^{-15}$

“Standard” 2nd Order PLL

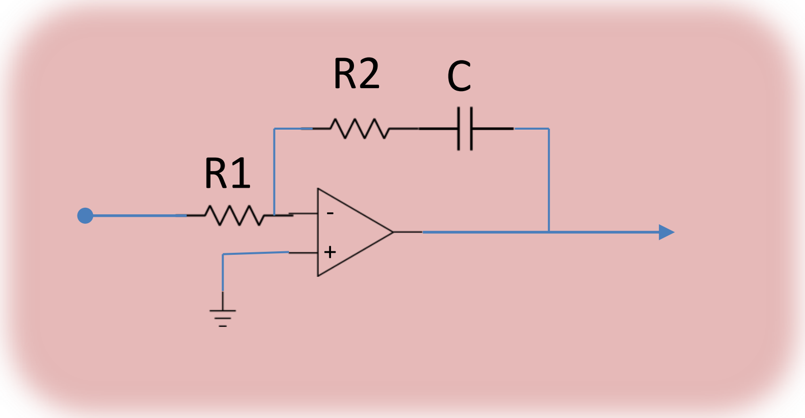


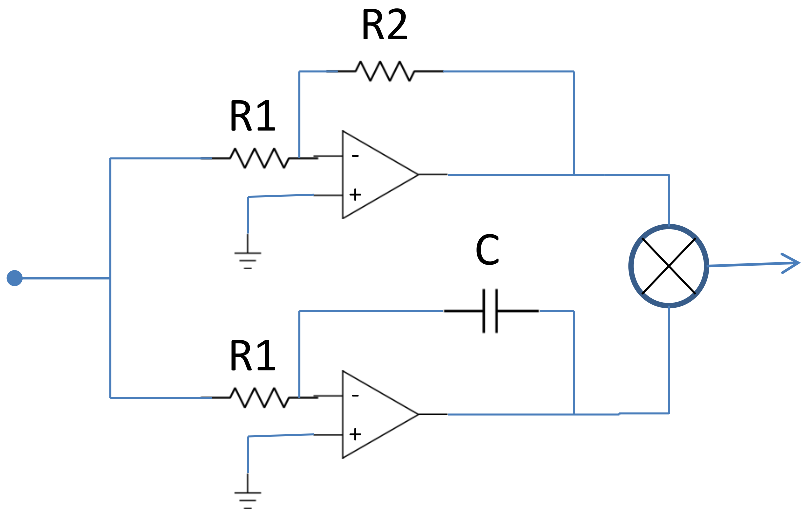
Classic Active loop filter

Natural frequency $\omega_n = \left(\frac{K_o K_d}{\tau_1}\right)^{1/2}$

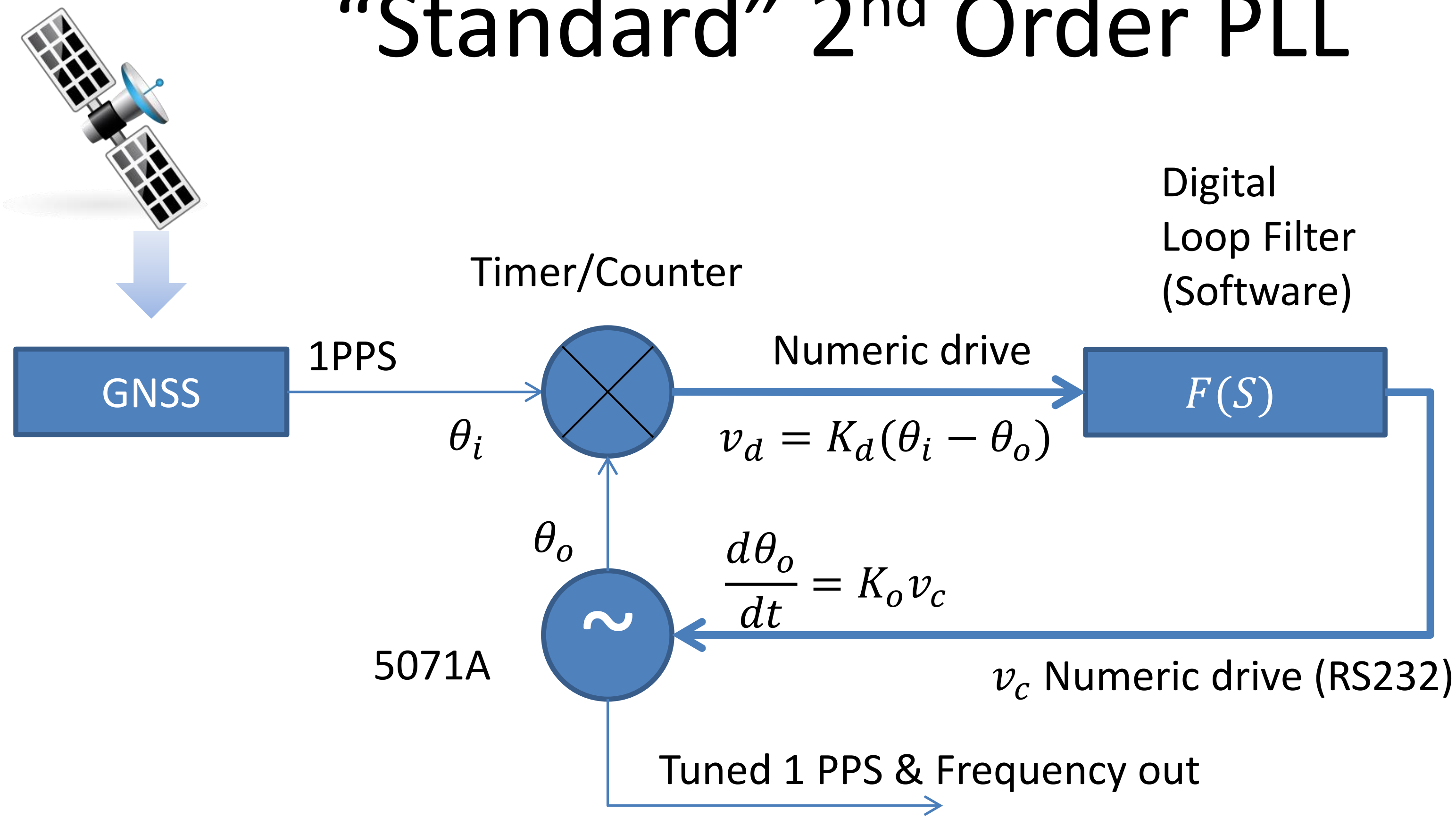
Damping Factor $\zeta = \frac{\tau_2}{2}\left(\frac{K_o K_d}{\tau_1}\right)^{1/2} = \frac{\tau_2 \omega_n}{2}$

Where:- $\tau_1 = R_1 C$ and $\tau_2 = R_2 C$





"Standard" 2nd Order PLL

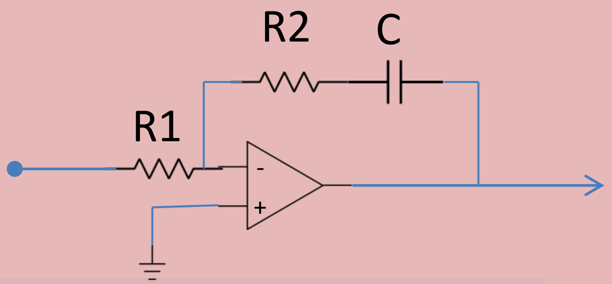


Set for 30 days settling times

Natural frequency $\omega_n = (\frac{K_o K_d}{\tau_1})^{1/2}$

Damping Factor $\zeta = \frac{\tau_2}{2}(\frac{K_o K_d}{\tau_1})^{1/2} = \frac{\tau_2 \omega_n}{2}$

Where:- $\tau_1 = R_1 C$ and $\tau_2 = R_2 C$



R1 = 1 Ω

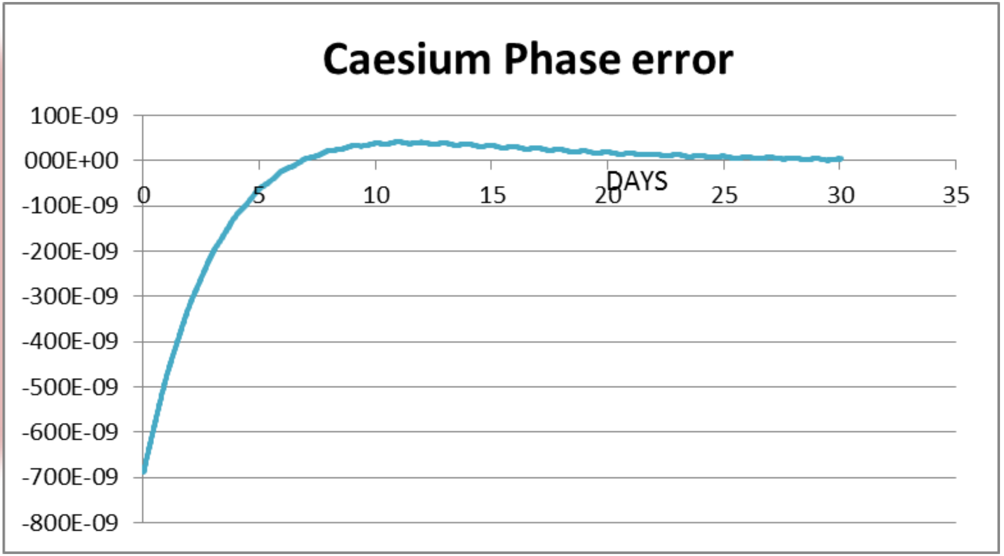
R2 = $5 * 10^9$ Ω = 5000MΩ

C = 1.6 F

Caesium gives $k_o = 1 * 10^{-15}$

Phase detector $k_d = 2 * \pi$

- Unrealistic test times



Pro's Cons

- Very good stability (Simulated)
- Caesium flicker noise dominates at output
  - $\leq 5 * 10^{-14}$

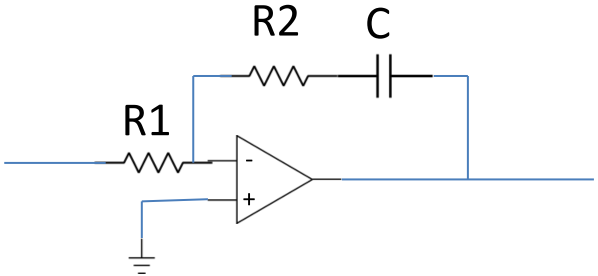
- Unrealistic development/test times
- Very long start-up times

Faster time constant

Natural frequency $\omega_n = \left(\frac{K_O K_d}{\tau_1}\right)^{1/2}$

Damping Factor $\zeta = \frac{\tau_2}{2}\left(\frac{K_O K_d}{\tau_1}\right)^{1/2} = \frac{\tau_2 \omega_n}{2}$

Where:- $\tau_1 = R_1 C$ and $\tau_2 = R_2 C$

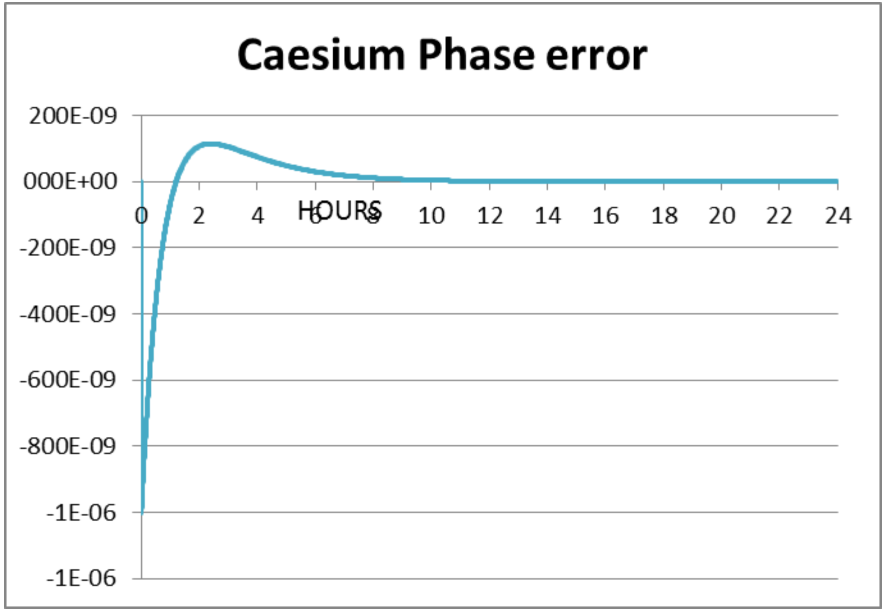


- Better test times
- Stick with this?

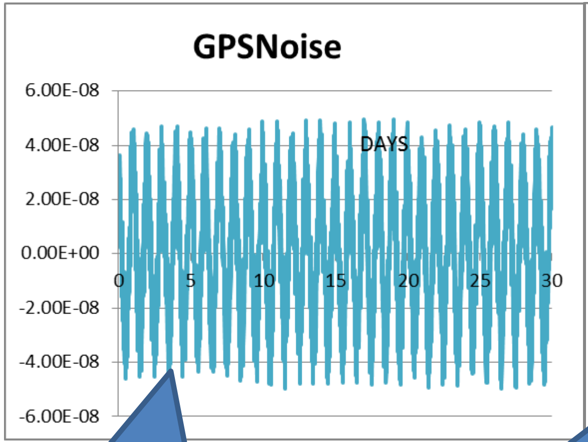
R1 = 1 Ω

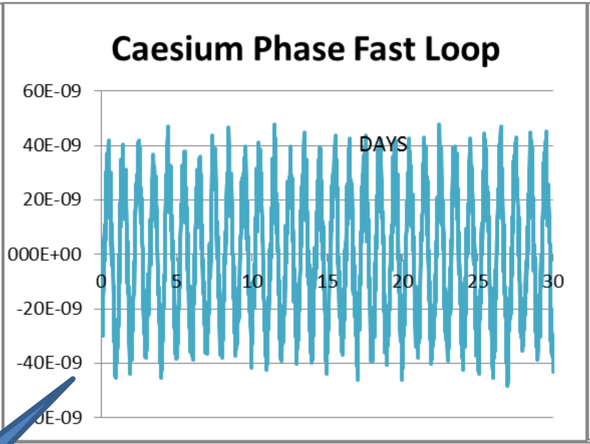
R2 = 5 $* \ 10^{91}\Omega$

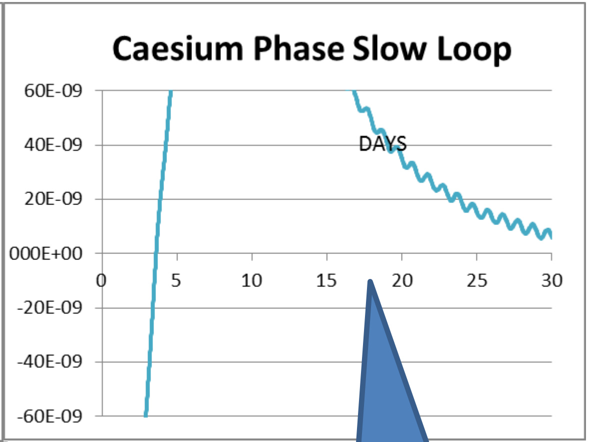
C = $2.16\ uF$



GPS Noise

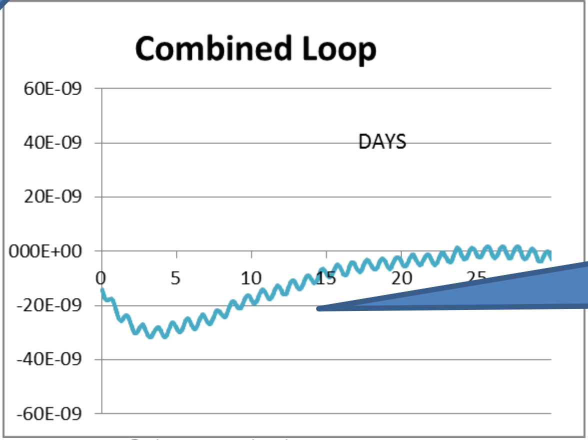






30ns P-P Diurnal
20ns P-P Random

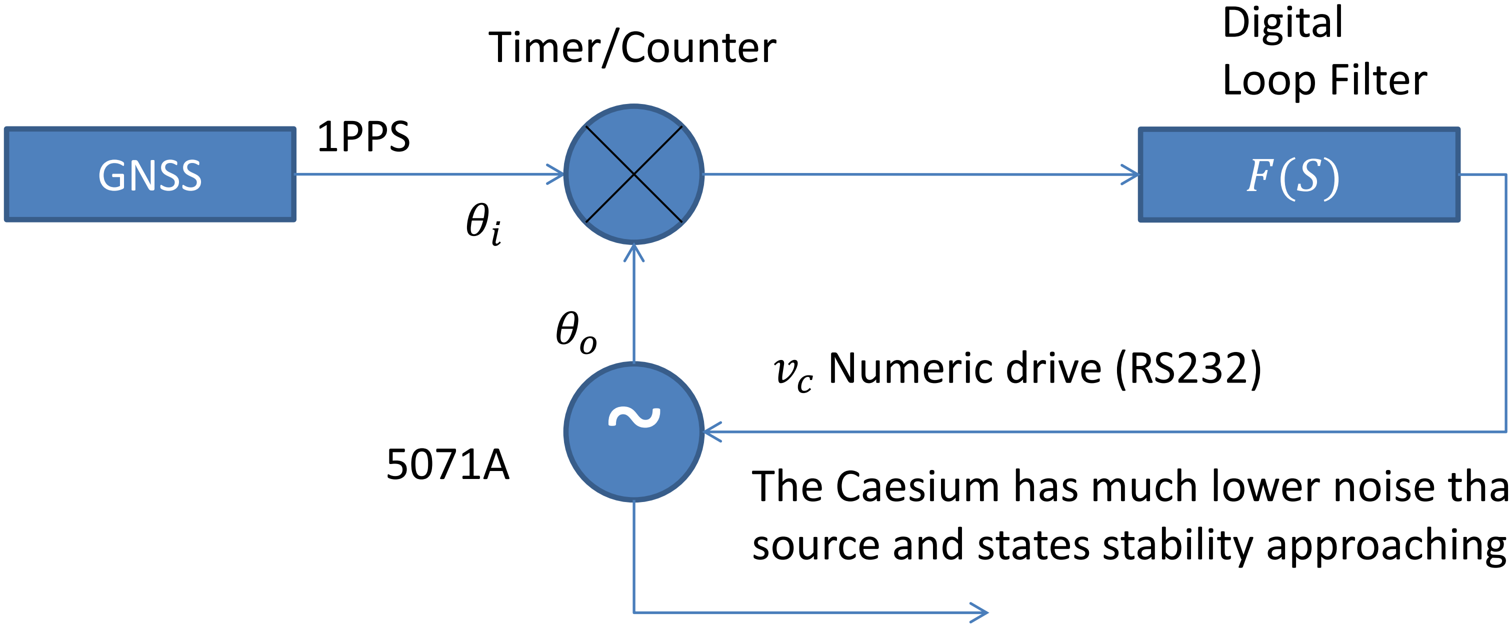
Most noise passed through



Good noise rejection but slow settling

Optimal – good noise rejection – serttling offset minimised

“Measuring” Performance

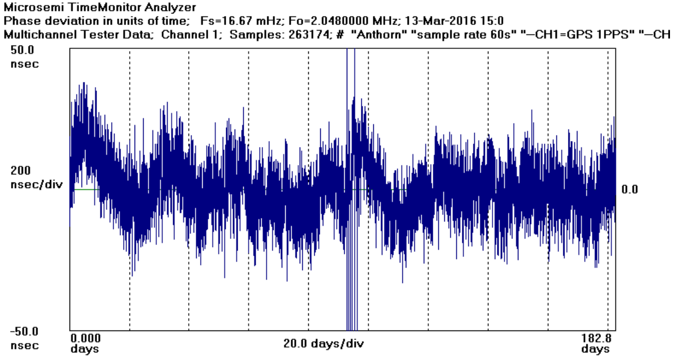


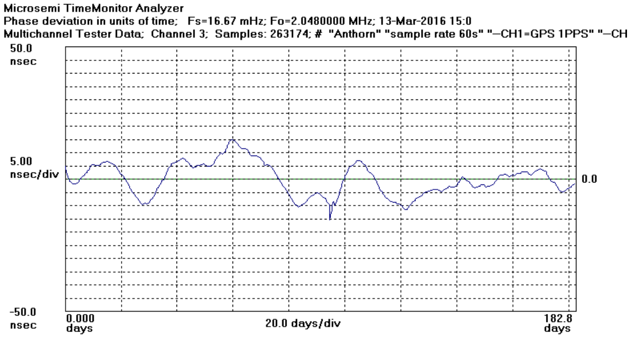
The Caesium has much lower noise than the source and states stability approaching $1 * 10^{-14}$

Δ We can infer phase system performance by differentiating the tuning commands.

No Hydrogen Maser required

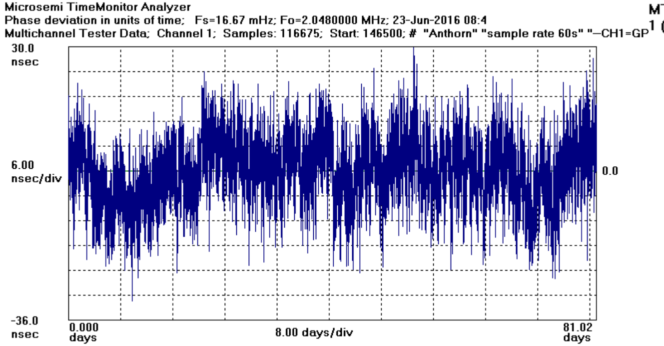
Real system results

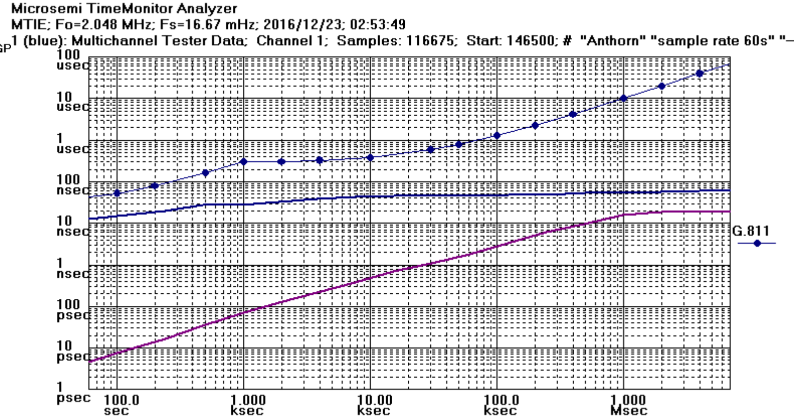




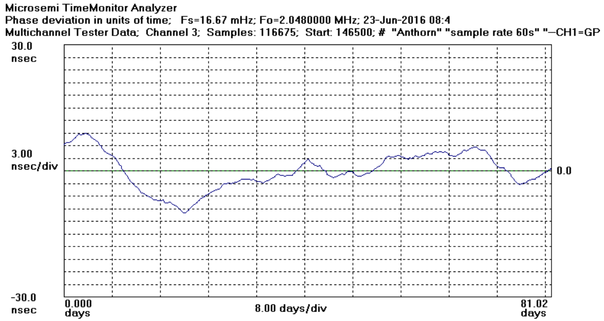
- Output from Phase detector
  - GPS Noise dominates
  - Peaks at 94 days are Space Weather event 1.5us Offsets
- Estimated output from Steering
  - Noise reduced to 15ns P-P

Real system results (60 days*)



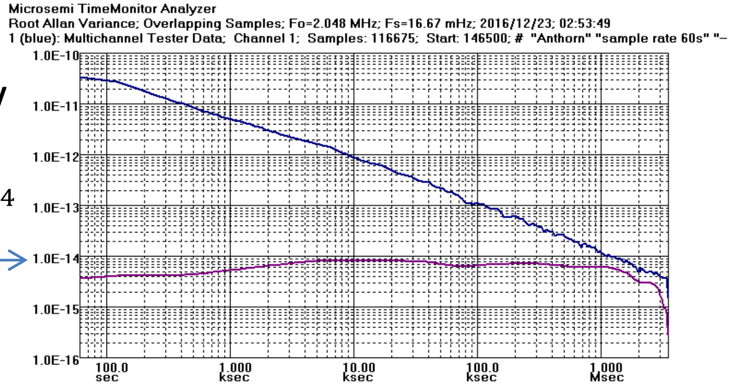


MTIE



ADEV

ADEV Below $1 * 10^{-14}$



* Last 60 days only to avoid space weather event in live data

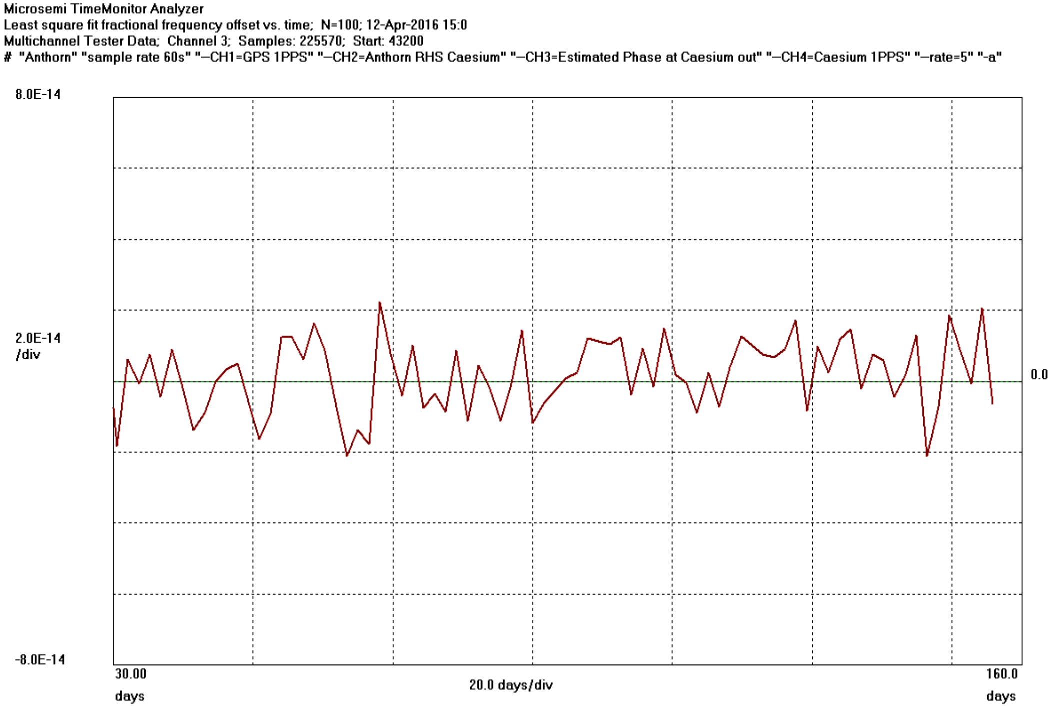
Holdover

- What triggers Holdover
  - Source failure
  - Unusual source noise excursions
  - Space Weather (Predicted and/or Detected)
  - Planned maintenance
  - Detected Jamming/Spoofing (GNSS)
  - Can afford to be paranoid about source health

Holdover Performance

- Assuming tuned Caesium better than $5 * 10^{-14}$
  - Better than $5ns$ per day
  - Long term as per 5071A datasheet
    - Compound of tuning error + Caesium. Better than $10ns$ per day
- Return from Holdover
  - Slow response only – so up to 30 days to leak out acquired error from holdover period. After 10 days in holdover – may be worth considering restart if 100ns is outside of desired specification

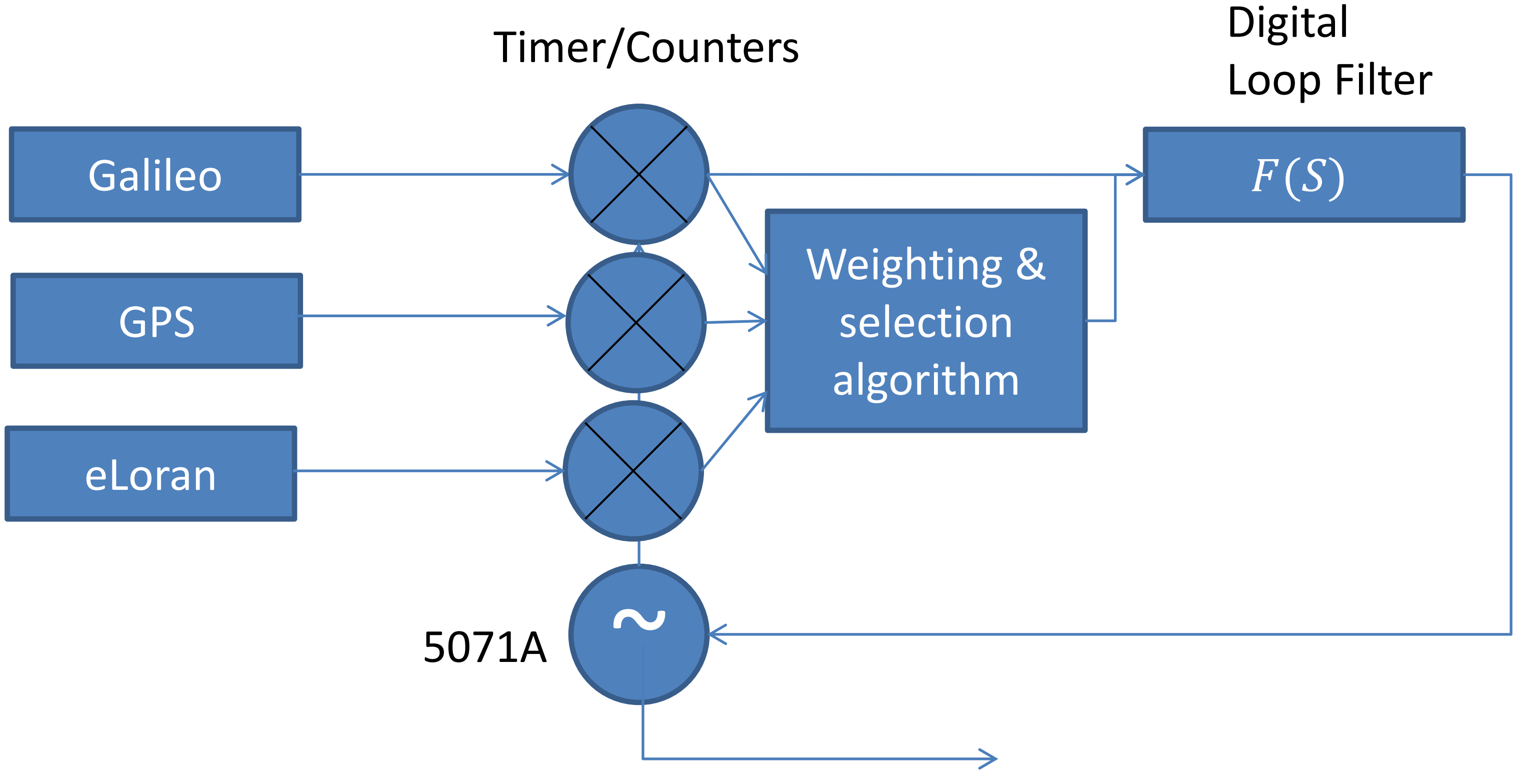
Real system results (160 days*)



Frequency statistics	
Mean	2.3E-15
Standard Error	2.8E-17
Median	2.2E-15
Mode	-1E-14
Standard Deviation	1.3E-14
Sample Variance	1.7E-28
Minimum	-3E-14
Maximum	3.7E-14
Confidence Level(95.0%)	5.4E-17

* Excludes first 30 days loop settling time

Multiple sources



Lessons

- Long time constants = Very long test/development
- Many noise sources still to be identified
  - The systems are not immune to local conditions
- Deployed systems must take account of start-up times
- Calibration difficult without a National Laboratory comparison

Thankyou

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